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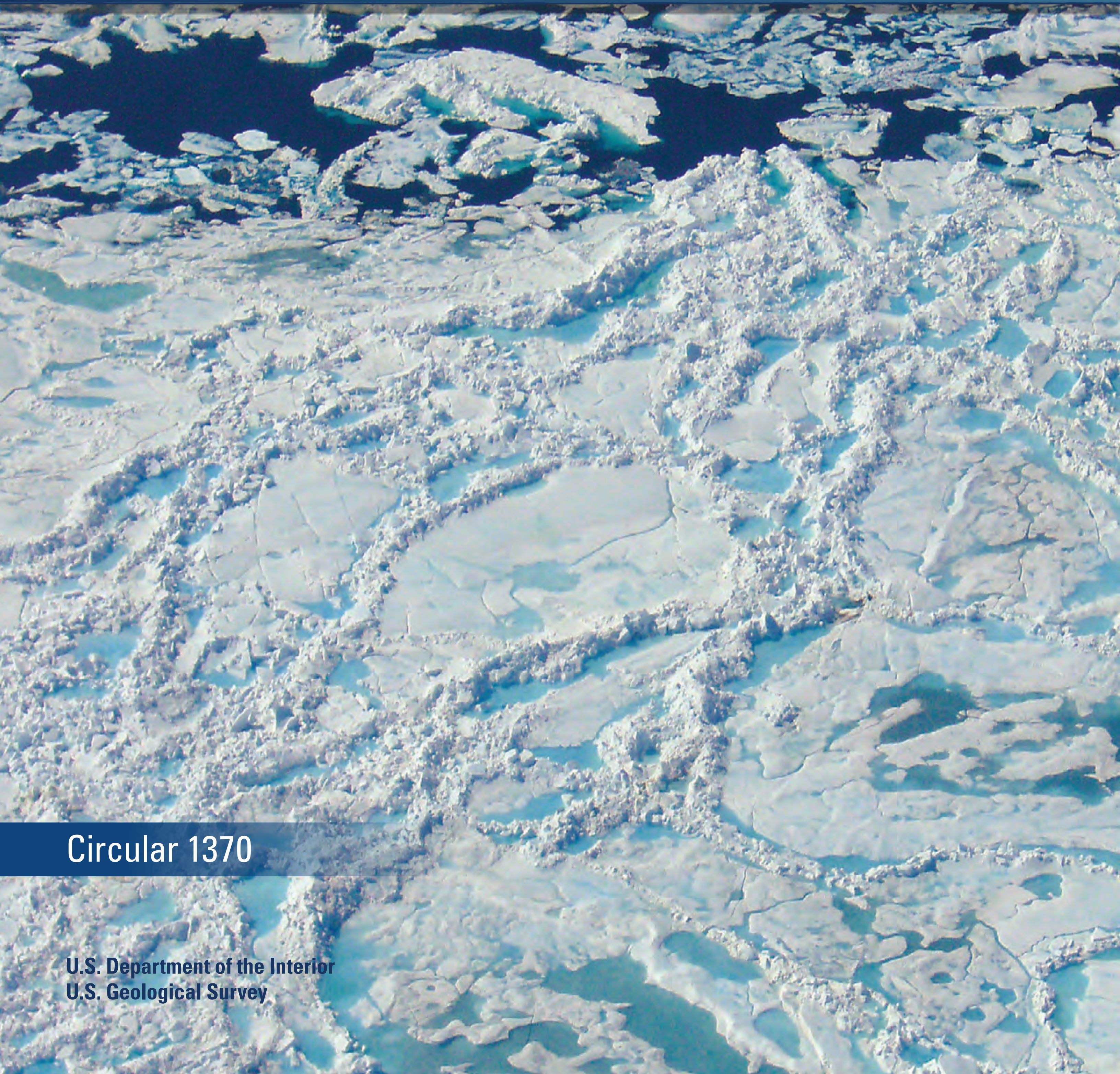
An Evaluation of the Science Needs to Inform Decisions on Outer Continental Shelf Energy Development in the Chukchi and Beaufort Seas, Alaska



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U.S. Geological Survey

Cover: Photograph depicts first-year summer sea ice with melt ponds typically found in the Chukchi Sea, Alaska. Photograph taken 100 nautical miles offshore west of Barrow, Alaska, July 8, 2010. (Photograph from U.S. Geological Survey files.)

An Evaluation of the Science Needs to Inform Decisions on Outer Continental Shelf Energy Development in the Chukchi and Beaufort Seas, Alaska

Edited by Leslie Holland-Bartels and Brenda Pierce

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

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Contents

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)

Conversion Factors—Continued

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
	Pressure	
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.01	bar
kilopascal (kPa)	0.2961	inch of mercury at 60°F (in Hg)
kilopascal (kPa)	0.1450	pound-force per inch (lbf/in)
kilopascal (kPa)	20.88	pound per square foot (lb/ft^2)
kilopascal (kPa)	0.1450	pound per square inch (lb/ft^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

Acronyms

2-D	two-dimensional
3-D	three-dimensional
ACEX	Arctic Coring Expedition
AEPS	Arctic Environmental Protection Strategy
ANILCA	Alaska National Interest Lands Conservation Act
ANIMIDA	Arctic Nearshore Impact Monitoring in the Development Area
ANS	Alaska North Slope
AOGCM	Atmosphere-Ocean General Circulation Model (global climate model)
AOOS	Alaska Ocean Observing System
AR4	IPCC Fourth Assessment Report
ARCS	ARCtic Satellite
ARRT	Alaska Regional Response Team
ASD	Azimuthal Stern Drive
ASRC	Arctic Slope Regional Corporation
BIOS	Baffin Island Oil Spill
BLM	Bureau of Land Management
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BOWFEST	Bowhead Whale Feeding Study
BSIERP	Bering Sea and Aleutian Island Integrated Ecosystem Research Program
BWASP	Bowhead Whale Aerial Survey
cANIMIDA	Continuation of the Arctic Nearshore Impact Monitoring in the Development Area
CANUSDIX	Canada-United States Dixon Entrance
CARA	Circum-Arctic Resource Appraisal
CEQ	Council on Environmental Quality
CIP	Capital Improvement Program
COMIDA	Chukchi Offshore Monitoring in Drilling Area Program
DASARs	Directional Autonomous Seafloor Acoustic Recorders
DBO	Distributed Biological Observatory
DPS	Distinct Population Segments
DOI	Department of Interior
EIS	Environmental Impact Statement
EP	Exploration Plan
EPPR	Emergency Prevention Preparedness and Response
ERA	Environmental Resource Area
ERMA	Emergency Response Management Application
ESA	Endangered Species Act
EVOS	*Exxon Valdez* Oil Spill
G&G	Geological and Geophysical
GOM	Gulf of Mexico
GPR	Ground Penetrating Radar
GPS	Global Positioning System
IARPC	Interagency Arctic Research Policy Committee
IBA	Important Bird Areas
IPCC	Intergovernmental Panel on Climate Change
ISB	*In-situ* Burning
JIP	Joint Industry Project
LOIS	Lamor Oil Ice Separator
LTK	Local Traditional Knowledge
MCDA	Multi-Criteria Decision Analysis
MMPA	Marine Mammal Protection Act
MMS	Minerals Management Service
MOR	Mineral-to-Oil Ratio
MORICE	Mechanical Oil Recovery in Ice-Infested Waters
NEPA	National Environmental Policy Act
NGO	Non-governmental Organization
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOBE	Newfoundland Offshore Burn Experiment
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NPR-A	National Petroleum Reserve-Alaska
NRC	National Research Council
NRDA	National Resource Damage Assessment

Acronyms—Continued

NSB	North Slope Borough
NSF	National Science Foundation
OCS	Outer Continental Shelf
OMA	Oil Mineral Aggregates
OPA 90	Oil Pollution Act of 1990
OSRA	Oil Spill Risk Analysis
OWM	Oil Weathering Model
PAH	Polycyclic aromatic hydrocarbons
PAME	Protection of the Arctic Marine Environment
PLFs	pingo-like-features
PTS	Permanent Threshold Shift
R&D	Research and Development
rms	Root-mean-squared
SDM	Structured Decision Making
SEL	Sound Exposure Level
SERVS	Ship Escort/Response Vessel System
SLP	Sea-Level atmospheric Pressure
SPL	Sound Pressure Level
SPM	suspended particulate matter
SRES	Special Report on Emissions Scenarios
TAPS	Trans-Alaska Pipeline System
TPS	Total Petroleum System
TTS	Temporary Threshold Shift
UNCLOS	U.N. Convention of Law of the Sea
USARC	U.S. Arctic Research Commission
USCGC	U.S. Coast Guard Cutter
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WAF	Water Accommodated Fraction
WSCs	Water Soluble Components

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Chapter 1

Framing the Assignment and Process

By Leslie Holland-Bartels and Brenda Pierce

"As a significant owner of Arctic resources, the United States has a responsibility to know what it owns, to understand basic biology, geology, and natural history of its assets, and to understand the population dynamics of the living resources it manages—alone, or in concert with the State of Alaska and other Nations"
(U.S. Arctic Research Commission, 2010).

"Among the greatest uncertainties in future energy supply and a subject of considerable environmental concern is the amount of oil and gas yet to be found in the Arctic"
(Gautier and others, 2009).

Background

On March 31, 2010, Secretary of the Interior Ken Salazar announced a national strategy for Outer Continental Shelf (OCS) oil and gas development. In that announcement, the Administration outlined a three-pronged approach (U.S. Department of the Interior, 2010a):

> *Development:* "…expand development and production throughout the Gulf of Mexico, including resource-rich areas of the Eastern Gulf of Mexico…"
>
> *Exploration:* "…expand oil and gas exploration in frontier areas, such as the Arctic Ocean and areas in the Atlantic Ocean, to gather the information necessary to develop resources in the right places and the right ways."
>
> *Conservation:* "…calls for the protection of special areas like Bristol Bay in Alaska…national treasure[s] that we must protect for future generations."

In a companion announcement (U.S. Department of the Interior, 2010b), within the Administration's "Exploration" component, the Secretary asked the U.S. Geological Survey (USGS) to conduct an initial, independent evaluation of the science needs that would inform the Administration's consideration of the right places and the right ways in which to develop oil and gas resources in the Arctic OCS, particularly focused on the Beaufort and Chukchi Seas (fig. 1–1). Why the focus on the Arctic OCS? First, oil resource potential is significant. On Alaska's North Slope, the Nation's largest oil field—Prudhoe Bay—has been in production for several decades. Oil has been produced from the Beaufort Sea OCS since the early 2000s and the Arctic OCS potential for production of additional oil and gas resources is very high. Accessing such resources will require development not only in the offshore waters of the Arctic OCS, but also additional infrastructure in the coastal areas of Alaska's North Slope. Beyond energy potential, this area (or region) supports unique fish and wildlife resources and ecosystems; and indigenous peoples who rely on these resources for subsistence. While the potential for and interest in energy resources is clear, there is significant public discourse over the Nation's abilities to develop such resources safely, to understand environmental and social consequences of any development, and to frame effective impact prevention and mitigation strategies. That discourse often revolves around different views on the sufficiency of the scientific information available to consider energy development decision options and to understand environmental sensitivity in this frontier area.

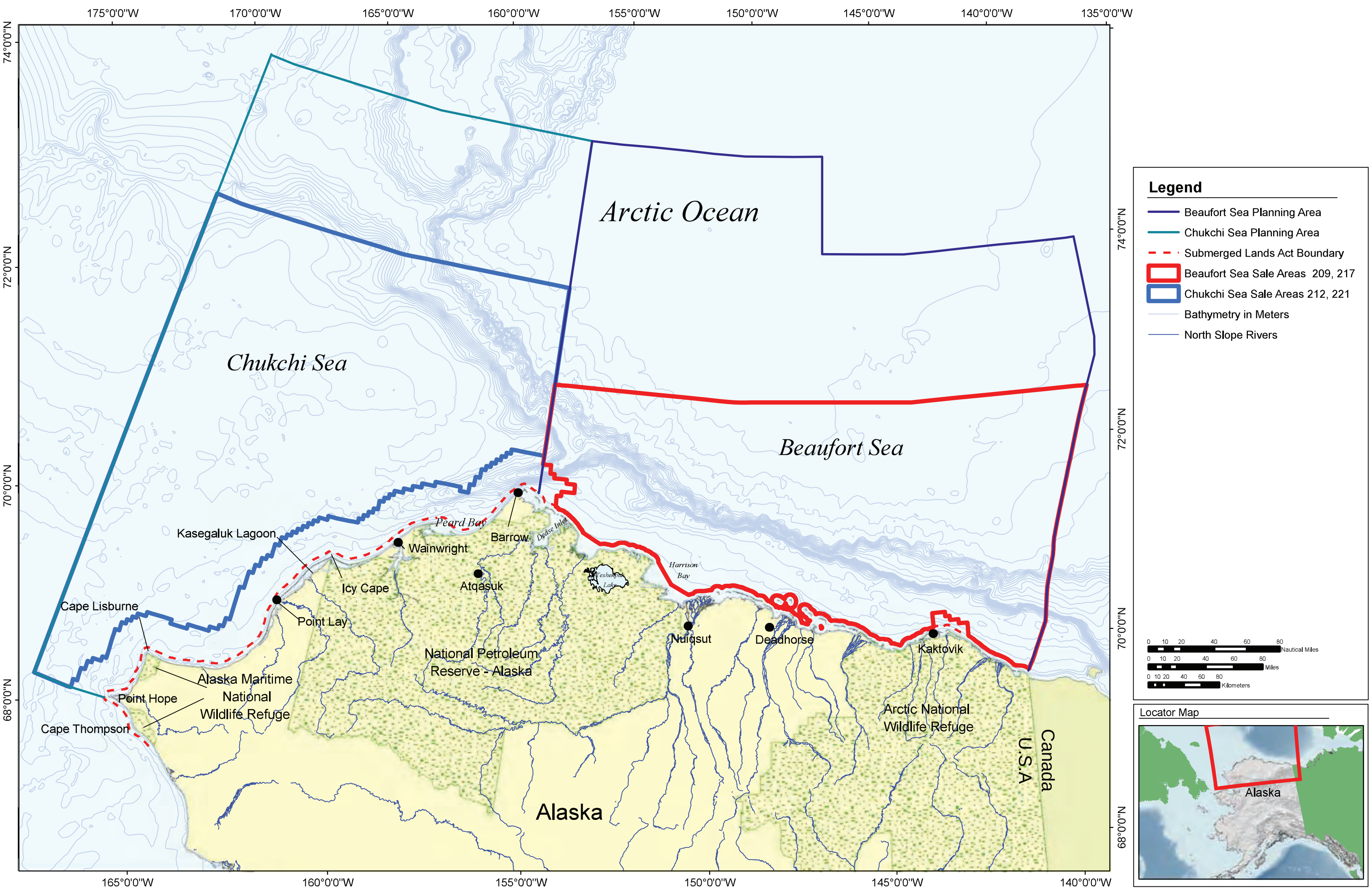

Figure 1–1. North Slope of Alaska from Point Hope to the United States–Canada border showing principal coastal communities, Outer Continental Shelf oil and gas leasing areas, and major Federal land holdings. From BOEMRE, the Bureau of Ocean Energy Management, Regulation and Enforcement, formerly the Minerals Management Service (2008).

Thus, the USGS was asked to summarize key existing scientific information, develop a rapid process to identify where knowledge gaps exist, and provide initial guidance of what research is needed to improve decision making. The USGS was asked to ensure that its analyses considered some key points already identified to the Secretary by a broad spectrum of vested parties. These four Issue Topics were articulated to the USGS as:

- **Climate Change Considerations:** How the likely effects of climate change over the expected lifetime of the development activities will either mitigate or compound the impacts from energy production in the Arctic environment?
- **Marine Mammals and Seismic Activities**: What effect seismic exploration activities may have on marine mammals, especially any particular concerns that may be unique to the Chukchi and Beaufort Seas?
- **Oil-Spill Response:** What is the research needed to allow for an effective and reliable oil-spill response in ice-covered regions?
- **Cumulative Impacts:** What are the cumulative impacts of potential energy development, including infrastructure and maintenance activities, off-shore and on-shore, related to ecosystems, landscapes, seascapes, water quality, seafloor and land stability, and subsistence hunting and fishing?

The Process

Our team (hereafter called the USGS OCS Team) was formed in May 2010 and comprised of scientists from the USGS with the assignment to conduct the requested analyses and to provide scientific recommendations for the four Issue Topics, above, to the Secretary of the Interior in April 2011. We conducted an initial examination of a wide range of public policy documents from vested parties and materials from the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE, formerly the Minerals Management Service), industry, non-governmental organizations, and others that affirmed views that “science gaps” and “sufficient science” vary. Interpretation of concepts are dynamic, tied to an individual’s or organization’s held beliefs, and what they most strongly value within their thought process when dealing with complexity and uncertainty. The decision(s) to develop resources in the Arctic is inherently complex because it must consider factors such as the significant economic and environmental stakes and risks, multiple objectives, and high levels of project uncertainty inherent in working in a frontier environment. The decision(s) also is difficult because of the complexity of the multiplicity of choices needing to be made and organizations that must make those choices. In a regulatory sense, BOEMRE is the vested decision body for the Federal government regarding oil and gas development in the Arctic OCS. However, in reality there are multiple Federal, State, and local and regional communities and organizations that influence the ultimate decision outcome (fig. 1–2), each of which has downstream responsibilities in the oil and gas leasing process and can have differing views of what science information is essential. The public also provides input during the Federal leasing process at many points (fig. 1–2). In the larger public policy arena, public opinion also influences both the political domain and the use of litigation tools. Here, the views of science sufficiency can be quite different. Thus, the USGS OCS Team took an inclusive approach to its “science gap and sufficiency” assignment by not only examining available literature, but also by gathering input from many elements of the “organization” that ultimately influence decisions about what science is “needed” for oil and gas development in the Arctic OCS. We analyzed some 400 relevant reports, workshop findings, policy documents (for example, see Regional Government, Environmental Group, and International Perspectives), and web sites, as well as key scientific journal literature. In addition, we held seven structured information sessions with key vested parties in which we ultimately engaged 46 entities (see Entities that Participated in Various USGS OCS Team Information Gathering Sessions). All of this information was incorporated into our considerations as we independently addressed the four topics requested by the Secretary of the Interior.

We started our process by conducting one-on-one expert consultations with some 20 entities. These parties had management responsibilities, had published key policy statements on relevant topics, or were conducting scientific projects with a nexus to our assignment. These discussions assisted us in understanding current views on scientific gaps, identifying key documents, and informing us of new and emerging scientific efforts or analyses.

Figure 1–2. This simplified schematic illustrates some of the decision points within two initial planning phases of the extensive Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) oil and gas leasing process—the 5-Year Plan and Individual Lease Sale processes, for which scientific information is required. BOEMRE has many decision points (blue) requiring scientific information. Examples of inputs also are shown from the public (brown) and other agencies including the U.S. Environmental Protection Agency (USEPA, green) and Federal natural resource agencies (U.S. Fish and Wildlife Service–USFWS and National Oceanic and Atmospheric Administration–NOAA, orange). (NPDES, National Pollutant Discharge Elimination System.)

Components of an overall policy position of a key regional government likely affected by Federal decisions on Arctic Outer Continental Shelf oil and gas development (North Slope Borough, 2009).

Regional Government Perspective

Baseline Science

- Require adequate baseline data prior to activity
- Support collaborative approaches
- Pre-leasing activities should mirror Bureau of Land Management's (BLM) pre-activity study program

Stricter Regulation

- Use of pipelines versus tanker transportation
- Apply regulations and stipulation more rigorously
- Improve standards in leasing process
- Require negotiation of Conflict Avoidance Agreements for marine mammals beyond whales

Cumulative Impacts

- Require area-wide impact discussions in impact statements and environmental assessment documents
- Include socio-cultural impacts
- Stipulate limits on projects
- Effective Coast Guard presence required
- Fund year-round oceangoing and airborne response capacities

Revenue Sharing

- Include in all development phases
- Use BLM Impact Aid Program or other early funding
- Broaden Coastal Impact Aid Program fund uses

Discharge/Emissions

- Require zero-volume discharge
- Subsistence consideration in Clean Water Act
- Do not allow "disaggregation" of an operation into separate emission permits, permit as one

Oil-Spill Prevention and Response

- Best available technologies
- Provable cleanup technologies
- Real-world demonstrations of capacities

Compulsory Marine Pilotage

- Require State-licensed marine pilots

Components of the overall policy position of a key conservation group on Federal decisions related to Arctic Outer Continental Shelf oil and gas development (Pew Environment Group, 2010).

Environmental Group Perspective

Science Plan

- Complete comprehensive plan
- Research and monitoring
- Independent science gap analysis
- Define ecologically sensitive areas and protect
- Incorporate traditional knowledge
- Increase research funding and collaboration

Oversight of Oil Development

- Review of plans and permits must be free of undue industry influence
- Review and oversight must involve all relevant agencies
- Enhanced inspections and testing
- Citizens' advisory councils incorporated into oversight
- Adequate funding for oversight

Oil-Spill Risk and Response

- Risk assessment must reflect Arctic conditions
- Technologies must address Arctic-specific risks
- Spill response systems and technologies must be proven in Arctic
- Response plans must include relief well and containment options
- A response gap must be prepared
- Infrastructure gaps must be assessed and addressed
- Spill trajectory models must be Arctic-based
- Worst-case scenarios must be based on actual conditions
- Improve response planning standards

Selected recommendations from the Arctic Council's Arctic Monitoring and Assessment Programme on oil and gas activities in the circumpolar Arctic (Skjoldal and others, 2010).

International Perspective

Oil-Spill Prevention

- Conduct risk assessments of means of transportation of oil
- Use best practices for transportation and storage
- Seasonal restrictions
- Improve capacities and coordination of spill prevention, preparedness, and response. Provide rapid and adequate response equipment and well-trained personnel

Best Practices

- Consult/collaborate with communities
- Reinject, clean, or safely dispose of wastes
- Transportation including pipelines to be built to highest industry and international standards
- Seasonal restrictions to avoid disturbance of species and sensitive areas

Monitoring to Improve Assessment

- Compliance monitoring is necessary
- Consistent, rigorous and integrated monitoring programs to detect changes in environment, society, and human health
- Apply new tools such as biological markers and sociological indicators of change
- Monitoring including physical, chemical, biological, and socio-economic conditions and based on international standards
- Monitoring to distinguish oil and gas activity impacts from others
- Coordination at regional scales to observe interactions and cumulative effects of multiple activities
- Site fidelity/local adaptation of Arctic species necessitates better understanding of population structure and monitoring
- Pan-Arctic monitoring of human health
- Better use and streamlining of the Environmental Impact Statements/Environmental Assessments

Gaps

- Improved technologies, particularly seismic
- Oil-spill clean-up technologies and technologies for ice, under-ice, and broken ice
- Comparative studies of socio-economic effects including compilation of relevant statistics pan-Arctic, studies of mitigation effectiveness, and comparative and case studies
- Site and population-specific study data on human heath. Obtaining insights from large industry activities in Russia
- Behavior and fate of oil in ice
- General need for better information on population (genetic and geographic) structure of animal populations
- Fundamental ecological interactions between species and oil and gas development
- Map ecologically sensitive areas and improve spill trajectory models
- Coordination of research is essential given the breadth of data, scale, timelines of needs

Entities that Participated in Various USGS OCS Team Information Gathering Sessions

Department of the Interior

- U.S. Fish and Wildlife Service
- National Park Service
- Bureau of Ocean Energy Management, Regulation and Enforcement
- Office of the Solicitor
- Office of Environmental Policy and Compliance–Anchorage Field Office

National Oceanic and Atmospheric Administration

- Office of Response and Restoration
- National Weather Service
- National Marine Fisheries Services–Alaska Fisheries Science Center

U.S. Environmental Protection Agency

U.S. Coast Guard 17th District

National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling

BP Exploration (Alaska)

ConocoPhillips Alaska Inc

Shell Exploration and Production

Marine Mammal Commission

Community of Barrow

North Slope Borough

- Mayor's Office
- Department of Wildlife Management
- Planning Department

Eskimo Whaling Commission

University of Alaska Fairbanks

University of Maryland

LGL Alaska

Coastal Response Research Center

ARB, Inc.

Oceanus Alaska

Battelle

United Fishermen's Marketing Association

North Pacific Research Board

Alaska Ocean Observing System

Ocean Conservancy

Pew Environment Group

The Nature Conservancy

North Slope Science Initiative

Oil Spill Recovery Institute

Audubon Alaska

World Wildlife Fund

Oceana

Earthjustice

State of Alaska

- Alaska Department of Natural Resources
- Division of Geological and Geophysical Surveys
- Division of Oil and Gas
- Alaska Department of Fish and Game
- Alaska Department of Environmental Conservation
- Alaska Oil and Gas Conservation Commission

Canada–US Northern Oil and Gas Research Forum 2010

This initial engagement was followed by a series of facilitated group expert consultations to gain a deeper understanding of decision constraints and perspectives on needed science. Five separate facilitated sessions were held with representatives from the energy industry, Federal regulators, nonregulatory parties (including nongovernmental environmental groups and relevant science boards, observatories, and institutes), North Slope representatives (including Borough and subsistence leaders and environmental and wildlife specialists), and agencies of the State of Alaska. Examples of the inputs provided from the sessions are provided in appendix A. Our purpose was not to obtain analytical survey data from the participants, but rather to use an analytical approach to focus discussions and to bring some level of consistency across all sessions for gathering input from these key stakeholder groups to the USGS task at hand.

During the consultations, participants were asked to brainstorm and identify issues/gaps under each of the four Issue Topics requiring scientific information that will affect their ability to accomplish their jobs. Results of those discussions can be found in appendix table A–1. The USGS OCS Team requested that the participants informally consider how important a science gap was to their decision making associated with oil and gas development on a 5-point scale from 0 (not considered) to 4 (foundational) and to assess the status of scientific information for the issue (0–no information to 4–robust) (see appendix table A–2).

Our objective was to refine our understanding of the priority for a science gap and the sufficiency of the existing information (fig. 1–3). Because our allotted time for each session was limited to 2 hours, most sessions did not complete the entire process of discussing all Issue Topics. We provided a summary of all materials to session participants and allowed them to provide additional input if they chose to do so at a later date. That additional information was included with the original session findings. Given time constraints, not all participants in any of the five consultations in this series chose to use this Grid Tool in their responses back to the USGS OCS Team, so we did not proceed with any detailed analyses of the observations derived from this approach. However, most participants of one of the focus groups did respond and we therefore include a preliminary analysis of their responses as an example of the types of information and insights that might be gained through the use of this or other information gathering tools (appendix table A–3).

In January 2011, the USGS OCS Team participated in the Alaska Marine Science Symposium in Anchorage, Alaska, to gain focused input from the science community on key topics that had arisen during our assignment. The USGS OCS Team contributed to and participated in the Symposium's Poster Session to interact with participants and held a 3-hour facilitated technical workshop dedicated to our task to obtain scientific input on areas of critical and fruitful investigation or approaches informative to the science gap analysis. The discussions were centered on four overarching scientific questions on topics that were consistently mentioned during our other expert consultations or in our literature assessments and that cross-cut the Issue Topics that are the focus of our assignment (fig. 1–4). These topics were:

- What weather and oceanographic data are immediately needed to improve spill risk assessments, response planning, and spill response; what approaches are recommended to obtain such data?
- What supplements to agency monitoring and approaches to integrated ecological monitoring are needed for improved development impact assessment, including spill assessment (Natural Resource Damage Assessment, recovery, and restoration) efforts?
- Given gaps in spatial and temporal understanding of resources, how (methods, approaches) can the extensive industry site-specific monitoring be coupled with synoptic governmental efforts to improve broader scale understanding?
- What are important differences in the physical and ecological conditions of the Beaufort and Chukchi Seas that need to be clearly understood to address the Secretary's commitment to OCS exploration in the "right place/right way"?

The 75 participants were provided background on the USGS OCS Team's assignment, context for each of the questions, and several discussion starter questions (appendix B). They were then asked to self-select one of the four breakout groups (above). After 45 minutes of facilitated discussion, the participants then self-selected a second breakout group. In this second series of discussions, participants started with the materials developed by the first group and continued discussion. At the end of these discussions, each breakout group reported out to the full workshop. Materials gathered during these consultations are summarized in appendix tables B–1 and B–2.

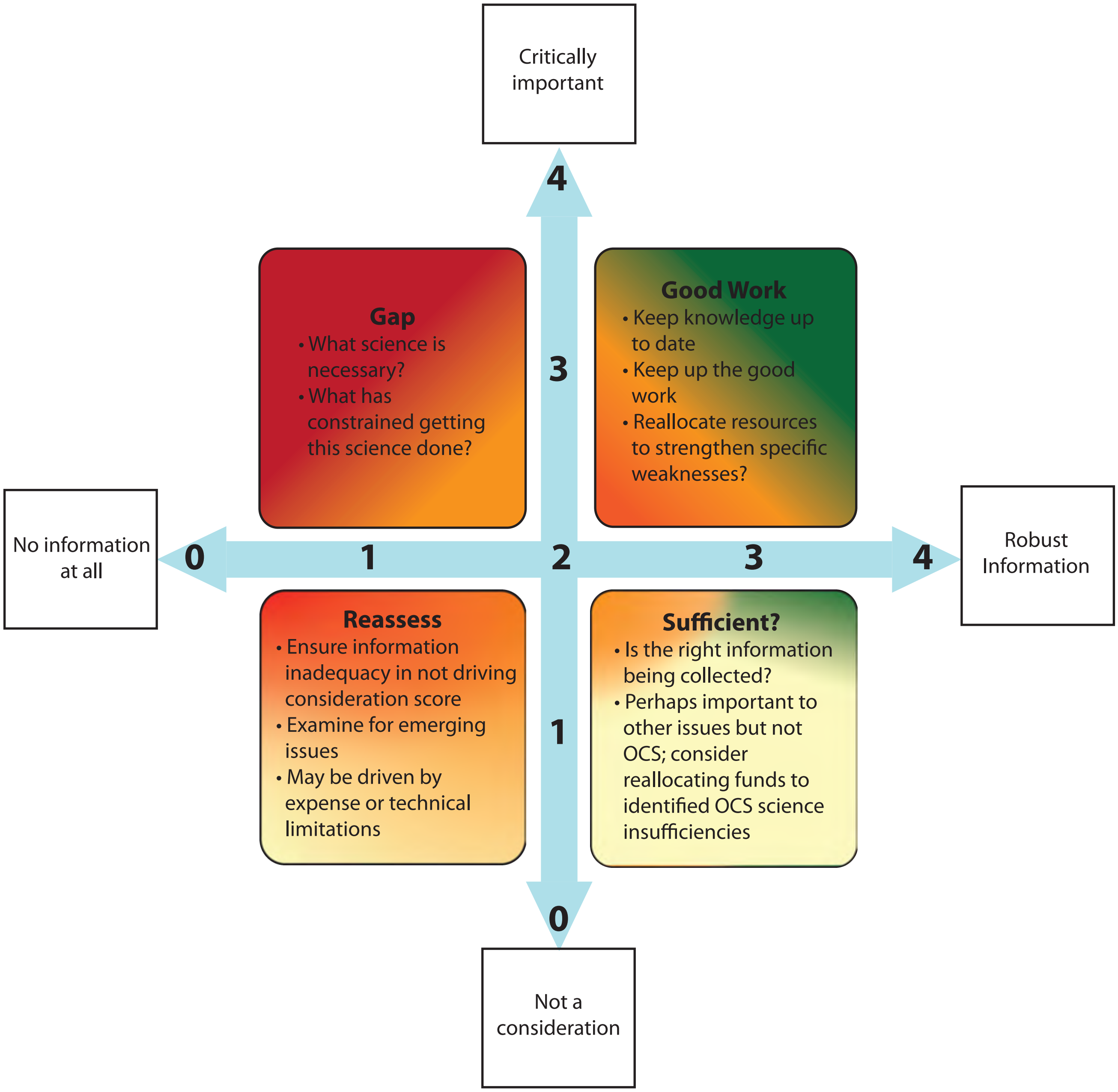

Figure 1–3. Grid tool used in the first series of structured consultations with industry, regulatory agencies, nonregulatory groups, North Slope representatives, and the State of Alaska. *Y*-axis represents the importance of an issue to an individual's decision making associated with oil and gas development. *X*-axis represents the participant's view of the status of the body of scientific information for that issue. When scores fell within a red or orange portion of the grid, we considered the topic to be an important gap for our initial analyses. Scoring is based on definitions provided in appendix table A–2.

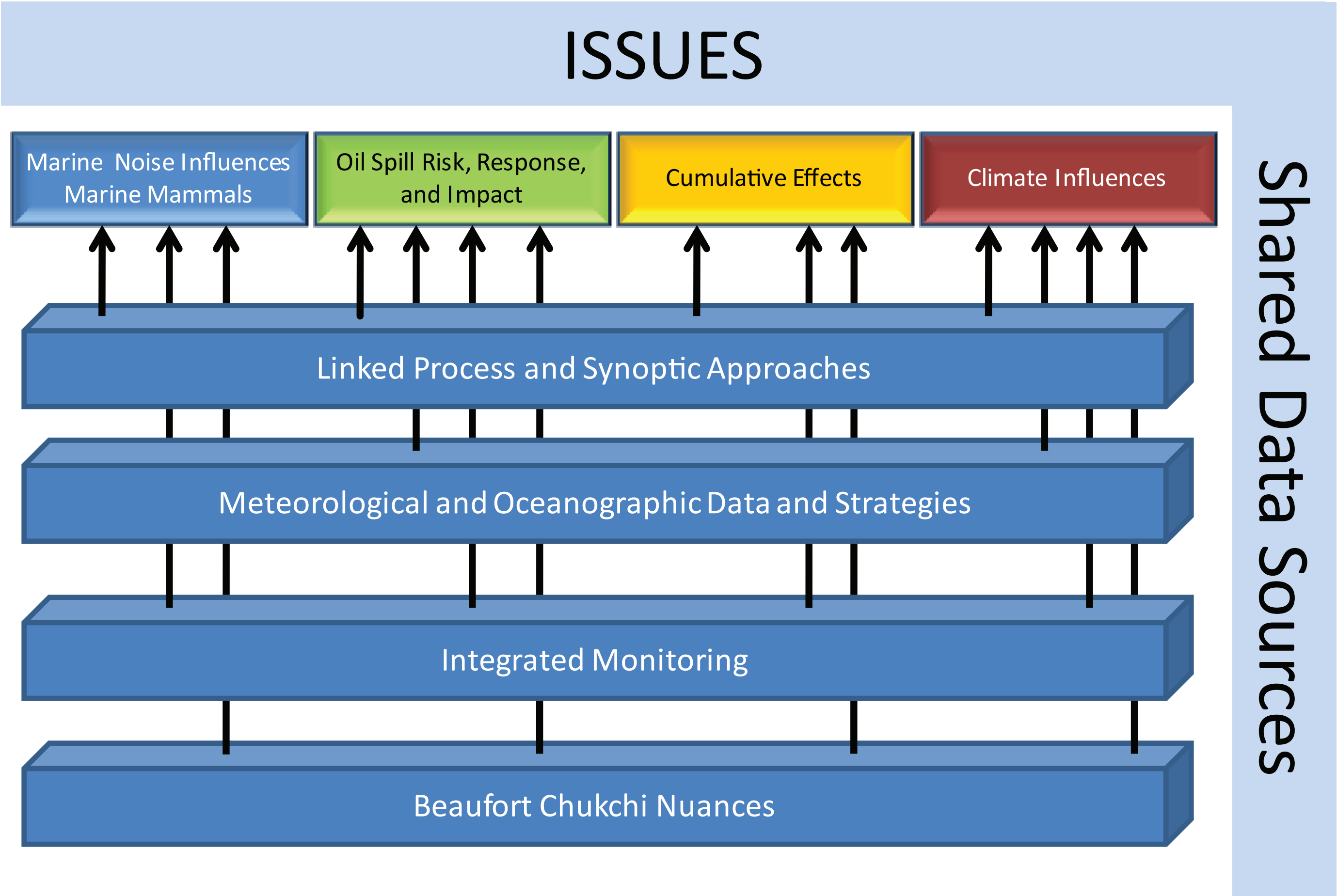

Figure 1–4. The USGS conducted two series of formal expert consultations. The first focused on the Issue Topics presented to the Team by the Secretary of the Interior (Issues) and the second focused on common cross-cutting science themes that emerged from the first consultations and was the subject of the Alaska Marine Science Symposium Workshop. Arrows illustrate examples of where the cross-cutting science themes inform the four Issue Topics of the USGS OCS Team's assignment.

In addition to these consultations, including the facilitated discussion session in Barrow, Alaska, described above, the USGS OCS Team held an open public session in Barrow to discuss community views on science issues and information gaps. Approximately 40 community members attended this session. This facilitated process was informal to encourage community members to have one-on-one discussions with individual team members on each Issue Topic. Posters with our Issue Topics were placed around the meeting room and each was attended by one or more members of the USGS OCS Team. Community concerns and suggestions were recorded during those discussions. In addition, attendees were able to leave their thoughts in writing if they desired. Information gathered from this session is included in appendix A, table A–1.

Following our review of the literature and expert consultations, the USGS OCS Team found that some of its emerging strategic findings and recommendations related to organized approaches to enhance the transparency and collaborative nature of evaluating science priorities in the multi-faceted Arctic oil and gas development decision-making environment. These findings will be discussed later in appropriate chapters. We mention this here because these discussions led us to conduct a 1-day prototyping exercise of a Structured Decision Making (SDM) concept (see appendix C). We took this additional step in our assignment because much of what we were hearing in our consultations was not solely about science—it was about perception and values. Identifying science gaps was not enough, in our opinion, to fully grasp the complexity of issues surrounding potential development in the Arctic. Thus, some tools that go beyond, but incorporate, science—such as SDM or similar—are of value in looking at what can/should be done about policy and implementation of Arctic development, and specifically what and where science can best inform decisions. The USGS OCS Team developed a broad outline of a decision framework to inform the DOI Arctic OCS energy exploration and development decision. This framework was developed as an example, or prototype, of a more fully articulated framework that could be developed with the input of the decision maker or delegates. That is, the decision framework presented here is both incomplete and is not assumed to represent the true aspects of the decision as understood by the decision maker; instead it is intended as an illustration of the value of this, or similar, approach. This simple prototype should serve the purpose of demonstrating the basic process of SDM and how it could be applied to synthesize and analyze science and policy information to inform Arctic OCS energy exploration and development decisions.

The Report

Our report is presented in a series of topical chapters, followed by a conclusion section, and various appendixes each written by a subset of the USGS OCS Team based on their areas of expertise. Three chapters (2, 3, and 4) provide foundational information on geology; ecology and subsistence; and climate settings important to our assignment. These chapters are followed by three chapters that examine the scientific understanding, science gaps, and science sufficiency questions on the Issue Topics provided to USGS—oil-spill response (Chapter 5), marine mammals and seismic activity (Chapter 6), and cumulative effects (Chapter 7). In addition to discussions in Chapter 3 about observed climate, we address the Issue Topic "Climate Change Considerations" in more detail in Chapter 4, and as it relates to oil-spill response in Chapter 5.

Based on our initial investigations, we chose to modify the Issue Topics slightly, due to what we were learning from the literature and during our consultations. The Marine Mammal and Seismic Activity Issue was reframed to consider the effects of anthropogenic noise on marine mammals more broadly rather than just that of seismic noise. We reframed the Oil Spill Response Issue to include science within the full decision framework that affects spill response. We considered science to better understand the potential effects of oil spills in pre-decisional planning; within spill contingency planning and spill response; and science required to address post-spill damage assessment and restoration considerations. We also examined lessons learned from the 1989 *Exxon Valdez* Oil Spill to identify valuable "pre-positioned" science and scientific approaches to improved response and reduced uncertainty in damage assessment and restoration efforts (appendix D).

We provide a series of findings and recommendations for consideration under our assignment as an independent examination of science gaps and sufficiency. These findings and recommendations are the informed opinions of the various authors as developed through the processes described above.

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Chapter 2

Geological Context

By Jonathan J. Kolak

Introduction

The purpose of this chapter is to describe the status of knowledge of the geologic framework of the Arctic, and how this knowledge underpins our understanding of energy resources—especially oil and gas accumulations in the Chukchi and Beaufort Seas—and supports estimates of the potential for these resources to be discovered, developed, transported to market, and ultimately contribute to the energy mix. The larger Arctic system is discussed as there are potentially significant drivers outside the planning areas that merit consideration when identifying Arctic research needs, particularly those aimed at reducing the uncertainty of estimates regarding oil and gas resource endowments or potential impacts resulting from aspects of oil and gas activities. In a previous study of the Arctic Outer Continental Shelf (OCS), the National Research Council (NRC) noted that "[t]here is a considerable range in the amount of data needed to provide adequate information for decisions regarding development, production, transportation, siting of onshore and offshore facilities, and termination of activities" (National Research Council, 1994).

Oil and gas have been produced in the Arctic for decades and oil has been produced from the Beaufort Sea OCS since the early 2000s (Bureau of Ocean Energy Management, Regulation and Enforcement, 2011). The confluence of several factors, including recent advances in technology and the retreat of sea ice, has intensified interest in the Arctic. The shrinking Arctic ice cap is one of the key drivers of increased interest in Arctic offshore oil and gas, as the increasingly ice-free ocean in the summertime creates and (or) extends the seasonal window of opportunity for ships to conduct seismic studies in parts of the Chukchi and Beaufort Seas (O'Rourke, 2010). There is a commensurate interest among Arctic Nations in mapping the continental margins beyond the Exclusive Economic Zone as part of Article 76 of the United Nations Convention of Law of the Sea (UNCLOS). The potential exists for lands included in the mapping claims submitted under Article 76 to be prospective for energy and other resources (O'Rourke, 2010).

Many activities are associated with the oil and gas resource lifecycle (Arctic Monitoring and Assessment Programme, 2007; Lifecycle Phases figure, p. 7). This chapter provides an overview of data availability and research needs associated with the evaluation phase, as information from this phase is used to define the geologic framework that underpins estimates of the resource endowment. Information from the geologic framework and resource estimates can be used as input for scenario modeling to evaluate the potential scope and scale of development and concomitant effects on society, environment, and ecosystems, including the risk of oil spills. Other research and development (R&D) needs pertaining to this lifecycle, such as technology R&D related to resource extraction and infrastructure/facilities construction given the particular challenges with the Arctic environment, are not addressed here, but constitute an important consideration in the larger picture. For example, a 1994 NRC study noted the importance of information of the ice gouging of the seabed and potential scouring problems (National Research Council, 1994). Since that study, there has been R&D investment to understand these processes better (C-CORE, 2008; Engels and others, 2008). Despite these investments, this area is recognized as one for which more information is needed, including new and innovative approaches to protect subsea pipelines from ice scour (U.S. Arctic Research Commission, 2010), and the potential for regional ice scour databases (IMV Projects Atlantic, 2008). Additional research needs germane to oil and gas activities on the U.S. Arctic OCS and recommendations for areas of advancement, including exploration, development, production, and transport infrastructure, are given in a recent assessment of cold region oil and gas technology (IMV Projects Atlantic, 2008).

Overview of Geologic Framework

Fundamental geological and geophysical research and information are critical to Earth science initiatives aimed at improving our understanding of the Arctic (U.S. Arctic Research Commission, 2010). Similarly, assessments of the Arctic energy resource endowment and the potential for resource extraction also depend on knowledge of regional geology. For this reason, obtaining geological and geophysical data is important for making appropriate comparisons and reducing uncertainty about resource potential, especially in frontier areas, to inform policy and other decisions that rely on estimates of resources (Minerals Management Service, 2006a).

Oil and gas resources typically are studied using a total petroleum systems approach (Magoon and Dow, 1994). A petroleum system is a holistic approach to systematically link elements of geological stratigraphic, structural, and tectonic history with the timing of discrete events such as maturation of source rocks and generation and expulsion of oil and gas and migration and accumulation of these resources within a geologic trap or seal (Magoon and Dow, 1994). The geologic elements of a total petroleum system (TPS) include (1) source-rock distribution, thickness, organic richness, thermal maturation, and petroleum generation and migration; (2) reservoir-rock type (conventional or continuous), distribution, and quality; and (3) character of traps and time of trap formation relative to petroleum generation and migration.

A thorough evaluation of these TPS elements requires that they be considered within the framework of the reconstructed geologic history, including research findings from detailed framework studies of stratigraphy, structural geology, heat flow, and geochronology, among others. This framework, considered in conjunction with analysis of petroleum geochemistry and modeling of petroleum generation and migration (Peters and others, 2006), and the analysis of historical petroleum exploration and production data, where available, provide the basis for probabilistic estimates of undiscovered, technically recoverable petroleum (oil, natural gas, and natural gas liquids) resources. These are resources that have yet to be discovered, but if found, could be extracted (produced) using currently available technology and industry practices. To place these in an economic context, the costs of finding and developing the undiscovered accumulations are estimated (Attanasi and Freeman, 2009). The cost functions that are constructed in these analyses show cost and resource-recovery possibilities, but they are not supply functions as defined by economists. However, the data that underlie the functions commonly provide the basis for market-supply models and development scenarios (Attanasi and Freeman, 2009).

It is important to keep in mind that risk and uncertainty are integral parts of every resource assessment and evaluation of economically recoverable resources; nearly every component of the assessment process incorporates a consideration of risk and uncertainty:

> "The accumulation of petroleum in significant quantities requires the juxtaposition of many complex geologic events: the accumulation of organic matter in a source rock; the maturation of this organic matter into petroleum; the presence of a reservoir rock with sufficient thickness, porosity, and permeability; the migration of the petroleum into a trap with adequate size and seals; and the preservation of the petroleum in the trap. Prior to drilling, the actual existence of these geologic conditions is unknown. Not only must all of these conditions coexist they must also converge at a particular location, an unlikely event that results in a high probability of failure often described as dry hole or geologic risk. Even if all of these conditions coexist at a particular location, there remains considerable uncertainty regarding the effectiveness of a seal, the size of a trap, the quality and thickness of the reservoir, and the volume and type of hydrocarbons that not only migrated into the trap, but were preserved and still remain to be recovered. In general, risk and uncertainty in estimates of undiscovered oil and natural gas are greatest for frontier areas that have had little or no past exploratory effort" (Minerals Management Service, 2006a).

Therefore, an improved understanding of the geologic framework, through availability of additional data and (or) application of new geologic concepts, can significantly influence estimates of resource potential. For example, the recent update of the undiscovered, technically recoverable oil and gas resources of the National Petroleum Reserve in Alaska (Houseknecht and others, 2010) led to the finding that the estimated volume of undiscovered oil is significantly lower than estimates released in 2002. The revision resulted mainly from new geologic information from recent exploration drilling that showed an abrupt transition from oil to gas and reduced reservoir quality in the Alpine sandstone reservoir 15–20 mi (about 24–32 km) west of the giant Alpine oil field.

In addition to estimates of total resource endowment, there exists uncertainty regarding the size distribution of undiscovered accumulations, and the probability of finding a large accumulation. This uncertainty is evident particularly in regions that are not maturely explored, such as the Arctic, and is an important factor to consider because large oil and gas accumulations are particularly important to future development due to the higher costs associated with oil and gas exploration, development, and production in the Arctic relative to other regions in the World. Generally, the discovery of large fields is important for offsetting the costs of new infrastructure. The development of the Prudhoe Bay field, for example, necessitated the construction of the Trans-Alaska Pipeline System (TAPS). Since then, development of smaller satellite oil accumulations has been rendered feasible because the bulk of the supporting infrastructure was already in place. Without the Prudhoe Bay field, it is not likely that the smaller Alaska North Slope oil fields would have been developed (Budzik, 2009).

Geology

The Arctic has long been recognized as a region with significant petroleum potential, but limited knowledge of the location, character, age, and geologic setting of sedimentary successions in this region has hindered the understanding of the petroleum potential. Areas that have had extensive oil and gas exploration and development, such as the North Slope of Alaska, are better understood than offshore regions with sparse geophysical data, such as the Amerasia Basin. As part of an effort to address this knowledge gap, a new map of Arctic geology with emphasis on sedimentary successions that might contain petroleum was compiled by Grantz and others (2010). The map delineates 143 sedimentary successions in the Arctic, among which geologic uncertainty varies greatly owing to the quality and density of available data. For this compilation, Grantz and others (2010) relied on several types of data, including aeromagnetic maps, airborne and satellite gravity data, seismic reflection and refraction data, piston cores, shallow drill holes, and bathymetry.

Recent scientific drilling in the Arctic Ocean has enhanced our understanding of Arctic geology. This drilling was feasible in large part due to developments in technology and logistics support that enabled operations in ice-covered areas. Previously, only shallow (15–50 ft; about 5–15 m) sediment samples could be obtained from the Arctic Ocean through gravity and piston coring (Coakley and Stein, 2010). However, in 2004, the completion of the International Ocean Drilling Program Expedition 302 (Arctic Coring Expedition, or ACEX) demonstrated for the first time that scientific drilling could be successfully completed in a permanently ice-covered part of the Arctic Ocean (Coakley and Stein, 2010). The ACEX penetrated more than 1,300 ft (400 m) of sediments on the Lomonosov ridge (Moran and others, 2006). In addition to providing information about the sediment depositional and climatic history of this setting, this study provided information useful for understanding the organic carbon sources and cycling and, ultimately, the potential for oil and gas generation.

The geologic connection between the Alaska North Slope (ANS) and offshore Alaska, coupled with the generally greater availability of onshore information, makes the ANS an important source of analog information for the Federal offshore planning areas. For example, ANS oil and gas exploration activities over the past decade have increasingly focused on stratigraphic traps, including the clinoform strata of the Cretaceous-Tertiary Brookian sequence (Houseknecht and others, 2009). The regional stratigraphic framework of these Lower Cretaceous clinoforms is relatively well known, but until recently, there have been few publications that detail the sequence stratigraphy of these features (Houseknecht and others, 2009). These features are important to study given that the development of the Nanuq and Qannik oil accumulations, taken together with the occurrence of oil-stains in rock outcrops of lower-slope sandstone facies, demonstrates the exploration potential in Lower Cretaceous clinoforms that occur beneath the western North Slope and Chukchi Sea (Houseknecht and others, 2009).

Vörösmarty and others (2010) acknowledged that given the remoteness of the Arctic, some of the most basic information needed for the exploration, exploitation, and recovery of non-renewable energy are inadequate and outdated. For example, the U.S. Arctic Research Commission (2010) reported that baseline maps of the State of Alaska are out of date and, for some areas, have errors in the range of kilometers. Similarly, the high-latitude margins of the Arctic Ocean remain only sparsely studied, largely due to the operational constraints imposed by sea-ice cover (Engels and others, 2008). As a result of these constraints, the morphology of the Alaska–Beaufort margin, except for the nearshore zone, has not been adequately mapped despite the significance of this region for important socio-economic and scientific issues, such as hydrocarbon deposits, gas-hydrate stability, and the history of Arctic Ocean circulation and ice cover (Engels and others, 2008).

In addition to regional framework geology, a key component for the study of petroleum systems is the identification and analysis of source rocks. The National Research Council (1994) recognized the need for "… geochemical studies related to source rock abundance, organic carbon types, and thermal maturity…" to further the understanding of petroleum systems and underpin estimates of undiscovered resources. Peters and others (2006, 2007) have investigated the origin of petroleum in northern Alaska.

The geochemical composition of oils and source rocks can be useful for inferring the identity and regional extent of active source rocks, which is regarded as a critical step in delineating petroleum systems (Peters and others, 2007). More recently, Tertiary oils have been demonstrated in the Mackenzie Delta of Canada and offshore of the Alaska North Slope, but exploration drilling has yet to penetrate a source rock that may have generated these oils (Smith, 2007). Study of the source-rock potential of some of the Tertiary black shales sampled during the ACEX indicated that these shales have a fair to good source-rock potential (Stein, 2007).

Recent studies of seismic and borehole data, and results from geologic modeling, indicate that good potential source rocks in the Lower Tertiary may be widespread across the entire Arctic Basin (Mann and others, 2009). The analyses of samples from the ACEX cores suggest the potential for organic-rich—and at least partly oil-prone—lower Paleogene strata in the Canada Basin, and despite the fact that viable source rocks are not typically penetrated during drilling activities along the Alaska-Canada margins, the potential existence of such source rocks is regarded as likely in the course of constructing geologic frameworks for the purpose of assessing petroleum resources (Houseknecht and Bird, in press). Geochemical analyses of oil samples can be helpful in studies of paleogeographic settings and reconstructions of tectonic history, as chemical constituents within these samples retain information about the depositional setting and paleogeography of the source rock (Peters and others, 2008). The model of possibly widespread Tertiary oils in the high Arctic was included in the recent U.S. Geological Survey Circum-Arctic Resource Appraisal (Bird and Houseknecht, in press; Houseknecht and Bird, in press). Many oil accumulations identified within Arctic Alaska petroleum systems appear to be mixtures of oil expelled from two or more petroleum source rocks (Peters and others, 2006; Houseknecht and Bird, in press). The character of the source rock systems is documented for the heavily explored area of the Arctic Alaska province, but in less explored areas, the source-rock quality is poorly known because of limited data (Houseknecht and Bird, in press). Other recent studies have focused on refining the understanding of petroleum systems in the adjacent Mackenzie Delta and Canadian Bent Horn Basin areas (Obermajer and others, 2010).

Geophysical Data

Geophysical information, including seismic, gravity, and magnetic surveys, is key to interpreting the geologic framework and provides underpinning to studies of energy resources. The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) has acquired approximately 90 percent of the data collected by industry in the Arctic OCS, but Alaska remains a largely frontier area with limited data coverage, a fact that necessitates acquisition of as much additional data as is feasible (Dellagiarino and Maloney, 2010). Seismic surveys can be characterized by a number of criteria including: the type of data collected, such as two-dimensional (2-D), three-dimensional (3-D), or high-resolution; the timing of the surveys, such as pre-lease or post-lease; the acoustic sound source, such as an air gun, water gun, sparker, pinger, or other source (Minerals Management Service and National Oceanic and Atmospheric Administration, 2007). The specific type of geophysical equipment used in data collection depends on the environment of deployment. For example, ocean-bottom cable seismic surveys are possible in the Beaufort Sea, but they are not anticipated to be used in the Chukchi OCS because of its greater water depths, as much as 12,500 ft (3,800 m) in parts of the planning area, and the greater efficiency of streamer operations in these conditions (Minerals Management Service and National Oceanic and Atmospheric Administration, 2007). Both 2-D and 3-D seismic surveys are the primary tools of oil and gas exploration, because they enable geologists and geophysicists to image, map, and interpret subsurface structures, identify favorable conditions for the entrapment of hydrocarbons, and optimally locate exploration and development wells for the purposes of maximizing production volumes (Minerals Management Service, 2009). These types of data are useful for basin analysis studies of petroleum systems concerning source rock maturation, hydrocarbon migration and trapping processes, and estimating in advance of drilling the potential magnitude and extent of overpressured zones in the subsurface (Huffman, 2002).

Public domain inventories of 2-D seismic data are available for onshore and offshore Alaska North Slope in the Chukchi Sea and Beaufort Sea planning areas (fig. 2–1). A large percentage of the geophysical data in the BOEMRE inventory is 2-D common depth point data collected along a survey line (table 2–1; Dellagiarino and Maloney, 2010). The BOEMRE does not perform any direct geological and geophysical (G&G) data-collection activities, but does issue permits to industry for collecting pre-lease G&G data. Data from pre-lease permits constitute approximately 90 percent of the BOEMRE database (Dellagiarino and Maloney, 2010). Regulations, promulgated in 1976, require that all pre-lease G&G information be held proprietary for 25 years, and then be released to the public (Dellagiarino and Maloney, 2010). Lessees and operators in turn are required by regulations to provide data from their leases to the BOEMRE (Dellagiarino and Maloney, 2010).

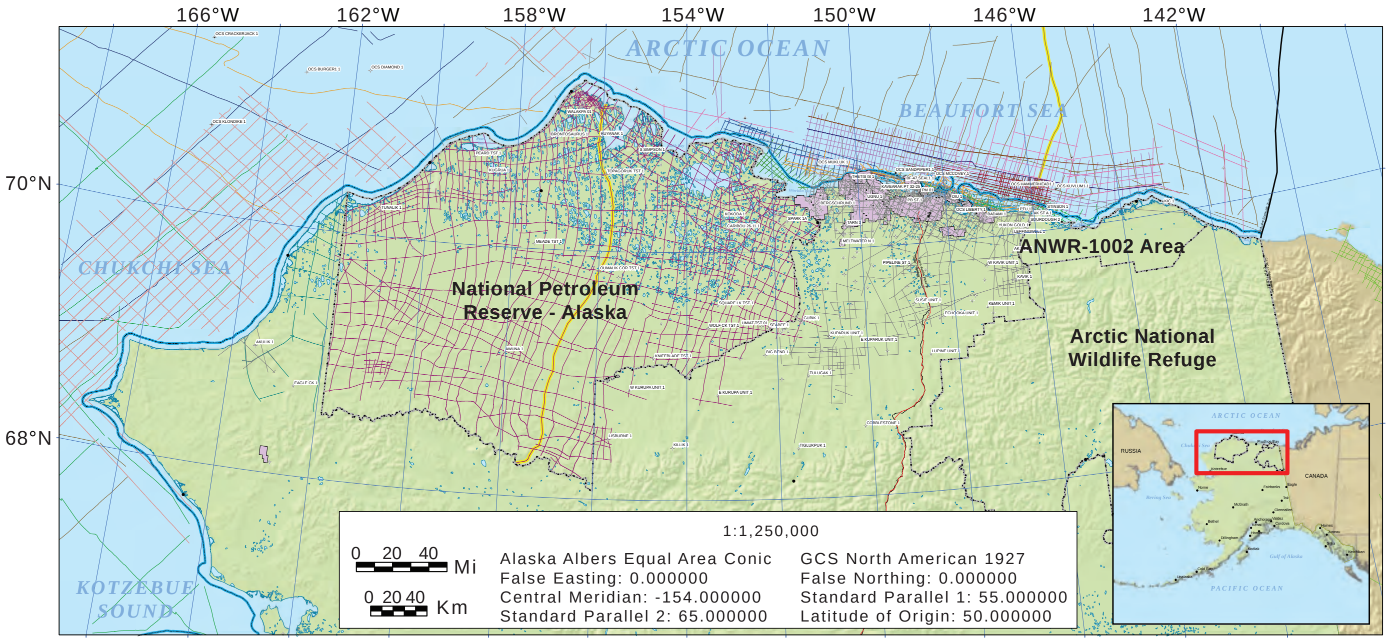

Figure 2–1. Map compilation showing transects (colored lines) of individual 2-D seismic surveys of the Alaska North Slope and offshore. The line colors correspond to different seismic datasets. The seismic data from these transects are publicly available. More information on these surveys, and a corresponding map for the spatial distribution of commercially available 2-D and 3-D seismic data, are available from State of Alaska (2008a).

Table 2–1. Summary of geological and geophysical data acquisition by data type and region, fiscal years 1968–2008.

[Modified from Dellagiarino and Maloney (2010; table 4) and G. Dellagiarino and S. Banet (BOEMRE, written commun., 2011). **3-D seismic**: Outer Continental Shelf (OCS) blocks equivalent]

Region	2-D seismic (line miles)	High resolution (line miles)	Gravity and magnetics (line miles)	3-D seismic
Alaska (total)	472,460	59,855	372,764	291
Beaufort	[1]*58,066*	*2,386*	*29,748*	*63*
Chukchi	[1]*94,938*	*4,620*	*87,433*	*226*
Atlantic	213,936	49,509	15,783	0
Gulf of Mexico	1,396,174	145,768	669,413	91,113
Pacific	132,841	30,582	110,150	52

[1]Total 2-D seismic data in the BOEMRE inventory for the Beaufort and Chukchi OCS areas are 70,000 and 111,000 line miles, respectively (see Dellagiarino and Maloney, 2010; their table 1), which includes data from other activities, such as scientific research.

Recent acquisition and analysis of 2-D seismic data have furthered the knowledge of the stratigraphic correlations within the Chukchi Shelf area (Dinkelman and others, 2008). High-resolution 2-D seismic data can augment the understanding of areas mapped with low-resolution seismic data. For example, low-resolution seismic data can be helpful in identifying and mapping the extent of clinoform depositional sequences, but a higher resolution approach is needed for identifying components of aggradational trajectories and interpreting the character of associated sequence boundaries and lowstand deposits (Houseknecht and others, 2009). The UNCLOS 2-D seismic data collected during the past few years have significantly greater resolution than previously available data. Already, we are recognizing stratigraphic and structural features—even beneath the Beaufort Shelf and slope—that have not been known previously (D.W. Houseknecht, U.S. Geological Survey, written commun., 2011). As these data (which cover a tiny fraction of the Canada Basin and its margins) become public, there will be significant revision of geologic knowledge, even in parts of the Arctic considered relatively well known. While assembling the geologic map of Arctic sedimentary successions, Grantz and others (2010) acknowledged that data on the subsurface geology of the Arctic region, seismic reflection and refraction data in particular, are insufficient to ensure that the identification of all sedimentary successions of the region are of sufficient size and character to be of interest for commercial hydrocarbon exploration. Despite this limitation, the authors assert that perhaps no more than a few successions were omitted in their synthesis.

An increasing percentage of geophysical information acquired in the BOEMRE Inventory across all OCS regions is 3-D seismic data (Dellagiarino and Maloney, 2010). The evolution of 3-D seismic technology enables a more accurate portrayal of subsurface structure and stratigraphy, and can reveal information about fluids within the subsurface. A newer form of information processing is Amplitude Variation with Offset, and a new type of data acquisition is 2-D or 3-D Four component (4-C), which involves the recording of marine seismic data with ocean bottom seismometers on the sea floor (Dellagiarino and Maloney, 2010). Data from 3-D seismic surveys are available in commercial inventories; no data currently are available in the public domain (State of Alaska, 2008a). For example, the recently collected 3-D seismic data on the Alaska North Slope and on the Chukchi Shelf are not available in the public domain, and so are not used to refine public knowledge of geology and petroleum potential. The growing need and utility of these 3-D seismic data give rise to an important knowledge gap. There is a disparity in the commercially available (proprietary) data relative to publicly available data (State of Alaska, 2008a).

Gravity and magnetic data, collectively referred to as potential fields data, have been collected in Alaska for more than 50 years, and a number of these datasets are available in the public domain (State of Alaska, 2008b). Gravity and magnetic data can be used to interpret regional geologic structures and trends, which have implications for oil and gas exploration and evaluation (Saltus and others, 2006). In particular, modern gravity and magnetic surveys typically contain short-wavelength data that, when processed using mathematical filters, can highlight shallow geologic features and trends in subsurface strata (Saltus and others, 2006). Gravity surveys measure the Earth's gravitational field at a series of locations over an area of interest (Dellagiarino and Maloney, 2010). The objective is to map density variations that may indicate different rock types, and the resulting gravity data typically are displayed as anomaly maps. Magnetic surveys measure components of the magnetic field at a series of locations over an area of interest to locate magnetic anomalies or to determine depth to basement (Dellagiarino and Maloney, 2010).

Despite the long history of data acquisition, there are gaps in data coverage across the State. That said, the existing network of gravity and magnetic data is sufficient to define regional anomalies and allows for high-resolution interpretations along major transportation corridors and in areas that have been heavily explored for energy and minerals resources (State of Alaska, 2008b). The collection of detailed, high-resolution aeromagnetic and gravity data spanning the entire North Slope and the integration of these data with existing regional seismic information is regarded as one of the key challenges for future geophysical work on the Alaska North Slope (Saltus and others, 2006). For example, aeromagnetic and gravity data in the western North Slope are sparse, but the regional compilations suggest that the North Slope magnetic high may connect to the geophysical anomaly underlying the Hanna Trough, a major tectonic element in the Chukchi Sea (Saltus and others, 2006). Greater availability of these data in the western North Slope would enable the testing of a hypothesis developed by Sherwood and others (2002) regarding the existence of a connection between the Devonian and later rifting of the Hanna Trough and tectonic events associated with the Ellesmerian depositional sequence beneath the North Slope (Saltus and others, 2006).

Systematic gravity data covering the entire Arctic Ocean are important for global gravity field models and large-scale geological and plate tectonic studies (Forsberg and Kenyon, 2004). Previously, there were "polar gaps" in gravity field data collected by satellites. To address this knowledge gap, an international initiative known as the Arctic Gravity Project (ArcGP) was undertaken. This project, completed in 2002, culminated in the compilation of a publicly available set of gravity data on a 5 × 5 ft grid of the entire Arctic region north of 64°N (Forsberg and Kenyon, 2004). Recently, a new method of gravity inversion with an embedded lithosphere thermal gravity anomaly correction has been applied to the ArcGP data with the aim of testing different plate reconstruction scenarios in an attempt to better constrain the plate tectonic history of the Amerasia Basin (Alvey and others, 2008). More recently, a new detailed marine gravity field for the Arctic Ocean has been derived solely from satellite data—ARCtic Satellite-only (ARCS) marine gravity field—which has increased the sensitivity to subtle perturbations in the gravitational field (McAdoo and others, 2008). The greater sensitivity of this new field, evident in the revelation of gravity lineations and tectonic fabric, may ultimately prove useful in constraining tectonic models for complex terranes such as the Amerasia Basin (McAdoo and others, 2008). At the time of their study, the ARCS coverage was limited to all Arctic areas south of 86°N, but the authors noted plans to augment the coverage with additional satellite data, thus extending coverage northward to 88°N (McAdoo and others, 2008).

Generally, the need for greater availability and density of geophysical data to provide comprehensive Arctic coverage and to address gaps specifically on the Alaska North Slope and offshore is echoed in the recent U.S. Arctic Research Commission (2010) report. To address these gaps, the U.S. Arctic Research Commission (2010) recommended that an Arctic resource assessment and Earth science research plan should include activities to address the major remaining geographic and geophysical "unknowns" of the Arctic region, such as the geology and tectonic history of the Arctic Ocean and the Bering Sea.

2.01. Finding: There has been a concerted effort over the last decade to better characterize Arctic geology through a combination of activities, including the collection of geophysical data, mapping the offshore, and successfully completing the first Arctic research drilling expedition. This knowledge base has enhanced our understanding of the tectonic and climatic history of the Arctic system, including carbon cycling, while providing insight into delineating Arctic petroleum systems.

Inventories of geophysical information exist in the public and commercial domains, including 2-D and 3-D seismic, gravity, and aeromagnetic data. Data from previous acquisition enable the synthesis of geologic frameworks as a basis for characterizing and delineating petroleum systems, estimating undiscovered resource endowments, and characterizing subsurface pressure-temperature conditions in these settings.

2.01. Recommendation: Much of the publicly available seismic data for the Arctic is 2-D and of older vintage. Additionally, Arctic seismic data are available at densities (number of track lines per square mile) lower than other offshore areas, such as the Gulf of Mexico. These older vintage data retain value for delineating geological relations, but there is a growing need for high-resolution and 3-D seismic data to better constrain these relationships.

Recent international meetings and working groups have determined that a better understanding of the geologic and plate tectonic history of the Arctic, especially the Amerasian Basin is needed, because the "age and direction(s) of rifting that formed the basin have far-reaching implications for the origin of its broad continental shelves, their oil and gas potential, and for claims to extend the Outer Continental Shelf limits under Article 76 of the United Nations Convention on Law of the Sea" (Miller and others, 2010). Recent scientific drilling activities (ACEX) have yielded information facilitating a better understanding of the tectonic history of the Arctic. Further activities in targeted areas of the Arctic Ocean are needed to enhance our understanding, and could supply scientific information needed to address a host of multidisciplinary studies.

Structural and stratigraphic investigations of the continental margins constitute a topic for which Federal research could play a critical part. All exploration to date has occurred on the continental shelves, where industry's most immediate interests lie. Meanwhile, tectonic and marine research has largely focused on the deep Arctic Basin, where current industry interest is minimal. Very few studies have been completed to date that bridge this gap.

In the rapidly changing Arctic data environment, improved assessment methodology is needed to accommodate rapid and efficient updates of resource estimates based on the availability of new data. Similarly, activities devoted to more rigorous application of analog information to inform assessment methodologies should be researched, developed, and implemented.

Overview of Exploration and Development Activities

Beaufort Sea Planning Area

The Beaufort Sea planning area shares many geologic similarities with the Alaska North Slope (Minerals Management Service, 2006b), but also includes geological elements that are strikingly different (Houseknecht and Bird, in press). Drilling in the Beaufort Sea OCS commenced in 1981, and through 1989, 20 wells had been drilled (Thomas and others, 2009). Depending on water depth, the OCS exploration wells are drilled from either an artificial island or large, heavy, usually bottom-anchored drilling structures. The first OCS oil discovery was Tern (Liberty) in 1983, followed by Seal/Northstar in 1984, Hammerhead in 1985, and Sandpiper in 1986. The largest oil discovery to date in the Beaufort OCS is the Kuvlum field, discovered in 1993, with estimated technically recoverable resources on the order of 400 million barrels of oil (Thomas and others, 2009). Water depths range from as little as 21 ft (6.4 m) at Liberty to as much as 103 ft (31.4 m) at Hammerhead (Thomas and others, 2009). These depth variations dictate the type of basic exploration drilling structure to be used and the type of production facility that would need to be built (Thomas and others, 2009). Northstar is located offshore in State of Alaska and Federal waters of the Beaufort Sea and is the first field to produce from Federal waters: development is from a totally contained offshore island and connected to shore by the first subsea pipeline on the Alaska North Slope (Thomas and others, 2009). Oil has been produced from the Northstar unit since 2001 (table 2–2; Bureau of Ocean Energy Management, Regulation and Enforcement, 2011). The onshore Alpine field in the Colville River Unit and the offshore Northstar field in the Beaufort Sea are recent examples of stand-alone fields that have been developed using advanced technology for drilling and production, while simultaneously reducing the development footprint (Thomas and others, 2009). The emerging development of the Liberty field through the use of directional drilling from onshore (BP Exploration (Alaska), Inc., 2007) is another example of the evolution in industry practices with respect to Arctic oil and gas development through incorporation of recent technological advances such as ultra-extended-reach drilling.

Table 2–2. Annual production totals from the Northstar Project in the Beaufort Sea.

[**Source:** BOEMRE, "Production Statistics for the Northstar Project," accessed March 9, 2011, at http://alaska.boemre.gov/fo/northstar/ns_production.pdf. Total Unitized Production is the volume of production from the entire unit, both from State and Federal leases. The State leases are allocated 82.160 percent of the total unitized production and the Federal leases are allocated the remaining 17.840 percent. BBLS, Stock Tank Barrels of Oil at Standard Conditions of 14.73 pounds per square inch absolute and 60 degrees Fahrenheit; N/A, not applicable]

Year	Total unitized yearly production volume (BBLS)	Total unitized average daily production rate (BBLS/day)	Yearly production volume from Federal leases (BBLS)	Average daily production from Federal leases (BBLS/day)
2001	1,256,883	20,417	225,834	3,642
2002	17,902,989	49,049	3,193,869	8,750
2003	22,970,112	62,932	4,097,868	11,227
2004	25,079,017	68,522	4,474,097	12,224
2005	22,421,483	61,429	3,999,993	10,959
2006	18,810,628	51,539	3,355,816	9,194
2007	13,877,290	39,877	2,475,709	7,114
2008	11,136,749	30,428	1,986,796	5,428
2009	7,981,210	22,482	1,423,848	4,011
2010	6,133,516	18,419	1,094,219	3,286
Totals	147,578,877	N/A	26,328,072	N/A

Chukchi Sea Planning Area

Five exploratory wells were drilled on the Chukchi Shelf during 1989–91: Klondike, Burger, Popcorn, Crackerjack, and Diamond (Minerals Management Service, 2006c). The Burger well was drilled to a measured depth of 8,202 ft (2,500 m), and two gas-bearing sandstones (Craig and Sherwood, 2004) were found. The Burger prospect, which has an area of closure exceeding 189,800 acres (760 km^2), was mapped using conventional 2-D seismic data as part of preparations for Lease Sale 109 in May 1988 (Craig and Sherwood, 2004). The information from these wells, in conjunction with regional seismic lines and other data, can be synthesized to yield a regional picture of the geologic framework, as shown in the Chukchi Shelf well correlation (fig. 2–2). This cross section of the geologic framework was updated using paleontologic interpretations by Mickey and others (2006) to refine the interpretations of the subsurface geology and well correlations. For example, the new micropaleontology data led to the exclusion of the Jurassic-aged unconformity from the Burger well stratigraphic column (Sherwood, 2006).

The resulting geologic framework from the synthesis of these data is useful in understanding the window for petroleum generation and occurrence and a picture of the potential subsurface pressures and temperatures that may be detected at depth. As can be seen in the updated geologic correlation, the incorporation of these data are useful for delineating the depths to the potential over pressured zone, the top of the oil generation zone, and the deepest reservoir of oil within the subsurface geology underlying the Chukchi Sea (Sherwood, 2006). In an analogous study, mud weight and pore pressure data from 250 exploration wells were used to delineate the fluid pressure regime in the Beaufort-Mackenzie Basin (Chen and others, 2010), and for identifying areas of potential over pressure. These data, in conjunction with studies of organic geochemistry and basin thermal structure in the Beaufort-Mackenzie Basin, have led to the development of new ideas for play types and petroleum system models (Chen and others, 2010).

These syntheses of geologic information are useful for understanding the driving forces for fluid flow in sedimentary basins, which can help in understanding the occurrence and distribution of oil and gas resources and fluid migration pathways (Peters and others, 2006; Chen and others, 2010). This information also can provide further insight into the total pressure conditions that may be found during drilling (Akhter and others, 2009), and thus be useful for guiding the exploration process (Huffman, 2002), as well as evaluating the potential risk for a blowout or loss of well control in advance of drilling operations. For example, one of the working papers from the National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling mentioned that:

> “The *Deepwater Horizon* containment efforts were complicated immensely by the depth of the wellhead and the high well pressures encountered at the Macondo well. Wells in both the Chukchi and the Beaufort Seas would be in far shallower water, which could make it easier to contain a blowout or riser leak. Shell asserts that well pressures in the Chukchi and Beaufort Seas would be approximately one-third to one-half of the pressures faced by BP at the Macondo well” (National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling, 2011).

Although the depth of water in which drilling would be conducted and the subsurface pressure detected by wells drilled in the Arctic OCS would be substantially lower than those at Macondo, it is important to remember that a potential spill offshore poses unique challenges for spill response in terms of how to access spilled oil when the area may have iced over, or be in seasonal slushy conditions, among other factors (National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling, 2011).

Potential for Additions to Global Supply from Northern Latitudes

Planning-Area Based

Resource assessments can be useful at various scales, such as for OCS programmatic planning, analyses of proposed legislation, or estimating effects on investment and revenues from various leasing and regulatory policies, like proposals for royalty relief (Minerals Management Service, 2006a). The BOEMRE routinely updates and revises its resource estimates to reflect changing conditions and knowledge. The BOEMRE conducts comprehensive national assessments of the undiscovered oil and gas resources on the OCS at least every 5 years. These periodic updates are necessary to incorporate changes in technology that occur with time, geological and geophysical data available to assessors, and geologic interpretations and models, which can lead to higher or lower estimates when the assessments are updated (Minerals Management Service, 2006a). The following excerpt, from the 2006 Report to Congress regarding a comprehensive inventory of U.S. OCS oil and natural gas resources, provides an

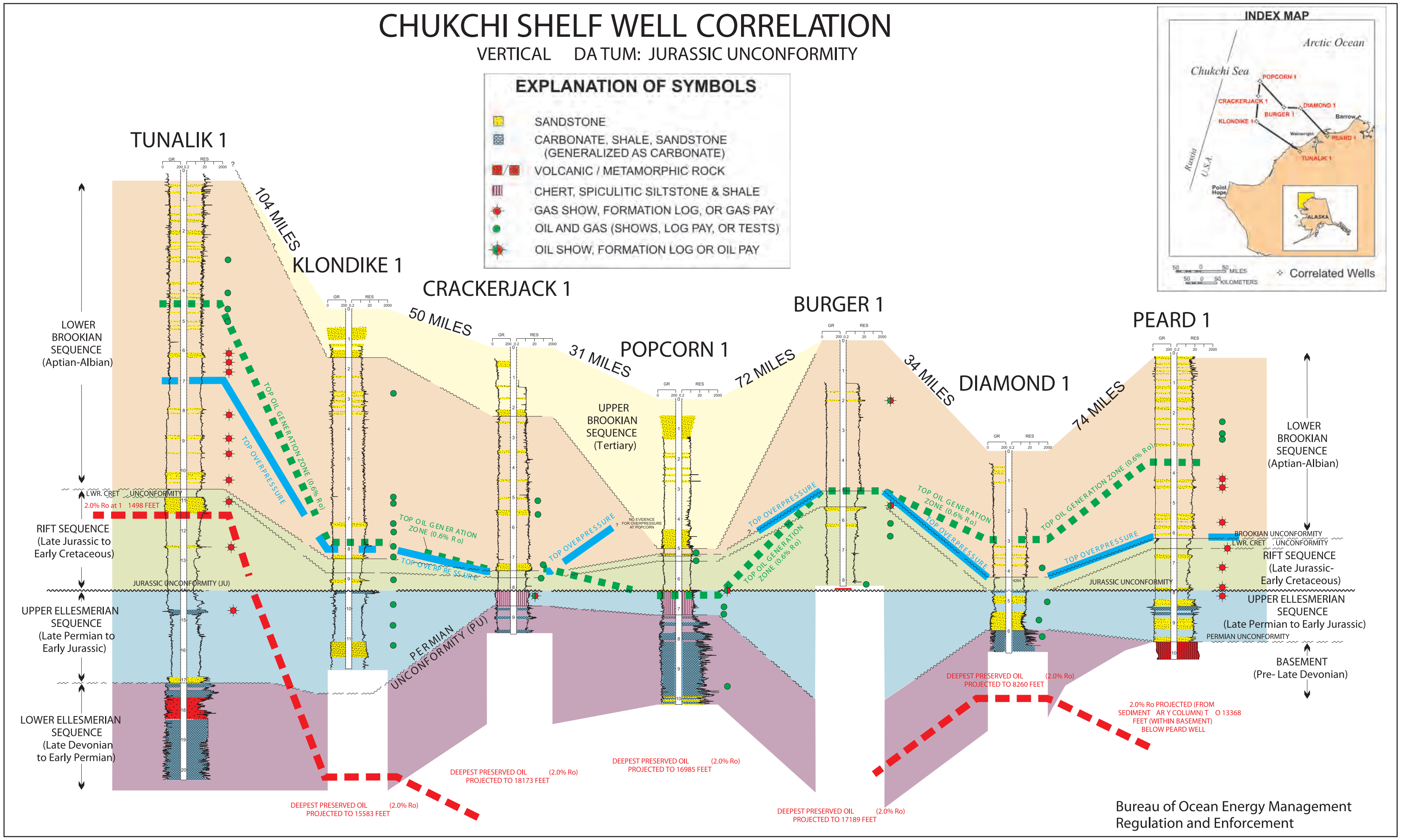

Figure 2–2. Geologic cross-section showing regional correlations among wells from the Chukchi Shelf and western Arctic Alaska. This cross-section depicts major stratigraphic relations and delineates approximate extent of oil generation windows and over pressured zones. From a 2009 well correlation update (K. Sherwood, Bureau of Ocean Energy Management , Regulation and Enforcement, written commun., 2011), and modified from Sherwood (2006), including new paleontologic interpretations published by Mickey and others (2006).

overview of the utility of resource assessments for informing decisions across sectors (public and private) and at varying scales:

> "Regional assessments may be prepared simply to develop an inventory of potential oil and natural gas resources as part of an evaluation of future supply options. Assessments may be undertaken to analyze the relative merits of oil and gas development proposals and alternatives versus other competing uses. Resource estimates provide critical input to decision makers regarding the virtues of various policy alternatives. Detailed site-specific assessments provide data essential for valuing Federal lands prior to leasing or analyzing industry exploration or development proposals. Large corporations and financial institutions use resource estimates for long-term planning, the analysis of investment options and as a guide in analyzing the future health of the oil and gas industry. Exploration companies use resource assessments to design exploration strategies and target expenditures. Increasingly, resource estimates are being used by the Administration, Congress, and the public to provide objective statements of how much oil and natural gas will be available for future domestic consumption" (Minerals Management Service, 2006a).

An assessment of the undiscovered oil and gas resources for the Alaska Federal offshore was completed in 2006 (Minerals Management Service, 2006d; fig. 2–3). Undiscovered, economically recoverable resources (table 2–3) consider costs associated with development and production. The economic estimates give the greatest insight into the areas that are most likely to be of interest for leasing and development in the near term, that is, the period covered by the next 5-year program (Minerals Management Service, 2006f). Often, these estimates are reported along with the basic economic assumptions, most commonly price (Minerals Management Service, 2006f).

Despite the inherent risk and uncertainty underlying estimates of undiscovered resource endowments, results from resource assessments frequently are used and reported in a manner that underemphasizes the inherent uncertainty, as users typically focus on the mean value (Minerals Management Service, 2006a). Two important points emerged from analysis of mean resource estimates (fig. 2–3). First, the increase in geologic knowledge and advances in technology and industry practice with time do not necessarily translate to increased estimates of undiscovered, technically recoverable resources with time. This point is evident in the mean undiscovered, technically recoverable natural gas resource endowment estimate for the Beaufort Sea OCS (fig. 2–3). A 2010 downward revision of the resource endowment, as compared to the previous assessment in 2002, also occurred for the undiscovered, technically recoverable oil and gas resources for the National Petroleum Reserve in Alaska (Houseknecht and others, 2010). In contrast, the mean estimate for undiscovered, technically recoverable natural gas resource endowment for the Chukchi Sea OCS was revised upward from 2000 to the 2006 assessment (fig. 2–3). Second, the F05 and F95 values plotted about the mean estimates from the 2006 OCS assessment (fig. 2–3) can be considered as an indication of the uncertainty associated with the mean resource estimate. Much of this statistical uncertainty can be attributed to the fact that Arctic Alaska is not a mature petroleum province from an exploration perspective. Considering these points, it is important to note the following:

> "All resource estimates are subject to continuing revision as undiscovered resources are converted to reserves and reserves to production and as improvements in data and assessment methods occur. The assessment results do not imply a rate of discovery or a likelihood of discovery and production within a specific time frame. However, uncertainty surrounding the estimates decreases as the asset progresses through this cycle. Resource estimates should be viewed from the perspective of the point in time the assessment was performed—based on the data, information, and methodology available at that time. In general, risk and uncertainty in estimates of undiscovered oil and natural gas are greatest for frontier areas that have had little or no past exploratory effort" (Minerals Management Service, 2006a).

The Beaufort Sea assessment province extends from the 3-mi limit of Alaska State waters to the 1,640 ft (500 m) isobath (Minerals Management Service, 2006b). Of the area of the Beaufort Sea OCS covered by the assessment province, all the estimated undiscovered, technically recoverable oil and gas resources are considered to be within 650 ft (200 m) water depth (Minerals Management Service, 2006e). Although water depths in the Chukchi Sea planning area can be as high as 12,500 ft (3,800 m) (Minerals Management Service, 2006c), all (100 percent) of the undiscovered, technically recoverable oil and gas resources estimated for the area are considered to be within 650 ft (200 m) water depth (Minerals Management Service, 2006e). For comparison with the other OCS regions, the proportions of the 2006 assessment mean estimates of undiscovered, technically recoverable resources considered to be within the same water depth range of 0 to 650 ft (0 to 200 m) are: Atlantic (39 percent oil and 38 percent gas), Gulf of Mexico (8.5 percent oil and 37 percent gas), and Pacific (30 percent oil and 31 percent gas) (Minerals Management Service, 2006e). Within each OCS region, these proportions vary by planning area.

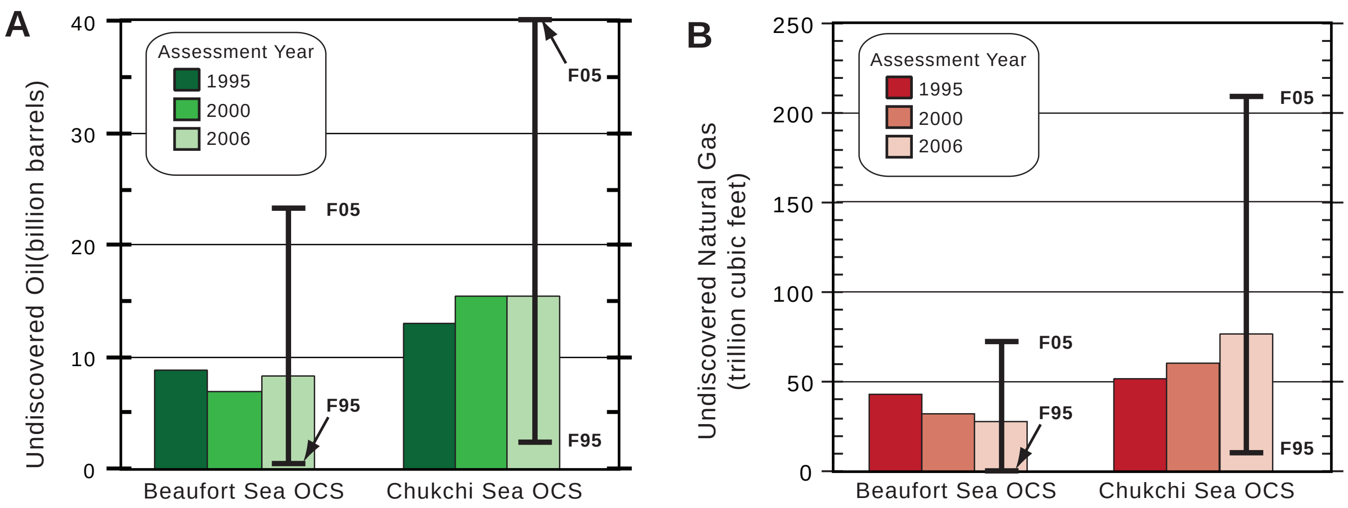

Figure 2–3. Comparison of mean estimates (solid colored bars) for undiscovered, technically recoverable resources for the assessment provinces within the Beaufort and Chukchi Sea OCS planning areas for (A) oil and (B) natural gas. Undiscovered oil estimates include oil plus natural gas liquids (condensate). The 2006 assessment F95 and F05 values, corresponding to a 95-percent probability (a 19 in 20 chance) and a 5-percent probability (a 1 in 20 chance), respectively, of more than these amounts being present, are plotted as an indication of uncertainty about the mean. Modified from Minerals Management Service (2006d, 2006f).

Table 2–3. 2006 National Assessment—Arctic Outer Continental Shelf, Arctic Subregion, Chukchi and Beaufort Shelves.

[Modified from Minerals Management Service (2006b, 2006c). F95 and F05 values correspond to a 95-percent probability (a 19 in 20 chance) and a 5-percent probability (a 1 in 20 chance). BBO, billion barrels oil; TCFG, trillion cubic feet gas; BBOE, billion barrels of oil equivalent; bbl, barrel; mcfg, thousand cubic feet gas]

Risked, undiscovered, technically recoverable oil and gas resources

	Oil and condensate (BBO)			Gas (TCFG)			BOE (BBOE)		
	F95	Mean	F05	F95	Mean	F05	F95	Mean	F05
Chukchi Shelf	2.32	15.38	40.08	10.32	76.77	209.53	4.15	29.04	77.36
Beaufort Shelf	0.41	8.22	23.24	0.65	27.65	72.18	0.53	13.14	36.08

Risked, undiscovered, economically recoverable oil and gas ($80/bbl, $12.10/mcfg)

	Oil and condensate (BBO)			Gas (TCFG)			BOE (BBOE)		
	F95	Mean	F05	F95	Mean	F05	F95	Mean	F05
Chukchi Shelf	1.52	12.00	32.66	6.01	54.44	153.70	2.59	21.68	60.01
Beaufort Shelf	0.34	6.92	21.17	0.54	19.97	59.38	0.44	10.47	31.74

These 2006 OCS assessment results do not preclude the occurrence of oil and gas resources at greater water depths within the Beaufort and Chukchi Sea planning areas. In delineating the Beaufort Sea province assessment boundary, the 1,640 ft (500 m) isobath was adopted as a practical limit for petroleum development; beyond this limit, the extreme water depths and ice conditions were considered likely to preclude exploration and development activities using existing technologies (Minerals Management Service, 2006b). Similarly, after considering the geology and operational adversity of the deep Arctic Ocean environment, the deep-water areas within the Chukchi Sea planning area were assessed with negligible technically recoverable oil and gas resources (Minerals Management Service, 2006c). All technically recoverable oil and gas resources of the Chukchi Sea planning area west of Hanna submarine canyon are considered to be south of the 328 ft (100 m) isobath; east of the canyon, all resources are considered to be south of the 1,640 ft (500 m) isobath (Minerals Management Service, 2006c).

Within the Context of Larger Arctic Region—Circum-Arctic Resource Appraisal (CARA)

Using a probabilistic, geology-based methodology, the USGS recently assessed the area north of the Arctic Circle and concluded that approximately 30 percent of the World's undiscovered gas and 13 percent of the World's undiscovered oil may occur in that region (fig. 2–4; Bird and others, 2008; Gautier and others, 2009a). Most of these resources occur offshore under less than 1,640 ft (500 m) of water. The deep oceanic basins are regarded as having low petroleum potential, whereas the Arctic continental shelves comprise one of the World's largest remaining prospective areas for petroleum hydrocarbons (Gautier and others, 2009a). In particular, the principal investigators concluded that the Chukchi and Beaufort Seas offshore Alaska, along with the adjacent areas of the Beaufort-Mackenzie Basin, might be the most oil prospective areas north of the Arctic Circle (Gautier and others, 2009b). The Beaufort-Mackenzie Basin is regarded as one of the most important basins for future petroleum supply in North America (Chen and others, 2010). The findings from the CARA are significant because they underscore the need for continuing international cooperation and collaboration as a component of overall planning with respect to oil and gas exploration and development in the Arctic.

The Arctic could contain some of the largest gas accumulations on Earth; however, the probability of finding another oil accumulation comparable to Prudhoe Bay is low (Gautier and others, 2009b). This result is significant in understanding potential development scenarios. As mentioned earlier, large oil and natural gas fields are particularly important with respect to future oil and natural gas development in the Arctic because the development costs in the Arctic are sufficiently high that large fields are necessary to pay for the required infrastructure (Budzik, 2009).

The estimated resources in the CARA were considered recoverable without regard to the possible presence of sea ice, and without reference to costs of exploration and development. That said, given the relatively higher costs associated with Arctic oil and gas extraction activities as compared to other regions of the World, the CARA study considered only accumulations with recoverable hydrocarbon volumes larger than 50 million barrels of oil or 300 billion cubic feet of gas (50 million barrels of oil equivalent) (Gautier and others, 2009a). Hydrocarbon accumulations with less than these threshold volumes were excluded from the study, as were unconventional resources, such as coalbed methane, gas hydrates, oil shales, and heavy oil and tar sands. Gautier and others (2009b) note that these estimates are intended as a baseline, given that in many study areas, the estimates are based on limited geologic information, and that our understanding of these resource endowments is certain to change as new data become available. For example, there are a number of areas assessed in the CARA study for which only seismic data (no wells) are available, and other areas that are devoid even of seismic data (fig. 2–5).

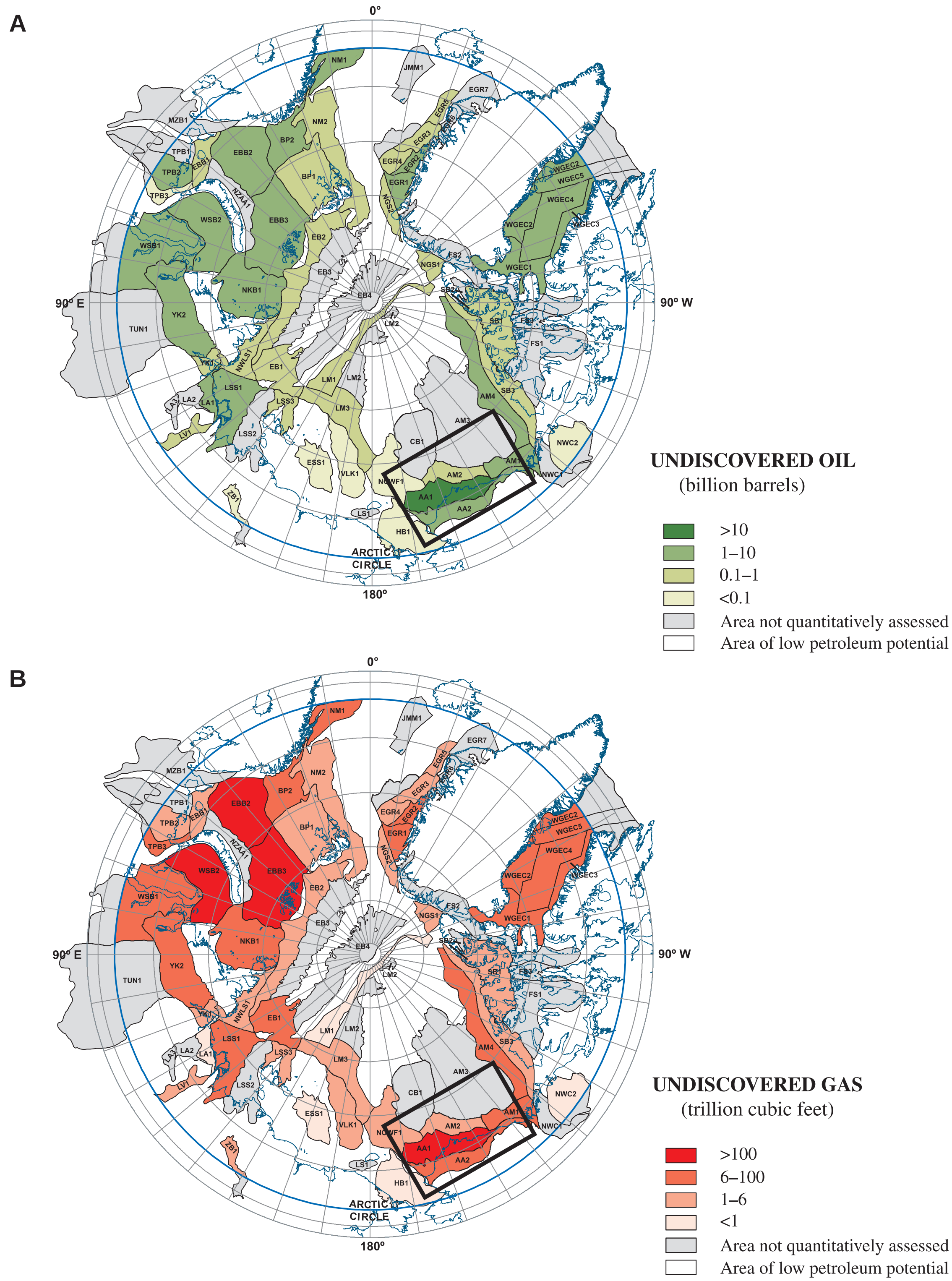

Figure 2–4. Assessment units of the Circum-Arctic Resource Appraisal, color-coded according to the mean estimated undiscovered, technically recoverable resources for (A) oil and (B) natural gas. The open rectangles denote the approximate location of the Alaska North Slope and Beaufort and Chukchi Seas Outer Continental Shelf areas. Modified from Gautier and others (2009a).

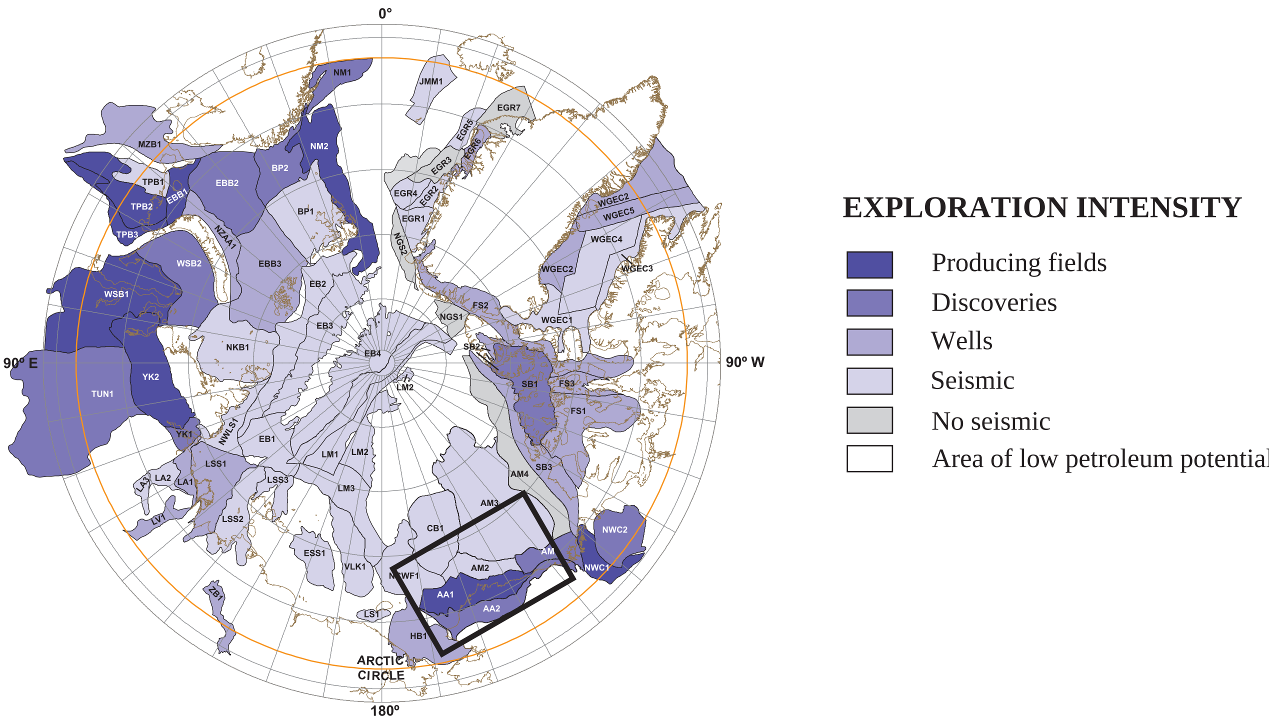

Figure 2–5. Assessment units of the Circum-Arctic Resource Appraisal, color-coded according to Exploration Intensity, as given by the highest level of petroleum exploration or development activity attained within an assessment unit. The open rectangle denotes the approximate location of the Alaska North Slope and Beaufort and Chukchi Seas Outer Continental Shelf areas. Modified from Gautier and others (in press).

More work is needed to better constrain the understanding of the occurrence and extent of these petroleum systems. Even the Alaska North Slope is not a mature petroleum province from an exploration perspective, although oil has been produced for decades. Most wells drilled to date in the Alaska North Slope, including those in State-owned onshore and nearshore Beaufort Sea areas, are clustered along the Barrow Arch in a relatively low density of approximately one exploration well per 22 mi^2 (about 57 km^2) (Thomas and others, 2009). A more refined understanding of the Arctic oil and gas resource endowment will become apparent with additional exploration wells (Budzik, 2009). Most oil development to date has been focused on conventional resources, although currently there is a growing emphasis on development of oil resources in low permeability reservoirs and extraction of heavy oil resources. Additionally, currently (2011) there is an emerging focus on the possible extraction of oil from source-rock systems. Future changes in the availability of infrastructure, such as a gas pipeline, could provide the impetus for additional exploration and development activities, particularly in areas where resources are currently stranded with respect to the market. During nearly seven decades of exploration in Arctic Alaska, only a few wells in recent years have been drilled with the specific objective of evaluating natural gas recovery. In the absence of a pipeline to move natural gas from northern Alaska to market, gas discoveries have largely been viewed as exploration failures and additional exploration drilling in large parts of the region has been discouraged. A gas pipeline would not only result in production of known gas resources but also would stimulate additional exploration in those parts of the region that are most underexplored. The associated oil and natural gas liquids (condensate) produced in conjunction with these resources also would increase oil production, although these volumes alone are not expected to be sufficient to extend the life of the TAPS (Thomas and others, 2009).

In addition to the interest in the Beaufort and Chukchi OCS, the Mackenzie Delta has been an exploration focus in Arctic Canada for decades. This interest is anticipated to continue despite the fact that commercial production has not yet begun (Kumar and others, 2009). As with the Alaska North Slope, the construction of pipeline infrastructure is regarded as critical to the development of oil and gas resources in the Mackenzie Delta–Beaufort Sea Basin, and construction can drive expansion into offshore resources of the Beaufort Sea (Voutier and others, 2008). Given the interest in the Mackenzie Gas Project and in anticipation that the Mackenzie Delta–Beaufort Sea region may be on the threshold of a extended period of oil and gas development, a process for developing the Beaufort Sea Strategic Regional Plan of Action (the Strategic Regional Plan) was launched (Voutier and others, 2008). This process culminated in the development of a Strategic Plan of Action by a multi-agency stakeholder group under the guidance of the Beaufort Sea Strategic Regional Plan of Action (2008) Steering Committee.

In support of these integrated ocean management-planning efforts, a digital atlas was compiled to bring together disparate datasets that illustrate the spatial interdependence of natural resources and human activities in oil and gas production and other matters (Dubuc and others, 2009). There is a continuing need to better integrate and disseminate existing data to support these types of multidisciplinary analyses while facilitating greater public data access, as noted by the National Research Council (1994) and recently echoed by Vörösmarty and others (2010). The North Slope Science Initiative (NSSI) could provide a similar mechanism for coordination, while also leveraging research opportunities to address emerging science issues (North Slope Science Initiative, 2009) and providing a basis for understanding potential effects of oil and gas development in a systematic context with other drivers, such as climate change.

Unconventional Resources

Overview

It is important to consider other energy resources in the context of resource development and extraction on the OCS. For example, unconventional energy sources, such as coalbed methane, gas hydrates, shale gas, tight gas sands, heavy oil, and both oil and gas in source rocks, are known to occur. A number of these resources are located onshore, nonetheless, their potential development may affect the development and extraction of resources from the OCS. For example, the existence of the heavy oil resources has long been recognized in the Arctic (Werner, 1987), and production of this resource commenced just last year (Mathews and Young, 2010). Historically, the discussions of Arctic Alaska resource potential have focused on conventional oil resources with less attention given to conventional gas and unconventional gas and liquid resources (Thomas and others, 2009). However, the recent development of shale gas resources in the conterminous United States, coupled with estimates of further potential, may affect the level of interest in developing natural gas in the Arctic (Budzik, 2009). Given this context, continued research into unconventional resources is important, among other things, as a basis for developing technologies to extract these resources safely while minimizing environmental impacts (Arctic Monitoring and Assessment Programme, 2007).

In its study of the Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope, the National Research Council (2003) used a development scenario, focused on oil and gas extraction activities, to evaluate potential development effects. The committee noted that other resources, including coal, and unconventional resources such as coalbed methane, could significantly alter the committee's scenarios. However, the uncertainties associated with economic and other factors obscured the capability to predict the timing and extent to which these resources might be used or when exploration might commence (National Research Council, 2003). Since that study, numerous research activities have expanded our knowledge of these resources. For example, the USGS assessed coalbed methane resources on the Alaska North Slope, and estimated a mean undiscovered, technically recoverable resource of roughly 18 trillion cubic feet of gas (Roberts and others, 2006). A substantial portion (more than 80 percent) of this resource is thought to occur within the Nanushuk Formation assessment unit, which is primarily within the National Petroleum Reserve in Alaska.

In the past year, production of heavy oil has commenced (Mathews and Young, 2010). However, the magnitude of the contribution from this resource to oil supply over the long term remains uncertain. Industry has invested considerable money over the years to develop and test technologies culminating in production of heavy oil (Triolo and others, 2005; Mathews and Young, 2010). One of the key factors to sustained development is the need for lighter oil to serve as a diluent to facilitate transfer through the Trans-Alaska Pipeline System. The Energy Information Administration, in its Annual Energy Outlook 2010 with projections to 2035, noted that the greatest uncertainty regarding Alaska oil projections is "…whether the heavy oil deposits located on the North Slope, which exceed 20 billion barrels of oil-in-place can be produced at recovery rates exceeding more than a few percent of the in-place resource" (U.S. Energy Information Administration, 2010).

Given recent advances in the geologic understanding of unconventional resources and developments in technology, the prospects of these resources contributing to the energy supply have improved such that these resources merit consideration in updated scenarios of energy resource supply. The U.S. Arctic Research Commission (2010) recently determined that, because much of the oil, heavy oil, gas, shale gas, gas hydrates, coal, and coalbed methane deposits within the U.S. Arctic are on Federal lands, further research of these resources should be undertaken with industry, the State of Alaska, and international partners in producing and consuming countries.

Gas Hydrate Studies: Energy Resources

Gas hydrates (or methane hydrates) are ice-like crystalline substances occurring in nature where a solid water lattice accommodates gas molecules (primarily methane, the major component of natural gas) in a cage-like structure, also known as clathrate. The amount of natural gas in methane hydrate worldwide is estimated to be far greater than the World's conventional natural gas resources. Gas hydrates form under conditions of relatively high pressure and low temperatures, such as those in the shallow subsurface under many of the oceans, including much of the deepwater OCS. Gas hydrates also occur under Arctic permafrost that exists onshore in northern Alaska, and the hydrate stability zone is expected to extend farther offshore into the Beaufort Sea OCS. The BOEMRE has recently identified evidence for the existence of hydrates in the Alaska Beaufort continental shelf through the analysis of seismic data and LWD (logging while drilling) gamma ray and resistivity logs from the Hammerhead Number 1 and 2 wells, although the lack of acoustic log data from these wells precludes the distinction between free gas and gas hydrate (Collett and others, 2011). Scientists conducting a sampling cruise aboard the USCGC *Healy* as part of the Extended Continental Shelf Project recently recovered gas hydrate in piston cores of sediment collected from the continental margin in the Beaufort Sea (Gibbons, 2010).

Early results from recent Arctic field programs have provided important new insights into characterization of producibility of gas hydrate reservoirs (Dallimore and Collett, 2005). Analysis of 3-D seismic data has been useful in delineating the lateral extent of gas hydrate accumulations. In 2007, a joint effort among BP Exploration (Alaska), the U.S. Department of Energy, and the USGS culminated in the completion of the Mount Elbert Gas Hydrate Stratigraphic Test Well in the Milne Point field on the Alaska North Slope. This test used 3-D seismic interpretations and wireline log correlations to derive pre-drill estimates of gas hydrate occurrence in the surbsurface (Rose and others, 2011). The Milne Point 3-D seismic analysis revealed a "patchy" nature to the occurrence of gas hydrate in the Eileen accumulations, with individual gas hydrate prospects ranging in size from about 0.1 to 2.7 mi^2 (0.3 to 7.0 km^2), indicating that gas hydrate accumulations in this setting may be more regionally extensive than previously thought. The thickness of these accumulations probably is highly variable (Collett and others, 2011).

In 2008, the USGS completed an assessment of the undiscovered, technically recoverable gas resources from gas hydrates on the Alaska North Slope (fig. 2–6; Collett and others, 2008), the first assessment of its kind. This study addressed gas hydrate resources onshore and underlying State-owned waters. The USGS estimated a mean technically recoverable resource of 85.4 TCF of gas, which accounts for approximately 11 percent of the volume of gas within all other undiscovered, technically recoverable gas resources estimated for the onshore and State waters of the United States. Many of the techniques used in this study to delineate the gas hydrate occurrences are transferable to studies of gas hydrate occurrences in the OCS.

Although limited data collection now allows some gas hydrate accumulations to be considered technically recoverable, there remain questions of long-term producibility and economic feasibility of these energy resource occurrences (Minerals Management Service, 2009). Collett and others (2008) highlighted that further research, including long-term production tests, are needed to demonstrate whether or not gas hydrates are an economically producible resource. A recent study by Osadetz and Chen (2010) refined the resource models used by the Geological Survey of Canada to re-evaluate the gas hydrate resources in the Canadian Beaufort Sea-Mackenzie Delta Basin, and the results of this work further underscored the need to study major Arctic deltas and continental shelves for characterizing the resource potential of these accumulations.

The Methane Hydrate Research and Development Act of 2000, later amended in Section 968 of Public Law 109-58 (30 U.S.C. 1902–The Energy Policy Act of 2005), directs several Federal agencies (led by the Department of Energy, and including BOEMRE, USGS, and the Bureau of Land Management) to cooperatively engage in gas hydrate research and development efforts. In 2010, the NRC evaluated the Department of Energy's Methane Hydrate Research and Development Program and concluded that research on methane hydrate to date has not revealed technical challenges that are insurmountable in the goal to achieve commercial production of methane from methane hydrate in an economically and environmentally feasible manner. In the course of its evaluation, the National Research Council (2010) identified areas critical to achieving the Program goals—design of production tests, appraisal and mitigation of environmental and geohazard issues related to production,

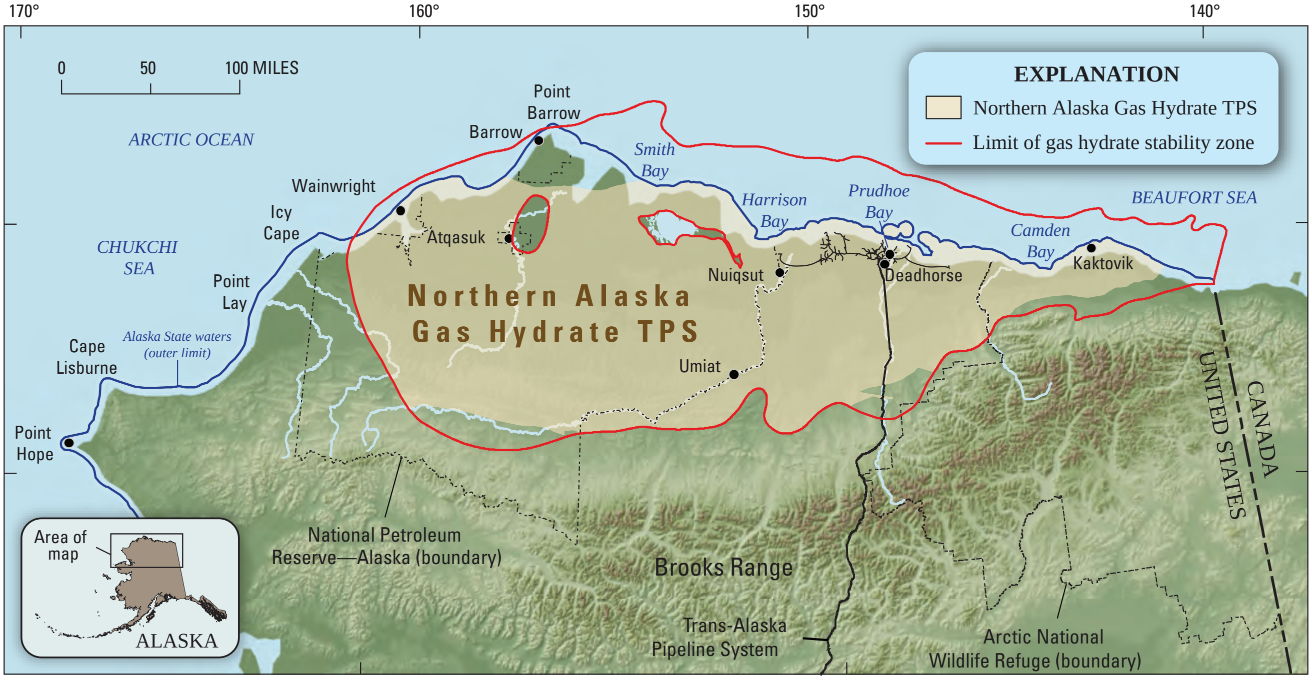

Figure 2–6. Map showing extent of the Northern Alaska Gas Hydrate Total Petroleum System (TPS) (shaded in tan), and the limit of gas hydrate stability zone in northern Alaska (red outline). Collett and others (2008) used this TPS as a basis for the first assessment of undiscovered, technically recoverable gas-hydrate resources beneath the Alaska North Slope and State-owned waters. Modified from Collett and others (2008).

and quantification of the resource. Specific National Research Council (2010) recommendations pertaining to the quantification of the resource include:

> "Pilot seismic surveys using existing geophysical methods optimized to map and quantify in-place methane hydrate accumulations;"
>
> "Improved understanding of *in-situ* properties of sediments containing methane hydrate through comprehensive testing (geophysical, geochemical, microbiological, geomechanical) of undisturbed natural drill cores and synthetic samples;" and
>
> "Consideration of the development of new geophysical imaging, processing, and quantification techniques, particularly with respect to quantifying the in-place resource."

In recognizing some of these knowledge gaps and research needs, the U.S. Arctic Research Commission (2010) recommended gas hydrate research (onshore and offshore) as one of the areas of emphasis for the Department of Energy's Arctic Energy Office. The U.S. Arctic Research Commission (2010) also noted that it may be appropriate to consider the inclusion of Arctic mapping and gas hydrates research activities within other agencies' resource assessment and earth science program plans.

Gas Hydrate Studies—Climate Change Linkages and Geohazards

In addition to the study of gas hydrates from an energy resource perspective, the potential linkages among subsea gas hydrates, climate change, and sea-level changes, particularly on the Beaufort continental slope, have long been recognized (Kayen and Lee, 1991). One of the key research questions regarding these linkages is discerning whether gas hydrate degassing plays a causative role in global warming, or is merely a response to the effects of rapid global warming (Ruppel and Pohlman, 2008). The long-term warming may lead to dissociation of the gas hydrates, during which gas is released. This release of gas can change the physical properties of the surrounding sediments and affect infrastructure through loss of borehole integrity and (or) regional subsidence (Lee and others, 2010). However, most of the scenarios that may suggest gas hydrates as a geohazard to traditional hydrocarbon infrastructure do not manifest themselves at the time the well is being drilled, but rather result as a consequence of the long-term warming of the sediment associated with hydrocarbon production (National Research Council, 2010).

The National Research Council (2010) review recommended that further studies are required to address the processes involved in (1) the transmission of methane from the subsurface through the methane-hydrate stability zone to the surface and (2) the subsequent fate of the released methane. Further, these studies should focus on degassing processes and potentially enhanced environmental effects from commercial production of methane from methane hydrate and from methane hydrate associated with other oil and gas developments (National Research Council, 2010). Recent study of gas venting on the Arctic seafloor focused on pingo-like-features (PLFs), which may be a direct result of gas hydrate decomposition, on the Beaufort Sea Shelf (Paull and others, 2007). The investigators recovered vibracore samples of sediments containing elevated methane concentrations from these PLFs (Paull and others, 2007). In a September 2009 study expedition, Methane in the Arctic Shelf/Slope, aboard the USCGC *Polar Sea*, collected sediments, water column, and atmospheric samples to improve the understanding of the fate and cycling of methane in these Arctic systems (Coffin and others, 2010). Coffin and others (2010) noted that a lack of data, "…particularly modern seismic, bathymetry and other remote sensing surveys across the U.S. Beaufort Shelf…" was one of the challenges to understanding the occurrence and fate of gas hydrates in these settings. These are important knowledge gaps to address, because despite the fact that gas hydrates typically are perceived as posing geohazard risks to industry, little documentation exists to constrain the extent and magnitude of these potential risks (National Research Council, 2010). At present, industry practice is to avoid methane hydrate-bearing areas during drilling and production for conventional oil and gas resources, but this avoidance will not be practical if gas hydrates are the production target (National Research Council, 2010).

With respect to potential commercial production of natural gas from gas hydrate, the National Research Council (2010) assigned particular importance to the need for better understanding of the potential environmental impacts of methane hydrate degassing. The seafloor hazards ("geohazards") resulting from methane hydrate dissociation as a result of oil and gas drilling and production are of specific importance. To that end, the National Research Council (2010) recommended that in addition to further characterization and quantification of gas hydrates, there should be research activities focused on designing production tests and appraising and mitigating environmental and geohazard issues related to production.

2.02. Finding: There have been significant advances in characterizing and understanding the geologic context of unconventional resources in the Alaska North Slope over the past decade (2000–2010). The potential viability of these resources may affect development scenarios and construction of infrastructure. Because potential extraction and transportation of resources from the OCS will require considerable additions to current infrastructure, an understanding of the potential role of these unconventional resources in the future energy supply is needed for development of holistic scenarios to inform resource management and infrastructure construction decisions.

2.02. Recommendation: Unconventional resources may directly and (or) indirectly affect potential scenarios for development within the Beaufort Sea and Chukchi Sea planning areas. Thus, further study of these energy resources (especially coalbed methane, heavy oil, oil and gas resources in source-rock systems, tight gas, and gas hydrates) are needed to better understand the potential of these resources to contribute to energy supply and to inform potential development scenarios.

Gas resources in tight reservoirs are known to occur beneath the Alaska North Slope and likely occur beneath the OCS areas as well. Further research characterizing these resources, including petrophysical investigations of source-rock systems, should be carried out to better understand the petroleum systems of the Arctic and to assess recoverable continuous-type resources, such as oil and gas resources in shale and tight sands.

Further research is needed to characterize gas hydrates in terms of an energy resource, as well as connections with climate change (and potential contribution to the greenhouse gas cycle) and geohazard issues. In particular, an improved understanding of gas hydrate occurrence, quantity, and stability in the Beaufort OCS planning area is needed, to inform energy resource decisions and potential for hazards, such as sediment and (or) slope stability, with respect to activities on the continental shelf, such as oil and gas development and infrastructure siting. Methane released from gas hydrate dissociation could represent a significant flux of greenhouse gas to the atmosphere. A better understanding of the linkages and feedbacks between gas hydrates and climate change is needed to address these issues.

Economics and Scenarios

Economic analyses of undiscovered, technically recoverable oil and gas resources typically consider the costs associated with finding, development, and production (Minerals Management Service, 2006f). These estimates of economically recoverable resources provide information about those areas that might receive the greatest interest in terms of leasing and development (Minerals Management Service, 2006f). They also provide information that can be used as input from which to construct development scenarios. These scenarios can be used to gauge the potential scope and scale of future development, while providing a basis for evaluating potential effects on the environment, and as such, Exploration and Development scenarios are a component of Environmental Impact Statements and Environmental Assessments (Coffman and others, 2002). The scenarios produce estimates of the infrastructure required to support anticipated exploration, development, and production, and are based on input from existing geologic data and undiscovered resource estimates, and estimates regarding the timing of discovery and rates of production at specified price paths (Coffman and others, 2002). For example, at the time of the Burger discovery in the Chukchi Sea OCS, it was recognized that new technology, including subsea wellheads, year-round operations in pack ice, and large-diameter high-pressure, dense phase subsea pipelines, would be needed to produce the gas from this accumulation, but that these had not yet been tested under conditions typical of the Chukchi Shelf environment (Craig and Sherwood, 2004). In addition to such challenges, the potential for development of the resources at Burger would require transport through an 80-mi subsea pipeline and further transport overland (about 320 mi) to Prudhoe Bay on the central North Slope (Craig and Sherwood, 2004). This underscores the importance of infrastructure to the development of this resource. This linkage was reiterated in a recent economic analysis of the ANS, which found that the extent of Chukchi Sea exploration and development activities will be significantly affected by the potential for expansion of petroleum-producing infrastructure to western NPRA as a means of facilitating transport of resources to market (Thomas and others, 2009).

What is important to recognize is that the complex interplay among the numerous factors associated with oil and gas development in the Arctic, including international geopolitics, future energy demand, climate change, and other fundamental parameters, such as the geologic setting of resources and estimated resource potential, collectively provide a significant challenge to precisely and accurately projecting the future activity (Arctic Monitoring and Assessment Programme, 2007). Previously, several models and methods were used in the analysis of economic impacts from oil and gas activities. The models and methods used typically varied from one planning area to another (Jack Faucett Associates, Inc., 2002), but efforts to develop more regionally expansive models have resulted in a more consistent approach, while recognizing there are differences from one region to another (Coffman and others, 2002). For example, the readily available regional economic impact models contain production functions based on national averages that do not accurately reflect the unique Arctic production function (Skolnik and Holleyman, 2002). Specific to Arctic oil and gas resources, factors such as remoteness, low temperatures, and shifting ice rule out traditional platforms, and require a modeling approach that accounts for these unique circumstances (Skolnik and Holleyman, 2002).

In addition to the modeling approaches developed specifically in support of Environmental Impact Statement and Environmental Assessment analyses, there have been a number of scenarios constructed to evaluate the potential scope and scale of oil and gas activities and associated effects in the Arctic OCS. Many of these analyses vary in terms of geographic scope or particular focus, such as:

- the National Research Council (2003), which included the Alaska North Slope and Beaufort Sea, but did not consider the Chukchi Sea area to the west of the North Slope;
- Thomas and others (2009), which included onshore Alaska, including Alaska National Wildlife Refuge, as well as the Beaufort and Chukchi Sea OCS areas; and
- Burden and others (2009), which focused on the Beaufort Sea, Chukchi Sea, and North Aleutian Basin areas.

The regional geological framework, petroleum geology, exploration history, and existing fields are used as a basis for understanding the prior exploration and development activities, and to develop a framework for assessing current and future opportunities, and estimate the quantities of economically recoverable oil and gas that could be developed (Thomas and others, 2009), an approach that is common to all such studies. In the short term—2005 to about 2020—Thomas and others (2009) estimated that oil exploration would target primarily the Central North Slope, NPRA, and Beaufort Sea OCS. Given the recently updated NPRA assessment (Houseknecht and others, 2010), this outlook may change in response to the refined understanding of the potential resource base.

For example, sample output summary from the Burden and others (2009) analysis is included (table 2–4). In the Burden and others (2009) study, the scenarios used to underpin the analysis were derived in part by scenarios published in Environmental Impact Statements (EIS) and other materials. The study authors acknowledged the uncertainty associated with cost estimates for items such as exploration and development wells, offshore platforms, and production facilities and infrastructure such as pipelines given the unique challenges in the Arctic (Burden and others, 2009). Although the potential for a gas pipeline through the NPRA has been recognized as a potential means for transporting gas produced from the Chukchi Sea OCS, particularly in light of the Burger discovery (Craig and Sherwood, 2004), such a development was not considered in the scenario because of the high level of uncertainty associated with that infrastructure. The estimates from scenarios such as Thomas and others (2009) also provide useful information to help understand the potential long-term viability of infrastructure, such as TAPS (fig. 2–7). Depending on the level of future exploration and development in the Arctic OCS, the challenge may not be whether there is sufficient production to sustain TAPs, but whether additional pipeline capacity is needed.

Table 2–4. A summary example of output from an Outer Continental Shelf (OCS) development scenario.

[Modified from Burden and others (2009, table 2)].

	Beaufort	Chukchi
Exploration		
Exploration/delineation wells	47	43
Exploration rig seasons	31	27
Development		
Number of offshore production platforms	7	4
Offshore/onshore pipelines (miles)	235	680
Shore bases / facilities		
Marine terminal	Yes	Yes
Liquefied natural gas facility	No	No
Production facility	Yes	Yes
Support base	Yes	Yes
Production		
Year 1st oil flows	2019	2022
Year 1st gas flows	2029	2036
Number of producing fields	7	4
Total cumulative volume produced (through 2057)		
Oil and gas (billion barrels of oil equivalent)	6.34	6.16
Oil and condensates (billion barrels)	5.10	4.79
Gas (trillion cubic feet)	6.96	7.78
Daily peak production		
Oil and condensates (barrels per day)	1,165,707	565,472
Gas (million cubic feet per day)	883	1,421

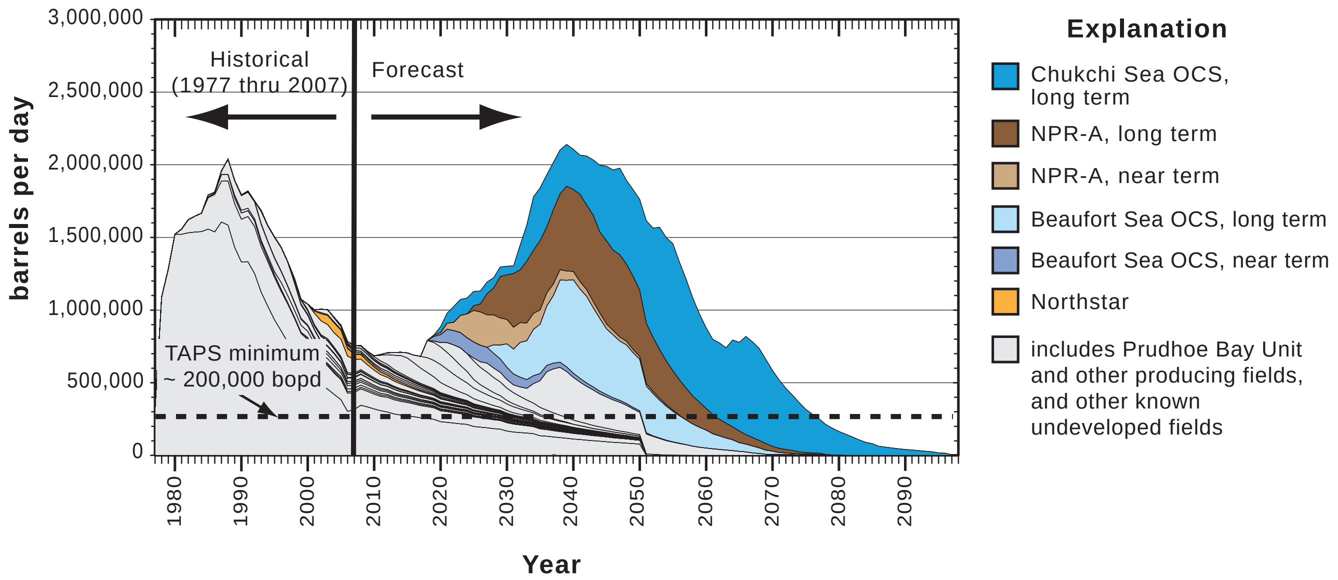

Figure 2–7. Scenario output for projected estimates of future oil production from producing, known, undeveloped, and undiscovered oil fields on the Alaska North Slope and offshore. This composited projection includes recognition of two potentially distinct time frames pertaining to Alaska North Slope exploration and development activities: near term (2008 to about 2018–2020), which is largely centered on oil, and long term (about 2020–2050), which may represent a shift towards natural gas as a significant, perhaps dominant, factor in exploration and development. TAPS, Trans-Alaska pipeline system; bopd, barrels of oil per day. Modified from Thomas and others (2009).

By providing estimates for the potential scope, scale, and timing of development, these scenarios also are helpful for planning purposes and for informing research priorities. For example, the National Research Council (2003) scenario estimated that it might be another 10–15 years (the early 2020s) before Beaufort OCS development would escalate much above historical levels, but that this estimated time lag

> "… also will provide time to more fully research and implement technologies that would reduce the environmental consequences of Beaufort Sea exploration and production, especially under conditions of broken ice."

There is need for a more comprehensive, holistic approach to building resource development and impact scenarios to inform planning. Such scenarios would consider activities beyond the planning areas to include other onshore resources, especially unconventional resources that may affect development decisions as well as infrastructure siting. Additionally, the National Research Council (2003) study determined that

> "… [i]f new technologies were developed, the life of the facilities at Prudhoe Bay and other major fields would be prolonged, as would use of the Trans-Alaska Pipeline."

The National Research Council (2003) study also noted that an important assumption underpinning its scenario is that

> "climate change will not be so great during the next 50 years as to render current exploration methods obsolete or foreclose modifications, such as use of Rolligons and new drilling platforms."

These findings underscore the need for scenarios that account for potential resources and infrastructure beyond the immediate planning areas and proposed activities, and consider these in the broader context of climate change, to develop a comprehensive and systematic analysis of the region. Such steps toward a more holistic approach to energy planning are favorably aligned with recommendations given during recent testimony by the National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling:

> "The [Macondo well] disaster signals the need to consider the broader context of the Nation's patterns of energy production and use, now and in the future—the elements of America's energy policy" (Graham and Reilly, 2011).

Although our understanding of the Arctic system has advanced, there remain data and knowledge gaps for a number of components in the system. The opportunity exists to leverage existing research infrastructure and future research activities to better characterize this system and lead to scientific advances in a number of disciplines. Vörösmarty and others (2010) recently noted that the challenge of successfully extracting non-renewable resources economically and securing environmental protection provides an excellent opportunity to forward interdisciplinary and multiscale research. In this context, there is a continuing need to support the collection, integration, and sharing of multiscale datasets describing the inventories of current and potential stocks of various non-renewable resources (Vörösmarty and others, 2010). Interagency and international fora, such as the North Slope Science Initiative, the Interagency Arctic Research Policy Committee (IARPC), and the Arctic Council, provide venues through which the appropriate integrated and collaborative research activities address these knowledge gaps. For example, the USARC has recommended that the IARPC adopt a Resource Assessment and Earth Science Theme in the U.S. Arctic Research Program, and subsequently amended this recommendation to include basic earth science research needs (U.S. Arctic Research Commission, 2010).

2.03. Finding: Although our understanding of the Arctic as a system has advanced, there remain data and knowledge gaps for a number of components in the system. There is a continuing need to facilitate the collection, integration, and sharing of multiscale, multidisciplinary datasets, and using these data to develop comprehensive, holistic approaches to building resource development and impact scenarios to inform planning.

2.03. Recommendation: Opportunities for enhanced international cooperation and collaboration. In particular, the Beaufort Sea-Mackenzie Delta (Canada) is an area with significant energy resource potential, and enhanced cooperation is important for baseline studies of resources, status, and trends, and developing overall models of development scenarios, potential impacts, and to address emerging science issues. The recent (2010) U.S.-Canada joint mission of the Extended Continental Shelf Project is one example of such collaboration. There exists the opportunity to identify these activities under the theme Resource Assessment and Earth Science in the U.S. Arctic Research Program adopted by the IARPC. In conjunction with these activities, there is a need for better integration of relevant information into a digital environment that can facilitate open and derivative analyses.

There also is significant potential for collaborative work with academia and the international community, especially with planned marine cruises that include seismic and solid-earth geophysical data collection, and sample collection, including coring.

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Chapter 3

Ecological and Subsistence Context

By Anthony R. DeGange and Lyman Thorsteinson

Introduction

This chapter provides a general overview of the physical and biological environments of the Beaufort and Chukchi Seas. We also include information on the human communities and subsistence resources of this area. This chapter, along with Chapter 2, Geological Context, which discusses the current knowledge of oil and gas resources, sets the stage for other chapters in this report that delve into greater detail on important aspects of these marine areas and resources and their relationship to oil and gas leasing, exploration, and development. In this chapter, we present findings and recommendations that speak to the state of the broader science foundation of the Arctic. This information informs specific oil and gas development-related discussions in later chapters. Two broad syntheses have recently captured much of this information, some of which is repeated here (Hopcroft and others, 2008a; Minerals Management Service, 2008). These summaries are authoritative and should be consulted to develop a broader framework of the previous research in the Beaufort and Chukchi Seas.

The Beaufort and Chukchi Seas are marginal seas of the Arctic Ocean (fig. 1–1). They lie north and northwest, respectively, of Alaska. Both seas are linked atmospherically via the Aleutian Low, whose variable position, strength and interactions with Arctic air masses affect meteorological conditions. They are linked oceanographically with the Pacific Ocean primarily via the Bering Strait, through which northward flow transports waters and organisms from the Bering Sea Shelf. The Beaufort Sea extends from Point Barrow in Alaska east to Banks and Victoria Islands of the Canadian Arctic Archipelago and the Amundsen Gulf. The Chukchi Sea extends from Point Barrow, Alaska and the Beaufort Sea in the east to Wrangell Island and the East Siberian Sea in the west. The Bering Strait forms the southern boundary of the Chukchi Sea and connects it with the Bering Sea and Pacific Ocean.

Physical Oceanography

(from Weingartner and others, 2008, and Minerals Management Services, 2008)

The marine topographies of the Beaufort and Chukchi Seas are starkly different (fig. 3–1). The Chukchi Sea is underlain by a broad continental shelf that extends nearly 900 km from the Bering Strait north to the shelf break. In contrast, the Beaufort Sea has a narrow continental shelf. East of Point Barrow, the continental shelf narrows to about 70 km and then widens again farther east near Mackenzie Bay and as it extends eastward into the Amundsen Gulf. The topography of this region includes Wrangel Island, at the approximate western boundary between the Chukchi and East Siberian Seas, and Herald and Hanna shoals in the Chukchi Sea Shelf north of Bering Strait. Submarine canyons include the Herald Valley and Central Channel in the Chukchi Sea, and the Barrow Canyon at the boundary between the Chukchi and Beaufort Seas. In the Beaufort Sea, there is little along-shelf variability in bathymetry, except for Barrow Canyon to the west and Mackenzie Valley near the Alaska-Canada border. There are numerous barrier islands along the Beaufort Sea coast and a number of bays and lagoons on both shorelines that form important wildlife habitats.

The water of the Beaufort Sea reflects three distinct oceanic regimes (Weingartner and others, 2008). The first consists of Pacific Ocean waters that exit the Chukchi Sea Shelf through the Barrow Canyon. The second is the offshore boundary of the continental shelf and slope. The upper layer is a westward flow that is the southern edge of the wind-driven Beaufort Gyre. Below that the flow is eastward over most of the slope. The third regime is formed by discharge from the Mackenzie River that intrudes into the Beaufort Sea through wind-forcing.

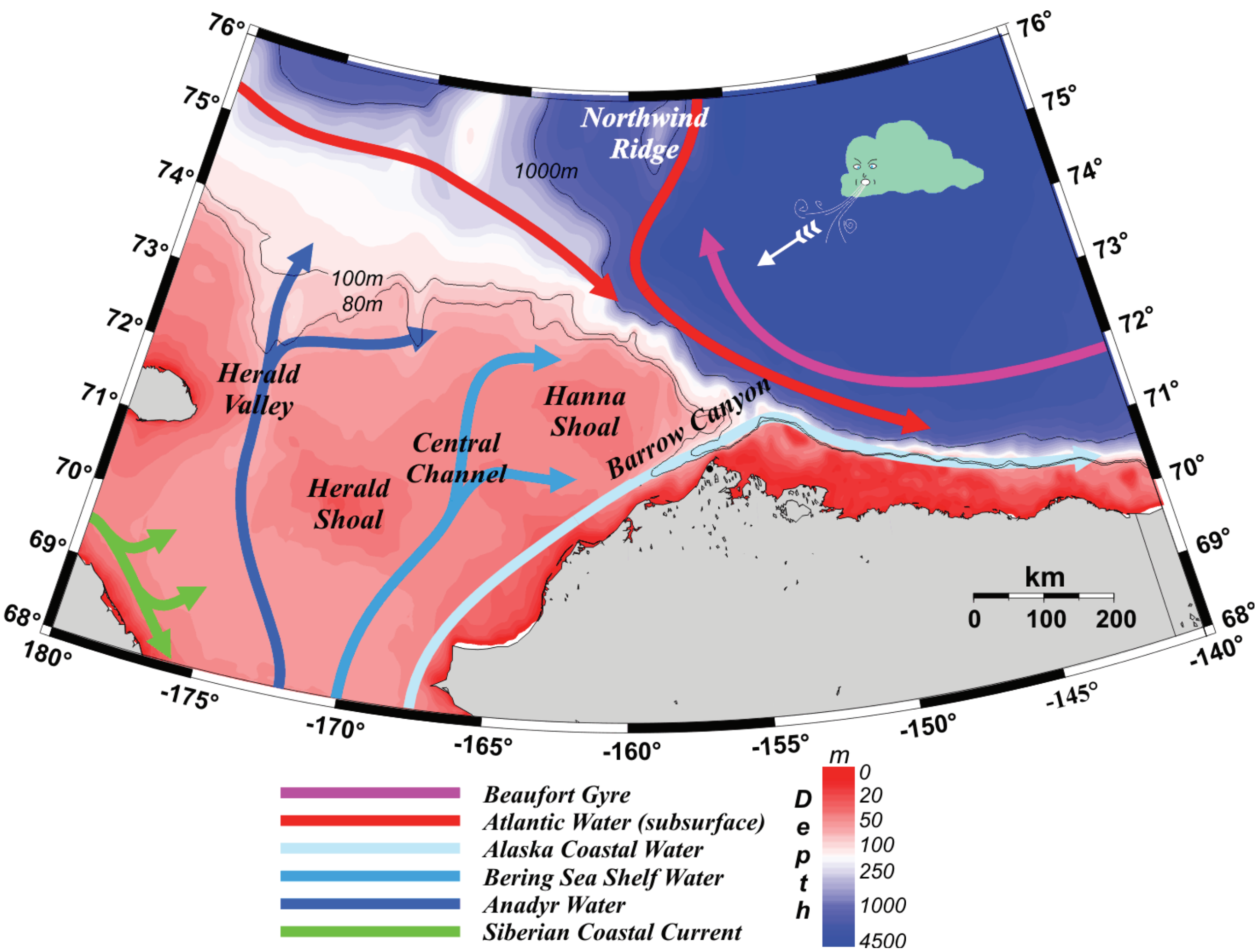


Figure 3–1. Schematic circulation map of the northern Chukchi Sea and western Beaufort Sea. From Weingartner and others (2008).

Surface circulation in the Beaufort Sea is dominated by the southern edge of the perpetual clockwise gyre of the Canadian Basin (fig. 3–1). The subsurface Beaufort Undercurrent flows in the opposite direction, to the east, over the Outer Continental Shelf. Currents in the shallower waters of the inner Beaufort Sea Shelf primarily are wind driven and, thus, can flow either east or west. Because the principal wind direction during the summer ice-free season is from the east, near-shore flow generally is from east to west.

Under persistent east winds, bottom marine water can move onshore, where it is forced to the surface. This upwelling of marine water can cause some otherwise brackish and warm areas along the coast to become colder and more saline.

The Chukchi Sea receives water flowing northward through the Bering Strait, driven by the 0.5 m drop in sea level between the Aleutian Basin of the Bering Sea and the Arctic Ocean. Coachmen and others (1975) provide a good overview of the northward movement of Bering Sea waters into the Chukchi Sea. Three distinct water masses, each of different origin move northward through the Bering Strait. Anadyr Water, cold, high salinity, nutrient-laden oceanic water that originates along the slope of the Bering Sea Shelf, flows northward through Anadyr Strait, west of St. Lawrence Island and into the central Chukchi Sea. As much as 72 percent of the water transported through the Bering Strait in the summer may come through Anadyr Strait. Alaska Coastal Water originates in the Gulf of Alaska. This low salinity, seasonally warm water hugs the Alaska coast as it transits the Bering Sea into the Chukchi Sea. It is influenced by freshwater run-off from major rivers in western Alaska. Bering Shelf Water is the resident water mass of the central shelf region south of St. Lawrence Island. It is intermediate in character between Anadyr and Alaska Coastal Water, is advected northward on both sides of St. Lawrence Island, and then flows through the Bering Strait where it mixes with the other water masses. These waters are an important source of plankton and carbon in the Chukchi and Beaufort Seas, influencing the distribution and abundance of marine biota and seasonal migrations of many species (Piatt and Springer, 2003; Hopcroft and others, 2008a; Weingartner and others, 2008). The deeper waters offshore in the northern Chukchi Sea also are a potentially important source of nutrient-rich waters.

3.01. Findings and Recommendations: Circulation processes along the Chukchi Sea shelfbreak and around Hanna Shoal in the northeast Chukchi Sea are poorly understood. The circulation here is part of a broader circulation field that connects the Chukchi and Beaufort slopes and carries waters draining from the western Chukchi Sea Shelf through Herald Valley to the eastern Beaufort Sea. There is high interest in the Hanna Shoal area for oil and gas exploration and development.

The wind field is poorly understood in the Beaufort Sea and these winds are important in shelf and slope dynamics and would influence the movement of pollutants in this area. Meteorological models and observational studies of the barrier winds and sea breeze effect should be undertaken in conjunction with a review of existing data to determine the scales of the along- and cross-shelf winds.

Circulation processes at the seaward edge of the landfast ice edge are complex insofar as these involve ice dynamics and wind and buoyancy forcing. Ice edge processes are critical in understanding how waters in inshore and offshore areas interact.

The large-scale circulation and thermohaline structure of the Beaufort Sea needs to be better understood with consideration given to the large inter-annual variability in winds and ice conditions.

Measurements and models of wave regimes and storm surges should be conducted for the Beaufort and Chukchi Seas. A preliminary review of the 60-year long Barrow wind record suggests that wind intensities and extremes have increased over the past 15 years. Summer/autumn ice retreat over the last decade also has been unprecedented. These changes will have a major influence on the wind wave and storm surge climate of the Beaufort Sea and should be factored into offshore, nearshore, and onshore development scenarios.

Sea Ice Dynamics

The presence of ice in the Arctic Outer Continental Shelf (OCS) is one of the most important physical conditions to be dealt with in developing OCS oil and gas resources. The seasonal sea ice cycle is a pervasive force in the Arctic, influencing human activities and many aspects of the region's natural history and shows great seasonal and inter-annual variability off the coast of Alaska. Generally speaking, there are two types of sea ice: fast ice that is anchored along the shore and free-floating pack ice which moves with winds and currents. These two types of ice interact to cause an extensive, somewhat predictable, system of flaw leads (swathes of open water in between ice) and polynyas off the coasts of the Chukchi and Beaufort Seas eastward to the Canadian Archipelago. These flaw leads and polynyas become more prevalent in the spring and are important features that dictate the seasonal movements and northward migrations of wildlife species, such as bowhead whales and marine birds.

Maximum sea-ice cover occurs in March or early April, lagging minimum insolation in late December by 3 months because of the heat capacity of the ocean and the cold atmosphere. At this time, essentially all of the Beaufort and Chukchi Seas are ice-covered (fig. 3–2). Winter ice cover extent in the Arctic has declined since the late 1970s (fig. 3–3) along the southern margins of sea-ice extent, but not dramatically so (fig. 3–2). Maximum retreat of the sea ice occurs in September, again lagging maximum insolation by about 3 months. The extent of sea-ice loss in September since the satellite record began has been dramatic (fig. 3–4). By September, in normal years, the ice pulls away from the Arctic coasts of Canada, Alaska, and Siberia, leaving a nearly continuous, relatively ice-free corridor around the permanent ice pack. This corridor varies in width. In recent years, the ice-free corridor has expanded to hundreds of kilometers in the East Siberian Sea and offshore of the northern Alaska coast. The contrasts between 1980, a representative year with extensive ice cover, and 1987, when sea-ice extent in the Arctic was at a record minimum, and the long-term median ice edge are dramatic (fig. 3–4).

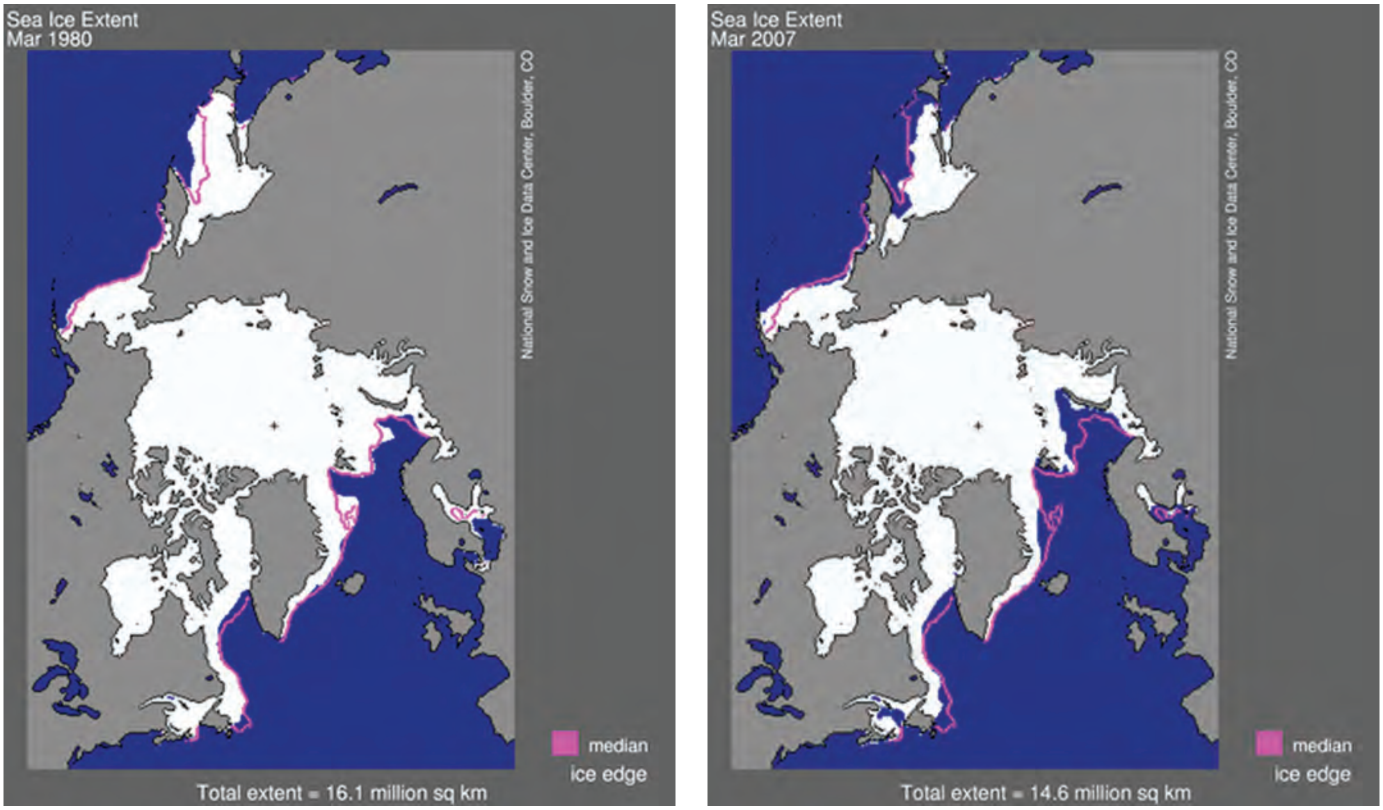


Figure 3–2. Maps showing sea-ice extent for single months and single years, using 1980 as an example of an extensive ice cover year, and 2007 as the record minimum year—maximum winter extent. The magenta line plots the long-term median ice edge based on years 1979–2000. Source: National Snow and Ice Data Center (2007a), accessed April 15, 2011, at http://nsidc.org/cgi-in/bist/bist.pl?annot=1&legend=1&scale=100&tab_cols=2&tab_rows=2&config=seaice_index&submit=Refresh&mo0=03&hemis0=N&img0=extn&mo1=09&hemis1=N&img1=extn&year0=1980&year1=2007.

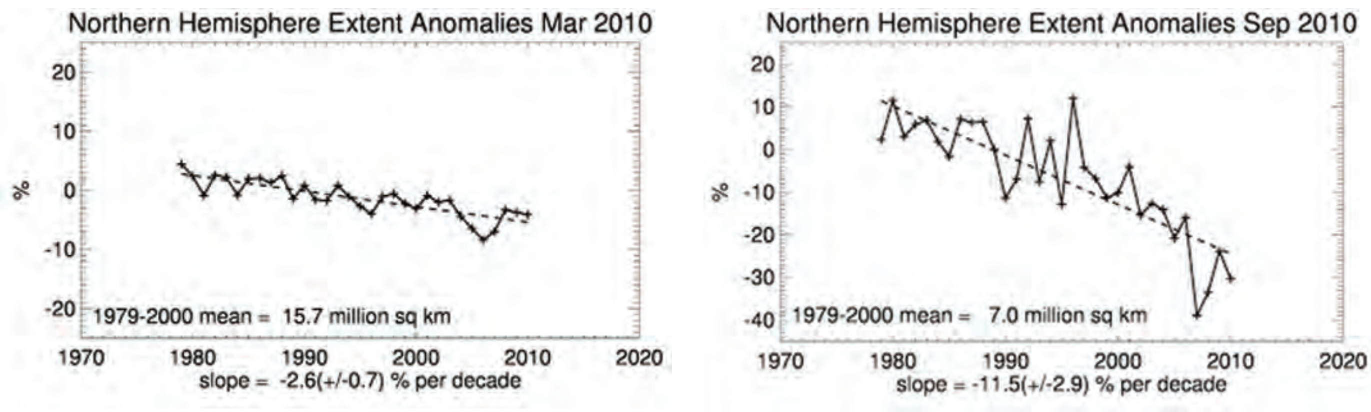


Figure 3–3. Plots of sea-ice extent anomalies for March (maximum sea-ice extent) and September (minimal sea-ice extent) expressed as percent-departure from average (that is, anomalies as compared to the 1979–2000 mean). Source: National Snow and Ice Data Center (2007b), accessed April 15, 2011, at http://nsidc.org/cgi-bin/bist/bist.pl?config=seaice_extent_trends&submit=Go%21.

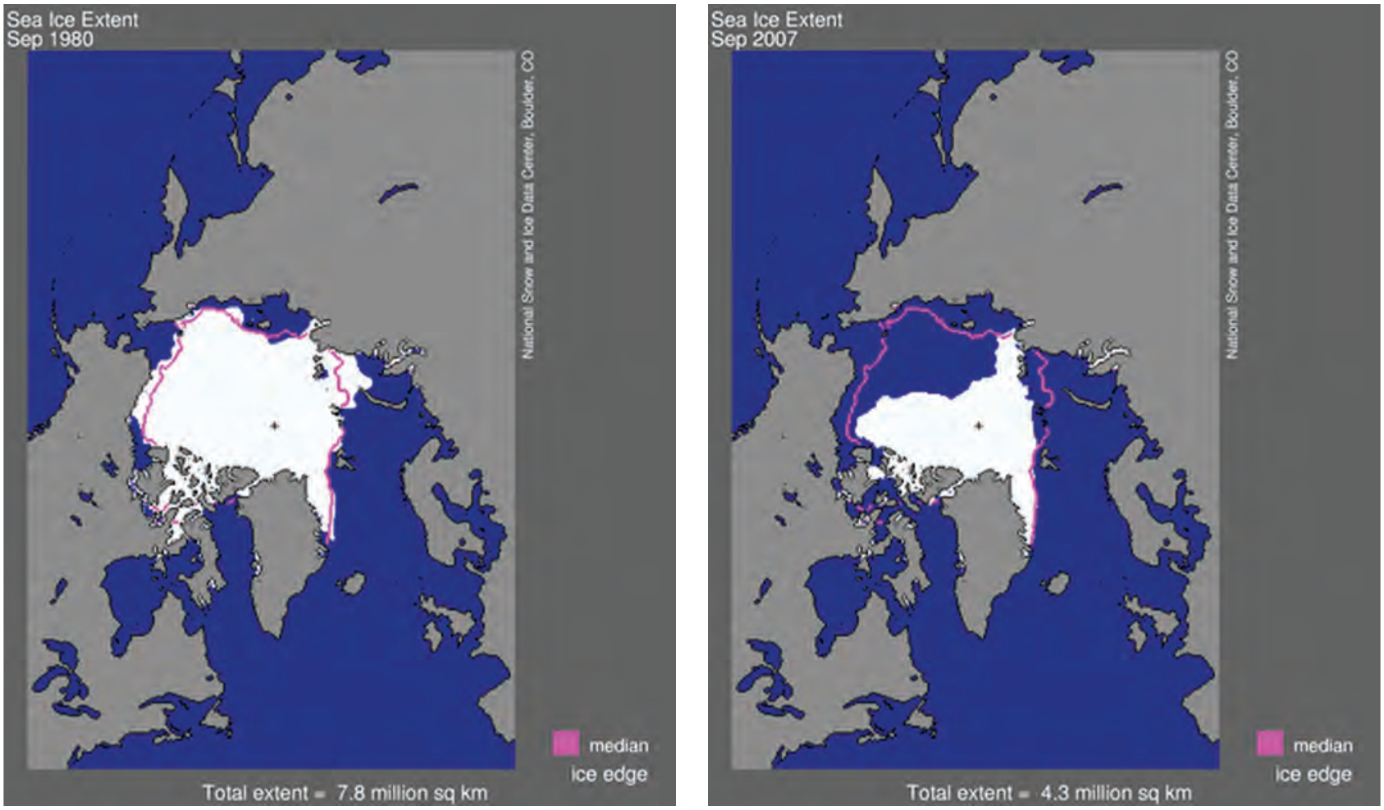


Figure 3–4. Maps showing sea-ice extent for single months and single years, using 1980 as an example of an extensive ice cover year, and 2007 as the record minimum year. The magenta line plots the long-term median ice edge based on years 1979–2000. Source: National Snow and Ice Data Center (2007a), accessed April 15, 2011, at http://nsidc.org/cgi-bin/bist/bist.pl?annot=1&legend=1&scale=100&tab_cols=2&tab_rows=2&config=seaice_index&submit=Refresh&mo0=03&hemis0=N&img0=extn&mo1=09&hemis1=N&img1=extn&year0=1980&year1=2007.

Even in years of extensive sea-ice retreat in the Beaufort and Chukchi Seas, storms and winds can cause changes in ice cover that can profoundly influence sea-ice dependent wildlife movements. For example in 2008, fragments of sea ice that were not visible to satellites persisted over the continental shelf of the eastern Chukchi Sea and were successfully exploited by walrus where they did not need to come ashore to rest. This contrasted with 2007, 2009, and 2010 when walrus did come ashore in northwest Alaska, presumably in response to a lack of sea ice over shallow continental shelf waters in the Chukchi Sea. Similarly in 2010, a large swath of broken ice persisted north of Cross Island in the central Alaska Beaufort and may have contributed to the lack of polar bears found on shore in August (L. Peacock, U.S. Geological Survey, oral commun., 2010).

In addition to dramatic decreases in sea-ice extent during late summer and autumn, the character of sea ice in the Arctic also is changing, tending to be younger and thinner (fig. 3–5). The longer sea ice remains in the Arctic Ocean the thicker it becomes as a result of additional freezing and through deformation. The thinning of Arctic Ocean sea ice has occurred largely because of the export of older, thicker sea ice out of the Arctic through Fram Strait, east of Greenland. This is important because younger, thinner ice is more vulnerable to melting as a result of warmer air and water temperatures, perpetuating a feedback cycle because of the ability of open ocean to absorb solar insolation.

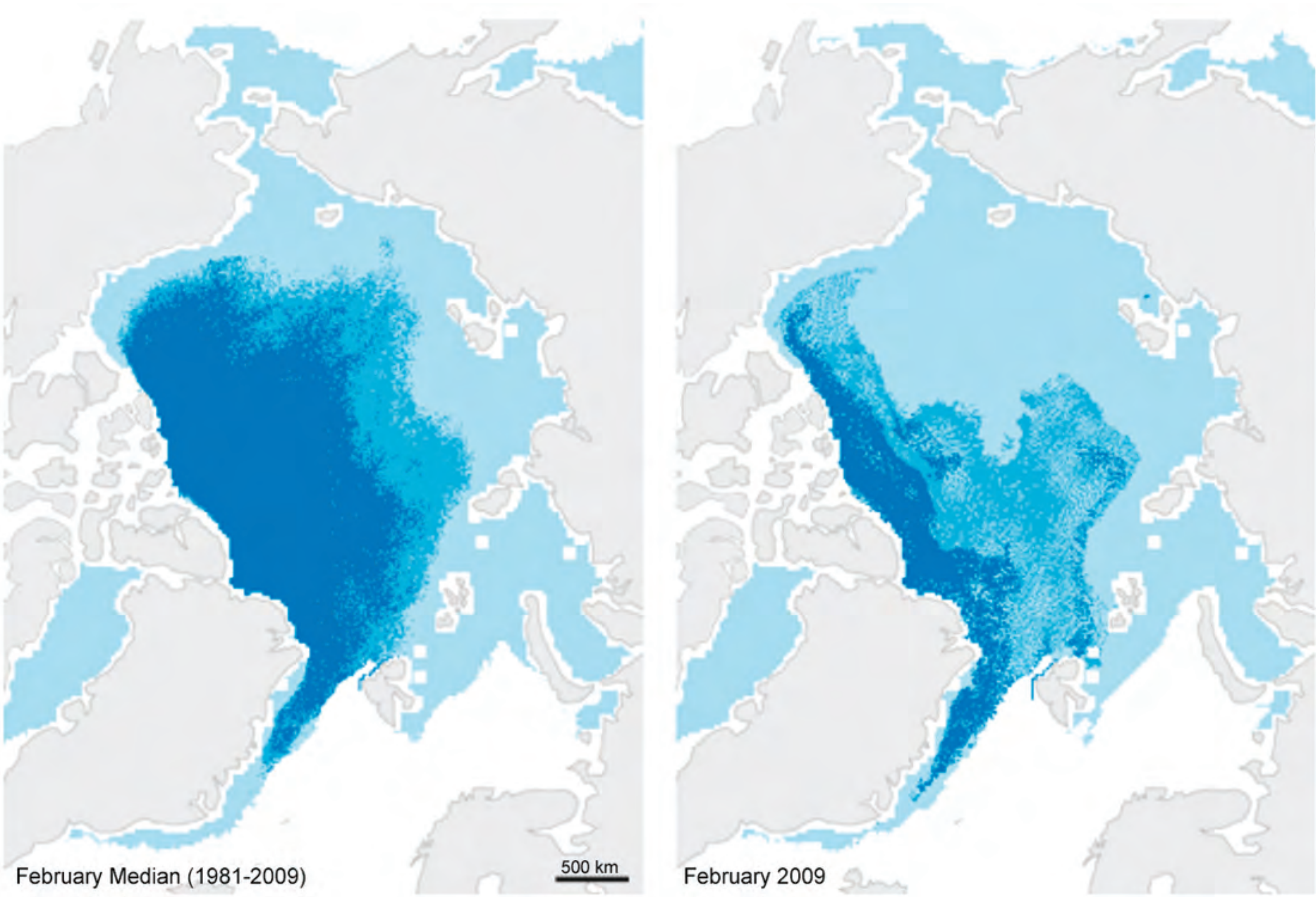


Figure 3–5. Maps showing old versus new ice in the Arctic for February. These maps show the median age of February sea ice from 1981 to 2009 (left) and February 2009 (right). As of February 2009, ice older than 2 years accounted for less than 10 percent of the ice cover. Dark blue equals ice greater than 2 years old; medium blue equals 2 year old ice; pale blue equals annual ice. Source: National Snow and Ice Data Center (2010), accessed April 15, 2011, at http://nsidc.org/sotc/sea_ice.html.

3.02. Findings and Recommendations: Ice seasons of shorter duration and longer open-water seasons will favor longer seasons for resource development and transportation.

The northern Chukchi and Beaufort Seas are undergoing rapid ice retreat that will result in a change in ocean dynamics that might alter upwelling and biological productivity. If so, this could have cascading effects on all aspects of marine and coastal ecosystems.

A reduction in the sea-ice cover and a lengthening of the ice-free season, particularly in autumn when wind speeds are strongest, will result in larger wind waves and storm surges, resulting in more rapid coastal erosion. These changes could influence patterns of abundance of fish and wildlife, subsistence use patterns, and how development occurs along the coast. Research is needed to understand how the wind wave field and storm surges will change in response to changes in sea ice concentration and extent.

Improved understanding is needed of the impact of the changing ice regime on species and on biological hot spots in the Chukchi Sea and southwestern Beaufort Sea ice, which have high levels of biological productivity.

Seafloor Substrates

Soft sediments dominate the seafloors of the continental shelves of the Beaufort and Chukchi Seas. These are largely combinations of muds, sands, and gravels (fig. 3–6). These soft-sediment bottoms support high densities and biomass of benthic invertebrates, particularly in the extensive shallow shelf areas of the Chukchi Sea where productivity is high (see Benthos). Only two areas with hard substrates have been identified in the entire region (Smith, 2010) (fig. 3–6)—one in Peard Bay, southwest of Barrow, and the other in Steffanson Sound near Prudhoe Bay that is known as the "boulder patch" (Dunton and others, 1982). The boulder patch is characterized as sediment with greater than 10 percent boulder cover. It provides attachment habitat for the endemic kelp *Laminaria solidungula* and other macroalgae, which are the primary carbon source for consumers living there.

Primary and Secondary Productivity

(from Hopcroft and others, 2008b; Stockwell and others, 2008; and Yager and others, 2008)

Within the Arctic, the combination of cold temperature, occurrence of sea ice, and extreme seasonal variations in light regimes controls phytoplankton growth and governs its spatial and temporal growth patterns. The stabilizing effect of sea ice allows production to occur near the surface under low light intensities. A large number of planktonic algae thrive in Arctic waters but there seem to be relatively few truly Arctic species. Estimates of phytoplankton biomass vary widely depending on the region, with the highest values found in the Chukchi Sea. Algal production and biomass in the Arctic primarily are controlled by light, stratification, and nutrient fields. On the shelves, advection and turbulent mixing of nutrients through the Bering Strait and local nutrient re-mineralization sustain extremely high primary production values on the Chukchi Sea Shelf (fig. 3–7). Much of that production is not grazed and falls to the seafloor to fuel benthic communities. In addition to phytoplankton, ice algae contribute to the total primary production of the Arctic Ocean with higher production values in first-year ice compared to multi-year ice. The contributions of ice algae to total primary production range from less than 1 percent in coastal regions up to 60 percent in the central Arctic Ocean.

Secondary producers include the microbes, protists, and zooplankton that consume phytoplankton and algae. Compared to phytoplankton and mesozooplankton, much less is known about the composition, distribution, and rates of activity of microbes and protists in the Arctic Ocean, and this confounds the ability to predict the impact of climate change or other disturbances on food webs and basic biogeochemical processes. Biomass of heterotrophic microbes in Arctic surface waters shows a strong response to seasonal changes in phytoplankton stocks. In the Chukchi Sea, concentrations of bacteria start out low in the spring, increase over the course of the bloom, and are highest in late summer. Heterotrophic protists include nanoflagellates, ciliates, and dinoflagella.

Recent work in the Gulf of Alaska, the Bering Sea, and shelf and slope regions of the western Arctic Ocean has confirmed the role of these organisms, known as microzooplankton, as consumers of phytoplankton in sub-Arctic and Arctic food webs. Although it is likely that phytoplankton and sea ice algae still represent a crucial food source for the larger zooplankton, utilization of microzooplankton as food is recognized as being of similar import, particularly during periods when phytoplankton standing stock is low or of poor quality. Because strong local pulses of primary production are a frequent characteristic of high-latitude oceans, including the Chukchi and Beaufort Seas, the response of microbes (including both bacteria and protists) to these pulses determines the rate of re-mineralization and the fraction of total production exported to the benthos. Weak microbial activity in the Arctic contributes to the high degree of bentho-pelagic coupling in many shelf regions of the Arctic and the consequent strength of demersal ecosystems.

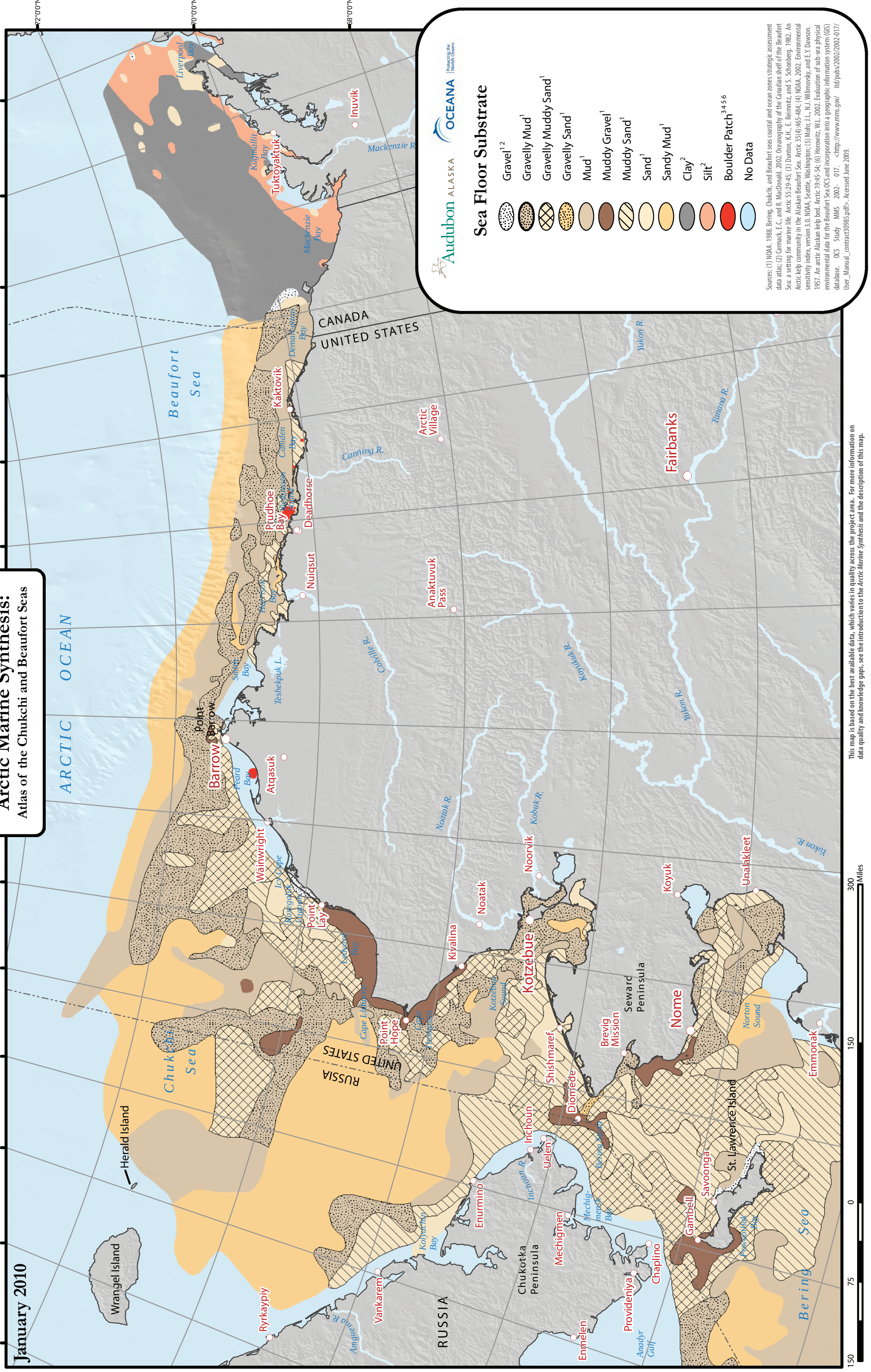


Figure 3–6. Seafloor substrates of the Alaska Beaufort and Chukchi Seas. From Smith (2010).

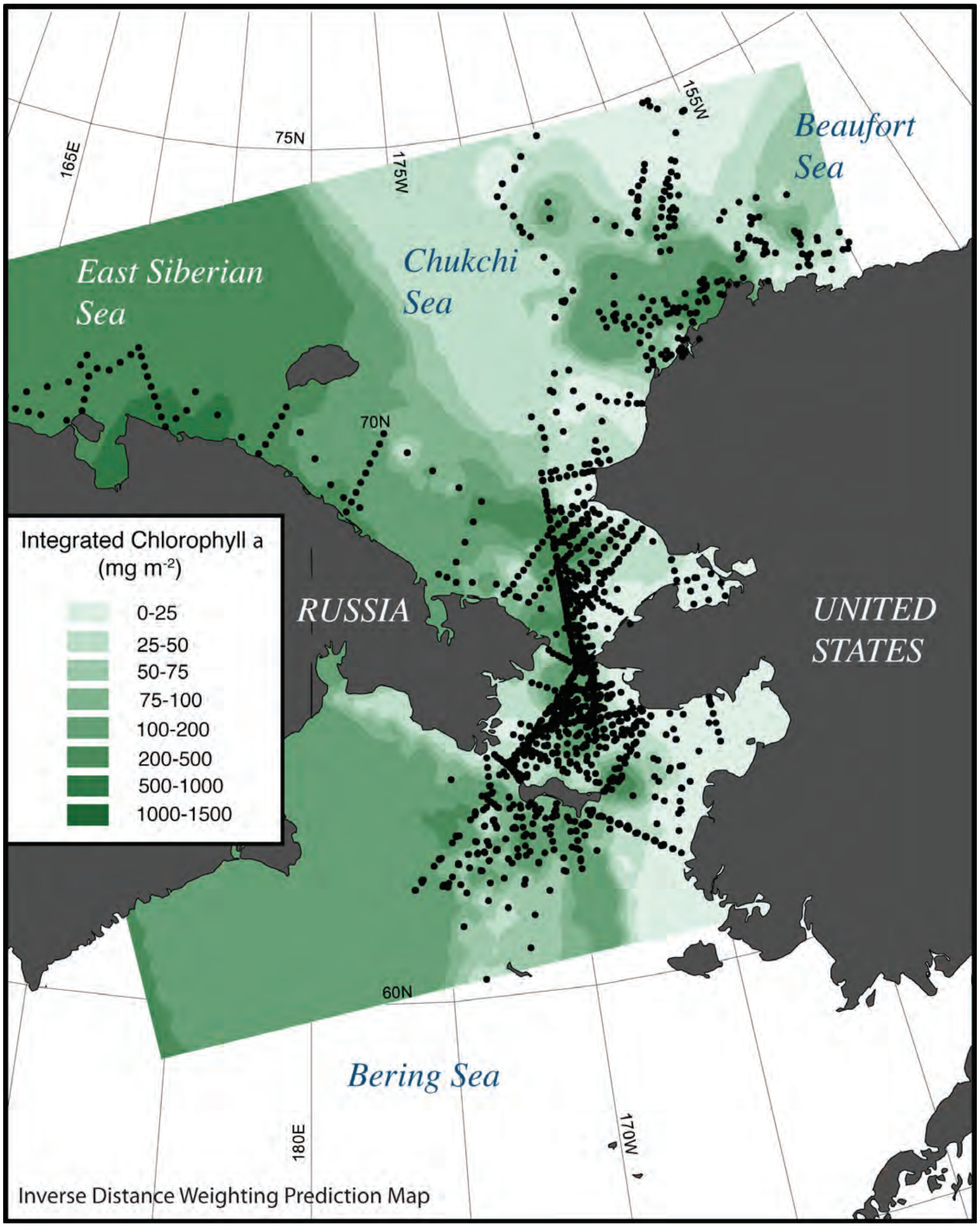


Figure 3–7. Contours of integrated chlorophyll *a* concentrations (mg m^{-2}, milligrams per square meter) based on discrete measurements (black points denote sampling locations), April–September 1976–2004 (Grebmeier and others, 2006).

Zooplankton are the major grazers of the primary production in the Arctic and determine the resources available to many higher trophic levels, such as fish, seabirds, and marine mammals. In the Chukchi Sea, large quantities of Pacific zooplankton enter the region through the Bering Strait, in a complicated mixture of water masses. The influx of the rich Pacific water determines the reproductive success of both the imported and resident zooplankton communities. Both inter-annual and long-term variation in climate will affect the relative transport of these various water masses and hence the composition, distribution, standing stock, and production of zooplankton and their predators in the Chukchi Sea. Zooplankton abundance and community structure also affect the amount and quality of carbon exported to the benthic communities in this region. In contrast, the Beaufort Sea primarily is Arctic in character, with cross-shelf exchange mechanisms more important in determining the relative contribution of “oceanic,” “shelf,” and estuarine species. In the Eastern Beaufort, the outflow of the McKenzie River has significant impact on both the composition of the zooplankton and its productivity. Thus, the Beaufort Sea is responding to a fundamentally different set of factors than the Chukchi Sea, even if they are both driven by similar climate-related variations and trends.

Although copepods typically predominate throughout the Arctic, there is a broad assemblage of other planktonic groups. Euphausiids are less abundant and diverse in Arctic waters than elsewhere, but can be important prey for higher trophic levels such as bowhead whales, birds, and fishes. Larvaceans (Appendicularians) have been shown to be abundant in Arctic polynyas, and are transported in high numbers through the Bering Strait into the Chukchi Sea. Similarly, important and common predatory groups, such as the chaetognaths, amphipods, ctenophores, and cnidarians have been reported on in detail by only a few surveys. Hyperiid amphipods also can be common in Arctic waters, and like chaetognaths, have a potential to graze a large proportion of the *Calanus* population. Relatively little is known of the abundance, composition, or ecology of the delicate gelatinous zooplankton, such as jellyfish. There are indications that climate change has resulted in increased numbers of jellyfish in the Bering Sea in recent years. Scientists have recorded jellyfish piled up several feet deep along shorelines near Barrow, Alaska. The ecological impact of these predators is substantial and underestimated in polar waters.

The ongoing reduction of the sea-ice cover will have major impacts on the ecosystems and biogeochemical fluxes on the extensive continental shelves of the Arctic Ocean. Many processes involved in the regulation of the vertical and trophic fluxes of particulate organic carbon, and the production of dissolved organic carbon, are controlled by the zooplankton. Knowledge of zooplankton community ecology, especially the temporal and spatial distribution patterns of the different classes of zooplankton, is needed to understand the role of sea-ice variability in dictating fluxes of biogenic carbon on and off the shelves.

3.03. Findings and Recommendations: Now that some recent baselines have been established for phytoplankton, microbes, and zooplankton, it is critical that long-term repeated measurements are established from the Bering Strait northward throughout the Chukchi Sea, and extending into the Beaufort Sea. Continued annual sampling at a series of fixed stations/transects during a consistent seasonal time-window is required to establish long-term and inter-annual trends.

Benthos

(from Bluhm and others, 2008)

Benthic food supply originates in surface waters and is highly seasonal in the Arctic. Densities of sedimenting particles and their nutritional values range vastly from the nutrient rich waters of the northern Bering and Chukchi Seas to the oligotrophic deep waters of the Arctic Basins. In general, however, comparisons of energy fluxes show that the benthic systems receive more energy in the Arctic than temperate and tropical systems.

Much of the broad, shallow shelf of the Chukchi Sea is strongly influenced by northward flowing nutrient-rich Pacific water through the Bering Strait, resulting in very high benthic biomass, which is among the highest worldwide in soft-sediment macrofaunal communities (fig. 3–8). Specifically, the south-central Chukchi Sea has the highest algal and faunal biomass on the combined Bering Sea and Chukchi Sea Shelf. This is the result of high settlement rates of organic production that is not grazed by microbes and zooplankton. These rich benthic communities, tied to high pelagic production and advection, serve as prey for a variety of diving sea birds and marine mammals, a key feature of the productive Chukchi Sea. Close to 1,200 species are known from the Chukchi Sea fauna to date with amphipods, clams, and polychaetes dominating infaunal community. Important macrofauna prey species for higher trophics include bivalves taken by walrus, in particular *Macoma* spp. and *Mya truncata* and benthic amphipods utilized by gray whales and bearded seals. Within the epifauna, ophiuroids dominate abundance and biomass in much of the surveyed Chukchi Sea, and other patchily distributed echinoderms (especially asteroids), gastropods, ascidians, sponges, cnidarians, and bryozoans also are locally abundant.

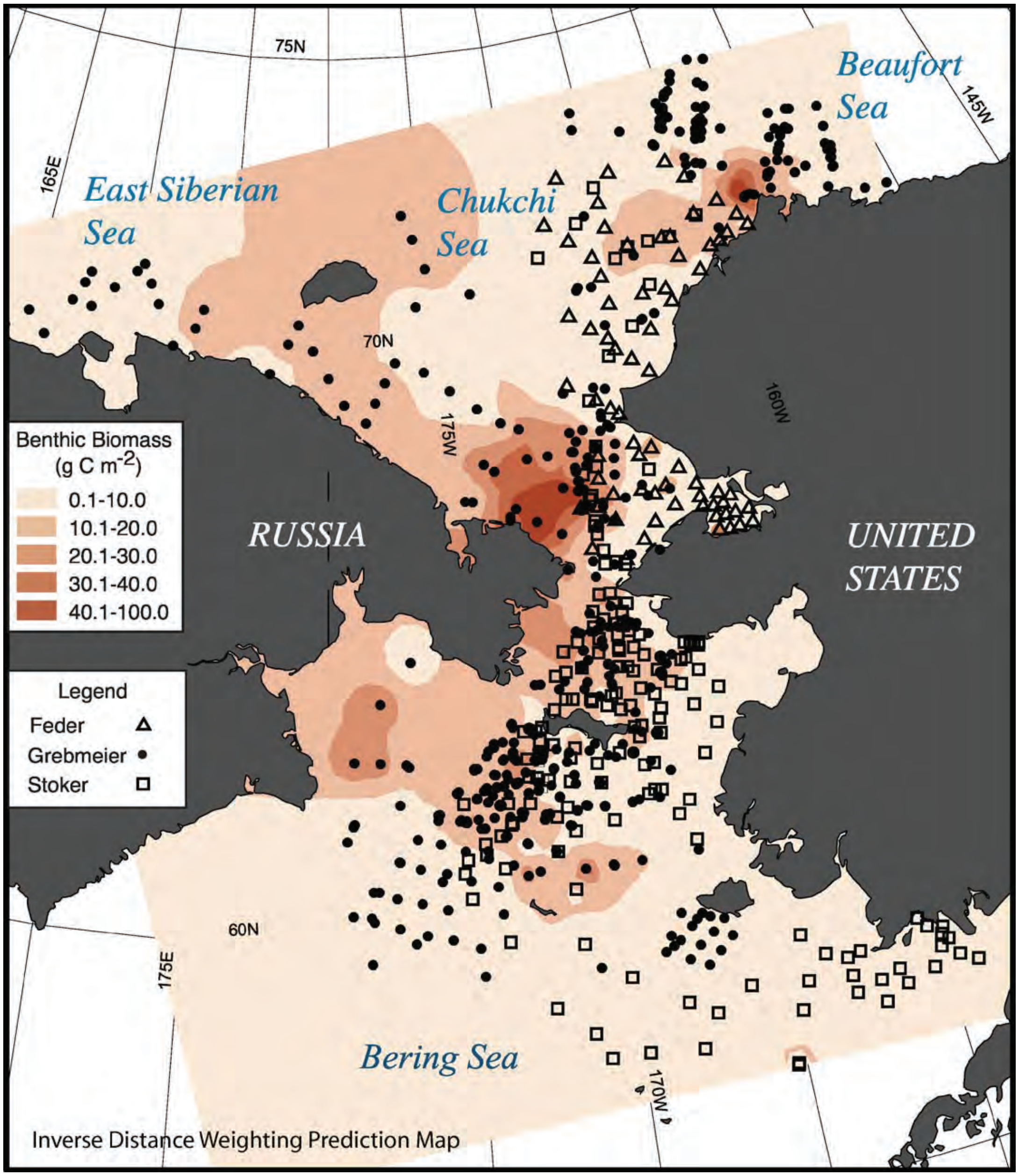


Figure 3–8. Benthic biomass distribution in the Chukchi and northern Bering Seas. (From Grebmeier and others, 2006.) (g C m^{-2}, grams of carbon per square meter.)

The comparatively narrow Beaufort Sea Shelf is influenced by large freshwater inflow from numerous small rivers and streams, the larger Colville and Mackenzie Rivers, and permafrost resulting in estuarine conditions in the nearshore. Because of this freshwater flow, non-marine sources of carbon may play an increasingly important role for the benthic food web in parts of the nearshore Beaufort Sea. The Beaufort Sea seafloor is dominated by soft sediments, but high ice cover and associated scouring, along with glacial erratics, have left coarser sediments (gravel and boulders) in various areas of the Beaufort Sea. The Alaskan part of the Beaufort Sea coast is fringed by sandy barrier islands forming numerous shallow lagoons with average depths less than 5 m and ecological traits different from those in the open water. Compared to the Chukchi Sea, productivity and benthic biomass in the Alaskan Beaufort Sea are dramatically lower. Consequently, benthic-pelagic coupling is not as pronounced as in the Chukchi Sea and food chains are longer.

Much less is known about the slopes of the Chukchi and especially the Beaufort Sea, and the adjacent basins (Bluhm and others, 2008). The existing investigations of the slopes and abyssal infaunal benthos in the western Arctic revealed low abundances and biomass values relative to the shelves, especially with increasing water depth and distance from the shelves. At taxonomic levels of phylum and orders, the soft-bottom deep Arctic macrofauna appear to be similar to the shelf communities: polychaetes, bivalves, and crustaceans are dominant, but on a family, genus, and species level, inventories differ from the shelves.

3.04. Findings and Recommendations: Regional hot spots for regular monitoring should include the southern Chukchi Sea, Barrow Canyon, and the Barter Island area. Secondly, source areas of organic and inorganic carbon should receive special attention, such as the inflow of nutrient-rich Anadyr water through the Bering Strait and river and permafrost run-off along the coastlines. The importance lies in regular sampling of the same areas to establish long-term time series.

Routine and robust monitoring of the benthos in areas of offshore development would be useful to establish trend information and to monitor the impacts of development and pollution.

Marine Mammals

The marine mammal fauna of the Chukchi and Beaufort Seas off the coast of Alaska are among the most diverse in the World and are of high scientific and public interest. Fifteen species and (or) stocks of marine mammal are common to the study area (table 3–1). Many of the species are used for subsistence purposes by Alaska Natives and many have an important symbolic role in cultural identity. Some have a high profile because they are covered by international conservation agreements (polar bear) or because they are classified as threatened or endangered under the Endangered Species Act (ESA). All marine mammals in the United States receive special protection under the Marine Mammal Protection Act (MMPA). The MMPA places a moratorium on the take, including harassment, of all marine mammals with special exemptions for subsistence use by Alaska Natives, for permitted activities such as research and public display, and for restricted permitted take incidental to commercial fishing and industrial activities. Additional protection is afforded to any species that is classified as depleted under the Act. Any species that is classified as threatened or endangered under ESA is automatically classified as depleted under MMPA. The marine mammals found in the Beaufort and Chukchi Seas study area include baleen and toothed whales, ice seals, walruses, and polar bears. For many of these species, their distribution, movements, and life history events are closely tied to the presence or absence of sea ice. Most species are harvested by coastal subsistence hunters, and they can make up a substantial proportion of the annual diet in coastal communities.

Status of Important Marine Mammal Stocks that Inhabit the Beaufort and Chukchi Seas

Information on the status of marine mammals is derived primarily from the most recent stock assessments provided by the National Marine Fisheries Service (NMFS) and U.S. Fish and Wildlife Service (USFWS) for whales, pinnipeds, Pacific walrus, and polar bears (Allen and Angliss, 2010). Some life history information on these marine mammal species also is included in the stock assessments, but is widely available elsewhere.

Bowhead Whale (*Balaena mysticetus*)

The western Arctic stock of the bowhead whale is almost exclusively an Arctic species. It summers in the Canadian Beaufort Sea, migrates through the U.S. Beaufort Sea into the Chukchi Sea and winters in the northern Bering Sea. They generally are associated with shelf and slope waters of the Arctic, where they feed primarily on copepods and euphausiids. With the advent of satellite telemetry, detailed information on bowhead whale movements are now available (Quakenbush and others, 2010) (fig. 3–9). Bowhead whales are classified as endangered under the ESA and depleted under the MMPA. The most recent (2001) estimate of the population of western Arctic bowhead whales is 10,545 and the population is increasing. Bowhead whales are an important subsistence species and are hunted in the spring and autumn as they pass coastal Alaska villages in the northern Bering, Chukchi, and Beaufort Seas. Noise, oil pollution, and climate warming are important concerns. Key information needs include: continued assessments of population size; integrative research on oceanography, prey availability, foraging and behavioral ecology; characterization of wintering habitat; and development of models incorporating data on whales, sea ice, and oceanography to predict the effects of climate change and anthropogenic impacts.

Table 3–1. Most common marine mammal stocks found in the Chukchi and Beaufort Seas of Alaska.

[Information primarily from Allen and Angliss (2010). Endangered Species Act (ESA) status: D, de-listed; E, endangered; P, proposed for listing; T, threatened]

Name	Stock	Estimated population	ESA status
Spotted seal (*Phoca largha*)	Alaska	Not available	
Bearded seal (*Erignathus barbatus*)	Alaska	Not available	P
Ringed seal (*Phoca hispida*)	Alaska	Not available	P
Ribbon seal (*Histriophoca fasciata*)	Alaska	Not available	
Beluga whale (*Delphinapterus leucas*)	Beaufort Sea	39,258	
	Eastern Chukchi Sea	3,710	
Harbor porpoise (*Phocoena phocoena*)	Bering Sea	48,215	
Gray whale (*Eschrictius robustus*)	Eastern North Pacific	18,813	D
Humpback whale (*Megaptera novaeangliae*)	Western North Pacific	938	E
Fin whale (*Balaenoptera physalus*)	Northeast Pacific	5,700	E
Minke whale (*Balaenoptera acutorostrata*)	Alaska	Not available	
Bowhead whale (*Balaena mysticetus*)	Western Arctic	10,545	E
Polar bear (*Ursus maritimus*)	Southern Beaufort Sea	1,526	T
	Chukchi/Bering Seas	2,000	T
Pacific walrus (*Odobenus rosmarus*)	Alaska	129,000	P

Gray Whale (*Eschrictius robustus*)

The eastern North Pacific stock of the gray whale winters and calves in lagoons on the Pacific side of Baja California, Mexico, and summers primarily in the shallow northern Bering and Chukchi Seas. It was formerly listed under the ESA, but responded well to protection from overexploitation and was delisted in 1994. Recent population estimates range from 18,178 to 29,758. The population is believed to be at or approaching carrying capacity. It is unclear how climate change will affect this species. Because the gray whale is primarily a benthic feeder, relaxation of the tight pelagic-benthic coupling that currently fuels high rates of benthic productivity in the Chukchi Sea would likely not favor this species.

Beluga Whale (*Delphinapterus leucas*)

Two stocks of beluga whale are found in the study area: the Beaufort Sea stock and the eastern Chukchi Sea stock. Satellite tagging suggests that the range of these two stocks may widely overlap. Whales tagged in Kasegaluk Lagoon in the Chukchi Sea moved north, with males moving into deep waters of the Beaufort Sea with more than 90-percent ice cover, and adult and immature females moving to the shelf break of the Chukchi Sea. The size of the eastern Chukchi Sea stock is not known but it is not believed to be declining. The Beaufort Sea stock numbers about 39,000 animals. It is assumed that most whales from these two stocks winter in the Bering Sea where they are closely associated with pack ice.

Ribbon Seal (*Histriophoca fasciata*)

The Alaska stock of the ribbon seal inhabits the Bering, Chukchi, and western Beaufort Seas and is associated with open water, pack ice, and rarely shorefast ice. They are most abundant in the northern edge of the ice front in the central and western Bering Sea in the winter and recent data suggest that they migrate into the Chukchi Sea in the summer. A reliable population estimate is not available. The NMFS received a petition to list the ribbon seal under the ESA in 2007. In December 2008, NMFS determined that listing the ribbon seal was not warranted (National Marine Fisheries Service, 2008). The NMFS concluded that although a gradual decline in the ribbon seal population is likely with a decrease in frequency of years with suitable sea-ice habitat, ribbon seals are not likely to become an endangered species within the foreseeable future (Boveng and others, 2008).

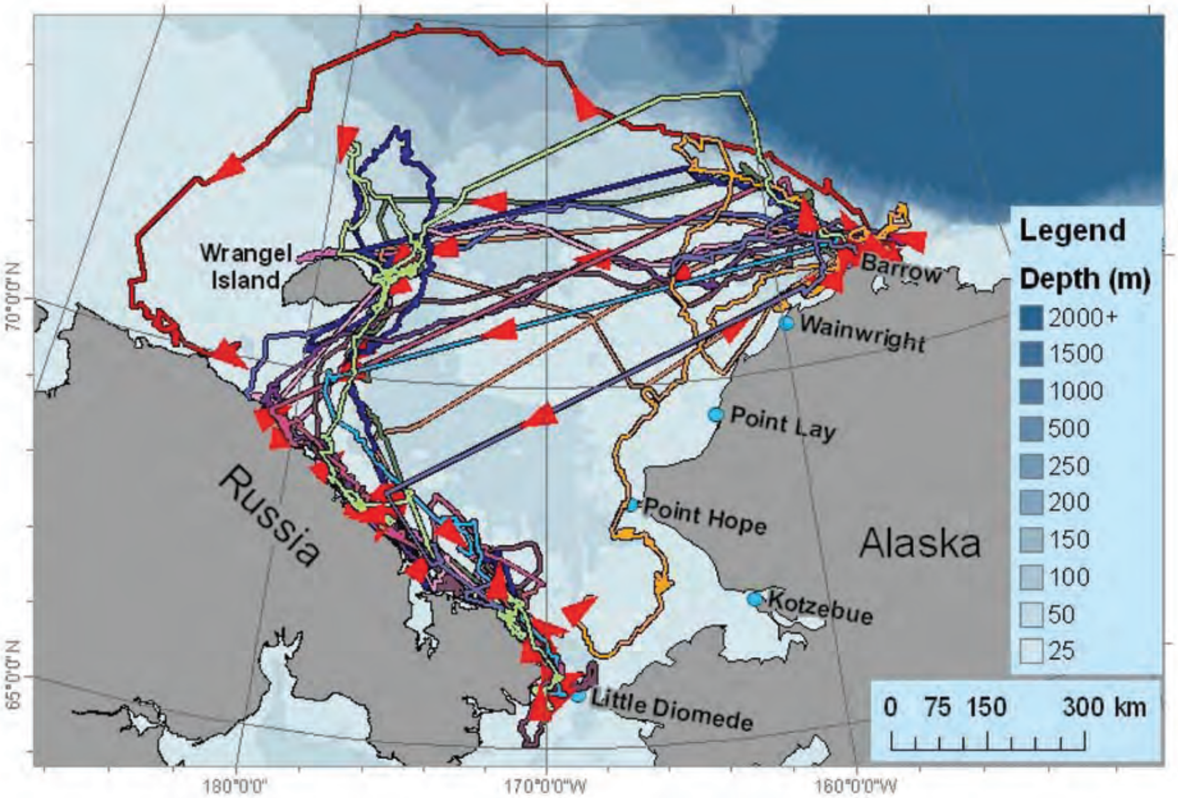
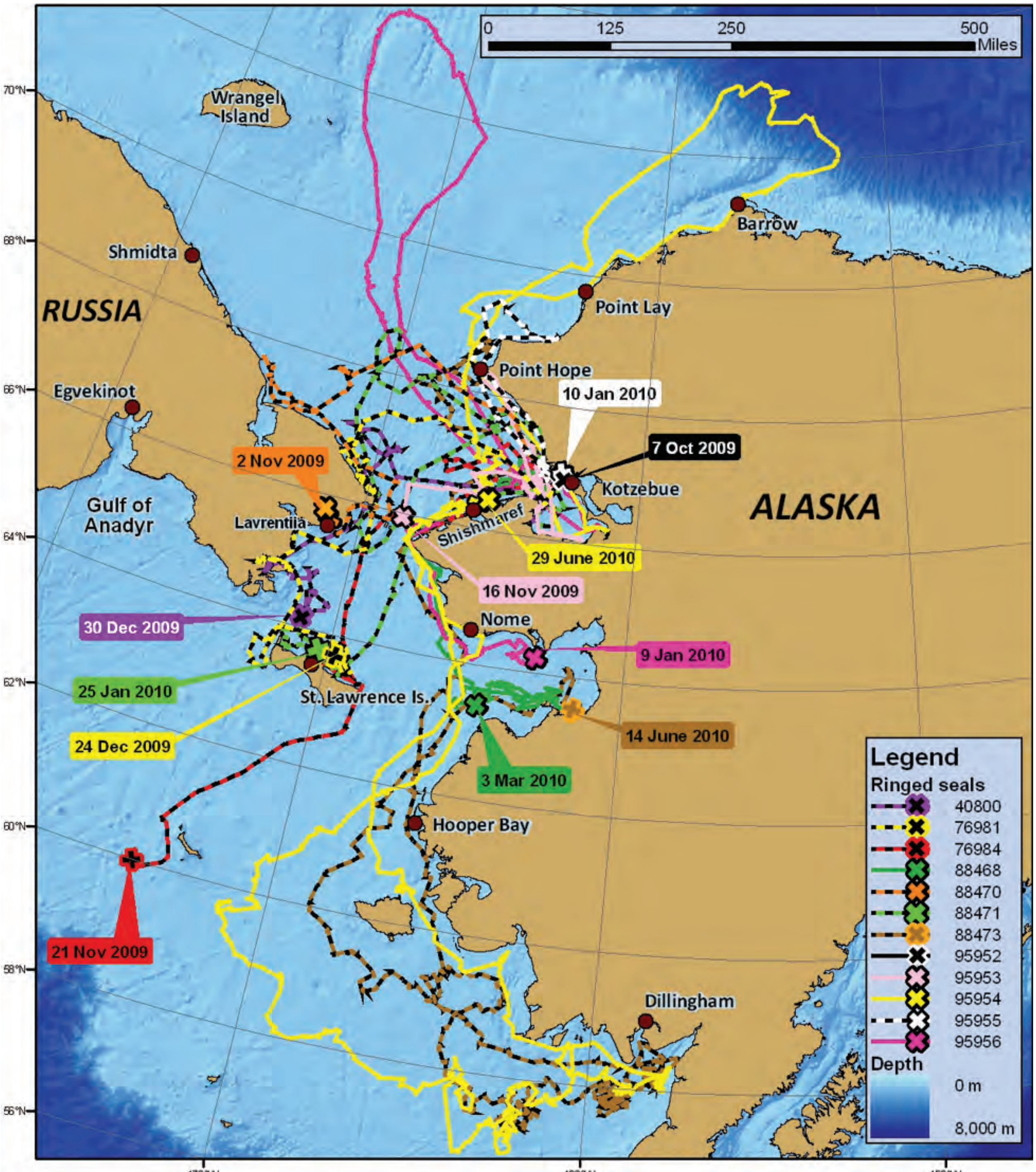


Figure 3–9. Track lines of bowhead whales in the Chukchi Sea in the autumn. Source: Alaska Department of Fish and Game (2009), accessed April 18, 2011, at http://www.adfg.alaska.gov/static/home/about/management/wildlifemanagement/marinemammals/pdfs/bow_move_chukchi_sea.pdf. Also see Quakenbush and others (2010) for detailed analysis of bowhead whale movements in the autumn and winter.

Ringed Seal (*Phoca hispida*)

Ringed seals are the most abundant of the ice seals in Alaska, are tightly associated with sea ice, and are an important subsistence species. Ringed seals are found throughout the Beaufort, Chukchi, and Bering Seas, as far south as Bristol Bay in years of extensive ice coverage. They are found in the study area year round, but some ringed seals obviously migrate south with the ice in the winter. Ringed seals are an ice seal that tend to prefer large floes (that is, greater than 48 m in diameter) and are often found in the interior ice pack where the sea-ice coverage is greater than 90 percent. Recent research suggests that ringed seal densities are higher in nearshore fast and pack ice and lower in offshore pack ice. They remain in contact with ice most of the year and pup on the ice in late winter-early spring in sub-nivean dens on the sea ice. An example of movement data now becoming available on ringed seals because of advances in satellite telemetry is shown in figure 3–10. An animation of these seasonal movements that also shows sea ice is available at Kotzebue IRA (2010; http://www.kotzebueira.org/current_projects.html).

A reliable estimate for the Alaska stock of ringed seals is not available but they probably number at least in the low hundreds of thousands. The NMFS received a petition to list ringed seals under the ESA on May 28, 2008, due to loss of sea-ice habitat caused by climate change in the Arctic. In December 2010, the NMFS published a proposed rule to list the ringed seal as a threatened species. This proposal included the Arctic, Okhotsk Sea, Baltic Sea, and Lake Ladoga subspecies of ringed seal (National Marine Fisheries Service, 2010a). Ringed seals of the Beaufort and Chukchi Seas are part of the Arctic subspecies. A fifth subspecies from Lake Saimaa in Finland was listed as endangered in 1993. Information gaps include: population size; stock structure; foraging ecology in relation to prey distributions and oceanography; relationship of changes in sea ice to distribution, movements, reproduction, and survival; models to predict the effects of climate change and anthropogenic impacts; and improved estimates of harvest.



Movements of 7 male (dashed lines) and 5 female (solid lines) ringed seals between 26 September 2009 and 29 June 2010. Cooperators include the Native Village of Kotzebue and the Alaska Department of Fish and Game with funding from the U.S. Fish and Wildlife Service, Tribal Wildlife Grant. Additional tags were funded by Shell and a grant from the National Fish and Wildlife Federation. The last known locations are labeled with an 'X'.

Figure 3–10. Movements of ringed seals marked with satellite transmitters near Kotzebue, Alaska. Source: Kotzebue IRA (2010), accessed April 18, 2011, at http://www.kotzebueira.org/current_projects2.html.

Bearded Seal (*Erignathus barbatus*)

Bearded seals, an important subsistence species, primarily are a benthic-feeding seal usually associated with shallow water over the continental shelf (less than 200 m) that is at least seasonally ice covered. During winter, they are most common in broken pack ice and also inhabit shorefast ice in some areas. In Alaska waters, bearded seals are distributed over the continental shelf of the Bering, Chukchi, and Beaufort Seas. This species also is found in the study area year round and like ringed seals, some individuals migrate south in the winter with the sea ice. There is no reliable population estimate for the Alaska stock of the bearded seal. Earlier estimates of abundance ranged from 250,000 to 300,000. The NMFS received a petition to list bearded seals under the ESA on May 28, 2008, due to loss of sea-ice habitat caused by climate change in the Arctic. The NMFS published a Federal Register notice in September 2008 indicating that there were sufficient data to warrant a status review of the species. In December 2010, the NMFS published a proposed rule to list the Beringia Sea and the Okhotsk Sea bearded seals as a threatened species (National Marine Fisheries Service, 2010b). Figure 3–11 is an example of the kinds of information on movements and distribution that are becoming available on this species and other ice seals through advances in satellite telemetry. An animation that depicts the southerly movements of bearded seals with advancing sea ice is available at Kotzebue IRA (2010; http://www.kotzebueira.org/current_projects.html). Information gaps include: population size; stock structure; foraging ecology in relation to prey distributions and oceanography; relationship of changes in sea ice to distribution, movements, reproduction, and survival; models to predict the effects of climate change and anthropogenic impacts; and improved estimates of harvest.

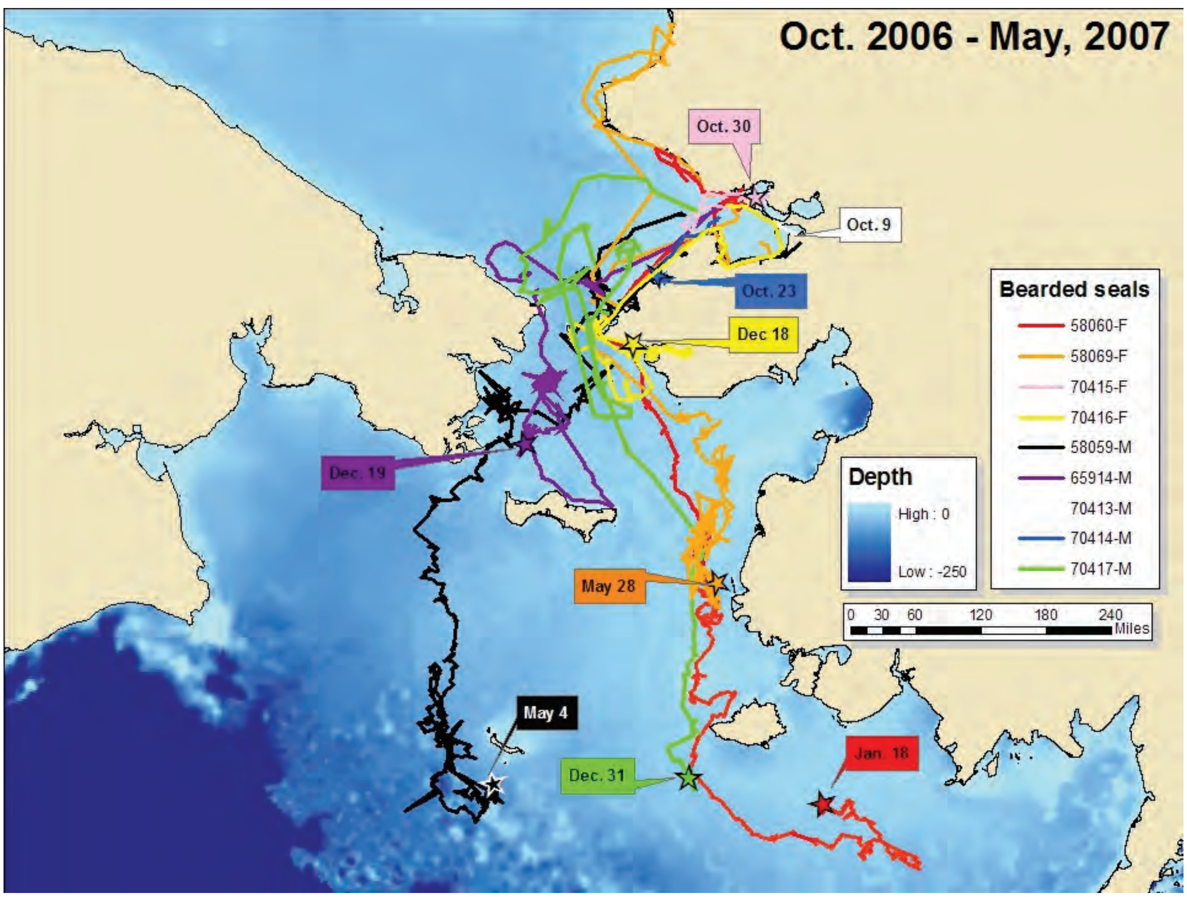


Figure 3–11. Movements of bearded seals tagged with satellite transmitters in the vicinity of Kotzebue. Source: Kotzebue IRA (2010), accessed April 18, 2011, at http://www.kotzebueira.org/current_projects.html.

Spotted Seal (*Phoca largha*)

Spotted seals are distributed along the continental shelf of the Bering, Chukchi, and Beaufort Seas. Satellite tagging studies showed that seals tagged in the northeastern Chukchi Sea moved south in October and passed through the Bering Strait in November. Seals overwintered in the Bering Sea along the ice edge and made east-west movements along the edge. A reliable estimate of spotted seal population abundance is currently not available, although the NMFS's current estimate for the eastern and central Bering Sea is about 101,500 (National Marine Fisheries Service, 2009). The NMFS received a petition on May 28, 2008, to list spotted seals under the ESA due to loss of sea-ice habitat caused by climate change in the Arctic, but concluded there are insufficient data to make reliable predictions of the effects of Arctic climate change on the Alaska spotted seal stock. In their Final Rule, the NMFS concluded that spotted seals in the Pacific exist as three Distinct Population Segments (DPS) and determined that only the southern DPS was threatened under the ESA (National Marine Fisheries Service, 2009). This DPS is located in the Sea of Japan and Yellow Sea, well outside of our geographic area of study. The NMFS published a Final Rule to that effect in October 2010 (National Marine Fisheries Service, 2010c).

Pacific Walrus (*Odobenus rosmarus*)

Pacific walrus range throughout the continental shelf waters of the Bering and Chukchi Seas, occasionally moving into the East Siberian Sea and the Beaufort Sea. They use sea ice over shallow, continental shelf waters as a moving platform for resting from which they dive to the seafloor for benthic invertebrates, such as clams. During the summer months, females and young migrate into the Chukchi Sea with the sea ice; however, thousands of animals, primarily adult males, aggregate near coastal haulouts in the Gulf of Anadyr, Bering Strait region, and in Bristol Bay. While in the Chukchi Sea, walruses are distributed broadly over the continental shelf, especially in the southern Chukchi Sea and along the coastlines of Chukotka and Northwest Alaska as indicated by satellite tags (fig. 3–12). Recent research has improved our understanding of how walruses use sea ice (Udevitz and others, 2009; Jay and others, 2010) and is beginning to shed light on how walruses will respond to diminishing sea ice in the Chukchi Sea (Jay and Fischbach, 2008; Fischbach and others, 2009; Jay and others, 2011). Modeling suggests a trend of worsening conditions for Pacific walrus through the end of this century (Jay and others, 2011). The estimate of the population from a 2006 survey of about 129,000 walruses is biased low because some areas known to be important to walrus were not surveyed due to poor weather conditions (Speckman and others, 2010). In February 2008, the USFWS received a petition to list the Pacific walrus under the ESA. On February 8, 2011, the USFWS announced that listing the Pacific walrus under the ESA was warranted, but precluded due to other higher priority listing actions. Like other ice-associated pinnipeds, walrus are difficult to study. Information gaps include: population size; stock structure; foraging ecology in relation to prey distributions and oceanography; relationship of changes in sea ice to distribution, movements, reproduction, and survival; models to predict the effects of climate change and anthropogenic impacts; and improved estimates of harvest. Impacts to walrus of changes in Arctic and subarctic ice dynamics are not well understood. Harvest and oil and gas development also are potential conservation concerns.

Polar Bear (*Ursus maritimus*)

Polar bears are perhaps the best known of the Arctic marine mammals in Alaska. Two stocks of polar bears are currently recognized in Alaska, the Chukchi Sea stock that is shared with Russia and the southern Beaufort Sea stock that is shared with Canada. The two stocks overlap widely in the vicinity of Point Barrow. Most polar bears remain with the sea ice throughout the year in the Beaufort and Chukchi Seas, but as sea ice retreats farther offshore in the summer and autumn increasing numbers of bears are coming to shore (Schliebe and others, 2008). In both seasonal and non-seasonal sea-ice environments, recent studies suggest that longer ice-free seasons are affecting polar bear size, recruitment and survival, and in some cases population size (Amstrup and others, 2008; Hunter and others, 2010; Regehr and others, 2010; Rode and others, 2010). The southern Beaufort Sea stock is currently estimated at 1,526 based on capture-recapture data. It has been difficult to derive an estimate for the Chukchi Sea stock, but it is estimated at about 2,000 bears based on an extrapolation of aerial den surveys. Both stocks of polar bears are classified as depleted under the MMPA and threatened under the ESA. Both stocks of polar bears are currently under study in Alaska, but comparatively less is known about polar bears in the Chukchi Sea.

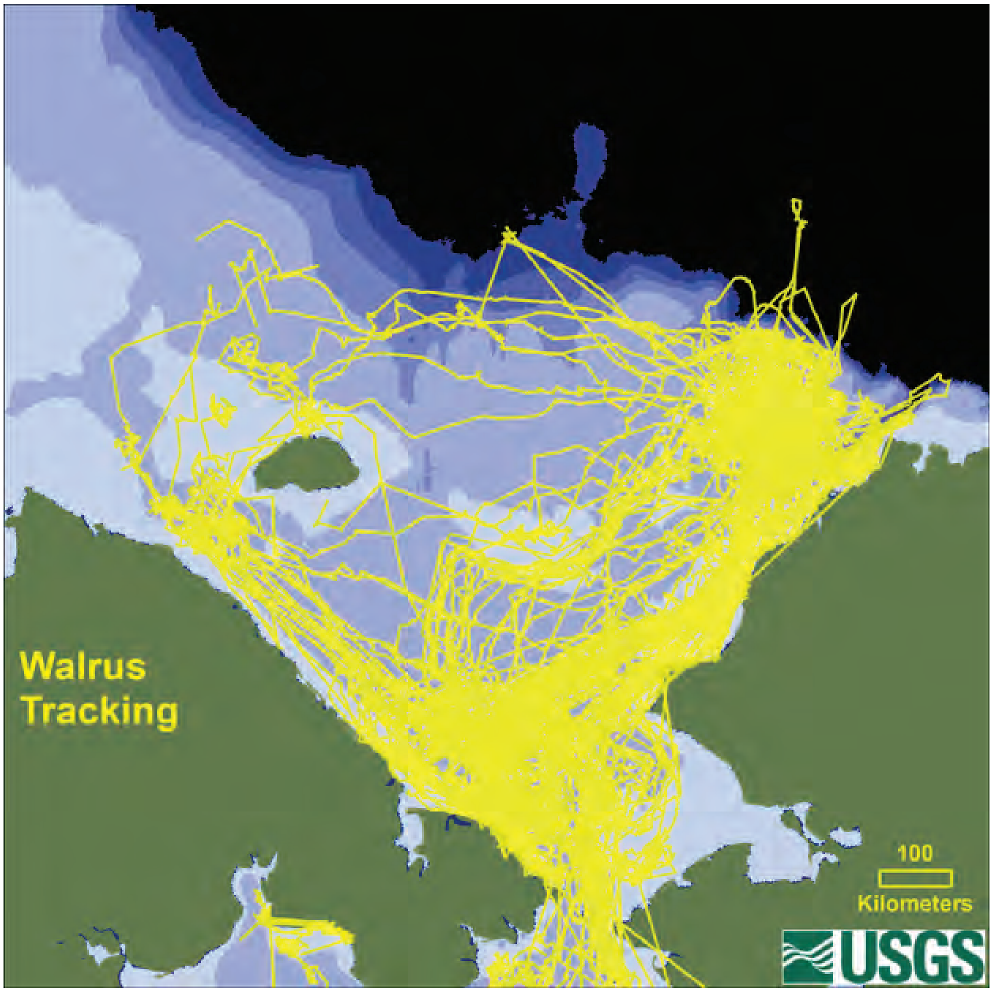


Figure 3–12. Tracks of Pacific walrus tagged with satellite transmitters depicting distribution over the continental shelf (U.S. Geological Survey, unpub. data, 2007–2010).

Overview—Arctic Marine Mammal Information Needs

Because of their high visibility, high public interest, and importance to subsistence harvesting, Arctic marine mammals have received considerable research interest. Yet, many Arctic marine mammals are challenging to study and little is known about basic life history metrics, movements, and populations. Considerable resources are devoted to research and management of Arctic marine mammals by management agencies [NMFS, USFWS, and Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)], and research organizations [for example, USGS, National Science Foundation (NSF), North Pacific Research Board] and considerable success has been achieved in better understanding some of these species. Polar bears in the southern Beaufort Sea are perhaps the best studied of all Arctic marine mammals in Alaska because they are accessible and visible, spending most of their lives on top of the sea ice, often close to shore. Most other marine mammals spend their lives either in the water or under the ice, sometimes far from shore, and are far more difficult to study. Particularly lacking are data on abundance, distribution, movements, age-specific vital rates, sea-ice habitat relationships, and human-marine mammal interactions, although data gaps are being filled for some species. Rapidly changing sea-ice conditions in the Arctic have exacerbated the difficulty in assessing and predicting the impacts of development on many marine mammal species.

3.05. Findings and Recommendations: Population enumeration is poor, even non-existent, for many species, and relatively good for a few. Without information on stock structure, however, which is poorly known for many species but fundamental to management, data are difficult to interpret even for species where abundance estimates exist.

There is little or no information about wintering distribution and habitats for most species except polar bears and gray whales. Existing data for most species are for non-winter months when researchers can access marine mammal habitat.

New modeling of the impact of oil pollution on marine mammals using updated oil-spill trajectory models, population models, satellite telemetry data, and new information on distribution and abundance would be informative for some species.

Trophic interactions of marine mammals were first studied 30 years ago. Although trophic structure generally is understood for most species (for example, general prey types, where they feed in the food web), seasonal, annual, and geographic variability in diet are poorly quantified and foraging areas are poorly described.

Thirty years ago, as part of Outer Continental Shelf Environmental Assessment Program (OCSEAP), the need for basic biological information about key forage species was highlighted by seabird and marine mammal researchers. Little progress has been made since those recommendations were made. Among the most important forage species are: Arctic cod (*Boreogadis saida*), saffron cod (*Eleginus gracilis*), sandlance (*Ammodytes hexapterus*), capelin (*Mallotus villosus*), copepods (*Calanus* spp.), and euphausiids (*Thysanoessa* spp.).

Threshold levels quantifying the anthropogenic effects (noise, hydrocarbons, contaminants, shipping, displacement, attractants, air pollution, commercial fishing, and so on) from industrial development on marine mammals are needed for select target species. Sensible mitigation measures should be the end-product of these research efforts.

Long-term ecological monitoring and life history analyses are needed for focal marine mammals. Measurements from infrequent studies can be very misleading. Because of great changes that have occurred in the Arctic, especially to sea ice, measures from studies conducted 30 years ago may or may not reflect current population dynamics. These types of studies are expensive, so thought should be given to identify and target "indicator" species although ESA requirements force study at the species level.

Conduct long-term, longitudinal studies of habitat use/foraging areas and trophic complexes at one or more biological hotspots—that is, include marine mammals in long-term and site-specific oceanographic studies such that data on habitat are obtained concurrent with information on marine mammal habitat selection. Long-term monitoring programs on most marine mammal species are lacking because of cost and complex logistics. Exceptions to this do exist (for example, mark-recapture studies in the southern Beaufort Sea for polar bears and annual aerial surveys for bowhead whales), but costs for these programs are high and are increasing.

Studies using advances in satellite telemetry have revolutionized our ability to track wildlife. Continued telemetry studies of a suite of pinnipeds, cetaceans, and polar bears are needed to understand spatial distribution, sea-ice relationships, migration strategies, and migration corridors and can be used to evaluate site-specific impacts of development activities.

Local residents are often the first to notice changes in fish and wildlife populations. Mechanisms should be developed to better solicit and integrate their local traditional knowledge (LTK) as a basic source of information.

Marine and Coastal Birds

Many bird species that reside in marine and coastal habitats (for example, seabirds, sea ducks, and loons) are highly vulnerable to oil pollution. Most marine birds that occur in the Beaufort and Chukchi Seas are there during the open water season; exceptions include eiders and seabirds that winter in polynyas and at the ice edge. Arrival times usually coincide with the formation of leads during spring migration to coastal breeding areas. Many seabirds (such as murres) and sea ducks (such as king and common eiders and long-tailed ducks) will closely follow leads during spring migration. Migration times vary between species, but spring migration for most species takes place between late March and late May. All marine and coastal birds breed outside the OCS lease sale areas, but spend time in the Chukchi and Beaufort Seas after breeding or during their non-breeding seasons. Departure times from the Beaufort and Chukchi Seas for the autumn and winter vary between species and often by sex within the same species, but most marine and coastal birds will have moved out of the Beaufort and Chukchi Seas by late autumn before or during the formation of sea ice. Detailed information on marine use of the Chukchi and Beaufort Seas by marine birds is relatively sparse. Johnson and Herter (1989) in their "Birds of the Beaufort Sea" summarize what was known of all birds from marine and coastal areas of the Beaufort Sea; a similar treatment of the birds of the Chukchi Sea is not available. Coastal and marine habitats of the Beaufort and Chukchi Seas contain a number of areas for birds that are of State, continental, and global importance (fig. 3–13). These Important Bird Areas, or IBAs, are sites that provide essential habitat for one or more species of bird. IBAs include sites for breeding, wintering, and (or) migrating birds and may be a few acres or thousands of acres, but usually they are discrete sites that stand out from the surrounding landscape. IBAs may include public or private lands, or both, and they may be protected or unprotected. To qualify as an IBA, sites must satisfy at least one of the following criteria. The site must support:

- Species of conservation concern (for example, threatened and endangered species);

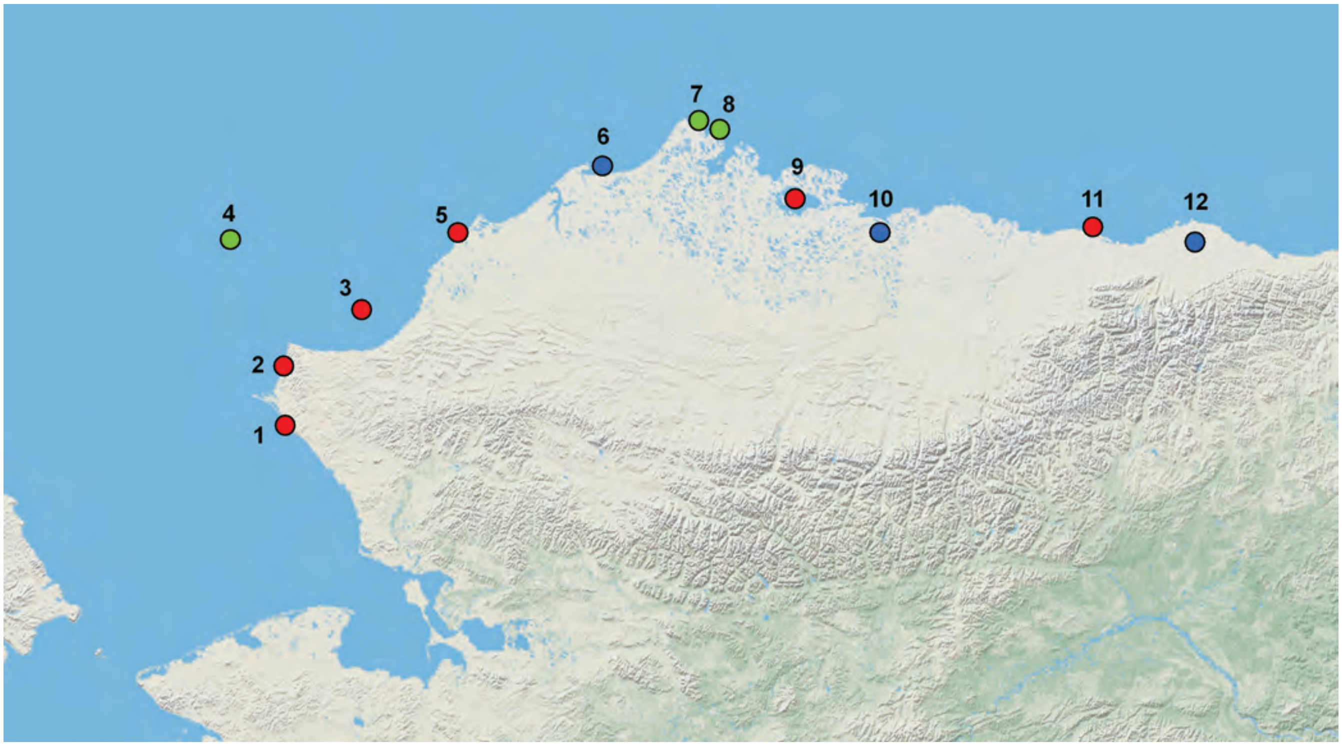


Figure 3–13. Important Bird Areas (IBAs) of the Beaufort and Chukchi Seas. Green dots = IBAs of State significance; Blue dots = IBAs of North American significance; Red dots = IBAs of global significance. Numbers are found in table 3–2. Source: Audubon Alaska (2011), accessed April 18, 2011, at http://ak.audubon.org/birds-science-education/important-bird-areas-0.

Table 3–2. National Audubon Society Important Bird Areas (IBAs) of the Beaufort and Chukchi Seas from the Point Hope area north and east to the United States-Canada border.

[Source: Audubon Alaska (2011), accessed April 18, 2011, at http://ak.audubon.org/birds-science-education/important-bird-areas-0. Map No. is shown in figure 3–13]

Map No.	IBA name	Primary reasons for designation
1	Cape Thompson	One of two major, cliff-nesting seabird colonies in the eastern Chukchi Sea
2	Cape Lisburne	The other major, cliff-nesting seabird colony in the eastern Chukchi Sea
3	Ledyard Bay	Critical Habitat for threatened spectacled eider; important marine habitat for seabirds
4	Southeast Chukchi (marine)	Important marine habitat for fulmars, shearwaters, auklets, and other seabirds
5	Kasegaluk Lagoon	Important feeding and staging area for shorebirds and Pacific black brant
6	Peard Bay	Important habitat for Pacific black brant, shorebirds, long-tailed ducks, and common and spectacled eiders
7	Cooper Island	Largest black guillemot colony and northernmost horned puffin colony in Alaska; site of long-term research project
8	Elson Lagoon	Important staging habitat for shorebirds, especially red phalaropes and a variety of waterfowl species
9	Teshekpuk Lake/Dease Inlet	Internationally recognized as a molting area for Arctic nesting geese
10	Colville River Delta	Major importance as breeding, feeding, and staging area for waterfowl, shorebirds, and raptors
11	Eastern Beaufort Sea Lagoons and Barrier Islands	Post-breeding habitat for waterfowl, especially long-tailed ducks, and red and red-necked phalaropes
12	Northeast Arctic Coastal Plain	Foraging and staging habitat for post-breeding lesser snow geese

- Restricted-ranges species (species vulnerable because they are not widely distributed);
- Species that are vulnerable because their populations are concentrated in one general habitat type or biome; or
- Species, or groups of similar species (such as waterfowl or shorebirds), that are vulnerable because they occur at high densities due to their congregatory behavior.

Colonial and Non-Colonial Seabirds

Nesting habitat for seabirds is limited in the area, so they are aggregated in a few very large colonies. Cliff-nesting seabirds reach their northern extent in the Chukchi Sea at Cape Lisburne and Cape Thompson. These colonies provide most of the cliff-nesting habitat for thick-billed murres (*Uria lomvia*) and black-legged kittiwakes (*Rissa tridactyla*) in the eastern Chukchi and are the largest colonies in the region with more than 200,000 birds present at each location. Horned puffins (*Fratercula corniculata*) breed at Cape Lisburne, as well as at Chamisso Island in Kotzebue Sound in the southern Chukchi Sea, and more recently at Cooper Island, a small barrier island in the western Beaufort Sea. A well-studied colony of black guillemots (*Cepphus grille*) is located at Cooper Island. Small colonies of glaucous gulls (*Larus hyperboreus*) and Arctic terns (*Sterna paradisaea*) are distributed in coastal areas throughout the study area (Sowls and others, 1978; Weiser and Powell, 2010). During the ice-free season, seabirds move into the Chukchi Sea from areas farther south and are distributed widely. These include murres (*Uria* spp.), black-legged kittiwakes (*Rissa tridactyla*), crested (*Aethia cristatella*), least (*Aethia pusilla*), and parakeet (*Cyclorrhynchus psittacula*) auklets, short-tailed shearwaters (*Puffinus tenuirostris*), northern fulmars (*Fulmarus glacialis*), jaegers (*Stercorarius* spp.), and others.

Kittlitz’s Murrelets (*Brachyramphus brevirostris*), a small, uncommon, non-colonial seabird that nests primarily in glaciated landscapes in southeast and south-central Alaska, west through the Aleutian Islands, also nest in small numbers on the Seward and Lisburne Peninsulas in northwest Alaska. At-sea records for this species exist in Kotzebue Sound, near Point Hope and in Ledyard Bay, including the Chukchi Sea oil and gas lease area and the Beaufort Sea (R. Day, Alaska Biological Research, Inc., oral commun., 2011). Kittlitz’s Murrelets are a species of conservation concern because of recent population declines in more southerly areas of their breeding range. They are considered a candidate species under the Endangered Species Act by the USFWS. Very little is known about their population status, distribution, and abundance in northwest Alaska.

Loons

Three species of loons nest in coastal areas of the Chukchi and Beaufort Seas and use coastal marine habitats for foraging: the red-throated loon (*Gavia stellata*), Pacific loon (*G. pacifica*), and yellow-billed loon (*G. adamsii*). Red-throated loons tend to nest in small tundra ponds close to the coast and feed primarily in saltwater during the breeding season, making trips back and forth to their nesting ponds. Both Pacific loons and yellow-billed loons nest on larger tundra lakes that contain fish. All loons use coastal marine habitats during parts of their annual cycle. Red-throated loons and yellow-billed loons have an interesting migration strategy. Birds from the North Slope migrate and winter in coastal habitats along the western North Pacific wintering as far south as the Korean Peninsula. In contrast, birds nesting on the Seward Peninsula winter in marine waters of western Alaska. Recent telemetry data indicate widespread use of coastal and marine habitats in the Chukchi Sea during breeding and migration (fig. 3–14).

The USFWS was petitioned to list the Alaska breeding population of yellow-billed loons, and after review determined that listing the species was warranted but precluded because of higher priority listing actions. It is a candidate species under the ESA. Relatively little is known about these species in Arctic Alaska, although all three species of loons are currently under study on the North Slope of Alaska. Ongoing concerns include disturbance from development (loons are particularly vulnerable to disturbance), oil pollution, and harvest.

Sea Ducks

Fifteen species of waterfowl make up the sea ducks, which nest in coastal areas or in freshwater habitats and winter primarily in coastal marine habitats. Five species dominate the sea duck avifauna of the Chukchi and Beaufort Seas: the long-tailed duck (*Clangula hyemalis*), and the eiders (common eider *Somateria mollissima*, king eider—*S. spectabilis*, spectacled eider—*S. fischeri*, and Steller’s eider—*Polysticta stelleri*). Common eiders, king eiders, and long-tailed ducks are the most abundant of the species. Eiders and long-tailed ducks are the first of the waterfowl to appear in the spring, exploiting leads in the ice as they open in the Chukchi and Beaufort Seas between shorefast and pack ice. Common eiders nest primarily in small colonies on barrier islands and other coastal habitats. Other sea ducks are more dispersed nesters across the North Slope. Sea ducks migrate in large numbers along the coasts of the Chukchi and Beaufort Seas to and from nesting grounds in Alaska and the Canadian Arctic, and are important subsistence species. Coastal lagoons of the Beaufort Sea are particularly important habitats for long-tailed ducks after breeding and before freeze-up.

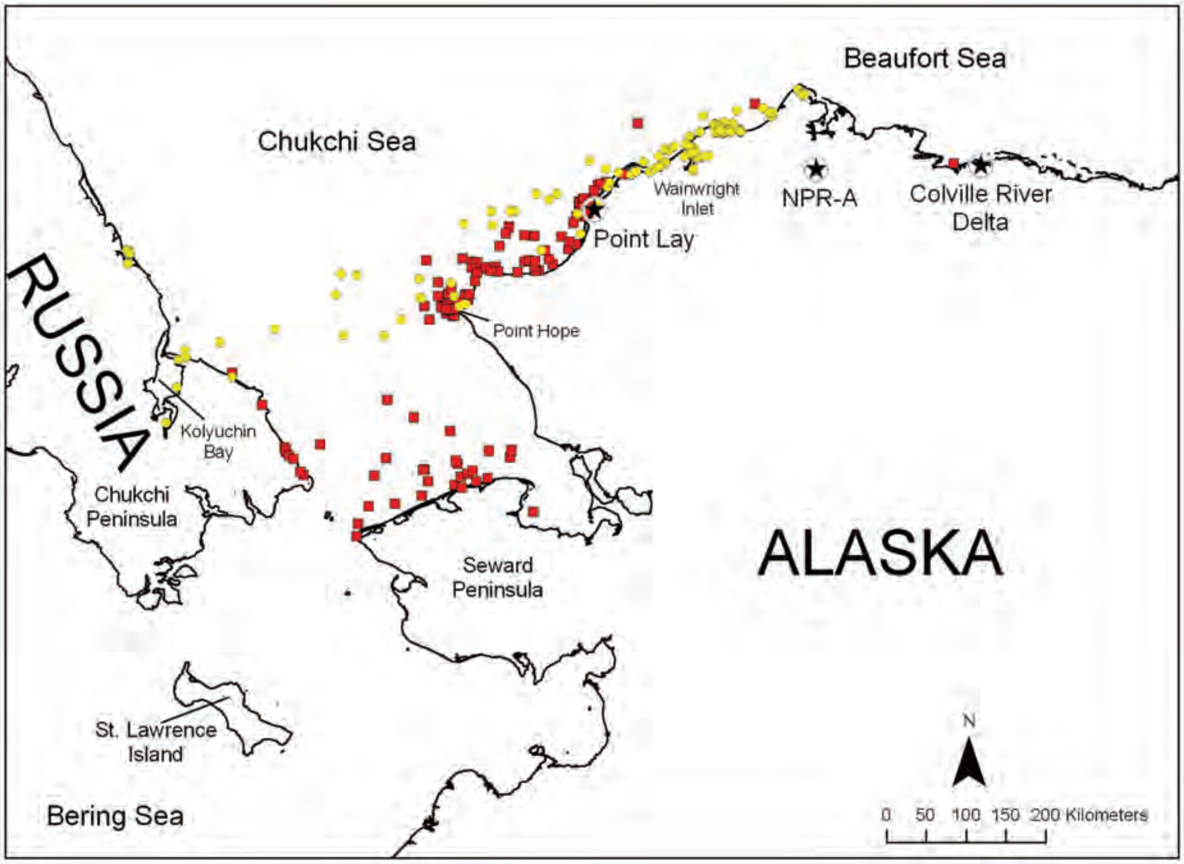


Figure 3–14. Locations of red-throated (red squares) and yellow-billed (yellow circles) loons based on satellite transmitters in 2010. Sites of original marking are indicated by stars (U.S. Geological Survey, unpub. data, 2010). (NPR-A, National Petroleum Reserve Alaska.)

Two species of eiders are of particular conservation concern for the Department of the Interior: spectacled eider and Steller's eider. Both are listed as threatened by the USFWS. Spectacled eiders breed across the North Slope of Alaska, especially west of the Prudhoe Bay area. They use coastal marine habitats during non-breeding in both the Beaufort and Chukchi Seas (fig. 3–15). Ledyard Bay in the Chukchi Sea is an important staging area and formally designated as Critical Habitat for this species. The entire World's population winters in highly dense concentrations within the sea ice of the northern Bering Sea (fig. 3–15) between St. Lawrence and St. Matthew Islands. An ongoing telemetry study will reveal new information about timing of migration, migratory pathways, and residence times in coastal areas of the Beaufort and Chukchi Seas that could be impacted by development activities.

Steller's eiders were formerly an abundant breeding bird on the Yukon Delta and the North Slope. During summer, they are now found primarily between Prudhoe Bay and Point Lay and number in the low thousands. Following breeding, they undergo a long migration to molting and wintering habitats on the Alaska Peninsula and the Aleutian Islands where they mix with the more abundant population of Steller's eiders that breeds in Russia.

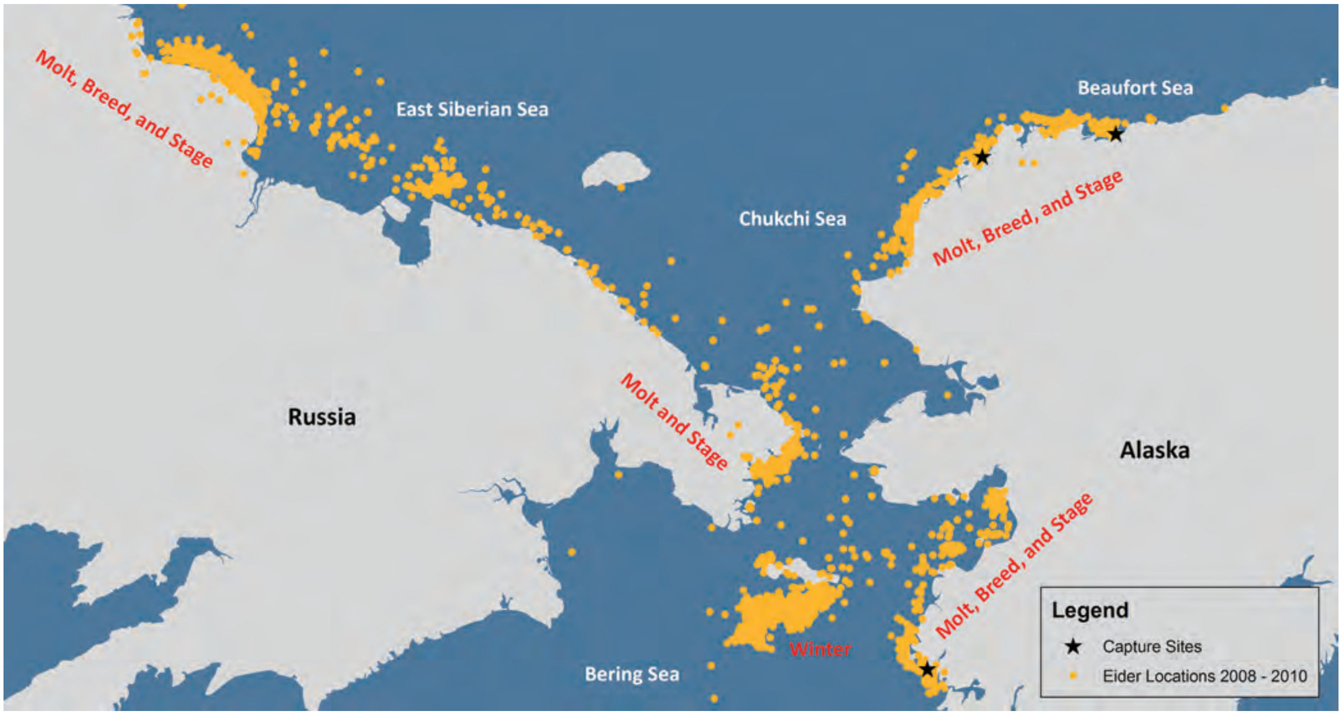


Figure 3–15. Locations (yellow dots) of spectacled eiders instrumented with satellite transmitters. Black stars are sites of original capture. Note use of the Beaufort Sea and Chukchi Sea coasts and extensive mixing of birds in United States and Russian waters (U.S. Geological Survey, unpub. data, 2010).

Geese and Swans

Geese and swans are the largest of the waterfowl that use coastal areas in the Chukchi and Beaufort Seas. The tundra swan (*Cygnus columbianus*) and four species of geese (greater white-fronted goose—*Anser albifrons*, lesser snow goose—*Chen caerulescens*, Pacific brant—*Branta bernicla nigricans*, and Canada goose—*B. canadensis*) exploit these habitats during the summer months. Tundra swans are a common breeding bird on tundra habitats of the coasts of the Beaufort and Chukchi Seas. Virtually the entire population of tundra swans that nest on the Beaufort Sea coast winter in the Atlantic Flyway. Marked swans nesting along the coast of the Chukchi Sea wintered in the Pacific Flyway.

All four species of geese breed in the study area. Greater white-fronted geese are abundant and breed within a 30 km strip along the coasts of the Chukchi and Beaufort Seas (Johnson and Herter, 1989). They winter in the Pacific and Central Flyways. Lesser snow geese nest colonially on Howe Island near Prudhoe Bay and west to the Meade River, Teshekpuk Lake, and the Colville River Delta. They also nest as far west as the Point Lay area on the coast of the Chukchi Sea (Ritchie and others, 2000). Lesser snow geese from Alaska primarily winter in California, New Mexico, and Mexico. Pacific brant nest on the Arctic Coastal Plain from the Sagavanirktok Delta west to the Barrow area and south to the Point Lay area on the coast of the Chukchi Sea (Stickney and Ritchie, 1996; Ritchie and others, 2000). They stage in the autumn at Izembek Lagoon and winter primarily on the Alaska Peninsula and south to Baja California, Mexico. Pacific brant have exhibited a significant and continuous population decline over the period 1965–2009. Suspected limiting factors include loss of wintering and staging habitats and harvest. The most critical habitats for waterfowl species in the Beaufort and Chukchi Seas area include coastal nesting colonies; pre- and post-breeding staging habitats in estuaries such as Kasegaluk Lagoon, Peard Bay, Smith Bay, and Harrison Bay; and molting sites in the large-lake and coastal areas northeast of Teshekpuk Lake. Breeding Canada geese have increased in numbers on the Arctic Coastal Plain over the last 2 decades, although the density of molting birds in the Teshekpuk Lake area has remained relatively stable over the past 30 years.

The Teshekpuk Lake area in the National Petroleum Reserve–Alaska (NPR–A) is an internationally important habitat for molting Arctic-nesting geese, especially white-fronts, brant, and Canada geese. Many failed-nesting and non-nesting brant from the Yukon-Kuskokwim Delta undergo a northward migration to molt in this area. Recent research suggests that brant are shifting molting sites within the NPR–A from freshwater lakes to coastal areas, perhaps in response to ecosystem changes related to saltwater intrusion into freshwater marshes that enhances growth of saltwater tolerant vegetation that brant favor (Flint and others, 2008; Lewis and others, 2010).

Shorebirds

Coastal areas of the Beaufort and Chukchi Seas support large numbers of breeding, staging, and migrating shorebirds. At least 29 species of shorebirds nest in this region, the most abundant being American golden plovers (*Pluvialis dominica*), semipalmated sandpipers (*Calidris pusilla*), pectoral sandpipers (*C. melanotos*), dunlin (*C. alpina*), long-billed dowitchers (*Limnodromus scolopaceus*), and red-necked (*Phalaropus lobatus*) and red (*P. fulicaria*) phalaropes (Alaska Shorebird Group, 2008). The Arctic Coastal Plain of Alaska is considered one of the premier shorebird breeding areas in the World. Distributions of shorebird species vary within the area; in general, the largest numbers and the greatest diversity occur west of the Colville River, although certain sites east of the Colville River (for example, Prudhoe Bay, Canning River Delta) also have high species richness. The Alaska Shorebird Group (2008) identified a number of areas on the coasts of the Chukchi and Beaufort Seas that are important to shorebirds. These include the Colville River Delta, the Canning River Delta, Kasegaluk Lagoon, Peard Bay, Elson Lagoon, and shorelines and barrier islands along the coastal plain of the Arctic National Wildlife Refuge.

All shorebirds are absent from the Arctic Coastal Plain and most also are absent from Alaska during the non-breeding season. Many undertake spectacular migrations to southern hemisphere wintering areas after gorging on invertebrates on western Alaska tideflats (for example, Gill and others, 2008). Because of that, Alaskan-breeding shorebirds are vulnerable to a variety of threats outside of Alaska (Alaska Shorebird Group, 2008).

All Alaska breeding species of shorebirds are considered at-risk. Alaska currently has 20 shorebird populations considered to be of high concern or imperiled and 21 populations of low to moderate concern. The Alaska Shorebird Group (2008) recognized American golden plover, upland sandpiper, whimbrel, bar-tailed godwit, red knot, sanderling, dunlin, and buff-breasted sandpiper as priority conservation species for the Arctic Coastal Plain. Many of these species, as well as pectoral, western, and semipalmated sandpipers, and red and red-necked phalaropes use coastal areas for feeding after breeding and prior to migration and could be vulnerable to development and oil spills. Phalaropes are the only shorebirds that also regularly use offshore areas.

Overview—Arctic Birds Information Needs

The most significant information need for birds using offshore marine and coastal regions of the study area is for recent data on species composition, distribution, and abundance. We know little about the present-day distribution of marine birds in the region; in fact, most of the data on distribution and abundance of birds in coastal and marine areas of the Chukchi and Beaufort Seas were gathered in the 1970s and 1980s (fig. 3–16) (U.S. Geological Survey, unpub. data, 1974–79, 1980–89, 1990–99, 2000–2008). These data show a wide variety of seabirds using this region, including loons and several marine geese and ducks in coastal areas; shearwaters, phalaropes, and auklets concentrated in early autumn in the Chukchi Sea; and Arctic specialists concentrated on the coast or offshore in the Beaufort Sea, for example, Ross's gull (*Rhodostethia rosea*), Sabine's Gull (*Xema sabini*), black guillemot, glaucous gull, jaegers, and Arctic tern. The present day distribution and abundance of these species are largely unknown, although declines are documented or suspected for several species (ivory gull [*Pagophila eburnean*], Ross's gull, some eider, and loon species), and it would require a repeat of historical surveys to assess changes. This is especially critical because of the large changes that have occurred in the Arctic, especially related to the diminished extent of sea ice in the Beaufort and Chukchi Seas in summer and autumn. Data collected in the 1970s and 1980s may no longer be relevant to management needs. This data gap is being addressed to some extent by the BOEMRE and USFWS through BOEMRE's Environmental Studies Program, and through Shell's Chukchi Offshore Monitoring In Drilling Area Program (COMIDA).

In addition to general information on distribution and abundance, integrated studies on seabird dynamics of the central Chukchi Sea in relation to oceanography, sea-ice change, and trophic dynamics are needed. The central Chukchi Sea is highly productive during summer, with extremely high levels of primary production and enormous standing crops of zooplankton. Most of this is due to the conveyor belt of rich waters brought north from the Bering/Anadyr current. In late summer/early autumn, the central Chukchi Sea also supports immigration of vast numbers of shearwaters, auklets, phalaropes, and other planktivorous seabirds. Most of what we know of the seabird movement into the Chukchi Sea is based on limited opportunistic surveys. A more detailed study of the dynamics of this area, including the lease sale area, is warranted given its strategic position north of the Bering Strait, and the pathway through which all vessels (including tankers) must travel to get to and from the Arctic Ocean.

Data needs are not restricted to marine areas. Continued monitoring of reproductive performance of seabirds at colonies at Cape Lisburne and Cooper Island are essential as colony performance provides a window into what is occurring in offshore marine areas. Coastal and inland areas also are changing and along with it the birds that depend on these habitats. Coastal erosion, saltwater intrusion, and thermokarsting are all active processes, resulting in habitat changes that will influence birds. Offshore development will result in onshore development as well, principally to support the offshore activities and to move oil and gas products, likely through pipelines to the Trans-Alaska pipeline. This infrastructure will require careful site planning and mitigation to prevent impacts to wildlife populations.

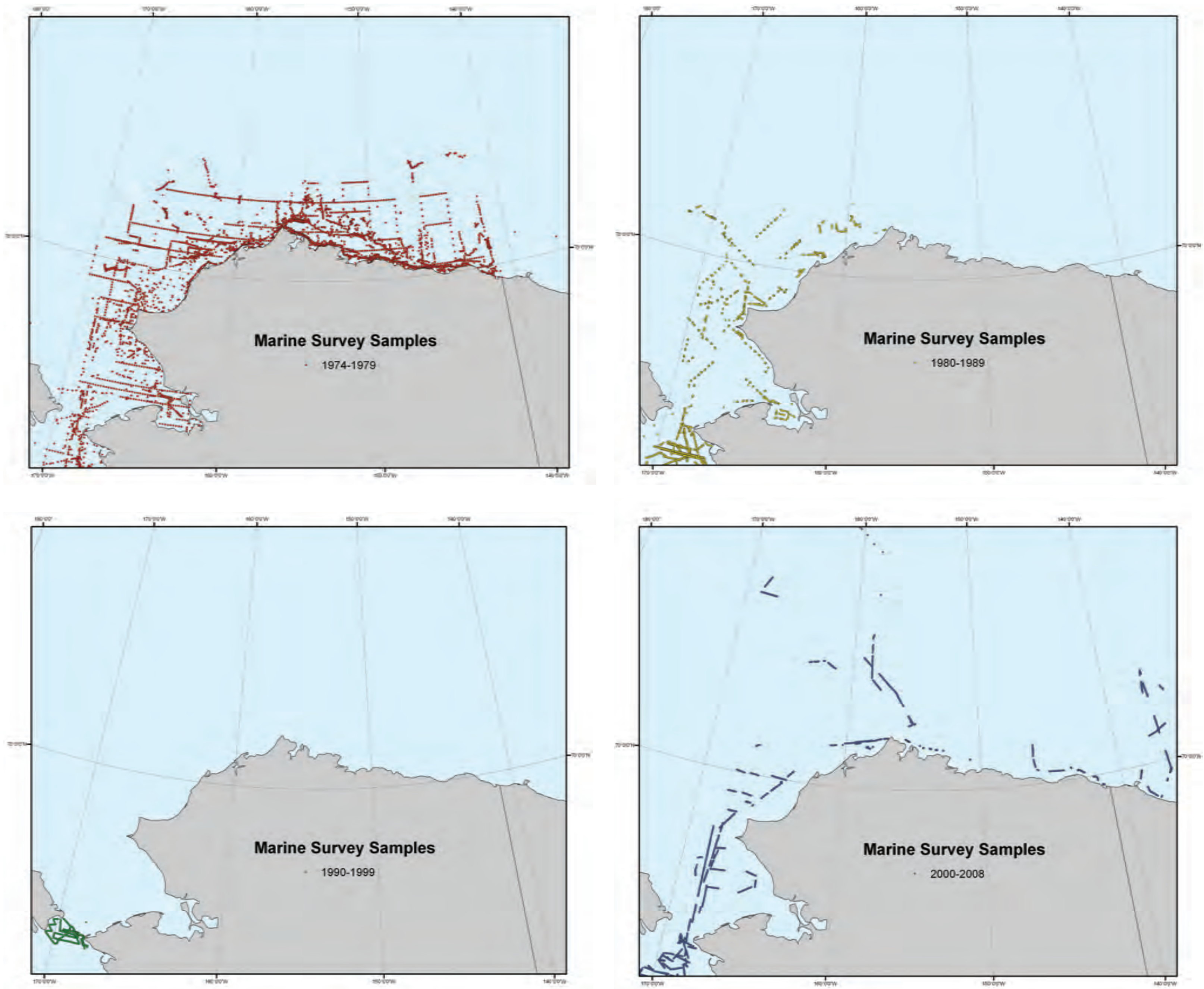


Figure 3–16. Distribution of marine bird surveys in the Beaufort and Chukchi Seas by decade showing disparity of temporal and spatial sampling among decades. Source: U.S. Geological Survey (2011), North Pacific Pelagic Seabird Database, accessed April 18, 2011, at http://alaska.usgs.gov/science/biology/nppsd/index.php

3.06. Findings and Recommendations: Recent at-sea information on marine birds for most of the study area is lacking or unpublished. Similarly, with the exception of information from Cooper Island and Cape Lisburne, much of the seabird colony information is out-of-date. Filling these data gaps would enhance our ability to measure the effects of climate change and assess the impacts of development and transportation.

The Chukchi Sea is a dynamic area for marine birds during the summer. Studies to examine seasonal dynamics of seabirds in the Chukchi Sea related to oceanography, climate, sea-ice dynamics, primary and secondary productivity and movements of birds from breeding colonies (for example, Cape Lisburne) are necessary. Studies in the Chukchi Sea Lease Sale Area have been underway by Shell to address this but are not yet published. Similar studies, but focused on sea ducks and their benthic habitats, also would be helpful to evaluate climate impacts and to assess impacts of oil and gas development.

Data from studies of birds at colonies, for example at Cooper Island and Cape Lisburne, need to be published and continued. Onshore studies of seabirds to measure abundance, productivity, and food habitats provide a unique window and understanding into offshore marine processes.

Modeling the impact of oil pollution on birds using oil-spill trajectory models, population models, satellite telemetry data, and new information on seabird distribution and abundance would be informative for some species.

A better understanding of the timing of migration and habitat use of at-risk species of waterbirds in the Chukchi and Beaufort Seas. New information based on satellite telemetry is available for common, king, and spectacled eiders, and red-throated and yellow-billed loons. Existing data need to be analyzed and published, and additional telemetry studies are necessary to assess timing and pathways of migration and use of coastal areas for foraging and molting for other species including Pacific brant, long-tailed ducks, and Pacific and Arctic (*G. arctica*) loons.

Coastal lagoons of the Chukchi and Beaufort Seas are important stopovers for migrating birds, particularly Pacific brant. Data on distribution, numbers, and periods when birds occur in coastal lagoons are needed to identify sensitive areas and times when disturbance should be minimized.

Further analyses and studies are needed to increase the understanding of seasonal and inter-annual variation in shorebird use (numbers of birds, timing of their use, change in site quality) of key post-breeding areas, especially coastal areas where oil development is likely to occur (for example, the deltas of the Meade, Ikpikpuk, Colville, Sagavanirktok, and Canning Rivers, and coastal sites on NPR–A).

Sea-level rise, increased frequency and severity of storms, and more frequent and severe episodes of coastal erosion and flooding are occurring or are predicted to occur in the study area and could have large impacts on migratory birds. Many northern shorebird and waterfowl species are dependent on these littoral habitats during some phase of their annual cycle. Understanding change in coastal geomorphology—from both physical and trophic standpoints and whether driven by climate change or other factors—is an important data gap.

If an oil spill were to occur in broken sea-ice habitats, or if lead systems were to become contaminated with oil, understanding and being able to predict what wildlife would be affected in these ice habitats and the effectiveness or consequences of hazing Arctic marine animals, including birds, will be important.

Local residents are often the first to notice changes in fish and wildlife populations. Mechanisms should be developed to better solicit and integrate local traditional knowledge as a basic source of information.

Marine and Diadromous Fish

The Alaskan Chukchi and western Beaufort Seas support at least 112 fish species (L. Thorsteinson, U.S. Geological Survey, written commun., 2010; also see Mecklenburg and others, 2002). Dominant families of fishes include lampreys, sleeper sharks, dogfish sharks, herrings, smelts, whitefishes, trouts and salmons, lanternfishes, cods, sticklebacks, greenlings, sculpins, sailfin sculpins, fathead sculpins, poachers, lumpsuckers, snailfishes, eelpouts, pricklebacks, gunnels, wolffishes, sand lances, and righteye flounders. Forty-nine species are known to be common to both the Beaufort and Chukchi Seas. Additional species are likely to be found in the Alaskan Arctic when coastal and offshore waters are more thoroughly surveyed.

Marine Arctic fishes of Alaska can be divided into two primary assemblages: marine fish and diadromous fish.

Marine Fish

Mecklenburg and others (2008) and Minerals Management Service (2008) recently described the state of knowledge of Arctic marine fishes. Marine waters support the most diverse, although least well known, fishes of the area. Studies of marine fishes in the region are very limited; most of the surveys/studies have been performed in coastal waters landward of the 200-m isobath, with few surveys having sampled deeper waters. Studies have been hampered by a lack of commercial fisheries, short ice-free seasons, and logistical difficulties. Marine fishes prefer the colder, more saline coastal water seaward of the nearshore brackish-water zone. As summer wanes, the nearshore zone of the Alaska Beaufort Sea becomes more saline due to decreased freshwater input from rivers and streams and marine intrusions associated with summer storms. During this time, marine fishes often share nearshore brackish waters with diadromous fishes, primarily to feed on the abundant epibenthic fauna or to spawn. In autumn, when diadromous fishes have moved out of the coastal area and into freshwater systems to spawn and overwinter, marine fishes remain in the nearshore area to feed. The USGS, in collaboration with BOEMRE, is currently developing an Arctic Marine Fish Ecology Catalog that will provide a complete set of species accounts and synthesize ecological knowledge about the marine ecology of fishes in the Chukchi and Beaufort Seas (Thorsteinson and others, 2011). This catalog also will include aspects of the human dimensions of fish use in the region by summarizing subsistence catch data to depict regional harvest patterns.

To better understand fish resources, the Minerals Management Service (2008) further refined the scale of primary fish assemblages into secondary, ecological assemblages based on fish behavior and ecology, and general oceanographic/landscape features, such as the continental shelf break or polar ice. These assemblages and their widespread or abundant species include: (1) the neritic-demersal assemblage (at or near the seafloor of the continental shelf) with twohorn and fourhorn sculpin, polar eelpout, and Arctic flounder; (2) the neritic-pelagic assemblage (within the water column of the continental shelf) with Pacific herring, Arctic cod, capelin, and Pacific sand lance; (3) the oceanic-demersal assemblage (living on or close to the bottom off the continental shelf—seaward of the 200-m isobath) with ogac, ribbed sculpin, spatulate sculpin, shorthorn sculpin, spinyhook sculpin, archer eelpout, pale eelpout, and daubed shanny; (4) the oceanic-pelagic assemblage (inhabiting the water column of oceanic waters seaward of the 200-m isobaths) with Pacific herring, Arctic cod, polar cod, pollock, Pacific sand lance, and the glacier lanternfish; and (5) the cryopelagic assemblage (inhabiting neritic or oceanic waters, but during their lifecycle, are associated with sea ice) with Arctic cod and Pacific sand lance.

Because of the influence of sea ice in the Arctic, and in particular the importance of Arctic cod in Arctic marine ecosystems, additional detail is provided here. The term “cryopelagic” is used to describe fishes that actively swim in neritic or oceanic waters but, during their lifecycle, are associated with drifting or fast ice. Both young and adult fishes can be associated with ice or water immediately beneath the ice. These relationships are usually trophic in nature, but in some cases, ice provides fishes with a shelter from predators. Andriyashev (1970) described what may be the first known cryopelagic fish species, the Arctic cod. Arctic cod are most common among broken ice or near the ice edge. Here, as the ice thaws and breaks up, phytoplankton and zooplankton develop and provide food for Arctic cod. It is possible that the fish also feed on organisms of the amphipod-diatom ice community inhabiting the lower ice layer. At the same time, cod apparently use sea ice as shelter from the numerous enemies attacking them from both water and air. Arctic cod play a significant role in relatively short food chains that directly, or indirectly, support subsistence lifestyles of indigenous people. The Arctic cod is a key prey of many marine mammals and seabirds as evidenced by their occurrence in the diets of belugas and ringed and bearded seals, Pacific walruses (occasionally), thick-billed and common murres, black guillemots, black-legged kittiwakes, northern fulmars, Arctic terns, and glaucous, Sabine’s, ivory, and Ross’s gulls. Arctic cod also are of indirect importance to polar bears and Arctic foxes, because their principal marine food, the ringed seal, also relies on them as food. Considerable research underscores the critical function of Arctic cod in Arctic marine ecosystems, because no alternate food source of equivalent trophic value exists.

Diadromous Fish

Diadromous fishes are those that move between and are able to live in fresh, brackish, and (or) marine waters due to various biological stimuli, such as feeding or reproduction, or ecological factors, such as temperature, oxygen level, or specific spawning-habitat need. Diadromous fishes include all migration types (anadromous, catadromous, and amphidromous) between marine and freshwaters, including single lifetime events, repetitive multiyear events, spawning migrations, feeding migrations, and seasonal movements between environments. Diadromous fishes inhabit many of the lakes, rivers, streams, interconnecting channels, and coastal waters of the North Slope. Common diadromous fishes include Arctic cisco, least cisco, Bering cisco, rainbow smelt (now Arctic smelt), humpback whitefish, broad whitefish, Dolly Varden char, and inconnu. The highest concentration and diversity of diadromous fishes in the area occur in river-delta areas, such as the Colville and the Sagavanirktok Rivers. Lakes that are accessible to diadromous fishes typically are inhabited by them in addition to resident freshwater fishes. The least cisco is the most abundant diadromous fish found in these lakes. With the first signs of spring breakup, adult and juvenile diadromous fishes move out of freshwater rivers and streams and into the brackish coastal waters.

Some diadromous fishes disperse widely from their streams of origin (for example, Arctic cisco and some Dolly Varden char). Others, like broad and humpback whitefish and least cisco, do not; they are seldom found anywhere but near the mainland shore. Most diadromous fishes initiate relatively long and complex annual migrations to and from coastal waters. However, some populations of Dolly Varden char, least cisco, and broad and humpback whitefish never leave freshwater. Arctic cisco in the Colville River area originate from spawning stocks of the Mackenzie River in Canada. The vast majority of the Arctic cisco inhabiting the Alaskan Beaufort Sea were carried there from Canada by westerly currents. During the Alaska phase of their life history, Arctic ciscos reside in the Colville River Delta from autumn to spring, and then forage into food-rich coastal waters during the brief Arctic summer. The Colville River, by virtue of its size, is the major overwintering site for Arctic cisco in Arctic Alaska, although other deltas, such as the Sagavanirktok, may harbor smaller populations. During the 3- to 4-month open-water season that follows spring breakup, diadromous fishes accumulate energy reserves for overwintering, and, if sexually mature, they spawn. Although their prey is concentrated in the nearshore zone, their preference for this area also is believed to be correlated with its warmer temperature.

Overview—Arctic Fish Information Needs

A combination of literature review and expert consultations was used to evaluate existing information and knowledge about Arctic marine and anadromous fishes in light of its adequacy for decision making. Baseline surveys for marine fish and shellfish resources tend to be dated for most of the study area (1960s to 1990s) with most data collections reflecting infrequent sampling with respect to time and geography and objectives for environmental assessment purposes more so than for fisheries management. In the past 5 years, Shell has sponsored surveys in the northeastern Chukchi Sea, National Oceanic and Atmospheric Administration (NOAA)/BOEMRE surveys offshore and to the west of Barrow, and NOAA/Russia expeditions into the northern Chukchi Sea and Arctic Basin. With respect to OCS oil and gas development, fisheries investigations have focused on coastal habitats and their use, primarily during open-water periods, by salmonid species valued in subsistence and small-scale commercial fisheries, and nearshore fishes that might be affected by changes in brackish water habitats by solid-fill causeways in and nearby Prudhoe Bay. The National Science Foundation and others have funded ecological research in the northern Bering and southeastern Chukchi Seas to investigate coupling of regional pelagic and benthic ecosystems.

Resource inventories for freshwater, marine, and anadromous/amphidromous fish are reasonably complete for the Chukchi and Beaufort Seas. Life cycle information is lacking for all species, and with respect to fish species, is most complete for Arctic cisco in the Colville River. Although information about the population dynamics for key species of ecological significance (for example, Arctic cod, sand lance, and capelin) or subsistence use (for example, Dolly Varden, Arctic cisco, and inconnu) is critical for analysis of potential oil-spill impacts or other ecosystem disturbances, this level of resolution does not exist. Potential oil-spill impacts in shallow, coastal waters during open-water periods (June–September) could seriously impact key anadromous/amphidromous fish populations including Dolly Varden (from rivers originating in the Brooks Range), whitefish (from lower energy rivers/lakes to the west of the Brooks Range and northwestern Alaska), and salmon (Kotzebue Sound). Similarly, existing life history and habitat utilization information suggest that certain marine populations that seasonally aggregate in nearshore and intertidal areas for spawning (for example, herring, capelin, and rainbow smelt [now Arctic smelt]) or feeding (for example, Arctic cod) could suffer significant losses from spills or associated onshore industrial developments supporting OCS activities (for example, tankers and service vessels, pipelines, or causeways and artificial islands) or other kinds of resource extraction (for example, gravel mining).

3.07. Findings and Recommendations: Information about status and trends, habitat requirements, relative distribution and abundance, and knowledge of life history stages of marine fish is incomplete and unavailable for large expanses of Arctic nearshore and shelf waters and should be developed for indicator species (that is, species that are broadly distributed, of subsistence or ecological significance, readily available for vulnerability assessments, and deemed sensitive to offshore oil and gas development). Onshore-offshore linkages associated with life history requirements have not been described.

Logistical, technological, and cost considerations have limited the practicality of winter surveys and under ice resource information is limited and inadequate for evaluation of impacts.

Greater reliance on modern scientific technologies and their applications, such as remote sensing, telemetry, genetics and molecular biology, and quantitative ecology (for example, predictive models) is needed to establish species environmental relationships, address existing gaps about relative importance of habitats, understand natural variation in fluctuating stocks, and to more accurately assess effects of proposed offshore oil and gas activities.

Effects of ocean variability on production cycles and the distributional behavior, movement, and abundance of marine and anadromous fishes should be emphasized in future research and monitoring on select resources in strategic locations and undertaken to understand natural trajectories of change and effects of human interactions.

Effects of environmental parameters on physiological processes [feeding, digestion, assimilation, growth, responses to stimuli (that is, orientation and swimming speed), and reproduction] are poorly known for most Arctic fish species. These processes are dependent on key water properties, including temperature, salinity, light penetration, and oxygen concentration. Animal health also is affected by the presence of toxic substances, infectious pathogens, and parasites.

Seismic and noise effects on fishery resources have not been studied and is a research need. Much information could be borrowed from marine mammal research in Alaska and elsewhere regarding natural ambient sound and anthropogenic sound levels to guide experimentation.

Effects of invasive species associated with increased tankering, vessel support, and offshore construction activities on important biological habitats and ecosystems are unknown.

Biological hotspots for long-term research and monitoring of coastal, marine, and human impacts need to be identified. Potential sites include: Bering Strait (marine ecosystem processes); Kasegaluk, Simpson, and Beaufort lagoons (nearshore fish assemblages); Barrow Canyon/Hannah Shoal (benthic productivity); Capes Lisburne and Thompson (seabird colony and fishery oceanography dynamics); Point Barrow (transitional biogeographic zone); Boulder Patch (kelp bottom ecosystem); Stefansson Sound/Camden Bay (Arctic cod ecology); Mackenzie, Colville, and Canning River Deltas (physical and biological onshore-offshore linkages); ice edge and polynyas (biological significance to fish, birds, and marine mammals).

Local residents are often the first to notice changes in fish and wildlife populations. Mechanisms should be developed to better solicit and integrate local traditional knowledge as a basic source of information.

Human Settlements, Demographics, and Political Organization

(from Minerals Management Service, 2008, and North Slope Borough, 2011)

Human communities that have been and could be affected by future offshore oil and gas development are located primarily along the coasts of the Beaufort and Chukchi Seas and include from east to west: Kaktovik, Nuiqsut, Atqasuk, Barrow, Wainwright, Point Lay, and Point Hope. Additional communities farther south along the Chukchi Sea coast, such as Kivalina, Kotzebue, and Shishmaref also could be impacted by development but are not discussed further here. The North Slope has a fairly homogeneous population of Iñupiat, approximately 72 percent in 1990 and 68.38 percent in 2000 of the population. The percentage in 2000 ranged from 89.1 percent Iñupiat in Nuiqsut to 64.0 percent Iñupiat in Barrow. Each of the Borough's communities, with the exception of Point Lay, has a city government. Although certain municipal powers were turned over to the North Slope Borough when it was formed in 1972, community governments play an important role in the administration of Borough programs. In addition, local governments administer some State and Federal programs, such as capital improvements and housing. This section provides a profile of the North Slope Borough and the communities that border the Beaufort and Chukchi Seas that have been and could be impacted by offshore oil and gas development.

The North Slope Borough. Prior to the discovery and development of oil and gas on the North Slope and the formation of the North Slope Borough (NSB) in 1972, the population of the five then-existing villages (that is, Barrow, Kaktovik, Anaktuvuk Pass, Point Hope, and Wainwright) totaled about 2,500 people. Each village had limited political power, social services, and infrastructure. Per capita and household incomes were low, and North Slope residents relied heavily on local subsistence resources for food, clothing, and heat. The majority of NSB growth since 1970 has been in the three communities established after the incorporation of the NSB; however, large investments have been made in the infrastructures of all NSB communities. Iñupiat society maintains a strong subsistence-based culture.

The formation of the NSB in 1972 was motivated, in part, by the desire to capture petroleum industry based property tax revenue for local improvement and to exercise a degree of control over the pattern of petroleum development through the permitting of onshore oil infrastructure. Other factors that contributed to the motivation include the exercise of local control over Federal education and health care and the providing of services by the State that were lacking. Communities deliberately transferred municipal power to the Borough government, including basic community services in 1974, education in 1975 with the formation of the North Slope School District, and public safety in 1976. The result has been a strong regional government.

The NSB provides nearly all municipal services to the villages, including the operation of basic services and facilities. The Borough's Capital Improvement Program (CIP) created most of the infrastructure that serves the needs of the communities. Through the provision of these services, the Borough either directly or indirectly provides the majority of full-time employment in the villages. The NSB government and the school district are the largest employers in the region. However, in the period from 1998 to 2003, NSB government employment declined as did employment in the CIP, primarily due to the completion of construction projects in communities outside of Barrow. Over the last 25 years, these services have improved the economic and social well-being for Borough residents in areas of health, social services, public safety, education, communications, and transportation. The Borough provides utilities in each of the communities, where a large majority of housing units now are connected to public water and sewer. The NSB Department of Health provides a hospital in Barrow and health clinics in outlying villages. Social services furnished by the Borough include housing, meals and transportation for seniors, mental health counseling, and day care. The Borough provides each of the villages with law enforcement, fire protection, and search and rescue services, with a combination of full-time employees and volunteers. Secondary-school facilities have been provided in each village, and postsecondary education opportunities have improved. The Borough owns and operates public airports in all the communities, except Barrow and Deadhorse where they are State operated, and fosters community well-being through creation and support of other institutions, such as the Commission on Iñupiaq History, Language, and Culture. Since peaking in 1986, oil tax revenues have declined as the value of oil production and pipeline infrastructure depreciates. As these revenues have declined, Borough expenditures have similarly declined.

Kaktovik. Incorporated in 1971, Kaktovik is the easternmost village in the NSB. Its 2006 population was 288; its population in 2004 of 284 was 84.0 percent Iñupiat. The village is on the north shore of Barter Island, one of the largest of a series of barrier islands along the north coast, situated between the Okpilak and Jago Rivers on the Beaufort Sea coast, and is located 300 mi east of Barrow. Kaktovik abuts the Arctic National Wildlife Refuge. Until the late 19th century, the island was a major trade center for the Iñupiat and was especially important as a bartering place for Iñupiat from Alaska and Inuit from Canada.

Nuiqsut. Nuiqsut sits on the west bank of the Nechelik Channel of the Colville River Delta, about 25 mi inland from the Arctic Ocean and approximately 150 mi southeast of Barrow. Its population in 2006 was 417; its 2000 population of 433 was 89.1 percent Iñupiat Eskimo. Nuiqsut, one of three abandoned Iñupiat villages in the North Slope region identified in the Alaska Native Claims Settlement Act, was resettled in 1973 by 27 families from Barrow. Today, Nuiqsut is experiencing rapid social and economic change due to the development of local infrastructure, the development of the Alpine oil producing facility, potential Alpine satellite development, and potential oil development in the National Petroleum Reserve, Alaska. Most of Nuiqsut's marine subsistence-harvest area lies adjacent to areas in the Beaufort Sea.

Barrow. Barrow is the largest community on the North Slope and is its regional center. In 1970, the Iñupiat population of Barrow represented 91 percent of the total population of Barrow, but by 1990, Iñupiat representation had decreased to 63 percent. Between 1980 and 1985, Barrow's population grew by 35 percent and by 2006, its population was 4,065. The dramatic change in population and demographics primarily is the indirect result of oil and gas development. Increased revenues from onshore oil development and production at Prudhoe Bay and in other smaller oil fields underwrote the NSB CIPs which, in turn, stimulated a boom in Barrow's economy and an influx of non-Alaskan Natives to the community. The social organization of the Barrow community has become diversified with the large increase in the number of immigrants of different ethnic groups. Traditional marine mammal hunts and other subsistence practices still are an active part of the culture. Barrow is the seat of Borough government and the largest regional community.

Atqasuk. Atqasuk is a small, predominantly Iñupiat community on the Meade River, about 60 mi south of Barrow. In 2000, there were 228 residents, 94.3 percent of whom were Iñupiat; in 2006, there were 237 community residents. The community was established in mid-1970 by Barrow residents who had traditional ties to the area. By July 1983, the population had increased to 231, a 166 percent increase since the first census in 1980. Social ties between Barrow and Atqasuk remain strong, and men from Atqasuk go to Barrow to join bowhead whaling crews. To a large degree, Atqasuk has avoided the rapid social and economic changes experienced by Barrow and Nuiqsut brought on by oil development activities, but future change could accelerate as a result of oil exploration and development in the Northwest NPR–A.

Wainwright. Wainwright is located on the Chukchi Sea 100 mi southwest of Barrow on the western boundary of the NPR–A. In 2000, there were 546 residents, 93 percent of whom were Iñupiat; in 2006, Wainwright's population was 517. All of Wainwright's subsistence marine resources are harvested offshore in the Chukchi Sea, and all of the community's terrestrial subsistence use areas are within NPR–A.

Point Lay. Point Lay is one of the more recently established Iñupiat villages on the Arctic coast, and has historically been occupied year-round by a small group of one or two families. The community has the smallest population of any community in the NSB. In 2000, there were 247 residents, 88.3 percent of whom were Iñupiat; in 2006, Point Lay's population was 235. It is the only unincorporated community in the NSB. About 90 mi southwest of Wainwright, the community sits on the Chukchi Sea coast at the edge of Kasegaluk Lagoon near the confluence of the Kokolik River and Kasegaluk Lagoon. The community was established in the 1920s and its resident population increased until the 1930s, when it began a slow decline, largely because of the decline in reindeer herding. By 1960, it was not included in the national census. The village was reestablished on a barrier island spit opposite the Kokolik River in the 1970s. Residents of Barrow, Wainwright, Point Hope, Kotzebue, and other Iñupiat with traditional ties to the area resettled there. The town then moved to its present mainland site south of the Kokolik Delta in 1981. The community is unique because its wild food dependence is relatively balanced between marine and terrestrial resources. Unlike the other communities, local hunters do not pursue the bowhead whale because the deeply indented shoreline and spring ice-lead patterns have prevented effective bowhead whaling. However, the village does participate in beluga whaling.

Point Hope. Point Hope had a population of 737 in 2006. In 2000, there were 757 residents, 90.6 percent of whom were Iñupiat. The community, 330 mi southwest of Barrow, is located on a large gravel spit that forms the westernmost extension of the northwest Alaska coast. Once called Tigaraq, it is one of the longest continuously occupied areas in Alaska. This likely is due to its proximity to marine mammal-migration corridors and favorable ice conditions that allow hunting in open leads early in the spring. Local government is the main employer of Point Hope residents. The city government was incorporated in 1966 and, in the early 1970s, the community moved, because of erosion and periodic storm-surge flooding, to its present location just east of the old settlement. Point Hope has better facilities than many other communities of the region, but concerns remain because of erosion and storm-surge flooding.

Tribal Governments. Kaktovik, Nuiqsut, Atqasuk, Barrow, Wainwright, Point Lay, and Point Hope also have either a traditional village or an Indian Reorganization Act (IRA) Tribal council. Historically, these Tribal governments provided some services and may partner with the Borough to manage and operate social-service programs. The Iñupiat Community of the Arctic Slope (ICAS), the regional Tribal government, recently has taken a more active and visible role in regional governance and in providing some services. Government-to-government consultations with these Tribal governments occur on major Federal actions directly affecting the Tribes, including OCS oil and gas actions.

Alaska Native Corporations. Collectively, village corporations are the third largest employer and the Arctic Slope Regional Corporation (ASRC) is the fourth largest employer in the region. The ASRC runs several subsidiary corporations and, along with village profit and not-for-profit corporations, has provided employment and other services to Borough communities. For example, ASRC and village corporations have provided employment and other public services to the communities, such as operation and maintenance of utilities and operation of stores, hotels, and restaurants, while nonprofit corporations primarily are involved in education, health/medical, public housing, and other community services through funding obtained from the Borough and Federal and State governments. Generally, much of the surface estate in and around the communities is owned by the village corporations, except in Barrow where land ownership is a mixture of public (Federal, State, Borough, Tribal, and village) and private (Alaska Native regional and village corporations and private individuals). Regional and village corporations are creating some employment through subsidiaries and joint ventures, and some companies involved in resource development have undertaken to increase local employment through training programs and other actions.

Local Traditional Knowledge

The information included in this report primarily is derived from “western” scientific studies. These are scientific observations, usually developed in a systematic fashion and often using instrumentation to record, understand, and predict the states of ecosystems and their dynamics (Huntington and others, 2004a). Science typically has a strong numeric component and attempts to quantify the variability associated with various scientific observations. In contrast, local traditional knowledge, also known as LTK, refers to knowledge gathered and maintained by groups of people, often indigenous people, based on intimate experience with their environment (Huntington and others, 2004a). Advocates of LTK have promoted its use in scientific research and ecological understanding (Huntington, 2000), and Huntington and others (2004a) argue that combining the two approaches can increase confidence in individual observations, broaden the scope of information about environmental change, and contribute to insights concerning mechanisms of change. Huntington and others (2004a) emphasize three characteristics of LTK: (1) it often emphasizes unusual events or conditions—these may be particularly relevant to safety; (2) the assessment of uncertainty (variability) is not explicitly addressed in LTK; and (3) it is typically local in spatial scale.

Because practitioners of LTK are usually local residents (and scientists often are not), LTK can be particularly useful in documenting changes in distribution and abundance of species (for example, increasing abundance of salmon in the Beaufort Sea), documenting subsistence harvest areas for various species (see S.R. Braund and Assoc., 2010a), and documenting changes in harvest patterns. But LTK also has been used to identify biases in survey design [see example for bowhead whale survey in Huntington (2000)] and problems associated with telemetry collar designs for tracking polar bears (G. Durner, U.S. Geological Survey, oral commun., 2010), and in combination with scientific information that has been used to more holistically define ranges and habitats used by animals over the course of their annual cycles (Huntington and others, 2004b).

S.R. Braund and Associates (2010b) recently conducted a literature review of North Slope marine LTK. This review includes information on the physical environment, public testimony of residents at hearings, subsistence use areas, and subsistence harvest studies.

Subsistence Resources

Generally, subsistence is considered hunting, fishing, and gathering for the primary purpose of acquiring traditional food. The Alaska National Interest Land Conservation Act (ANILCA) defines subsistence as the customary and traditional uses by rural Alaska residents of wild, renewable resources for direct personal or family consumption such as food, shelter, fuel, clothing, tools, or transportation; for the making and selling of handicraft articles out of nonedible byproducts of fish and wildlife resources taken for personal or family consumption; for barter or sharing for personal or family consumption; and for customary trade (16 U.S.C. § 3113). This ANILCA framework is the basis for all current documentation of Alaskan subsistence activity, both by State and Federal governments.

Subsistence activities are assigned the highest cultural values by the Iñupiat and provide a sense of identity in addition to being an important economic pursuit. Besides their dietary benefits, subsistence resources provide materials for personal and family use, and the sharing of resources that helps maintain traditional Iñupiat family organization. Subsistence resources also provide special foods for religious and social occasions, such as Nalukataq, which celebrates the bowhead whale harvest. The sharing, trading, and bartering of subsistence foods structure relationships among communities, while at the same time the giving of these foods helps maintain ties with family members elsewhere in Alaska. Additionally, subsistence provides a link to the market economy; many households within the communities earn cash from crafting whale baleen and walrus ivory and from harvesting fur-bearing mammals.

Subsistence harvest data are primarily from the Alaska Department of Fish and Game Community Subsistence Information System and the North Slope Borough (Bacon and others, 2009). Although subsistence-resource harvests differ from community to community in northern and northwestern Alaska, with a few local exceptions, the combination of marine mammals, large terrestrial mammals, fish and waterfowl are the primary groupings of resources harvested across the North Slope (fig. 3–17). Of the marine mammals, the bowhead whale is the preferred meat and the subsistence resource of primary importance because it provides a unique and powerful cultural basis for sharing and community cooperation. Of the terrestrial mammals, caribou are the most important (Bacon and others, 2009). Depending on the community, fish is the second or third most important resource after caribou and bowhead whales. Pinnipeds and various types of birds also are considered primary subsistence species. Waterfowl are particularly important during the spring, when they provide variety to the subsistence diet (Bacon and others, 2009). Although North Slope residents concentrate their harvests on certain high value target species and species groups, the overall subsistence harvest is quite diverse (table 3–3).

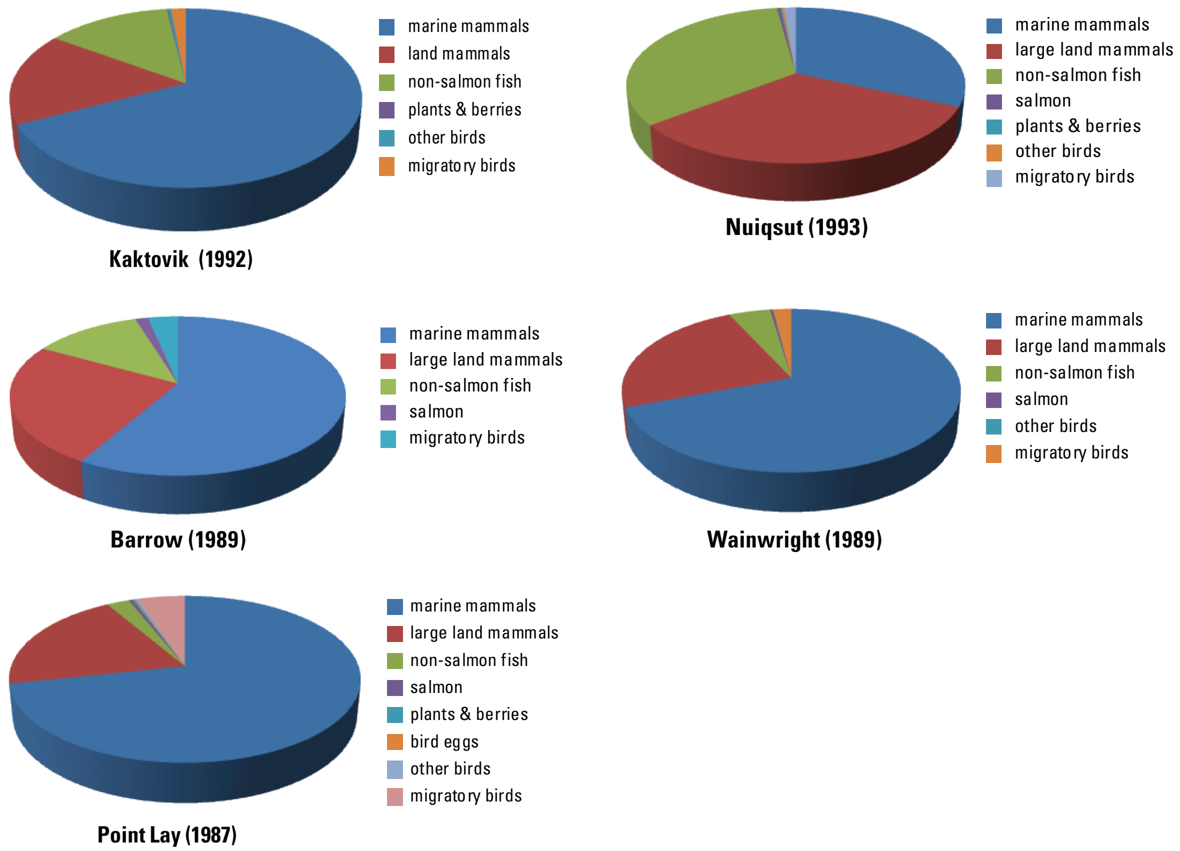


Figure 3–17. Estimated annual harvest of various subsistence resources (pounds) (data that make up these pie charts are relatively old, but still provide a relative sense of the importance of various resources in the subsistence economies of North Slope villages). Adapted from the Alaska Department of Fish and Game (2011), accessed April 18, 2011, at http://www.subsistence.adfg.state.ak.us/CSIS/.

Table 3–3. Species and numbers harvested by Barrow residents, 1987–90.

[3-year average data from Minerals Management Services (2008)]

Species	3-year average
Bowhead whale	9
Walrus	81
Bearded seal	174
Ringed seal	394
Spotted seal	3
Polar bear	21
Beluga whale	0
Caribou	1,595
Moose	48
Dall sheep	11
Brown bear	1
Porcupine	2
Ground squirrel	14

Species	3-year average
Wolverine	2
Arctic fox	129
Red fox	5
Wolf	0
Ermine	0
Whitefish	28,683
Non-specified	1,760
Round	953
Broad	17,352
Humpback	1,840
Least cisco	5,819
Arctic cisco	958
Grayling	9,914

Species	3-year average
Arctic char	83
Burbot	676
Lake trout	147
Northern pike	4
Salmon	788
Non-specified	169
Chum	182
Pink	92
Silver	334
King	12
Capelin	1,435
Rainbow smelt	526
Arctic cod	8,321

Species	3-year average
Tomcod	65
Sculpin	4
Geese	3,384
Non-specified	144
Brant	440
White-front	2,795
Snow	4
Canada	1
Eiders	6,087
Ptarmigan	1,378
Other birds	30

In addition to accurate, timely information on the composition of subsistence harvests by North Slope residents, information on where those harvests take place also is of high importance in planning industrial activities in coastal and marine areas of the Beaufort and Chukchi Seas. S.R. Braund and Associates (2010a) recently conducted a literature review of North Slope marine traditional knowledge and included maps showing subsistence harvest areas for important subsistence species, such as whales, seals, walrus, polar bears, waterfowl, fish, and invertebrates. Examples of maps for Kaktovik are shown in figures 3–18 and 3–19.

Ongoing work by USGS, in collaboration with BOEMRE's Alaska Region, is providing additional information and analysis on the human dimensions of fish use for subsistence communities bordering the Chukchi and Beaufort seas, including Canada. The following section is excerpted primarily from Thorsteinson and others (2011). In some cases, fish provides more of a dietary contribution than any other food source. In the Kotzebue Sound area, fully one-third to one-half of the total subsistence harvest by weight consists of fish (fig. 3–20). Although the inhabitants of the North Slope are often considered to depend much less on fishing and more on marine mammal hunting, significant harvests of fish are still made. The fact that fish comprise more than 10 percent of the total subsistence harvest of Barrow is remarkable, considering the number of bowhead whales harvested yearly at that location. Farther east at Nuiqsut, fish are the largest single contributors to the subsistence economy at nearly 40 percent of the total harvest.

Those areas less directly dependent on fish are mostly still reliant on them as a secondary resource in times of scarcity. Furthermore, fishing is an important family activity for much of the population not otherwise engaged in the hunting of sea mammals or caribou, including women, children, and elders. Previous research on Beaufort Sea and Chukchi Sea subsistence fisheries has to this point been limited in scope either geographically or chronologically: few studies have combined data for the U.S. and Canadian Arctic, and few include data from multiple years or otherwise longer-term perspectives than one or two season's worth of catches.

Ongoing USGS research (Thorsteinson and others, 2011) seeks to produce a synthetic, broad-view analysis of fishing in its larger regional, cultural, and temporal context. Multi-year catch reconstruction analyses have recently been published both for the Arctic coasts of Alaska and the Northwest Territories. This makes it possible to determine each community's "typical" local fishing tradition. Interviews with those currently or previously involved in fishing also provide an important contribution, particularly in the form of compilations of local traditional knowledge.

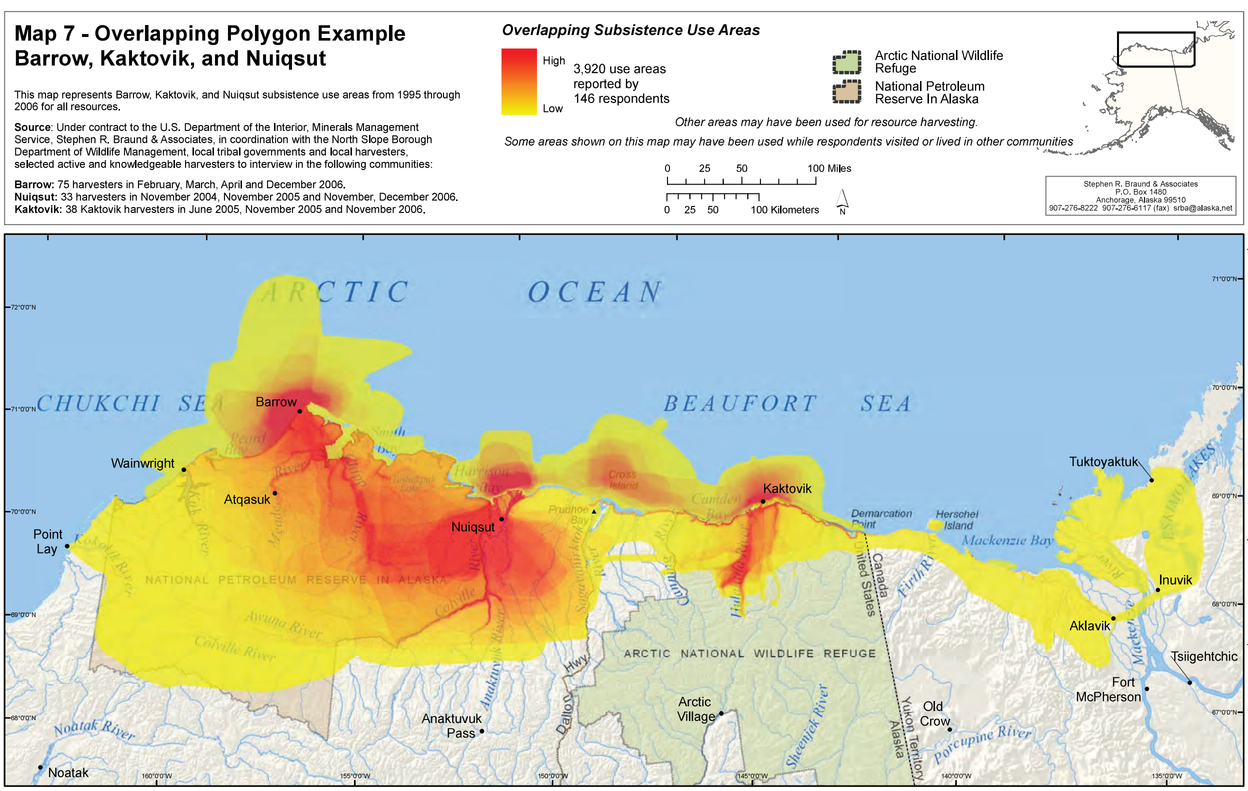


Figure 3–18. Overlapping subsistence use areas for Barrow, Kaktovik, and Nuiqsut. From S.R. Braund and Associates (2010a).

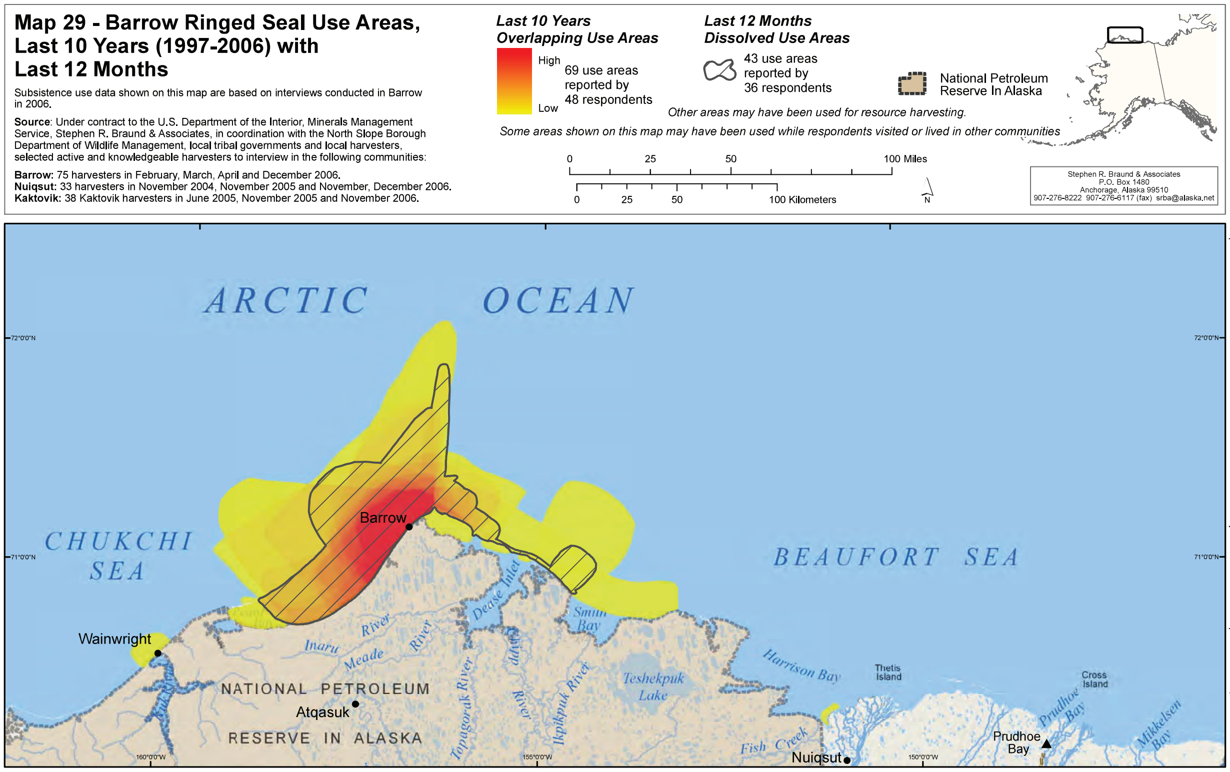


Figure 3–19. Subsistence use areas for ringed seals for the Barrow area. From S.R. Braund and Associates (2010a).

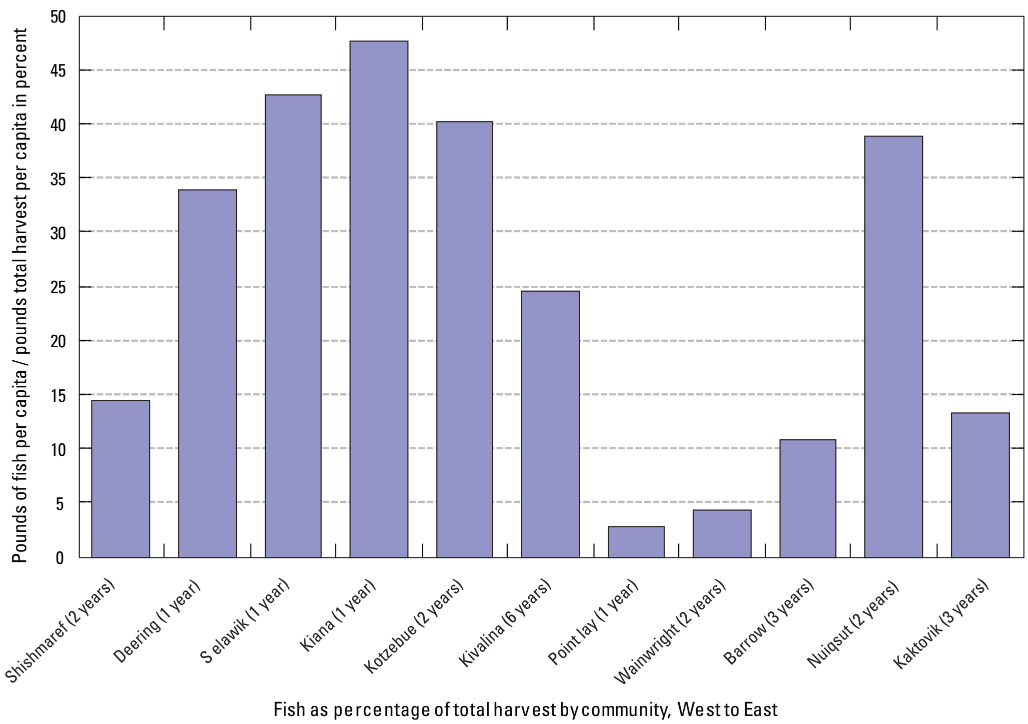
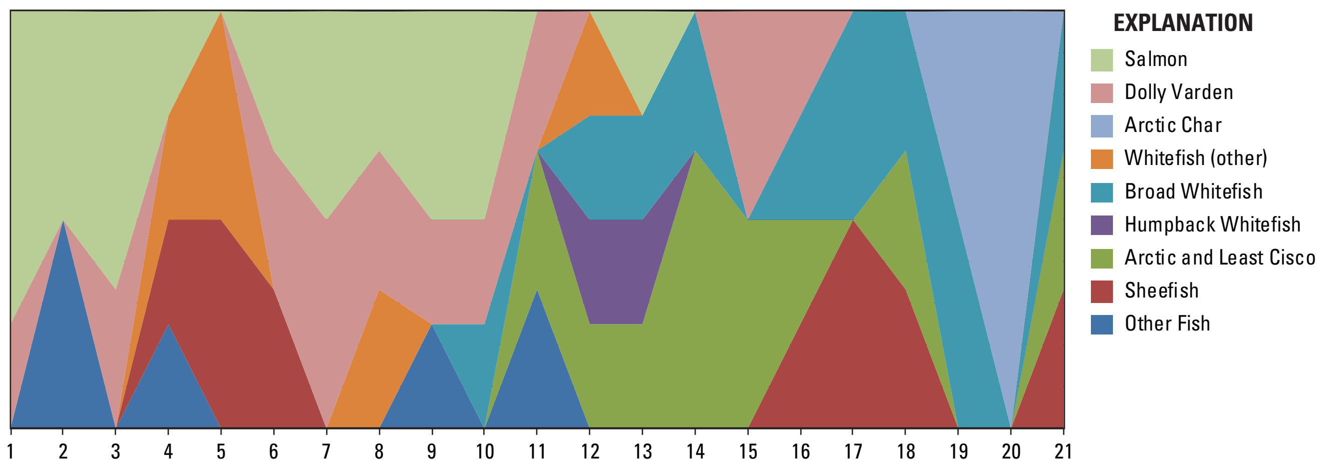
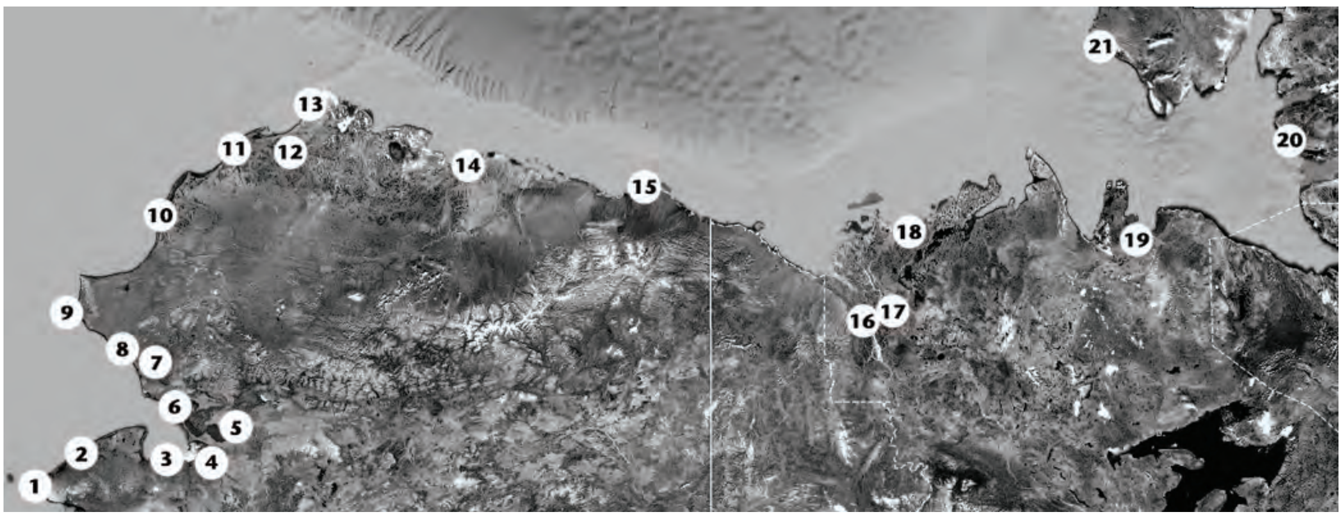


Figure 3–20. Fish as a percentage of total overall subsistence harvest by community, West to East. Based on harvest records of the Alaska Department of Fish and Game (2011), accessed April 18, 2011, at http://www.subsistence.adfg.state.ak.us/CSIS/.





Map No.	Community	Map No.	Community
1	Wales	12	Atqasuk
2	Shishmaref	13	Barrow
3	Deering	14	Nuiqsut
4	Buckland	15	Kaktovik
5	Selawik	16	Aklavik
6	Kotzebue	17	Inuvik
7	Noatak	18	Tuktoyaktuk
8	Kivalina	19	Paulatuk
9	Point Hope	20	Holman
10	Point Lay	21	Sachs Harbour
11	Wainwright		

Figure 3–21. Visualization of the major subsistence fish species for each numbered coastal community in the Beaufort and Chukchi Seas, including the Canadian Beaufort.

When the four most important marine and anadromous fish species for each community are visualized on a west-east axis (fig. 3–21), the relationship between geography and human fishing habits may be understood; specifically, the great variability in local fisheries becomes apparent both on the local and regional level. Now, as in the past, the vast majority of the total catch consists of species that are either anadromous (migrating from the ocean to rivers in order to spawn) or that are otherwise known to live in both fresh and salt water and to move between the two.

According to the Alaskan catch reconstruction study mentioned above, the total yearly subsistence harvest of fish from Wales to Kaktovik in 1950 was approximately the same as in 2006 (450–500 tons), with little deviation over several decades. In comparison, commercial harvests for the same area were extremely variable from year to year, with occasionally very large (about 3,000 tons) harvests in the 1970s and 1980s. Total commercial harvests have been declining since the late 1980s, unlike the comparatively stable subsistence harvest levels. Nearly the entire commercial harvest is from the southwestern Seward Peninsula/Kotzebue Sound region (fig. 3–21).

To put the harvest estimates in perspective, it is useful to compare them to the total weight of bowhead whales harvested by the same populations. In 2008, communities north of the Bering Strait harvested 32 bowhead whales. Using a standard individual weight of 23.4 tons from a sample with approximately the same average size, the total harvested whale biomass for that year may be estimated at 750 tons. Viewed in the light of the whale data, the estimated 1950–2006 yearly fish harvests amount to 60–70 percent of the total harvested whale biomass for that year.

Primary subsistence species. Salmon make a notable contribution to people's diets only as far north and east as Point Lay, although small numbers of all five salmon species are occasionally caught as far to the east as Amundsen Gulf. Generally speaking, the closer a community's proximity to the more temperate and productive Bering Sea, the greater the number of salmon species caught and the greater the contribution of salmon to the local population's diet. This corresponds directly to the distribution of spawning populations of various salmon species. Chum salmon (*Oncorhynchus keta*) have the widest range and are the type of salmon utilized to the greatest extent.

Dolly Varden trout (*Salvelinus malma*), another anadromous salmonid species, make a significant dietary contribution across a very large area. Communities from the Seward Peninsula east to Kaktovik rely heavily on this species. Reliance on this species by humans is heaviest from Kotzebue to Wainwright and in Kaktovik (this easternmost community being closest to the spawning populations of the Brooks Range rivers (Viavant, 2001). Dolly Varden are not normally found to the east of Kaktovik; communities to the east of the Babbage and Firth Rivers rely instead on a closely related species, Arctic char (*Salvelinus alpinus*).

Further north and east, a variety of whitefish and cisco species (genus Coregonus) gradually replace salmonids as the basis of the subsistence fishery. Sheefish (*Stenodus leucichthys*, also Inconnu), another coregonid species, are important in the area of the central Kotzebue Sound as well as in the Mackenzie Delta on the eastern North Slope.

3.08. Findings and Recommendations: Subsistence harvests are seasonally and regionally variable. Although general usage patterns are known, village surveys have been conducted intermittently. In some cases, the data are old enough and may no longer be representative of actual harvests.

Future work is needed to fully understand the environmental, ecological, and cultural context of Beaufort Sea and Chukchi Sea subsistence harvests. To predict or model with any degree of accuracy the future of Arctic subsistence, with or without the impact of hydrocarbon exploration and extraction, a greater understanding of the past and present will be necessary.

Because local patterns of resource exploitation are closely tailored to local environments and ecologies, they are potentially vulnerable to the effects of climate change and oil and gas development. The impact of climate change need not necessarily be harmful to human subsistence. A growing body of anecdotal evidence suggests that previously rare salmon species are appearing with greater frequency on the North Slope. New runs and greater numbers of salmon in the future could well provide the basis of new subsistence traditions. However, the unpredictable effects of climatic instability on fish and wildlife populations are not likely to be a net benefit to Arctic subsistence users in the near future.

Oil and gas exploration and development pose a potential hazard to native subsistence livelihoods. Anadromous fish, marine mammals, and marine birds are crucial to human subsistence across the study area and are potentially vulnerable to disturbance and (or) pollutants associated with exploration, drilling, and transportation. Many fish species (including those not directly sought after for human use) comprise a major portion of the diets of sea mammals and birds that in turn sustain human populations.

Subsistence users may be among the first to notice changes in abundance and distribution of fish and wildlife species as it relates to climate change, development, and other stressors. Local traditional knowledge should be more formally incorporated and integrated into resource assessments.

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Chapter 4

Climate Change Considerations

By Gary D. Clow, Anthony R. DeGange, Dirk V. Derksen, and Christian E. Zimmerman

Introduction

Owing to the high northerly latitude, climate conditions in the Beaufort and Chukchi Seas are relatively severe. Sea ice is present most of the year, temperatures average about -27°C during the sunless winter period but occasionally drop to -48°C, powerful storms move through the area from time to time, and 'white out' conditions are common due to blowing snow. Summer temperatures are much milder, but still are only a few degrees above freezing. Although the sun is above the horizon 24 hours a day during summer, low-level clouds and fog are very common once the sea ice begins to melt. Indigenous plants and animals are highly adapted to these extreme conditions, as is the local Iñupiat culture. The oil and gas industry has adapted as well, running on-shore seismic exploration lines during the winter when the fragile tundra is both frozen and covered with snow, and therefore more resilient to vehicle traffic. On-shore exploration drilling typically is done during the winter from ice pads constructed for this purpose, while the movement of heavy drilling equipment across the tundra is facilitated by the construction of ice roads.

It is well established that climate conditions in this region have recently been undergoing a remarkable change, particularly during the last 20 years (Arctic Council, 2005; Intergovernmental Panel on Climate Change, 2007). Environmental changes include warmer air and ocean temperatures, earlier spring snowmelt, a marked decrease in the extent and thickness of sea ice, accelerated coastal erosion, and permafrost degradation. These changes in the physical environment are impacting biological and human systems in a number of ways. Shrubs are increasing on the Arctic coastal plain, as well as various other habitat changes. The distribution of some animal species (for example, walrus and polar bear) are changing in response to the loss of sea ice during at least part of the year. Subsistence hunting has been impacted. And the number of days seismic exploration vehicles can operate on the tundra without causing environmental harm has decreased from 200 to 100 over the last 30 years (Arctic Council, 2005).

Climate projections for the next 50–100 years produced by global climate models consistently show a pronounced warming over the Arctic, accelerated sea-ice loss, and continued permafrost degradation (Intergovernmental Panel on Climate Change, 2007). Of all areas on Earth, the Arctic has the greatest sensitivity to changes in greenhouse gases, primarily due to the (snow/ice) albedo-temperature feedback. Within the Arctic itself, some of the largest changes are expected to occur in the Bering, Beaufort, and Chukchi Seas (Chapman and Walsh, 2007; Walsh, 2008). If realized, the projected climate changes will ultimately affect nearly every aspect of the Arctic environment. This is a major concern from a biological standpoint because the indigenous plants and animals are so highly adapted to the extreme conditions that have been the norm in the Arctic. The projected climate changes will undoubtedly stress these highly adapted biological systems. In this chapter, we: (1) examine those aspects of the projected mid-century climate changes relevant for oil and gas activities in the Beaufort and Chukchi Seas, and (2) examine how the projected climate changes may impact fish, birds, and marine mammals within the Arctic Outer Continental Shelf (OCS). The former is important for evaluating how future changes in climate may either mitigate or compound the effects of Arctic energy development (for example, see Chapter 5, Oil-Spill Risk, Response, and Impact), while the latter is needed to assess the cumulative impacts on the environment of climate change, oil and gas activities, and other factors (see Chapter 7, Cumulative Impacts). Future climate change will, to some degree, affect the environment in which Arctic OCS exploration and development activities occur, the infrastructure needed to support those activities, day-to-day operations including ship and aircraft logistics, factors that make oil spills more-or-less likely to occur, and the difficulty-or-ease of responding to those spills. Because of rapid climate-related changes projected to occur in the Arctic OCS, management agencies will need to manage adaptively, supported by long-term research and monitoring programs to effectively evaluate management practices.

Available Information. The primary source of information about future climate conditions in the Arctic is the suite of projections provided by fully coupled atmosphere-ocean global climate models (AOGCMs) driven by different greenhouse-gas emission scenarios. Secondary sources include downscaled[1] AOGCM projections, physical understanding of the processes governing regional climate processes, and recently observed climate changes. Results from the most recent set of AOGCM future climate simulations were summarized in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4 2007; Intergovernmental Panel on Climate Change, 2007). This assessment, which synthesized the results from thousands of scientific papers on climate change, included climate projections from 21 AOGCMs from around the World. Climate projections for the Arctic were earlier summarized in the Arctic Climate Impact Assessment (Arctic Council, 2005), although these results were based on a small subset (five) of the previous generation of AOGCMs reported in the Third IPCC Assessment (Intergovernmental Panel on Climate Change, 2001). These models had coarser resolution and tended to have larger biases. Chapman and Walsh (2007) and Walsh (2008) synthesized the results from 14 of the recent IPCC AR4 AOGCMs, focusing specifically on the Arctic. Although the projected values for most climate variables have not changed much since the release of the IPCC AR4 in 2007, the magnitude of sea-level rise during this century is an exception. Most in the scientific community now view the AR4's estimate of sea-level rise to be far too low. The uncertainties of the AR4 projected sea-ice extent during this century also were enormous. Significant work has been done to reduce these uncertainties since the release of the IPCC AR4. For these variables, we rely on more recent estimates reported in the scientific literature. The next IPCC Assessment (AR5) is scheduled to be released in June 2013. Substantial improvements in our current understanding of future climate conditions in the Arctic are not expected before this time. Lacking synthesis documents, information about projected changes to important biological systems within the Arctic OCS are found in individual reports in the scientific literature.

Key documents:

Arctic Climate Impact Assessment, 2005 (Arctic Council, 2005).

Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4), 2007.

Arctic Ocean Synthesis: Analysis of Climate Change Impacts in the Chukchi and Beaufort Seas with Strategies for Future Research, 2008 (Hopcroft and others, 2008).

Arctic Sea Ice Decline: Projected Changes in Timing and Extent of Sea Ice in the Bering and Chukchi Seas, 2010 (Douglas, 2010).

Future Climate Changes and Impacts, the Next 50 Years

Physical Environment

Model Validation. The degree to which we can have confidence in the future climate projections for the Arctic depends to a large extent on how well the models replicate the current climate in this region. For the AR4 AOGCMs, each of the models were used to simulate Arctic climate conditions during 1981–2000; the values and spatial pattern of climate variables were then compared with observations (Chapman and Walsh, 2007). Each of the models also were subject to tests to see how well they replicate the observed seasonal cycle during 1958–2000, both for Alaska and for the entire Arctic (Walsh and others, 2008). Given the tremendous variation of solar radiation between summer and winter at high northern latitudes, this test exercises the models over a much larger range of forcing conditions than that associated with the projected greenhouse gas emissions during the 21st century. To provide a better sense of the uncertainties in the projections, the results of these tests are discussed below for those climate variables for which they are available.

[1]Various techniques can be used to 'downscale' the coarse global AOGCM projections to much higher spatial resolutions. These methods can overcome some of the limitations in the coarse-scale global models as long as the large-scale atmospheric circulation produced by the AOGCMs does not contain significant errors or biases.

Across-Model Scatter and Ensemble Averages. In numerical weather prediction and climate modeling, the average of a suite of models generally out-performs (is more accurate than) any individual model. This is because errors in the models tend to cancel out in the averaging process. Hence, the 'ensemble-average' is often given as the best estimate of future climate conditions. The range of results among the suite of models (across-model scatter) also provides valuable information. A large range of model results for a climate variable tells us the results are fairly uncertain, due to the different ways the models are attempting to represent critical processes, or for a number of other reasons. A small range of model results gives us some confidence that the result is robust.

Emission Scenarios. Projections of future climate change depend a great deal on future human activities. Given the enormous uncertainty of these activities, a set of 'emission scenarios' have been developed that hopefully bracket the path humans actually take during the 21st century. Each scenario makes different assumptions about the rates of technological and economic development, population growth, land-use changes, and thus of future greenhouse gas emissions and the amount of atmospheric particulates (for example, sulfate aerosols). Details about the scenarios are described in the Special Report on Emissions Scenarios (SRES, Nakićenović and others, 2000). Some scenarios (for example, SRES B1) are intended to represent the emissions from a globalized World with an environmental focus that emphasizes sustainability, while others (for example, SRES A2) represent a highly regionalized World in which each region independently pursues rapid economic development. Of the 40 scenarios originally developed for the SRES, six commonly are used as 'marker' scenarios for future climate experiments. The AOGCMs used to project future climate conditions require vast amounts of computer resources. Given the constraints on these resources, the Intergovernmental Panel on Climate Change (IPCC) decided to select a subset of three of these marker scenarios for the future climate experiments reported in its Fourth Assessment Report (AR4). From an emissions perspective, they can be viewed as 'low' (B1), 'medium' (A1B), and 'high' (A2) emission scenarios. The IPCC working group (WG1) responsible for the future climate simulations clearly stated that their selection of these three scenarios was not meant to imply that they are in some way preferable or more likely than any of the others. The rate at which carbon dioxide (CO_2) is being added to the atmosphere is currently higher than any of the three AR4 emission scenarios (Le Quéré and others, 2009).

SRES Emissions Scenarios Used for the AR4 Future Climate Projections:

B1	'low' emission rates
A1B	'medium' emission rates
A2	'high' emission rates

Uncertainties in Future Climate Projections. For Arctic OCS decision making, it is important to recognize the scientific gaps and sources of uncertainty in the future climate projections for the Beaufort and Chukchi Seas. These include:

1. Several aspects of the Arctic climate system that are known to be extremely important are not particularly well represented in the current generation of models. These include clouds (especially low-level clouds) and sea ice.
2. Our understanding of the Arctic climate system is still incomplete due to the complex nature of the atmosphere-land-cryosphere-ocean-ecosystem interactions that occur there, making it difficult to build models that are capable of accurately simulating all these interactions.
3. The climate of the Arctic has a high degree of natural variability compared to the rest of the Earth. This reduces our ability somewhat to predict how climate is likely to change in the Arctic over the next few decades.
4. Future changes of greenhouse-gas concentrations and other forcing agents (for example, sulfate aerosols and atmospheric dust) on which the model projections rely are uncertain.

The international science community is continually working to fill scientific gaps and reduce uncertainties. Steady progress is being made, although given the complexity of the problems, the time frame for significant advances to occur is on the order of 5–10 years. Despite these gaps and uncertainties, the current generation of models is able to replicate many aspects of the Arctic climate system fairly well as discussed next in this chapter.

Atmosphere

Surface Air Temperature. Results from model validation tests show that the 14-member AR4 AOGCM ensemble used for Arctic climate projections (Chapman and Walsh, 2007; Walsh, 2008; Walsh and others, 2008) is able to simulate the magnitude and spatial pattern of surface air temperature in the Arctic quite well for each of the four seasons. The magnitude and spatial pattern of inter-annual variability during the test period (1981–2000) are well simulated, as is the seasonal cycle. Through roughly 2070, the range of results among the models (across-model scatter) is roughly comparable to the range associated with our future emissions pathway (across-scenario scatter). After 2070, the across-scenario scatter dominates. Considering both the across-model and across-scenario scatter, the total range of projected mean annual surface air temperatures for the entire Arctic north of 60°N ranges from +1.0°C to +4.5°C by 2050. Although the range is large, none of the models project a decrease in temperature in the Beaufort and Chukchi Seas by mid-century for any season for any of the emission scenarios.

As discussed above, the best estimate of projected climate conditions is provided by the ensemble average. As with the individual models, the 14-member ensemble average shows a pronounced warming in the Arctic during the cold seasons, particularly during autumn and winter (fig. 4–1). Within the Arctic, the regions projected to experience the greatest warming are the Chukchi and Beaufort Seas due to the influx of warmer Pacific water through the Bering Strait, extensive sea-ice retreat during the summer, delayed freeze-up in the autumn, and thinner sea ice during the winter. For the A1B ('medium') emission scenario, the ensemble-mean surface-air warming in the Chukchi and Beaufort Seas is roughly 5°C during autumn by mid-century (2040–2059), while the projected winter warming is slightly higher (6°C). In contrast, the projected summer warming is only about 1°C in this region by mid-century (A1B scenario) because any additional energy in the climate system during the summer is used to melt ice rather than warm temperatures. The spatial and seasonal patterns of warming are very similar for the other emission scenarios, although the magnitude of the changes are smaller and larger for the B1 and A2 emission scenarios, respectively. There is a tendency for the models that performed best (smallest errors) during Arctic validation tests to project the greatest warming in this region. Thus, the magnitude of the mid-century warming for the Beaufort and Chukchi Seas (stated above) based on ensemble averages is conservative, especially for the cold seasons.

Sea-Level Pressure. The distribution of atmospheric sea-level pressure (SLP) provides important insights into atmospheric circulation, storm tracks, precipitation patterns, and near-surface winds. As at mid-latitudes, the pressure field in the Arctic displays much more spatial variability during the winter than during the summer, reflecting more intense atmospheric circulation during the cold season. Results from model validation tests show that the 14-member AR4 AOGCMs used to study the Arctic (Chapman and Walsh, 2007; Walsh, 2008; Walsh and others, 2008) capture the seasonal SLP patterns in the Arctic fairly well, although not as well as for surface air temperature. Compared to the observations, the prevalent anticyclone in atmospheric circulation over the Arctic Ocean (the Beaufort Sea High) is broadened and shifted northwards in the model simulations. SLP biases may partly result from distortions to the Arctic atmospheric circulation caused by the Greenland Ice Sheet, something that is not well represented in the current generation of AOGCMs. There also is a great diversity of model responses regarding the Aleutian Low related to their present inability to adequately represent the competing effects of the El Niño-Southern Oscillation and North American mesoscale model variability patterns. Although SLP biases still exist, the biases are much smaller than they were for the previous generation of models in both the North Pacific and downstream of the Greenland Ice Sheet. Thus, the ability of the AOGCMs to accurately simulate SLP in the Arctic is steadily improving.

One of the most striking results from the future climate projections for the Arctic is the significant decrease in winter SLP centered over the Bering, Beaufort, and Chukchi Seas (fig. 4–2). This is a robust result shown by nearly all the models. Among the 14-member AR4 AOGCM suite, the best-performing models during model validation tests project the greatest SLP decrease in this region. This SLP depression likely is related to the decrease of sea ice in the Bering, Beaufort, and Chukchi Seas and the consequential shift in the surface-temperature pattern (Chapman and Walsh, 2007; Walsh, 2008). Smaller SLP decreases are projected to occur during the other seasons as well, with autumn again showing a significant decrease over the Bering, Beaufort, and Chukchi Seas similar to the winter pattern, but with about one-half the pressure decrease. The projected SLP decrease over the Arctic is associated with a poleward expansion of the planet's Hadley Circulation by mid-century, which will move storm tracks farther north by several degrees.

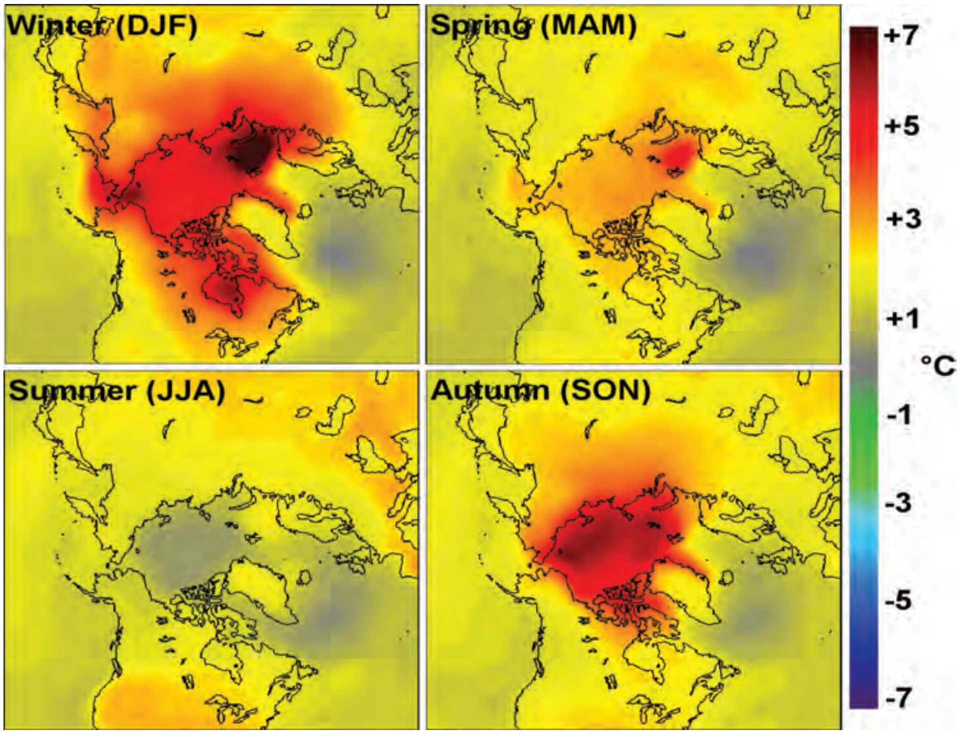

Figure 4–1. Projected changes in surface air temperature for 2040–2059, relative to 1981–2000, based on the SRES A1B emission scenario. Maps show the ensemble average for each season. (From Walsh, 2008.) (DJF, December-January-February; MAM, March-April-May; JJA, June-July-August; SON, September-October-November.)

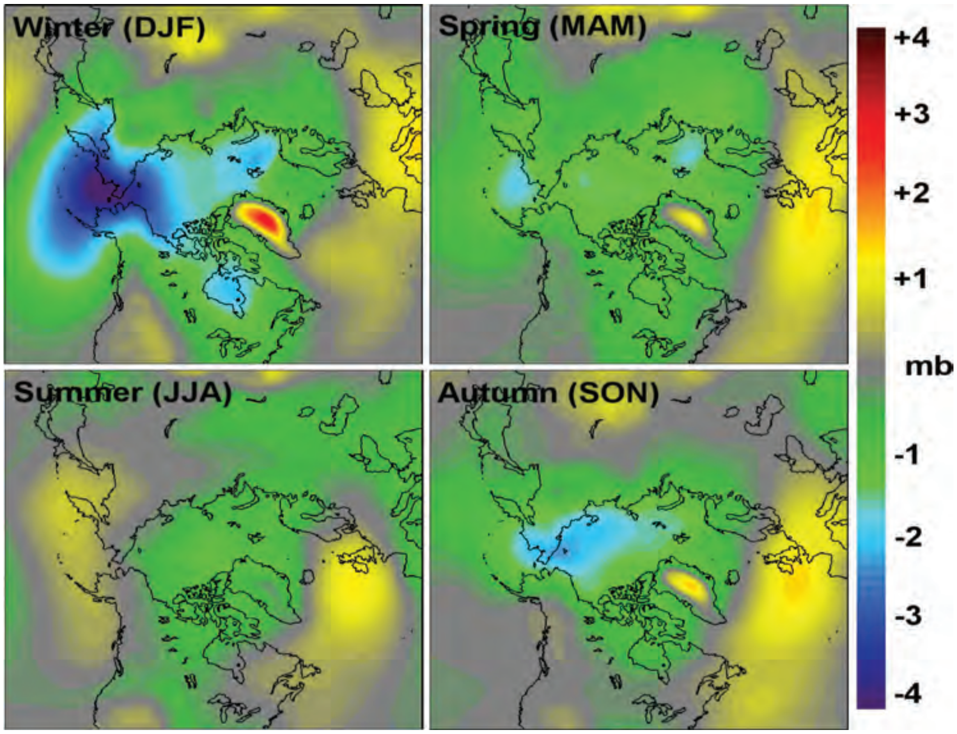

Figure 4–2. Projected changes in sea-level pressure for 2040–2059, relative to 1981–2000, based on the SRES A1B emission scenario. Maps show the ensemble average for each season. (From Walsh, 2008.) (DJF, December-January-February; MAM, March-April-May; JJA, June-July-August; SON, September-October-November.)

Storms and Winds. The pronounced changes in SLP projected to occur in the Bering, Beaufort, and Chukchi Seas during autumn and winter are expected to impact storm tracks and surface winds, although exactly what those changes are is not entirely clear. We will first discuss winds associated with the average SLP patterns for each season. Although the winds rapidly change on a daily basis due to passing weather systems, there are some patterns that consistently reappear. These persistent wind patterns largely drive the mean near-surface ocean currents and the movement of sea ice. Under current climate conditions, the primary SLP features that consistently appear in the Pacific sector of the Arctic during winter are the Aleutian Low and a ‘bridge’ of high pressure that extends between northwestern Canada and Eurasia. During spring, high pressure over Canada and Eurasia diminishes as the continents warm up, leaving a closed high-pressure cell (anticyclone) over the western Arctic Ocean known as the Beaufort Sea High (BSH), while the Aleutian Low exists in a somewhat diminished form. The SLP field is relatively featureless during the summer. During autumn, the BSH and Aleutian Low reform, producing an SLP field similar to spring. High winds (> 15 m/s) often occur in the Beaufort and Chukchi Seas in conjunction with the BSH during the transition seasons (spring and autumn), and with the analogous high-pressure bridge during winter. By mid-century, the western half of the Beaufort Sea High is expected to weaken during autumn as it is difficult to establish high pressure over the relatively warm water of the ice-free Chukchi Sea. With a contracted (and displaced) BSH, autumn winds associated with the mean SLP pattern may be more of a southerly nature in the Chukchi Sea (that is, from the Bering Strait) than at present, while winds in the Beaufort Sea will remain primarily easterly over the shelf. During winter, the Aleutian Low is projected to migrate northward, as is the high pressure bridge between Canada and Eurasia. Migration of the bridge may again be linked to the difficulty of establishing high pressure over areas of decreased sea ice as the ice edge is projected to be farther north at this time of year than at present (2011). The net effect is to move the boundary between the Aleutian Low and the high-pressure bridge from a location approximately over the Bering Strait to a new location over the Chukchi Sea by about mid-century. This situation may strengthen the predominantly easterly winds in the Beaufort and Chukchi Seas associated with the mean winter SLP pattern. Although SLP is projected to decrease slightly during spring and summer, the decrease is spatially uniform across the region so no significant change is anticipated for the mean SLP winds during spring or summer. These seasonal wind projections are somewhat uncertain because they rely on the projected SLP patterns, which are somewhat uncertain as previously discussed. Still, the seasonal wind projections in the Chukchi and Beaufort Seas make sense on purely physical grounds, given the decrease of sea ice there. The magnitude of the changes is currently unknown.

The pronounced SLP decrease in the Bering, Beaufort, and Chukchi Seas during winter, and to a lesser extent autumn, *may* suggest an increase in storm activity in this region during autumn and winter. However, the bulk of the SLP decrease also could be due to warmer air temperatures associated with the decrease of sea ice or other factors. Nevertheless, several arguments can be made suggesting that it will be stormier during autumn and winter.

1. As the Aleutian Low is an expression of the dominant cold-season storm track, and the Aleutian Low is projected to migrate northward, a greater percentage of storms originating in the North Pacific are expected to follow a more northerly track through the Bering Sea into the west coast of Alaska by mid-century rather than crossing the Aleutian Islands into the Gulf of Alaska (Chapman and Walsh, 2007). Although relatively few North Pacific storms currently penetrate into the Chukchi and Beaufort Seas through the Bering Strait, this likely will be a more common occurrence in the future, especially during winter.

2. With the projected decrease of sea ice in the Chukchi and Beaufort Seas, more heat and moisture will be available to power storms in this region during autumn. This in itself is expected to increase the frequency and intensity of storms.

3. The strong temperature contrast at the autumn sea-ice edge, which is projected to persist longer in the Beaufort and Chukchi Seas by mid-century, is likely to favor the formation and intensification of Arctic cyclones (Serreze and Barry, 2005).

4. Polar Lows (fig. 4–3) are intense maritime mesocyclones that develop when cold continental air is advected over relatively warm water. With the projected decrease of sea ice in the Chukchi and Beaufort Seas, Polar Lows are expected to occur more frequently in the future as cold Siberian air moves over open water in the Chukchi Sea during autumn. Thus, Polar Lows are expected to occur more frequently during autumn in the future.

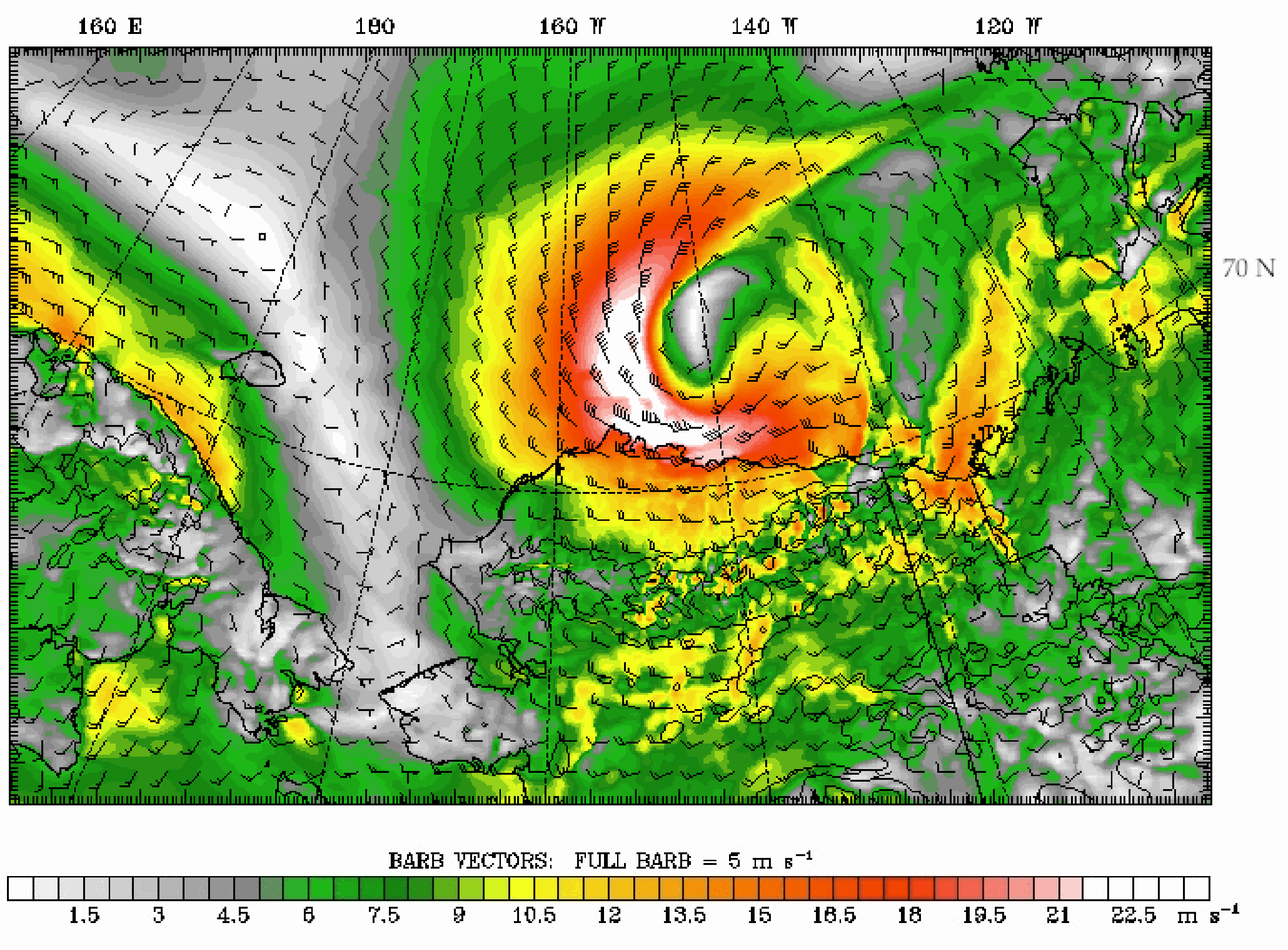

Figure 4–3. Wind field for a Polar Low passing eastward through the Chukchi and Beaufort Seas during August 2000. Storms such as these can present a significant hazard to activities on the Arctic OCS. Barb vectors indicate wind speed. A full barb equals 5 meters per second.

One observation in support of an increased frequency of autumn and winter storms by mid-century is that today cyclones are twice as likely to occur in the Beaufort and Chukchi Seas during summer and autumn as they are during winter or spring (Serreze and Barry, 2005). By mid-century, today's autumn conditions are projected to occur in early winter. None of these ideas have been as of yet rigorously tested through numerical experiments or other means. Thus, an increase in the frequency and (or) intensity of autumn and winter storms in the Beaufort and Chukchi Seas, although likely based on physical arguments, remains uncertain. In addition, the magnitude of any such changes is unknown. Projected changes in the degree of summer storminess are highly uncertain as arguments can be made for both increases and decreases in summer storm activity.

Clouds. The Arctic marine environment is one of the cloudier places on Earth. Clouds affect Arctic ecosystems by modulating the amount of sunlight available for plant photosynthesis in marine and terrestrial environments. Once sea-ice melting begins in the spring, the fraction of the Arctic Ocean covered by low-level clouds and fog rapidly increases from 20 to more than 65 percent. These low clouds can drastically reduce visibility, affecting ship and aircraft operations. Upon the formation of new sea ice in the autumn, the fraction of low-level clouds over the Arctic Ocean gradually diminishes back to about 20 percent. AOGCMs consistently project that the Arctic will become cloudier by mid-century. Much of this increase is projected to occur near the tropopause in the form of high-level clouds (consistent across models). A smaller increase also is projected to occur near the surface as low-level clouds, although deficiencies in the AOGCMs regarding boundary-layer processes and low-level clouds make this AOGCM result less certain. However, because the models project warmer temperatures during summer and autumn, there will be a decrease in the number of ice nuclei available to scavenge moisture out of the air during these seasons. Thus, on purely physical grounds, low-level clouds are expected to be more prevalent in the Beaufort and Chukchi Seas during the open-water season. In addition, low-level clouds are expected to occur over a greater fraction of the year in the Beaufort and Chukchi Seas as the frequency of low-level clouds in the Arctic maritime environment is highly correlated with the availability of open water.

Precipitation. Precipitation is an important freshwater input to the Arctic Ocean that helps reduce the salinity of the surface waters (upper 50–200 m), and thus is of critical importance to marine ecosystems as well as assisting with the formation and persistence of sea ice. Model validation tests of the 14-member AOGCM suite used for Arctic climate simulations show that the models are able to simulate the overall seasonal cycle in the Arctic. The spatial pattern of precipitation biases is more complex than for either temperature or SLP with strong biases occurring in the vicinity of major mountain ranges. Precipitation biases in the individual models and the ensemble average are relatively small in the Beaufort and Chukchi Seas. Projections of precipitation by AOGCMs generally are less reliable than for air temperature or SLP. Nearly all the AOGCMs project a significant increase in precipitation in the Arctic by mid-century, although the magnitude and spatial pattern of those increases vary considerably among the models. The intensity of precipitation events also is projected to increase, as is the number of wet days (that is, days when precipitation occurs). Nearly all of the precipitation increase is attributable to the fact that warmer air can hold more moisture which is then available for precipitation, and very little is due to changes in atmospheric circulation (Higgins and Cassano, 2010). By mid-century, the projected ensemble-average precipitation increase in the Beaufort and Chukchi Seas is roughly 25 percent during winter, and 15 percent during summer (A1B emissions scenario). During Arctic validation tests, there was a tendency for the best performing AOGCMs (smallest errors) to project the largest precipitation increases. Thus, the magnitude of the mid-century precipitation increase given by the ensemble average may be conservative.

Ocean

Sea Ice. The distribution, thickness, and seasonality of sea ice are fundamental in shaping the physical environment of the Beaufort and Chukchi Seas. The presence or absence of sea ice strongly affects regional temperatures; SLP and hence atmospheric circulation; the availability of moisture for clouds, precipitation, and icing conditions; and the development of Arctic mesocyclones, including Polar Lows. In addition, sea ice is intimately connected with the biological communities of the Arctic marine environment, including shielding organisms from the coldest wintertime temperatures, serving as a breeding and feeding platform for marine mammals, and modulating the amount of sunlight available for photosynthesis by phytoplankton. Sea ice undergoes a strong seasonal cycle, completely covering the Arctic Ocean during the winter and spring, while extensive melting during the summer generally leaves the periphery of the Arctic Ocean ice-free adjacent to Alaska and Siberia by September (the month of minimum sea-ice extent). One of the primary drivers for the transport of sea ice out of the Arctic Basin into the North Atlantic is the clockwise pattern of winds associated with the Beaufort Sea High.

One of the most dramatic changes in the Arctic during the last few decades has been the significant decrease of sea ice during the summer; the September sea-ice extent decreased almost 25 percent between 1976 and 2006, leaving the Beaufort and Chukchi Seas essentially ice-free during September to well above 75°N in recent years. Given the projections of significant warming in the Arctic during this century, a concern that naturally arises is whether the Arctic Ocean will become largely ice-free during the summer in the not too distant future. Nearly all AR4 AOGCMs that could be used to address this question underestimate the observed decrease in sea ice during recent years. There are significant doubts about the models' abilities to project future trends in sea ice. The enormous range of sea-ice projections among all AOCGMs through the end of the century only adds to these doubts. Several studies have been done since the release of the IPCC AR4 to look at this issue. Wang and Overland (2009) concluded that the late-summer Arctic Ocean may become nearly ice-free in September by 2037 based on the A1B and A2 emissions scenarios, essentially confirming an earlier result (Holland and others, 2006) that it could become ice-free by 2040. More recently, Zhang (2010) also found that the Arctic could become ice-free by the late 2030s while Boè and others (2009) concluded that 2066–2085 is the first 20-year period when the Arctic is likely to be ice-free in September. As with temperature, SLP, and precipitation, the later study found that the AOGCMs that are best at simulating the observed sea-ice extent over the last 30 years have the highest sensitivity to greenhouse gas emissions and hence project the earliest ice-free summers in the Arctic. Focusing on the Bering and Chukchi Seas, Douglas (2010) found that sea ice typically retreats northward through the Bering Strait in June and that this is unlikely to change much through mid-century. Thus, June is a hinge-point in the annual sea-ice cycle that is linked to the annual cycle of solar radiation. Following June, sea-ice melting is projected to be more rapid and extensive, leaving the shelves of the Chukchi and Beaufort Seas largely ice-free during August–October by mid-century. Substantial amounts of ice are not projected to reappear on the shelves of the Chukchi and Beaufort Seas until November, followed by the advance of the ice edge through the Bering Strait in December. Thus, complete freeze-up of the Chukchi and Beaufort Seas is expected to be delayed about 1 month by mid-century (Douglas, 2010). Again, the exact timing of these events is uncertain due to the inherent uncertainty of the sea-ice projections. Based on the median ice coverage from 14 AOGCMs used in the IPCC AR4, the number of open-water days in the Beaufort and Chukchi Seas is projected to increase by 50–75 by mid-century (Walsh, 2008). Finally, it is important to stress that the projected decrease of sea ice is a seasonal phenomena. Sea ice will still be present in the Beaufort and Chukchi Seas for most of the year. In addition, for those months when it is present, the ice pack will be thinner and therefore more dynamic than it historically has been.

Sea Level. Recent research shows that erosion rates for coastal bluffs consisting of ice-rich permafrost are very sensitive to changes in water level on the Beaufort Sea during the summer and autumn. When near-coastal water levels rise in response to wind stress, erosion rates go up dramatically as lower portions of the bluffs are immersed in relatively warm water. Conversely, when winds drive the water off-shore lowering water levels, erosion rates are very low. Given this observation, rising sea levels have the potential to greatly accelerate coastal erosion rates. Barrier islands also will be strongly affected by rising sea levels. In the IPCC AR4 report, global sea levels are projected to rise 0.18–0.6 m by the end of this century. However, sea-level rise is not expected to be uniform and there is substantial spatial variability among the models. The Arctic Ocean is projected to experience the greatest sea-level rise on the planet due to a combination of thermal expansion, which is projected to be greater here than elsewhere, and a decrease of salinity related to increased precipitation at high northern latitudes. The Bering and Beaufort Seas are one of the few areas on Earth where the projected sea-level rise exceeds the inter-model range.

Following the release of the AR4 report in 2007, the consensus of the science community was that the AR4 sea-level rise projections are much too low. At the time of the AR4 report, the dynamics of the large ice sheets in Greenland and Antarctica were too poorly understood to make reliable model estimates. Hence, the dynamics of the large ice sheets were not included in the AR4 sea-level projections. Subsequent work has placed some constraints on this very important effect. Using a semi-empirical approach that analyzed how sea level has varied in the past in response to global temperature change, Vermeer and Rahmstorf (2009) estimate global sea-level rise to be in the range 0.75–1.9 m by 2100 for the six SRES marker emissions scenarios, or about three times the AR4 projections. The comparable mid-century sea-level rise is estimated to be 0.3–0.5 m. Using a very different kinematic approach to establish realistic constraints on the dynamic response of the large sheets (that is, there are limits to how fast ice in an ice sheet can move to the coast and then out to sea), Pfeffer and others (2008) find that the upper limit for sea-level rise by 2100 is about 2 m, close to Vermeer and Rahmstorf's (2009) upper limit. Using more realistic values for glaciological parameters, Pfeffer and others (2008) estimate a more plausible total sea-level rise to be about 0.8 m by 2100 (about 0.35 m by mid-century), close to Vermeer and Rahmstorf's (2009) lower limit. In summary, once the dynamics of the large ice sheets are considered, the best current estimates for mid-century global sea-level rise are in the range of 0.3–0.4 m. This range should be treated as a lower bound for the Beaufort and Chukchi Seas as sea level is expected to rise faster in the Arctic Ocean than elsewhere.

Acidification. About one-third of the anthropogenic CO_2 released into the atmosphere is absorbed by the oceans, making them more acidic and thereby lowering the concentration of carbonate ions. These ions are required by a number of marine organisms, such as plankton and shellfish, in order for them to make the calcium carbonate needed for their shells and skeletons. Once the concentration of carbonate ions becomes low enough, calcium carbonate begins to dissolve and the waters become corrosive to calcifying organisms. Because cold water can absorb more CO_2 than warm water, and the saturation point for calcium carbonate occurs at a lower threshold in relatively fresh water than in saline water, the Arctic Ocean is expected to reach the point of calcium carbonate dissolution sooner than the other oceans as atmospheric CO_2 concentrations rise. Recent simulations using global ocean models suggest that the surface waters of the Arctic Ocean will become undersaturated with respect to calcium carbonate, and therefore corrosive, within a decade (Steinacher and others, 2009). Recent observations show that the surface waters of the Canada Basin (Beaufort Sea) have already reached this point, at least during the summer when the surface waters are freshened by extensive sea-ice melting (Yamamoto-Kawai and others, 2009). This is the first deep ocean basin where the projected corrosive conditions for calcifying organisms have been observed. There are significant concerns about the impact of acidification on marine organisms and marine ecosystems in the Arctic. Although the biological response to acidification will likely vary across species and life stages, both benthic and planktonic calcifying organisms are expected to be impacted. As both types of organisms are important elements of the Arctic food web, Arctic marine ecosystems are likely to be disrupted (Orr and others, 2005; Yamamoto-Kawai and others, 2009). For the ‘low’ emissions B1 scenario, more than 50 percent of the Arctic surface waters are projected to become corrosive to calcifying organisms by the end of the century, while for the A2 ‘high’ emissions scenario, 100 percent of the surface waters will become corrosive.

Circulation. Water from the Pacific Ocean flowing through the Bering Strait has a tremendous influence on the characteristics of the Chukchi Shelf, and to a lesser extent on the Beaufort Shelf (Hopcroft and others, 2008). The heat flux associated with the Bering Strait inflow is large, comparable to the solar input to the Chukchi Sea. This heat pre-conditions ice in the Chukchi Sea for solar-driven melt in early summer and delays the freeze-up in autumn (Woodgate and others, 2010). The Pacific inflow is the single largest source of freshwater to the Arctic Ocean, providing almost 50 percent of the total freshwater input. The nutrient-rich Pacific waters sustain an exceptionally high productivity in the southern Chukchi Sea, making it a unique ecological region within the Arctic. The force driving the northward flow through the Bering Strait is thought to be the pressure-head difference between the Pacific and Arctic Oceans. This is opposed by the prevailing northeasterly winds. Significant variations in both the Pacific-Arctic pressure-head difference and the prevailing winds lead to considerable variation in the northerly flow of Pacific water through the Bering Strait. On the Beaufort Shelf, the prevailing easterly winds drive the shelf waters (and the ice pack when present) to the west, although the details of the circulation structure are poorly understood. Strong wind-driven upwelling at the shelfbreak can occur once the ice edge moves seaward of the shelfbreak. This probably is a critical process for supplying nutrients to the Beaufort Shelf. Given the projected changes in temperature, SLP, precipitation (and hence salinity), and sea ice, the dynamics and circulation patterns of the Arctic Ocean and Bering Strait inflow likely will change during this century. However, little work has been done as of yet to predict the details of those changes. Development of Arctic Ocean models is currently an area of active research (Arctic Ocean Model Intercomparison Project).

Coastal Zone

The coastal zone consists of an assemblage of habitats important for many Arctic species. In addition, much of the infrastructure (for example, pipelines, storage tanks) needed to support oil and gas activities in the Beaufort and Chukchi Seas will necessarily cross the coastal zone or be located within the coastal zone. The coast of the Beaufort Sea is particularly vulnerable to climate change impacts while the coast of the Chukchi Sea appears to be less so.

1. Much of the Beaufort coast is less than 1–2 m above current sea level. Thus, portions of this coast are expected to be inundated by mid-century given the projections of sea-level rise.

2. Combined with the low topography, large storm surges that occasionally happen in this region have the potential to do substantial damage to the Beaufort coast and structures built on it, as well as to the offshore barrier islands. For example, a major storm during September 1970 carried driftwood logs 1.5–3.4 m above normal sea level, and up to 5 km inland along portions of the Beaufort coast (Reimnitz and Maurer, 1979). Storm surges during autumn carrying blocks of pack ice can do substantial damage as they pound the barrier islands and the coast. Although storms with the intensity of the September 1970 storm are rare, they may become more common during autumn in the future (see Atmospheric section). Given the projected sea-level rise, storm surges also will penetrate farther inland by mid-century.

3. In areas of ice-rich permafrost (that is, most of the Beaufort Sea coast), coastal erosion rates are expected to accelerate (fig. 4–4) due to a number of factors. First, sea ice which normally protects the coast from erosion during the cold seasons will be present less of the year, allowing wind-generated waves to impact the coastal bluffs for a greater amount of time each year. Second, with the projected Arctic warming, permafrost will be mechanically weaker during the summer and autumn than at present and thus more susceptible to erosion. Third, with the projected sea-level rise, the lower portions of the coastal bluffs will be immersed in relatively warm water a greater fraction of the time, a situation that enhances erosion rates. Fourth, based on physical factors, the frequency and (or) intensity of Polar Lows and other autumn storms likely will increase. If this does occur, the mechanical energy delivered by waves from these storms will further accelerate coastal erosion rates.

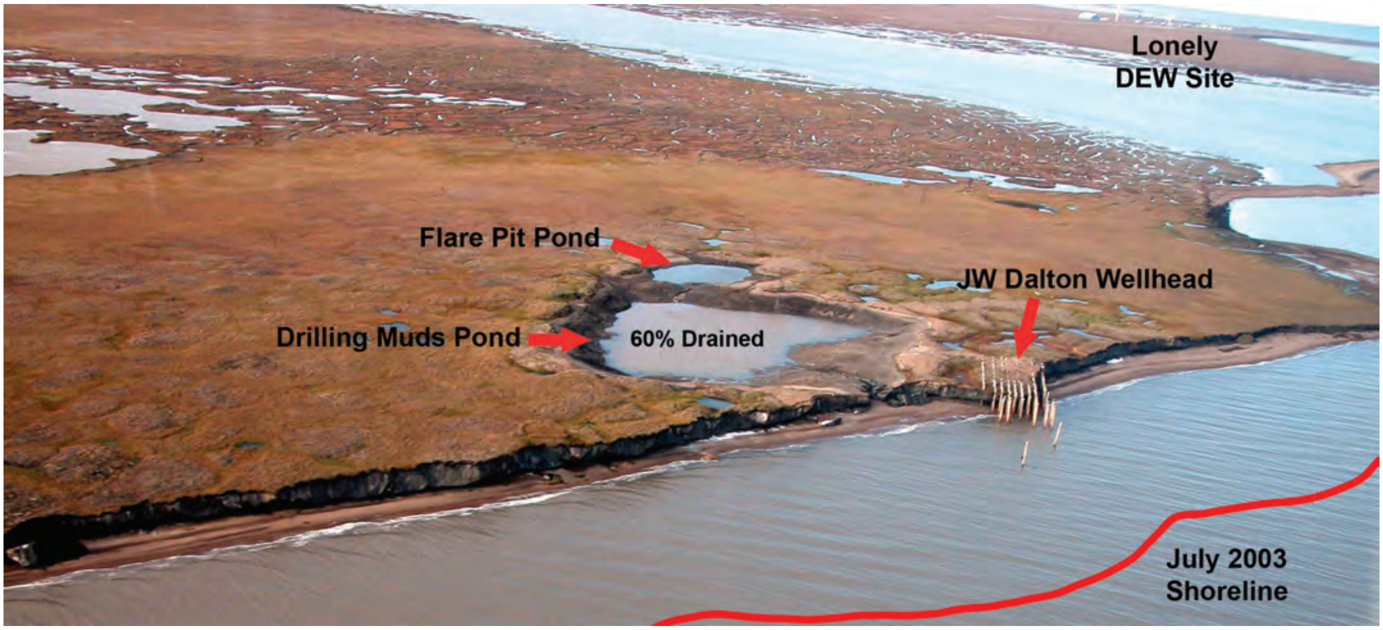

Figure 4–4. JW Dalton well site on the Beaufort Sea coast, National Petroleum Reserve-Alaska (NPR-A). Photograph taken by S. Flora, Bureau of Land Management, September 2004. Approximately 100 m of coastal erosion occurred at this site during the summer of 2004.

Data collected by the USGS show that mean annual ground temperatures on the Arctic Coastal Plain adjacent to the Beaufort and Chukchi Seas have warmed about 3.5°C since 1989 (Clow, 2008). In conjunction with this warming, a large increase in permafrost degradation has been observed (Jorgenson and others, 2006). This recent degradation primarily is due to the degradation of massive ice wedges within permafrost that have been stable for thousands of years. With continued warming, it is estimated that permafrost degradation (thermokarst) can ultimately affect 10–30 percent of the landscape in this region, which would significantly impact ecosystems and present a challenge to the infrastructure. Permafrost degradation along the coasts of the Beaufort and Chukchi Seas is expected to continue through mid-century, although the percentage of landscape affected by that time is presently unknown.

Biology

The biological communities indigenous to the coastal and marine areas of the Beaufort and Chukchi Seas are highly adapted to the extreme conditions of this environment. Because of this high degree of adaptation, the projected changes to the physical environment of this region are expected to have a significant impact on fish and wildlife populations. Considerable uncertainty exists in how these changes will affect many individual species, but there is general agreement that these changes will favor some species while being detrimental to others.

With projected warming temperatures and further decreases in sea ice, terrestrial and marine populations generally are expected to shift northward with probable large-scale ecosystem shifts in species abundance, food web changes, and increased competition for habitats. Among the factors that are of particular importance in the Beaufort and Chukchi Seas region from a biological perspective are the projected decrease of sea ice, circulation changes, ocean acidification, and coastal erosion. The present-day Arctic marine ecosystem is in many ways adapted to the sea-ice cover. At the base of the food chain, phytoplankton blooms are intense at the summer ice edge. Zooplankton are the primary grazers of these phytoplankton, and it is the success of the zooplankton communities that ultimately determines the food resources available to Arctic fish, seabirds, and marine mammals. Thus, changes in the thickness, extent, and seasonal location of the sea-ice cover can have repercussions throughout the Arctic food web. Potential repercussions include changes in predator-prey relationships among Arctic cod, seals, and polar bears, for example. Loss of sea ice also can have a direct impact on ice-obligate marine mammals (for example, ringed seals, walrus, polar bears) as it serves as an important rearing, feeding, and resting platform for these animals. In the Chukchi Sea, the bulk of the nutrients needed for the production of organic compounds at the base of the food web ("primary production") are of Pacific origin, carried northward by currents through the Bering Strait. In the Beaufort Sea, winds promote upwelling of subsurface waters at the continental shelfbreak, bringing nutrients from the Canada Basin onto the shelf. In either case, changes in wind and ocean circulation patterns will alter the distribution of nutrients available for primary production, with consequences for the entire food web. In addition, ocean acidification is expected to negatively impact planktonic and benthic calcifying organisms in this region, both of which are important elements of the Arctic food web. Due to the combined effects of sea-level rise, storm surges, and accelerated coastal erosion, habitats critical to many species in the coastal zone and barrier islands are expected to be impacted by the projected climate changes.

Climate-related changes in the physical landscape and in biological communities will have far-reaching impacts to the human populations on the North Slope of Alaska who still rely to a large extent on subsistence foods. Access to coastal and marine areas will change as a result of coastal erosion, sea-level rise, and changes to sea ice. Opportunities to hunt some species (for example, ice seals) may decrease, but opportunities to hunt others may increase, at least in the short term. The value of local traditional knowledge from those that live there can play a bigger role in documenting changes in the distributions and status of fish and wildlife populations.

Fish

At least 98 species of marine fish are known to inhabit the Beaufort and Chukchi Seas (Mecklenburg and others, 2002). Because of the paucity of commercial fisheries in Arctic Alaska, knowledge of fish ecology in this region is among the poorest in Alaska, but it is slowly improving. The current understanding of population-level change expected from climate change in Arctic fish species is hindered by a lack of long-term data and a poor understanding of Arctic fish ecology. Present-day relationships between biological and environmental parameters must be understood to provide the foundation for assessing future climate-change effects on fish populations and, in many cases, this basic foundation is poor or lacking, making it difficult to predict the response of Arctic fishes to climate change. In general, a pole-ward shift of fish distributions is predicted, as is a reduction or extinction of species that are narrowly adapted to Arctic environments (Wrona and others, 2006).

Climate-change effects on Arctic freshwater and nearshore ecosystems are expected to result in changes to water temperature, hydrology, ice regimes, salinity, pH, biogeochemical processes, primary production, food-web interactions, and the distribution of prey species. How any single species or population responds to these changes probably will vary among locations and depend on the life history and range of habitats used (Reist and others, 2006a). Numerous questions remain concerning the potential impacts (positive versus negative) resulting from changes in large-scale environmental drivers to fish in freshwater, nearshore, and marine habitats (fig. 4–5). The projected warming of marine waters and changes in salinity, especially in nearshore waters, are expected to impact the distribution, growth, and survival of fishes, many of which rely on nearshore waters as critical migratory and feeding corridors.

Fish of the Beaufort and Chukchi Seas can be broadly categorized in two groups based on their use of marine habitats: marine species use marine (that is, saltwater) habitats exclusively while anadromous species migrate between freshwater and marine habitats (see Chapter 3, Ecological and Subsistence Context). Given the difference in reliance on marine habitats, the two groups are likely to respond differently to climate change. Anadromous species spawn in freshwaters and feed in marine waters and integrate climate change effects across freshwater, estuarine, and marine habitats. For such species, the total effect is expected to be significantly greater (Reist and others, 2006a, 2006b).

Anadromous Fish. How anadromous fish of the Beaufort and Chukchi Seas will respond to climate change will range from positive to negative in overall effect and will vary among species and among populations (Reist and others, 2006a). Because anadromous fish migrate between marine and freshwater habitats, sometimes annually, they will integrate the impacts of climate change in both the freshwater and marine habitats, potentially leading to a greater impact than that experienced by resident freshwater or marine species. Climate-change effects on such fishes may be driven by changes in hydrology (timing and quantity of flow), timing of freeze-up and break-up, and thermal regime. These environmental changes may impact the timing of upstream migration by adults, overwinter survival of adults, overwinter survival of incubating eggs, and timing of downstream migration by juveniles and adults as they migrate to the ocean. Environmental factors affecting growth, survival, and reproduction in Arctic fishes are numerous, act differently on different life stages, and include temperature, salinity, ice extent, current or flow of water, turbidity, and pH. Because migratory timing is an adaptation to local conditions, in general, non-linear changes to marine and freshwater habitats of any of these factors may result in decreased survival if conditions in freshwater and marine habitats result in a mis-match in timing of saltwater entry (Burkett and others, 2005).

Several species of anadromous fish are found in waters of the Beaufort and Chukchi Seas including: Dolly Varden, Arctic cisco, least cisco, Bering cisco, broad whitefish, humpback whitefish, rainbow smelt, pink salmon, and chum salmon. All these species spawn in freshwater and rely on a narrow band of brackish water along the coast for migration to and from feeding and spawning locations with the exception of Pacific salmon, which presumably migrate farther offshore or to the northern Bering Sea. Because warming and changing salinity are predicted to be most severe in this nearshore region, these

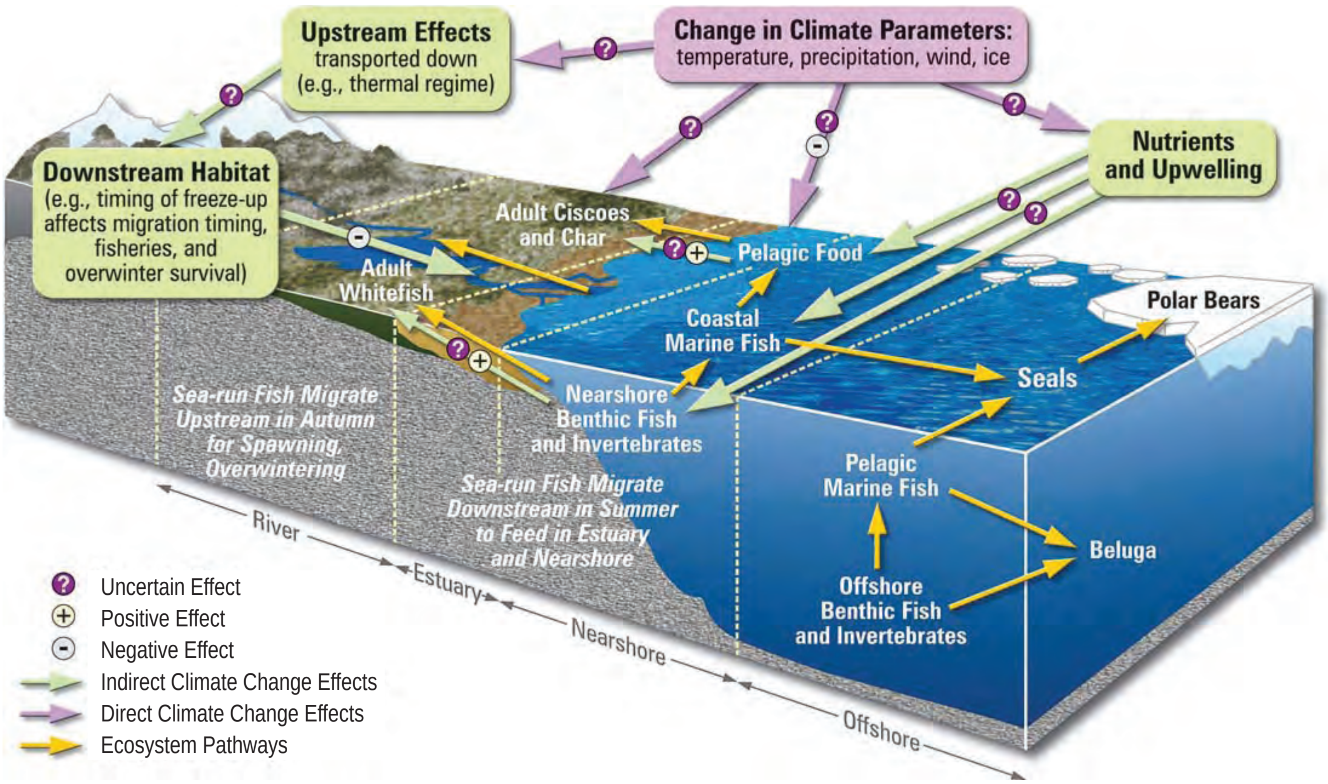

Figure 4–5. Schematic showing some of the potential direct effects of climate change on Arctic aquatic environments and some potential indirect effects on fishes. The complexity of the interactions makes it difficult to predict climate-change effects on these fishes. (From Wrona and others, 2005.)

fish are expected to be most impacted by climate effects. Arctic cisco, for example, spawn in the Mackenzie River and shortly after hatching, juveniles migrate downstream and out of the Mackenzie River Delta where they are swept west to Alaskan waters of the Beaufort Sea by nearshore wind-driven currents (Fechhelm and Griffiths, 1990). Potential changes in wind regimes or current patterns could, therefore, have significant impacts on the number of Arctic cisco recruiting to Alaskan waters. Arctic cisco have been captured as far as 15 km offshore but are presumed to rely most heavily on nearshore waters within 15 km of the coast. As a result, changes to prey resources due to projected warming, decreased sea ice, changes in freshwater inputs, and changes in nutrient availability may affect survival and growth of Arctic cisco.

Similarly, Dolly Varden spawn in a few spring-fed streams of the eastern North Slope of Alaska and rivers draining to the Chukchi Sea and migrate downstream to marine waters. Little is known about the extent of marine migrations by Dolly Varden in waters of the Beaufort Sea but evidence from the southern Chukchi Sea suggests that marine migrations may be long-distance and Dolly Varden may have little fidelity to overwintering habitats. Dolly Varden tagging experiments indicate that marine migrations by anadromous fishes may be extensive and suggest that populations in the Beaufort and Chukchi Seas may be characterized by complex migratory behaviors and interconnections among streams, further complicating our ability to predict the results of climate change on these species. Because Dolly Varden and Pacific salmon are likely to migrate south through the Bering Strait, they also are subject to climate related shifts in the Bering Sea ecosystem, where increases in temperature, decreases in sea ice, and shifts in species composition have been observed (Grebmeier and others, 2006).

In addition to physical oceanographic changes in migration corridors, fish may be affected by changes in food resources. Resent research suggests an increasing growth trend for juvenile Arctic cisco as they migrate from the Mackenzie River through the nearshore Beaufort Sea (von Biela and others, 2011). Correlations with environmental data suggest that decreased sea-ice concentrations and increased river discharge fueled primary production, which resulted in increased prey species (copepods) and increased juvenile growth. While Arctic cisco are characterized by increased growth during their first year of life, which appears to be correlated with climate change, it is unclear how this increase in growth translates to survival or reproduction. Typically, increased growth is assumed to indicate better conditions and, hence, increased survival. Further work is needed to determine if increased growth during early life history of Arctic cisco translates to increased adult growth, reproduction, or survival. Similar trends of increasing juvenile growth have been predicted for other Arctic fish species (Reist and others, 2006b).

Distributional changes are likely to be observed in anadromous fishes including colonization by fishes such as Pacific salmon. With warming water temperatures, decreasing sea ice, and perennial freshwater flow, colonization of Arctic rivers by Pacific salmon is expected and may have dramatic impacts on aquatic productivity and species composition (North Pacific Research Board, 2005). Because Pacific salmon die after spawning and thus transport nutrients gained during marine rearing into spawning rivers, their colonization of relatively nutrient-poor Arctic rivers is likely to result in changes to nutrient dynamics with resulting changes to biotic communities, both within aquatic and associated terrestrial and estuarine ecosystems (Gende and others, 2002). While all five species of Pacific salmon have been captured in the North American Arctic, it is not clear that successful spawning populations exist north and east of Point Hope, Alaska. While reports of Pacific salmon captured across this region have increased in recent years, it has been suggested that Pacific salmon captured north and east of Point Hope were strays from other regions (Stephenson, 2006). Lack of suitable spawning habitats and extremely cold temperatures are the suspected reasons that salmon straying to the Arctic have not established perpetuating spawning populations (Craig and Haldorson, 1986).

Dolly Varden, like Pacific salmon, are substrate spawners and spawn in streams between the Colville River and Mackenzie River (Daum and others, 1984). Streams currently used by spawning Dolly Varden are mountain streams containing perennial springs. Dolly Varden do not spawn in rivers west of the Colville River because these streams lack perennial flow (Craig, 1989). The distribution of Dolly Varden habitats is, therefore, severely restricted. This distribution suggests that other substrate spawning salmonids (such as Pacific salmon) will be limited by suitable spawning habitats and may be predicted by the current distribution of Dolly Varden. Development of incubating salmon is strongly controlled by temperature and currently observed winter water temperatures are too cold to allow for successful incubation of Pacific salmon in many rivers draining to the Beaufort Sea, although more data are needed to determine the potential distribution of adequate salmon spawning habitats. Temperatures also are presently too cold in the Arctic Ocean to allow for overwinter at-sea survival of salmon and salmon would need to migrate to the northern Bering Sea (Irvine and others, 2009). While it remains uncertain when Pacific salmon will establish sustaining populations in rivers north of the Brooks Range, it appears possible that with the warming and changes in salinity projected in the next 50 years, salmon populations could be established.

Marine Fish. Changes to marine environments due to a changing climate potentially can affect marine fish in a number of ways, leading to distributional changes, increased or decreased mortality, and changes in the timing of reproduction and in growth. Very little is presently known about marine fish populations in the Beaufort and Chukchi Seas. Because of this, the North Pacific Fishery Management Council recently adopted a precautionary fishery management plan prohibiting commercial fishing in the region until the science is available to better understand fish populations there (North Pacific Fisheries Management Council, 2009). Other regions of the Arctic have recently seen changes in marine fish populations that are believed to be climate related. For example, the distribution of marine species in the North Atlantic Ocean has changed in response to warming sea surface temperatures (SSTs) (Rose, 2005). Near Greenland, warming SSTs have resulted in a replacement of cod by shrimp (Hamilton and others, 2003). Similarly in the sub-Arctic waters of the Bering Sea, decreases in spawning Greenland turbot and increases in spawning walleye pollock between 1965 and 2004, have been attributed to warming SSTs and decreased sea ice (Overland and Stabeno, 2004). Detection of these shifts was only possible because data existed from long-term and standardized surveys. Similar surveys are not available in the Chukchi and Beaufort Seas making it difficult to detect shifts in the distribution or ecology of these marine fish, or to determine exactly how these fish will respond to climate change.

Among marine fish, Arctic cod is one of the most abundant fish in the Arctic and is an important predator and prey species. Arctic cod commonly is found in the diets of beluga whales, ringed and bearded seals, and several sea birds. Given their abundance and trophic importance, Arctic cod play an important role in Arctic marine ecosystems and climate-mediated changes in their abundance, distribution, survival, or nutritional content will have cascading effects across the Arctic marine ecosystem. Arctic cod are closely associated with sea ice (Crawford and Jorgenson, 1993) and, therefore, projected decreases in sea ice and changes in salinity are likely to affect the distribution and survival of Arctic cod (Gaston and others, 2003).

Evidence for shifts in the distributional range of fish species in the Beaufort Sea has been recently observed. In 2008, National Oceanic and Atmospheric Administration (NOAA) Fisheries Service conducted an offshore survey of Beaufort Sea fish species and compared species composition of the catch with surveys conducted in 1976 and 1977.

During the 2008 survey, five species of fish not previously encountered in the Beaufort Sea, including Bering flounder, walleye pollock, bigeye sculpin, and Pacific cod were captured (Loggerwell, 2008). It is believed that these fish represent an expansion of range from the Bering Sea. Snow crab of commercial size also were captured during this survey. This is the first time that snow crab of commercial size were observed in the Arctic.

There is high inter-annual, seasonal, and short-term variation in salinity and temperature of the Beaufort Sea nearshore environment that is driven by a complex interaction of wind, riverine freshwater discharge, sea ice, and oceanographic processes. Fish occurrence, abundance, and community structure is driven by these variables. For example, in 30-km transects across the nearshore, salinity varied strongly among years: ranging from 3 to 29 psu (practical salinity units) in 1988 and 1991, and greater than 25 psu in 1990 (Jarvela and Thorsteinson, 1999). In that study, Arctic cod were never encountered in salinities less than 14.2 psu. Given the strong association between climate and oceanographic processes (see Ocean section), further work is needed to assess the population response of marine fish to a changing oceanographic environment.

Ocean acidification may have significant direct and indirect impacts on marine fish in the Beaufort and Chukchi Seas because the relative rate of change in sea-water acidification is highest at high latitudes (Orr and others, 2005; Fabry and others, 2009). Potential impacts to prey species with calcareous skeletal structures may result in significant and unknown changes to food webs that support marine fishes. Further, direct physiological impacts to marine fishes may result in changes in skeletal or scale growth but these impacts are not fully understood. Recent research suggests that migration and homing can be impaired by acidification (Munday and others, 2009), a potentially critical problem because so many Arctic fish species are migratory. Further work is needed to evaluate the potential impacts of ocean acidification on fishes of the Beaufort and Chukchi Seas.

Birds

Arctic birds will be impacted by climate change in a variety of ways. Over the next 50 years, the abundance and distribution of bird populations in the Beaufort and Chukchi Seas (and adjacent coastal plains) are likely to be impacted by changes to critical nesting and rearing habitats, the availability and quality of food resources, the incidence and distribution of avian diseases, the frequency of predation, and whether the timing of migration and nesting can be adjusted sufficiently to accommodate projected seasonal environmental and food-availability changes (for example, melting of the winter snowpack and sea ice, subsequent greening of the tundra, emergence of aquatic insects) (Martin and others, 2009). Bird species that are unable to adequately adjust to a change in the seasonal timing of optimal food resources during the breeding season, and other important events in their annual life cycle, are likely to diminish (for example, Stenseth and Mysterud, 2002; Gaston and others, 2009). Because most bird species that occupy the Arctic are migratory, with some undergoing spectacular migrations to the southern hemisphere, climate effects outside of Alaska, also may have strong influences on Alaskan-nesting birds.

Seabirds. Climate effects are best known for black guillemots that nest on Cooper Island in the western Beaufort Sea and cliff-nesting seabirds that breed in the southern Chukchi Sea although the issue is not well studied. At Cooper Island, decreases in summer pack-ice extent are correlated with changes in black guillemot population size, breeding success, and food provided to nestlings (Moline and others, 2008). Both breeding productivity and the percentage of Arctic cod in the diet have decreased as the distance to the summer ice edge has increased in recent years. Declines in productivity recently have been exacerbated by predation of guillemot nestlings by polar bears who are coming onshore on the Beaufort Sea coast (including Cooper Island) in increasing numbers as sea ice retreats far offshore each summer. Declines in Arctic cod during the nesting season associated with sea-ice retreat also might have been a factor in poor reproductive success of black-legged kittiwakes at Cape Lisburne in the eastern Chukchi Sea since the early 1990s (Roseneau, 2010).

Sea Ducks. A diversity of marine waterfowl occurs within the Arctic OCS and adjacent terrestrial habitats of the Beaufort and Chukchi Seas. Keystone species include Steller's eider, spectacled eider, king eider, Pacific common eider, and long-tailed duck. Sea ducks are omnivorous with diets that include a diversity of freshwater invertebrates (insects, crustaceans, mollusks) and aquatic plants during the breeding season, and marine invertebrates, fishes (sculpin, cod), and algae during the molting and wintering periods (Goudie and others, 1999; Petersen and others, 1999a). Despite the projected increase in precipitation, there may be a reduction of moist and flooded tundra habitats by mid-century due to the improved drainage expected to occur with warming ground temperatures and a deepening active layer. If this occurs, it would reduce some invertebrate taxa important to sea ducks during the nesting period. Consequently, there may be decreases in productivity and abundance of sea ducks, as well as potential redistribution for some species. The projected warming of marine waters and changes in salinity regimes, especially in near-shore waters, are expected to compromise marine invertebrate abundance and the value of these critical habitats to foraging sea ducks. Spectacled eiders are a threatened species under authority of the Endangered Species Act. They, as well as several other species of sea ducks, use polynyas and open leads in fast ice during the non-breeding season (Petersen and others, 1999b;

Petersen, 2009). Sea ice that surrounds polynyas and leads provides a substrate for resting birds during periods when they are not actively diving for bivalves and other marine invertebrates, and it also reduces wave action that may contribute to increased energy expenditure of diving ducks. A decrease of autumn sea ice is predicted to have negative consequences on thermodynamics and energetics of wintering sea ducks (Petersen and Douglas, 2004). Pacific common eiders and long-tailed ducks nest on barrier islands of the Chukchi and Beaufort Seas. These habitats are expected to be particularly vulnerable to projected climate changes. With rising sea levels, the size of the barrier islands is expected to shrink and they are more likely to be over-washed by storm surges. In addition, with the projected decrease in sea ice and a likely increase in autumn storm frequency, both the erosion and migration rates of these islands are expected to increase. These events will likely result in loss of nest habitat. Projected environmental changes in the Beaufort and Chukchi Seas and adjacent land masses are likely to result in significant changes in the incidence and distribution of avian diseases, such as influenzas, Newcastle's Disease, and cholera (Acevedo-Whitehouse and Duffus, 2009). In concert with other factors already limiting some Arctic-breeding sea ducks (Steller's eider, spectacled eider, long-tailed duck), emerging diseases are expected to further reduce populations. The population dynamics of lemmings also affect nesting success of sea ducks (and other waterbirds). In years of low lemming abundance, waterfowl, their eggs, and young are of increased importance as prey of predators, such as Arctic foxes, ravens, and jaegers. Therefore, climate-related changes in microtine rodent populations may indirectly affect sea duck productivity.

Loons. All five of the World's species of loons (yellow-billed, red-throated, Arctic, common, and Pacific) occur within the Arctic OCS and adjacent landmasses of the Beaufort and Chukchi Seas (Johnson and Herter, 1989; North, 1994; Barr and others, 2000; Russell, 2002a, 2002b; Evers and others, 2010). They are dispersed in their breeding distribution and occur primarily in freshwater, coastal habitats during the summer nesting period. For most of their annual cycle, they are dependent on marine habitats including estuaries, embayments, and pelagic areas. Loons feed primarily on freshwater and marine fishes and some invertebrates. Increasing freshwater and oceanic temperatures, and changes to hydrology may have direct impacts on forage fishes important in the diets of these species. The abundance and distribution of loons on the Arctic Coastal Plain will be primarily dictated by the ecological response of a few key fish species (for example, sticklebacks and ciscos) to climate change. Loss of sea ice and a larger expanse of open water in near-shore areas of the Beaufort and Chukchi Seas have been shown to contribute to extensive erosion of coastal habitats important to breeding loons. Furthermore, increased oceanic warming, especially in near-shore areas of the Arctic OCS, along with alteration of barrier island systems resulting from storm events, will likely negatively affect the composition and biomass of marine fishes exploited by loons (Martin and others, 2009).

Shorebirds. More than 25 species of waders nest in freshwater and palustrine habitats of the Arctic Coastal Plain of the Beaufort and Chukchi Seas (Alaska Shorebird Group, 2008). Shorebirds have diverse diets that include terrestrial and aquatic invertebrates. Warming temperatures are expected to influence the timing and patterns of insect (terrestrial and aquatic) emergence and peak densities, which may result in an ecological mismatch for some species that are not able to adjust migration phenology to keep track of advancement of spring phenomena in Arctic breeding areas (Meltofte and others, 2007). Accumulation of organic matter may affect habitats of breeding populations of some species depending on the rate at which it occurs and how this in turn influences the availability of invertebrate prey species. Likewise, predicted acidification of aquatic habitats associated with increasing atmospheric CO_2 levels may reduce diversity and biomass of invertebrates important in the diets of species such as phalaropes. As previously noted, improved drainage and a deepening active layer due to the projected warming may lead to a reduction in aquatic and semi-aquatic habitats on the Arctic Coastal Plain. If a significant reduction of these habitats does occur, it will negatively affect invertebrate productivity and availability, as well as a loss of nesting and rearing habitats for shorebirds. The red phalarope is dependent on food resources associated with offshore pack ice during the pre- and post-breeding periods. The dynamics of sea ice under changing climate scenarios may affect timing and availability of these resources and consequently affect survival of this species. Breeding shorebirds on the Arctic Coastal Plain also may be affected by increased predation associated with increasing numbers of avian predators, such as ravens, foxes, and glaucous gulls on the North Slope (Alaska Shorebird Group, 2008, Weiser and Powell, 2010).

Geese. Pacific black brant, lesser snow goose, Canada goose, cackling goose, and greater white-fronted goose are the prominent species that occur within the subject area. All are grazers that exploit grasses and sedges that occur adjacent to freshwater basins and salt-tolerant plants that dominate near-shore and inter-tidal zones. Forage quality, rather than quantity, is considered the most important factor limiting survival. Clearly, warmer ambient temperatures will affect the growing season on the Arctic Coastal Plain and consequently plant biomass, but not necessarily forage quality. Sea-level rise in concert with increased storm-surge frequency and elevated water temperature has resulted in significant erosion of coastal habitats that are critical to nesting and molting birds, and this trend is expected to continue through mid-century. Additionally, it has been demonstrated that increased storm surge heights within the last decade have caused intrusion of salt water in low-lying areas of the Arctic Coastal Plain of the Beaufort and Chukchi Seas, which initially results in barren areas of no value to herbivorous geese (Flint and others, 2008). However, an influx of marine waters provides conditions suitable for salt-tolerant plants that also may generate expansive, single-species "grazing lawn" that can be exploited by geese during the pre- and post-breeding periods. Warming ambient temperatures in combination with drying conditions on the Arctic Coastal Plain have been shown to favor invasion of woody plants, such as willows and alders, which replace grasses, sedges, and forbs important as nesting cover and forage for geese. The trend towards an increasing prevalence of woody plants on the Arctic Coastal Plain is expected to continue through mid-century.

Marine Mammals

Factors that can affect marine mammals in Alaska are of concern to many in the United States, Canada, and Russia. Climate change is a pervasive force that could influence other factors that affect marine mammals in the Beaufort and Chukchi Seas, such as oil and gas development, shipping, tourism, and subsistence hunting. Many Arctic marine mammals are associated with sea ice for all or part of their annual life cycle. Climate change also could affect marine mammals through a number of pathways, for example,

- decreases in sea ice that could affect foods, foraging or other aspects of their life cycles;
- increased primary and secondary production;
- reduced benthic and pelagic biomass in coastal/shelf areas due to increased river runoff and change in turbidity and salinity; and
- increased pelagic grazing and recycling in open water of the Chukchi Sea at the expense of the current tight benthic-pelagic coupling in ice-covered shelf regions.

Should these scenarios come to fruition, pelagic-feeding and generalist marine mammals might have an advantage over benthic shelf-feeding, ice-dependent species such as walrus and bearded seals (Bluhm and Gradinger, 2008). Moore and Huntington (2008) developed a useful conceptual model (fig. 4–6) that examines the potential impacts of climate

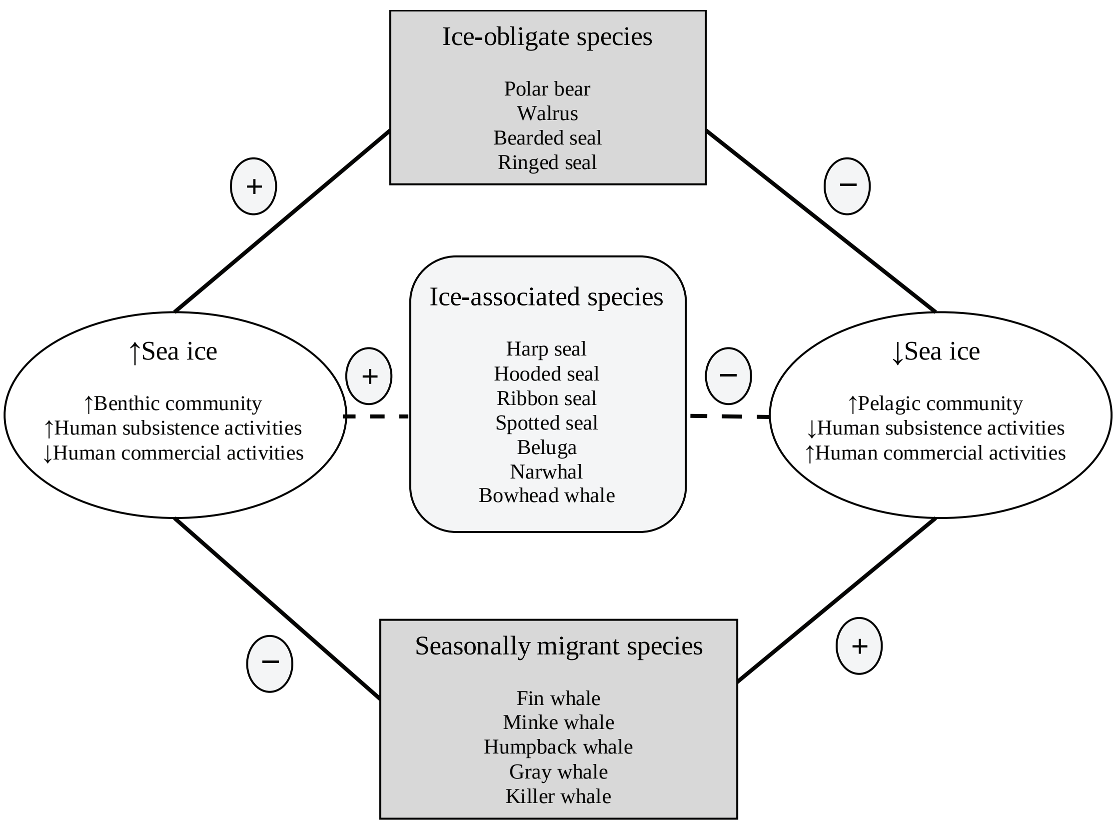

Figure 4–6. A conceptual model of sea-ice impacts on ice-obligate, ice-associated, and seasonally migrant marine mammal species: positive impacts are indicated by circled plus signs; negative impacts by circled minus signs. Dashed lines indicate uncertainty regarding potential impacts of sea-ice gain or loss for ice-associated species. (From Moore and Huntington, 2008.)

change to Arctic marine mammals based on the gain or loss of sea ice. Ice-obligate species, such as polar bears and walrus, are sensitive to the loss of sea ice because they depend on it for hunting, breeding, and resting. The impacts to ice-associated species are harder to predict; some species such as ribbon seals and spotted seals seasonally rely on sea ice for whelping, but apparently can survive without sea ice during the remainder of the year. The seasonally migrant cetacean species are likely to benefit from sea-ice loss due to greater access to Arctic waters.

Whales. Seven species of whales are found in Arctic waters of the Beaufort and Chukchi Seas: bowhead whale, beluga, fin whale, humpback whale, gray whale, minke whale, and killer whale. Bowhead whales and belugas are capable of living in waters that are highly ice-covered. Beluga whales are known to seasonally migrate to 80°N with greater than 90 percent ice cover (Suydam and others, 2001). However, bowhead whales and beluga also are capable of surviving at great distances from sea ice and sometimes select open-water habitats (Moore, 2000). Decreases in sea ice may enhance feeding opportunities on prey, at least for bowhead whales (Moore and Laidre, 2006). Another indication of how bowhead whales are responding to decreased sea ice is that the population has increased steadily during roughly two decades of sea-ice loss in the western Beaufort Sea (George and others, 2004). This suggests that sea-ice loss is not hindering productivity of this population as it slowly recovers from commercial over-exploitation. Although the long-term effects of climate change on bowhead whales are unclear, from the perspective of sea ice, this species will likely fair well compared with highly ice-dependent species (George and others, 2008).

For migrant whales, it is likely they will range farther north and remain longer in response to declining sea-ice cover. These species now occur within seasonal sea-ice habitats in the Bering Sea where they feed primarily on forage fishes whose stocks may have increased as a result of a boost to pelagic community production predicted to accompany decreases in sea ice (Hunt and others, 2002; Moore and Huntington, 2008). There is evidence that gray whales are responding to ecosystem change by feeding predominantly in the Chukchi Sea as opposed to the northern Bering Sea, coincident with a decline in amphipods in the Chirikov Basin of the Bering Sea (George and others, 2008). Evidence for migrant whales overwintering farther north in recent years includes fin whales overwintering in the Bering Sea (Moore and Huntington, 2008), humpback whales wintering in southeast Alaska and Kodiak, and gray whales overwintering in the western Beaufort Sea (Moore and others, 2006).

With the exception of beluga and killer whales, all of the whales in the Beaufort and Chukchi Seas are filter feeders, feeding primarily on plankton and invertebrates with calcareous exoskeletons. Recent simulations using global ocean models suggest the surface waters of the Arctic Ocean will become undersaturated with respect to calcium carbonate, and therefore corrosive to calcifying organisms, within a decade (Steinacher and others, 2009). For filter-feeding whales, there are concerns about the impact of acidification on their invertebrate prey. Although the biological response to acidification will likely vary across species and life stages, both benthic and planktonic calcifying organisms are expected to be impacted, as are the whales that feed on them. The extent to which filter-feeding whales will be impacted is currently unknown.

Pinnipeds (Ice Seals and Pacific Walrus). Four species of ice seals are found in the Beaufort and Chukchi Seas of Alaska: ringed, bearded, ribbon, and spotted seals. Ringed and bearded seals are considered ice-obligate species, whereas the ribbon and spotted seals are ice-associated species (Moore and Huntington, 2008). All four species are at least seasonally dependent on sea ice, using it as a platform for resting, breeding, whelping, nursing, and molting. But ribbon and spotted seals use sea ice for much shorter durations of time. The ribbon seal is pelagic during the ice-free season, whereas the spotted seal uses terrestrial haulouts and feeds at sea during the open-water season. The Pacific walrus is considered an ice-obligate species (Moore and Huntington, 2008).

Laidre and others (2008) developed a climate-change sensitivity index for Arctic marine mammals. They considered walrus, spotted seal, and ribbon seal to be moderately sensitive and ringed and bearded seals to be least sensitive. Ringed and bearded seals were deemed to have lower sensitivity to climate change because of their large population size, wide circumpolar distributions, and plasticity in regards to habitat specificity, diet diversity, movements, and site fidelity. Ribbon seals, spotted seals, and Pacific walrus all have smaller populations that are restricted to the western North Pacific, Bering, Chukchi, and Beaufort Seas. All five species were determined to be highly sensitive to sea-ice changes (Laidre and others, 2008).

Bearded seals are distributed across the circumpolar Arctic. They generally prefer ice habitat that is in constant motion and produces natural openings, such as leads, fractures, and polynyas for breathing, hauling out on the ice, and access to water for foraging. They are primarily a benthic feeding seal. To remain associated with their preferred ice habitat, they generally move north in late spring and summer as the ice melts and retreats, and then move south in the autumn as sea-ice forms (Cameron and others, 2010). Bearded seals whelp on the ice and pups enter the water shortly after birth as a means to avoid predation. They also use sea ice as a platform to haul out during the annual molt, which is concentrated during late spring and early summer (National Marine Fisheries Service, 2010b). The main concern about the conservation status of bearded seals stems from the likelihood that their sea-ice habitat has been modified by climate warming and will likely continue to decrease in extent through mid- to late century. A second concern related to greenhouse gas emissions, is the modification of habitat by ocean acidification, which may alter prey populations and trophic relationships for bearded seals. To adapt to a regime of decreased sea ice, bearded seals likely will need to shift their nursing, rearing, and molting areas to ice-covered seas north of the Bering Strait, where projections suggest there is potential for the ice edge to retreat to deep waters of the Arctic Basin. There appears to be a high threat that decreases in spring and summer sea ice will result in a large separation between sea ice resting areas and benthic feeding habitat. Decreases in sea ice suitable for molting and pup maturation also appear to pose a high threat. Based primarily on projected changes to sea ice, the National Marine Fisheries Service (NMFS) recently proposed the Beringia subspecies of bearded seal be listed as threatened under the Endangered Species Act (ESA) (National Marine Fisheries Service, 2010b).

The Arctic ringed seal is the most widespread and abundant of the five subspecies of ringed seals and is found across the circumpolar Arctic including the Beaufort and Chukchi Seas. The main concern about the conservation status of ringed seals is the likelihood that their sea-ice habitat has been modified by climate warming and likely will continue to decrease in extent through mid-late century. Ringed seals depend on sea ice for reproduction. They build lairs under the drifting snow on sea ice where they give birth and nurse their pups (Kelly and others, 2010). Following weaning, ringed seals undergo molt and spend large amounts of time basking in the sun on sea ice. The NMFS recently proposed Arctic ringed seals for listing under the ESA (National Marine Fisheries Service, 2010a) because of the implications of climate change on this species. The proposal concludes that within this century, snow cover is forecast to be inadequate for the formation and occupation of birth lairs over most of the subspecies' range. The projected decrease in sea ice, and especially snow cover, will likely lead to decreased pup survival and a substantial decline in the abundance of the Arctic subspecies. Predation risk from polar bears, Arctic foxes, gulls, and ravens is expected to increase with declining snow depth and duration of snow cover. Although loss of sea ice and snow cover is the principal justification for the proposed listing, other factors such as changes to their prey base from ocean acidification, increased shipping, and oil and gas development could negatively affect ringed seals. The significance of these other threats would increase for populations diminished by the effects of climate change (National Marine Fisheries Service, 2010a).

Ribbon seals use annually formed sea ice for reproduction and molting in the spring, but are largely unassociated with sea ice during summer, autumn, and early winter (Boveng and others, 2008). They have an apparent affinity for stable, moderate-sized ice floes that are slightly interior to the pack ice edge where they give birth, nurse, and later molt. In years of low ice, ribbon seals likely will adjust by shifting their breeding locations in response to the position of the ice edge, as they have likely done in the past in response to inter-annual sea ice variability. Decreased availability of stable ice platforms for adults to complete their molt out of the water may lower survival, but it is not currently possible to quantify this impact or the extent to which ribbon seals may adapt by shifting locations for molting. Changes in ribbon seal prey, anticipated in response to habitat changes resulting from ocean warming and loss of sea ice, have the potential for negative impacts, but these impacts are not well understood. Some changes already documented in the Bering Sea could be beneficial. For example, several fish species, including walleye pollock (*Theragra chalcogramma*), a common ribbon seal prey, have shown northward distribution shifts in response to warming. The NMFS has found that listing the ribbon seal under the ESA is not warranted (National Marine Fisheries Service, 2008). Although the ribbon seal abundance is likely to decline gradually, primarily from slight but chronic impacts on reproduction and survival caused by reduced frequency of years with sea ice of suitable extent, quality, and duration of persistence, the NMFS concluded it is not in danger of extinction or likely to become an endangered species (National Marine Fisheries Service, 2008).

The distribution of spotted seals is seasonally related to life history events that can be broadly divided into two periods: late autumn through spring, when breeding, whelping, nursing, and molting all take place in association with sea ice on which the seals haul out; and summer through autumn, when the sea ice has melted and spotted seals remain closer to shore to use land for hauling out. The annual timing of spotted seals' reproduction has evolved to coincide with the average period of maximum extent and stability of the seasonal sea ice. Sea ice provides a platform away from land predators during the breeding, whelping, nursing, and molting periods. When sea ice begins to form in the autumn, spotted seals start to occupy it immediately, concentrating on the early ice that forms near river mouths and estuaries. In winter, as the ice thickens and becomes shorefast along the coasts, spotted seals move seaward to areas near the ice front with broken ice floes. Spotted seals are divisible into three Distinct Population Segments (DPS) (Boveng and others, 2009), of which the Bering DPS (Bering, Chukchi, and Beaufort Seas) is most relevant to this report. While the effects of climate change may decrease suitable habitat for spotted seals in the southern portion of the Bering DPS' range, such losses may be offset, in part, by increases in suitable habitat in the north. Even if sea ice were to completely vanish from the Bering Sea, this population of spotted seals may adjust by relocating their breeding grounds to follow the northward shift of the annual ice front into the Chukchi Sea. Therefore, the Bering DPS is not presently in danger of extinction nor likely to become an endangered species. The NMFS has concluded that listing the Bering DPS of spotted seals as threatened or endangered is not presently warranted (National Marine Fisheries Service, 2009).

Pacific walrus use sea ice throughout much of their annual cycle. In winter, the entire population uses sea ice in the Bering Sea and in late winter are found in distinct breeding aggregations in the southeast, central, and western Bering Sea. As the sea ice retreats in spring, most male walrus move to terrestrial haulouts in Bristol Bay and on the Chukotka Peninsula (Russia). Females and young stay with the ice as it retreats into the Chukchi Sea. Walrus are dependent on sea ice as a platform for birthing, nursing, and resting between foraging trips. They are a benthic feeder, feeding on bivalves and other invertebrates on the seafloor. Summer sea-ice extent in the Chukchi Sea has decreased rapidly in recent years, retreating off the shallow continental shelf and over deep Arctic Ocean waters where walruses presumably cannot feed. Declines in sea-ice extent, duration, and thickness are expected to continue (Douglas, 2010). Over the past decade, the number of walrus coming to shore along the coastline of the Chukchi Sea in Russia has increased. Female and young walrus are arriving earlier and staying longer at coastal haulouts as summer ice disappears. Numbers in the tens of thousands have been reported anecdotally from some haulouts in Chukotka and large walrus aggregations also were observed along the northwest Alaska coast in autumn 2007, 2009, and 2010. Walrus are able to survive using terrestrial haulouts, but there are potentially two primary impacts of this behavioral change. First, the ability of the benthic food supply within foraging range of coastal haulouts to support large numbers of walruses over the long term is a concern. Second, as demonstrated in Russia and in Alaska in 2009, calves on terrestrial haulouts are susceptible to disturbances and can be killed when walruses stampede to safety in the water (Fischbach and others, 2009). The USGS developed a Bayesian network model to integrate potential effects of changing environmental conditions and anthropogenic stressors on the future status of the Pacific walrus population for four time periods through the 21st century (Jay and others, 2011). Outcome probabilities through the century reflected a clear trend of worsening conditions for Pacific walrus. The summed probabilities for vulnerable, rare, and extirpated outcome states increased from a level of 5 percent in 2004 to 22 percent by 2050 and 40 percent by 2095. In the model, sea-ice habitat and harvest levels had the greatest influence on future population outcomes. Other potential stressors, such as ocean acidification, had much smaller influences on walrus outcomes, mostly because of uncertainty in future states of these variables and our current poor understanding of their influence on walrus abundance. In response to a petition to list Pacific walrus under the ESA, the U.S. Fish and Wildlife Service (USFWS) completed a status review, and in February 2011, concluded that listing the Pacific walrus was warranted, but precluded, due to other higher priority listing actions (U.S. Fish and Wildlife Service, 2011).

Polar Bears. Polar bears are dependent on sea ice for much of their life history. Polar bears are an ice-obligate species (Moore and Huntington, 2008) considered to be one of the most sensitive of Arctic marine mammals to climate change (Laidre and others, 2008). Although range-wide, polar bears use sea ice to varying degrees depending on its seasonal availability, in the Beaufort and Chukchi Seas, they spend most of their time on sea ice where they hunt for their primary prey, ringed and bearded seals. Polar bears breed on the sea ice and many females in the Beaufort Sea den on sea ice although they also den on land. In places where polar bears come ashore for long periods of time because the sea ice seasonally disappears, such as in Hudson Bay and Davis Strait, polar bears largely fast until the sea ice returns in the autumn and can again hunt seals. Research has begun to document the effects of decreasing sea ice on this species. In western Hudson Bay, sea ice is now absent for about 3 weeks longer than just a few decades ago. There, survival of the youngest and oldest bears has declined and is correlated with years of earlier sea ice break-up. The western Hudson Bay polar bear population is now believed to be in decline (Regehr and others, 2007). In the southern Beaufort Sea, where polar bears have historically denned on sea ice in large numbers, more polar bears are now denning on land (Fischbach and others, 2007). The growth rate of the polar bear population in the southern Beaufort Sea was related to the length of time sea ice was absent from the continental shelf, with about 127 days as the break point between good years and bad years (Regehr and others, 2009). Based on this relationship, modeling using AOGCM climate projections suggests that the Beaufort Sea polar bear population will decline to just a fraction of its current size by the end of this century (Hunter and others, 2010). Declines in sea ice, presumably mediated through poorer hunting of ice seals, has also resulted in diminished size of polar bears in the southern Beaufort Sea (Rode and others, 2010). As sea ice has retreated farther and farther away from the Beaufort Sea coast of Alaska, more bears are showing up on shore where many forage on carcasses of subsistence-harvested bowhead whales. It is unclear which strategy, staying with the sea ice as it retreats offshore or moving to the coast, is better for polar bears; this is currently under investigation. Modeling by the USGS suggests that if current patterns of sea ice loss continue, up to two-thirds of the current World's polar bear population will disappear by the end of this century (Amstrup and others, 2008). The polar bear was listed as threatened by the USFWS in May 2008.

Expected Climate and Environmental Changes in the Beaufort and Chukchi Seas by Mid-Century

Significant climate changes are projected to occur in the Arctic OCS by mid-century as we summarize in table 4–1. These will affect the physical environment in which Arctic OCS energy activities occur, biological systems, which also may be impacted by Arctic OCS energy activities (cumulative impacts), and indigenous populations. Here, we list a number of findings regarding the projected climate changes in the Arctic OCS that are most relevant to oil and gas activities and how those changes may affect fish, birds, and marine mammals within the Arctic OCS. How these changes may either mitigate or compound the effects of Arctic energy development is largely described in other chapters of this report (for example, see Chapter 5, Oil-Spill Risk, Response, and Impacts and Chapter 7, Cumulative Impacts). There is a strong seasonality to many of these changes. Some of the changes will compound the effects of Arctic energy activities while others will tend to mitigate them. By judiciously choosing when energy activities occur, environmental risks associated with those activities may be minimized. Finally, we offer a few recommendations.

Table 4–1. Projected climate-change impacts for Beaufort and Chukchi Seas landform areas.

[–, no direct impact, or little impact, relative to the other landform areas]

	Coastal plain	Coast	Continental shelf
Warmer temperatures	Accelerated permafrost degradation. Biological shifts.	Accelerated coastal erosion. Biological shifts.	Warmer surface waters. Reduced sea ice. Biological shifts.
Increased precipitation	Warmer ground temperatures due to thicker snow pack.	Warmer ground temperatures due to thicker snow pack.	Reduced salinity of surface waters.
Increased clouds/fog	Less radiation available for photosynthesis. Reduced visibility.	Less radiation available for photosynthesis. Reduced visibility.	Less radiation available for photosynthesis. Reduced visibility.
Storms	–	Accelerated coastal erosion. Increased storm surges.	More wave action.
Reduced sea ice	–	Accelerated coastal erosion.	Increased light in water column. Warmer surface waters. More wave action. Circulation changes. Biological shifts.
Sea-level rise	–	Areas of western Beaufort coast will be inundated.	Barrier islands shrink.
Ocean acidification	–	–	Disruptions to the food web, marine ecosystems.
Ocean circulation	–	–	Changes in availability and distribution of nutrients.

4.01. Findings:

- *Temperature*. Significant temperature increases are projected to occur in the Beaufort and Chukchi Seas by mid-century, particularly during the autumn and winter. For the A1B ('medium') emission scenario, autumn temperatures are projected to increase roughly 5°C in this region by mid-century, while winter and summer temperatures are projected to increase about 6°C and about 1°C, respectively. These values, based on ensemble averages probably are conservative.
- *Sea Ice*. The seasonal extent and thickness of sea ice are projected to continue to decrease. The Beaufort and Chukchi Seas will still be ice-covered during winter and spring. As at present (2011), the ice edge is projected to move northward through the Bering Strait roughly during June at mid-century. Rapid and extensive summer melting is expected to leave the Beaufort and Chukchi Seas largely ice-free during August–October. Complete freeze-up of the Beaufort and Chukchi Seas is expected to be delayed about 1 month by mid-century, with the ice edge moving back through the Bering Strait in December. The projected timing of the onset of melting in the Beaufort and Chukchi Seas is fairly robust, while that of the autumn freeze-up is much less certain. The ice pack, when present, will be thinner and therefore more dynamic than it historically has been.
- *Precipitation*. Significant precipitation increases are projected to occur during all seasons with the largest percentage of changes occurring during autumn and winter. The intensity of precipitation events also is projected to increase, as is the number of days when precipitation occurs. For the A1B scenario, current models project a 30–50 percent increase during the winter in this region and a 20–30 percent increase during summer. Mid-century values may be roughly one-half this. There is considerable uncertainty associated with the magnitude of the increases. Precipitation increases are expected to contribute to a freshening of the surface waters in the Arctic Ocean.
- *Clouds*. Models consistently project that the Arctic will become cloudier by mid-century. Some of the increase is expected to occur in the form of high-level clouds. Low-level clouds and fog are expected to become more prevalent during the open-water season. In addition, because low-level clouds and fog tend to be associated with open water, they are expected to be present over a greater fraction of the year due to the decrease of sea ice.
- *Icing Conditions*. Icing conditions are expected to occur more frequently in the coastal and marine environments of the Arctic OCS as open-water conditions persist longer during autumn.
- *Winds*. By mid-century, the western side of the Beaufort Sea High (atmospheric anticyclone) may weaken during the autumn season, allowing winds in the Chukchi Sea to be of a more southerly nature (that is, from the Bering Strait) than at present. During winter, the boundary between the Aleutian Low and the high-pressure bridge between Canada and Eurasia is expected to move northward into a location over the Chukchi Sea. This situation may strengthen the predominantly easterly winds during the winter.
- *Storms*. An increase in the frequency and (or) intensity of Polar Lows and other storms during autumn and winter appears likely in the Beaufort and Chukchi Seas based on a number of physical arguments. However, these ideas have not as of yet been rigorously tested so the projected increase in autumn/winter storminess remains uncertain. Projected changes in the degree of summer storminess are highly uncertain.
- *Sea Level*. Current estimates for global sea-level rise are in the range 0.3–0.4 m by mid-century. Sea-level rise in the Beaufort and Chukchi Seas is expected to be somewhat higher due to enhanced thermal expansion and a decrease in salinity. Some areas of the western Beaufort Sea coast are expected to be inundated by rising seas and barrier islands are expected to shrink. Low-lying areas will be increasingly susceptible to damage from storm surges. Artificial islands and causeways built for offshore energy development will be increasingly vulnerable to inundation from sea-level rise and damage from storm surges.
- *Coastal Zone*. The low-lying ice-rich Beaufort Sea coast appears to be particularly vulnerable to climate change impacts, while the Chukchi Sea coast is less so. The expected impacts include: inundation of low-lying coastal areas due to sea-level rise, greater damage caused by storm surges, and accelerated coastal erosion due to a number of factors. Permafrost degradation is expected to increase along both coasts. Barrier islands also are expected to be increasingly susceptible to climate change impacts. A loss of critical habitat is expected for many Arctic species that currently utilize the coastal zone and (or) nearby barrier islands. Unless properly engineered, land-based infrastructure (for example, pipelines, storage tanks) designed to support offshore energy development will be much more vulnerable to damage due to sea-level rise, storm surges, permafrost degradation, and accelerated coastal erosion.
- *Ocean Acidification*. Surface waters in the Arctic Ocean are expected to become increasingly corrosive (acidic) to calcifying organisms, potentially with significant impacts on the Arctic food web and marine ecosystems.
- *Ocean Circulation*. Given the projected changes in many of the factors that control ocean currents (for example, temperature, salinity, wind-fields, sea ice), it is likely that circulation patterns in the Beaufort and Chukchi Seas will change during this century. However, little work has been done as of yet to predict the details of those changes.

4.01. Findings:—Continued

- *Fish.* The distribution, abundance, and species composition of fish populations in the Beaufort and Chukchi Seas and adjacent freshwaters will very likely change over the next 50 years due to climate change. A northward shift of some species and reductions in species with narrow adaptation to Arctic conditions is likely. It is difficult to predict specific changes because we lack critical information concerning relationships between environmental and biological parameters for most species inhabiting this region. Although anadromous fish in the Beaufort and Chukchi Seas are, in general, likely to be more strongly impacted by climate change than marine fish, changing sea ice conditions, salinity, and ocean acidification may strongly impact both diadromous and some marine fish species.
- *Birds.* The distribution, abundance, and species composition of bird populations in the Beaufort and Chukchi Seas and nearby coastal plains will very likely change over the next 50 years due to climate change. The details of those changes remain uncertain due to the high degree of complexity in climate-ecosystem interactions.
- *Whales.* Bowhead whales are not expected to be negatively impacted by decreases in sea ice. Migrant whales (fin, minke, humpback, gray, killer) are likely to be seen more frequently in the Beaufort and Chukchi Seas, and to remain there longer each season in response to decreasing sea ice cover. However, continued acidification of the Arctic Ocean is likely to negatively impact calcifying organisms that form an important part of the diet of filter-feeding Arctic whales (bowhead, fin, humpback, gray, minke).
- *Pinnipeds (Ice Seals and Pacific Walrus).* Bearded seals and Arctic ringed seals are expected to be negatively impacted by projected decreases in sea ice in the Beaufort and Chukchi Seas. The population of ribbon seals likely will decline gradually in the future with projected decreases in the timing and extent of sea ice, but the ribbon seal is not likely to become threatened in the foreseeable future. The seasonal distribution of spotted seals within the Bering, Chukchi, and Beaufort Seas may adjust in response to changing sea ice extent, following the sea-ice front farther north during the summer. The walrus population is expected to be negatively impacted by ocean acidification, which will reduce their benthic food supply, and by continued decreases in sea ice, which will separate them from the majority of their benthic foraging areas.
- *Polar Bears.* The polar bear populations of the Beaufort and Chukchi Seas are expected to be severely impacted by projected decreases of sea ice cover.

4.01. Recommendations:

- *Regional Climate Modeling and Climate Impact Assessments.* The science community is actively engaged in developing state-of-the-art global climate models (AOGCMs) under the auspices of the International Panel on Climate Change (IPCC). However, these models lack the resolution needed to address many of the issues discussed in this report. Support for the development of fully integrated (atmosphere-ocean-land) regional climate models specifically for the Arctic region, as well as periodic Arctic climate impact assessments, is important.
- *Storms.* Several physical arguments have been advanced suggesting the frequency and (or) intensity of storms is likely to increase during autumn and winter. It may be possible to test these ideas without further advances in the AOGCM models. Thus, these tests could be done in the near term. Little is known about how storminess also may change during the summer. Because the Arctic is somewhat decoupled from the global climate system during the summer, it may be possible to investigate changes in future summer storminess with regional climate models. We recommend these investigations be done as soon as possible to reduce the uncertainty of the storminess projections.
- *Ocean Circulation.* Little work has been done as of yet projecting how circulation patterns in the Beaufort and Chukchi Seas may change during the next 50 years. Because those patterns are critical in shaping both the physical and biological environments of the Arctic OCS, and are an important element of spill response models, support for research aimed at better understanding how these patterns may change in the future is important.
- *Biota.* To better assess the potential impact of future climate change on biota in the Beaufort and Chukchi Seas, (1) more research focused on the response of species to changes in various environmental factors should be done, and (2) periodic population and distributional surveys should be undertaken.
- *Science to Inform Arctic OCS Activities.* The best climate models we have today suggest significant environmental changes will occur in the Arctic OCS by mid-century. Given the uncertainties in the magnitude and timing of these changes, and their impact on biological systems, it would be prudent to use an adaptive management approach to Arctic OCS activities. Such an approach would periodically incorporate new knowledge gained from monitoring systems designed to track the actual trajectory of climate change within the Arctic OCS, new research that for example elucidates the response of Arctic biological systems to climate change, and from better climate-prediction models as they are developed.

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Chapter 5

Oil-Spill Risk, Response, and Impact

By Leslie Holland-Bartels and Jonathan J. Kolak

Introduction / Rationale

Parties with interest in oil and gas development decisions in the Arctic Offshore Continental Shelf (OCS) have varying views and concerns over the probability that such activities will result in an oil spill in the Arctic. They also differ in their views of how prepared government and industry are to respond to and understand the consequences of any such spills. The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) expresses the challenge the Nation faces in understanding and balancing the risks to its environmental assets as it explores and utilizes energy endowments.

> ***"Estimating large oil-spill occurrence or large oil-spill contact is an exercise in probability. Uncertainty exists regarding whether exploration or development will occur at all and, if it does, the location, number, and size of large oil spill(s) and the wind, ice, and current conditions at the time of a spill(s). Although some of the uncertainty reflects incomplete or imperfect data, a considerable amount of uncertainty exists simply because it is difficult to predict events 15–40 years into the future" (Minerals Management Service, 2008a).***

The tiered decision process used to inform OCS actions regarding whether and how to proceed with oil and gas development involves making decisions that in the early planning phases have high unknowns but progress to actions whose potential effects and footprint can often be more easily judged. For example, the Federal planning process for oil and gas development steps from general, national OCS-wide 5-year plans, which have the highest unknowns, to lease sale plans, to individual exploration activities, with significantly more project detail. After the U.S. Geological Survey (USGS) OCS Team completed its preliminary examination of documents, it was evident that scientific and technical information related to our Issue Topic of Oil-Spill Response (research needs to allow for an effective and reliable oil-spill response in ice-covered regions) occurs throughout the tiered planning and decision process. Similarly, science needs exist for other agencies that are "downstream" of these planning and decision processes. Within the leasing decision process, for example, there are biological opinions (such as those from the National Marine Fisheries Service, 2008; U.S. Fish and Wildlife Service, 2009) or water and air permit actions (from the U.S. Environmental Protection Agency). There are other processes outside the leasing process that also have a critical nexus to decision making about energy development, and these also require information. For example, while not specific to any leasing process, the Alaska Regional Response Team (ARRT; 2010) provides Federal, State, and local governmental agencies with the means to participate in response to pollution incidents. The ARRT also provides these governments' overall joint spill preparedness and response plans, and its policies on spill countermeasure use are important to spill response in the Arctic and elsewhere. Industry may have the capability to use dispersants; however, they cannot do so without following ARRT guidelines. Similarly, the Natural Resource Damage Assessment (NRDA; National Oceanic and Atmospheric Administration, 2011), which takes place after a spill event and is outside of the BOEMRE program, is an important consideration within the decision framework of many of those that participated in our expert consultations. The main questions are, can the environmental consequences of any potential oil spill in the Arctic be understood and quantified sufficiently to judge the risks and benefits of energy development, and can restoration be accomplished should a spill occur? Uncertainty in the answer to those questions influences public perception, which in turn feeds into the various permitting processes, or into legislative or litigation action. Planning and (or) regulatory actions are taken by a wide range of entities that require scientific and technological information. Based on these considerations we reframed our assignment to consider science needs within the full array of issues that influence the public's perception on the ability to develop effective and reliable responses to oil spills in the Arctic.

First, we provide a brief description of major on-going efforts that identify necessary science and related technologies to help minimize the probabilities of an oil spill and to improve spill preparedness activities. We then focus our examination on how scientific information informs and what gaps might exist for these subjects: (1) estimating the potential effects of oil spills in pre-decisional planning, (2) informing spill contingency planning and spill response, and (3) informing post-spill damage assessment and restoration considerations. At the conclusion of this chapter, we bring in materials first presented in Chapter 4, Climate Change Considerations related to potential future climate conditions in the Arctic and how any changes in environmental conditions might influence our present understanding of oil-spill risk, response, and impact.

Overarching Efforts and Real-Time Communications

The engagement and investment to develop data, approaches, and technologies that inform effective spill response comprise an ongoing and rapidly evolving effort that the USGS OCS Team wanted to ensure was not lost as we delve into specific details later in this chapter. It is best reflected in the numerous on-going study programs and recent documents, forums, and bibliographies that examine research and other preparedness issues. The BOEMRE environmental (Bureau of Ocean Energy Management, Regulation and Enforcement, 2010b) and technology (Bureau of Ocean Energy Management, Regulation and Enforcement, 2010c) programs and ongoing Joint Industry Program (JIP) activities, such as SINTEF (2010), provide up-to-date links to proposed, ongoing, and completed projects. The Prince William Sound Oil Spill Recovery Institute, established by Congress under the Oil Pollution Action of 1990 to support research, education, and demonstration projects designed to address oil spills in Arctic and sub-Arctic marine environments, maintains an active program to examine science associated with issues like the fate and effects of spilled oil in the Arctic and the ability of spill responders to mitigate impacts of spilled oil as reflected in their 2011–2015 Research Plan (Prince William Sound Oil Spill Recovery Institute, 2010).

Scientists, managers, and regulators meet often in a variety of venues to present the most recent progress and challenges. For example, the 2011 Alaska Marine Science Symposium sponsored a workshop "Lessons Learned from the Gulf of Mexico" (http://vislab-ccom.unh.edu/~schwehr/2011AkMarSciSym/, accessed March 30, 2011). Speakers discussed aspects of the *Deepwater Horizon* oil-spill response approaches and challenges as they might inform Alaska spill preparedness. The 2007 International Oil and Ice Workshop (http://www.boemre.gov/tarprojects/587/webpages/home.html, accessed May 5, 2011), the second such workshop, brought together an international audience to advance knowledge of spill response in cold water and ice, including remote sensing, enhancements to mechanical recovery systems, chemical herders in ice, cold-water dispersants, experimental spills, case studies, and ongoing and future research programs. The bi-national U.S. and Canada Northern Oil and Gas Research Forum and the BOEMRE Information Technology Meetings offer opportunities to share new information in many topical areas. Discussions cover, for example, environmental conditions in exploration areas, interaction of oil and gas activities with sensitive coastal habitats, ice engineering for offshore operations, oil-spill prevention and management in the Arctic, and monitoring for cumulative effects. Presentations are publicly available (for example, North Slope Science Initiative, 2010; Bureau of Ocean Energy Management, Regulation and Enforcement, 2011a). Focused workshops, such as the U.S. Coast Guard (2010) on operating in the Arctic or Coastal Response Research Center (2009, 2010), examine factors to improve preparation and response to marine incidents and document practitioner perspectives on operational and science gaps. A wide variety of near real-time information related to oil and gas development considerations is generated and shared in a variety of these forums. The question is not if such information is being produced, but rather what that information is and how it moves into the appropriate planning and decision processes of regulators and other vested parties.

5.01. Finding: The level of information and the number of entities generating scientific and technical information on spill preparedness topics are increasing exponentially as enhanced attention is turned towards the Arctic in general, and resource development more specifically. Individually, sources are well structured, but they roll up to a complex information challenge. It is difficult to know which identified needs are being addressed fully or partially, what new issues or insights have emerged, or how one should weigh the importance of identified gaps.

5.01. Recommendation: The coordinated organization of data for access and distribution by all parties of particular workshop findings and recommendations would improve the value of such forums to help guide science planning and funding decisions. A holistic and up-to-date analysis of recommendations and insights presented in these "real-time" symposia also would help clarify and bring more transparency to what new or continued science investments are needed. Potential approaches to consider are systems similar to the National Biological Information Infrastructure portal (http://www.nbii.gov/) or enhancements of existing systems, such as Alaska Ocean Observing System (AOOS) (http://www.aoos.org/) or the North Slope Science Initiative (http://www.northslope.org/).

Minimize Spill Probabilities Through Infrastructure Decisions

The USGS OCS Team is not well positioned to rigorously consider the state of knowledge or key information and technology gaps related to infrastructure engineering. However, it generally is accepted that effective Arctic technologies are the first step in overall oil-spill risk minimization. In addition to technologies, a sound understanding of bathymetry, ice scour, and shoreline erosion data and processes can improve infrastructure siting decisions. The BOEMRE has an active program to develop safety-related information in advance of future operations in the Arctic. As part of their Technology Assessment and Research Program, engineering properties and forces of moving ice on structures and pipelines are being studied (http://www.boemre.gov/tarprojectcategories/ice.htm, accessed March 30, 2011). The IMV Projects Atlantic (2008) assessed the current state of offshore technology in Arctic and sub-Arctic regions that might be applied in the Beaufort, Chukchi, and Bering Seas. They suggested the following to be valuable:

- development of a regional ice gouge database for the U.S. Beaufort and Chukchi Seas;
- identification of ice gouge recurrence rates;
- collection of multi-year ice thickness distribution, ridge dimensions and frequency within a floe, floe-size distribution, floe-speed distribution;
- definition of first-year ice thickness distribution, ridge dimensions;
- development of a regional geotechnical database;
- advancements in allowable/acceptable pipeline strain limits, repair techniques, leak detection systems;
- advancements in subsea protection systems, and trenching technologies;
- increased clarity on emergency well-control requirements; and
- advancements in determining maximum gouge depth based on ice strength and driving forces.

The IMV Projects Atlantic authors also examined open-water conditions with large fetches and waves because of the potential and now realized higher waves resulting from greater ice-free periods. The authors felt limited in their ability to consider this topic and supported the need for the compilation and collection of ice, meteorological, and oceanographic information to be used by all parties involved in infrastructure decisions. The generation of such data is an ongoing process within the BOEMRE annual studies process.

As noted above, information exchanges, such as the bi-national U.S. and Canada Northern Oil and Gas Forums, offer the best insight into topics that need to be addressed in the near term. Practitioners are investigating approaches to address ice forces on offshore platforms; offshore structure design challenges from ice load, scour, and thaw strain; predictive advances for critical sea-ice characteristics; extreme ice events; and impacts of increased open-water summer storms. These and other international forums support rapid and efficient transfer of state-of-the-art information on advancing technological challenges and successes.

Examples of the BOEMRE Technology Assessment and Research Program titles for Arctic safety and ice mechanics projects.

(http://www.boemre.gov/tarprojectcategories/ice.htm)

- Sea-ice scaling effects
- Engineering model for ice/soil/pipeline interaction
- Sea Ice Mechanics Workshop
- Safety/integrity of Arctic marine pipelines
- Scour and Arctic Marine Pipeline Workshop
- Risk assessment for ice damage to seabed facilities
- Ice Scour and Arctic Marine Pipeline Workshop
- 22nd International Offshore Mechanics and Arctic Engineering Conference
- Construction and maintenance of ice islands: Current practice and future research
- Measurement and control of underwater noise from oil drilling and production operations
- Design options for offshore pipelines in the U.S. Beaufort and Chukchi Seas
- Arctic offshore technology assessment of exploration and production options for cold regions of the U.S. Outer Continental Shelf
- Banff 1999, 2001, 2003 Pipeline Workshops
- Sea spray icing of drilling and production platforms
- Assessment of superstructure ice protection as applied to offshore oil operations safety
- Seabed scour and buried-pipeline deformation due to ice ridges
- Collection and archiving of environmental data relevant to design of Arctic structures
- Beaufort and Chukchi Seas ice design criteria
- Frictional sliding of sea ice
- Tracking ice islands and extreme ice features from Ellesmere Island to the Chukchi Sea
- 2009 freeze-up study of the Alaskan Beaufort Sea and Chukchi Sea
- ICESTRUCT JIP: Ice Effects on Arctic Offshore Structures
- Arctic Offshore Technology Assessment
- 2010 freeze-up study of the Alaskan Beaufort and Chukchi Seas

5.02. Finding: Significant coordinated international effort by industry and governments is taking place to develop safe and effective infrastructure and technologies to access energy resources in ice-covered Arctic waters. It appears that potential individual stress points are being well analyzed. Practitioners are investigating approaches to address offshore structure design challenges from forces, such as: ice load, scour, and thaw strain; and predictive advances for critical sea-ice characteristics, extreme ice events, and impacts of increased open-water summer storms. It was not evident to us how these efforts come together in a holistic analysis of full system risks to identify sensitive infrastructure components and the priority science and technology needed to enhance performance and safety. The types of physical threats to infrastructure related to ice (described above) generally are known but their distribution and the degree of the threat across the geography of potential leasing areas were not fully evident in our limited examination.

5.02. Recommendation: Efforts by the BOEMRE and industry to facilitate discussions of infrastructure needs and advances should receive continued support. For example, the recommendations of the BOEMRE-commissioned study by IMV Projects Atlantic (2008) to compile and collect ice, meteorological, and oceanographic information to be used by all parties involved in infrastructure decisions should continue to be considered and incorporated into the annual Federal and industry work planning process. However, many-faceted and different entities examine infrastructure needs and potential solutions and this is a highly technical discipline. Thus, communication of advances and discussion of remaining critical needs could be enhanced through a coordinated, transparent full-cycle risk model. While this would be valuable within the engineering and technical community, such an approach also could provide a more effective means for the non-engineering community to see, understand, and engage in discussions about development benefits and risks.

Assessing Risks and Potential Effects of Oil Spills

Background

Oil-spill risk analyses and their models and input data requirements used in Beaufort Sea and Chukchi Sea Planning Area decisions follow national protocols outlined in numerous documents (for example, Minerals Management Service, 2006 [appendix C], 2008a; Bureau of Ocean Energy Management, Regulation and Enforcement, 2010a). The major modeled components in these analyses include estimates of spill occurrence, spill trajectories, oil weathering patterns, and intersection probabilities with specific landscape units that are used to estimate fate and effect.

Two key probability analyses are considered—the hazard-based Conditional Probability and the risk-based Combined Probability. The former assumes a spill has occurred and then estimates the percent chance that a large spill would reach coastal habitats or other critical assets (for example, archeological sites, harbors). The latter expresses the percent chance of one or more oil spills ≥1,000 barrels (bbl) occurring and that such oil contacts a certain environmental resource area or land segment. The chance of one or more large spills occurring is derived from the spill rate (obtained from a fault-tree analysis discussed below) and the assumed resource volume. These analytically derived risk probabilities are subsequently combined with best available ecological information to qualitatively express potential impacts as illustrated in this excerpt from the Minerals Management Service (2007):

> " The Oil-Spill-Risk Analysis (OSRA) model estimates a 40% chance of one or more large spills ≥1,000 bbl occurring over the production life of Alternative I, but only 1% chance of one or more large spills occurring and contacting the U.S. Chukchi coastline within 3 days over the production life of Alternative I. If a large oil spill did contact this coastline, the oil probably would persist in a few of the tidal and subtidal sediments for a couple of decades, leading to a local but moderate effect on the few intertidal lower trophic-level organisms. The chance of one or more large spills contacting the U.S. Chukchi coastline increases to 6% within 30 days over the production life of Alternative I, demonstrating the advantages of requirements for rapid response capability."

Estimation of Spill Occurrence

Because there is limited Arctic OCS development, sufficient historical data on offshore Arctic oil spills do not exist to calculate spill probabilities directly. The BOEMRE has used Gulf of Mexico (GOM) and Pacific OCS data as analogs. However, since 2002, the BOEMRE has modified and supplemented these data to represent expected Arctic performance for large spills through a statistical fault-tree approach (for example, Bercha Group, Inc., 2006a, 2006b, 2008a, 2008b). Figure 5–1 shows a typical fault tree for both large pipeline and platform spills. Input rational is developed for Arctic modified effects, such as for process plant and storage tank release, structural failure, storms, and collision events (table 5–1). Arctic-unique effects are additive components whose quantifications are done in a "relatively cursory" way based on judgment (Minerals Management Service, 2006, appendix C). Updating the methodology and input data are a regular part of the BOEMRE Alaska OCS annual study planning process. For example, the 2011 proposed plan includes the updating of the fault-tree analyses with any new oil-spill occurrence reports, geohazard data, or GOM OCS historical data inputs; generation of fault-tree analyses for Arctic oil and gas lease sales based on the BOEMRE exploration and development scenarios; and generating life-of-field oil-spill occurrence rates and indicators (Prentki, 2010).

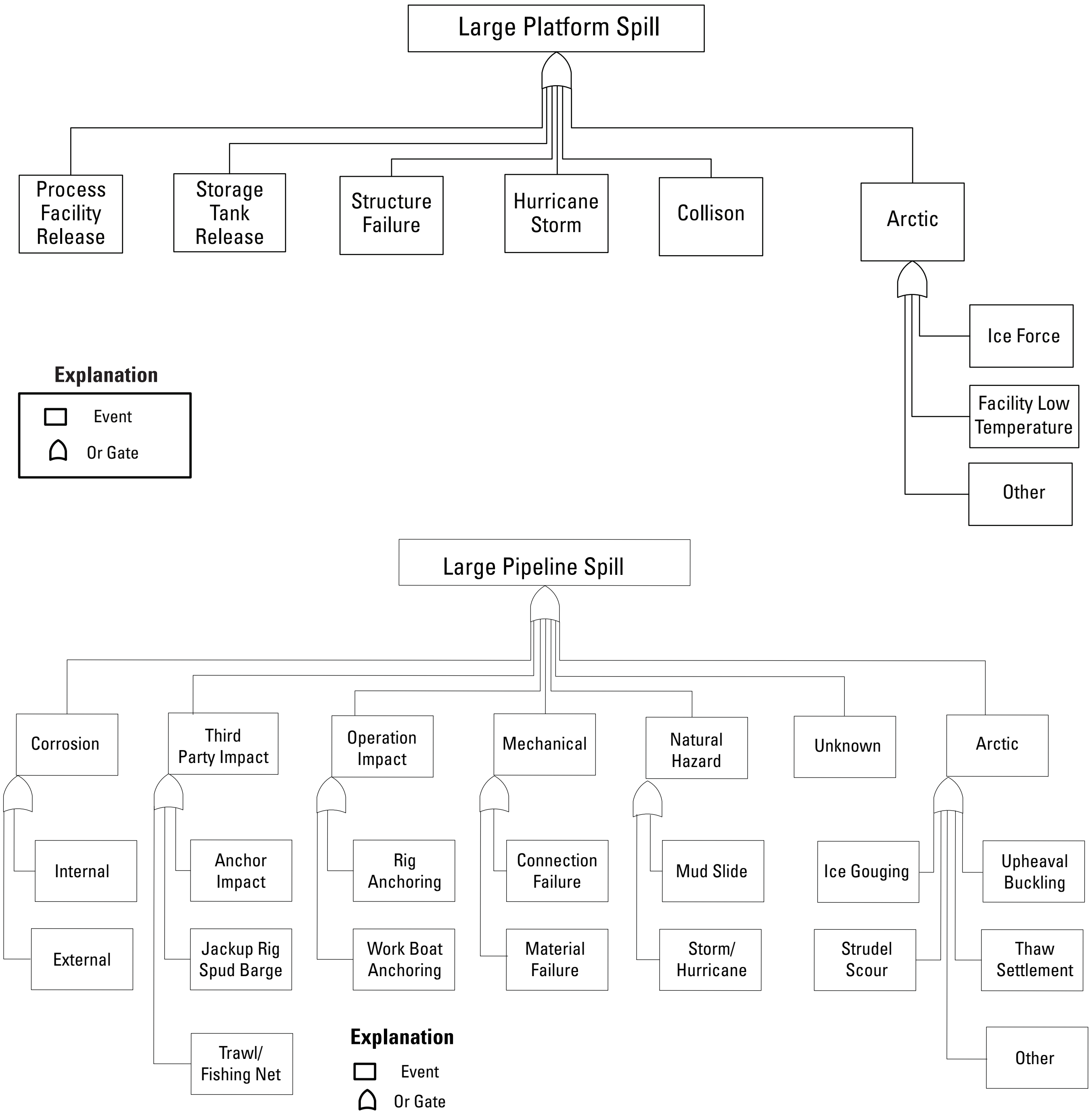


Figure 5–1. Typical fault tree for pipeline or large platform spill outlining key inputs including Arctic-specific factors, such as upheaval bucking, ice gouging, thaw settlement, scour and ice force, and facility temperature (Minerals Management Service, 2006, appendix C, figs. C–2 and C–3).

Table 5–1. Example of platform fault-tree input rational for Arctic modifications and unique considerations from Gulf of Mexico base data.

[Minerals Management Service, 2006, appendix C, table C–2. **Spill size:** All, all spill sizes combined; SM, small (≥50 and <100 bbl) and medium (≥100 and <1,000 bbl); HL, large (≥1,000 and <10,000 bbl) and huge (≥10,000 bbl)]

Event classification	Spill size	Percentage of frequency change			Reason
		Shallow	Medium	Deep	
Arctic modified					
Process facility release	All	(30)	(30)	(30)	State-of-the-art now, high quality control, high inspection and maintenance requirements
Storage tank release	All	(30)	(30)	(30)	State-of-the-art now, high quality control, high inspection and maintenance requirements
Structural failure	All	(20)	(20)	(20)	High safety factor, monitoring programs
Hurricane/storm	All	(50)	(40)	(30)	Less severe storms
Collision	All	(50)	(50)	(50)	Very low traffic density
—		Frequency increment per 10^4 well-year			—
		Median	Median	Median	
		Expected	Expected	Expected	
Arctic unique					
Ice force	SM	0.1447	0.2170	0.3256	Assumed 10,000 year return period ice force causes spill 4 percent of occupancy 85 percent of the spills are SM
		0.0340	0.0510	0.0765	
	HL	0.0255	0.0383	0.0575	
		0.0060	0.0090	0.0135	
Facility low temperature	SM	0.1000	0.1000	0.1000	Assumed 10 percent of historical process facilities release frequency and corresponding spill size distribution
		0.1000	0.1000	0.1000	
	HL	0.0080	0.0080	0.0080	
		0.0080	0.0080	0.0080	
—	SM	0.0244	0.0316	0.0424	10 percent of above
		0.0134	0.0151	0.0177	
	HL	0.0033	0.0046	0.0065	
		0.0014	0.0017	0.0022	

5.03. Finding: The spill probability—fault-tree process—is a well documented, transparent, and best available approach to deal with estimations of spill likelihood in the Arctic OCS given that regional historical data on spills are not available. However, the approach depends on accurate adjustments of non-Arctic data to likely Arctic outcomes, which are admittedly done in a somewhat cursory manner. Climate change considerations also may alter the validity of spill frequency adjustments. For example, adjustment of GOM spill frequency probabilities downward because of an assumption that storms are less severe in the Arctic and that a reduced collision rate exists because of less traffic (table 5–1) as compared to GOM values may need to be reconsidered. For example, increases in storm severity and traffic patterns have already been observed and may increase in response to changing climate and ice conditions in the Arctic (see Chapter 4, Climate Change Considerations).

5.03. Recommendation: Continued updating of spill data, re-examination of statistical approaches used in the application of non-Arctic analogs (see Eschenbach and others, 2010), and rigorous development and incorporation of climate-influenced forecasts on factors such as storms, vessel traffic, or other fault-tree model adjustments would provide improved understanding of and confidence in spill risk estimates over the proposed project life.

Spilled-Oil Weathering and Persistence

The weathering characteristics of spilled oil influence the range of drift and spreading considered within spill trajectory assessments and dictate the effectiveness of chemical dispersants, *in-situ* burning, or mechanical responses (Daling and others, 1997; Prenki and others, 2004; fig. 5–2). The BOEMRE employs the Norwegian-developed and field tested (Daling and others, 1997; Daling and Strøm, 1999) SINTEF Oil Weathering Model (OWM) that incorporates oil density, viscosity, pour point, flash point, and water content and physical processes, such as spreading, evaporation, oil-in-water dispersion, and water uptake, as factors within its model-weathering calculations. The OWM is run over a 30-day time horizon, but has not been verified against field data for more than 4–5 days, nor does the SINTEF OWM incorporate the effects of currents, beaching, photo-oxidation, microbiological degradation, adsorption to particles, or encapsulation by ice that might affect degradation rates and toxicological characteristics. A summary of the model and uses within OCS analyses are presented by Prentki and others (2004).

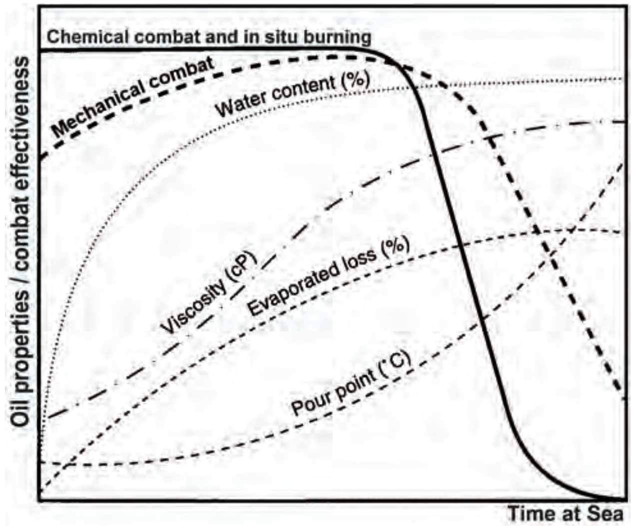


Figure 5–2. Schematic from Daling and others (1997, fig. 2) showing how oil properties change over time and influence spill response tool effectiveness.

Weathering is the combination of numerous physical, chemical, and biogeochemical processes acting to alter the phase and (or) composition of the oil. The processes affecting the weathering of oil spilled in open water, even in cold-water environments, generally are well understood (Fingas, 2008b). Many of the fundamental processes—such as evaporation, dissolution, spreading, and photodegradation—affecting oil weathering in the Arctic also occur elsewhere, but may occur at different rates given the specific meteorological conditions present in the Arctic. Yet, when compared with the current body of knowledge regarding oil weathering processes in open-water and temperate conditions, the body of knowledge regarding these processes in the context of Arctic oil spills is "very limited" (Brandvik and Faksness, 2009).

Laboratory testing provides a view into the nominal response of various oil types to weathering under different environmental conditions. Simulations of spills in various ice conditions have been done (for example, Prentki and others, 2004), but with limited field testing. The JIP on oil spill contingency for Arctic and ice-covered waters addresses some of these shortfalls by conducting a suite of studies from laboratory testing to full-scale field tests. Efforts, such as those by Brandvik and others (2010a) to conduct mesoscale weathering experiments in both the laboratory and at small-scale field scales, provide data to improve the capacity of oil weathering models to better predict oil weathering in cold and ice scenarios. Oil properties (for example, evaporation, emulsification, natural dispersion, flash point) have been experimentally assessed in the laboratory through time in different ice coverages (for example, 0, 30, 50, 70, 90 percent) and for different oils; these assessments directly inform spill response planning. Mesoscale field experiments conducted under the JIP, such as those conducted in Svalbard, Norway (Brandvik and others, 2010a) reduce the uncertainties of oil behavior characteristics that are critical to spill trajectory models and spill contingency plan strategies. For example, Brandvik and others (2010a) found that ice presence can slow weathering processes such as evaporation and emulsification, and can extend the operational window for the use of tools such as dispersants and *in-situ* burning.

Oil emulsification is an important weathering process to understand because emulsification can inhibit the effectiveness of oil-spill countermeasures, and preserve some of the constituents in oil that would otherwise tend to degrade—such as n-alkanes and some classes of polycyclic aromatic hydrocarbons (PAHs). This preservation also can prolong the potential for spilled oil to serve as a source of toxic contaminants, such as PAHs, to the environment. For example, Short and others (2007) noted that residual emulsified oil ("oil mousse") contained abundant levels of these compounds in subsurface sediments of Prince William Sound shorelines some 16 years after the *Exxon Valdez* oil spill, indicating that the "…remaining subsurface oil may persist for decades with little change."

There has been extensive study of water-in-oil emulsions (Fingas, 2008b) under different conditions ranging in scale from laboratory bench top to field tests. Three categories of emulsions—stable, unstable, and meso-stable—with distinct physical properties generally are recognized. For example, viscosity can vary by several orders of magnitude across these categories, and thus have ramifications for the fate and transport of emulsified oil in the marine environment. The composition of the source oil is a key factor affecting the potential of forming and the resulting stability of emulsions. The addition of energy, such as through wave action, is needed to initiate emulsification, but the threshold energy level needed to initiate this process is not well understood. Recent attempts to derive empirical models describing the formation of oil-in-water emulsions have been hindered by our limited understanding of the chemical behavior of oil constituents in the environment (Fingas, 2008b).

Sea ice also can affect the formation of water-in-oil emulsions. Studies conducted on the fate of oil released in multi-year ice documented that ice morphology is a key parameter affecting oil weathering in the presence of ice (Payne and others, 1991). These researchers have observed that

> "[m]elting first-year ice produced substantial amounts of slush ice, and a stable water-in-oil emulsion of Prudhoe Bay crude oil containing up to 60 percent water was formed within 4 hours of the onset of wave agitation in this slush ice field. In contrast, rotting multi-year ice appeared to have a much lower tendency to produce a slush ice matrix during melting, and the formation of stable water-in-oil emulsions occurred over a relatively longer period of time."

A better understanding of these processes could help delineate the timeframe over which emulsions can form and the "time window" for effective operational response. Knowledge of the stability of emulsions over time underpins monitoring the fate and transport of spilled oil through trajectory modeling and the compilation of oil weathering budgets.

Full-scale field experiments provide invaluable ground-truthing and adaptive learning opportunities. Few such experiments have been conducted in the Arctic and none in U.S. waters. Sørstrøm (2009) and Brandvik and others (2010b) document the most recent large-scale effort conducted in the Barents Sea in spring 2009. Oil weathering experiments, oil distribution and bioavailability, and actual systems of spill contingency were assessed. Field data support findings from mesoscale laboratory efforts on the nature of physical and chemical change as oil weathers under ice conditions.

Persistence of oil was significantly underestimated after the *Exxon Valdez* oil spill. Short and others (2007) found that during early stages of the spill, less viscous oil readily percolated into finer grained beaches and, as the spill progressed along the Gulf of Alaska, more exposed and bouldered beaches allowed the increasingly viscous oil to percolate into "protected" interstitial areas. It remains unclear what "refugia" sea ice and eroding shoreline characteristics in the Arctic may offer oil and what might be the influences on the spatial or temporal degradation of oil. Oil spilled under the ice may be incorporated into the ice sheet where comparatively little weathering/degradation may occur; however, during the spring melt, the encapsulated oil may be released and undergo evaporation and other processes. For this reason, the effect of sea ice on oil weathering is a critical consideration to oil spill contingency planning and response in the Arctic. A substantial body of work was conducted during the 1970s and 1980s to characterize the fundamental processes affecting how oil may become incorporated within ice, and subsequently affect oil weathering (Payne and others, 1991). This incorporation may occur fairly rapidly, in as little as 18 to 72 hours, depending on the time of year (Dickins and Buist, 1981). Recent studies of oil-in-ice interactions addressed a knowledge gap pertaining to how these interactions may affect the efficacy and (or) timing of the potential deployment of spill countermeasures. Brandvik and Faksness (2009) reported that:

> "[o]perationally important weathering processes for oil spill operations like water uptake, emulsion stability and viscosity vary with oil type. Normally they increase relatively fast with increased weathering time in open water. In ice-infested water, several studies have indicated that this increase with time (for example, water content) can be drastically changed depending on ice type, ice coverage and energy conditions in the ice. Little knowledge concerning this is available today, and only for a limited number of oil types and ice regimes… ."

One example of the need to understand these processes in the context of oil-spill response operations is as follows:

> "after only a few hours of weathering on open waters, an oil spill may become too viscous for application of dispersants; yet that same spilled oil, if associated with dense ice, may be amenable to treatment with dispersants even after several days of weathering" (Brandvik and Faksness, 2009).

As a result, the presence of sea ice may serve to inhibit natural weathering processes, and could thus serve to expand the operational "time window" for deployment of spill countermeasures.

Seasonal variations in sea ice also merit consideration for oil-spill response. For example, if oil was spilled under ice in the spring (after May), the oil might not become encapsulated in the ice due to insufficient new ice growth before seasonal melting commenced (Buist and others, 2008a). Conversely, a spill occurring just prior to or during freeze-up (Lewis and others, 2008) may become rapidly incorporated in ice, such that response efforts could include a combination of oil recovery and ice tracking and monitoring operations. State-of-the-art models, such as the SINTEF model, require detailed physical and chemical information to characterize the oil-ice interaction; such level of detail typically is not available (Brandvik and others, 2006). Further, Brandvik and others (2006) reported that the state of modeling of oil weathering in the presence of sea ice remained constrained by the ability to model sea-ice physics at the appropriate scale. The need to further refine and verify these models of physical processes on oil fate and transport is identified as an information need for oil-spill response in the Arctic (U.S. Arctic Research Commission, 2010).

One of the key processes of oil weathering is the extent and nature of interaction of oil with brine channels in ice. For example, in earlier studies, Payne and others (1991) noted that

> "[i]f oil is released into water under freezing conditions of active ice growth, lower molecular weight aromatic components can be advected with the sinking brine generated during frazil ice formation to the stable bottom boundary layer where, as conservative dissolved compounds, they can persist without evaporation for periods of up to several months."

To further investigate the fate of hydrocarbons from spilled oil in ice, Faksness and Brandvik (2008) conducted field experiments to evaluate the potential for dissolution of water-soluble components (WSCs) into and through first-year (annual) ice. The transport of WSCs from the oil through the ice was documented, and low but detectable concentrations of these components at the bottom of the ice core were measured. This transport mechanism may serve as a vector by which biota at the bottom of the ice sheet are exposed to these WSCs, with the potential for entrainment into the Arctic marine food web. The authors compared the field studies with laboratory experiments—using the Chemical Response to Oil Spills: Ecological Effect Research Forum procedure—and the similar distribution of WSCs in both sets of samples was interpreted to reflect that the brine channels in the ice sheet serve as a transport mechanism of WSCs from oil, through ice via the channels, and into the underlying water.

Natural biodegradation of oil in the marine environment is part of the process of oil weathering, and biostimulation and bioaugmentation have been considered as oil-spill countermeasures (Swannell and others, 1996). In general, however, oil biodegradation rates are difficult to predict, given the influence of oil type, variability of substrates, and other variable factors, such as temperature and nutrients (Zahed and others, 2010). In 1981, an experimental spill, known as the Baffin Island Oil Spill (BIOS) Project, was conducted on the northern tip of Baffin Island in Nunavut, Canada, as a means of studying natural biodegradation from an Arctic marine oil spill (Sergy and Blackall, 1987). Although much of the original oil has naturally degraded over time, follow-up studies have shown that some patches of the spilled oil remain essentially unaltered after decades of exposure (Prince and others, 2002). The interactions with sea ice may affect oil biodegradation processes, and can provide routes for components from spilled oil to enter the Arctic marine food web (Faksness and Brandvik, 2008).

A good understanding of ambient microbial communities and processes is needed for the water column, sediments, and ice to understand the potential for microbial degradation of oil in the Arctic, and the potential impact of this on oil fate and ecosystem uptake. There have been recent activities to increase our knowledge in these areas (Interagency Coordinating Committee on Oil Pollution Research, 2009). Braddock and others (2004) noted that despite large-scale development on the Alaska North Slope, there was limited understanding of microbial communities in this setting, and much of this derived from studies that were decades old. Garneau and others (2009) reiterated this point, noting that the microbial characteristics of the coastal Arctic Ocean have been little explored, but that studies conducted to date on the Mackenzie Shelf in the Beaufort Sea provide information on the existence of diverse and active microbial communities, with variation among communities across salinity gradients. A survey of microbial populations from offshore of Barrow and

5.04. Finding: The interaction of ice and oil has long been recognized as an important factor affecting oil fate and toxicity in the Arctic environment. Recent studies have focused on oil-water partitioning (water-soluble compounds, WSCs) associated with ice melt and brine channel flux in the ice column.

5.04. Recommendation: There is a need to better understand oil-in-ice weathering, particularly as it relates to the effectiveness of spill response countermeasures and the potential for ecosystem exposure. Oil-water partitioning is recognized as needing further study, especially the potential toxicity of the partitioned phases, as oil trapped in ice may remain relatively fresh (that is, toxic). This process also points to the potential for a longer term spill response that follows the initial event for potentially several months given seasonal changes to the ice column (melting).

Prudhoe Bay, Alaska, provides a more recent characterization of endemic populations and metabolic capability to degrade petroleum hydrocarbons (Braddock and others, 2004). Braddock and others (2004) reported that the total microscopic counts of bacteria and culturable heterotrophs in the sediment samples were comparable with estimates from studies conducted in the 1970s and 1980s in the same areas. Kirchman and others (2010) investigated potential seasonal and spatial variations of bacterial community structures in the Arctic Ocean to help improve the fundamental understanding of relationships between bacteria and phytoplankton in the Arctic Ocean, which appear to differ from those found in lower latitude oceans. This information helps inform our understanding of primary production during the rapid transition from spring to summer when ice coverage decreases in the Arctic Ocean. In water column samples collected from various locations in the Chukchi and Beaufort Seas, there generally was no significant seasonal variation in communities despite strong seasonal gradients in biogeochemical properties (Kirchman and others, 2010). These findings may have ramifications regarding the ecophysiological flexibility of bacterial communities in the areas sampled (Kirchman and others, 2010). This is an area for further research as it could have implications for the adaptability of indigenous microbial communities to changes in carbon source, such as in the event of an oil spill.

Recent studies following the *Deepwater Horizon* oil spill have shown the importance of characterizing not only the indigenous microbial communities in benthic sediments, but also those in the water column. In particular, Hazen and others (2010) reported natural biodegradation of the dispersed oil plume in deep water. Because the microbial communities appeared to rapidly adapt—as reflected in hydrocarbon-degrading genes—in response to the oil plume, the researchers concluded that there was potential for intrinsic bioremediation of oil contaminants in the deep sea. As such, these communities may have an important role in the fate of hydrocarbons in the GOM (Hazen and others, 2010). Analogous studies of indigenous microbial populations in the Arctic are warranted to gain a better understanding of the potential for these processes to naturally attenuate an Arctic oil spill.

Oil-Spill-Trajectory Models

The OSRA Model (Smith and others, 1982) as refined by Labelle and Anderson (1985), Ji and others (2004), and others simulates oil-spill transport and is dependent on realistic wind velocity and ocean surface current data, as well as accurate information of the ecological, economic, and (or) social resources located along coastlines that might be transected by oil. State-of-the-art trajectory models and quality input data for spill trajectory likelihoods are represented by analyses for the GOM. Johnson and others (2007) reaffirm the conclusions of Ji and others (2004) that oil-spill risk analyses are dependent on detailed information of ocean currents and wind fields. The ocean current inputs are computed from an ocean circulation model driven by analyzed meteorological forces through models such as the Princeton-Dynalysis Ocean Model, which have been extensively assessed with field observations in the GOM (Herring and others, 1999) including data from some 340 drifting buoys (Ji and others, 2004). Similar rigorous data are not presently available for the Arctic OCS, but a strong scientific framework is emerging for 3-D coupled ice-ocean models and 2-D ice-associated oil spill models (for example, Wang and others 2003, 2010) that will improve as knowledge about oceanographic characteristics of the Beaufort and Chukchi Seas increases. Efforts to understand and address data insufficiencies are the focus of numerous ongoing studies by BOEMRE, the Alaska Ocean Observing System, and others.

5.05. Finding: Natural biodegradation of oil in the marine environment is part of the process of oil weathering. The presence of microbial communities gives rise to the potential for intrinsic bioremediation of oil spills. Indigenous microbial populations in the Arctic may play an important role in the fate of hydrocarbons following an oil spill. However, the effect of these populations on such oil weathering in the Arctic is not well understood.

5.05. Recommendation: Recent studies underscore the need to better characterize Arctic-based indigenous microbial populations in the water column and benthic sediment, and define rates of microbial processes. This will ultimately allow for the full characterization of the role such communities have in the oil weathering process.

Well documented analyses of data and technology needs for meteorological and physical oceanography can be found in Beaufort Sea assessments by Hoefler Consulting (2006, 2007) and Weingartner and others (2010a). Present Arctic assets are listed within the interactive Alaska Ocean Observing System's Arctic Assets Application (fig. 5–3). Hoefler Consulting (2006) recommends the establishment of a redundant sensor system. The current lack of redundancy may result in a critical link remaining down for some time should it fail, due to weather and logistical limitations to access the site and the cost of site visits. Such a system also would serve as an enhanced Arctic coast-wide network to serve spill response goals and inform broader questions such as how climate change may affect system dynamics (fig. 5–4). Weingartner and others (2010a) outline a series of large-scale studies that would help define the critical oceanographic characteristics of the Beaufort Sea OCS to better inform pre- and post-spill modeling/response. These also would define environmentally sensitive marine areas by examining oceanographic exchanges, understanding shelf-basin exchange via wind and eddies, better defining characteristics of the coastal boundary and under-ice river plumes, and defining the sea-ice boundary through examination of thickness and under-ice topography. New analyses of mooring data by Weingartner and others (2009) provide a scientific foundation to understand likely movement of a spill in near-shore waters, such as oil spilled beneath landfast ice. Such work appears to be more mature for the Beaufort Sea dating back to efforts under the 1970s Outer Continental Shelf Environmental Assessment Program (OCSEAP, for example, Aagaard, 1981), but attention to Chukchi Sea conditions has increased (for example, Weingartner and others, 2005). Newly installed high-frequency land-based radar (fig. 5–5) holds promise to provide near-shore real-time current data of value for spill modeling, as well as for spill response (Potter and Weingartner, 2009; Weingartner and others, 2010b). The International Ocean Observing System (2009) presents partner perspectives on the present needs for this technology for all their regional networks. Should development in the Arctic OCS continue, it is likely that an increased number of such sites should be considered. Regardless of the development future, while the number of Arctic sites presently is not dramatically different from those in the GOM, the Arctic has fewer oceanographic assets (for example, buoys) in general and would benefit from increased access to this new technology. Analyses critical to such large-scale integrated efforts to better understand oceanographic circulation factors in Arctic oil-spill risk analyses are ongoing through BOEMRE (fig. 5–6).

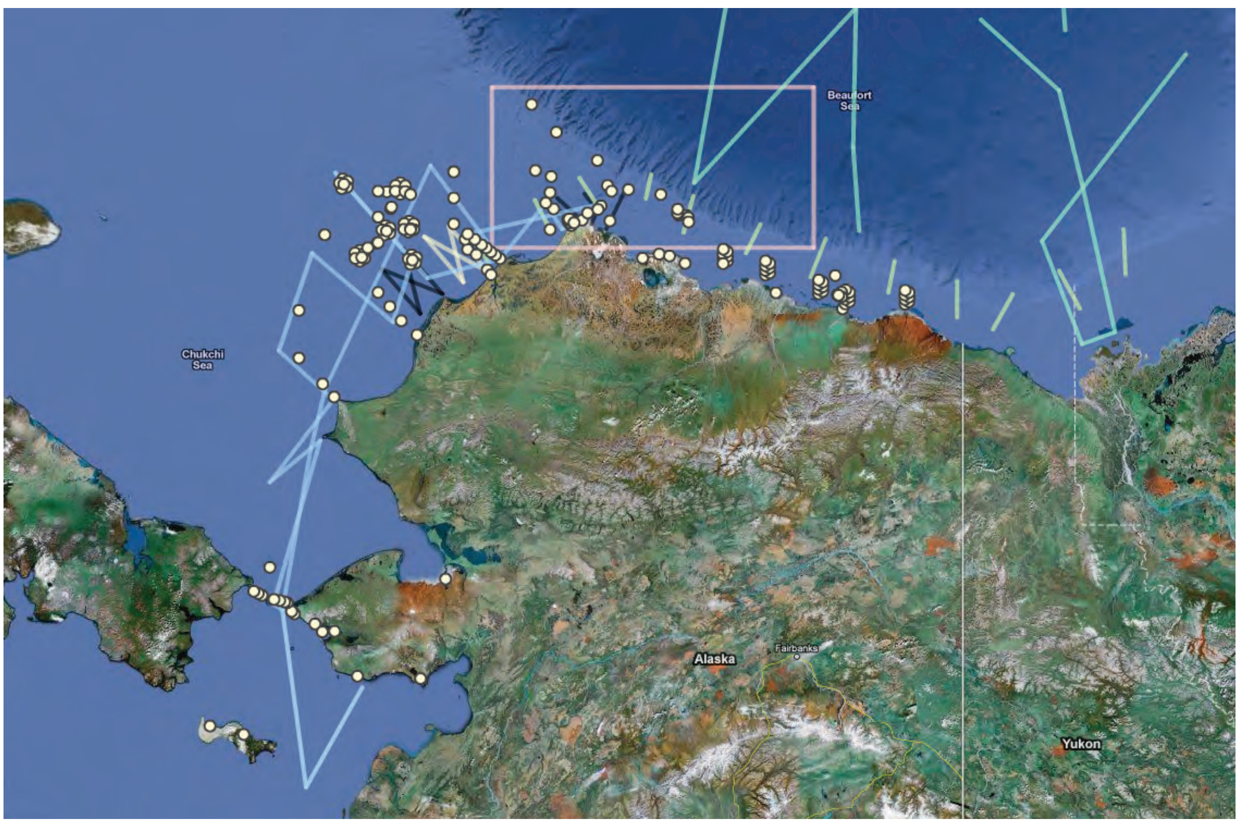
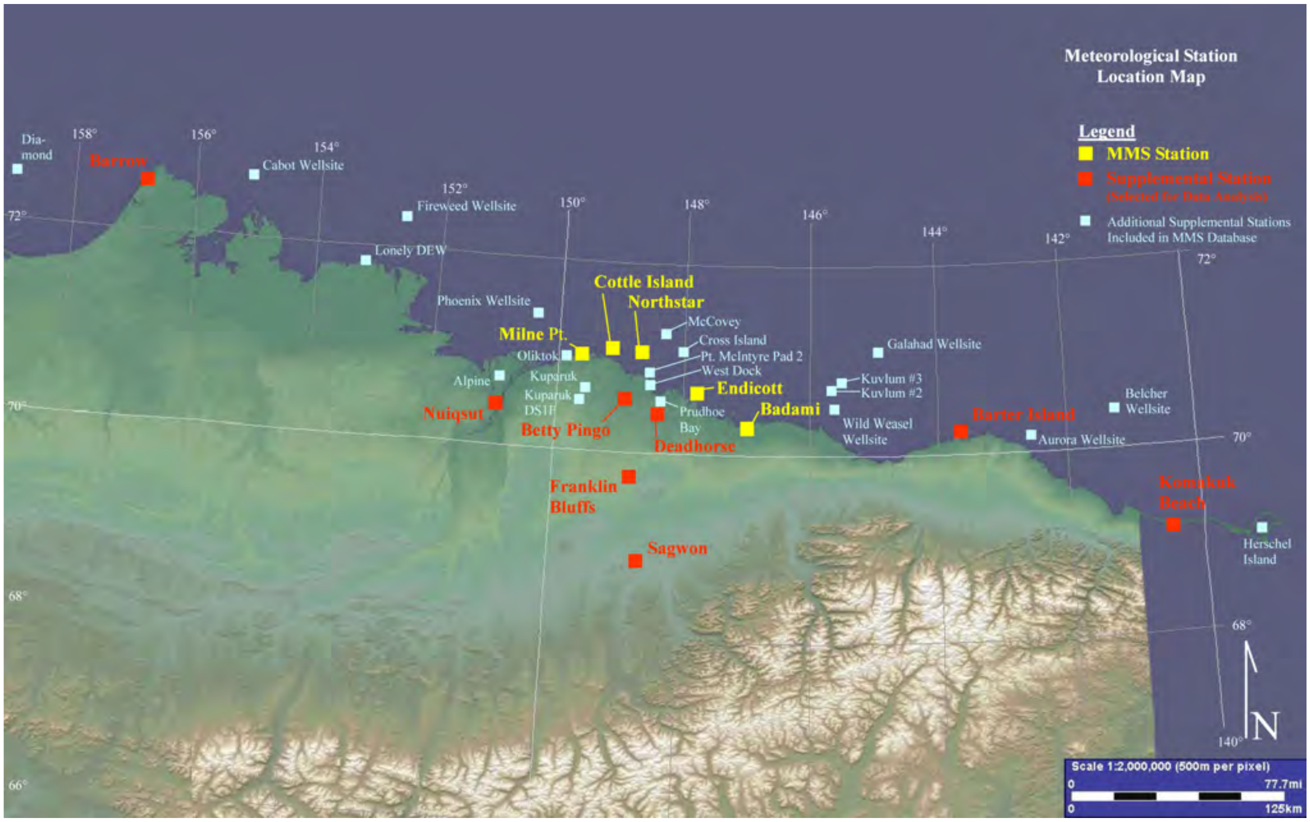


Figure 5–3. Examples of recent oceanographic cruises and sensor assets in the Beaufort and Chukchi Seas taken from the interactive Alaska Ocean Observing System's Arctic Assets Application. (Screen grab: http://data.aoos.org/maps/arctic_assets.php, last accessed February 1, 2011.)



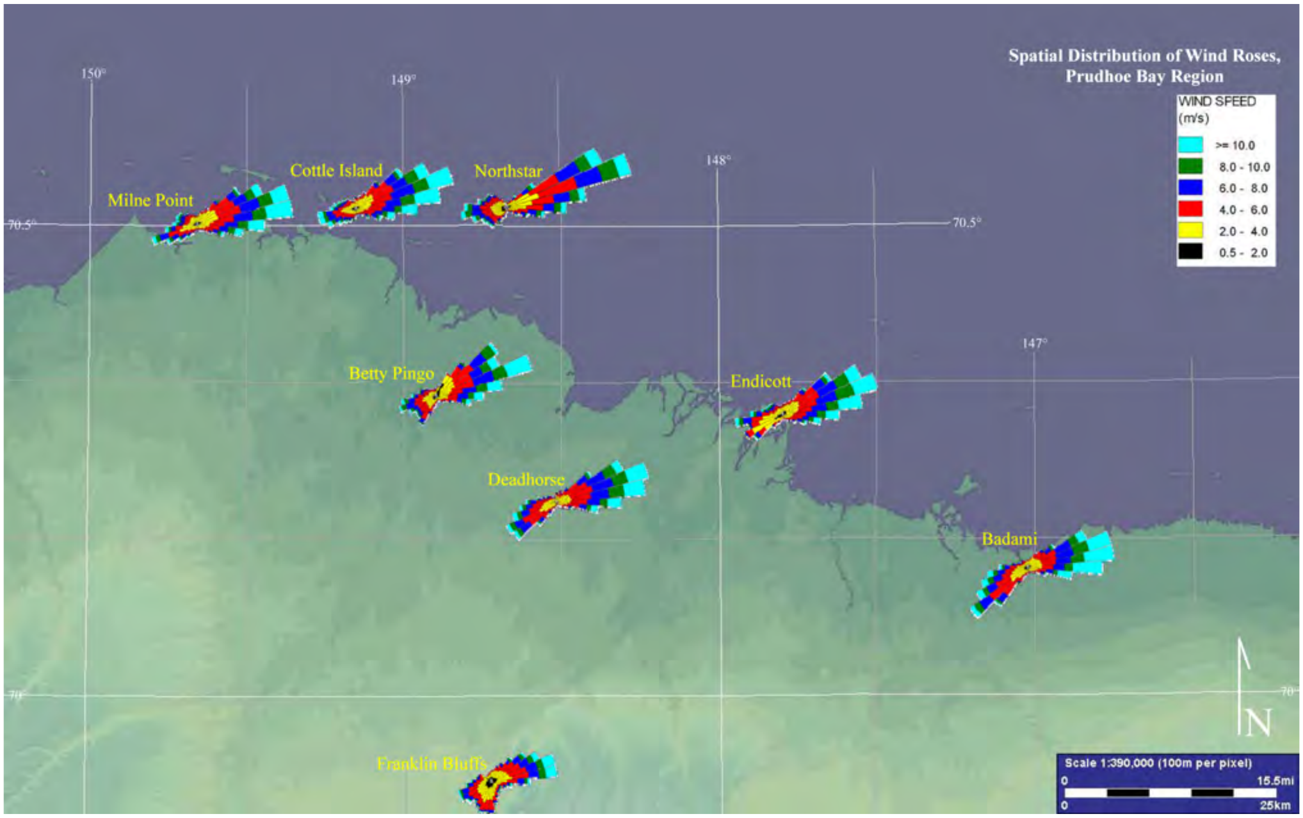


Figure 5–4. Examples of meteorological sites for the Beaufort Sea and spatial distribution wind roses generated by such stations, and other meteorological data useful for spill planning and response (from Hoefler Consulting, 2007, figs. 3–2, 4–21). (MMS, Minerals Management Service.)

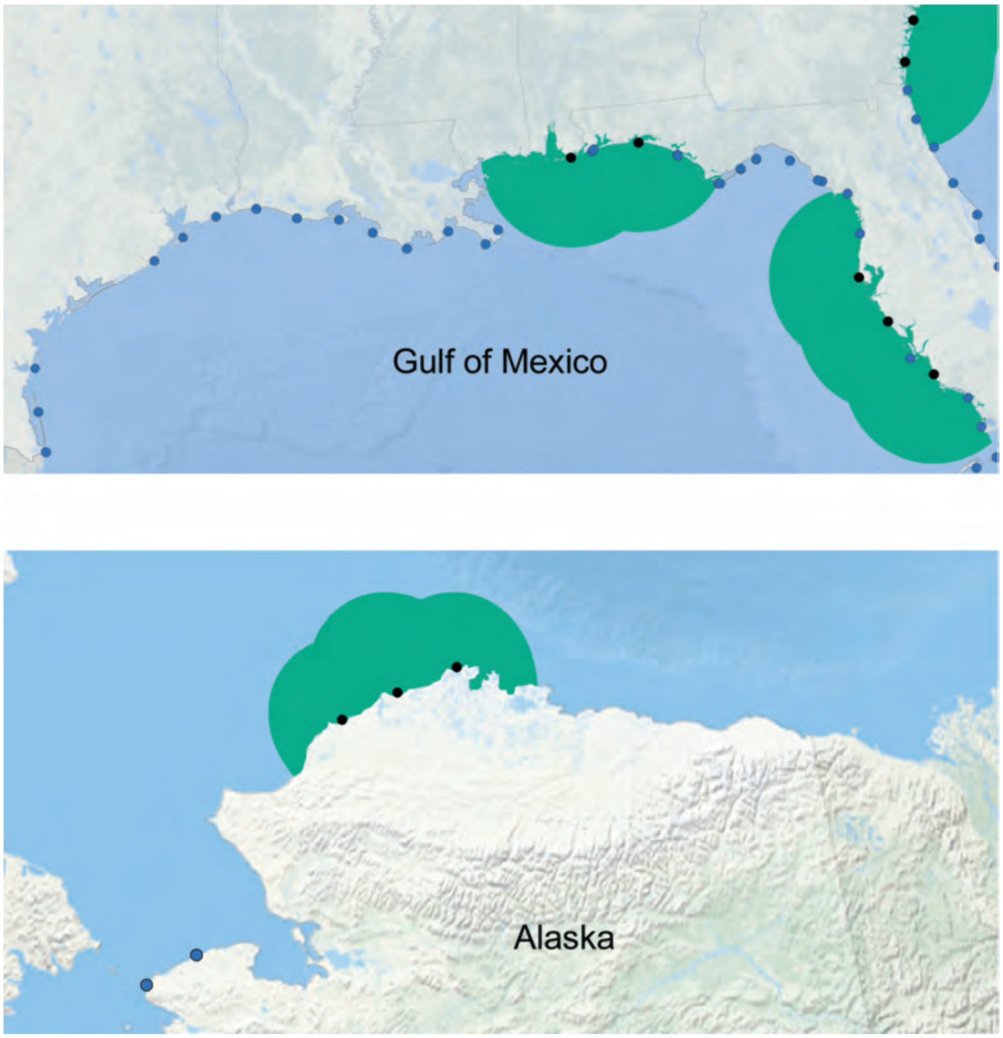


Figure 5–5. Existing High Frequency Radar (HFR) sites (black dots) and proposed sites (blue dots) modified from International Ocean Observing System (2009). The map of Alaska's North Slope and the Gulf of Mexico are to scale to demonstrate existing and proposed coverages (indicated by green areas) for these two major OCS regions.

5.06. Finding: The modeling framework used by the BOEMRE throughout its OCS program is well developed and has undergone rigorous analysis. However, physical oceanography and meteorology of the Arctic OCS are highly dynamic and not well understood because of the challenge of instrumenting a remote ice-influenced system such as the Arctic OCS. This is particularly true for the Chukchi Sea. Thus, the physical understanding of the Arctic OCS needed to inform models is not comparable with that of the GOM. This also is true for circulation or weather modeling that informs oil-spill-trajectory models. Outputs from such trajectory models influence ecological affect analyses, which are limited by the accuracy and precision of the physical data that inform them.

PROGRESSION IN UNDERSTANDING

SYSTEMATIC TACKLING OF CRITICAL QUESTIONS

OCEANOGRAPHY CIRCULATION MODELING

2011	Agency Workshop: Hindcast vs. Forecast in a changing Arctic
2007	Wind, Ocean, Ice Circulation Fields from Multiple Production Models | New Sea Ice Dynamic Models
2006+	OCS Arctic Mesoscale Meteorological Model
2003	Agency Workshop on Small-Scale Sea-Ice and Ocean Modelling
2001+	Arctic Ocean Model Intercomparison Project (international effort to improve Arctic Models)
2000	Assimilation of satellite data into model validation and testing into coupled model
1999	Agency use of multi-year hindcast simulations of coupled model
1996	Agency incorporates historical NWS wind fields into hindcast coupled model
1995+	Start of Coupled Model Intercomparison Project
1990+	Start of Atmospheric Model Intercomparison Project
1987	Agency develops coupled ice/ocean/atmospheric models for Arctic OCS
1984	Agency develops winter stochastic Beaufort ice model
1982	3-dimensional Ice-Ocean Model with stochastic winds
1979	2-dimensional open water circulation model for inshore Beaufort Sea using observed shoreline winds

Figure 5–6. Schematic illustrating the progression of science developed under the BOEMRE OCS Environmental Studies Program to better inform an understanding of ocean circulation critical to topics such as oil-spill-trajectory models [Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), written commun., 2011].

5.06. Recommendation: Existing recommendations for the Beaufort Sea from Weingartner and others (2010a) and Hoefler Consulting (2006, 2007), if implemented, could significantly improve the weather and oceanographic data required by trajectory models. These recommendations include establishment of a redundant meteorological sensor system to enhance Arctic coast-wide spill response goals and a series of large-scale studies of oceanographic exchanges, shelf-basin exchanges via wind and eddies, coastal boundary, under-ice river plumes, and sea-ice boundary to better inform pre- and post-spill modeling and response. We did not find similar synthesized recommendations for the Chukchi Sea. If they do not exist, then producing such analyses would be quite valuable to improve model confidence. Physical oceanographic and meteorological data help inform a wide variety of issues in the Arctic. The international Arctic resource community might benefit from a broader discussion on core data needs and the efficient development of multi-purpose, multi-agency monitoring networks to inform energy development needs as well as climate forecasting, aviation, and shipping safety. The visualization and serving of data through a fully operational Arctic node similar to that of the Alaska Ocean Observing System would help ensure efficient access to information and improved asset planning that is critical in the Arctic where scientific instrumentation costs are high.

Ecological and Social Resource Intersection Analyses

Ultimately, oil-spill-trajectory models and their supporting oceanographic inputs are used to inform analyses of potential effects of spills on areas of environmental, social, and (or) economic interest. The processes described in the section "Oil-Spill-Trajectory Models" define where oil might transect an area (for example, shoreline, reef, migration route) in a very quantitative analytical approach that can be tested for sensitivity and become a foundation for documented improvement when new data or insights are developed (for example, Wang and others, 2010). The value of the area (for example, for subsistence, cultural needs, community infrastructure, or wildlife habitat) is based on best available information. Analysts designate segments important to various resources, and the time periods that those resources occupy that spatial location. This process is often done collaboratively through "expert" discussions and reviews of available literature and is well presented, for example, in the Draft Environmental Impact Statement for the Beaufort and Chukchi Seas multiple lease sales 209, 212, 217, 221 (Minerals Management Service, 2008a). An example of an Environmental Resource Area (ERA) designation and supporting scientific literature (fig. 5–7, table 5–2) helps illustrate the scientific foundation behind the resource designations. There is a significant range in the data that support ERAs from quite limited or dated [for example the Outer Kotzebue Sound (ERA 57)] to those with some 10 supporting sources covering some 40 years (for example the Chukchi Spring Lead System, ERA 19, table 5–2). The USGS OCS Team believes that the literature presented represents a current picture of available scientific information. However, unlike the earlier components of the Risk Assessment Process, the ecological considerations in the assessment are qualitative in nature with no measures of data quality or data uncertainty. It is difficult to judge the value of existing information in the decision-making process, or where and what new ecological data would result in substantially improved decision making. In other words, one cannot run a sensitivity analysis under the present process to examine how important the limitations of the literature or variation in expert opinion might be to the decision-making process.

The challenge to quantitatively include ecological resources is not unique to the Arctic OCS process, but exists throughout the discipline of environmental assessment. Emerging information products and tools, such as those developed by the Alaska Ocean Observing System and Smith's (2010) Arctic Marine Synthesis: Atlas of the Chukchi and Beaufort Seas, represent emergent approaches about data quality and sufficiency that can be built upon. These products and tools represent great advances for the Arctic, where much remains unknown; many different entities conduct work; the landscapes are remote and enormous; and each piece of information is expensive to collect. Even with such tools, insights into what ecological resources might be at risk and the data gaps that are most critical to fill will rely on a mix of expert knowledge and existing data for some time. Structured Decision Making and its supporting tools, from the simplest influence diagrams to the more complex mixed analytical and expert Bayesian Network models, provide discipline to technical or value-based deliberations (for example, Varis 1997; Faber and others, 2002) and can provide inputs to and complement existing regulatory processes. These tools are particularly helpful when there is disagreement about whether a decision needs more information and what information might improve that decision.

5.07. Finding: Oil-spill risk assessment processes have a strong, transparent, and quantitative model framework through the spill-trajectory model phase. The social and (or) ecological value of an area and the potential impact should oil transect it is based on "expert" discussions and review of available literature. They are more qualitative in nature, with limited measures of data quality or data uncertainty expressed.

5.07. Recommendation: The application of the maturing science of Structured Decision Making and supporting tools (from the simplest influence diagrams to the more complex mixed analytical and expert Bayesian Network models) could provide a transparent and quantitative discipline to technical or value-based deliberations. Such collaborative processes could help better define what uncertainty is unacceptable to vested parties and what new information could address that uncertainty in a structured and testable manner.

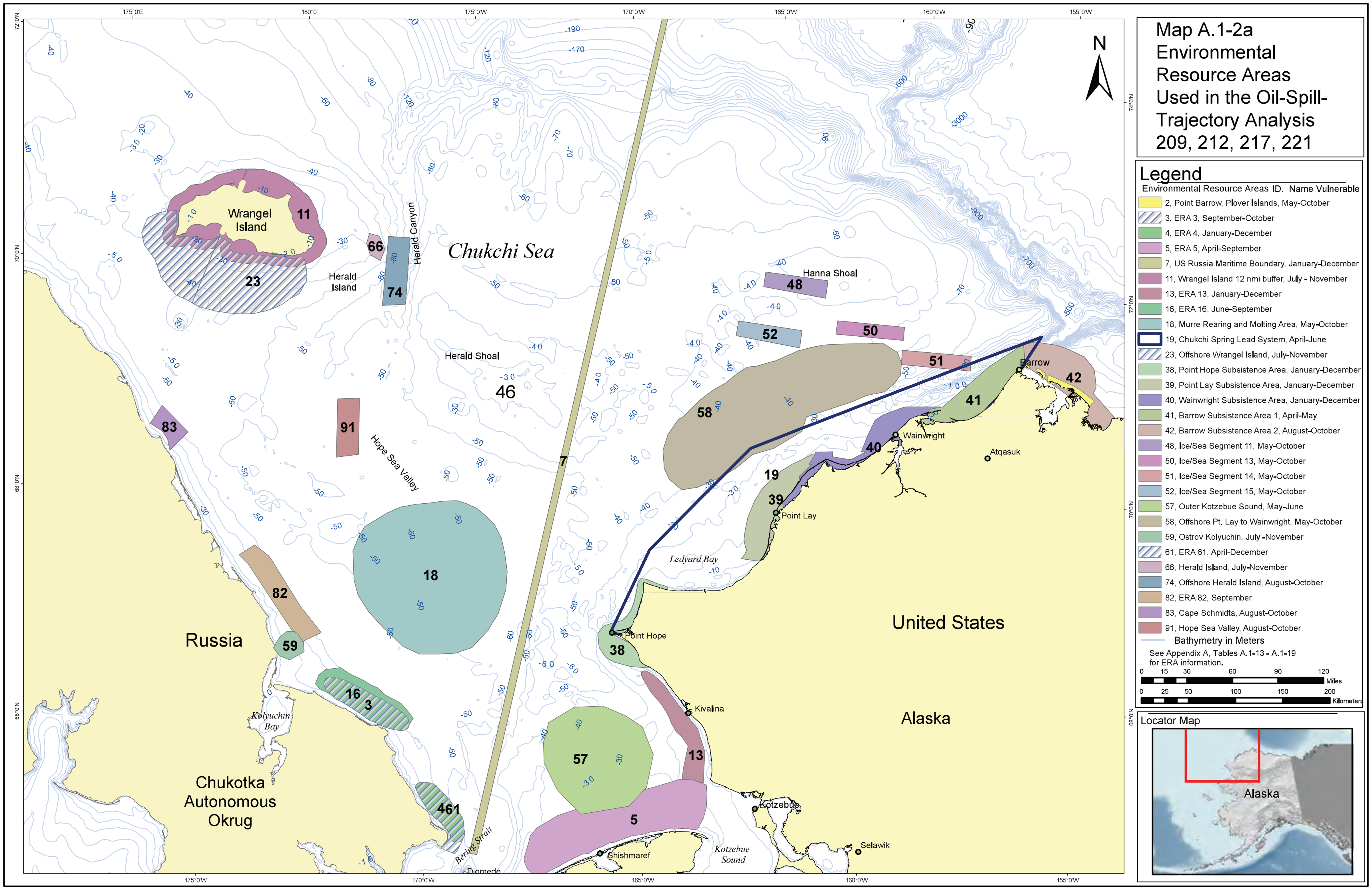


Figure 5–7. Example of Environmental Resource Areas (ERAs) used in the oil-spill-trajectory model (Minerals Management Service, 2008a, appendix A).

Table 5–2. Example of resource definition and supporting literature for Environmental Resource Areas (ERA) presented in figure 5–7.

[Modified from Mineral Management Services, 2008a. ERA IDs found in figure 5–7. References are found in Minerals Management Service, 2008a]

ERA ID	Vulnerable	General resource	Specific resource	Reference
2	May–October	Birds, barrier island	Spectacled eiders, Long tailed ducks	Lehnhausen and Quinlan, 1981; Johnson, 1993; Johnson, Wiggins, and Wainwright, 1993; Laing and Platte, 1994; Dau and Larned, 2004
3	September–October	Subsistence	Bowhead whales, Grey whales, walrus	Mel'nikov and Bobkov, 1993.
4	January–December	Subsistence	Bowhead whales, Grey whales, walrus	Mel'nikov and Bobkov, 1993.
5	April–September	Subsistence	Polar Bears, walrus, weals	Sobelman, 1985; Wisniewski, 2005.
7	January–December	Lower tropic	International Russian waters	U.S. Dept. of State, 1990.
11	July–November	Marine mammals	Polar bears, walrus	Kochnev, 2002; Kochnev and others, 2003; Kochnev, In prep.; Fay, 1982.
13	January–December	Whales	Beluga whales	Suydam and others, 2001; Suydam, Lowry and Frost, 2005.
13	January–December	Subsistence	Polar bears, walrus, weals, Bowhead whales, Beluga whales	Burch, 1985.
16	June–September	Whales	Bowhead whales, Gray whales	Mel'nikov and Bobkov, 1993; Bogoslovskaya,Votrogov and Krupnik, 1982.
18	May–October	Birds	Murre foraging, rearing, and molting area	Springer and others, 1984; Piatt and Springer, 2003
19	April–June	Birds, marine mammals	Seabird foraging; spring migration area for Long tailed ducks, eiders, loons	Swartz, 1967; Connors, Myers, and Pitelka,1979; Sowls and others, 1978; Gill, Handel and Connors, 1985; Johnson and Herter, 1989; Piatt and others, 1991; Piatt and Springer, 2003; Oppel, 2007.
23	July–November	Marine mammals	Walrus	Fay, 1982; Jay, 2007. pers. commun.
38	January–December	Subsistence	Beluga whales, Bowhead whales, walrus, seals	Braund and Burnham, 1984.
39	January–December	Subsistence	Fish, seals, waterfowl, Beluga whales	Braund and Burnham, 1984; Impact Assessment, 1989; Huntington and Mymrin, 1996; USDOI, BLM and MMS, 2003.
40	January–December	Subsistence	Bowhead whales, Beluga whales	Braund and Burnham, 1984; Braund & Associates, 1993a, Kassam and Wainwright Traditional Council, 2001; USDOI, BLM, and MMS, 2003.
41	April–May	Subsistence	Bowhead whales, Beluga whales, walrus, Waterfowl, seals, ocean fish	Braund and Burnham, 1984; S.R. Braund & Associates, 1993b; North Slope Borough, 2001; USDOI, BLM and MMS, 2003.
42	August–October	Subsistence	Bowhead whales, Beluga whales, walrus, waterfowl, seals, ocean rish	Braund and Burnham, 1984; Braund and Associates, 1993b; North Slope Borough, 2001; USDOI, BLM, and MMS, 2003.
48	May–October	Whales	Bowhead whales,gray whales, walrus	Moore and DeMaster, 1997.
50	May–October	Marine mammals	Walrus	Fay, 1982; Jay, 2007. pers. commun.
51	May–October	Marine mammals	Walrus	Fay, 1982; Jay, 2007. pers. commun.
52	May–October	Marine mammals	Walrus	Fay, 1982; Jay, 2007. pers. commun.
57	May–June	Marine mammals	Walrus	Fay, 1982; Jay, 2007. pers. commun.
58	May–October	Marine mammals	Walrus	Fay, 1982; Jay, 2007. pers. commun.
59	July–November	Marine mammals	Polar bears, walrus	Kochnev and others, 2003; Kochnev, In prep.; Fay, 1982.
61	April–December	Whales	Bowhead, fin, and humpback whales	Melnikov, 2000; Melnikov and Bobkov, 1993; Melnikov, and others 2004; USDOC, NMFS, 2006; Rice, 1974, Bogoslovskaya, Votrogov and Krupnik, 1982; Marqueette and others 1982; Mizroch, In Prep.; Mizroch, Rice and Breiwick,1984; Angliss and Outlaw 2005; 2007.
66	July–November	Marine mammals	Polar bears, walrus	Ovsyanikov,1998; Stishov, 1991, Fay, 1982; Jay, 2007 pers. com.
74	August–October	Whales, Polar Bears, Walrus	Bowhead whales	Bogoslovskaya and others 1982.
82	September	Whales	Bowhead whales	Mel'nikov and Bobkov, 1993; Bogoslovskaya,Votrogov and Krupnik, 1982.
83	August–October	Whales	Bowhead whales	Bogoslovskaya, Votrogov and Krupnik, 1982
91	August–October	Whales	Bowhead whales	Bogoslovskaya, Votrogov and Krupnik, 1982

Science and Oil-Spill Contingency Planning

Contingency plans, as defined under the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (http://www.epa.gov/oem/content/lawsregs/ncpover.htm), require information, much of which is not within the purview of science (for example, response resources, command and control structures, communications, and relationship to other plans). Here, we discuss points where scientific insights and data help inform the planning process. For example, the 2008 International Oil Spill Conference (2008) outlined factors that may be desired in plans (table 5–3). The areas of potential spill coverage must be defined based on scenarios identified in a risk analysis. Presently, for the Arctic such scenarios are limited (Alaska Regional Response Team, 2010). Whether part of the formal NCP process or not, assessment of risk and development of plans include spill scenarios, surface trajectories, subsurface trajectories, stochastic modeling, real-time forecasting, oil characterization, oil fate and effects modeling, and oil weathering. Much of the foundational science for these elements is similar to that required in oil-spill risk assessments detailed previously and will not be described again.

During our expert consultations, participants raised a number of issues relevant to this topic. Potential spill volume is an early input to and an overriding influence on the spill scenario and requires an understanding of the source reservoir volume and pressure. Several entities we met with felt there was insufficient information to reasonably constrain estimates of likely spill volume. In particular, Coast Guard leaders responsible for spill response in the Arctic felt this was an essential input to the series of downstream decisions that they must make within spill contingency plans.

Table 5–3. Spill Response Planning and Assessment Categories as suggested in the 2008 International Oil Spill Conference proposed guide on response planning and readiness assessments.

[Modified from International Oil Spill Conference, 2008, table 1]

Setting the Stage	**Operational Response**
1. Legislation and regulation	16. Source control, salvage, and firefighting
2. Multi-national agreements	17. Response technologies
Developing a Plan	18. Waste management
3. Resources at risk	19. Wildlife recovery
4. Spill risk analysis	**Response Support**
5. Risk minimization	20. Spill monitoring, tracking, and sampling
6. Evaluation of response technologies	21. Cleanup assessment
7. Net environmental benefit analysis	22. Data management and success
8. Expert information sources	23. Logistics
9. Contingency planning	24. Finance, administration, and procurement
Organization and Communications	25. Demobilization
10. Response management systems	**Developing and Sustaining Response Capability and Readiness**
11. Notification systems	26. Exercises
12. Communications	27. Training
13. Safety for responders and public	28. Sustainability and improvement
14. Security	
15. Public information development and distribution	

5.08. Finding: Because of the frontier nature of oil and gas exploration in the U.S. Arctic, few empirical data are available to constrain the estimates of oil reservoir volume and pressure patterns throughout the Arctic OCS, which results in uncertainty within spill risk assessments and oil-spill contingency planning.

5.08. Recommendation: A national investment in foundational geologic and geophysical data can provide an improved understanding of how oil and gas resources are formed and emplaced in reservoirs in the Arctic. However, substantial improvements in estimates will require data from exploration wells that are made publicly available.

In our consultations, various parties expressed the need to develop and test approaches to address "Organization and Communication" capacities for spill response. For example, the National Oceanic and Atmospheric Administration (NOAA) and key partners are actively expanding the successful Emergency Response Management Application (ERMA®) system, most recently used during the *Deepwater Horizon* oil spill in the GOM, to Arctic planning and response. This geospatial decision-support tool combines product output from NOAA sources as well as datasets agreed upon by stakeholders (Coastal Response Research Center, 2011) to provide onsite coordinators critical background and real-time data.

We are not aware of any large-scale field testing of the types of assets and communications that must come together rapidly and successfully for a spill event in the Beaufort or Chukchi Seas. However, the 2009 "Sound Predictions" effort by the Alaska Ocean Observing System (AOOS; 2009) and others in Prince William Sound (Gulf of Alaska) is an example of operational testing that can better improve the science/data component of oil-spill response. Through such field experimentation, the accuracy of ocean current and weather model forecasts, data access, and the utility of an ocean observing system for oil-spill response can be assessed and improved. Underpinning any of these efforts is the need to have data easily accessible and current. The Alaska Data Integration Working Group (2011) is a broad effort to facilitate improved data transparency and access across organizations that will feed well into the needs of Arctic ERMA® and AOOS.

5.09. Finding: Management, spill response, and science communities are actively engaged in developing essential decision support and ocean observing systems. However, these systems are not yet fully funded, operational, or fully tested for Arctic waters.

5.09. Recommendation: Significant improvements in spill preparedness could be accomplished through the completion of decision support and data systems, such as the Arctic Emergency Response Management Application, the Alaska Ocean Observing System, and the State-Federal Alaska Data Integration Working Group. Field testing of assets and data systems as was done in the 2009 "Sound Predictions" experiment in Prince William Sound, Alaska, could significantly improve preparedness by highlighting significant data and operational needs.

Oil-Spill Response

All spill response requires effective planning, tracking, surveillance, and understanding of environmental considerations. For the Arctic, the unique challenge is to understand how oil will move if spilled; how it will respond to environmental conditions; what natural and cultural resources and historical properties are at risk; and how effective response tools will be in cold and ice-covered conditions. Many of the topics we have discussed in our oil-spill risk assessment sections inform actions during oil-spill response. The need for a multi-faceted science and technology effort as the foundation to an efficient and effective oil-spill response capacity is widely understood particularly because of unique Arctic challenges and is evident in the focus on this topic applied under the BOEMRE OCS research program (fig. 5–8).

PROGRESSION IN UNDERSTANDING

SYSTEMATIC TACKLING OF CRITICAL QUESTIONS

OIL IN ICE

Multiple Research Programs*

1990-Present	MMS Technology Assessment and Research Program Arctic Oil Spill Response
1985-Present	SINTEF Oil spill/ice
1982-1984	State of Alaska/Oil Industry Tier II Studies
1980-1984	Canadian Offshore Oil Spill Research Association
1977-Present	Arctic and Marine Oilspill Program
1976-1987	Dome Petroleum Research Program
1975-Present	Alaska Outer Continental Shelf Environmental Assessment Program (OCSEAP) | NOAA | BLM | MMS | BOEMRE
1973-1977	Canada Beaufort Sea Project
1970-1979	Arctic Petroleum and East Coast Operators Associations

Accidental Oil Spills In Ice

1974-2006	Bouchard #65 | Snake River | Potomac | Kurdistan | Cepheus | Antonio Gramsci | Chesapeake Trader | Saraband | Seabulk Pride

Experimental Oil Spills Under Ice

1970	North Slope | Chukchi
1980	Beaufort Sea
1990	Eastern Canada | Beaufort Sea | European Arctic
2000	European Arctic
2010	European Arctic

* Each listed program is searchable on the Internet.

Figure 5–8. Schematic illustrating progression of science developed under the BOEMRE OCS Environmental Studies Program to better understand the behavior of oil in ice [Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), written commun., 2011]. BLM, Bureau of Land Management; MMS, Minerals Management Service (now BOEMRE); NOAA, National Oceanic and Atmospheric Administration; OCSEAP, Outer Continental Shelf Environmental Assessment Program.

Response Gap

In later sections, we focus on the various spill response methods and technologies as they relate to Arctic and ice-covered waters. Those included are containment and mechanical recovery, burning, bioremediation, and enhanced dispersion. The materials we discuss in those sections highlight the scientific issues, progress, and information gaps that have been expressed for each of the various tools. However, here we discuss the broader issue of oil-spill countermeasures and the topic of "response gap." Lessons learned from the 1989 *Exxon Valdez* oil spill in the sub-Arctic waters of Prince William Sound Alaska (see appendix D) and the most recent 2010 *Deepwater Horizon* oil spill in the GOM (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011) reiterate that there is no single response technique suitable for all circumstances. The National Research Council (NRC; 2003) stated that reliance on only one recovery system is "unlikely to be successful" to respond to an oil spill offshore of the Alaska North Slope. Most recently, Lee (2010) emphasized the need for the availability of multiple tools, and the challenges in the Arctic of ice dynamics, cold temperatures, and limited light in the winter. Many individual tools will not be available to responders at specific times because of wind, sea, ice, or light conditions (table 5–4; also see Nuka Research and Planning Group, LCC, 2007b; Nuka Research and Planning Group, LCC and Pearson Consulting, LCC, 2010). Understanding what combination of countermeasures will likely be available under the temporal and spatial variability of the Arctic is essential to assess environmental risks from any potential spilled oil. Beyond that, as discussed previously in Chapter 4, Climate Change Considerations, environmental conditions in the Arctic that affect countermeasure effectiveness are changing. And they are changing in complex ways not yet understood.

5.10. Finding: While efforts are ongoing to develop countermeasures to address the potential of an oil spill in Arctic and ice-covered waters, it remains unclear when and where any one of these countermeasures, or countermeasures in combination, will be available under current and future weather, sea state, ice, and light conditions of the Arctic—or whether they will work even if available.

5.10. Recommendation: Spill planning and response would benefit from a collaboratively derived Response Gap analysis of countermeasures, a rigorous analysis of the likelihood of the availability of a multi-countermeasure suite in different Arctic locations and seasons, and the forecasting of climate change influences on the Response Gap. While industry is responsible for stockpiling response equipment, continuation of the Federal and Joint Industry Program approach could inform efforts to develop suites of new technologies and approaches to improve effective response in the Arctic. An independent analysis of the Response Gap could help better articulate what overall risks exist from potential failures in spill response.

Mechanical Containment and Recovery

A number of recent advances have been made in mechanical containment and recovery devices as oil-spill mitigation countermeasures (Brandvik and others, 2006; Minerals Management Service, 2008b). However, the effectiveness of mechanical countermeasures, particularly in ice-infested waters, poses an ongoing challenge (World Wildlife Fund, 2009). In a recent review of technologies to improve oil-spill response effectiveness in the Arctic, Nuka Research and Planning Group, LCC (2007a) documented a number of promising mechanical recovery technologies that could be utilized in open water, but some of these lacked sufficient field testing in ice conditions to evaluate their effectiveness. Mechanical containment and recovery countermeasures, such as booming, sorbents, and skimmers, are affected by the presence of sea ice. Their recovery rate of spilled oil diminishes rapidly with increasing amounts of sea ice. For example, ice can induce tears in booming, or can clog skimmer systems and prevent them from encountering spilled oil. One additional challenge with mechanical recovery systems is the need for a platform from which to operate or deploy, requiring the availability of ice-class vessels, tugs, or barges to support response activities (World Wildlife Fund, 2009). With sea ice coverage greater than about 60 percent, the ice itself can potentially serve as a natural containment barrier (Dickins and Buist, 1999). There also is a need for mechanical recovery systems capable of removing oil that is under the ice (Brandvik and others, 2006).

There are a number of types of booms available depending on whether the purpose of the booming is to contain the spill for recovery purposes (containment or diversion booming) or to protect sensitive areas from the spilled oil (exclusion or deflection booming) (DeCola and others, 2006). Recent advances in technology have been made to extend the capability of ice booms, adapting technology that had been in use for several decades to protect water intakes upstream of hydroelectric power plants into a countermeasure for oil-spill response. Ice booms also have the capability to assist other mechanical recovery systems by providing an ice-free environment, and in separating oil from ice

Table 5–4. One example of physical and timing limitations on oil-spill response tools for the U.S. Arctic.

[From Nuka Research and Planning Group, LCC and Pearson Consulting, LCC (2010, tables 6–1, 6–2). Color code: Green, conditions generally considered to be favorable; yellow, conditions may impede response operations; red, response would not be possible. **Visibility:** Moderate, light fog or less than 1 mile visibility; Low, heavy fog, less than one-quarter mile visibility, or darkness. n/a, not applicable; mph, miles per hour; ft, feet]

Limiting factor	Ice coverage					Wind			Wave height			Visibility		
Conditions	<10%	11% to 30%	31% to 70%	>70%	Solid ice	0–20 mph	21–35 mph	>35 mph	<3 ft	3–6 ft	>6 ft	High	Mod-erate	Low
Mechanical recovery with no ice management	Yellow	Red	Red	Red	Green	Green	Yellow	Red	Green	Yellow	Red	Green	Yellow	Red
Mechanical recovery with ice management	Green	Yellow	Red	Red	n/a	Green	Yellow	Red	Green	Yellow	Red	Green	Yellow	Red
In-situ burning	Yellow	Green	Green	Yellow	Green	Green	Red	Red	Green	Yellow	Red	Green	Yellow	Red

Environmental factors and response gaps (Estimated percentage of time when operating limits are impaired or exceeded in U.S. Arctic)			
Winter (January–March)	**Spring (April–June)**	**Summer (July–September)**	**Fall (October–December)**
Ice Condition: solid (100%) Approximate daylight hours: 4.5 Average number days peak gust >30: 20 (22%) Average number of days of fog: 51 (57%) Average external minimum temperature: -49°F	Ice condition: solid (80%), Broken Ice (20%) Approximate daylight hours: 19 Average number of days peak gust >30: 12 (1%) Average number of days of fog: 53 (58%) Average external minimum temperature: -9°F	Ice condition: broken ice (60%) Open Water (40%) Approximate daylight hours: 21 Average number of days peak gust >30: 19 (21%) Average number of days of fog: 44 (49%) Average external minimum temperature: 20°F	Ice condition: open water (20%), Broken ice (60%), solid (20%) Approximate daylight hours: 5.5 Average number of days peak gust >30: 30 (34%) Average number of days of fog: 51 (57%) Average external minimum temperature: -32°F

(Abdelnour and Comfort, 2001; Abdelnour and others, 2001). Fire-resistant booms also have been developed for *in-situ* burning, as a means of containing and concentrating the oil into a layer atop the water surface that is sufficiently thick to sustain ignition and burning (Tebeau, 2003; Potter and Buist, 2008). There are a couple notable partnerships that culminated in the development of mechanical oil recovery systems for deployment in ice-infested waters—the Mechanical Oil Recovery in Ice-Infested Waters (MORICE) project (Jensen and Mullin, 2003) and the Lamor Oil Ice Separator (LOIS) (Minerals Management Service, 2008b). The concept for MORICE emerged from a review of the status of mechanical recovery devices and culminated in the development of a full-scale system that was tested at the National Oil Spill Response Research and Renewable Energy Test Facility in 2002, under a variety of ice conditions and under relatively mild weather conditions (Jensen and Mullin, 2003). The LOIS is a commercially available mechanical recovery system consisting of an oscillating ice grid that washes oil from ice chunks as they move along a grid; the oil is subsequently concentrated for recovery by a skimmer (Minerals Management Service, 2008b).

Skimming systems are designed to recover oil from the water surface. Recent overviews of the state-of-the-art of these technologies are given in Brandvik and others (2006), Nuka Research and Planning Group, LLC (2007a), Hänninen and Sassi (2010), S.L. Ross Environmental Research, Ltd., and others (2010), and Fingas (2011a). There have been recent efforts to develop standardized testing protocols for determining the recovery capacity of skimmer systems (Schmidt and others, 2009). Oleophilic skimmers are the most common type of mechanical oil-spill response equipment (Broje and Keller, 2006). Efforts to develop better skimmer systems for cold and ice conditions (Broje and Keller, 2006; Keller and Clark, 2008) have found they still have limited oil encounter and recovery rates. Thus, S.L. Ross Environmental Research, Ltd., and others (2010) recommended that deployment of skimmers in the Beaufort Sea may be best suited for responding to oil spills covering a small area and with relatively small ice pieces, given the current limitations of the oil encounter and recovery rates.

The National Research Council review (2003) cited results from a Robertson and DeCola (2001) study involving a field trial using a barge-based recovery system in a simulated spill response on the North Slope under varying seasonal ice conditions. The authors found that realistic maximum operation limits for mechanical recovery of a simulated spill ranged from about 0 to 1 percent in fall ice conditions; about 10 percent in spring ice conditions without ice management; and about 30 percent in spring ice conditions with extensive ice management. The National Research Council (2003) noted that given these estimates, reliance only on mechanical recovery systems to respond to an oil spill offshore of the Alaska North Slope is "unlikely to be successful." They called into question the viability of mechanical recovery technologies to clean up spills, particularly large oil spills, in broken ice, citing statements by the Alaska Department of Environmental Conservation that the mechanical recovery technologies available then were not likely to be successful in the Beaufort and Chukchi Seas. The NRC also noted that the results of research on the effectiveness and environmental liabilities and advantages of alternative countermeasures, such as dispersants and *in-situ* burning, especially in broken-ice conditions, would be useful in facilitating needed contingency planning. The potential scale of the response needed to an offshore oil spill in ice-infested waters is a major challenge to the mechanical recovery systems, as many of these technologies appear best suited for batch recovery of spilled oil in pits or ice leads (Nuka Research and Planning Group, LLC, 2007a). In a recent review commissioned by the Canadian Environmental Studies Research Funds, S.L. Ross Environmental Research, Ltd., and others (2010) noted that

> "[t]here has been little research done with regard to the problem of removing oil from larger ice floes with diameters ranging from 10s to 1,000s of meters that typify breakup and pack ice conditions during winter in the Beaufort Sea."

5.11. Finding: There are a number of recent technological advances in mechanical containment and recovery devices as oil-spill mitigation countermeasures. The effectiveness of mechanical countermeasures, particularly in ice-infested waters, poses an ongoing challenge. Scaling up test results from laboratory- and mesoscale testing into practical field recovery rates is a recognized information need. Further, an understanding of the types and (or) amounts of platforms needed to deploy these devices is needed. This lack of information currently is a limiting factor in translating the technological advances from these devices into an operational context, particularly at the scale at which these devices might be deployed in response to a large spill event in the presence of sea ice.

5.11. Recommendation: An evaluation of the presence or lack of standardized testing approaches (especially wave tanks), the cross-comparability of results, and collaborative development of protocols would be beneficial. This information would inform the practical recovery limits that can be achieved during response operations, and refine our understanding of the appropriate setting and scale at which these devices could be effectively deployed. Finally, there remains a need to further develop mechanical recovery systems to recover oil accumulated under ice.

In a recent review of countermeasure technologies for spill response in Beaufort Sea spring breakup or fall-freeze-up seasons, Solsberg (2008) reported that there have been advances made in mechanical recovery systems. However, many of these may face severe limitations during deployment due to ice-processing challenges, extreme weather (freezing) conditions, and changing conditions in the ice itself. Nuka Research and Planning Group, LLC (2007b) points out that the range of ice conditions that may be encountered in the Beaufort Sea is an important factor when determining what types of technologies are "appropriate and reliable" for oil-spill response and recovery. For example,

> "[a]vailable estimates from mechanical response in broken ice vary from 1 to 20 percent depending on the degree of ice coverage and if responding during freeze-up or spring break-up. This compares with estimates of 5 to 30 percent for open ocean response without broken ice. Recent barge trials on the Beaufort Sea demonstrated that even trace amounts of ice (less than 1/10 ice coverage) can cause significantly reduced efficiencies in mechanical recovery" (Minerals Management Service, 2008b).

One of the challenges to oil recovery in ice-infested waters is the availability of ice coverage information on the time scales (shorter) and conditions (dynamic) of a spill response operation. Solsberg (2008) noted that

> "[a] common way of presenting the potential use of countermeasures in Arctic conditions is a chart or table that assigns the standard approaches of mechanical operations, *in-situ* burning and dispersant application to a specific range of ice cover. The problem with this approach, however, is that conditions in Beaufort Sea ice are so dynamic during the transition seasons that any response would likely prove to be limited to a small (time) window of opportunity—leave alone the obvious safety concerns."

For any countermeasure, and mechanical recovery systems in particular, it is important to have a better understanding of ice drift and oil movement so as to inform response operations and deployment of appropriate countermeasures (Solsberg, 2008). The ability to predict ice movements to inform the use of mechanical recovery systems dovetails with other information needs for an improved understanding of the Arctic Ocean and sea ice. Uniting monitoring and process studies and facilitating modeling at different scales will lead to better understanding of sea ice response to various forcing factors (U.S. Arctic Research Commission, 2010).

5.12. Finding: One of the challenges to mechanical oil recovery in ice-infested waters is the availability of ice coverage information, on the short time scales and in the dynamic conditions of a spill response operation.

5.12. Recommendation: There is a need to develop a system with the ability to make short-term ice dynamics forecasts to inform windows for mechanical recovery operations and to improve recovery technologies in the "ice gap" (about 30 to 70 percent ice coverage). From an operational perspective, there also is a need for information to inform response planning in the event of shifting ice coverage.

In-Situ Burning

In-situ burning (ISB) has been studied for several decades as a response tool for oil spills in ice. Some of the earliest activities were laboratory, tank, and field studies conducted in the 1970s associated with drilling in the Canadian Beaufort Sea (Potter and Buist, 2008). Later oil exploration efforts in Svalbard (1980–94) also considered ISB as a primary countermeasure for use in Arctic oil spills (Brandvik and others, 2006).

One of the key challenges to the effectiveness of ISB is maintaining sufficient thickness of oil to sustain a burn. The minimum ignitable thickness of a fresh crude oil slick on water is about 1 mm, whereas for aged, unemulsified crude oil the minimum thickness is on the order of 2–5 mm (Potter and Buist, 2008). Emulsification is an important process affecting the effectiveness or the response window of opportunity for use of ISB, because the oil in the emulsion is not able to reach a temperature to burn until the water is first boiled off (Potter and Buist, 2008). Emissions from ISB include the release to the atmosphere as well as burn residue. The residue from an ISB may float on water or sink, depending on the oil type and the extent of the burn.

There is a large body of scientific work based on laboratory, mesoscale, and to some extent field trials that demonstrate ISB to be effective in removing oil from the water surface under Arctic conditions, but it remains to be determined whether these results translate into real-world conditions. The effectiveness of ISB can be affected by weather and sea-state conditions, but ice is a particular challenge. At ice coverage exceeding 70 percent, ISB can be conducted without any mechanical containment systems, as the ice provides a natural barrier to restrict the movement of oil across the water surface. At ice concentrations less than

30 percent, open-water ISB may be feasible (Brandvik and others, 2006; Potter and Buist, 2008), including the use of oil containment with a fire-resistant boom. Ice concentrations of 30–70 percent are considered to be the "most difficult from an *in-situ* burning perspective" (Juurmaa, 2006). The particular challenge for ISB in ice concentrations in this range is that these ice concentrations are high enough to impede the effectiveness of mechanical containment systems, yet too low to serve as a natural containment barrier for the oil (Brandvik and others, 2006; Potter and Buist, 2008).

In addition to the abundance of sea ice, the type of sea ice present can impact the effectiveness of ISB. S.L. Ross Environmental Research, Ltd., and others (1998) reported that for freeze-up scenarios at low and medium ice concentration, ISB offered little advantage over containment and recovery techniques. However, there was potential to contain and burn oil in their 70-percent ice scenario as suggested above. For break-up scenarios, burning on water provided effectiveness similar to containment and recovery. And, burning oil on floes or concentrated in melt pools was as effective as on-water burning or containment and recovery approaches. Conducting ISB in pack ice during break-up may be more effective at removing spilled oil than when there is a similar amount of ice coverage during the fall freeze-up, because the fall freeze-up generates significant amounts of slush ice that can impede containment of slicks (Potter and Buist, 2008). In a recent review of countermeasures in the Beaufort Sea, Solsberg (2008) noted that

> "…the relative behaviour of spilled oil and ice require further investigation to determine how feasible it is, in fact, to burn oil during the transition seasons .... While small and meso-scale testing is needed, field work is the ultimate means of measuring the feasibility of burning."

Brandvik and others (2010a) report ISB efficiencies ranging from 50 to 90 percent from a field test (during about 70–90 percent ice coverage) and mesoscale laboratory experiments in a wave tank under varying ice coverage conditions (at 0, 50, and 90 percent). In field and the mesoscale trials at 90-percent ice coverage, ISB had a longer window of opportunity (about 120 and about 140 hours, respectively). Mesoscale experiments at 0-percent ice coverage had less than a 5-hour window of opportunity and slightly better at 50-percent ice coverage (about 10 hours). The authors concluded that the favorable comparisons among results from the field test and mesoscale basin experiments at high percentage ice coverage were an indication that the mesoscale trials could be considered to reflect realistic conditions (Brandvik and others, 2010a). In the course of the field experiment, the authors noted that strong winds caused the dense ice field being tested to move at a rate of approximately 40 km/d (Brandvik and others, 2010b), underscoring the need for information on weather and coupled ice-transport conditions to inform potential oil-spill responses operations.

As we discussed in section, "Spilled-Oil Weathering and Persistence," in the event spilled oil becomes entrained in ice, the rate of oil weathering may be slowed to the extent that the response window for using ISB is expanded. For example, oil in brine channels could potentially be released during spring ice melt in melt pools. Oil that is released from ice during the melting and collects in pools atop the pack ice may be treatable by ISB (Brandvik and others, 2010a). However, this approach could provide an additional exposure route to wildlife given that melt pools can form thaw holes, which in turn may serve as breathing holes for wildlife and provide an important ecosystem for other marine life (World Wildlife Fund, 2009). Features such as leads, polynyas, and ice edges tend to be focal points of biological activity, as well as targets for pooled spilled oil (World Wildlife Fund, 2009).

5.13. Finding: There is a large body of scientific work demonstrating that *in-situ* burning (ISB) of oil is effective in removing spilled oil from the water surface under certain experimentally controlled Arctic conditions. However, there are insufficient data to assess the effectiveness of ISB under the full suite of real-world conditions that might be experienced during a response to an oil spill.

5.13. Recommendation: Many of the mesoscale and field tests show a considerable range in the *in-situ* burning (ISB) effectiveness. However, because ISB is one of the few response options that exist for the Arctic, it is important to conduct additional research to improve its effectiveness. Thus, further focused study is essential to better define the applicability of ISB under various conditions.

There are a number of studies on the emissions from ISB, including air emissions (soot and gases) and ISB residues, which could float to the water surface or sink to the ocean floor. Recent syntheses of the state-of-knowledge on atmospheric emissions from ISB are given in Potter and Buist (2008), S.L. Ross Environmental Research, Ltd., and others (2010), and Fingas (2011b). Recent studies of atmospheric emissions from ISB point to the need for an expanded characterization of the composition of air emissions. For example, Aurell and Gullett (2010) studied atmospheric ISB emissions in the GOM during the *Deepwater Horizon* oil-spill response and found examples of halogenated organic compounds (toxic environmental pollutants) above background levels. These results contrast with previous conclusions drawn from limited mesoscale laboratory studies of ISB. These compounds have potential health effects, such as immunotoxicity, carcinogenicity, and teratogenicity. S.L. Ross Environmental Research, Ltd., and others (2010) provide an overview of the environmental issues with ISB and the evolution of ISB procedures confirming that most research has focused on characterizing the atmospheric emissions from ISB with fewer studies characterizing and testing for potential toxicity arising from ISB residues. Nuka Research and Planning Group, LCC and Pearson Consulting, LCC (2010) point out that earlier studies have shown that there is greater potential for ISB to form residues in the presence of sea ice than when ISB is conducted in open water—citing Fingas (2004) and Buist and others (2003). Previous studies have acknowledged that ISB residues may contain toxic materials, and should be removed from the marine environment where possible (Nuka Research and Planning Group, LCC and Pearson Consulting, LCC, 2010). Nuka Research and Planning Group, LCC, and Pearson Consulting, LCC (2010) cite previous studies, such as the American Petroleum Institute (2004) that investigated the proclivity for ISB residues to sink and identified the need for technologies to recover sunken ISB residues. Potter and Buist (2008) stated that residues from efficient burns of crude oil generally are environmentally inert, but that potential environmental effects are derived from physical properties, including whether residues float or sink, and what chemical constituents are retained. In that regard, the potential for residues that will sink can be predicted based on the properties of the initial oil to some extent.

Several field and mesoscale efforts are informative on the topic of concentrations of toxics (for example, polycyclic aromatic hydrocarbons or PAHs) resulting from ISB. One foundational study is the Newfoundland Offshore Burn Experiment (NOBE; Fingas and others, 1995). In addition to extensive characterization of the atmospheric emissions, including soot and gases, from the NOBE, Fingas and others (1995) also analyzed the residue from the experiment. They reported that the residues resembled highly weathered oil with lower amounts of PAHs than the starting oil. However, Brenner and others (1990) found that PAH concentrations in ISB residues and Alberta sweet crude oil samples were comparable and that there was a lower total amount of PAHs emitted via smoke at thinner slick layers (2-mm versus 10-mm layer). In a synthesis of data from 45 mesoscale burns, Fingas and others (2001) found that PAHs in the soot and residue were about 2–8 percent of that in the starting oil. Wang and others (1999) conducted detailed chemical analyses on ISB residues from several mesoscale burns in Mobile Bay, AL. They concluded that high-molecular weight PAHs were derived largely from the combustion process itself. Garrett and others (2000) also support this finding. Therefore, there is a need for thorough chemical analysis in conjunction with measurement of ISB effectiveness under mesoscale and larger test conditions. The potential for less effective burns resulting from ice and weather conditions may yield higher amounts of high-molecular weight PAHs. This is consistent with Buist and others (1999) who found that the chemical composition of residue depends on the parent oil, the degree of weathering, and the efficiency of the burn. Levels of PAHs in residue could be as much as 40 percent more than in the parent, but considering the volume reduction accomplished by burning, the total amount of PAHs could be a fraction of what was in the slick before ignition.

There has been limited research on the toxicological effects of burnt oil relative to other oil-spill remediation techniques and some results appear contradictory (Cohen and Nugegoda, 2000). DeCola and others (2006) echoed this idea and stated that few published data exist on sublethal effects of burn residues, and no information on impacts of burn residues to benthic-feeding whales. Some insights on the comparative toxicity of ISB residues can be gleaned from Cohen and Nugegoda (2000). They tested the water accommodated fraction (WAF) from crude oil, chemically dispersed crude, and burnt crude oil. They found that of the three elements, dispersed crude oil WAF was the most toxic and burnt crude oil WAF was the least toxic to their marine fish test species. But, they also noted that sublethal toxicities of crude oil WAF and burnt crude oil WAF were observed at dilutions seven to eight times less than in the dispersed crude oil WAF. These results leave the relative toxicity ISB residue on marine organisms unclear.

Despite the relatively few studies characterizing ISB residues and potential toxicological or other effects, there appears to be a general operational consensus that

ISB residues should be collected and removed from the environment (for example, Buist and others 1999). This concept is included in the ARRT's *In-Situ* Burning Guidelines for Alaska, Revision 1 (Alaska Department of Environmental Conservation and others, 2008), which states that

> "[t]he toxicological properties and effects of the residue demonstrate the need and importance of a residue recovery plan which is an operational requirement."

They further note that the longer term effects of ISB residues on marine organisms have not been investigated.

Recently, in the *Deepwater Horizon* oil-spill response, the National Marine Fisheries Service and others (2010) issued a temporary emergency rule closing a specific portion of the GOM to red shrimp fishing due to the presence of ISB residues. Such actions underscore the continuing need for additional information on the composition, characteristics, bioavailability/bioaccessibility of ISB residues, as well as emissions from ISB, to inform response decisions and natural resource damage assessments and restoration activities.

5.14. Finding: There are relatively few studies characterizing emissions and residues from *in-situ* burning (ISB), including their potential toxicology. However, the studies that do exist suggest there is a potential for health effects from compounds released from ISB. Robust characterization of likely ISB air plumes and toxicological testing, especially on potential effects to benthic organisms, of ISB residue are lacking.

5.14. Recommendation: Our review underscores the importance of three points:

1. There is a need for thorough chemical analysis and measurement of *in-situ* burning (ISB) effectiveness under mesoscale and larger test conditions.
2. Better characterization of ISB residues is needed, especially toxicity, physical properties, and bioavailability of contaminants contained within the residue matrix; this is especially true in relation to potential effects to benthic communities.
3. Improving pre- and post-spill plume modeling would help inform whether or not an ISB should be conducted and would facilitate On-Scene Coordinator decisions on measures to protect local populations. The potential effect of "fall out" from a smoke plume that goes over land-based (plant) subsistence resources is of particular concern.

Dispersants

Dispersants are chemical mixtures consisting of three main items: surfactants, solvents, and additives. The surfactant molecules contain components that tend to bond with water (hydrophilic) and others that tend to bond with oil (oleophilic). Thus, the aim of dispersants as a spill mitigation countermeasure is not to reduce the volume of spilled oil in the environment—in contrast with other countermeasures such as mechanical recovery and ISB—but rather to facilitate the mixing and dispersion of spilled oil within the water column by promoting the formation of tiny oil droplets and preventing the recoalescence of those droplets into larger accumulations, such as slicks. The National Research Council recently (2005) conducted an extensive review of the effectiveness and impacts from the application of dispersants to oil spills, which we will summarize briefly here. Based on our expert consultations, the findings in the NRC report remain valid and applicable to the issue of data gaps for the Arctic. They noted that the

> "…objective of dispersant use is to enhance the amount of oil that physically mixes into the water column, reducing the potential that a surface slick will contaminate shoreline habitats… [but] increase[s] the potential exposure of water-column and benthic biota to spilled oil. Dispersant application thus represents a conscious decision to increase the hydrocarbon load… on one component of the ecosystem…reducing the load on another… This trade-off reflects the complex interplay of many variables, including the type of oil spilled, the volume of the spill, sea state and weather, water depth, degree of turbulence (thus mixing and dilution of the oil), and relative abundance and life stages of resident organisms" (National Research Council, 2005).

Some of the key questions regarding dispersant applications, and recommendations for research priorities most applicable to our assignment from National Research Council (2005) are:

- Is the spilled oil or refined product known to be dispersible?

  Example: The need for research into the mechanisms and rates of weathering processes—including parameters such as the rheology of chemistry of both oil and dispersants and energy dissipation—affecting the chemical effectiveness of dispersants, including both bench-scale and well-coordinated wave-tank studies.

- Are the environmental conditions conducive to the successful application of dispersants and their effectiveness?

  Example: The need for research in support of modeling and forecasting of the effectiveness of a dispersant application, including the need for data from wave-tank studies and the updating of protocols for Specialized Monitoring of Advanced Response Technologies.

- Will the effective use of dispersants reduce the impacts of the spill to shoreline and water surface resources without significantly increasing impacts to water-column and benthic resources?

  Example: The need for research into improving oil trajectory and fate models for both planning and real-time decision-making needs, with appropriately designed experiments to verify and validate these models. Such experiments could include research into quantifying weathering rates and fate of chemically dispersed oil droplets relative to undispersed oil.

Subsequent research activities have targeted these knowledge gaps, some of which are highlighted in the Biennial Report of the Interagency Coordinating Committee on Oil Pollution Research (2009) and the synthesis of the Arctic Oil Spill Response Research and Development Program (Minerals Management Service, 2008b). Fingas (2008a) also conducted a review of scientific literature related to oil-spill dispersants, spanning the years 1997–2008 and noted that a Canadian Research Council workshop on dispersant research priorities established priorities similar to those of the NRC.

5.15. Finding: Although significant research and technological studies have examined chemical dispersants over the past decade, including focus on cold-water and Arctic applications, the scientific understanding is yet incomplete.

5.15. Recommendation: Our examination suggests that substantial scientific and technical work as outlined by various expert groups still must be done before dispersants can be considered a practical response tool for the Arctic.

There has been recent work to develop new formulations of dispersants (Nedwed and others, 2008) that can be applied to an oil slick as a gel, and thus potentially be more effective on oils with higher viscosities. Such advances may hold promise for extending the response window for dispersant application by facilitating use on higher viscosity oil slicks stemming from either weathering oil or due to the cold temperatures.

Li and others (2008) note that two of the most important factors in the effectiveness of a chemical dispersant are the energy dissipation rate which affects the penetration of oil into the bulk aqueous phase and the particle size distribution of the dispersed oil. Waves can provide a significant source of mixing energy to the dispersion process. Thus the effectiveness of dispersants is derived from a physical-chemical process that includes the chemical properties of the oil and dispersant, and the physical action of the waves (National Research Council, 2005; Li and others, 2008). Vörösmarty and others (2010) note that sea-ice cover is especially important to address in studies of Arctic Ocean circulation given the unique momentum and buoyancy forcing that arise from overlying sea-ice cover. Furthermore, dispersants can be effective in broken ice provided there is some mixing energy available, and wave reflection among broken and brash ice may serve as highly localized sources of mixing energy (Minerals Management Service, 2008b). Given this potential source of mixing energy, there also is a need to characterize specific energy distributions on a more localized scale, that is, at the point of dispersant application, such as energy added from the ship's propellers or via high-pressure water systems to enhance mixing (Sørstrøm and others, 2010). A recent study by Nedwed and others (2007) tested the potential for an azimuthal stern drive (ASD) from an icebreaker as a means to provide the mixing energy necessary to disperse chemically treated oil slicks in broken ice. The authors found that this approach holds promise for mixing and dispersion of oil spilled on top of and under continuous ice and within leads, and could significantly supplement the dispersion that would take place with wave energy alone.

The issue of energy dissipation may help to describe some of the disparity observed across studies. For example, Belore and others (2009) in a study of dispersant application at the National Oil Spill Response Research and Renewable Energy Test Facility achieved dispersant effectiveness results that generally were higher than results from similar testing at a different facility, and the authors postulate this difference could have been due to higher wave energies achieved during their tank studies. Likewise, Venosa and others (2008) in a series of wave tank experiments found that the energy of the system had a strong influence on the ability to transfer oil from the surface into the water column even with the aid of dispersants. Further, Venosa and others (2008) noted a difference in the effectiveness of the two dispersants they tested and postulated that some dispersants may be more suitable for low- to moderate-energy settings, whereas others may be better suited for application in moderate to higher energy conditions.

As discussed previously, the weathering of oil entrained in sea ice may be inhibited. When it is subsequently released as the ice melts, the timeframe may be significantly extended for dispersant use as a countermeasure (Dickins and others, 2008; Brandvik and others, 2010a). This process would significantly alter the paradigm under which the "response window" for application of dispersants to spilled oil is viewed (Lewis and Daling, 2007). Further characterization of the effectiveness of dispersants under these conditions is needed to inform the "response window." This underscores the recommendation raised in National Research Council (2005) that

> "[r]elevant state and federal agencies and industry should develop and implement a focused series of studies that will enable the technical support staff advising decisionmakers to better predict the effectiveness of dispersant application for different oil types and environmental conditions over time."

Brandvik and others (2006) report that dispersants can be a suitable mitigation countermeasure in Arctic waters, both open water and up to 50-percent ice covered. In a recent review of dispersant effectiveness under Arctic conditions, Lewis and Daling (2007) identify that factors such as salinity of sea ice and colder temperatures affect the viscosity of spilled oil and may reduce the effectiveness of dispersant applications. These conditions also inhibit oil weathering factors, such as the formation of emulsions (Fingas, 2008b). Thus, the window of opportunity during which dispersants may be effective may be extended. Laboratory studies by Moles and others (2002) found that at the conditions typical of Alaskan estuaries and marine waters, dispersant effectiveness was at study detection limits (less than 10 percent). Some dispersants are more sensitive to salinity and temperature, and measured effectiveness can vary by roughly a factor of 10 or more (Lewis and Daling, 2007). However, recent results from tests conducted at the National Oil Spill Response Research and Renewable Energy Test Facility using four Alaskan North Slope crude oils and two dispersants found that the dispersants were more than 90 percent effective at dispersing fresh and weathered forms of the oils under cold weather conditions (Mullin and others, 2008; Belore and others, 2009).

5.16. Finding: How environmental conditions might actually affect dispersant effectiveness during oil-spill response is not yet well understood. As noted in our review, it has not yet been established whether wave-tank experimental conditions are typical or representative of wave conditions that could be encountered at sea with ice present. Factors, such as salinity and temperature, also can vary dispersant effectiveness by a factor of 10 or more.

5.16. Recommendation: We concur with the National Research Council (2005) recommendation that a focused series of studies should be developed and implemented that will enable practitioners to better predict the effectiveness of dispersant use for different oil and environmental conditions. For example, further study of oceanographic characteristics such as salinity, temperature, and circulation and wave patterns, and the influence of sea ice cover on these, in the Arctic Ocean would facilitate our understanding of the magnitude of the effectiveness of dispersants as a countermeasure against an oil spill in the Beaufort and Chukchi Seas. This information, aided by increased monitoring and prediction of winds, currents, temperature, and salinity, would be particularly useful in understanding the regional aspects of dispersant applications.

In addition to understanding the window of opportunity during which dispersants can be successfully used, there is a need to improve our understanding of the long-term viability of the dispersed oil. Fingas (2008a) reported that many researchers recognize that oil-spill dispersants are not stable and will destabilize and rise to the surface: half-lives of dispersions may be between 4 and 24 hours. However, in a recent study (Nedwed and others, 2007) using an ASD icebreaker to enhance mixing energy in a Canadian basin test, the researchers postulated that the dispersed oil would be "… unlikely to resurface even in very low energy conditions" based on their study results.

There is uncertainty regarding the effects of dispersants on marine organisms in the Arctic (World Wildlife Fund, 2009). One of the uncertainties is the potential effect of dispersants on the natural processes of microbial degradation of oil and how this may affect the toxicity of the residual oil. One of the key compound classes within crude oil, in terms of toxicity and other long-term deleterious effects on ecosystems, are PAHs, yet there are few studies to date that quantify the fate and potential for biodegradation of these compounds (National Research Council, 2005). Recent reviews (National Research Council, 2005; Fingas, 2008a) indicate that a scientific consensus regarding the effect of dispersants on toxicity of dispersed oil and effects on biodegradation of oil is lacking. The National Research Council (2005) concluded that there was no compelling evidence that the toxicity of chemically dispersed oil is enhanced relative to that of physically dispersed oil or that there were any reproducible effects of chemical dispersion on the rate of biodegradation of crude oil. However, Fingas (2008a) reported that

> "[i]t is clear, on the basis of current literature that the surfactants in some of the current dispersant formulations can inhibit biodegradation."

Lindstrom and Braddock (2002) reported that "the effect of dispersant on biodegradation of a specific hydrocarbon was not predictable by class [of hydrocarbon]" and either an increase or a decrease in the toxicity of the residual oil could result. Adding to this discussion, Zahed and others, 2010) found that the dispersant Corexit 9500 appeared to enhance biodegradation of crude oil, including at higher initial concentrations of crude oil, based on laboratory-scale bioremediation trials.

In contrast, there are a number of earlier studies indicating that chemically dispersed oil is more toxic to marine organisms than untreated oil (Pew Environment Group, 2010). The National Research Council (2005) found that

> "[i]n order to better understand the fate and effects of dispersed oil, studies should be conducted to estimate the relative contribution to toxicity of dissolved-, colloidal-, and particulate phase oil in representative species."

Fingas (2008a) states that

> "[l]ong-term effects of chemically-dispersed oil are poorly-studied and relatively unknown at this point in time. Again little has changed from the first review in 2002, but it is very clear now that the toxicity of dispersed oil is greater than that of physically dispersed oil, primarily because of the large increase (5 to 50 times) in the amount of aromatics and PAHs in the water column."

Subsea dispersants were used for the first time during the *Deepwater Horizon* oil spill and in larger quantities, both surface and subsurface, than during any previous spill (Pew Environment Group, 2010). Given this large-scale application of dispersants, there is a critical need to understand the potential toxicity of dispersants and other effects on marine organisms (Judson and others, 2010). Samples collected following the application of dispersants to the *Deepwater Horizon* oil spill have documented the presence of one of the dispersant surfactants in deepwater hydrocarbon plumes at 1,000–1,200 m water depth (Kujawinski and others, 2011). The researchers concluded that the surfactant itself underwent no biodegradation. Researchers also noted that they could not yet determine if the dispersant application successfully reduced the size of the oil droplets or facilitated the entrainment of these droplets within the deepwater plume (Kujawinski and others, 2011). Finally, because of the emphasis now placed on subsea dispersant use by the National Response Team, it will be important to address research needs regarding such use. However, the USGS OCS Team had insufficient time to consider this new emerging issue. We note here that further consideration of the potential applicability of the technique to Arctic scenarios and any unique Arctic consequences of such use should be assessed.

5.17. Finding: The interplay of factors such as weather and sea ice on the "window of opportunity" for use of dispersants and how sea-ice conditions may affect the stability of dispersed oil is yet not well understood. The understanding of the potential toxicological effects of dispersants on Arctic ecosystems is lacking.

5.17. Recommendation: Surface dispersants are used in response to oil spills internationally, but improving the understanding of the "window of opportunity" for potential deployment of all dispersants in the Arctic is needed. A more extensive understanding of the toxic and sublethal effects and ramifications for microbial communities (and the natural biodegradation of oil) also is needed.

Chemical Herders

Chemical herders—also referred to as oil collecting agents—are chemicals applied to the water surrounding an oil spill in order to thicken the spill, without the need for mechanical containment, to a point that it can sustain a burn (Buist and others, 2008a; Minerals Management Service, 2008b). Chemical herders constitute an oil-spill countermeasure that can be used in conjunction with ISB (Sørstrøm and others, 2010). This is because one of the critically limiting factors with ISB is the need to have a slick that is sufficiently thick to sustain a burn. Recent studies are also investigating the potential for application of chemical herders to enhance mechanical recovery of oil when used in conjunction with deployment of skimmers, and the potential for herding agents to contract the slick area, and thus improve the efficacy of dispersant applications (S.L. Ross Environmental Research, Ltd., 2010).

Chemical herders have been available for several decades (Buist and others, 2008b), but not used extensively offshore to date because they are effective under largely calm conditions (S.L. Ross Environmental Research, Ltd., 2010). There are currently no commercially available chemical herders approved for use in Arctic waters (World Wildlife Fund, 2009).

Reviews on the state-of-the-art of oil-spill countermeasures, as by D.F. Dickins Associates, Ltd. (2004), have identified chemical herder behavior in ice environments as a knowledge gap. Subsequent research activities (Interagency Coordinating Committee on Oil Pollution Research, 2009; Minerals Management Service, 2008b; and Buist and others, 2008a) have sought to address this gap. Recent studies have focused on the potential utility of herders in responding to oil spills in cold waters, and particularly in ice-covered waters. For example, Minerals Management Service (2008b) suggested that

> "[i]n loose broken ice…. conditions, even with no possibility of booming, if these slicks could be thickened to the 2- to 5-mm range, effective burns could be conducted."

In this context, herding agents may be helpful in the "ice response gap" window of 30- to 70-percent coverage (World Wildlife Fund, 2009).

These recent studies (as with ISB and dispersants) involved public-private sector collaborations, such as BOEMRE and ExxonMobil (Minerals Management Service, 2008b), and the JIP on oil-spill contingency for Arctic and ice-covered waters. International cooperation, at a variety of scales, also has facilitated research from laboratory testing to mid-scale testing at the U.S. Army Cold Regions Research and Engineering Laboratory, the National Oil Spill Response Research and Renewable Energy Test Facility, and the Fire Training Grounds in Prudhoe Bay, Alaska. Recently, two full-scale burn experiments involving the use of chemical herders were conducted in the offshore of Svalbard, Norway (Minerals Management Service, 2008b; Pew Environment Group, 2010). One large-scale experiment with chemical herders was carried out on a free-floating crude oil slick in low (10 percent) ice coverage as part of the JIP Oil-in-Ice effort in 2008 (Sørstrøm and others, 2010). One of the formulations used in recent studies of chemical herders in cold-water conditions is the U.S. Navy cold-water herder formulation (Buist and others, 2008b; Buist, 2010). This herding agent was successful in producing slicks in excess of 3 mm and in significantly contracting oil slicks in the presence of ice (Buist, 2010). One of the recommendations from this work is to conduct a large-scale field trial to test the effectiveness of chemical herding (as a precursor to ISB) in pack ice, and to investigate the influence of wind and sea conditions on this potential spill mitigation countermeasure. One of the key objectives would be to determine how long a herded slick can maintain its thickness with regular re-application of the surfactant under a realistic scale (Buist, 2010). New formulations of chemical herders are under development and testing (Buist and others, 2010).

While an important measure in support of ISB, the application of chemical herders may affect other recovery and mitigation countermeasures. S.L. Ross Environmental Research, Ltd. (2010) notes that

> "…the active ingredient in herding agents (the surfactant) renders sorbent pads less hydrophobic and their water retention increases considerably. This could be a significant detriment to oleophilic skimmers such as drums, discs and rope mops whose recovery surfaces contact herding agent (SIC). This should not be an issue with other skimmers types such as weirs and vacuums."

The question of potential toxicity of chemical herding agents to marine species is noted in the literature (Buist and others, 2008a; World Wildlife Fund, 2009). Although direct toxicity data appear to be lacking, it has been postulated that the risk posed to the marine environment may be modest (Buist and others, 2008b). Buist and others (2008a) note that toxicity data on the U.S. National Contingency Plan (NCP) website indicate that one herder, for example, is only about one-half as toxic as approved chemical dispersants. Toxicity information, from Material Safety Data Sheets, for the components of the U.S. Navy chemical herder is given in Buist (2010). However, information on toxicity that is currently required in Subpart J of the NCP does not necessarily relate to species of concern to Alaska. Research on the potential toxicity of chemical herders to Arctic and subsistence marine organisms would help determine if short- and (or) long-term effects might occur.

5.18. Finding: Although chemical herders are important to improved effectiveness of *in-situ* burn countermeasures, they affect oil recovery efficiencies from various mechanical recovery systems. The resulting trade-offs in countermeasure efficiencies are not fully understood under Arctic field conditions. The toxicity of chemical herders to organisms may not be significant, but this belief has not been validated for Arctic species of concern.

5.18. Recommendation: A better understanding of the comparative value and impact of chemical herders may be warranted to inform oil-spill response scenarios and the timing for deployment of various countermeasures, particularly given the potential for a second-stage recovery effort during ice melt to target oil that had previously been entrained in sea ice. Developing toxicological data for Arctic species of interest would better define the relative value and impact of chemical herders within the countermeasure suite of available tools.

Oil-Mineral Aggregates

The association of oil and fine mineral particulates, typically referred to as oil-mineral aggregates (OMAs) or oil-suspended particulate matter aggregates and oil and fine particle interaction, has long been recognized as a process by which hydrocarbons are transported in marine systems (Owens, 1999). Several case studies, spills of opportunity, and field studies—such as the Baffin Island Oil Spill (BIOS) project—have demonstrated that this oil-clay flocculation process merits consideration in conjunction with other oil-degradation processes (physical weathering, photodegradation, and biodegradation) in understanding the natural attenuation and removal of oil from shorelines (Owens and others, 1994). This process garnered considerable attention in studies of coastal processes following the *Exxon Valdez* oil spill, as researchers noted the association between oil and mineral fines as a mechanism for the natural removal and attenuation of hydrocarbons on the shoreline (Bragg and Yang, 1995). Once formed, OMAs are relatively stable structures, the particle-size distribution and density (or buoyancy) of which are dependent on the mineral-to-oil ratio (MOR) in the structure. Both the composition of the oil and the type of mineral fines can affect this ratio (Zhang and others, 2010). Some basic OMA properties are in need of further study, such as the size distribution of the OMAs, particularly in the presence of dispersants, and how this may affect the settling velocity of OMAs in the water column. There is relatively little known about the specific effect of salinity and clay mineral type on OMA formation (Li and others, 2007). The Arctic Ocean in general is fresher than other marine environments studied. Thus, understanding how regional salinity may affect OMA formation is important. Further, the potential timing of a spill event could influence these processes. For example, should a spill coincide with the spring melt (Yunker and others, 2002), associated discharge pulse from the Mackenzie River system salinity levels would be greatly reduced at some regional scale. The discharge from this fluvial system could significantly affect the salinity and (or) suspended particulate matter (SPM) concentrations, particularly in the nearshore environment. The fate and transport of OMAs are important considerations for oil-spill-trajectory modeling in nearshore waters (Sterling and others, 2004).

Given the natural propensity for oil and SPM to form OMAs, there exists the potential that OMAs also could be used as an oil-spill countermeasure. The Canadian Coast Guard has recently conducted studies looking into the potential utility of this process as a countermeasure to combat oil spills in ice-covered waters (Cloutier and Doyon, 2008). The Centre for Offshore Oil, Gas and Energy Research also is conducting research into this potential use of OMAs, such as the application of mineral fines as a powder or an aerosol mixture to oil slicks at the surface (Lee and others, 2009). In the event additional mixing energy is needed, one potential mechanism under consideration is adding mixing energy to accelerate the OMA formation process (Lee and others, 2009). Utilization of the OMA formation process may be a helpful tool to address the 'ice response gap' in which conventional mechanical technologies may not be effective (Lee and others, 2009).

If OMAs are considered for use in the Arctic, a thorough understanding of how OMAs are incorporated into the sea ice, such as slush, is needed. This understanding is important to oil fate and transport analyses, as OMAs could be transported with the slush ice away from the site of the spill. Payne and others (1991) studied the process by which oil-contaminated sediments could be incorporated into sea ice and thus it is likely that sea ice also could have scavenging potential for OMAs and facilitate greater dispersal of oil (as OMA) over a much larger area.

There is a need to understand how the potential process of OMA formation may be affected by other countermeasures used in response to an oil spill. For example,

> "[t]he synergistic effect of dispersants and mineral fines enhances the transfer of oil from the surface downward into the water column; and a large number of small particles is produced as a result of interaction of dispersants and mineral fines with crude oil" (Li and others, 2008).

Li and others (2007) utilized wave-tank studies to examine these processes, and found that OMA formation can occur with both physically- and chemically-dispersed oil. These studies were conducted under breaking waves. Absent this energy, it is unclear of the effect. Li and others (2007) note that additional factors, such as oil type and weathering state, the type of mineral fines, and the MOR are areas for future study as well as testing under a variety of sea-energy conditions.

Detection, Monitoring, and Tracking

There are numerous technologies available for use in detecting and tracking oil spills on open water, and on top of, within, or under sea ice. These can include: GPS tracking buoys (Dickins and Buist, 1999); tethered balloons (Dome Petroleum Limited and others, 1982); satellite imagery; airborne reconnaissance; trained visual observers; ground, airborne, and space remote sensing technologies; vessel surveillance; optical methods (still and video cameras); unmanned aerial systems (Lehr, 2008); and on-ice surveys. Recent technological advances in the development of lightweight sensors with improved sensitivity (Brown and Fingas, 2009) can augment the utility of these platforms through deployment of multi-sensor systems. For example, there are now efforts investigating the use of a tethered balloon to carry a visible and infrared surveillance system as a means of augmenting real-time spill monitoring capabilities (Prince William Sound Oil Spill Recovery Institute, 2009). In oil-spill response, a suite of these techniques is needed to accommodate the spatial and temporal (especially real-time) needs, as many factors, such as percent ice coverage and thickness, oil slick thickness, oil type and state of weathering, and weather conditions, affect the utility of these technologies. Several recent syntheses, including Dickins (2010), S.L. Ross Environmental Research, Ltd., and others (2010), Interagency Coordinating Committee on Oil Polution Research (2009), Brown and Fingas (2009), Jha and others (2008), Minerals Management Service (2008b), and Tebeau (2003), have documented advances in these technologies over the past decade.

In a review of these technologies and their general effectiveness in response, DeCola and others (2006) noted that

> "estimates vary regarding the impacts of sea ice on spill surveillance and tracking. Response experts often use 50 percent ice coverage as a rule-of-thumb for defining the extent to which open water detection and mapping may be applied. When ice coverage exceeds 50 percent, methods such as visual observation become much less reliable because of problems in detecting the presence of oil in ice leads; however, remote sensing technologies may still apply."

Some technologies require further testing under Arctic conditions. For example, a critical gap identified in spill response is the lack of capability to accurately measure and map the thickness of oil on water and to rapidly send this information to response personnel in the command post (Mineral Management Service, 2008b). World Wildlife Fund (2009) noted that the combination of multi-spectral aerial imagery and infrared detection shows promise for mapping oil slick thickness, but that these tools need further refinement under Arctic conditions and with specific Arctic oil types in order to better demonstrate their feasibility as an operational tool in Arctic oil-spill response. Similarly, DeCola and others (2006) stated that the

> "latest generation of high resolution radar satellites could be used to map large spills in an open pack condition, but radar signatures of new ice, oil, and calm water can be very confusing."

Several recent BOEMRE efforts focus on mapping the thickness of oil, including Bureau of Ocean Energy Management, Regulation and Enforcement (2011b).

In a study of ground penetrating radar (GPR), D.F. Dickins Associates (2005) found that, at frequencies above 800 MHz, GPR yielded clear, well defined frequency, phase, and amplitude anomalies where oil was known to be present at the ice/water interface and trapped within ice tested under lab conditions. The agreement of experimental results with initial modeling indicates the potential to accurately predict GPR response to a variety of Arctic spill scenarios and radar parameters.

Overall, the results clearly demonstrate the potential for detecting oil under sea ice with GPR. Measurements with GPR and airborne radar were conducted over an intentional oil spill in Svea, Svalbard, Norway, in April 2006 and in April 2008 (Dickins and others, 2008). The overall results from two field tests are very promising in that they indicate that GPR using currently available systems is capable of detecting and mapping oil in ice over a broad operational time window from early to late winter, typically November to April in the Beaufort Sea area. This timeframe covers approximately 70 percent of the nearshore fast ice season in most years. The current generation GPR is capable of mapping oil under or trapped within growing winter ice from 30 to 210 cm. Minimum oil thickness detection limit appears to be roughly 2 cm.

Airborne radar also was tested and found to detect oil on frozen ground under snow and oil encapsulated in or under fresh ice. The test also showed that radar can detect oil in and under first year ice with relatively even top and bottom surfaces. Detecting oil through multi-year ice or rafter/ridged first year ice is expected to be difficult because of the voids and jumbled blocks of rough ice which may scatter the radar signal in many different directions.

The time of year also may be important to the detection of oil on or under ice. The overall results from a Dickins and Bradford (2008) study of airborne radar system capabilities in selected Arctic spill scenarios indicate that currently available systems are capable of detecting and mapping oil in ice over a broad operational time window in the Beaufort Sea area. The most reliable months for detection are January and February with results in November, December, and March depending on the internal brine volume of the ice (combination of salinity and temperature). There are still challenges in detecting oil early in the winter with thin, high salinity ice sheets (October) and in the spring (May/June) with warm thick ice having a high volume of liquid brine. During these periods, higher powered radar systems and (or) a corresponding improvement in signal to noise ratios would need to be developed to cover the beginning and end phases of the ice cycle. Detection of trapped oil is not as critical during May and June, however, as the oil will naturally surface through the porous ice and provide a clear visual indication of the presence of residual trapped oil.

Based on previous work, there are limited prospects for developing operational radar based systems to detect oil in sea ice that is floating, but not bottom fast ice. The optimum direction for future radar research and development needs to focus on systems that can evolve into practical operational devices, readily deployed and maintained in Arctic conditions. Future tests need to combine both laboratory and field trials with oil spilled under ice. A sole reliance on laboratory or tank tests will not provide an adequate basis for developing operational systems for future use.

Satellite imagery also is an important component and can inform oil-spill response and other operations in the Arctic, although radar systems are the most practical because of their ability to be used during both the day and the night, and during most cloud cover conditions. For example, as part of the JIP Oil-in-Ice project to assess the overall capabilities of Synthetic Aperture Radar satellites to detect oil spills in ice and monitor ice conditions, Babiker and others (2010) commented that high quality ice information and all-weather satellite coverage is viewed as essential by most companies with operators in the Arctic. Regular satellite surveillance minimizes the need for floating rigs to disconnect riser and drill string in response to advancing ice features and reduces spill risk. In addition, seismic surveys may be completed more efficiently by taking into account ice conditions.

The most effective solution may not be a single sensor, but rather could require the integration of several different technologies (Brown and Fingas, 2009). In a recent review of the state-of-knowledge regarding airborne remote sensing, Dickins and Andersen (2010) noted that multi-spectral remote sensing, when supplemented by visual observation from trained observers, is presently the most effective method for detecting and mapping the presence and spatial distribution of oil on water. There have been many recent studies to test a variety of sensors under different conditions. In their review, Jha and others (2008) stated that laser fluorosensors were the best available sensor for oil-spill surveillance, given the ability to detect oil against many backgrounds, including ice and the shoreline. However, the authors cautioned that no single sensor is capable of providing all requisite information needed to support an effective oil-spill surveillance operation. Advances in technology also may be needed to produce smaller, less energy-intensive systems that could be installed on smaller airframes that are more widely available and (or) affordable to oil-spill responders and government regulators (Brown and Fingas, 2009).

5.19. Finding: There are numerous technologies available for use in detecting and tracking oil spills on open water and in or under sea ice, with varying levels of detection and spatial resolution. Improvements have been made to individual sensors over the past decade; these improvements are documented in a number of available syntheses. Of these, the laser fluorosensor is among the most highly regarded in terms of ability to detect oil in certain snow and ice conditions (Brown and Fingas, 2009). However, there is consensus in the scientific and response communities that no single sensor or approach is sufficient to address all the needs for effective Arctic oil-spill response, particularly given other challenges, such as long hours of darkness and the presence of sea ice. In this regard, high quality ice information and all-weather satellite coverage are viewed as essential by most Arctic operators (Arctic Council, 2009). Given the limitations for each individual type of sensor, packages of multi-sensor systems appear to hold the most promise for versatile and comprehensive remote sensing. Hence, there is growing emphasis on the development of multi-sensor systems that can be deployed from a variety of platforms.

5.19. Recommendation:

1. For spilled oil detection in and (or) under ice, two avenues stand out as the likely focus of future development: acoustics (including the potential use of ultrasound), and electromagnetic (primarily the wave domain systems commonly referred to as impulse radars or ground-penetrating radars). Further testing could be pursued in both these areas. Continued development of practical operational systems for detecting oil in or under ice will be extremely challenging. It is recommended that the latest evolution of the acoustic system first tried in the 1980s be tested over a realistic mix of first year sea ice under field conditions. At the same time, it would be valuable to test the capabilities of the latest generation of ground-penetrating radars in areas of bottom-fast ice where the interface is ice to frozen sediment rather than ice to water.
2. Of the sensors currently available, the laser fluorosensor appears to hold the most promise, given its potential to detect oil in the presence of ice and snow. However, to facilitate broader use of this sensor and its incorporation into multi-sensory packages that can be deployed from a variety of platforms, a reduction in the size and energy consumption—requiring advances in solid-state laser technology—of these systems is critical (Brown and Fingas, 2009).
3. More work is needed on testing of multi-sensor systems to inform remote-sensing operations for spill response. In particular, expanded testing of unmanned aircraft systems is needed to augment observations from trained observers.
4. Research is needed to enhance satellite remote sensing and surface validation capabilities, including development and (or) refinement of satellite-based oil detection algorithms for ice-covered areas.
5. Assessing system performance under real-world conditions during a future offshore controlled spill exercise is seen as a critical need. Such an exercise would provide information essential to refining these capabilities from an operational standpoint.

Field Trials and International Coordination

The National Research Council (1994) recommended

> "the design and completion of one or more experimental oil spills in the general area of the Chukchi and Beaufort Seas. We believe that experimental spills are essential because they can contribute to the scientific understanding of processes, and fill data gaps, about the interaction of ice and oil. These tests also can contribute to accurate assessments of the abilities and limits of countermeasures, and remediation and restoration procedures. The data from recent tests should be evaluated. Carefully controlled field tests would be an invaluable extension of such work into a realistic environmental setting."

This finding appears to remain valid today. The lack of any consistent regulatory framework to facilitate field trials with oil represents a critical science and technology obstacle to achieving real progress in the field of at-sea spill response. Most significant technical advances in Arctic spill response can be attributed to a series of highly successful field trials with oil carried out in U.S., Canadian, and Norwegian waters. Many of these trials have involved moderate-size releases at an affordable cost and have been carried out safely and in an environmentally responsible manner with a high degree of confidence, through a rigorous process of program design and execution. A major point regarding the near-term possibilities for new field trials with oil revolves around the likelihood of obtaining appropriate permits for such experimentation (D.F. Dickins and Associates, 2004). Permits, obtainable in Canada and Norway, are considered unlikely in the United States given that all permit applications have been declined during the last 10 years and no spills in U.S. waters for experimental purposes have been allowed for nearly two decades.

Certainly the previously discussed JIP efforts represent a strong international science and technical collaboration. In addition, at a government level, the Emergency Prevention Preparedness and Response (EPPR) Working Group establishes a framework for future cooperation in responding to the threat of environmental emergencies in the Arctic. The EPPR works within the Arctic Environmental Protection Strategy (AEPS), which was adopted by Canada, Denmark/Greenland, Finland, Iceland, Norway, the Russian Federation, Sweden and the United States through the Ministerial Declaration at Rovaniemi, Finland in 1991. The other working groups within AEPS are the Arctic Monitoring and Assessment Program, Protection of the Arctic Marine Environment, Conservation of Arctic Flora and Fauna, and Sustainable Development and Utilization. The EPPR Working Group provides a forum in which member governments and indigenous peoples work to better prevent, prepare for, and respond to environmental threats from discharges of pollution from activities which take place in the Arctic. The EPPR operates through a system of National Contacts and meets at least annually to assess progress and to develop EPPR Work Plans. EPPR efforts include risk analyses; response exercises for emergencies such as radiological accidents and major oil spills; assessing environmental agreements; evaluating warning systems and communication networks; and sharing experience and technical information, including research and development data.

While not in Arctic waters, CANUSDIX, an effort between Canada and the United States, is a unique annual exercise held near Dixon Entrance, at the southern tip of the Alaskan panhandle and is an example of an innovative combination of spill scenarios, training workshops, equipment deployment, and coordinated multi-year planning (for example, see Canadian Coast Guard, 2010). Like the Arctic, coordinated planning and exercising by partner agencies are a necessity for Dixon Entrance, an environment that also is remote, environmentally sensitive, and characterized by severe weather and limited infrastructure (Gardner and others, 2008).

5.20. Finding: Exercises such as CANUSDIX, an annual emergency response exercise between Canada and the United States near Dixon Entrance at the southern tip of the Alaskan panhandle, and the previously discussed Alaska Ocean Observing System's and others "Sound Predictions" effort in Prince William Sound, Gulf of Alaska, provide practical means to not only identify operational weaknesses but are the only existing practical tools to routinely determine if and what model, real-time data, and data management uncertainties and weaknesses significantly affect desired operational outcomes.

5.20. Recommendation: Efforts to conduct exercises such as CANUSDIX and "Sound Predictions" in the Arctic could significantly advance understanding of the tactical science and information issues that must be addressed. Even if there is not a broader acceptance of conducting actual oil-spill field trials, having scientific protocols in place to take advantage of "spills of opportunities" are essential.

Natural Damage Assessment, Recovery, and Restoration Phase

Background

Discussed in this section are those research needs required to defensibly assess resource injuries, recovery progress, and restoration approaches should oil be released. Our intent is not to suggest that a spill is likely, but to think through such a scenario in a very broad sense and identify approaches and types of scientific information that might reduce societal uncertainties about government capacity to deal with the consequences of oil spills in the Beaufort Sea or Chukchi Sea Planning Areas.

The primary legal framework to determine resource damage is vested within the Natural Resource Damage Assessment (NRDA) process. The NRDA generally is implemented in three phases, which require the natural resource trustees, which in the case of a spill in the Beaufort or Chukchi Seas include the State of Alaska, NOAA, and the Department of the Interior (DOI), to:

1. Determine whether injury to public trust resources has occurred (Preliminary Assessment);
2. Quantify injuries and identify possible restoration projects (Injury Assessment/Restoration Planning); and
3. Implement restoration strategies and monitor effectiveness of such actions.

These are straightforward in language but as stated by the National Oceanic and Atmospheric Administration (2011):

> “Although the concept of assessing injuries may sound simple, understanding complex ecosystems, the services these ecosystems provide, and the injuries caused by oil and hazardous substances takes time—often years. The season the resource was injured, the type of oil or hazardous substance, and the amount and duration of the release are among the factors that affect how quickly resources are assessed and restoration and recovery occurs. The rigorous scientific studies that are necessary to prove injury to resources and services—and withstand scrutiny in a court of law—also may take years to implement and complete.”

It is unlikely that even with foreknowledge of where and when an oil spill might occur the suite of baseline information useful to NRDA would be fully available (for example, population, physiological, or toxicological). This is particularly true for the Arctic OCS because of the suite of physical and ecological uncertainties discussed throughout this report, as well as the practical challenges inherent in Arctic research in general. Here, because of the nature of our assignment, we have not attempted to review the scientific literature that would inform the likely exponential suite of possible scenarios and associated potential injured resources that would inform the NRDA-related activities. Instead, we examine strategic science and approach capacities in the Arctic and potential gaps in those capacities that might be informative. We also take advantage of insights gained from the 1989 *Exxon Valdez* oil spill (appendix D) in Prince William Sound, Alaska (http://www.evostc.state.ak.us/ website, accessed May 11, 2011), and the more recent *Deepwater Horizon* oil spill in the GOM to inform our assignment.

Scenarios and Science Planning

Both the *Exxon Valdez* oil spill and the 2010 *Deepwater Horizon* oil spill demonstrate the logistical, technical, and scientific challenges of responding to rare, but significant events. The success of the NRDA process, particularly in the “Preliminary Assessment” stage is dependent on the rigorous collection of time critical and (or) ephemeral information. Previous large oil spills have demonstrated that access to immediate post-spill survival, physiological, behavioral, toxicological, and habitat information could have improved the ultimate level of confidence in NRDA findings. Despite previous lessons learned from the *Exxon Valdez* oil spill, coordinated science plans for the integrated collection of critical data needed for NRDA-related activities have not been prepared in the areas of proposed development. A coordinated joint State–Federal Gulf Coast Ecosystem Restoration Council to inform strategic and efficient restoration efforts into the future has been proposed (Recommendation E6: National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011) as was the case after the *Exxon Valdez* oil spill; however, the opportunity to collect much of the time critical data will be past before such establishment. In the case of the *Deepwater Horizon* oil spill, the region had fairly easy and robust access to scientific capacities (multiple Federal and State laboratories, academic specialists), extensive citizen volunteers to help capture early resource mortality data, and community infrastructure (for example, boats), all of which improved the likelihood that critical early post-spill data were captured. The Arctic OCS and coastal environment is not similarly positioned.

Although the *Exxon Valdez* oil spill is scientifically informative for many aspects of our later discussions, it was a spill that occurred from tanker grounding rather than from drilling activities. Thus, contemporary environmental studies of the nature produced through the BOEMRE Environmental Studies Program for the Arctic OCS described previously were not available. The spill also occurred after a period of ocean climate regime shift (for example, Anderson and Piatt, 1999), whose consequence to effective injury and recovery assessment was not well understood for some time into restoration efforts. In that regard, our existing scientific foundation and progress towards expanded understanding of the distribution of species, potential fate and effect of oil, and the nature of environmental change (including changing climate scenarios) could be argued to be more robust than was available for Prince William Sound in 1989. There is the current effort invested in environmental studies under the BOEMRE, project efforts by industry (for example, Funk and others, 2010), the agency mission-specific monitoring ongoing at both Federal and State levels, and the broad collation and synthesis efforts by many parties (for example, Smith, 2010).

The existing Oil Spill Risk Assessment (OSRA) framework described earlier, while at some level limited because of the qualitative manner in which ecological information is presently incorporated, does provide information on likely landscapes and resources affected under simulated spills. This foundation is valuable and provides information useful to better understand and narrow the range *a priori* of likely NRDA injured resources under the various oil-spill scenarios.

In the report prepared by Integral Consulting Inc. (2006) for the *Exxon Valdez* Oil Spill Trustees Council, scientists who gained experience from the *Exxon Valdez* oil spill provided a strong foundation for understanding the types of scientific information needed to assess recovery status, lingering oil impacts, and restoration progress to inform what types of "pre-spill" data should be readily available (fig. 5–9). Information on population characteristics (for example, abundance and productivity, physiological metrics, and habitat) and exposure metrics (for example, bioaccessibility, exposure pathways, and biomarkers) all must come together in a weight-of-evidence to inform NRDA activities (Integral Consulting Inc., 2006, fig. B–4).

5.21. Finding: The remoteness of the Arctic OCS, the small resident population, and limited community infrastructure likely would limit the probability of early science responses that were seen during the *Deepwater Horizon* or *Exxon Valdez* oil spills, resulting in the loss of time-critical data informative to Natural Resource Damage Assessment.

5.21. Recommendation: The development and pre-positioning of a multi-agency coordinated Oil Spill Science Contingency Plan could potentially mitigate some of the challenges inherent in spill response in the Arctic. The planning process itself would be valuable by identifying what skills and protocols exist or need to be developed. The *Deepwater Horizon* oil-spill response demonstrated the need for local citizen engagement in sample collections. This is likely more true in the Arctic, due to access limitations. Local community members could be the first available on scene. Consideration of a "Citizen Scientist" program as a component of Science Contingency Plans might be fruitful.

5.22. Finding: The Oil Spill Risk Assessment (OSRA) process employed by the BOEMRE provides information to help define where natural resources might be exposed to oil under various spill scenarios.

5.22. Recommendation: A strategic follow-on analysis to the present Environment Resource Area OSRA that would examine the state of knowledge of specific NRDA metrics (for example, see fig. 5–9) could help identify specific population, physiological, habitat, and exposure data for future NRDA activities. This would help establish priorities for needed science under BOEMRE-focused planning as well as ongoing efforts by science and resource agencies.

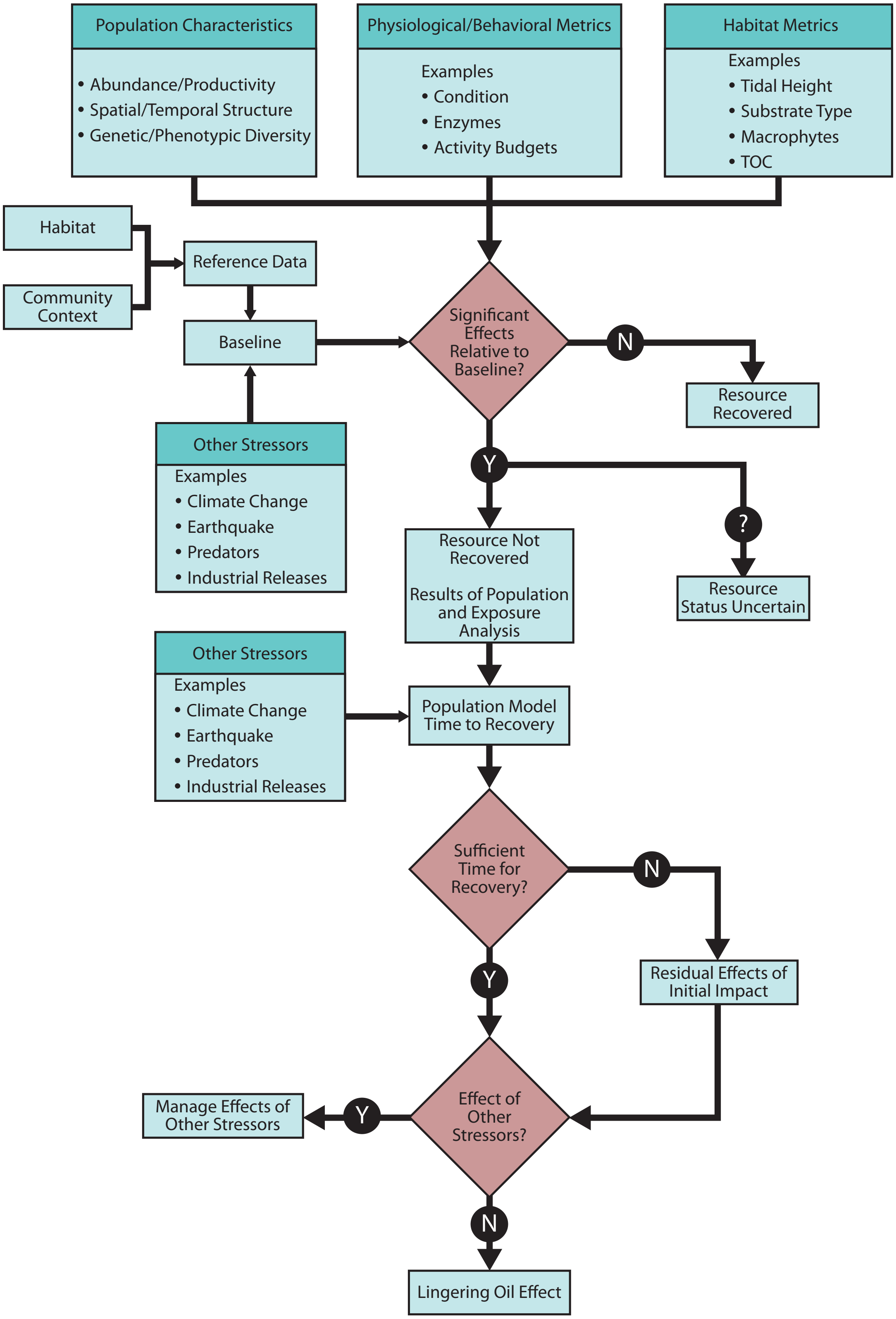


Figure 5–9. Factors incorporated into population level evaluations of recovery status (modified from Integral Consulting Inc., 2006, figs. B3 and B5). TOC, total organic carbon; N, No; Y, Yes.

Integrated Monitoring and Process Understanding

As discussed elsewhere in our report, there are high accumulated uncertainties associated with any development activity in the Arctic and what science is "essential" to informing decisions. In addition to project uncertainty, climate changes may affect the relevancy of historical data to future decisions, and there is a huge spatial extent under consideration. Thus, having the "right" science, at the "right" time, and at the "right" scale is problematic. In such an environment, there may be great value to a more aggressive science strategy to integrate sampling approaches to ultimately improve inferences from sampling available at one scale to another, or one time or location to another. As discussed above, the same could be said for the ability to develop a full pre-understanding of all the essential NRDA metrics for each potential injured resource (or resource being examined in pre-decisional leasing documents). Here, we discuss several elements of this challenge and potential approaches to provide some level of mitigation.

Several existing study programs for the Beaufort and (or) Chukchi Seas serve as examples of approaches that may provide the framework for improving our ability to scale understanding from one level to another. The BOEMRE has undertaken a wide variety of integrated monitoring efforts over the last decade. These include:

1. ANIMIDA, the "Arctic Nearshore Impact Monitoring in the Development Area" study designed to assess potential environmental contaminant inputs from Beaufort Sea oil and gas development and its continuation cANIMIDA (for example, Boehm, 2001; Neff and Associates, LLC, 2010), and
2. COMIDA, the "Chukchi Sea Offshore Monitoring in Drilling Area" effort which conducts an extensive multi-study examination of the environment.

Both these efforts provide a mid-scale view of environmental background conditions associated with prospects. When coupled with the more detailed prospect-specific industry efforts such as those in the Chukchi Sea Lease Area, significant process and scaleable information could be generated informative to both permitting and future NRDA needs (fig. 5–10).

Another approach that is likely valuable in the effort to better generate and understand factors critical to NRDA, particularly in a changing climate, is formal integrated multidisciplinary monitoring and process studies. The *Exxon Valdez* oil spill can be used as an example to gain perspective—more than 30 biological resource types were considered to be injured by the *Exxon Valdez* Oil Spill Trustee Council during the *Exxon Valdez* Oil Spill NRDA process (*Exxon Valdez* Oil Spill Trustee Council, 2001) with the majority recovered or recovering and four viewed as not recovered or recovery unknown by 2010 (*Exxon Valdez* Oil Spill Trustee Council, 2010). The challenge faced by the Trustee Council to judge recovery was largely due to:

1. Variability in population estimates as a result of highly mobile fish, birds, and marine mammals causing wide confidence limits for population size estimation;
2. Lack of pre-spill data;
3. Interaction of the spill and other natural factors (for example, climate) that constrained the ability to judge the role of oil in population status; and
4. Geographic scale of studies conducted both before and after the spill which ranged from scales to assess populations to others keyed to localized effects and oil exposure.

To compensate for incomplete information, injury often was inferred from comparisons of oiled and unoiled areas, with recovery defined as a return to conditions comparable to those of unoiled areas. Confidence in such designs is limited because of natural variability among sites oiled and unoiled prior to a spill. Ultimately, efforts turned towards the development of ecosystem-based integrated studies to attempt to better establish population status relative to recovery and factors still constraining recovery through a weight-of-evidence approach across suites of species whose status remained uncertain (*Exxon Valdez* Oil Spill Trustee Council, 1994). Efforts like those described in Peterson and Holland-Bartels (2002) for a suite of species whose recovery status was still uncertain or deemed non-recovered after extensive study and some 5 years after the oil spill highlight that coordinated multi-species sampling and coupled hypothesis-driven studies can mitigate many weaknesses in incomplete pre-spill data. Efforts such as those proposed by Grebmeier and others (2010) for a Distributed Biological Observatory (DBO) or underway in the Bering Sea and Aleutian Island Integrated Ecosystem Research Program (BSIERP, http://bsierp.nprb.org/) of the North Pacific Research Board and National Science Foundation offer examples of approaches that could well serve the full suite of interested parties and their decision-making requirements that cascade out of DOI OCS decisions.

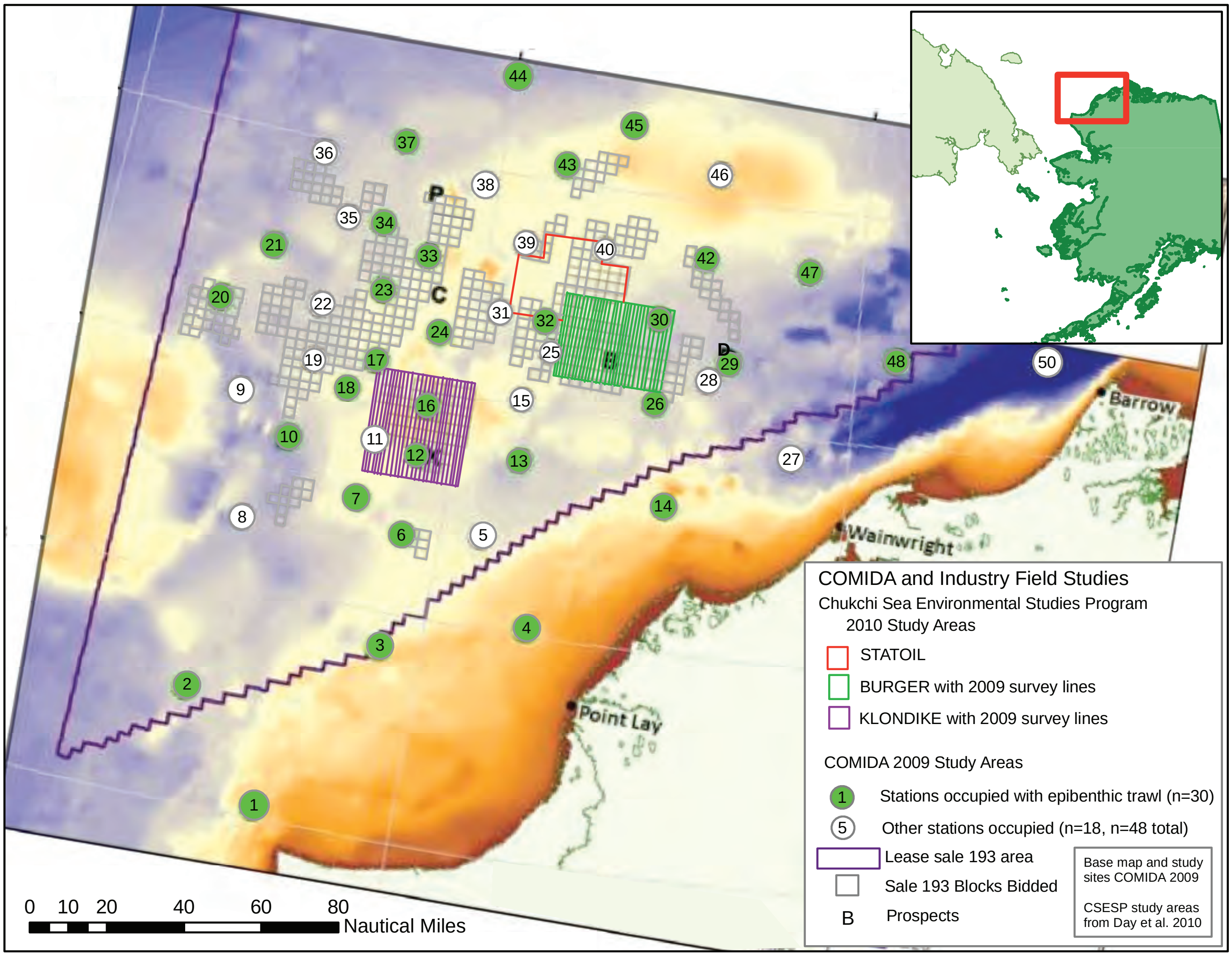


Figure 5–10. Example of the BOEMRE-sponsored COMIDA sampling and the more spatially detailed industry-sponsored sampling (modified from Dunton, 2010; Day, 2010).

5.23. Finding: Significant advances have taken place with the COMIDA ("Chukchi Sea Offshore Monitoring in Drilling Area") and cANIMIDA ("continuation of the Arctic Nearshore Impact Monitoring in the Development Area")-like efforts funded by the BOEMRE and the more spatially detailed efforts by industry. Such efforts individually provide critical information on ecosystems, potential anthropogenic effects from development, and climate factors.

5.23. Recommendation: The benefits from these individual efforts to improve scientifically defensible inference of findings to different geographic and temporal scales could be significantly enhanced through additional focused coordination and joint study planning. Discussions in a workshop format to outline specific experimental designs presently employed and to discuss fruitful efforts to link study efforts might be beneficial as one approach.

The DBO (fig. 5–11), as envisioned by Grebmeier and others (2010), would provide a monitoring and experimental framework:

> "…to detect, measure, and track the combined effects of changing oceanographic conditions on the ecosystem….[with] holistic, integrating measurements of basic oceanographic variables [and] with data on species- and trophic level interactions, from primary producers to marine mammals… The DBO is envisioned as an array to identify and consistently monitor biophysical responses in four pivotal geographic areas that exhibit high productivity, biodiversity, and rates of change. …The DBO would support a suite of *in-situ* time-series measurements to evaluate ecosystem status, supplemented by satellite observations. Sea ice observations include ice and snow thickness and biological sampling to evaluate changes to productivity in sea ice systems and habitat sustainability for predators."

A DBO approach, which would bring value to resource missions beyond that required by the BOEMRE, would require a concerted multi-agency and international planning effort. However, once established, a DBO might provide a critical and essential complement to mission-specific sampling by the BOEMRE and species studies by NOAA, U.S. Fish and Wildlife Service, and (or) the State of Alaska. This is particularly true as climate is hypothesized to force significant ecosystem-level changes that will require rigorous understanding if they are to be defensibly incorporated into OCS-specific or the broad array of other agencies mission considerations.

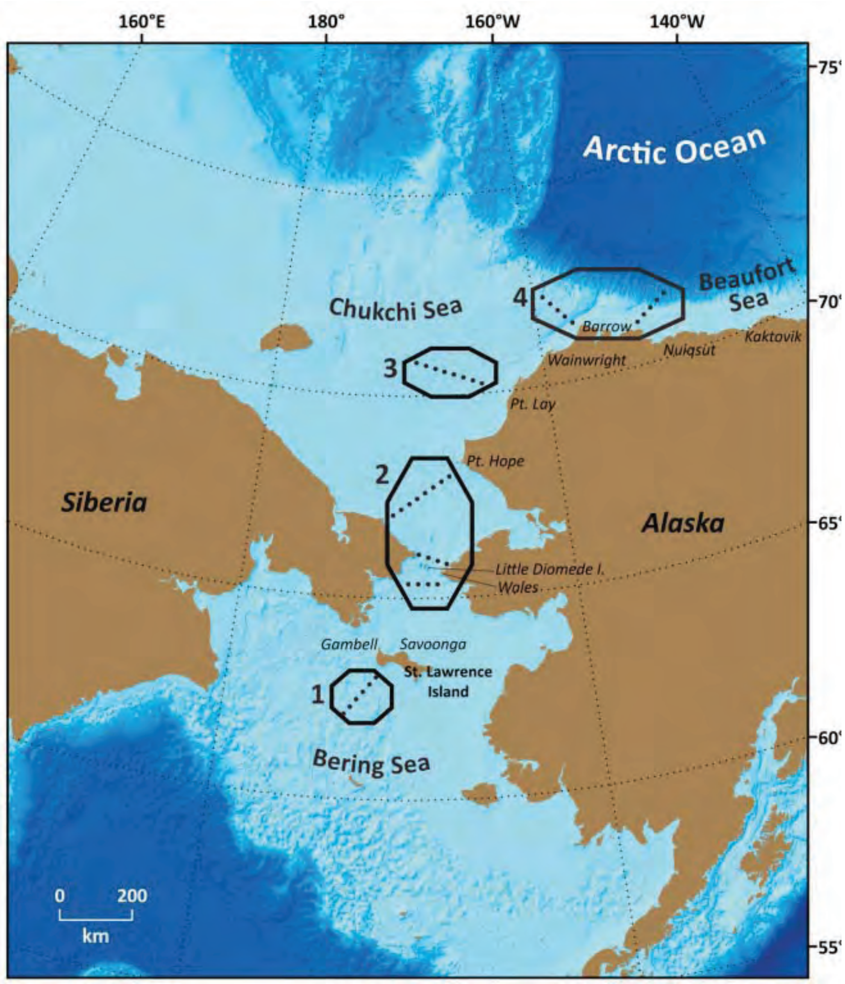


Figure 5–11. Schematic of the location of the proposed Distributed Biological Observatory for standard hydrological and biological measurements in the Bering, Chukchi, and Beaufort Seas (Grebmeier and others, 2010).

5.24. Finding: The Arctic environment is highly variable both physically and biologically. Here, it is difficult to conduct and maintain the suite of individual surveys and sampling efforts of ecosystem components at sufficient levels to understand potential future impacts from development. As was demonstrated in the *Exxon Valdez* Trustee Council recovery science efforts, this is particularly true for information needed to establish population status.

5.24. Recommendation: The Distributed Biological Observatory concept is one that holds significant scientific promise to mitigate some of the major constraints to a defensible science framework for critical Arctic decision making.

5.25. Finding: Similar to findings 5.23 and 5.24, the nature of resource variability and uncertainty in the Arctic challenges the development of the full suite of scientific information needed by decision makers and vested parties relative to resource management in the Arctic.

5.25. Recommendation: The BSIERP (North Pacific Research Board-National Science Foundation Bering Sea and Aleutian Island Integrated Ecosystem Research Project) and the DBO (Distributed Biological Observatory) concepts and enhanced industry-COMIDA ("Chukchi Sea Offshore Monitoring in Drilling Area")-like efforts offer the potential to create a transparent and scientifically rigorous study framework to support and enhance existing BOEMRE and other organizational interests in the Arctic.

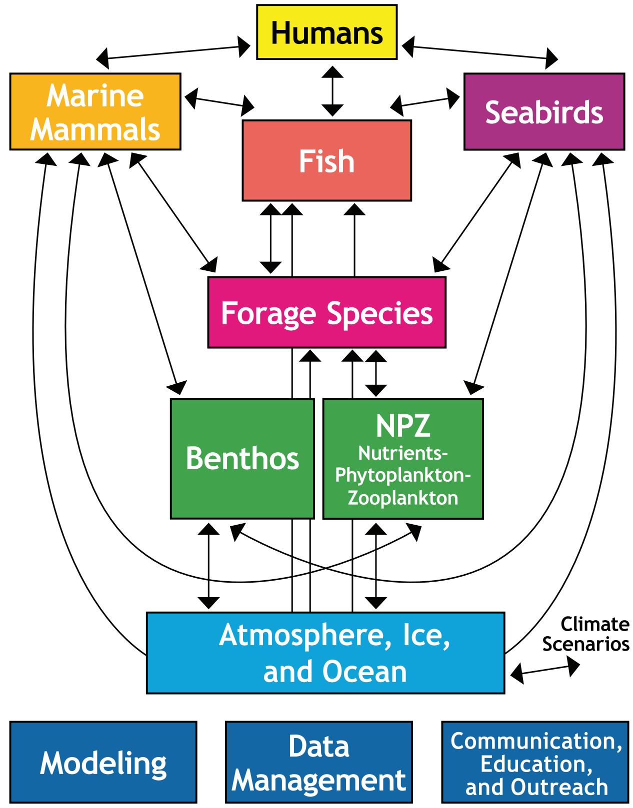


Figure 5–12. Conceptual design of the North Pacific Research Board Bering Sea and Aleutian Island Integrated Ecosystem Program. Graphic available at: http://doc.nprb.org/web/BSIERP/zzWebsite/proj_mgmt/01.10_bsag_web.pdf, accessed March 8, 2011.

Finally, the conceptual approach used by the North Pacific Research Board in its BSIERP, which considers commercial fishery research within the context of an ecosystem framework, offers another successful approach to understanding anthropogenic factors in the context of complex ecosystems and changing environments (North Pacific Research Board, 2006). The BSIERP was envisioned to address scientific challenges to effective fishery management associated with expected changes in the ecosystem such as:

- "Physical phenomena (for example, weather patterns, sea ice characteristics, transport, mixed layer dynamics, temperature, nutrient fluxes);
- Composition, abundance, distribution, and demographic parameters of biological components from plankton to seabirds and marine mammals;
- Strength of existing predator-prey linkages and development of new linkages;
- Human strategies for resource extraction, transportation, and community adaptation."

This effort considered hypotheses that included how the distributions and abundances of species might be changing; characteristics of physical and chemical attribute change; changes in lower trophic level production; processes controlling energy pathways; the role of climate change in these processes; and the economic and sociological impacts of a changing ecosystem on the coastal communities and resource users of the Bering Sea. The concepts and the efficient approaches forwarded under the BSIERP (fig. 5–12) are appealing when considering the functionally similar challenges of resource decision making for the Arctic.

As a final consideration, any of these larger integrated approaches, as well as the existing BOEMRE program, requires input from many other resource programs. Should these efforts be lost or reduced, the science-based decision making about oil and gas development in the Arctic may be compromised. For example, Grabmeier and others (2010) discuss that the DBO would require collaboration and joint data collection with vessel cruises through the Pacific Arctic Group network of governments and scientists working in the Pacific Arctic, inclusion within international Sustaining Arctic Observing Networks, and (or) Arctic Council (website: http://www.arctic-council.org/, accessed May 10, 2011) efforts. The BSIERP, as mentioned previously, is a close partnership with the National Science Foundation with strong in-kind funding leverage from mission work from many State and Federal agencies. Thus, not only is the support for new collaborations key to developing enhanced insights for oil and gas development in the Arctic, but also the maintenance of core agency mission work. One only has to turn to the environmental documents of the BOEMRE (for example, Minerals Management Service, 2006) or to the data sources that were the basis of "The Arctic Marine Synthesis: Atlas of the Chukchi and Beaufort Seas" document (Smith, 2010) to capture the critical nature of core mission work of other Federal and State agencies. The amount of such existing work is encouraging, but the general quality as defined by spatial and temporal coverage should be increased (appendix E, table E–1).

5.26. Finding: The information that presently supports science-based decision making on oil and gas development in the Arctic comes from both the topic-focused work of agencies such as BOEMRE, and the efforts of broader agency-specific mission work of many Federal, State, community, and nongovernmental entities.

5.26. Recommendation: The ability to develop oil and gas resources in as safe and environmentally sound a way as feasible relies on many data sources outside the formal annual planning process of the BOEMRE. Understanding the potential jeopardy these data collections might be in across organizations because of different planning processes and national and regional priorities, and development of a strategic collaboration to maintain and enhance such scientific efforts could prove valuable. Such information could be identified as part of an overall science plan.

Oil-Spill Risk, Response, and Impact Under Future Climate Considerations

In Chapter 4, Climate Change Considerations, the authors discuss how physical characteristics important to oil-spill risk, response, and impact may change under climate forecasts in the next 50 years. A number of significant changes are expected to occur in the physical environment of the Beaufort and Chukchi Seas. Some of these changes will stress the biological systems that are so highly adapted to the extreme conditions of this region. These changes are also expected to affect the environment in which Arctic OCS exploration and development activities occur. Some climate changes will mitigate the environmental risks of energy development in the region, while others will compound them. The interactions between future climate change over the next 50 years and potential energy development within the Arctic OCS are described briefly in the following paragraphs.

- *Temperature:* Extremely cold temperatures are cited as a factor contributing to the risk of accidents and spills. The large warming projected to occur within the Arctic OCS during autumn and winter is expected to reduce the risk of accidents and spills during those seasons, as is the more modest warming during spring.

- *Sea Ice:* The Chukchi and Beaufort shelves are expected to be ice-free for a greater period of time each year. This will reduce the portion of the year when the presence of sea ice may contribute to the risk of accidents resulting in spills, and will increase the time when spill sites will be accessible to vessels without icebreaking capabilities. Mechanical devices for recovering oil (booms, skimmers, pumps) may function more effectively for a greater part of the year. However, sea ice will still be present throughout winter and spring. With its projected reduced thickness, the ice pack will be more dynamic, increasing the risk of spill-producing accidents during these seasons. Oil-spill response may be more difficult in the more dynamic sea-ice environment.

- *Clouds:* The increasing prevalence of low-level clouds and fog during the open-water season will increase the occurrence of poor-visibility conditions during summer and autumn. In addition, these poor-visibility conditions are expected to occur over a greater fraction of the year, extending into late autumn. Poor visibility is a factor that increases the risk of accidents resulting in oil spills, makes vessel and aircraft operations extremely dangerous, increases the response time of vessels and aircraft trying to respond to an accident or spill, hampers onsite spill response operations once the needed equipment and personnel arrive, and makes it difficult to monitor the location and condition of a spill by using aircraft. The projected increase in high-level clouds (all seasons) compounds the problem by limiting satellite-based surveillance. In contrast to summer and autumn, the occurrence of low-level clouds and fog is not projected to change substantially during winter or spring.

- *Icing Conditions:* Icing conditions present a significant hazard in the Arctic, both to personnel and equipment. These conditions are expected to occur more frequently during autumn. Icing conditions increase the risk of accidents resulting in oil spills, make aircraft operations extremely dangerous, increase the response time of aircraft trying to respond to an accident or spill, and hamper onsite spill response operations once the needed equipment and personnel arrive. This is primarily an autumn phenomena, and is not expected to increase risks during winter, spring, or summer.

- *Precipitation:* The increasing frequency and intensity of precipitation (all seasons), as well as the number of wet days, may elevate the risk of accidents resulting in oil spills. Such conditions also may make it more difficult to respond to spills when they occur. Increased precipitation during winter and spring may contribute to the severity of 'white-out' conditions which greatly reduce visibility. The projected increase in precipitation is expected to reduce the salinity of the surface waters in the Beaufort and Chukchi Seas, potentially reducing the effectiveness of chemical dispersants applied to oil spills.
- *Storms:* A number of physical arguments suggest Arctic cyclones, including Polar Lows, will become more frequent and (or) more intense during autumn and winter. Although this projected change has not yet been rigorously tested (and so is uncertain), we note that there are no physical arguments to suggest storms will become less frequent and (or) less intense during these seasons. An increase in storminess during autumn and winter, if it occurs, will increase the risk of accidents resulting in oil spills if oil and gas operations are conducted during those seasons. Such storms would increase the frequency of strong winds (autumn, winter) and rough seas (autumn). High winds can prevent or hamper aircraft and vessel access to spill sites, adversely affecting spill response times. Mechanical recovery systems and ISB are hampered by high winds. Accurate application of chemical dispersants is more difficult during high winds. However, rough seas may enhance the effectiveness of chemical dispersants once applied to a spill. Rough seas, drifting pack ice, and storm surges may cause significant damage to offshore equipment, artificial islands, and onshore coastal infrastructure. At this time, there are no convincing arguments that storms will become either more or less frequent during spring or summer.
- *Sea-Level Rise:* Artificial islands and causeways built for offshore energy development will be increasingly vulnerable to inundation from sea-level rise and damage from storm surges. This risk can be substantially reduced through proper engineering that takes sea-level rise into account.
- *Coastal Zone:* Land-based infrastructure (for example, pipelines, storage tanks) designed to support offshore energy development will be much more vulnerable to damage due to sea-level rise, storm surges, permafrost degradation, and accelerated coastal erosion. Proper engineering and site selection may mitigate this risk to a large extent.

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Chapter 6

Marine Mammals and Anthropogenic Noise

By Deborah R. Hutchinson and Richard C. Ferrero

Introduction

In the ocean realm, where vision often is limited by turbidity and darkness, marine mammals rely upon hearing as their primary sense. The scientific consensus is that audition is used in a wide range of activities, for example, to communicate, to forage, to hunt, to sense the environment, to navigate, to socialize, to seek mates, to find open water amidst ice, and to flee predators. Cetacean and pinniped auditory systems are adapted to exploit the ease with which sound travels in water—roughly five times faster than in air, and for far greater distances. For marine mammals, the oceans are relatively opaque to light, but transparent to sound.

The oceans also are noisy places. Among the natural contributors to ocean ambient noise are wind, rain, waves, ice cracking, surf, earthquakes, volcanoes, lightning strikes, and biological sources including the wide array of sounds made by marine mammals. Superimposed on these sounds are manmade ("anthropogenic") sounds from shipping, industrial activities, naval operations, marine research, aquaculture, and aircraft, among others. For the same reasons that marine mammals use sound for survival and reproduction, humans use sound as the most cost-effective and efficient tool for remote sensing and mapping of the seafloor and sub-seafloor to understand, among other issues, habitats and mineral and energy resources. The characteristics of all these sources of sound can be intermittent or sustained, loud or barely audible, and cover a wide range of frequencies (for example, Wenz, 1962). The Arctic Outer Continental Shelf (OCS) is one of the few relatively pristine regions on Earth where shipping and coastal community development is minimal. With the possible exception of the Prudhoe Bay region, the introduction of anthropogenic sound also has been minimal, because of the harsh ice-covered, cold, and remote location. Hence the Arctic offers the potential opportunity to understand the impacts of anthropogenic sound before animals have become widely sensitized, habituated, or disturbed by chronic manmade sounds.

It has been recognized for some time that human-generated noise has the potential to have deleterious effects on marine mammals (for example, Payne and Webb, 1971; Greene and Richardson, 1988; Richardson and others, 1995; Gordon and others, 2004; Southall and others, 2007; Tyack, 2008, 2009). Elevated background noise from manmade sources may prevent animals from hearing sounds they use for their survival or reproduction (masking). Manmade sound may trigger behavior changes, such as avoidance or displacement, which interrupts normal activities. Loud sounds may cause temporary or permanent changes in hearing. Some sounds also may initiate physiological stress responses or even physical injury that could affect survival or reproduction. The great challenge in understanding these impacts is that studying wild populations of Arctic marine mammals is expensive, difficult, and sometimes dangerous. Furthermore, extrapolating limited observations from individual animals to understand longer term characteristics of a population is often more speculative than substantive.

The past two decades have witnessed a growth in concern about and research into human-generated sound in the oceans and its potential impacts on the health and sustainability of marine mammals. A synthesis book was published in 1995 (Richardson and others, 1995). Four National Research Council (NRC) reports have directly explored the association between anthropogenic noise and marine mammals (National Research Council, 1994, 2000, 2003a, 2005). The Marine Mammal Commission also has published synthesis documents (Vos and Reeves, 2005; Marine Mammal Commission, 2007; Simpkins and others, 2007; Bradley and Stern, 2008). Additional syntheses have explored the effects of anthropogenic sound on marine mammals, including seismic studies (for example, Ketten, 1997; Popper and others, 1997; National Resources Defense Council, 1999; Au and others, 2000; Wartzok and others, 2004; Southall and others, 2007; Tyack, 2008; Marine Ecology Progress Series, 2009). Special studies have investigated the effects of oil and gas activities, particularly seismic experiments, on marine mammals (for example, National Research Council, 2003b; Tolstoy and others, 2009); and a Joint Industry Project (JIP) on sound produced from exploration and production (E&P) developed a report identifying knowledge gaps and recommended research for anthropogenic sound and marine life (Thorson and others, 2005). Phase 2 of this JIP lasted from 2006 to 2009 with additional publications (International Association of Oil & Gas Producers, 2011) and a third phase began in January 2010. The U.S. interagency task force on Anthropogenic Sound and the Marine Environment issued an integrated research plan in 2009 (Southall and others, 2009). Since 2006, the Acoustic Ecology Institute has released annual summaries of science, policy, and legal developments related to ocean noise (Acoustic Ecology Institute, 2007).

Marine mammals known to occur in the U.S. Arctic OCS include both year-round or seasonal inhabitants as well as a broader collection of occasional visitors. Cetaceans most notably associated with the Beaufort and Chukchi Seas include bowhead, beluga, and gray whales with less frequent sightings of harbor porpoise, and fin, humpback, and killer whales. Five pinniped species are found in these waters, including ringed, bearded, ribbon, and spotted seals, as well as Pacific walrus. Likewise, polar bears are found throughout this area.

In this chapter, which focuses on the impacts of sound in the Arctic, we emphasize species that could potentially be affected at the population level (owing to more frequent occurrence than the occasional visit)—bowhead, beluga, and gray whales; ringed, ribbon, bearded, and spotted seals; Pacific walrus; and polar bears (table 6–1). In addition, several of these species warrant close attention given their legal status. Bowhead and fin whales have long been listed as endangered under the Endangered Species Act (ESA). The polar bear was listed as threatened in 2008 (U.S. Fish and Wildlife Service, 2008) and in November 2010, the U.S. Fish and Wildlife Service (USFWS) further designated critical habitat for the polar bear (U.S. Fish and Wildlife Service, 2010). The gray whale was considered endangered until 1994, when it was delisted (National Marine Fisheries Service, 1994). Among the pinnipeds, National Marine Fisheries Service (NMFS) initiated an ESA consultation for the four Arctic seal species—the ribbon seal (National Marine Fisheries Service, 2008a) and the spotted seal (National Marine Fisheries Service, 2009a) did not warrant listing action for U.S. waters; however, in December 2010, NMFS proposed that the U.S. Arctic populations of the bearded (National Marine Fisheries Service, 2010a) and ringed (National Marine Fisheries Service, 2010b) seals warranted threatened listings. USFWS recently published a finding for Pacific walrus of warranted but precluded under ESA (U.S. Fish and Wildlife Service, 2011).

Aside from these species or population specific considerations, this collection of marine mammals derives unique stewardship consideration through multiple layers of legislative mandate. The Marine Mammal Protection Act (MMPA), the Endangered Species Act (ESA), and the National Environmental Policy Act (NEPA) are important drivers in management decisions and the need for science to support them. Of these and with particular relevance to this report, NEPA particularly affects the Department of the Interior because of the regulatory responsibilities of the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) for offshore oil and gas development. The National Oceanic and Atmospheric Administration (NOAA)/NMFS and USFWS share responsibility for implementing MMPA and ESA, with a particular concern for authorizing activities that produce anthropogenic sound in the oceans.

Table 6–1. Marine mammals of concern in the Arctic Outer Continental Shelf.

[From Allen and Angliss (2010) unless otherwise noted. **Locale:** B, Beaufort abundance; C, Chukchi abundance; P, Pacific abundance; T, total abundance. **Population status:** +, increasing; ?, unknown. **MMPA** (Marine Mammal Protection Act) **ESA** (Endangered Species Act) **status:** From http://www.nmfs.noaa.gov/pr/species/; Cd, candidate; E, endangered; D, depleted; DL, delisted; Th, threatened]

Common name	Latin name	Locale	Stock abundance	Population status	MMPA ESA status
Bowhead whale	*Balaena mysticetus*	T	9,400	+	E,D
Beluga whale	*Delphinapterus leucas*	B	32,500	?	
		C	3,700	?	
Gray whale	*Eschrichtius robustus*	P	17,500	+	DL
Ringed seal	*Pusa hispida*	T	?	?	Cd
Ribbon seal	*Histriophoca fasciata*	T	?	?	
Bearded seal	*Erignathus barbatus*	T	?	?	Cd
Spotted seal	*Phoca largha*	T	?	?	
Pacific walrus	*Odobenus rosmarus divergens*	T	129,000	?	Cd[1]
Polar bear	*Ursus maritimus*	C	2,000	?	Th
		B	1,800	?	

[1]U.S. Fish and Wildlife Service (2011).

Despite the research and interest in the impacts of noise on marine mammals, considerable controversy surrounds how MMPA, NEPA, and ESA are applied to regulate offshore activities and protect marine mammals. A recent court case in the Arctic OCS is the July 2010 decision halting activities under Lease Sale 193 in the Chukchi Sea citing the need for further environmental review. Tension exists between the advocates for more precautionary approaches to decision making and regulation (National Resources Defense Council, 1999) and the regulatory agencies implementing MMPA and ESA (that is, NMFS and USFWS). Both behavioral and auditory effects associated with anthropogenic sound are considered “takes” under MMPA and ESA, especially if the effects are considered “biologically significant,” a finding that also is controversial in how “biologically significant” is determined and applied (National Research Council, 2003a, 2005).

6.01. Finding: For all the many studies conducted on ocean noise and marine mammals, large uncertainty still exists in extrapolating how impacts of noise on individual animals may affect survivorship or reproductive rates of populations. The National Research Council (2005) addressed how to determine “when noise causes biologically significant effects” (subtitle of the report) but the proposed model involves five core components for which transition inputs and outputs are not always specified or quantified (for example, Clark and others, 2009). More work is needed that is designed to determine how to most effectively determine the impacts of noise at both individual and population levels.

6.01. Recommendation: Investment in efforts such as those of BP and the North Slope Borough with the University of California, Santa Barbara—Cumulative Effects of Anthropogenic Underwater Sound on Marine Mammals—which is to summarize and synthesize the literature on effects of anthropogenic sound on marine mammals, develop suggested approaches for routinely assess such effects, and to define fruitful avenues of future research (http://www.eri.ucsb.edu/adminstrative/research_awards_icess, accessed April 1, 2011)—and the conduct of resulting high priority research would improve the science foundation for a myriad of planning and permitting actions related to Arctic OCS.

Finally, marine mammals are integral to the culture and identity of the Iñupiat Native community of the North Slope of Alaska. The bowhead whale is a vital dietary component, source of bone and baleen for traditional crafts, and an essential symbol of the subsistence culture of the Iñupiat community. The MMPA protections for marine mammals include making them available for subsistence hunting. Annual hunting quotas for the bowhead whale are determined by the International Whaling Commission. The U.S. quotas are allotted to the 11 North Slope communities by the Alaska Eskimo Whaling Commission. For 2010, NOAA issued a quota of 75 strikes to the Alaska Eskimo Whaling Commission. Walruses, polar bears, and seals also are hunted and used by the Native community. A significant recurring concern of the Native community is that oil and gas related activities may displace marine mammals from hunting grounds, thereby threatening the livelihood and existence of the Native community. Moreover, they seek to ensure that local traditional knowledge is used to augment understanding of seasonal movements, distributions, and abundance of marine mammals (for example, Noongwook and others, 2007).

In response to concerns about noise associated with oil and gas activities in the Arctic, NOAA/NMFS initiated an Environmental Impact Statement (EIS) on the effects of Arctic OCS oil and gas activities (seismic and exploratory drilling), and held scoping meetings in February and March 2010, in seven North Slope villages and Anchorage (National Marine Fisheries Service, 2010d). The EIS, still in preparation, examines the effects of oil and gas activities, including noise, on marine mammal species and stocks, as well as their effects on communities and subsistence.

Characterization of Sound in the Oceans

Sound is not intuitive to measure or describe. Technically, sound travels in water as a mechanical vibration, or pressure wave (also called a p-wave) comprising mechanical particle motion oscillations associated with alternating compressions and rarefactions. The physics of sound measurement and transmission are covered in many places and are only briefly summarized here, for example, American National Standards Institute (1986, 1994), Richardson and others (1995), National Research Council (2003), and Erbe (2011). Sound is composed of waves of varying frequencies (measured in cycles/second, Hz) that are of sufficient strength to be detected. In basic terms, sound can be loud or soft, high frequency or low frequency, continuous or pulsed, and its measured loudness and pitch will depend on how distant or close one is to the source. The description of sound necessarily involves relative measures of its character (for example, compared to a reference), and will depend on whether the measurement is done at the source or at some distance from the source. Complicating the characterization is that sound in water attenuates and weakens as it travels ("propagates") away from the source, depending on factors such as salinity and temperature of the water, presence or absence of ice, reflection off the sea or ice surface, the depth of the water, and hardness of the seafloor (in coastal waters). Because higher sound frequencies attenuate more rapidly, low-frequency sounds also travel farther than higher frequency sounds. Hence the sound characteristics at the source (where the sound is created) may have very different characteristics by the time they travel to the marine mammal (where the sound is received).

The methods used to measure sound magnitude include pressure, energy, and intensity. For any acoustic wave, the measure of the pressure on the sound wave can be from zero-to-peak (zero to maximum pressure), peak-to-peak (maximum negative to maximum positive pressure), or a root-mean-squared (rms) value (average of the squared pressure over the duration of a pulse) (fig. 6–1). Sound Pressure Level (SPL) gives the sound pressure relative to a reference pressure, which for water is 1 micropascal (μPa). Because of the large dynamic range of sound pressures, the decibel unit (dB) quantifies pressures (relative to the reference pressure) on a logarithmic scale, so that the SPL of a sound in water using the rms value is given as 20log10(P/Pref), where Pref is 1 μPa and the units are dB re 1 μPa (rms). Sounds at the source typically are standardized to 1 m distance from the source and are given in units of dB re 1 μPa (rms) at 1 m. Sound Pressure Level using the rms approach is the current metric used in MMPA for establishing zones of safety for marine mammals.

Sound also can be characterized by energy, which integrates the pressure through a time window and is proportional to the time integral of pressure squared. Typically, 1 second is the standard for the time, and is referred to as a Sound Exposure Level (SEL), in units of dB re 1 μPa2s. Intensity measures the energy that passes through a unit area per unit time and also generally is derived from pressure squared. Sound Exposure Level is sometimes used to understand sound propagation for seismic arrays (Tolstoy and others, 2009).

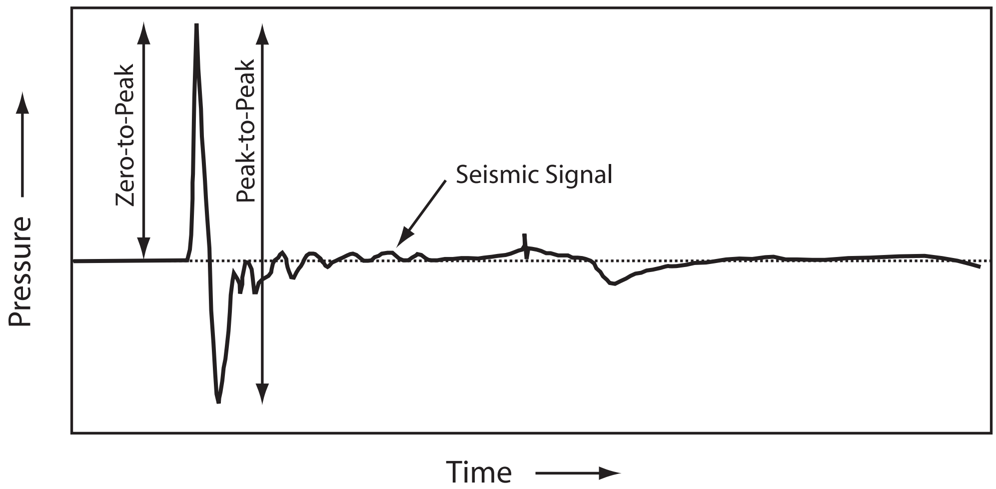


Figure 6–1. Example of a seismic sound signal showing how zero-to-peak and peak-to-peak pressure would be measured.

The use of the logarithmic scale can be confusing. For example, a doubling of pressure will add 6 dB to the SPL, whereas a doubling of intensity adds only 3 dB. For a sound pulse such as an airgun, where the pulse duration is less than 1 second, the SEL value will always be less than the SPL (rms) value. Further, the SPL (rms) will be less than SPL (zero-to-peak) and both will be less than SPL (peak-to-peak). Hence it is important to be rigorous in describing and measuring sound levels to specify SPL versus SEL and to identify whether SPL is for peak-to-peak, zero-to-peak, or rms. The media frequently quote dB estimates for measurements that do not specify the type of SPL or SEL measurement. Further, dB measurements in water use a reference of 1 µPa whereas for air the reference is 20 µPa, rendering comparisons between the two inappropriate. Imprecision in describing sound adds confusion and sometimes alarm to reasoned public discourse. Because sound also contains different frequency contents, the SPL of different sound sources in not necessarily additive (and, if additive, must be added using logarithmic, rather than linear, rules).

Airgun size is classified by its chamber volume. The way this volume is related to level of sound also is not linear. Excellent summaries describe how changes in source strength, operating pressure, and number of airguns in an array affect SPL measurements (Dragoset, 1990, 2000).

Although the current regulatory framework uses the SPL (rms) pressure measurement, some researchers have suggested that the energy metric, SEL, is more useful because total energy enables sounds of differing durations to be more readily compared (for example, Southall and others, 2007; Tolstoy and others, 2009). It perhaps may be most useful to use both. Extremely high but nearly instantaneous sound waves have low energy levels (because the energy is averaged over a much longer time frame than the duration of the pulse), but may still cause damage to auditory or other tissues. Additionally, cumulative energy contained in low-amplitude sounds may interfere with hearing after long exposures. As an example, one can imagine how a gunshot or firecracker going off near one's ear would affect hearing, and also imagine how working with constant background noise for a long period of time also might affect hearing.

Different animal species have different frequency sensitivities. Five functional hearing groups of marine mammals exist based on their presumed hearing frequency range (for example, Southall and others, 2007), which are summarized in table 6–2. Only four of these apply to the Arctic marine mammals of interest (the high-frequency cetaceans, such as harbor porpoise, which are only seasonally present in the Arctic in low abundance, are not among the subjects of this chapter). It is important to note that sound frequencies particularly greater than 1,000 Hz (1 kHz) attenuate rapidly in water.

A useful diagram summarizing the magnitude and frequency of different kinds of sounds found in the oceans is that created by Wenz (1962), which is still widely used (fig. 6–2).

Table 6–2. Arctic Outer Continental Shelf Marine Mammal Hearing Groups.

[Modified from Southall and others (2007) for the marine mammals of interest in this report. Hz, hertz; kHz, kilohertz]

Functional hearing group	Genera	Estimated auditory bandwidth
Low-frequency cetaceans	*Balaena, Eschrichtius*	7 Hz – 22 kHz
Mid-frequency cetaceans	*Delphinus*	150 Hz – 160 kHz
High-frequency cetaceans	(none)	200 Hz – 180 kHz
Pinnipeds in water	*Erignathus, Histriophoca, Pusa*	75 Hz – 75 kHz
Pinnipeds in air	(same as species in water)	75 Hz – 30 kHz

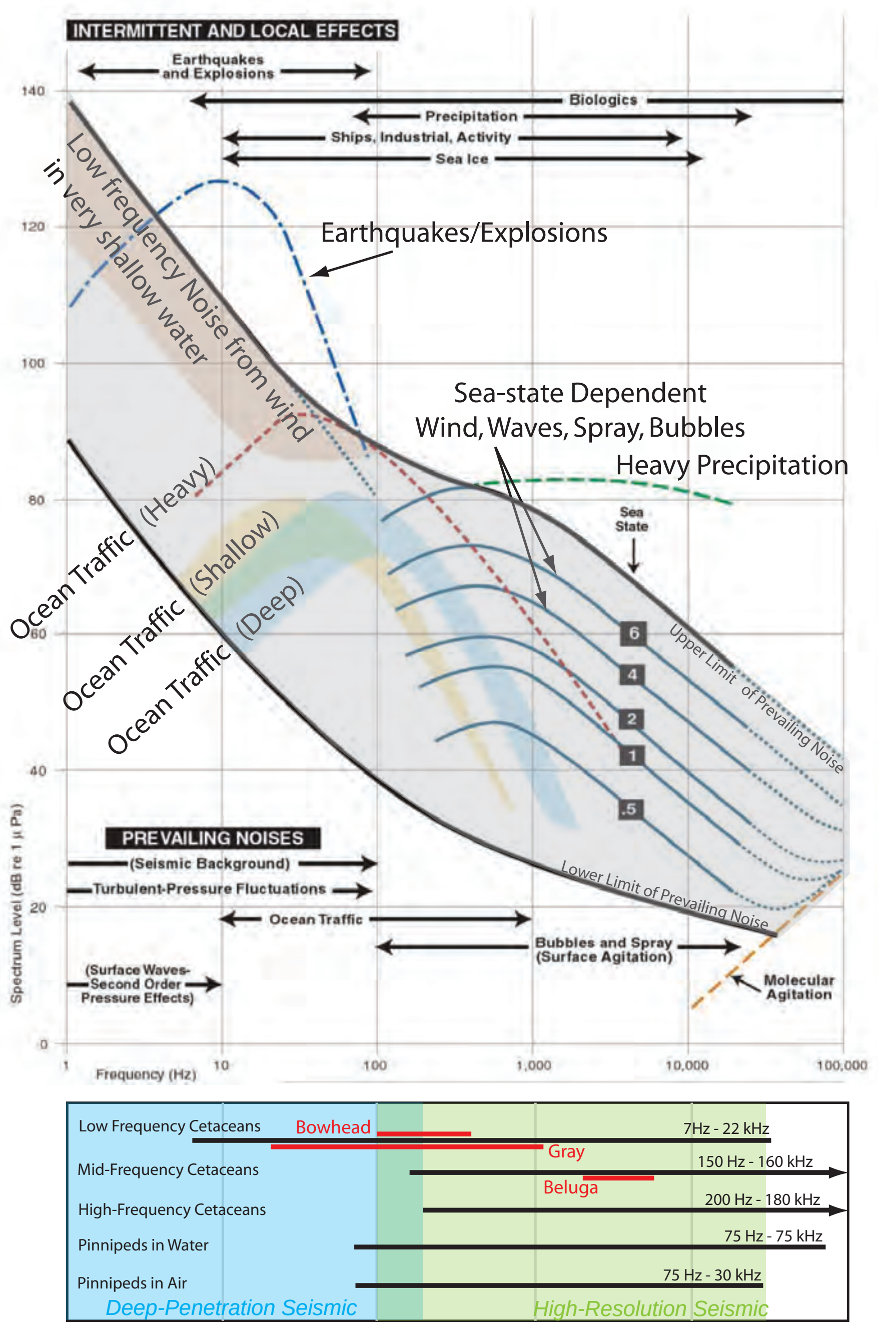


Figure 6–2. Upper: diagram showing pressure spectral density of marine ambient noise modified from Wenz (1962) and National Research Council (2003b). The gray shaded region gives the general band of ambient noise and the contained curves identify specific sources of sound contributing to the ambient noise. Lower: marine mammal hearing groups and their estimated auditory bandwidth (black lines) as defined by Southall and others (2007). Dominant bandwidth for selected whales (red lines) is from National Research Council (2000). Approximate frequency ranges for deep-penetration (blue) and high-resolution (green) seismic surveys are superimposed on the cetacean ranges.

Anthropogenic Sound Categories

For the purposes of understanding anthropogenic sound in the Arctic OCS, we use seven categories of sound. These categories discriminate among the source level, frequency (Hz), and temporal patterns of the sound. The source level is the SPL (rms) measured or estimated/modeled at 1 m from the source. The frequency is captured as a power spectrum that relates sound level and frequency. The temporal pattern of sound refers to its occurrence, as in transient (for example, explosion), continuous (for example, drilling), or pulsed (for example, seismic airguns). The seven categories are:

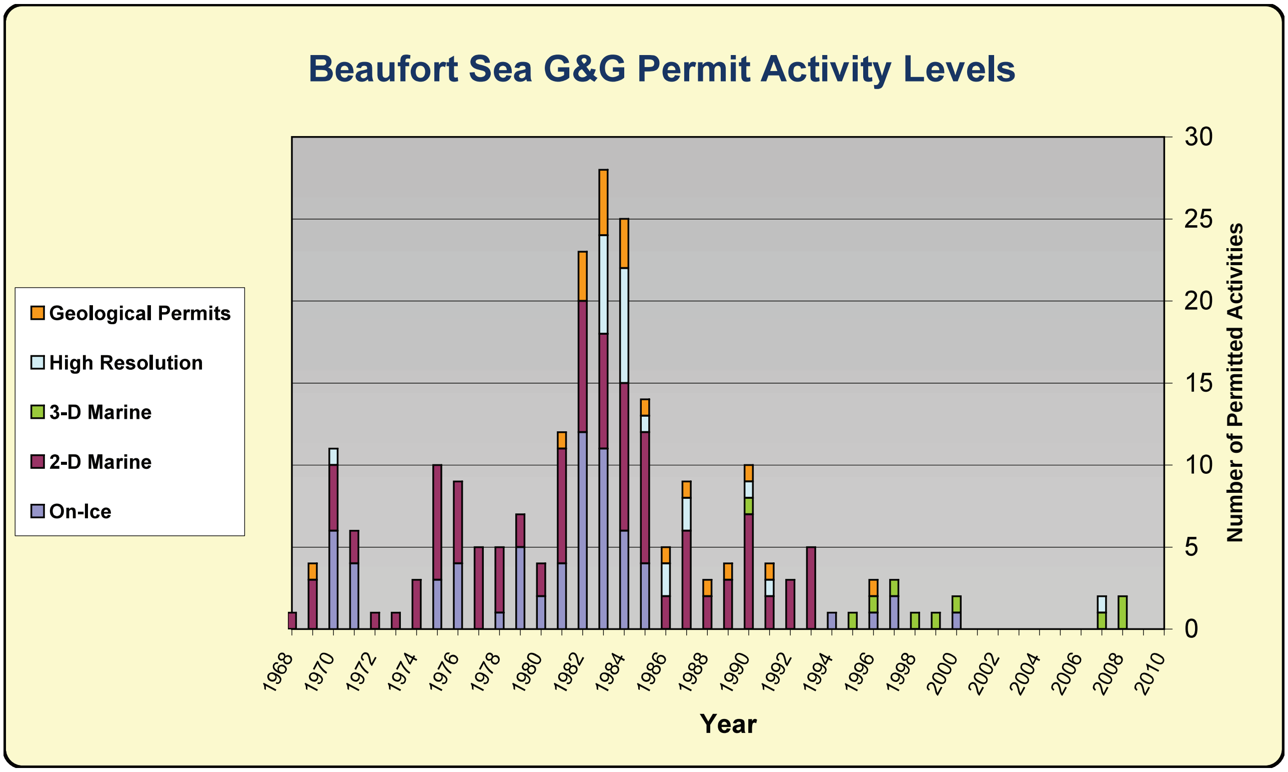
1. **Deep-penetration seismic surveys**

   Deep-penetration, low-frequency seismic surveys are considered to be high-energy intermittent pulsed sounds, typically two-dimensional (2-D) regional surveys and three-dimensional (3-D) local surveys utilizing airgun arrays consisting of several large to many small airguns. The frequency level generally is from several to 100–250 Hz. The purpose of these surveys is to image geology at moderate to crustal depths for geologic framework and exploration purposes.

   Statistics maintained by BOEMRE (See websites accessed April 30, 2011, at http://alaska.boemre.gov/re/permits/xpermits/arctic_charts.pdf, http://alaska.boemre.gov/re/permits/xpermits/arctic_table.pdf, and http://alaska.boemre.gov/fo/Geohazards/chukchi_hazard_surveys.mdb) show that deep-penetration surveys in the Beaufort and Chukchi regions for oil and gas exploration have been historically, and continue to be, the most plentiful types of surveys conducted. Since 1968, there have been 119 open-water exploration surveys in the Beaufort region and 48 in the Chukchi region. An additional 67 on-ice seismic surveys were conducted in the Beaufort region between 1970 and 2000. The peak in seismic permits for both areas occurred in the early to mid-1980s with a maximum of nine permits issued for marine 2-D geophysical surveys in the Beaufort region in 1984 and a maximum of six permits for similar work in the Chukchi region in 1985 (fig. 6–3). Recently (since 1994), there have been no 2-D surveys in the Beaufort region and only one in the Chukchi region (in 2006). This decrease in 2-D surveys contrasts with the growth of 3-D exploration surveys: since 1990, there have been ten 3-D surveys in the Beaufort region, but only three in the Chukchi region. The trends from these permits suggest that future oil and gas seismic exploration activity in the Beaufort and Chukchi regions is likely to be with 3-D surveys. Details about the surveys, such as time of year, lease block locations, and duration of surveys are available from BOEMRE. These BOEMRE statistics do not include seismic programs that might have occurred in Canada or Russia for oil and gas activities (for which the air gun sounds could propagate into U.S. waters). Nor do the BOEMRE statistics cover seismic activities conducted by U.S. or foreign research groups for non-petroleum related purposes (for example, 2005 NSF-funded seismic transect across the pole aboard the U.S. Coast Guard Cutter (USCGC) *Healy*, or the 2007–10 United Nations Convention on Law of the Sea (UNCLOS) work conducted aboard the Canadian icebreaker CGGS *Louis S. St-Laurent*). Hence these statistics are representative of the bulk of the seismic exploration work, but underestimate total seismic activities.

6.02. Finding: Despite the large number of seismic surveys conducted over time in the Beaufort and Chukchi Seas, an inventory/database of seismic sound sources used in the Arctic Ocean does not exist.

6.02. Recommendation: Such an inventory would provide standardized information about source arrays (for example, number of airguns, dimensions of arrays, frequencies, firing pressure), physical oceanographic conditions at the time of measurement, and timing and duration of surveys. Such a database could be used to evaluate multiple sound sources that a marine mammal might hear in space and time, and help validate models that estimate sound propagation. The database may ultimately reduce the need for expensive or redundant acoustic modeling and monitoring, especially in sensitive or biologically significant habitats as well as contribute to developing more effective mitigation strategies.



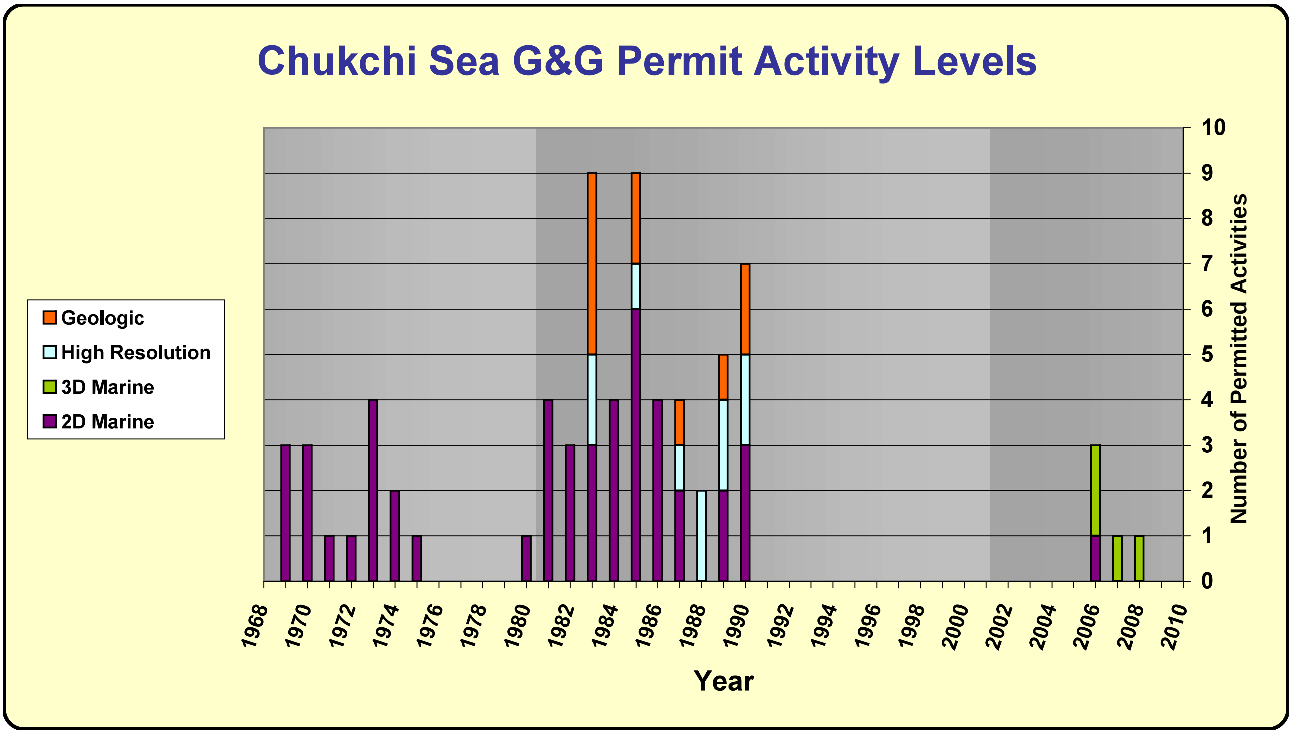


Figure 6–3. BOEMRE permitted exploration seismic activities in the Beaufort (upper) and Chukchi (lower) Seas since 1968. High-resolution seismic surveys done to address site-specific hazards related to drilling are not included in this chart. The peak number of seismic surveys occurred in the 1980s. Source: Bureau of Ocean Energy Management, Regulation and Enforcement, written commun., February 2011. G&G, geological and geophysical.

2. **High-resolution seismic surveys**

High-resolution seismic surveys are considered to be mid-to high-frequency, low-energy intermittent pulsed sound, typically used in shallow hazards surveys for siting drill holes (including strudel surveys to understand ice scour) or high-resolution surveys for understanding near-seafloor geologic evolution. The sources usually are not airgun arrays but consist of boomer, sparker, chirp, and individual (or arrays of several) small water guns or Generator-Injector airguns (GI-guns). The frequency range generally is from 100 Hz to several kilohertz.

High-resolution surveys related to oil and gas activities have occurred in the Beaufort Sea [see Minerals Management Service (2007) for permitted activities and see Horowitz (2002) for additional high-resolution surveys in the Beaufort Sea] and Chukchi Sea (see Minerals Management Service, 2007). These surveys are required to address safety and risk assessment prior to siting final drill locations. Hence, these kinds of surveys are expected to increase when drilling resumes in order to satisfy permitting requirements. Because of the generally lower energy and higher frequencies associated with these surveys, these surveys are often considered to be lower impact on marine mammals, although some studies are beginning to question this conclusion (for example, Southall and others, 2007).

The distinction between deep-penetration and high-resolution seismic categories separates both the frequency and energy levels of the different survey types. Figure 6–2 shows how the deep-penetration surveys overlap primarily with the low-frequency cetaceans (such as the bowhead and gray whales). The high-resolution surveys overlap primarily with the mid- and high-frequency cetaceans (such as the beluga whale). Figure 6–4 illustrates how the higher energy of the deep-penetration surveys results in significantly larger zones of mitigation under MMPA compared to high-resolution seismic surveys.

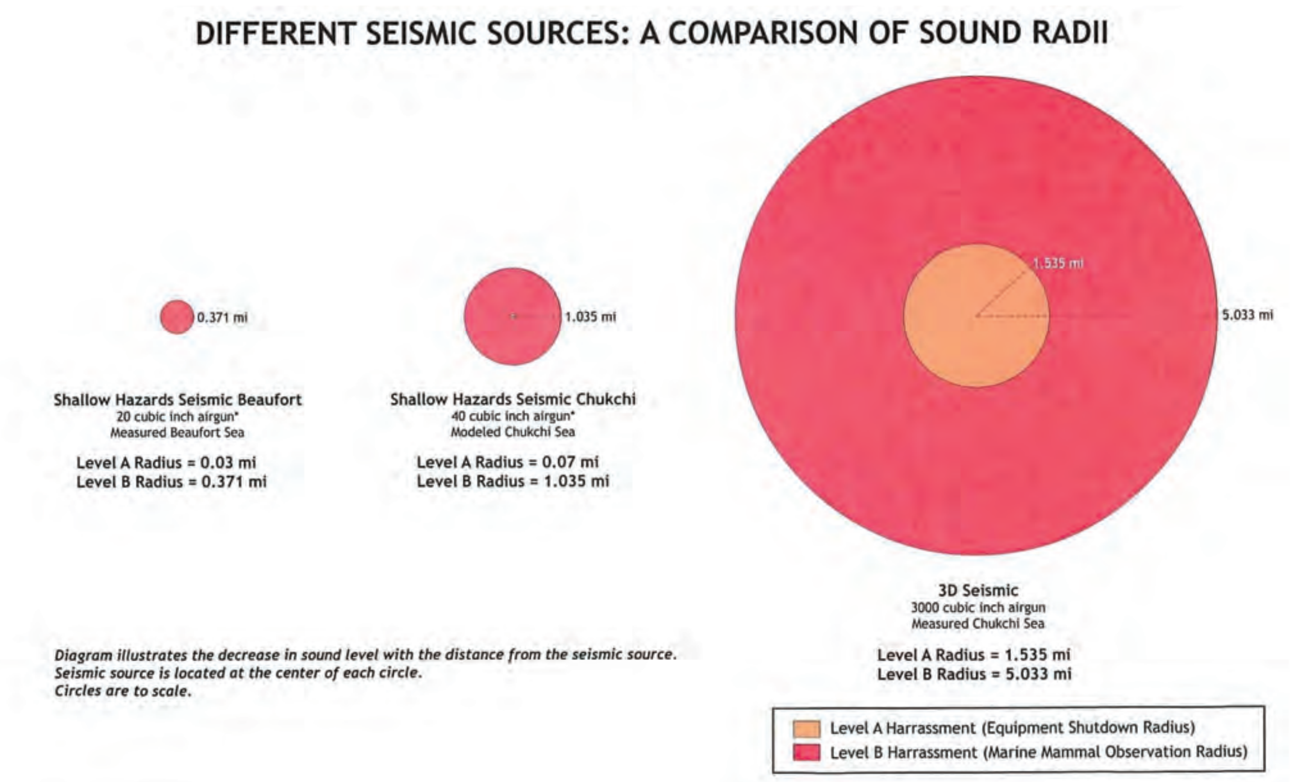


Figure 6–4. Comparison of zones of mitigation under MMPA for deep-penetration (right) and high-resolution seismic surveys (middle, left). Inner and outer circles are for Level A and B harassment, respectively. Source: Jana Lage, Bureau of Ocean Energy Management, Regulation and Enforcement, January 2011.

3. **Drilling activities**

Drilling activities generate continuous, generally low-energy sound at low frequencies (for example, less than several tens of hertz) that decay to ambient noise levels within 1 to several kilometers (Richardson and others, 1995). There are variations depending on type of drill rig (for example, gravel island versus semi-submersible) and type of drilling (for example, rotary versus hammering).

Drilling in the Arctic OCS has been limited to shelf-depth waters (generally less than 100 m water depth). Winter ice currently precludes the installation of year-round floating or semisubmersible drill rigs used in conventional open-water deep-water drilling operations. Benchmark noise studies of gravel-island and shallow-water caisson and semisubmersible drilling have been done for the Beaufort OCS around Prudhoe Bay (Greene, 1987; Richardson and others, 1995). Additional monitoring of the noise of drilling continues through the present (for example, with the BP Liberty gravel-island drilling reported in the last 3 years of NOAA/BOEMRE Arctic Ocean Open Water meetings). The data collected as part of monitoring are not publicly available, and the reports associated with these monitoring studies show images and analyses that are sometimes in peer-reviewed journals (for example, Blackwell and others, 2004a), but generally only available in gray literature.

4. **Ships/Vessels**

Ship and vessel noise is continuous and consists of a combination of frequencies that are both broadband (over a range of frequencies) and narrow band (tonal at specific frequencies). Ships are considered a major contributor to ocean noise at frequencies less than 500 Hz (National Research Council, 2005) with significant spatial variability associated with shipping lanes and ports. Levels and frequencies of sounds are dependent on vessel size, design, and mode of propulsion. Smaller vessels with small propellers and high revolutions per minute generate noise at higher frequencies. There is an abundant literature on shipping noise (for example, National Research Council, 2005).

Although there are currently no commercial shipping lanes in the Arctic OCS, the possibility exists for these routes to develop as summer ice retreats or disappears with climate warming, as well as for large cruise vessels to bring tourists to the Beaufort and Chukchi Seas. Currently, the commercial ship traffic occurs with barges in the near shore in open water during the summer, primarily to re-supply the Native community with bulk supplies. Gray literature exists for the sounds made by individual ships participating in oil and gas activities in the Arctic OCS as a result of permits issued under MMPA that generally require measurements of ship noise prior to the start of exploration activities. These data are not readily available digitally, although reports written as a result of the oil and gas activity sometimes include summaries of the noise studies.

6.03. Finding: As in Finding 6.02 for seismic survey-generated noise, there is a similar lack of an organized inventory/database for the noise generated by vessel types that presently frequent the Arctic Ocean, or may do so in the future with changing ice conditions.

6.03. Recommendation: An inventory and synthesis of vessel noise for vessels used in the Arctic Ocean will enable researchers to understand the contributions of potential new ship traffic to ambient background levels of noise in the Arctic. This inventory/database should contain standardized information about vessel noise, duration, time of measurement, and location. Most industry exploration activities measure ship noise prior to commencing surveying as part of the permitting process.

5. **Icebreaking**

Icebreaking is a special category of ship and vessel noise that is associated with higher levels of sound because of the additional power required for a vessel to break thin ice continuously or thicker ice through backing and ramming.

Icebreaking also is unique to ice-covered regions such as the Arctic. Some of the earliest studies on the sound of icebreaking were done in the Arctic (for example, Richardson and others, 1995, and references therein) and these studies continue to be cited extensively in the absence of more recent publications. Roth and Schmidt (2010) presents interpretations of the noise of icebreaking for USCGC *Healy* during a 2008 cruise and compares SPLs at 5/10 ice coverage and greater. The noise of continuous icebreaking exceeded the noise of backing and ramming by about 5 dB. The inclusion of icebreaking as potential impact for Level B marine mammal harassment under MMPA is new in 2010 (Haley and others, 2010).

6.04. Finding: Icebreakers, an important subset of vessels used in the Arctic from a noise and marine mammal encounter perspective, are highlighted in addition to the more general vessel topic of Finding 6.03. There are essentially no data relating the noise of icebreaking to the type of icebreaker, and the character of the ice (for example, percent coverage, age of ice, thickness of ice). Preliminary data included in Haley and others (2010) suggest that the noise from icebreaking is not of higher amplitude than a modest seismic array. But, the paucity of data on icebreaker-generated noise is particularly critical because of sea ice's importance as habitat for many marine mammals. It is difficult at present, if not impossible, to know how to define "takes" from icebreaking or how to predict its impact on marine mammals.

6.04. Recommendation: As in Recommendations 6.02 and 6.03, the development of a standardized inventory/database would greatly facilitate the accumulation of information required to better understand the characteristics of icebreaker-generated noise under different ice, oceanographic, and operating conditions.

6. Construction

Construction for the purposes of this report is considered to include localized relatively brief duration or one-time noise associated with, for example, siting drill rigs, installing pipelines, developing shore-based infrastructure such as docks and piers, building ice roads on sea ice, and so on. Similar to drilling activities, the noise associated with construction generally is at the lower frequencies (less than several hundred hertz) and attenuates relatively close to the location of construction. Unlike drilling, the noise generally is short-term for the duration of the construction project only.

For the Arctic OCS, shore-fast and winter sea ice preclude year-round floating or surface structures. Hence the noise of construction has been limited to near-shore (Beaufort) and shallow water (Chukchi) seasonal activities. A large literature exists on the sounds of construction related to developing the Liberty and Northstar prospects in the Beaufort Sea (for example, Richardson and others, 1995). Dredging is not yet an activity conducted along the North Slope (Beaufort/Chukchi) shorelines.

7. Aircraft overflight

Aircraft (including helicopters and fixed-wing aircraft) are a special category of noise because of (a) the potential transient nature of the noise, (b) the complications of relating source level and propagation paths through air and water, and (c) the potential impacts to marine mammals (seals, walrus, and polar bear) that spend considerable time out of the water. It is only for a relatively narrow angular cone beneath the aircraft (about 13° for calm water, Richardson and others, 1995) that the noise of the aircraft penetrates into the water. At larger angles, the sound is effectively reflected at the sea surface. Hence, the height and speed of the aircraft, in addition to the noise it generates, affect how much of the ocean surface will be insonified. Moreover, a persistent challenge in interpreting observations of marine mammal behavior associated with the presence of aircraft is to know whether the aircraft sound or the visual presence of the aircraft has triggered the disturbance.

In the Arctic OCS, aircraft are used in offshore oil and gas activities as well as in conducting monitoring and population assessments of marine mammals (for example, Bowhead Whale Aerial Survey Program, BWASP). Shell also has proposed using drones to monitor for marine mammals near seismic operations (A. Macrander, Shell Exploration and Production, oral commun., March 2010) to augment visual monitoring in areas far offshore (such as the Chukchi) where manned fixed-wing aircraft monitoring is impractical or unsafe.

6.05. Finding: Aircraft represent another potential sound source that must be considered along with seismic (Finding 6.02), vessel (Finding 6.03), and icebreaker (Finding 6.04) sources. Very little information exists that quantifies aircraft noise as a function of aircraft type and approach geometry.

6.05. Recommendation: Information that quantifies aircraft noise as a function of aircraft type and approach geometry would help to understand the responses of several species of Arctic OCS marine mammals to overflight.

8. Other Considerations

To completely understand the contribution and impacts of anthropogenic noise to the environment, knowledge of the levels and spatial-temporal variability of background (ambient, non-anthropogenic) noise is essential, as well as which anthropogenic sounds occur simultaneously. The magnitude of ambient sound gives context to understanding increased sound levels from anthropogenic sources. However, it is important to correctly characterize the sound, because not all these sounds are additive when occurring together, owing to the different frequencies, shapes, and amplitudes of the different sources of sound.

6.06. Finding: The overall ambient noise budgets of the Arctic, particularly how they vary temporally (for example, seasonally) and spatially (for example, shallow versus deep water) are not well known. Very little data exist to inventory the seasonal and spatial levels of ambient noise in the Beaufort and Chukchi Seas. Some annual measurements in specific locations are beginning to be done and seasonal measurements are recorded as by-recordings of listening to and locating whale calls before, during, and after seismic surveys in the Beaufort and Chukchi Seas (for example, Blackwell and others, 2007; Kosiara and others, 2008).

6.06. Recommendation: A time-series database of ambient ocean noise for the Arctic will be essential for understanding the changes to ambient noise created through climate warming and seasonal reductions in sea ice so that the distinction of impacts between anthropogenic and natural sources on marine mammals can be made.

A little-studied factor that also will affect sound measurements in the oceans is ocean acidification, the process by which the oceans become more acidic because of the anthropogenic emissions of carbon dioxide (for example, Ilyina and others, 2009). Because propagation of sound in the oceans is affected by the dissolved chemical constituents, an increase in ocean acidity will decrease the absorbtion of sound, that is, increase the propagation of sound. According to models, this affect may be greatest in high latitudes in the frequency ranges of 100 Hz to 10 kHz, or exactly in the range that encompasses both deep-penetration and high-frequency seismic surveys (Ilyina and others, 2009).

Potential Effects of Sound Exposure

A range of effects may result from exposure of marine mammals to anthropogenic sound, ranging from no observable effect to physical injury or, in the extreme, death. As with people, the reactions of marine mammals can depend on factors such as species, individual, age, sex, prior experience with the sound, activity at the time of the sound, and behavioral state. When observing animals in the natural environment, external non-auditory stimuli also may affect reactions. In this section, we describe some of the potential effects of exposure to anthropogenic sound sources, which may or may not result in observable or measurable behavioral changes.

1. No Observable Effect

Marine mammals have been observed in close proximity to loud sound sources associated with oil and gas activities (for example, Richardson and others, 1995). They could be unaffected by the sound, they could be tolerating the sound because critical resources were in the area (food, mates, open water, haulout sites, and so on), or they could be deaf. The individuals could be unaffected because their auditory systems are insensitive to the frequency-intensity combinations of the sound. Alternatively, the individuals may be able to detect the sound, and may have reacted during their first exposures, but over time have learned that the sound is of no consequence and thus have become habituated, evidence of which is reduced or absent response during subsequent exposures.

There are documented cases of apparent tolerance of marine mammals to noise, which also demonstrate much variability. For example, bowhead whales tolerated an increase in 40 dB in seismic survey noise when feeding in summer as opposed to during the fall migration (Richardson and others, 1995, 1999).

2. Sensitization

Sensitization occurs when an individual associates a specific sound with a specific outcome that alters the animal's behavior. Evidence of sensitization is observed in animals that change their behavior when they receive sound levels that are far below levels associated with auditory interference or injury. For example, seals that survive hunting or harassment (for example, by humans, polar bears, or killer whales) likely will take the appropriate actions as soon as they detect sounds made by the hunters in the future.

3. **Avoidance/Displacement**

Marine mammals may avoid sound sources, or be displaced from areas associated with the sound. This behavior has been observed in bowhead whales from underwater acoustic monitoring, which has shown that the calls of bowhead whales deflect seaward away from the sound of airguns during nearshore seismic surveys (Blackwell and others, 2007). An uncertainty associated with this deflection behavior is whether all whales exhibited the displacement or only those whales making calls. When whales cease calling in the presence of nearby seismic signals, this is a variant on avoidance and displacement (for example, Blackwell and others, 2010).

4. **Masking**

Masking is the decreased ability to detect one sound due to the presence of another sound. Fletcher (1940) suggested that masking of a signal is especially pronounced if the frequency spectrum of the masking noise overlaps within a critical band around the frequency of the signal. Most anthropogenic underwater activities produce sound at frequencies below 1 kHz, which is within the frequency band used for communication signals of baleen whales, and some toothed whales, such as belugas (for example, Clark and others, 2009). It may not be possible to distinguish hearing loss (that is, an animal that fails to detect a signal because of reduced hearing) from masking (that is, an animal with a normally functioning auditory system that fails to detect a signal because it is masked by a louder sound of similar frequency).

An increase in ambient ocean noise (for example, by increased shipping in a region) can contribute to masking. If marine mammal navigation or communication signals are masked by anthropogenic noise, there will be obvious implications for population cohesion and other social interactions. However, it is important to note that masking has never been conclusively demonstrated in free-ranging marine mammals, only implied by observations of animals changing their calling in the presence of anthropogenic sound.

5. **Auditory Threshold Shift**

Exposure to loud or repetitive sounds may degrade the individual's ability to hear, with effects ranging from reversible temporary threshold shifts (TTS) to permanent reduction in thresholds (PTS) at narrow or broad frequencies (Kryter, 1994). TTS is recoverable and is considered to result from the temporary, noninjurious distortion of hearing-related tissues. An animal that experiences a TTS suffers no injury to its auditory system but temporarily may not perceive some sounds due to the reduction in sensitivity. In contrast, PTS results from the nonrecoverable destruction of tissues within the auditory system and is considered an injury in the U.S. regulatory environment (see summary in Southall and others, 2007). Recent anatomical and behavioral studies suggest that cetaceans may be more resistant than many land mammals to TTS, having evolved in a relatively high noise environment. Data suggest, however, that, like humans, cetaceans suffer from hearing loss as a result of increasing age (Ketten, 1997).

6. **Physiological Stress Responses**

Although several reviews have entertained the possibility that noise induces a physiological stress response in marine mammals, there have been few studies. Romano and others (2004) exposed a captive beluga whale to sounds from a seismic water gun and measured various hormones in the blood, including cortisol, before and after exposure. They measured changes that were considered detrimental. These changes increased with increasing sound levels. Thomas and others (1990), however, did not find elevated stress hormone levels in the blood after playbacks of oil drilling platform noise to captive belugas. Because of the inherent difficulty, if not impossibility, of taking frequent tissue or blood samples from live wild animals, conclusions about physiological stress responses will remain the purview of studies of captive animals.

7. **Physical Injury**

PTS is considered an injury and can occur either after long exposure to a sound (for example, Richardson and others, 1995) or from instantaneous exposure to very high sound levels, such as an explosion. There is some speculation that anthropogenic sound has the ability to induce other injurious effects, such as debilitating bubble formation or tissue damage in deep- or long-diving species (Houser and others, 2001). While evidence of tissue damage (including auditory structures) has been reported, this has been associated with exposure to extremely loud sounds associated with use of explosives or military training and testing (Jepson and others, 2003; National Research Council, 2005). To the best of our knowledge, this has little relevance to the sound sources and levels and environmental acoustics associated with OCS oil and gas exploration and production.

8. **Cascading Effects**

Vessel noise, in addition to potentially impacting marine mammals, produces sounds in the hearing range of fish (Amoser and others, 2004). If anthropogenic sound affects the distribution of fish, it could therefore impact marine mammals that rely on those fish. Vessels (that is, trawlers, ferries, small boats) also can alter behavior in fish (for example, induce avoidance, alter swimming speed and direction, and alter schooling behavior), similar to marine mammals (for example, Engås and others, 1995).

Although the above list produces convenient categories for describing the possible effects of sound on marine mammals, in actuality, linking an effect to an observation and an explanation is much more difficult. For example, if a marine mammal tolerates a sound, it may represent acclimation or habituation of some kind, but it also may represent an unrelenting need, for example, for feeding or reproduction, to remain in a particular location despite exposure to a potentially damaging sound. Alternatively, the sound may be harmless. Science, however, is based on observations, and in the absence of observable changes, it is risky to attempt to speculate about contributions of potential invisible factors.

6.07. Finding: Substantial challenges exist to confidently interpret the magnitude and significance of the potential effects of anthropogenic sound on marine mammals. Limitations in our understanding affect the confidence that many entities expressed during the USGS OCS Team expert consultations (see appendix A). The topic of the impact of anthropogenic sound on marine mammals remains a key topic of concern.

6.07. Recommendation: Continued or new attention to the following topics could significantly improve the assessment and potential mitigation of human-generated noise effects on marine mammals of concern. Some of these challenges are:

1. Attempting to distinguish between transient or ephemeral behavioral effects of sound versus those that are more meaningful to survival or reproduction. An example would be walruses waking up and raising their heads when they hear a sound, as compared to injury or mortality caused by the same walruses stampeding into the water when they hear a sound. A second example would be the movement of animals away from a sound source—is displacement fractional relative to the animals' normal movements, or is it substantial, and how long does it persist?

2. Using observations of individual animals to make inferences about possible implications for populations. In general, the body of available scientific information supports the potential for near-term reaction of individuals to various forms of anthropogenic sound sources, but long-term impacts at the population level are not well understood.

3. Using one set of observations for predicting reactions when the interaction parameters are different. The same sounds may elicit different responses at different times of year or in different locations associated with different types of activity (for example, migration, feeding, reproduction, sheltering).

4. The degree to which context of a sound influences a reaction. In some instances, animals of a given species may occupy locations with substantial types of some noise (for example, pipe-driving) but avoid other locations where the anthropogenic sound levels are much lower. For example, ringed seals may forage nearby active seismic surveys, but escape reactions will be elicited when they detect faint sounds of polar bears or subsistence hunting boats.

5. The degree to which we can discriminate between the effects of sound, other aspects of human activity, and environment variation, especially for understanding behavior of animals in the wild. An animal that is observed in close proximity to a loud sound source could be unaffected by the sound, it could be tolerating the sound because critical resources were in the area (for example, food, mates, open water, haulout sites), or it could be deaf. The observed behavior is the sum of the external environmental stimuli detected by the animal, behavior of its peers, behavior of other species, plus the animal's physiological state. Further, if the source of sound has been close enough to the animal that it was visible and perhaps detectable by other sensory cues, such as odor or vibration, the animal could be reacting to these other cues. Unless research demonstrates that individuals are exposed only to sound, the precautionary interpretation is that the sound can be associated with the behavior rather than that the sound explains the behavior.

6. Quantifying secondary or cumulative effects of sound on population persistence. While sound may alter the behavior of individual animals, other factors also may affect outcomes (for example if sound caused prey abundance or availability to change). Cumulative effects also may occur but are difficult to quantify (for example, if physiological stress caused by sound exposure combines with stress induced by environmental contaminants to affect a population). These are difficult, if not impossible, measurements to make on wild animals.

Monitoring and Mitigation

Both the ESA and the MMPA require monitoring and mitigation measures to protect marine mammals from potential harm caused by exposure to anthropogenic sound sources. The MMPA places a moratorium on “takes” of marine mammals, in which “take” means “to hunt, harass, capture or kill” (from National Marine Fisheries Service, 2008b). Exceptions exist, for example, for subsistence hunting, and exceptions also can be granted for example, for incidental takes associated with fishing. For permitting, harassment for MMPA is further defined as level A (in which the harassment has the potential to cause death or injury) or level B (in which the harassment has the potential to disturb the animal by disrupting its behavior) (National Marine Fisheries Services, 2009b).

The USGS OCS Team’s expert consultations (appendix A) raised concerns about both monitoring and mitigation strategies, particularly by the Marine Mammal Commission and the Alaskan Native Community. Protected species observers are required participants on many oil and gas exploration and development activities to monitor marine mammals and determine when mitigation strategies must be implemented. Data recorded by these observers are inconsistent. This inconsistency limits how these datasets can be integrated and merged for a more complete picture of marine mammal behavior in the presence of anthropogenic sound. As technology advances, the requirements for monitoring also have evolved, so that deficiencies in visual observations (for example, only possible for daylight hours) can be augmented by acoustic observations (for example, passive acoustic monitoring). Despite the array of tools available for monitoring (ship observations, aerial observations, acoustic monitoring, infrared detection, and so on), no single monitoring strategy gives a complete picture of the marine mammal presence. Hence monitoring contains inherent uncertainty about missing animals, which raises questions about how effective monitoring is for ensuring whether “takes” occur.

Mitigation also is problematic. First, the objectives of mitigation (for example, to avoid hearing impairment or to minimize disturbance) may require multiple criteria. Yet, a single, simple criterion is the easiest to implement. Second, some mitigation measures significantly restrict human activities with little evidence of benefit to marine mammals. Third, a standard mitigation strategy is applied broadly (for example, one for cetaceans, another for pinnipeds). Yet, the hearing ranges and communication frequencies differ for different species, raising questions whether mitigations strategies should be specific to a species (for example, Southall and others, 2007). Fourth, practical decisions about regulatory and mitigation issues are being made based on best available, but incomplete, knowledge which raises questions about how defensible these decisions are. And, finally, many concerns and questions raised by managers require integration across a range of temporal and spatial scales, involve understanding the ecosystem in which the marine mammals live, and now commonly require evaluating species responses to climate change. Regulators and scientists are in agreement that additional data are needed for each marine mammal species, such as baseline data on current abundance, seasonal distribution, movements, population dynamics, and other basic biological information.

Bowhead Whale (*Balaena mysticetus*)

Of the five recognized stocks of bowhead whales, the Bering-Chukchi-Beaufort (BCB) stock frequents the Alaska Arctic coastal area. As part of its annual migration, the bowhead whale passes from the Bering Sea to the Chukchi and Beaufort Seas en route to its summer grounds in the Canadian Arctic and returns to the northern Bering Sea in the autumn (Moore and Reeves, 1993; Moore and others, 2000). Its migration routes along the Alaska coastline and in the Chukchi Sea (fig. 6–5) overlap with the current areas of leasing and oil and gas exploration and production.

Of the baleen whales, the U.S. bowhead is among the most studied. The convergence of three events served to promote research about the bowhead whale. First was the recognized depletion of the bowhead population, initially in the early 1900s when it was given protected status by the International Convention for the Regulation of Whaling and later when the bowhead was listed as endangered under the ESA of 1973 and further protected by MMPA. Second was the controversy accompanying the proposed ban on subsistence whaling by the International Whaling Commission in 1977, which led to negotiation of a reduced subsistence harvest to be accompanied by expanded research about the bowhead. Finally, the mid-1970s initiated the first oil and gas activities in the Arctic OCS for which research into the impacts of oil and gas activities on the bowhead whale was required under ESA and MMPA. Consequently, the late 1970s and early 1980s were a time of many observations and publications about BCB bowhead whales, especially as they reacted to anthropogenic activities (for example, Richardson and others, 1986, 1987). These early studies were followed by seminal syntheses in the 1990s (for example, Richardson and others, 1995) and served to raise awareness more broadly of marine mammal and ocean sound issues (for example, National Research Council, 1994). As mentioned earlier, the bowhead whale is still listed as endangered under ESA. The Native community participates in setting hunting quotas and bowhead management through the Alaska Eskimo Whaling Commission (2007, website accessed April 30, 2011, at http://www.alaska-aewc.com/aboutus.asp).

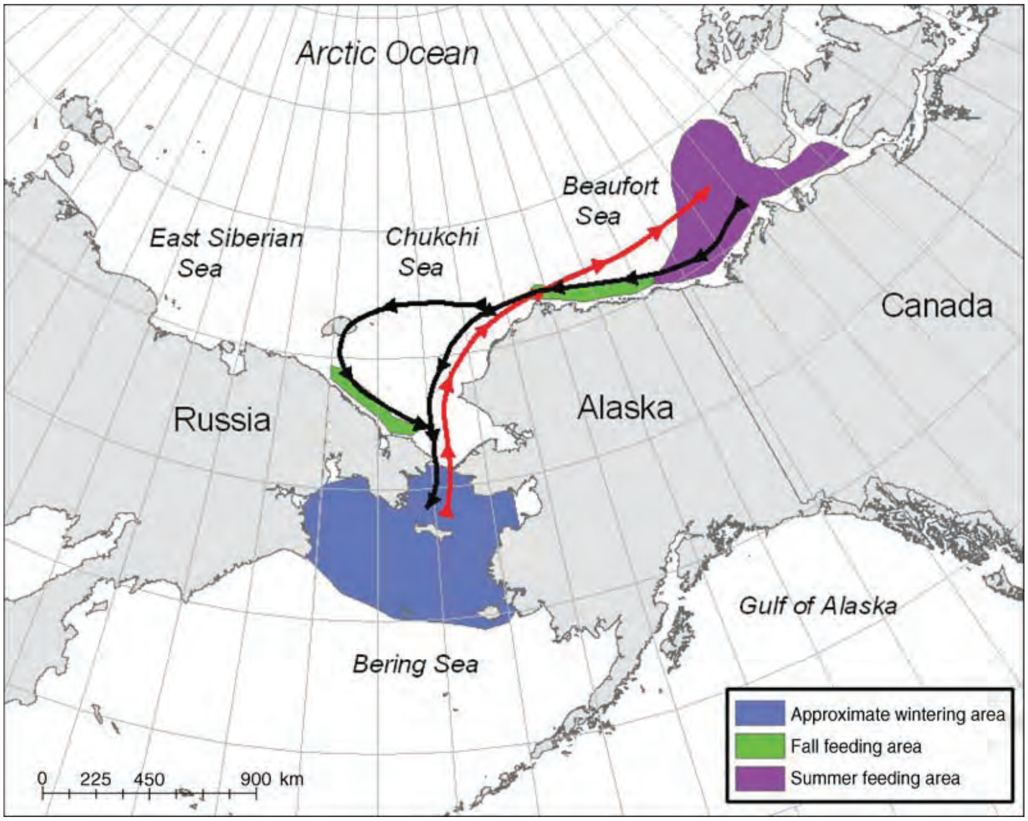


Figure 6–5. Seasonal occurrences of the Bowhead whale in winter (blue), summer (purple), and fall (green) migration feeding areas, together with general migration paths (arrows). From Moore and Laidre (2006).

Many of these early studies combined observations of bowhead behavior with anthropogenic noise, for example seismic surveys (Fraker and others, 1985; Richardson and others, 1986), ship movement (LGL Ecological Research Associates, Inc., 1982), drilling and dredging (Richardson and others, 1987, 1990), icebreaking (Richardson and others, 1995), and aircraft noise (Richardson and others, 1985). Details of these studies identify sound levels, whale distances from the sound sources, context of whale activities where available (for example, feeding, migrating), and behavioral changes. These studies also revealed the general vocalization frequencies of bowhead whales (100–400 Hz dominant, 25–3,500 Hz range), calling patterns, and loudness (for example, Ljungblad and others, 1982; Clark and Johnson, 1984; Würsig and others, 1989; Würsig and Clark, 1993), although the age, sex, and activity associated with the individuals making the sounds were largely unknown. Missing from these early studies is whether the observed behaviors and (or) behavior changes are biologically meaningful and affect the survival of either the individual or the bowhead population. The BCB bowhead population, however, is estimated at about 9,400 and is increasing at about 3 per year (Allen and Angliss, 2010).

Since the mid-1990s, both observational data and new kinds of studies have focused on understanding the habitat, behavior, and distribution of BCB bowhead whales, both in relation to anthropogenic noise and as baseline data to help understand the life histories of the species. One of the longest term monitoring programs is the Bowhead Whale Aerial Survey Project (BWASP; Bureau of Ocean Energy Management, Regulation and Enforcement, 2011) begun in 1979 and now a multi-agency effort to understand the distribution of whales during the summer, open-water months. A parallel effort, the Chukchi Offshore Monitoring in Drilling Area (COMIDA), began in 2008. One objective of this effort was to study the distribution of whales during the summer, open-water months in the Chukchi Sea Planning Area, a resumption of similar surveys that were conducted for many years between 1979 and 1991. The Bowhead Whale Feeding Ecology Study (BOWFEST) is a multiyear and multi-organization collaborative study integrating aerial surveys, physical oceanography, acoustic monitoring, local traditional knowledge, and ecosystem analysis to understand the late summer distribution of bowhead whales and sources of food in the vicinity of Barrow, Alaska (for example, Ashjian and others, 2010; Moore and others, 2010). The aerial surveys also can be used to study other topics, such as the relationship between the ice edge and location of migration (Treacy, 2002; Treacy and others, 2006). Researchers are conducting long-term (multi-year) deployments of acoustic buoys to record ambient ocean noise and build baseline time series datasets of ambient ocean noise, at least for the few locations where the buoys are located (Scripps Whale Acoustic Lab, 2007). Most of these long-term and new-generation studies are funded to collect data for better understanding the impact of petroleum-related activities on the bowhead whale.

A significant database of bowhead whale vocalizations exists as a result of BOEMRE research (for example, Heimlich and others, 2010) and both BP and Shell drilling and seismic activities in the Beaufort Sea (for example, Blackwell and others, 2007). The BOEMRE research has utilized long-term buoy deployments as part of BOWFEST. BP has utilized Directional Autonomous Seafloor Acoustic Recorders (DASARs) to localize and record bowhead whale calls around the Northstar production facility on a gravel island offshore Prudhoe Bay. This monitoring has occurred since the facility began production in 2000. Shell also has funded acquisition of acoustic data from multiple arrays of DASARs on the Beaufort Shelf as part of its monitoring and mitigation strategy for its seismic exploration program (for example, Thode and others, 2008). DASARs have been deployed in multiple years for more than 50 days in open-water conditions with the intention of being able to conduct statistical analyses of whale vocalizations before, during, and after seismic surveys (for example, Mathias and others, 2008). Despite shorter peer-reviewed publications interpreting the results of these studies, these databases of vocalizations generally are proprietary and the substantive reports associated with full analysis reside in industry archives that are not routinely accessible by the public. These DASAR records also have been used to investigate long-range sound propagation under the ice and in open water north of Alaska (Thode and others, 2010).

Perhaps the greatest challenge in observations of any marine mammal, including the bowhead, is that of visual observations (such as with BWASP) can miss animals that are submerged or hidden, and acoustic monitoring (such as with DASARs) misses animals that are not vocalizing. Adding a new dimension to understanding the behavior and distribution of bowhead whales is a tagging program that began in 2006, utilizing Native community whaling captains and scientists working together to tag bowheads in the Barrow (AK) and Tuktoyaktuk (Canada) areas. Satellite tracking of individual whales has provided information on dive behavior, movement and use of habitat (Alaska Department of Fish and Game, 2011). Integrating these observations with the details of seismic (or other anthropogenic) noise is not always rigorous because the details of the seismic (or other anthropogenic) signals are not always publicized or known other than in a general sense.

For the seven noise categories, we discuss observations of bowhead behavior for all but the seismic low-energy category. In the summers of 1980–84, general activities of bowheads exposed to underwater pulses from seismic vessels 6–99 km away were observed (Richardson and others, 1986). Activities were indistinguishable from those without seismic noise; there was no detectable avoidance. In a test involving a seismic vessel (30 airguns, source level 248 dB re: 1 μPa, closest point of approach = 1.5 km), bowheads began to orient away when the airgun array began to fire 7.5 km away. However, some whales continued apparent near-bottom feeding until the vessel was 3 km away. In general, bowheads exhibit avoidance reactions when they receive seismic pulses stronger than about 160 dB re: 1 μPa. Evidence of reactions to lower received levels remains inconclusive.

Playback studies have found that most bowhead whales avoided drillship or dredging noise with broad-band frequency range (20–1,000 Hz) when received levels were around 115 dB re 1μPa, levels that could occur 3–11 km from typical drilling and dredging vessels (Richardson and others, 1990). This equates to a response threshold of about 110 dB re 1μPa in the 1/3-octave band where industrial noise is most prominent. Whales may be observed in locations with higher noise levels, possibly because alternative habitat is not available (Richardson and Greene, 1993).

Bowheads reacted to boats or small ships in two main ways. When boats were nearby, whales altered their surfacing and diving patterns by decreasing the mean time at the surface and mean dive duration. When boats closed to within 3 km, the whales, in addition to the above responses, swam rapidly away from the boat and scattered (LGL Ecological Research Associates, Inc., 1982). In contrast, bowheads were sighted as close as 6 km from a seismic ship firing 12 large sleeve exploders. Surfacing and respiration behavior was similar to that without seismic noise.

Bowhead whales were less responsive to passing aircraft when actively engaged in feeding, social activities, or mating, than when resting (Richardson and others, 1995). Opportunistic observations of behavioral responses of bowhead whales to a helicopter and fixed-wing aircraft suggested that the helicopter elicited only few responses, and most of those occurred when the helicopter was at altitudes equal to or less than 150 m and lateral distances equal to or less than 250 m. For the fixed-wing aircraft, very few bowheads were observed to react, and of those, most reactions occurred when the fixed-wing aircraft was at altitudes equal to or less than 182 m and lateral distances equal to or less than 250 m. Most observations of aircraft disturbance have been made from aircraft creating the disturbance, greatly limiting what can be observed, and precluding comparison of behavior before, during, and after disturbance.

In many of these studies, conclusions often have qualifications, for example, of bowhead deflection in one observation but not in another. These studies have raised the importance of understanding context of the whale activity at the time of the observation. Limited visual or acoustic observations of wild animals or of small sample sizes emphasize the difficulty of generalizing from specific animals in specific conditions to conclusions about the potential effects on the population. As a whole, there are essentially no observations about physical injury or quantitative indicators of stress responses, because of the difficulty of making these measurements on wild animals. Moreover, although there are exceptions, physiological measures of stress rarely point to a single causal factor and thus typically are better indices of overall health of the habitat in which the population lives.

6.08. Finding: There are many observations and databases related to bowhead whales, but no major integration or synthesis, especially for linkages to anthropogenic noise.

6.08. Recommendation: A synthesis of existing databases on bowhead population abundance and structure with databases giving sources and levels of anthropogenic noise would provide a comprehensive framework for analyzing how sounds impact the whales. This would presumably require public access to the many databases that are within government and industry purview for rigorous integration. Particularly illustrative will be integrating observations from tagged animals to overall activities.

For the first time in 2010, NOAA, together with BOEMRE conducted a peer-review analysis of applications for oil-and-gas-related activities in the Beaufort and Chukchi OCS areas, and has publicly released the summary of their findings (National Marine Fisheries Service, 2010e). One of the recommendations is to consider sound from an ecosystem perspective. They recommend transitioning away from using a single metric of acoustic exposure (that is, sound pressure level) to measure the potential effects of anthropogenic sound on marine mammals; and to integrate single-criteria mitigation strategies (the practical approach) with comprehensive assessment. Additional recommendations for improving aerial surveys, near-field and far-field visual monitoring, and collecting routine baseline biological information were included. This peer-review panel integrated scientists, regulators, and members of the Native community.

For all that is known about the BCB bowhead whale and behavior in the presence of anthropogenic sounds, relatively little is known about long-term trends or the biological significance of these observations. During the Incidental Harassment Authorization permitting process for seismic surveys, NOAA receives comments from the Native community, non-governmental organizations, and the Marine Mammal Commission (among others) that tend to consistently cluster into categories:

(a) More baseline data are needed to understand behavior when there are no seismic surveys;

(b) More verification of sound source levels is required;

(c) More holistic monitoring strategies that integrate visual, acoustic, and other observations are needed; and

(d) More precautionary approaches to mitigation and defining the radii of safety zones are warranted.

6.09. Finding: Although research is ongoing, the understanding of essential spatial and temporal habitat needs of the bowhead whale, particularly the oceanographic parameters that most influence foraging, breeding, raising young, and migrating is not yet sufficient to confidently determine the times and places where whales might be most impacted by anthropogenic sounds.

6.09. Recommendation: Understanding the essential spatial and temporal habitat needs for the bowhead whale (for example, Ashjian and others, 2010) needs to include those areas where the introduction of anthropogenic sounds might significantly disrupt the whale at key parts of its life cycle. This knowledge base should incorporate local traditional knowledge of bowhead whales (and other marine mammals) and their habitat contributed by the Native community.

6.10. Finding: Much scientific attention focuses on understanding the cumulative impacts of anthropogenic sounds at the population demographic level for marine mammals, in large part because of regulatory requirements. However, the USGS OCS Team heard often in our expert consultations that how noise affects individual behaviors, short of any health effect, is of great importance to Native communities because of concerns of impacts on potential hunting success of the subsistence community (see appendix A). For example, if the impact means a whale deflects offshore it then is unavailable for subsistence use.

6.10. Recommendation: Behavioral alterations are important factors that need to be understood and monitored to ensure effective mitigation during the hunting seasons to minimize impacts to subsistence hunting. This issue would benefit from enhanced integration of industry and agency acoustical monitoring network data (whale vocalizations), satellite telemetry data of whale movements, local traditional knowledge observations, and application of new statistical approaches to assess behavioral responses (for example, Blackwell and others, 2010) as a framework to better judge under what conditions whales may behaviorally respond to (for example, avoid) noise sources.

Beluga Whale (*Delphinapterus leucas*)

The Beluga, or white, whale has long been known to be a highly vocal species (for example, Schevill and Lawrence, 1949) and carries the nickname of canary of the sea. Using sound, particularly for echolocation, is a trademark of this species (Au and others, 1985, 1987).

Beluga whales are managed as two distinct populations in the Arctic OCS: the Eastern Chukchi stock and the Beaufort stock. This distinction is based on distribution patterns (Lowry and others, 1989) and is supported by molecular genetic studies (O'Corry-Crowe and others, 1997). The Beaufort stock is estimated to be ten times larger than the Eastern Chukchi stock (32,500 versus 3,700; Allen and Angliss, 2010). Neither of the Eastern Chukchi or Beaufort stocks is considered threatened or endangered (National Marine Fisheries Service, 2010f). Analysis of biological samples of beluga whales harvested for subsistence use has revealed much about stock structure, contaminant levels, age, growth, and reproductive status, though these statistics may be biased by hunting method (for example, Suydam, 2009). Belugas are harvested primarily by villages along the Chukchi Sea: a recent analysis of historical data showed that only 1 percent of the subsistence take of whales in Barrow between 1962 and 1982 was beluga whales, and none were harvested between 1987 and 1989 (Braund and Kruse, 2009). The Native community participates in managing the Eastern Chukchi and Beaufort stocks through the Alaska Beluga Whale Committee.

Beluga whales also were among the first whales tagged and tracked in the Arctic (National Marine Fisheries Service, 2010g). These early tagging studies revealed that some beluga whales ventured deep within ice of greater than 90 percent coverage in the summer (for example, Suydam and others, 2005). These tagging studies have been used to understand beluga movement and distribution (for example, Richard and others, 2001; Suydam and others, 2001) as well as diving behavior (Heide-Jørgensen and others, 1998; Kingsley and others, 2001). Arctic OCS belugas migrate annually from their wintering grounds presumably in the Bering Sea to their summer grounds in the Chukchi and Beaufort Seas (Allen and Angliss, 2010). Thus it is important to include seasonal information for understanding potential effects of anthropogenic sound on these stocks.

Beluga whales survive in captivity and are therefore accessible for research on life habit and functions that could not be conducted easily on whales in the wild. For example, they can directionally echolocate targets in a narrow and slightly upward tilted forward direction (Penner and others, 1986; Au and others, 1987). Although the underwater hearing sensitivity of belugas is quite large (Awbrey and others, 1988; Johnson and others, 1989b), they are most sensitive to about 20–80 kHz, which is mostly above the frequencies produced in large energy low-frequency seismic surveys used in oil exploration (fig. 6–2). In-air hearing has not been measured in belugas, but cetacean ears are adapted for underwater function and thus in-air hearing likely is very insensitive. Belugas also have been extensively studied for temporary threshold shifts in hearing, documented through disruption of trained behaviors (Finneran and others, 2000, 2002; Schlundt and others, 2000). Full recovery of baseline hearing and responses occurred within hours. These studies suggest that there is potential for acoustic disturbance, possibly from low-frequency surveys but more likely from higher frequency sound than is used in deep-penetration surveys.

There are many published studies about hearing, behavior, and responses of beluga whales to the kinds of sounds associated with Arctic oil and gas activities. When exposed to vessel noise, beluga whales can exhibit a variety of behaviors ranging from no response to fleeing (see Wartzok and others, 2004). Behavioral responses associated with this type of noise exposure often are considered transient. An unknown is whether repeated short-term behavioral responses translate to cumulative or population-level impacts (Bejder and others, 2006). At this time, there is limited information on whether and to what extent beluga whale migration will be affected by changes in shipping.

Beluga reactions to icebreaking are among the most cited and dramatic in the literature. Observations of changes in pod cohesion, surfacing behavior, and call types indicate that belugas detected the presence of icebreaker vessels at distances greater than 80 km. They exhibited strong avoidance responses at distances 35–50 km away and travelled up to 80 km from the ship track and typically remained away for 1–2 days (Finley and others, 1990). Bioacoustic models suggest that bubbler systems and cavitation associated with icebreaker movement have the ability to potentially mask hearing and vocalization of Arctic inhabitants (Erbe and Farmer, 1998, 2000). For beluga whales, it was hypothesized that the zone of masking could extend from 14 to 71 km from the source (Erbe and Farmer, 2000). There is an increased possibility of temporary threshold shift if animals are exposed

6.11. Finding: Beluga whales appear to be unusually sensitive to the sounds of icebreaking.

6.11. Recommendation: Understanding the sensitivity of beluga whales to icebreaking might require knowledge of the history of exposure to icebreaking or other anthropogenic factors to account for the possibility that some belugas may be either habituated or sensitized to this type of human activity. Application of telemetry to capture information on individual movement histories and access to noise histories (for example, from inventories suggested in Findings 6.02, 6.03, and 6.04) may be required.

to these types of sounds for an extended duration (that is, for animals that do not or cannot alter behavior to avoid this type of exposure if, for example, they are confined to a lead within heavy ice).

The reaction of beluga whales to drilling activities has been mixed and may be related to context. Observations have been made around "operational" artificial islands (Fraker, 1977a, 1977b; Fraker and Fraker, 1979), around a stationary drillship (Norton Fraker and Fraker, 1982), and in playback experiments with drilling noise (Richardson and others, 1990, 1991a). The variety of responses (or lack of responses) from these observations "may be another example of the degree to which belugas can adapt to repeated or ongoing manmade noise when it is not associated with negative consequences" (Richardson and others, 1995, p. 283).

Short-term behavioral responses of beluga whales to helicopters and fixed-wing aircraft have been noted since the late 1970s. Behaviors classified as reactions consisted of short surfacings, immediate dives or turns, changes in behavior state, vigorous swimming, and breaching (Caron and Smith, 1990; Richardson and others, 1991b, 1995). For both helicopters and fixed-wing aircrafts, the observed avoidance reactions by belugas generally occurred when the aircraft was at altitudes equal to or less than 150 m and lateral distances equal to or less than 250 m. The dominant low-frequency components of aircraft sound may be inaudible, or at most only weakly audible, to belugas. Mid-frequency sound components, visual cues, or both, probably are important in eliciting beluga reactions to aircraft.

6.12. Finding: The present understanding of the essential spatial and temporal habitat needs of the beluga whale in the Arctic is limited and constrains the ability to confidently understand and efficiently mitigate potential anthropogenic noise impacts. Similar data limitations exist for many other marine mammal species that will be noted in subsequent Findings and Recommendations.

6.12. Recommendation: Better understanding and inventory of essential spatial and temporal habitat needs of the beluga whale, particularly the oceanographic parameters that determine foraging, breeding, raising young, and migrating, will help managers determine how best to protect belugas from the impacts of anthropogenic sounds. Knowledge of these critical habitats for the beluga whale will enable managers to better identify and protect those places and times where the introduction of anthropogenic noise might significantly disrupt the whale at key parts of its life cycle.

Gray Whale (*Eschrichtius robustus*)

The gray whales that frequent the Chukchi and Beaufort Seas are managed as part of the eastern North Pacific gray whale population. Gray whales were first listed as endangered in 1970 in the Endangered Species Conservation Act, the precursor of the Endangered Species Act. After status reviews in 1984 and 1991, the eastern North Pacific gray whale was delisted from ESA in 1994 (see historical summary in National Marine Fisheries Service, 1994). The NMFS conducted a 5-year status review of the stock in 1999 (Rugh and others, 1999). In October 2010, the NMFS received a petition to again list the gray whale under ESA (California Gray Whale Coalition, 2010), but declined to do so in the 60-day review (National Marine Fisheries Service, 2010c). The eastern Pacific stock has an estimated minimum population size of about 17,500 with a population increasing at 1.9–2.6 percent per year (Allen and Angliss, 2010). Gray whales typically are not harvested as a subsistence resource.

Gray whales engage in one of the longest annual migrations of any marine mammal, travelling thousands of kilometers from as far south as Baja California in the winter to the Chukchi Sea in the summer. Although gray whales sometimes are seen around Barrow, they are a rare occurrence when seen east of Barrow in the Beaufort Sea (Nelson and others, 1993). The long coastal migration may expose this whale to more anthropogenic threats than the other Arctic whales because of its migration past major urban centers and sources of pollution (Rugh and others, 1999). There are some indications that, in the last decade, gray whales have moved farther into the Beaufort Sea and delayed their southbound migration in the fall (for example, Moore and others, 2003, 2007; Moore and Overland, 2008). Gray whales have been sighted more frequently near Barrow and their calls have been recorded in instruments deployed on the Beaufort Shelf during the winter (Stafford and others, 2007). Some of these changes may be related to changes in the physical environment of the north Bering Sea (Grebmeier and others, 2006).

Studies show gray whales, similar to other baleen whales, produce sounds generally below 1 kHz (Crane and Lashkari, 1996). Whereas gray whale response to anthropogenic sound has been studied in lower latitudes, the degree to which those results are predictive of whale responses in the Arctic OCS areas is speculative in part because the whales have highly structured annual cycles of feeding (summer in high latitudes) and breeding (winter in low latitudes). In one experiment with a long-range sonar, migrating whales avoided exposure to the signals when the source was placed within their migration corridor (Clark and others, 1999). However, in all cases, whales resumed their normal activities within tens of minutes after the initial exposure to the signal, making minor course changes to go around the source. When the source was relocated outside of the migration corridor, but with the signal level increased so as to reproduce the same sound field inside the corridor, the whales continued their migration unabated. This result stresses the importance of context in interpreting animals' responses to underwater sounds (Clark and others, 1999).

Gray whale responses to airgun shots included changes in swimming speed and direction away from the sound sources (Malme and others, 1984), changes from feeding with a resumption of feeding after exposure (Malme and others, 1988), changes in call rates and structure (Dahlheim, 1987), and changes in surface behavior (Moore and Clarke, 2002). Some behavioral responses were dramatic—whales were seen to move into the shallow surf zone and into sound shadows of rocks (Malme and others, 1983, 1984). Approximately one-half of the gray whales exposed to a single airgun in the Bering Sea showed avoidance and noticeable changes in respiration behavior (Malme and others, 1986, 1988). There is essentially no information describing gray whale behavior in the presence of mid- and high-frequency pulsed sources.

Drilling and other continuous sounds have triggered avoidance responses in playback experiments with migrating gray whales (Malme and others, 1983, 1984). There are some data suggesting that gray whales respond to variations in underwater noise by changing the structure and timing of their calls (Dahlheim and others, 1984; Dahlheim, 1987), but it is unknown whether these changes in calling affected survival or reproduction. Gray whales were virtually absent from a wintering lagoon in Baja California, for several years during which shipping increased, possibly caused by the near-constant dredging needed to keep the channel open. Whales returned to the lagoon after shipping decreased (Jones and Swartz, 1984). Much of the nearshore range of the gray whale is heavily used by vessels and other human activity, which suggests habituation to or coexistence with noisy human activities (Richardson and others, 1995).

Gray whale responses to aircraft are variable and may be context dependent. Some observations suggest that mother-calf pairs off Alaska may be particularly sensitive to small (for example, turboprop) survey aircraft (Ljungblad and others, 1983). Mating gray whales did not react immediately to the arrival of a survey aircraft but dispersed after it had circled for a few minutes (Clarke and others, 1989). Migrating gray whales rarely showed detectable reactions to a straight-line overflight by a fixed-wing aircraft at 60 m altitude (Green and others, 1992). Playbacks of helicopter noise caused minor avoidance reactions in gray whales, suggesting that helicopter sound (rather than visual cues) could affect gray whales (Malme and others, 1983).

6.13. Finding: The present understanding of the essential spatial and temporal habitat needs of the gray whale in the Arctic is limited and constrains the ability to presently confidently understand and efficiently mitigate potential anthropogenic noise impacts.

6.13. Recommendation: Better understanding and inventory are needed of essential spatial and temporal habitat needs of the gray whale during its summering in the Chukchi and Beaufort Seas, particularly the oceanographic parameters that determine foraging, breeding, raising young, and migrating. Knowledge of these essential habitats for the gray whale will enable managers to better identify and protect those places and times where the introduction of anthropogenic noise might significantly disrupt the whale at key parts of its life cycle. The Chukchi Sea is of primary interest because it is a major foraging ground for the gray whale (Rice and Wolman, 1971; Fay, 1982). Because the development of petroleum resources (or mining for sand) in the Chukchi Sea could occur in regions of high concentration of prey species, the gray whale may be particularly vulnerable to petroleum-related development in the Arctic OCS (Nelson and others, 1994).

Polar Bear (*Ursus maritimus*)

Polar bears, the top predators in the Arctic marine ecosystem, are managed as two distinct populations, the southern Beaufort stock (primarily in the southern Beaufort Sea) and the Chukchi-Bering stock, which occurs farther south and west in both the U.S. and Russian Chukchi Sea (Amstrup and others, 2004). Based on satellite radio-telemetry data, a large overlap occurs between these two populations (Amstrup and others, 2004, 2005). In 2008, the U.S. Fish and Wildlife Service (2008) published a final determination to list polar bears as threatened under ESA. In 2010, the USFWS further published a final determination of critical habitat associated with the listing (U.S. Fish and Wildlife Service, 2010).

Polar bears are a well-studied Arctic marine mammal. Research on polar bears in Alaska has occurred since the late 1960s and numerous estimates of population stock exist (for example, Amstrup, 1986, 1995; McDonald and Amstrup, 2001; Allen and Angliss, 2010). Radiotelemetry was initiated in 1981, followed soon after with satellite telemetry, for understanding survival and recruitment. Genetic studies have helped identify discrete populations (for example, Paetkau and others, 1999; Amstrup, 2003). Sufficient data exist to model their distribution and denning patterns and examine population status and trends (for example, Aars and others, 2006).

Studies also have associated polar bears with "ecoregions" (for example, Amstrup and others, 2007). Polar bears tend to be more abundant over shallow water of the polar continental shelves, suggesting that these areas of higher productivity and therefore higher concentrations of potential prey are preferred habitat (Amstrup and others, 2000, 2004; Durner and others, 2007). Polar bears move in response to changing ice conditions and prey availability (Stirling and others, 1993; Arthur and others, 1996; Ferguson and others, 2000a, 2000b; Mauritzen and others, 2001; Durner and others, 2004, 2006, 2009). There are some data indicating that polar bear distribution may reflect factors such as prey availability, energetic costs, and safer ice conditions (for example, Mauritzen and others, 2003).

Despite the abundant research on the baseline biological information of the polar bear, relatively little information exists regarding its hearing, use of its auditory functions in survival or reproduction, and impacts from anthropogenic sounds. Importantly, in contrast to other marine mammals, the polar bear spends most of its life out of the water. When swimming, it carries its head above the water surface. Thus, while extremely intense underwater sound may impact a polar bear while in the water, the impacts of anthropogenic sound are considered primarily to be from sounds in air.

There are no measurements of the underwater hearing of polar bears. In-air hearing was measured using evoked auditory potentials on three anesthetized polar bears for frequencies of 1.4–22.5 kHz (Nachtigall and others, 2007). Results can not be taken as measures of absolute sensitivity, but sensitivity was relatively flat across the range of frequencies tested with a slight peak from about 11.2–22.5 kHz.

Ecological observations support these measured hearing ranges. Ringed seals (*Phoca hispida*) and bearded seals (*Erignathus barbatus*) are prominent in the diet of polar bears. Ringed seals produce underwater sounds in these frequency ranges (2–8 kHz; Stirling, 1973) suggesting that polar bear hearing can optimally detect and locate this preferred prey. Playback of ringed seal calls in the air has triggered changes in behavior in captive polar bears (for example, Cushing and others, 1988). Polar bears also may be able to detect and locate bearded seals by their distinctive underwater trills (Stirling and Thomas, 2003).

Many observations document polar bear responses to anthropogenic sound. On-ice seismic techniques (Vibroseis) have caused polar bears to locally (and temporarily) leave the area (Richardson and others, 1995). Moore and Quimby (1975) reported that females with cubs abandoned their dens during nearby seismic exploration activity, and this effect was more pronounced early in the denning season (Linnell and others, 2000). Polar bears appear to tolerate sounds and vibrations associated with stationary drill rigs on caissons and artificial islands (Stirling, 1988; Amstrup, 1993). Polar bear reactions to vessels and icebreakers are unremarkable (Fay and others, 1984). Reactions may include walking, running, or swimming away, and generally are of short duration; some bears show no reactions (for example, Richardson and others, 1995, and references therein). Helicopters are sometimes used to frighten polar bears away from human activities or facilities, and low-flying aircraft are known to cause polar bears to run away (Shideler, 1993). In general, these studies support the notion that polar bears may be sensitive to some kinds of in-air sounds.

6.14. Finding: Joint industry-agency programs have successfully mitigated, to date, the disturbance effects of oil and gas activities, including noise, on polar bears in the U.S. Arctic. An example of this has been the development of polar bear denning models to help define potential denning sites for avoidance during winter on-land seismic surveys and the application of Forward-Looking Infrared (FLIR) imagery for real-time monitoring and den avoidance. But declines in sea ice are resulting in changes in polar bear distribution and in denning habitat, as well as body condition and survival patterns, and portend declines in overall population size.

6.14. Recommendation: Broadly, and with respect to noise, to successfully mitigate the effects of existing and new development in the Arctic under changing climate conditions will require continual reassessment of what is understood about polar bear distribution and habitats to ensure mitigation measures are accomplishing intended outcomes.

Ice Seals

Of the Arctic marine mammals, ice seals remain the least known and studied. For each of the ice seal species, the 2009 stock assessment begins “A reliable minimum population estimate for this stock cannot presently be determined because current reliable estimates of abundance are not available” (Allen and Angliss, 2010). Subsistence harvests are incompletely known (for example, Allen and Angliss, 2010). Some progress is being made to identify habitat requirements (for example, Cameron and others, 2010). The large range over which these animals are found, their generally low densities, cryptic or incompletely understood behaviors, their habitat across multiple political boundaries, lack of information about how ice seals use habitat, the inability to correct inventories for seals in the water, and the high costs associated with surveying large areas remain the greatest impediments to improving the knowledge base (Boveng and others, 2008, 2009).

6.15. Finding: There is a basic lack of information about ice seals. Key information about the abundance, distribution, and vital aspects of ice seals is incomplete. (Information on ice seal auditory characteristics and response to sound also is lacking and will be discussed in Findings and Recommendations 6.16 and 6.17).

6.15. Recommendation: Habitat requirements of ice seals need to be better identified and quantified, particularly the importance of habitat in the context of seasonal activities. Annual harvest rates for subsistence needs should be estimated more consistently. Knowledge of such basic biological information should be integrated across political boundaries of the Nations in which the species occur (for example, Canada and Russia). For example, ringed seals from the Beaufort and Chukchi Seas were radio- and satellite-tracked showing that in the summer, they ranged up to 1,800 km from their winter/spring home, but returned to the same small (1–2 km^2) winter sites (Kelly and others, 2010). During the ice-bound winter and spring (including breeding season), ringed seals are therefore spatially limited in their foraging ability for significant parts of the year. If ringed seals cannot habituate to oil and gas activities or utilize human-free habitat, they may be limited in their ability to adapt.

Four species of ice seals are found in the Chukchi and Beaufort Seas: bearded (*Erignathus barbatus*), ribbon (*Histriophoca fasciata*), ringed (*Pusa hispida*), and spotted (*Phoca largha*). In contrast to the three species that are year-round Beaufort and Chukchi inhabitants, the spotted seal is only a seasonal summer visitor to the Beaufort and Chukchi Seas. Neither spotted nor ribbon seals are listed as threatened or endangered according to ESA (table 6–3).

The distribution and life history of these seals are intimately linked to the presence of ice and snow: mating occurs near the ice edge; subnivean lairs (for the ringed seals) are utilized as dens for whelping and nurturing pups; whelping coincides with near-maximum ice extent; and adult seals undergo annual molting after which seals spend prolonged periods out of water on the ice warming the skin in the sun during late spring and summer (Hopcroft and others, 2008). The timing of snow and ice melt may be critical to the survival or reproduction of ringed seals (for example, Kelly, 2001; Smith and Harwood, 2001; Stirling and Smith, 2004). When they are not breeding, ice seals may move hundreds or thousands of miles through the Arctic and surrounding waters (Kapel and others, 1998; Lowry and others, 1998; Harwood and others, 2000).

During the late 1970s and 1980s, the OCS Environmental Assessment Program (OCSEAP) funded and supported numerous studies of ice seals in conjunction with the increased OCS exploration activities in the Arctic, identifying some of the diet and trophic relations for these animals. After a hiatus in the 1990s, renewed research began with the formation of the Ice Seals Committee in 2005 consisting of members of the Native community for the purpose of developing a coordinated plan for management of ice seals in Alaska (for example, Ice Seal Committee, 2006). Tagging of bearded seals (starting in 2004) and ringed seals (starting in 2007) initiated with the Native village of Kotzebue (http://kotzebueira.org, accessed April 14, 2011) and biologists significantly added to the knowledge base about specific individuals for the duration

Table 6–3. Ice Seals—Endangered Species Act (ESA) Information.

Seal	Status review	Federal Register Notice	ESA listed for the Arctic
Bearded	Cameron and others, 2010	December 10, 2010	Candidate
Ribbon	Boveng and others, 2008	December 30, 2008	No
Ringed	Kelly and others, 2010	December 10, 2010	Candidate
Spotted	Boveng and others, 2009	October 20, 2009 October 22, 2010	No

of the tagging (generally less than 1 year). Each of the ice seal species has undergone extensive reviews in the past 4 years as part of the process by which the NOAA determines whether the species should be listed under the ESA. The major reviews summarizing biological knowledge of the species and associated Federal Register notices for ice seals are given in table 6–3.

Bearded and ringed seals are primary prey of polar bears as well as food for the Native community. The bearded seal is the largest of the seals and preys on benthic organisms. Hence they are more frequently found in shallow water areas where light can sustain a benthic ecosystem (for example, less than 200 m water depth). The ringed seal, also an important food source for the Native community, is the smallest of the ice seals and feeds on fish, so it can travel long distances over deep water along and within the ice (Kelly and others, 2010).

As with other marine mammals, ice seals are thought to use sound to aid in navigation, to socialize, and to avoid predators. Typically, pinnipeds are thought to spend as much as 80 percent of their time in the water (Gordon and others, 2004); thus anthropogenic sound associated with seismic surveys, vessel noise, icebreaking, and drilling may potentially disturb their habitat, distribution, and behavior. Ice seals make variable vocalizations in the water, generally associated with mating (for example, Watkins and Ray, 1977; Boveng and others, 2009; Cameron and others, 2010). The underwater hearing sensitivity for ringed seals showed peak sensitivities between about 4–16 kHz, although sensitivity to frequencies below 1 kHz was not measured (Terhune and Ronald, 1975). Based on the similarity of these hearing ranges to the hearing of many other pinnipeds, one might expect that the other ice seals also have hearing at similar ranges (Moore and Schusterman, 1987). A recent review suggests that the auditory bandwidth generalized for all pinnipeds in water should be about 75 Hz – 75 kHz (Southall and others, 2007). Most seismic surveys have peak energy below 200 Hz, hence the level of disturbance expected from large seismic surveys is at the low end of pinniped hearing.

6.16. Finding: Basic auditory information about ice seals is lacking.

6.16. Recommendation: Key information about the amplitude, character, seasonal variation, and function of vocalizations of ice seals as well as studies of pinniped diving profiles, auditory structures, and physiological effects of sound are needed. This information is essential for determining whether and how anthropogenic sounds could mask, impact, or injure these animals.

The effects of seismic surveys on ice seals have been summarized in the 2010 status review of the bearded seal:

> "Reported seal responses to seismic surveys have been variable and often contradictory, although they do suggest that pinnipeds frequently do not avoid the area within a few hundred meters of operating airgun arrays (Brueggeman and others, 1991; Harris and others, 2001; Miller and Davis, 2002). Telemetry work by Thompson and others (1998) indicated that harbor seals and grey seals (*Halichoerus grypus*) exhibit strong avoidance behavior of small seismic airgun arrays, including swimming rapidly away from seismic sources, ceasing feeding activities, and hauling out, possibly to avoid underwater noise. The behavior of most of the seals reportedly returned to normal within 2 hours of the seismic array falling silent. The authors suggested that responses to more powerful commercial arrays might be more dramatic and occur at greater ranges."
>
> (Cameron and others, 2010, p. 162)

Tagging studies conducted on ringed seals in 2001, when Canadian marine seismic surveys were occurring, did not appear to affect the timing or route of the western fall migration of ringed seals in the Beaufort Sea (Cott and others, 2003). Ringed seals in the Prudhoe Bay region often tolerated exposure to high received levels (180–190 dB re: 1 µPa rms) of low-frequency sound pulses from airgun arrays, with little evidence of changes in behavior and no more than localized avoidance (Harris and others, 2001; Moulton and Lawson, 2002). Many seals remained within 100–200 m of the operating airguns, which is often within the radius where received sound levels are greater than 190 dB re 1 µPa (rms). There are seemingly inconsistent results concerning reactions of seals to small airgun sources (Blackwell and others, 2004b). The seals may initially show an avoidance response to these sounds, but rapidly habituate, demonstrated by their adjustment to Acoustic Harassment Devices that are similar to sounds used in sub-bottom surveys (Richardson, 2002).

There are few data on auditory threshold shifts, either temporary or permanent, for ice seals. In experiments done primarily on sea lions, the results from pulsed sounds (Finneran and others, 2003) and continuous, but lower energy, octave band noise (Kastak and others, 1999, 2005) demonstrated the importance of considering both amplitude and duration when estimating the impacts of sounds on marine mammals and these results are reiterated by Southall and others (2007). Each of the ice seal reviews conducted by the NOAA (table 6–3) suggested that "Although it is unlikely that airgun operations during most seismic surveys would cause PTS in (bearded, ribbon, ringed, or ice) seals, caution is warranted given the limited knowledge about noise induced hearing damage in this species."

Reactions of most pinnipeds to drilling and related activities have not been extensively studied. Ringed seals are often seen near drillships drilling in the Arctic during summer and autumn. As part of construction efforts for the Northstar oil production island 5 km offshore of Long Island, northwest of Prudhoe Bay, Alaska, in the western Beaufort Sea, ringed seals showed little or no reaction to any industrial noise except approaching helicopters (Blackwell and others, 2004b). There is no evidence of reduced seal densities near the Northstar gravel island drilling platform (Moulton and others, 2003). Very few data exist for the effects of vessels and icebreaking on ice seals, but observations suggest sensitivity occurs only when icebreaking occurred within several hundred meters of the seals (for example, Kanik and others, 1980; Brueggeman and others, 1992). It was not clear whether vessel noise or visual cues triggered the escape responses.

Noise disturbance to ice seals also must account for in-air sound, although few data exist for this. When on the ice, ringed seals and bearded seals often dive when approached by low-flying aircraft or helicopters, but do not always do so (Burns and others, 1982). Spotted seals may be particularly sensitive to low-flying aircraft leading to concerns about potential separation of mothers and pups during nursing (Frost and others, 1993; Richardson and others, 1995). The levels of received sound are unknown in these observations.

6.17. Finding: There is a lack of information on the response of ice seals to aircraft or differential response to fixed-wing aircraft versus helicopter.

6.17. Recommendation: Controlled exposure (sound playback) experiments with ice seals might aid in understanding their hearing sensitivities and reactions. At any given moment, behavior in free-ranging animals is controlled by a multitude of factors including the individual's internal physiological state, physical environmental conditions, time of day and time of year, the behavior and distribution of peers, behavior and distribution of other species (including predators and prey), and human activity. When making passive observations, any observed behavior in an individual may be caused by the anthropogenic factor under study, other natural factors, or some combination of both. Controlled exposure is a quasi-experimental method used to evaluate response to sound by observing the behavior of free-ranging animals before, during, and after exposure to specific sound (for example, Tyack, 2009), either by playback of recorded sounds using an underwater sound system or by controlling the sound of a vessel, sensor (for example, sonar), or tool (for example, airgun, bubbler, pipe driver).

These experiments might determine whether observed responses could have been caused by the sight, sound, or vibration associated with the noise.

Pacific Walrus (*Odobenus rosmarus divergens*)

The Pacific walrus ranges across the continental shelf of the Bering and Chukchi Seas but is only infrequently observed in the Beaufort Sea (for example, Allen and Angliss, 2010). Walruses winter in the Bering Sea in large communities and move north with the ice edge as the pack ice recedes each summer (Fay, 1982). Ice is essential for their existence, providing a location to rest, molt, give birth, and escape predators (Richard, 1990). Land aggregations are becoming more common as the ice recedes north of the Chukchi and Beaufort Shelf edges (Jay and Fischbach, 2008). Although walruses can dive deeper than 200 m (Born and others, 2005), they typically live where water depths are less than 80 m so that the benthic communities they prefer for prey are more easily reached (Fay and Burns, 1988; Jay and others, 2001). Radio tags and more recently satellite tags are beginning to yield more continuous measurements of walrus activities (Jay and Fischbach, 2008). Walruses can significantly disturb seafloor sediment during feeding on benthic organisms, and are thought to be a major influence the structure of benthic ecosystems of the Chukchi and Bering Seas (for example, Oliver and others, 1983).

The current estimate of minimum population size for the Pacific walrus is approximately 129,000 individuals, with insufficient data to determine annual trends in abundance (Allen and Angliss, 2010). As a result of a petition filed by the Center for Biological Diversity in 2008, the USFWS issued a 90-day finding on September 10, 2009, that the petitioners had submitted enough scientific information to indicate that listing of the Pacific walrus under ESA may be warranted (U.S. Fish and Wildlife Service, 2009). On February 10, 2011, the USFWS issued their 12-month finding that listing the Pacific walrus as endangered or threatened is "warranted but precluded" (U.S. Fish and Wildlife Service, 2011).

Walruses can be extremely vocal when out of the water and produce a variety of sounds in the water (Ray and Watkins, 1975). Only the male walrus makes the unusual "bell" sound comprising two frequencies produced in succession (Schevill and others, 1966). Tests of hearing on captive walruses indicate that underwater hearing sensitivity covers a broad range of frequencies, with the best hearing generally above 1 kHz, although sensitivity was good down to 125 Hz (Kastelein and others, 2002). In-air hearing sensitivity was measured from 125 Hz to 8 kHz, with best sensitivity between 1 and 8 kHz and rapid decline below 1 kHz (Kastelein and others, 1993, 1996). Similar to ice seals, low-frequency seismic surveys are likely to impact the low-end of the walrus hearing spectrum whereas medium- to high-frequency hazards surveys are more likely to coincide with the range of walrus hearing.

Walrus appear to be sensitive to some noises and can stampede from haulouts in response to sight, sound, and odors of humans (for example, Fischbach and others, 2009). It is not currently understood whether these reactions are uniformly caused by visual, olfactory, or vibrational cues rather than noise. A similar uncertainty exists about the cause of some walrus reactions to vessels either in open water or during icebreaking, particularly whether avoidance responses are triggered by ship noise versus sight and smell of the vessel (for example, Fay and Kelly, 1982; Fay and others, 1984). When near icebreakers, most walruses on ice were more cautious of vessels compared to walruses in the water (Fay and others, 1984). The observed reactions were commonly waking up, raising their heads, or entering the water. Some walruses in the water reacted by hauling themselves out of the water.

Walrus responses to drilling operations are closely linked to icebreaking because of ice management during drilling. During the 1989–91 drilling of the Popcorn, Burger, Crackerjack, and Diamond wells in the Chukchi Sea (Minerals Management Service, 2005), escape responses were more frequent the closer the icebreaker operated to the walrus (Brueggeman and others, 1990, 1991, 1992). Evidence from aerial surveys in one study suggested that walruses may have avoided the area of icebreaking by as much as 10–15 km (Brueggeman and others, 1990), which contrasts with reports of avoidance only at much shorter distances (Fay and others, 1984). Icebreaking may have the potential to cause behavioral avoidance or injury, and for these communal large animals, may degrade habitat by reducing floe size and availability for haul out. Animals that show no avoidance may be undisturbed, but alternatively may be disturbed but have no avenue of escape.

Responses of walrus to aircraft (both helicopters and fixed-wing aircraft) were similar, in that the level of response was usually related to distance and altitude of the approaching aircraft (Johnson and others, 1989a). Aircraft overflight of walrus haulout locations have triggered stampedes from flight elevations of 150–800 m (Fay, 1981; Ovsyanikov and others, 1994). Stampedes may lead to trauma, injury, and death of walruses, particularly calves. One study identified different reaction distances depending on whether a helicopter approached the walrus group from an upwind or downwind direction (Fay and others, 1984), raising the possibility that smell could have been a factor in the response.

6.18. Finding: Considerable uncertainty exists about whether walrus reactions to anthropogenic activities are caused by sight, sound, or smell. Quantitative data are lacking about the character of deep-penetration, high-resolution seismic and other acoustic sounds (such as sonar or chirp) and the responses of walruses to these sounds.

6.18. Recommendation: Basic information about walrus reactions to anthropogenic sound, particularly seismic and acoustic sounds, needs to be better documented and studied. Detailed studies that examine responses in controlled environments could help efficiently elucidate key areas of walrus response. This information coupled with quantitative characterizations of anthropogenic noise sources could better define whether and how these kinds of anthropogenic sounds could mask, impact, or injure walrus.

6.19. Finding: There is a newly emerging, yet still incomplete understanding of the manner in which walruses select their benthic foraging habitats (Jay and others, 2011) and limited information on the role of walruses in ecosystem structure. Such information is needed (in concert with information in Recommendation 6.18) to assess if seasonal, annual, or persistent sources of anthropogenic sound may cause walruses to avoid certain places or times. And, if so, what the effect might be to both population and ecosystem.

6.19. Recommendation: Better understanding and inventory of essential spatial and temporal habitat needs of Pacific walrus during its summering in the Chukchi Sea, particularly the oceanographic parameters that determine foraging, are needed. Should evidence develop that walrus are displaced due to human-generated sound, future studies will be needed to assess if cascading ecological consequences result. Walrus modify the seafloor during their foraging by resuspending sediments, which in turn may enhance primary productivity by releasing nutrients into the water and maintaining sand substrates on the seafloor as fine-grained muds and silts are suspended, for example, and carried by the Alaska Coastal Current (Nelson and others, 1994).

Conclusions: While scientific uncertainty exists regarding the scope and nature of environmental disturbances arising from anthropogenic sound sources in the oceans, and particularly in the Beaufort and Chukchi Seas, some simple conclusions may still be drawn.

- Sound is of vital biological importance to the marine mammals of interest in the Arctic, and anthropogenic noise can have various adverse effects. The wide-scale introduction of commercial, military, and research activities into Arctic areas that will accompany oil and gas activities, with concomitant associated increases in anthropogenic sound, are very likely to impact both the acoustic environment and the sound-centric marine mammals living there.
- Vessel activities and other industrial sound sources increase sound in the oceans; the Beaufort and Chukchi Seas offer the unique opportunity to measure and understand both the increase in anthropogenic sound and its potential impacts on marine mammals because these areas are essentially pristine with limited anthropogenic sound sources compared to the rest of the oceans around the United States.
- Different species hear and use sound differently. Therefore, impacts from anthropogenic sound will vary by sound source (for example, vessel operation, seismic, and hydroacoustic devices, icebreaker operations), as well as by marine mammal species.
- Very few of the impacts from anthropogenic sound are expected to include direct physical injuries to hearing (or other systems) of the marine mammals.
- Concern regarding behavioral disturbance and avoidance of key areas is a major concern for the Native community. Any change in individual marine mammal behavior that causes the animal to move away from coastal waters, particularly the bowhead whale, has the potential to make the animals unavailable for subsistence hunting.
- Cumulative-, population-, and ecosystem-level impacts of exposure to chronic sources of anthropogenic sound from oil and gas activities remain poorly understood but are important considerations, particularly for the survival, sustainability, and reproductive health of marine mammals.
- Key knowledge gaps include baseline data from which to measure the changes that might be caused by the introduction of anthropogenic sound, inventories of anthropogenic sound (especially vessels and seismic sources), and the spatial and temporal habitat needs of the marine mammals of concern.
- The Native community has much at stake in the regulatory process and has much knowledge, both traditional and local, to offer in augmenting scientific studies about marine mammals and anthropogenic sound.

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Chapter 7

Cumulative Impacts

By Brenda Pierce

Introduction

The final topic the USGS OCS Team was asked to consider was that of cumulative effects. Here we examine the state of cumulative impact or effect assessment approaches and the present challenges of conducting science-based cumulative effect analyses in the Arctic. Cumulative impacts are the combined, incremental effects of human activity.

Cumulative impacts can result from factors that may be insignificant by themselves but significant when interacting and (or) accumulating over time and space, through repetition, or in combination with other effects. When actions are considered individually or independently, their combined consequences—or cumulative impact—may not be fully considered or evaluated. This results in not understanding, and not considering, the long range impact of multiple decisions over a large area.

The impetus to study and evaluate cumulative impacts lies with the passage of the National Environmental Policy Act (NEPA) of 1969. The NEPA requires Federal agencies to develop Environmental Impact Statements and Environmental Assessments for major projects. However, if these studies are done independently of one another and considered separately, the studies may not take into account cumulative effects from each activity on the whole and the projects' effects may not be fully accounted for nor be taken into account in the final decision.

The Council on Environmental Quality (CEQ) was established under NEPA. The CEQ's regulations (40 CFR Part 1500–1508) implementing the procedural provisions of the NEPA (Council on Environmental Quality, 1997) define cumulative effects as:

> "The impact of the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions."

The words "effects" and "impacts" are used synonymously in CEQ's NEPA regulations, which govern NEPA implementation (Council on Environmental Quality, 1984). Effects and (or) impacts are meant to be inclusive and include ecological, aesthetic, historical, economic, social, and health, and are both beneficial and detrimental.

Cumulative effects result from spatial (geographic) and temporal (time) environmental disturbances and both must be given consideration in analyzing cumulative impacts.

The National Research Council (NRC) conducted a study on the cumulative effects of oil and gas activities on Alaska's North Slope (National Research Council, 2003). That study, which focused on the onshore portion of oil and gas development, is the most comprehensive look at the considerations that should go into cumulative impact analyses. The National Research Council (2003) emphasized the fact that significant research has been carried out in Arctic Alaska over the last several decades, but that an integrated, comprehensive assessment of those effects has not been attempted. That is still true today—there are a significant number of important and landmark environmental studies, and there are some studies of cumulative effects, but no integrated, comprehensive assessment of those effects has been conducted or even attempted.

Policy decisions are usually made at the regional or national level, but environmental effects are usually analyzed and assessed at the project level. Decisions and permitting of industrial activities are often done on a case by case basis by many different entities and therefore without the benefit of a comprehensive plan or understanding of the scope, intensity, and consequences of the industrial activities. Long-term decision making and land and resource management must take into account the cumulative impact of the nature and extent of the benefits and challenges and the costs of both.

Considerations in Conducting Cumulative Impact Studies

The Council on Environmental Quality's (1997) guidance emphasizes the need to incorporate a cumulative impact evaluation in the development of alternatives for an Environmental Analysis or Environmental Impact Statement. It stresses that only by considering cumulative effects can appropriate mitigation and monitoring measures be effectively developed.

The CEQ suggests that in conducting cumulative impact analysis, the life cycle of effects and impact zones, rather than individual projects, should be evaluated. It emphasizes that looking at the affected environment in a cumulative impact analysis is basically the same as it is in a project-specific analysis, with the important addition that the analysis should be extended in terms of geography, time, and the potential for resource or system interactions. In project-specific NEPA analysis, description of the affected environment is based on a list of resources that may be directly or indirectly affected by the proposed project. In cumulative effects analysis, there is an attempt to identify and characterize effects of other actions, including those of other geographic areas or other time frames, on these same resources.

To conduct a cumulative effects analysis, one should understand what would occur in the absence of a given activity. This is best done when there are reliable baseline data available for the analysis and by using tools that indicate ecological integrity and landscape conditions. This is important because when an analysis is performed, the baseline or thresholds of environmental change are set, thus influencing the cumulative impact assessment. Effects typically accumulate as the result of repeated activities, but also may be affected by a single action or event if significant. Therefore, a full cumulative impact analysis requires multiple assessments.

It is very important to be transparent regarding the uncertainties associated with any of these studies, especially in cumulative impact. There will always be uncertainty, as there will never be enough data and information on every facet of the impact of development to know the impact in its full extent. Therefore, it is important to be transparent about what data do or do not exist and what is modeled and what is empirical, so the users of the information understand the extent of the uncertainty surrounding the assessment or impact.

Conducting cumulative impact analysis needs to be an iterative process. Results from cumulative impact assessments should contribute to refining alternatives and designing mitigation techniques and approaches. Thus, monitoring change and the accuracy of the predictions made is an important part of cumulative impact analysis and contributes directly to the success of the mitigation measures.

The U.S. Environmental Protection Agency (USEPA) has review guidance regarding the NEPA and cumulative effects and suggests that its reviewers determine whether resources are cumulatively impacted by considering the following (U.S. Environmental Protection Agency, 1999):

1. Whether the resource is vulnerable to incremental effects;
2. Whether the proposed action is one of several similar actions in the same geographic area;
3. Whether other activities in the area have similar effects on resources;
4. Whether these effects have been historically significant for this resource; and
5. Whether other analyses in the area have identified a cumulative effects concern.

Some project analyses consider only certain resources and only direct impacts or limited impacts among those particular resources. To conduct a cumulative impact analysis, consideration must be given to a broader array of effects, such as ecosystems functions (for example, ability to minimize downstream flooding or improve water quality) instead of simply the acreage of wetland potentially lost by a project. Other potential effects to consider, as suggested by the U.S. Environmental Protection Agency (1999), include changes in hydrologic patterns, alteration of discharge and water retention rates, changes in water velocity, secondary or tertiary effects of chemicals in the wetland and how plants may take up those chemicals, to name just a few.

Additionally, some analyses limit the area considered to those areas over which an agency might have direct purview or management authority (U.S. Environmental Protection Agency, 1999). This limits the full evaluation of cumulative impacts, because impacts may be caused by factors outside the specific project's spatial or temporal scope, including the life of the project. For example, the effects sometimes last longer than the project's useful life, and (or) future related or unrelated projects will be additive to the effects of the one considered project, and so should not be evaluated independently.

The USEPA guidance document (U.S. Environmental Protection Agency, 1999) points out that past environmental conditions are not adequately addressed in most cumulative impact analyses—not fully analyzing how the system has changed from previous conditions and thus not fully accounting for the cumulative impact. Because the Arctic has had very little development thus far, we are in a somewhat unique situation in which there have been few previous impacts so today's conditions form our baseline.

It is true that there have been activities in the Arctic, including seismic surveys in State and Federal waters, some drilling, acoustic surveys, vessel traffic, aircraft surveys, and hunting activities, but the amount is less than in many other areas under consideration for oil and gas development. Human industrial activities in the Alaskan Arctic have been limited primarily to petroleum-related activities in the southeastern Beaufort Sea. The Arctic environment is experiencing large-scale transformation associated with climate change that eventually may result in an opening of frontier areas to increased human developments and commerce associated with fisheries, shipping, and tourism. The relative absence of human activity presents a unique regional opportunity to develop and analyze the cumulative impacts in a relatively pristine environment and show how cumulative effects can be studied and properly evaluated.

To evaluate or analyze cumulative impacts, one needs to determine whether the effects interact or accumulate over time and space. Effects most often accumulate as a result of repeated or compounded activities. However, individual or single actions also can contribute to cumulative impacts, especially if the effects persist for a long time and (or) are augmented by the effects of other activities. As early as 1986, a National Research Council (1986) study identified the most important factors in regards to cumulative effects (and were reiterated in the 2003 NRC study). These factors generally agree with the Council on Environmental Quality's (1997) identified examples of cumulative effects:

- Time crowding—frequent and repeated effects on a single environmental medium.
- Space crowding—high density of effects on a single environmental medium.
- Compounding effects—synergistic effects attributable to multiple sources on a single environmental medium.
- Thresholds—effects that become qualitatively different once some threshold of disturbance is reached.
- Nibbling—progressive loss of habitat resulting from a sequence of activities, each of which is fairly innocuous, but the consequences for the environment accumulate.

Because cumulative impact assessments are difficult undertakings, the National Research Council (2003) described several essential components:

- Specify the class of actions whose effects are to be analyzed.
- Designate the appropriate time and space domain in which the relevant actions occur.
- Identify and characterize the set of receptors to be assessed.
- Determine the magnitude of effects on receptors and whether those effects are accumulating.

Thus, for example, specific *activities* might include seismic exploration and whether these activities had significant effects on specific *receptors*, such as specific species or subsistence hunting. One of the most challenging aspects of conducting a cumulative impact analysis is determining the area and vulnerable resources over which the effects have occurred or will occur.

In addition to identifying and evaluating the accumulation of effects, factors such as magnitude, biotic impact, recovery times, and socioeconomic importance must be evaluated.

Arctic Alaska

Energy and mineral resources are significant in Arctic Alaska (Chapter 2, Geological Context), and the large potential of oil and natural gas resources is of near term interest. Production of some of these resources is already underway, especially onshore, yet many of the areas of Arctic Alaska have not yet been influenced by such industrial activity. As sea ice continues to retreat and allows for more navigation, use of Arctic waters for activities, such as tourism and shipping, is expected to add to the effects of industrial development. Further complicating the issues are those of transboundary impacts—including the United States and Canada for the Beaufort Sea and the United States and Russia for the Chukchi Sea. These factors complicate the delineation and understanding of cumulative impacts, as well as the ability to develop effective monitoring.

There are benefits to energy and mineral production, but there also are social and environmental costs and impacts. Each individual development activity affects the ecosystem, including marine life, habitat, air quality, water quality, and local communities. These effects, combined with those of other projects or activities, will have unanticipated additional, or cumulative, impacts. Climate change adds significant complexity to cumulative impacts, perhaps more so in the Arctic where its effects may be more pronounced. The climate of the Arctic (Chapter 4, Climate Change Considerations) is a complicating factor in evaluating cumulative impacts in that recovery from disturbance in the Arctic may take much longer than in warmer climates.

Cumulative effects analyses have been done by various groups since the passage of the NEPA, but conducting such analyses remains extremely challenging because of the complexity and variety of factors that might impact cumulative disturbances. Although studies and research have been done by many organizations on many factors in the Arctic, there has been relatively little specific focus on a holistic, integrated, comprehensive assessment of cumulative effects of industrial activities in the Arctic.

An additional complicating factor is that Arctic research is conducted by a myriad of entities, and the management of Arctic resources is overseen by many different groups with different mandates, interests, and budgets, and thus research needs. Different agencies have different responsibilities—for air, water, endangered and (or) migratory species, and so on. No single organization has the responsibility for comprehensive planning for oil and gas development in Arctic Alaska. This is, in part, why much of the information is not synthesized or integrated. There is value to having different groups conduct research and analysis, and to some degree management, but there needs to be more coordination and an integrated decision-making process for these large areas that are potentially going to be developed. If an integrated decision-making process is not implemented, then the project-based approach to environmental impact analysis will preclude true cumulative impact analysis or evaluation.

7.01. Finding: Cumulative effects analysis can benefit from applications of sophisticated geospatial technologies, regular synthesis of environmental data and information, ecological forecasting, and multidimensional evaluations of planned human developments. These elements exist for the Arctic OCS at some level, but are insufficient or not well integrated to support comprehensive cumulative impact analyses.

7.01. Recommendation: More coordination and comprehensive planning are needed among the various stakeholders in the Arctic, including those with responsibility for resources, those that conduct research, and those that use resources. These groups should all have input into coordinated, comprehensive cumulative impact analyses. Shared stakeholder visions regarding purpose and data sharing may reduce redundancies and help streamline regulatory processes. These actions must be informed by improved access to information through geospatial technologies, regular synthesis of research, forecasting, and multidimensional evaluations of human developments.

Further complicating the analysis of cumulative impact, especially in the Arctic, the National Research Council study (2003) pointed out that technological advances have significantly changed many factors related to petroleum development, including the type of resource obtained, as well as how and where it can be produced (for example, directional drilling, ice roads, and so on). Technology develops very rapidly when the stakes are large, and it adds a complicating factor to predicting cumulative impact. Climate change, also, significantly impacts the ability to predict or even determine cumulative impact. As climate change is expected to accelerate in the future, its effect on cumulative impact is difficult to predict. It will, however, likely influence petroleum and other development and in turn, those activities on the environment.

The National Research Council (2003) study outlined specific issues (only some of which follow) that must be addressed when considering cumulative effects on Arctic Alaska. Many of these issues are related to onshore development, as the study was focused on the Alaska's North Slope. However, this list, which is not comprehensive, gives a sense of the many issues that must be considered when addressing comprehensive cumulative impact assessments:

- Industrial activity has grown on the North Slope with oil field development, pad development, interconnecting roads, pipelines, power lines, and other infrastructure. Environmental effects of these structures occur both at the site as well as up to a few miles/several kilometers away, but visual impact can be farther. There also is an issue of legacy sites, including abandoned infrastructure and unrestored landscapes. However, there has been significant improvement in reducing the drilling footprint with technological advances, such as directional drilling, replacing gravel pads with ice pads, and other developments.
- Off-road damage to tundra originates primarily from seismic operations. Most of the damage is legacy damage, caused by earlier surveys, but is long term and persistent. Technology, as well as seasonal limitations to off-road travel, has substantially improved and has significantly reduced, but not totally eliminated, damage to the tundra. It is difficult to predict what will be the impact as drilling expands into new areas and as climate continues to warm.
- Roads affect areas of development like they do in many areas by increasing dust, habitat fragmentation, and permafrost effects. Roads also can allow access by hunters, tourists, and others to an area previously difficult to access. Yet, roads can enhance communications among isolated communities and increase contacts between the North Slope and those communities outside the area.

- Animal and plant impacts (terrestrial and marine) include those to bowhead whales and denning polar bears. These may affect predator densities (related to new food sources people bring to the oil fields) and may impact the reproductive capabilities of some species, but that is not yet known. Some species on the North Slope are in decline here and elsewhere, and industrial activities may affect those trends. The Arctic Coastal Plain contains some of the richest areas of Arctic fens, thaw lakes, and tussock tundra in the World. Despite its low biological productivity, the Arctic Ocean supports a specialized biotic community, especially near the coast. Many species of plants and animals are found onshore and offshore.

- Oil spills to date have been from pipelines but there have been no major oil spills from oil field operations. Small spills in the oil fields are not large enough nor frequent enough to be considered in a cumulative impact evaluation, but a future large oil spill, especially offshore in sea ice, would likely accumulate, especially as there is no comprehensive method for clean-up of spilled oil in sea ice.

- Air quality and the effects of air pollution on the North Slope are areas in which relatively little research is conducted. As a result, there is no quantitative baseline and it is very difficult to determine local effects from long-range transport of air contaminants.

- Human factors—

  Socioeconomic changes.—Oil development, and attendant modern Western culture, has resulted in major and most likely irreversible changes to North Slope communities. Changes include funds for schools, housing, health care, and other community services, as well as changes in culture, diet, disease, and economic systems. These changes, which are viewed by some as both positive and negative, are complex and cumulative, because they are multifactoral and interactive. Just as oil revenues have changed the North Slope community, both positively and negatively, declining revenues also will affect life there and additional cumulative impacts will occur should financial resources decline.

  Impact on subsistence activities.—The Iñupiat of the North Slope have a nutritional and cultural relationship with the bowhead whale and offshore industrial activity is largely viewed as a major threat. Bowhead whales are affected by noise (as discussed in Chapter 6, Marine Mammals and Anthropogenic Noise), which alters their migratory pathways, which in turn puts hunters at risk by having to travel farther, by increasing exposure to adverse weather, and by increasing the possibility that the whale meat will not last on the return journey home. Increasing awareness of these risks has led to agreements on limiting or moving activities, but the Iñupiat still view the possibility of an offshore oil spill as a potential catastrophe. These threats are cumulative because they interact and because they are repeated with each new lease sale or activity.

  Aesthetic, cultural, spiritual impacts.—Oil development activities have changed the Alaskan landscape so that there is an accumulation of aesthetic, cultural, and spiritual consequences, including lessening scenic values and diminishment of the solitude of the area, the wilderness, and the "spirit of the land."

  Human health effects.—The direct health effects of petroleum activities have not been well documented in Arctic villages. Within Native communities, there are increased alcohol and drug use, increasing obesity, and other issues, but it is not possible to determine which are specifically tied to petroleum activities. Effects on traditional foods and their consumption are of great concern. It also is not possible to determine the degree to which increased financial resources have contributed to improving the quality of health care and accessibility and have offset the adverse effects of oil and the oil industry.

7.02. Finding: There are no known studies that attempt to separate the effects of oil and gas activities from other causes of socioeconomic change in communities of the North Slope of Alaska.

7.02. Recommendation: Develop a cost/benefit analysis of petroleum activities on residents of the North Slope of Alaska, to understand what effect onshore development has had and to provide a baseline for the effects of potential offshore development.

The National Research Council (2003) cumulative effects report makes the point that some information on the effects of development should be gathered concurrent with information on oil and gas activities, so as to maximize learning opportunities and promote better and (or) adaptive management. The study recommended filling the knowledge gaps by undertaking numerous studies. We have only included those that have specific impact on offshore development potential:

1. Comprehensive planning—decisions generally are made on a case-by-case basis, without a comprehensive plan or regulatory strategy;
2. Ecosystem research—ecosystem-level research is largely lacking at the regional scale in Arctic Alaska; most studies have been local in nature;
3. Offshore oil spills—this was of such concern to the NRC committee that it recommended research into mitigating their effects, as well as research in how to deflect marine mammals from spill areas, and clean-up technologies should a spill occur;
4. Zones of influence—impacts from industrial development are not limited to the specific area of development, but extend some ways beyond and there is a need for quantification of those effects;
5. Human communities—there is important missing information on the effects (beneficial and harmful) to the North Slope communities; a better mechanism is needed to increase Alaska Native input into the research process and a way to translate their observations into hypotheses that can be addressed by research;
6. Human health effects—health effects of oil and gas activities are not well documented;
7. Air contamination and its effects;
8. Bowhead whales—better information is needed on the migratory and acoustic behavior of bowhead whales, including from multiple sources and their feeding patterns;
9. How to deal with uncertainty—because there will never be sufficient data to meet all needs for information, transparency is needed when a model or statistical evaluation is performed to assess an environmental effect, which gives voice to the uncertainty surrounding the use of models;
10. Trade-offs—effects of industrial development may accumulate despite efforts to minimize impacts; it is open to discussion whether the benefits derived from oil and gas activities are worth the trade-offs of their impacts; the nature and extent of these impacts must be fully acknowledged and incorporated into regulatory strategies and decision making.

There is a significant body of work on the actual and potential effect of oil and gas activity in Arctic Alaska, as well as on the physical, biotic, and human environment that could be used for cumulative impact analysis. For example, the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) provided figure 7–1 showing the progression in understanding through time of the social systems in Arctic Alaska. This is but one organization that funds research in the Arctic.

The BOEMRE formally consults with other organizations regarding environmental impacts on potential petroleum development in the Beaufort and Chukchi Seas, including the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS). These organizations have published biological opinions and environmental impact statements regarding development (National Marine Fisheries Service, 2008, 2009; National Oceanic and Atmospheric Administration, 2009; U.S. Fish and Wildlife Service, 2009).

There is a growing recognition of the interaction of factors and issues. Shell Gulf of Mexico Inc. submitted an Exploration Plan to the BOEMRE for several exploration blocks from OCS Lease Sale 193 (February 2008) in the Chukchi Sea, Alaska, in July 2009 to conduct exploration drilling and evaluate petroleum potential in three prospects (Minerals Management Service, 2009). Shell proposed to drill several exploration wells within its lease blocks. Its Exploration Plan (EP) includes an environmental impact analysis, a Chukchi Sea Regional oil discharge prevention and contingency plan, environmental monitoring information, site-specific geohazards survey data and assessment, and mitigation measures. With the EP, Shell submitted a Plan of Cooperation to reduce potential conflicts with subsistence activities, and a description of their Cultural Awareness and Health, Safety, Security, and Environmental Awareness Programs. In addition to these documents, Shell submitted reports relating to distribution and abundance of seabirds, acoustic modeling of underwater noise, bird strike avoidance, marine mammal surveys, and drill mud impacts from exploratory drilling.

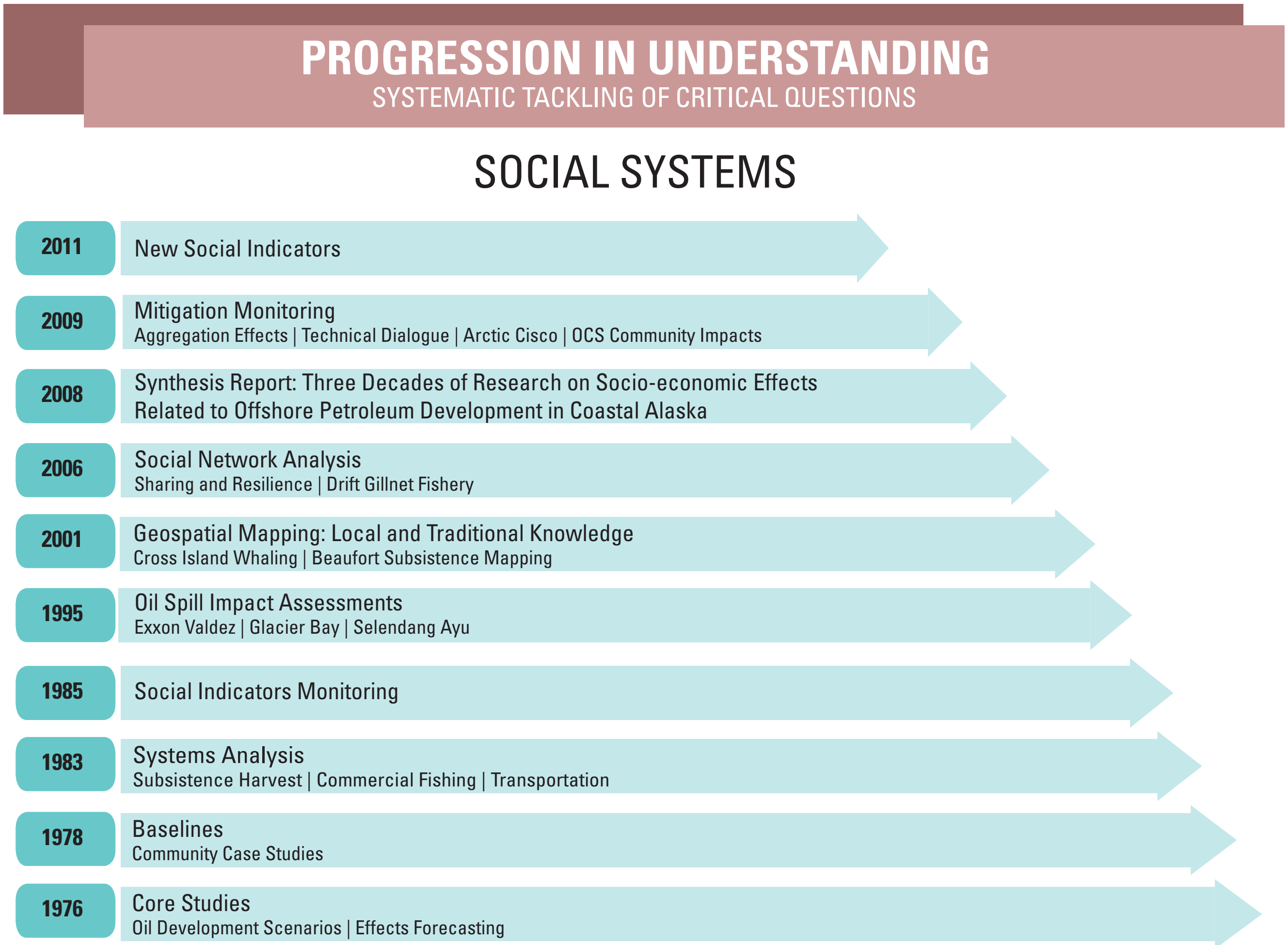

Figure 7–1. Example of studies funded by the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE, written commun., 2011).

Despite the growing awareness and care that is taken to evaluate environmental impacts, there is still grave concern regarding the cumulative impacts to the environment as a whole and to native communities. This concern was voiced in a number of our structured discussion sessions (see appendix A).

Although there is a great deal of information on the Arctic Ocean, including the Chukchi and Beaufort Seas, the information is not synthesized and is not integrated. This has implications for impact analysis, but especially for cumulative impact analysis. The data and information also are not collected in a geospatially sufficient manner to provide as strong a data underpinning as we have on land (fig. 7–2).

There also is a body of knowledge regarding behavioral animal studies related to drilling activities (related to the full range of activities including impacts from boats, aircraft, noise, light, and more), but some studies are anecdotal and cite behavior of animals in certain circumstances, certain times of the year, with certain activities. It is unclear if there is any synthesis of cumulative impacts, especially of repeated behavior. Because there is not yet offshore development in the U.S. Arctic, now is the optimal time to develop studies to determine cumulative impact, which includes a full synthesis of the literature and studies that are available to determine what is already known and what remains uncertain. There is a great deal of literature on different species, activities, behavior, and a synthesis of these studies would likely show findings different than individual studies.

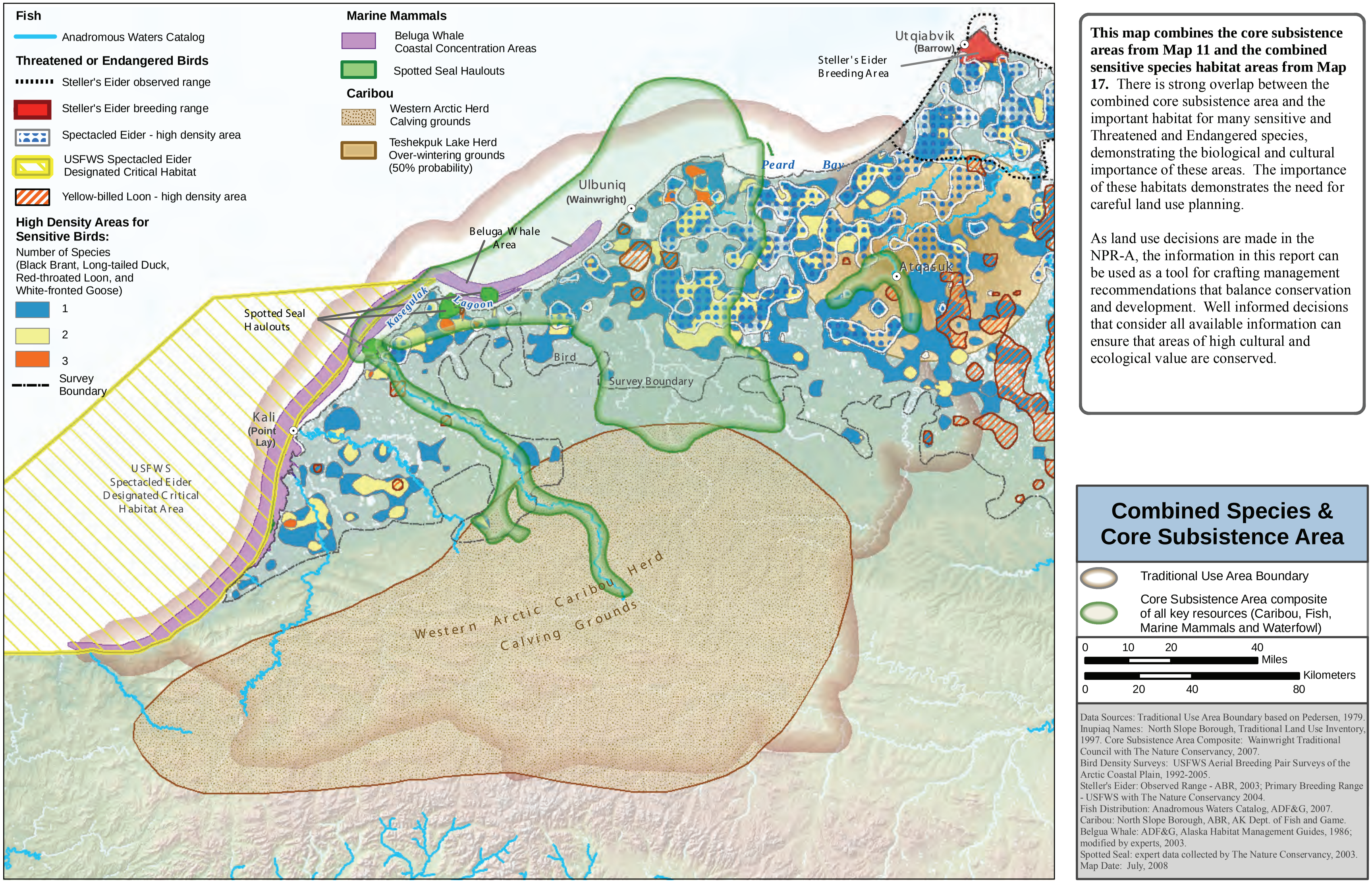

Figure 7–2. Map showing combined sensitive species habitat areas and core subsistence areas for onshore Arctic Alaska. Similar data and visualizations are yet not available at this level for the Arctic OCS. (The Nature Conservancy and Wainwright Traditional Council, 2008.)

7.03. Finding: There is a growing volume of scientific information for the Arctic and the Arctic OCS, more specifically, that is not synthesized and is not integrated. This has implications for confident impact analyses, but particularly for the development of rigorous cumulative impact analyses.

7.03. Recommendation: A thorough synthesis of the existing Arctic literature needs to be conducted to develop a body of knowledge about cumulative impacts. This analysis would point out where studies show consistency and where there is need for more robust analysis of cumulative impacts on certain species or during certain times of the year or during certain behaviors (breeding, feeding, migrating, molting, staging, for example). Significant mitigation measures are being planned and in many cases may be enough (temporary disturbance for certain species during certain times of the year). But a thorough analysis of the literature would give greater assurance of the scientific validity of such assumptions, especially since the literature is detailed and plentiful for some species and sparse and anecdotal for others. This literature synthesis and evaluation should be supplemented with local traditional knowledge. This baseline for cumulative impact analysis will also help in dealing with the effects of climate change on cumulative impact. The data reviewed in the synthesis need to be made digital, where appropriate, so as to facilitate combining data sets and providing a foundation upon which to add more data and to identify data gaps.

Through reviewing the literature and looking at the issues associated with industrial activity, this author compiled a list of just some of the issues that need to be evaluated and how they accumulate when considering a comprehensive cumulative impact evaluation of offshore development:

1. How the resource will be transported—pipeline or tanker?;
2. What onshore infrastructure will be needed to support offshore exploration and development?;
3. How this onshore infrastructure will impact current Alaska North Slope oil and gas development and the cumulative impacts of that development and the two (onshore and offshore) combined;
4. Whether or not offshore development will affect or be affected by the coastal erosion currently occurring at unprecedented rates;
5. Invasive species;
6. Potential from oil spills (not just from drilling activities, but from other factors, such as ships);
7. Socioeconomic changes to affected communities; and
8. Effect on or interaction with subsistence activities.

This is but a small list of factors that need to be considered, in addition to the others listed in this chapter (climate change effects and others) and the other chapters of this report (such as effect on marine mammals, ecosystems, and oil-spill risk).

Effects of Climate Change on Cumulative Impact Analysis

Climate change and resulting ecosystem changes complicate evaluating cumulative effects. Continued climate change effects will themselves accumulate and affect sea ice, plant and animal distribution (both terrestrial and marine), permafrost, human activities, and oil field operations.

The National Research Council (2003) found in their assessment that it appeared customary for practitioners to assume that the only source of environmental change in the evaluation of cumulative impacts is the action under study and that the environmental setting itself does not affect the analysis. Climate change, however, alters this assumption especially in Arctic Alaska, because the climate is changing rapidly and is affecting the landscape and environment itself, independent of, and in addition to, any potential petroleum activity. These factors must be taken into account when evaluating cumulative effects.

Climate change is only peripherally considered in most cumulative impact evaluations or assessments. Climate change can have significant effect on the ecosystem, which in turn will be additive to other impacts, although not directly related. An excellent example of this can be seen in figure 7–3, which illustrates the shift from benthic to pelagic ecosystems, which is already being documented in Arctic waters.

The conditions that are postulated to occur with climate change may have a profound effect on the environment even in the absence of development, and thus will have a profound effect on any cumulative impact analysis. Yet little is understood about how to incorporate these changes into a cumulative impact assessment.

7.04. Finding: Climate change considerations in cumulative impact evaluations are often peripherally handled with limited analytical rigor. Yet, climate change can significantly affect ecosystems, which in turn will be additive to other impacts under consideration.

7.04. Recommendation: A methodology needs to be developed to incorporate climate change effects into a cumulative effects analysis that is transparent, robust, and sufficiently structured to incorporate existing scientific uncertainty about future climate scenarios.

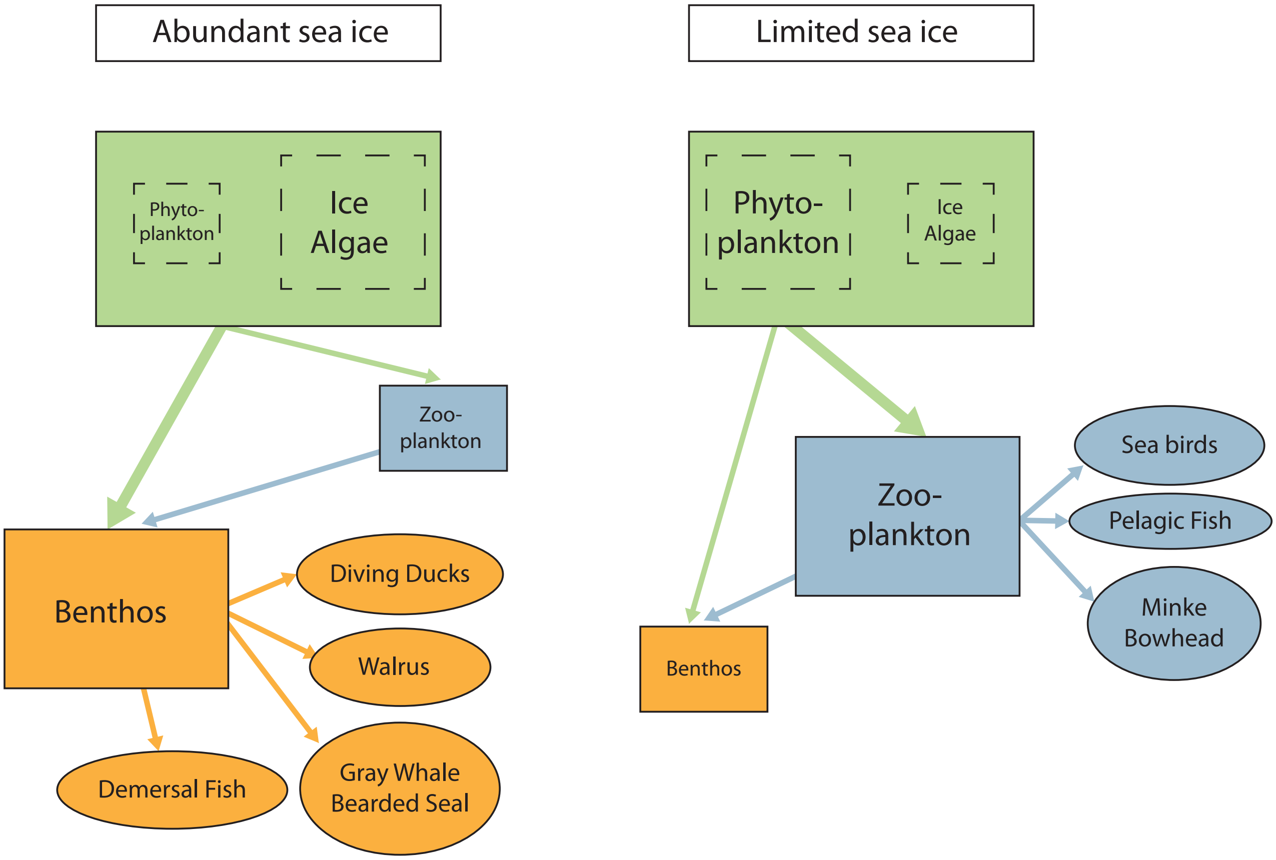

Figure 7–3. How different ice conditions may affect Arctic marine ecosystems (Bluhm and others, 2008).

Methodology for Cumulative Impact Analysis

No universally accepted framework or approach for cumulative effects analysis exists and, thus, there are different approaches to cumulative impact analysis. Further, each government agency handles it differently. This leads to the perception that cumulative impacts are ignored, or when not ignored, are met with confusion. This issue was voiced in each of the structured listening sessions. However, there are accepted general principles that need to be included in all cumulative effects analysis—the analysis needs to be conducted within a context of understanding the resources, ecosystem, and human community thresholds, that is, levels of stress beyond which the desired condition degrades (Council on Environmental Quality, 1997). Determining this threshold is often difficult and problematic. Cumulative impact analysis is complex and difficult, and impacted by a number of factors, but confusion is increased by the different approaches and scales. The different approaches make the results or findings very difficult to compare and contrast. A single methodology could be consistently applied to different areas, account for regional variables, and allow for a comparison of results. Different factors are currently counted in many different ways and words and terms are used differently by different groups: for example, what are threshold indicators; what mitigation measures are prompted when (what kind of threshold has been passed); what are acceptable impacts. A single Department of the Interior approach (1) could alleviate the perception that factors are not being weighed equally (either positive or negative impacts); (2) will resolve the issue of cumulative impact analysis being done differently in different planning areas by different agencies; and (3) will increase the clarity about what is really being considered. One approach also will address the perception that individual development projects are not being adequately addressed by cumulative impact analysis.

The National Research Council (2003) report was unable to attribute the absolute degree of importance to effects, so it attempted a descriptive approach to the importance of the effects. Since then, there have been efforts to develop standardized, quantitative approaches to cumulative effects [for example, Johnson and others (2005) and Halpern and others (2008)], but these have only described some of the impacts and no benefits of proposed activities. Another study that bears watching is the BP- and North Slope Borough-funded study at the University of California, Santa Barbara to develop an approach to quantitatively assess the cumulative impact of noise on marine mammals (namely gray whales and bowheads). These are excellent examples from which to build, but more work needs to be done.

What seems to be missing from many of the cumulative impact analyses is the consideration of future actions. This is very difficult to do, but in an area such as the Arctic where development is still relatively new, one must consider future development in order to account for cumulative impact. The challenge of trying to determine future development is exacerbated by the various oversight responsibilities of the different agencies. Consideration must be given to developing a consistent approach to "reasonably foreseeable future actions," to account for the various projects among and between the various agencies, geographic regions, and time frames, but not overestimate projects that may never be developed. What is considered reasonable and foreseeable is going to be different in each area, but guidelines, definitions, and thresholds need to be developed so they are common and consistent.

Monitoring is an important part of the iterative nature of cumulative impact analysis, to assess the accuracy of predictions of effects and to evaluate the success of mitigation. Consequences should be evaluated repeatedly in the cumulative impact analysis and a monitoring program should include the following (Council on Environmental Quality, 1997):

1. Measurable indicators of the magnitude and direction of ecological and social change;
2. Appropriate timeframe;
3. Appropriate temporal and spatial scales;
4. Means of assessing causality; and
5. Means of measuring mitigation.

It also is important to note that possible effects, both positive and negative, are perceived differently by different groups and individuals. It is not clear that there is a method to attribute a degree of importance to effects, so often the effects are descriptive or qualitative instead of quantitative.

Recently, ecosystem-based marine spatial planning (MSP) is being discussed as a possible tool for assessing and managing for cumulative effects of multiple activities (Foley and others, 2010) as well as a viable strategy for managing human activities in Federal waters. Marine spatial planning is a comprehensive, adaptive, integrated, ecosystem-based spatial planning process for analyzing current and anticipated uses of the oceans (National Ocean Council, 2010, accessed March 31, 2011, at http://www.whitehouse.gov/administration/eop/oceans/cmsp). MSP is a process that analyzes the spatial distribution of activities in the ocean so that ecosystem health and services can be protected and that existing and future uses can be maintained, reducing use conflict. Some MSP efforts, notably those in Norway, explicitly cover multiple sectors including oil and gas development (Olsen and others, 2007). Marine spatial planning takes into account two fundamental principles, namely those of context and uncertainty (Foley and others, 2010), as well as stakeholder input—all issues mentioned previously as important to consider when conducting cumulative impact analysis. Marine spatial planning, as outlined in a number of studies, many of which are described in Foley and others (2010), can be used to reduce the level of cumulative impacts in any one area, as well as the number of trade-offs and conflicts between users and between users and the ecosystem.

7.05. Finding: No universally accepted framework or approach for cumulative effects analysis exists, which leads to the perception among some stakeholders that cumulative effects are ignored. The lack of a clear structure and quantitative analytical process leads stakeholders to question the sufficiency of approaches taken and validity of resulting findings.

7.05. Recommendation: A methodology for comprehensive, quantitative cumulative impact analysis that is transparent, externally vetted, and adopted consistently across at least the Bureaus of the Department of the Interior should be developed. In order to help develop the methodology, an evaluation of the various approaches should be conducted, including marine spatial planning, to determine best practices of all agencies both domestic and international. A common language and a common set of metrics should be developed. One methodology that can take into account regional variables should be developed. The analysis should include more than single projects, and the scope of the analysis should be determined by an expert panel. The approach should define the information needed for a decision and what to do when a decision is required but there are no data. The methodology and resultant analysis should include a plan for the number and types of projects in the region and be able to account for both positive and negative tradeoffs. An approach must be developed to incorporate or predict reasonable future development and monitoring of impacts as development progresses.

Conclusion

The evaluation of cumulative impacts—the combined, incremental effects of human activity—has a basis in NEPA and is guided by CEQ guidelines. In practice, study of cumulative impacts is complex and difficult, especially when consideration is given to potential future development and the overprint of climate change. There is confusion among all parties interested in cumulative impacts regarding what they are and how to evaluate them. Several agencies and organizations evaluate cumulative effects, but there is little coordination of efforts or resultant findings. Furthermore, there is no universally accepted methodology for the study of cumulative impacts. Society's ability to judge the potential effects of oil, gas, and other development considerations in the Arctic would benefit greatly from the creation of a methodology for comprehensive cumulative impact analysis to be adopted consistently. To develop such a new methodology will require an evaluation of best practices across all agencies, domestic and international, and taking advantage of new analytical approaches emerging in fields outside of environmental sciences. A consistent national approach, with common language and a common set of metrics that can take into account regional variables, would allow for the scientific underpinning of an assessment for Arctic development to be viewed relative to actions elsewhere. Efforts to develop such a methodology should consider how best to incorporate more than single projects. Any new approach needs to define the amount of data needed for a decision and what to do when a decision is needed and there are few or no data. The methodology and resultant analysis should include a plan for the number and types of projects in the region and be able to account for both positive and negative tradeoffs. An approach must be developed that is flexible and robust enough to incorporate or predict reasonable future development and define essential monitoring of impacts as development progresses. Synthesis activities must be regularly conducted to document our growing understanding of ecosystems and effects. Development and implementation of cumulative impact analysis must include the various stakeholders in the Arctic. A thorough synthesis of the existing Arctic literature is needed to develop a body of knowledge about cumulative impacts from which to develop the cumulative impact assessment. This synthesis also will aid in incorporating climate change into the new cumulative impact assessment methodology. Only in this way will we start to appreciate what cumulative impacts, both positive and negative, will truly be associated with development in the Arctic.

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Chapter 8

Conclusions

By Brenda Pierce and Leslie Holland-Bartels

The Arctic has had relatively little industrial development thus far, giving us a unique opportunity to determine the future land use and resource management of this area and "get it right." We have the chance to study the environment and all its components and how any changes (human-induced or natural, including climate change) will affect the Arctic. Specific and detailed USGS summaries of key existing scientific information, key knowledge gaps, and recommendations are found in each chapter. Those recommendations are important for understanding what the USGS discovered in the course of this study and to help inform and improve decision making. Within this conclusions section, we provide a higher level summary and synthesis of our findings to help inform the Secretary of the Interior's considerations of the right places and the right ways in which to develop oil and gas resources in the Arctic Outer Continental Shelf.

Impacting all Arctic components and affecting any resource management strategies will be climate change. Climate conditions in the Arctic have recently been undergoing a marked change, particularly during the last 20 years. Environmental changes include warmer air and ocean temperatures, earlier spring snowmelt, a marked decrease in the extent and thickness of sea ice, accelerated coastal erosion, permafrost degradation, an increase in shrubs on the Arctic coastal plain, and other habitat changes. These changes in the physical environment influence biological, human, and industrial systems in a number of ways:

- The distribution of some animal species (for example, walrus and polar bear) is responding to changes in, or the loss of, critical habitat (for example, sea ice) during parts of the year.
- This in turns impacts subsistence hunting.
- The number of days seismic exploration vehicles can operate on the tundra without causing environmental harm has decreased from 200 to 100 over the last 30 years.

Climate projections for the next 50–100 years produced by global climate models consistently show a pronounced warming over the Arctic, accelerated sea-ice loss, and continued permafrost degradation. Of all areas on Earth, the Arctic has the greatest sensitivity to changes in greenhouse gases, with some of the largest changes expected to occur in the Bering, Beaufort, and Chukchi Seas. If realized, these projected climate changes will ultimately affect nearly every aspect of the Arctic environment. This is a major concern from a biological standpoint because the indigenous plants and animals are so highly adapted to the specific extreme conditions that have been the norm in the Arctic.

The effects of climate change are anticipated to influence all components of the Arctic ecosystem, and Arctic Outer Continental Shelf energy activities may exacerbate those changes, unless careful analysis of risks and tradeoffs is conducted. By judiciously planning when energy activities occur, environmental risks associated with those activities may be reduced. For example, extreme cold is a contributing factor in drilling accidents and spills, and thus the significant warming of mean autumn and winter temperatures expected by mid-century will lessen the likelihood of accidents and spills. Although portions of the Chukchi and Beaufort Seas are expected to be ice-free for a greater period of time each year, the pack ice is predicted to be more dynamic at certain times, increasing the risk of accidents and making oil-spill response more difficult during these times. Ice seasons of shorter duration and longer open-water seasons could have profound effects on many different components of the Arctic system, likely affecting Arctic ecosystems and the species within them, especially in areas of particularly high biological productivity and potentially allowing for longer seasons of energy development and transportation.

Climate change also may affect:

- clouds, which in turn affect visibility;
- icing conditions, which are a significant hazard in the Arctic, and can increase the potential for accidents and make response more difficult;
- precipitation, an increase of which would hinder spill response and increase the potential for accidents;
- storms (possibly increasing in frequency or intensity during certain parts of the year);
- sea-level rise, which can affect coastal areas and infrastructure;
- ocean acidification, which can significantly impact calcifying organisms due to the corrosive effect of the acid on their shells and would have reverberations throughout the Arctic food chain;
- ocean circulation patterns, which are likely to change, although what those changes would be and what their effects would be are highly uncertain.

Climate change also will impact organisms in the Arctic (including fish, birds, whales), pinnipeds (ice seals and walrus), and polar bears in many different ways including through the warming of Arctic waters from sea-ice declines and from changes in the food chain notably from the potential effects of acidification of the Arctic Ocean.

Understanding climate change is an important piece of any type of development in the Arctic. More research needs to be conducted on the proposed effects of climate change on factors such as storms and ocean circulation. Storminess will directly affect the safety of oil and gas development. Ocean circulation patterns are critical in shaping both the physical and biological environments of the Arctic Outer Continental Shelf. The science community is actively engaged in developing state-of-the-art global climate models, but these models currently lack the resolution needed to address many of the issues discussed in this report. The United States, as one of the Arctic Nations, would benefit greatly from participating in the development of fully integrated (atmosphere-ocean-land) regional climate modeling efforts. Continued and enhanced efforts in this arena, specifically for the Arctic region, will provide a fundamental tool needed to better understand the degree and nature of any consequences of climate change as it relates to decisions regarding energy development in the Arctic. Periodic Arctic climate impact assessments can help ensure that an up-to-date scientific understanding of climate is achieved.

This theme of fully integrated regional modeling and analysis resonated throughout every topic that we studied. Our analysis of the many different literature sources—scientific reports, public policy documents, workshop findings, web sites—and discussions with a diverse range of stakeholders has resulted in a recognition that in recent years there has been a concerted effort to obtain more data and information on and conduct more research in the Arctic, so there is a great deal of information existing about the Arctic. Yet, in many ways, relatively little is known about the Arctic in large part because many of the studies are targeted in focus and independently conducted with limited synthesis, even within studies on the same topics. There is a critical need for large-scale synoptic efforts that synthesize the many different studies on the full range of topics by the numerous researchers and organizations examining the Arctic. However, there also is a need for some very specific research to address the identified science gaps (in the previous chapters, specifically, and here in general).

Recent research and evaluation efforts in the Arctic have resulted in better understanding of Arctic geology, including the acquisition of geophysical data, offshore mapping, and successfully completing the first Arctic research drilling expedition. Such efforts also have enhanced our understanding of the tectonic and climatic history of the Arctic system, including carbon cycling, and delineating Arctic petroleum systems. Yet, there is a growing need for 3-D seismic data in the Arctic in order to better understand the geologic history of the area and its oil and gas potential (conventional and unconventional), to provide information regarding the safe development of these resources, and to support claims regarding the Outer Continental Shelf under Article 76 of the U.N. Convention on Law of the Sea.

Improved estimates of the oil and gas resources in the Arctic are needed to provide a better baseline for effective resource management. But characterization of the oil reservoir volume and pressure also is needed throughout the Arctic Outer Continental Shelf, as these parameters have direct bearing on oil-spill risk assessment and oil-spill contingency planning. Underpinning research in foundational geology and geophysics can provide an improved understanding of how oil and gas resources are formed and emplaced in reservoirs in the Arctic.

Information on the physical oceanography (such as circulation processes and wind) is critical for oil-spill modeling, oil-spill response, and cleanup efforts, as well as for understanding biological resources. The physical oceanography and meteorological Arctic Outer Continental Shelf characteristics that are inputs into this modeling are highly dynamic as a result of complex factors including ocean source waters, freshwater inflows, and ice melt differences between the Chukchi and Beaufort planning areas. Such complexities are not yet well understood because of the challenge of instrumenting a remote ice-influenced system such as the Arctic Outer Continental Shelf. Thus, the physical understanding of the Arctic Outer Continental Shelf is not comparable with that of the Gulf of Mexico Outer Continental Shelf, nor is the circulation or weather modeling that informs oil-spill trajectory models yet of similar rigor. Outputs from such trajectory models also influence ecological effect analyses, as well as spill contingency planning and real-time response considerations. These analyses are limited by the accuracy and precision of the physical data that inform them. In addition, physical oceanographic and meteorological data help inform a wide variety of issues in the Arctic beyond trajectory modeling or contingency planning. The United States and Canada might benefit from the development of multi-purpose, multi-agency funded monitoring networks that could inform climate forecasting, aviation and shipping safety, and oil-spill response and mitigation plans. The visualization and serving of data through tools of the Alaska Ocean Observing System (AOOS) and (or) the Emergency Response Management Application under development for the Arctic (Arctic ERMA) would ensure efficient access to information and improved asset planning that is critical in the high cost instrumentation environment of the Arctic.

Development in the Arctic is challenging and complex because of the many unknowns and because of the inherent risks of working in frontier and relatively pristine environments. Beyond the focused question of “science gaps” the USGS Outer Continental Shelf Team was challenged with, we observed a need to evaluate all relevant information available to help develop guidelines, best practices, regulations, and policies. Lessons learned from all existing Arctic or sub-Arctic examples must be used to inform future decisions and optimize future actions. The *Exxon Valdez* oil spill in 1989 was the largest oil spill in United States waters until the *Deepwater Horizon* spill of 2010. The lessons learned from the *Exxon Valdez* oil spill are included in our report for the purposes of highlighting Alaska-based experience ranging from spill response through Natural Resource Damage Assessment components. Any Arctic Outer Continental Shelf evaluation and planning effort for oil development can benefit from the lessons learned from *Exxon Valdez* oil spill, which can better inform overall preparedness and particularly oil-spill prevention and response.

Current information and recent baselines developed for different components of the Arctic ecosystems need to be supplemented with ongoing monitoring so as to understand the changes in the ecosystem and monitor its health. Information is needed on all levels of species, from phytoplankton, microbes, and zooplankton, to fish and birds, to marine mammals. It is important to include not just those species that live in the Arctic year-round, but also migratory species as well.

A particular concern, voiced by many stakeholders and cited in the literature, is the impact of noise on marine mammals. Even with multiple studies conducted on ocean noise and marine mammals, large uncertainty still exists in understanding how impacts to individual animals may affect characteristics in the populations and research is needed on this topic. An inventory of seismic sound sources used in the Arctic Ocean does not exist. Such an inventory would provide standardized information about source, physical oceanographic conditions, and timing and duration of surveys. This database could be used to evaluate multiple sound sources that a marine mammal might hear in space and time, and help validate models that estimate sound propagation. The database may ultimately reduce the need for expensive or redundant acoustic modeling and monitoring, especially in sensitive or biologically significant habitats, as well as contribute to developing more effective mitigation strategies. Further, there is a need for an inventory of all non-natural noise in the Arctic Ocean, such as vessel noise, ship-induced icebreaking, and aircraft. Such databases will be important to distinguish between anthropogenic and natural sources of noise impacts to marine mammals and will point out where there are significant information gaps (there is relatively little information on any of these). Data gaps also include the overall ambient noise budgets of the Arctic and how these vary seasonally and spatially. These data are needed because substantial challenges remain for scientists to understand the magnitude and significance of potential effects of anthropogenic sound on marine mammals. Additional research is needed to discriminate between the effects of sound, other aspects of human activity, and environmental variation (natural background). A synthesis of existing data on whale population abundance, structure, and habitats would provide a framework for analyzing how sound impacts whales and help managers determine times and places where whales might be most impacted by anthropogenic sounds. Similarly, fundamental biologic and habitat information about ice-dependent species, such as ice seals, is lacking, as is any information on how anthropogenic sound impacts them. This information needs to be obtained and integrated into these anthropogenic effects databases. In addition, walrus reactions to anthropogenic sounds also need to be better documented and studied (there is even considerable uncertainty as to whether walrus reactions to anthropogenic activities are caused by sight, sound, or smell) and a better understanding and inventory of habitat needs for walrus are needed.

There is a continuing need to facilitate the collection, integration, and sharing of multi-scale data sets to advance our understanding of the Arctic as a complex, interdependent system. Such multidisciplinary data sets need to be used to develop comprehensive, holistic approaches to resource development and impact scenarios to inform planning. The multiple agencies, responsible for different parts of the system, make this task challenging, but it is a critical need. There must be a comprehensive approach taken to any type of industrial development in the Arctic. This comprehensive approach would benefit greatly from international cooperation and coordination. We share a border with Canada, which faces many of the same questions and challenges that we do, and other countries, particularly those of northern Europe, have experience from which we could benefit.

Also resonating throughout many of the issues examined was the challenge of relating the rapidly emerging science and technical information to the decision-making process. The level of information, the number of agencies and entities generating information, and the manner in which information from these sources is served is becoming more important as attention is turned towards the Arctic in general, and resource development in the Arctic more specifically. These information sources, while individually well structured, roll up to a complex information picture that is a challenge to interpret. It is difficult, if not impossible, in attempting to examine such information holistically, to know which needs are being addressed fully or partially, what new information needs or insights have emerged, how one weighs the relative importance of the information, and which new or continued investments are critical to reducing uncertainty among vested parties.

This information challenge is particularly important when it comes to evaluating cumulative impacts. Cumulative impacts are the combined, incremental effects of human activity. Cumulative impacts can result from factors which may be insignificant by themselves but significant when interacting and (or) accumulating over time and space, through repetition, or from a combination with other effects. When actions are considered individually or independently, their combined consequences—or cumulative impact—may not be fully considered or evaluated. This results in misunderstanding, and failure to consider the long range impact of multiple decisions over a large area or over time. Policy decisions are usually made at the regional or national level, but environmental effects are usually analyzed and assessed at the project level. Decisions about and permitting of industrial activities are often done on a case by case basis by multiple entities responsible for oversight of different aspects of the activity. These entities often operate without the benefit of a comprehensive plan or understanding of the scope, intensity, and consequences of the industrial activities, especially if overseen by another entity. Long-term decision making must take into account the cumulative nature and extent of the development benefits and challenges, and the costs and risks of both.

Cumulative effects analysis requires application of sophisticated geospatial technologies, regular synthesis of environmental data and information, ecological forecasting, and multidimensional evaluations of planned human developments. Thus, there is need for more coordination and comprehensive planning among the various stakeholders in the Arctic, including those with responsibility for resources, those that conduct research, and those that use resources. In order to conduct cumulative impact analysis, a thorough synthesis of the existing Arctic literature that builds on the initial work in this report needs to be conducted to develop a body of knowledge about cumulative impacts, a theme that resonates throughout this report. It is critical that this cumulative impact information synthesis and evaluation include local traditional knowledge. The indigenous, subsistence community is extremely knowledgeable about the environment, ecosystem, and changing conditions of the Arctic. Local traditional knowledge is a critical resource and should be incorporated into all of the above syntheses and databases described throughout this report.

Equally important is the critical need to develop a methodology for comprehensive, quantitative cumulative impact analysis that is transparent, externally vetted, and adopted consistently. An evaluation of the current approaches should be conducted, including marine spatial planning, to determine best practices and develop a common language and a shared set of metrics. An approach must be developed to incorporate or predict reasonable future development and the monitoring of impacts as development progresses.

The subsistence community and culture are an essential component of the Arctic and all of the issues studied in this report will have an impact on these people and their way of life. To predict with any degree of accuracy the future of Arctic subsistence, with or without energy exploration and development, will require a greater understanding of the potential changes in local environments and ecologies because subsistence patterns closely correlate to these factors. Thus, subsistence patterns are vulnerable to the effects of climate change and anthropogenic development (whether it be oil and gas development, shipping, tourism, or another). Additional information is needed to determine the potential hazard to native subsistence livelihoods from oil and gas exploration and development, since such development can impact all parts of the spectrum from the specific subsistence animals themselves through their food chain and ecosystem.

In discussions with individuals and groups in the course of our assignment, and to some degree in the literature, it became clear that evaluating the science and filling identified science gaps will not be enough to address the issues surrounding energy development in the Arctic. Opinions on development run the gamut from "there is already enough science" to "there will never be enough science." There are areas of significant scientific research that form a sound basis upon which to make decisions; there are areas where additional science is needed; but there also is an area in which more than science is needed. For that reason, we offer the appendix on Structured Decision Making (SDM), as an example of a type of tool that might be used to help inform decisions about energy development in the Arctic. SDM is a tool to help decision makers when a great deal of complex information and substantial uncertainty exists about the potential effects of development on the many resources of management interest. SDM consists of deconstructing decisions into their component parts, analyzing each part, and synthesizing the parts into a decision framework that can produce direct recommendations to decision makers about which decision is most likely to lead to attainment of their management objectives. This process helps the decision maker develop the fullest possible understanding of the complexities of the decision, including decision objectives, tradeoffs, uncertainties, and risks.

As stated in Chapter 1, Framing the Assignment and Process, our discussions and analyses highlighted that science sufficiency and science gaps are not absolutes but exist in large part in the eye of the beholder. As dynamic concepts, they are tied to an individual's or organization's held beliefs and what weighs most heavily in the decision process when complexity and uncertainty come into play. Whether to develop oil and gas resources, where they might be developed, when they might be developed, and what science is needed to inform those decisions are complex questions because Arctic Outer Continental Shelf development, particularly in the Chukchi Sea, would be a new, frontier activity with limited information and previous experience to guide the decisions being made. Positions about how to deal with any complex issue are informed by a mix of held and technically derived beliefs, and science influences those beliefs to different degrees. So, the questions become:

> How necessary does the vested party consider new information to its decision process? and

> How informative is the available science to be considered (uncertainty, applicability)?

Because of the complex nature and diversity that exist across human belief structures and the difficult-to-study and changing nature of Arctic ecological systems, development of full agreement about science sufficiency is a challenge.

Thus, while there is a growing base of scientific and technical information for the Arctic, which is synopsized in this report, as are critical science gaps to be addressed, many of the challenges emerging in Arctic oil and gas development decision making are beyond the ability of science alone to resolve. There is no "silver bullet." However, we believe a few strategic actions can better support decision making and make for a more transparent process for all vested parties to express, understand, and perhaps balance their respective views on tradeoffs associated with "inaction until more information is in hand" versus "action not sufficiently informed."

In conclusion, the use of SDM approaches brings vested and interested stakeholders into the decision process in a transparent and documented way. The process allows for learning and adaptation, which are critical concepts in a changing frontier environment like the Arctic and we encourage its use. Second, oil and gas development decision making occurs within the broader context of Arctic issues. A collaborative and comprehensive Arctic science planning process would bring great value to the decisions required to proceed with development of oil and gas and other strategic assets in the Arctic in a changing climate environment. Such a science plan and its implementation must be informed by an SDM-like process and the syntheses of information we discussed earlier. Third, the Arctic science and resource community, and particularly the Alaska community, is a model of collaboration. We found throughout our consultations an open and energized desire to understand different views on development and to find means to move forward. Thus, the development of integrated monitoring efforts and collaborative science efforts across governmental, industry, and nongovernmental entities can be accomplished. However, we believe focused attention is required to envision and implement such a fully collaborative environment. Finally, our study found many excellent examples of thoughtful analyses of science and technology needs to inform oil and gas development decisions in the Arctic. Our recommendations and findings add to those already in the literature. To move forward, we strongly recommend that a collaborative implementation process that includes appropriate measures of accountability for all responsible parties/entities be put in place. In our many discussions, we heard from managers, responders, scientists, and community members that they are willing to engage in discussing information needs but that they have a growing expectation that those needs will be considered and, if appropriate, addressed in a visible and traceable manner.

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Appendix A. Expert Consultations

Table A–1. Input received during the five facilitated expert consultations and the North Slope Public Session.

[Participants were asked to identify issues/gaps under each of the four Issue Topics (Climate Change, Oil-Spill Response, Marine Mammals and Noise, and Cumulative Impacts) requiring scientific knowledge that will affect their ability to accomplish their jobs. Sessions often did not cover all four Issue Topics as noted by dark blue. EIS, Environmental impact statement; LTK, local traditional knowledge; NSB, North Slope Borough; OCS, Arctic Outer Continental Shelf]

Issue topics and detailed input	Industry session	North Slope session	Federal session	Non-regulatory session	State session	North Slope public session
Climate change						
Hardware for data collection, especially in shoulder seasons	X					
Lack of climate data	X					
Ability to down scale models to regional development	X			X		
Lack of data collection network/coordination of research (data sharing…)	X					
Issues created by multiple agencies' climate agendas	X					
Unknown biological response to climate change and adaptability			X	X		
Adequacy of physical models for climate change				X		
Baseline data for biological systems (spatial and temporal)				X		
Use of existing technology/resources to understand climate change in the Arctic				X		
Predictability of refugia in time and space				X		
Relationship between water chemistry and environmental changes due to climate change				X		
Human response to climate change (for example, ship traffic, noise, hunting patterns, fishing, subsistence)				X		X
Relationship between subsistence use/Native culture and changing environmental conditions				X		X
Construction must be sufficient to cover any range of conditions including climate change						X
What happens to platforms at the end of their productive life?						X
Oil-spill response						
Inability to conduct field tests	X					X
Secondary data are perceived as not applicable	X					
Inability to access gray literature (in electronic forms)	X					
Detection and tracking				X		
Mechanical response				X		
Risk assessment				X		
Ice management				X		
Non-mechanical response options—Dispersants				X	X	X
Ecosystems and human response to spill				X		
Impacts of spill response on ecosystems and human systems				X		
Capacity assessment				X		
Fate and effect of spill				X		X

Table A–1. Input received during the five facilitated expert consultations and the North Slope Public Session.—Continued

Issue topics and detailed input	Industry session	North Slope session	Federal session	Non-regulatory session	State session	North Slope public session
Oil-spill response—Continued						
Baseline for damage assessments				X		
Sensitivity mapping and response planning				X		
Planned response options				X		
Protocols and standards (damage assessment, restoration)				X		
Information availability				X		
Well safety/control					X	
Systems for humans monitoring wells and identifying issues, ability to reduce human error					X	
Regulations to prevent accidents					X	
Public perception on response capability					X	
Contaminant load in environment—baseline					X	
Ability to test response equipment and methods					X	
Decision making and critical time needs during response					X	
Length of time oil persists in the Arctic environment					X	
Oil spill response gap analysis						X
A combination Coast Guard Oil Spill Response Team						X
Toxicity of dispersant on Arctic ocean organisms						X
Timing of drilling of relief well(s) in case of blowouts						X
Closeness/locations of oil spill cleanup team and equipment						X
Drilling only during favorable times of the year, to mitigate the chance of a catastrophic event						X
Marine mammals and noise						
There is no standard for measuring underwater sounds (science)	X		X		X	
Acoustic propagation is not well understood	X	X				
Lack of understanding of what sound levels cause impacts (behavioral changes, fallout from behavior changes, and other considerations)	X					X
Context of received noise levels for marine mammals, feeding versus migrating, habitual versus naïve	X	X				
Mitigation/quieting technology	X					
Development of remote sensing technology	X					
Effects of anthropogenic sound on bowhead whales from multiple sources/projects	X	X	X			X
Baseline data for species other than bowhead whale, especially related to climate change and seismic noise	X	X			X	X
Knowledge of spatial/temporal distribution, use of satellite tagging/aerial surveys/acoustic surveys	X	X		X		
Baseline data for the current state of the Chukchi Sea and ability to track changes and new species		X	X			

Table A–1. Input received during the five facilitated expert consultations and the North Slope Public Session.—Continued

Issue topics and detailed input	Industry session	North Slope session	Federal session	Non-regulatory session	State session	North Slope public session
Marine mammals and noise—Continued						
Ability to translate impacts on individual bowhead whales to larger bowhead populations		X				
Ability for LTK to document changes in the area as well as identify new species		X				
Information sharing among groups to reduce the risk of redundancy (seismic)		X	X			
Baseline information on natural sound levels and anthropogenic sound levels	X	X				
Information on the ability of marine mammals to communicate function with increased anthropogenic noise (ship traffic from multiple sources) and animal health		X	X			
Information about climate change and ice		X				
Information on ship strikes/ship interactions/entanglements		X	X			
Amount of seismic information being collected		X				
Need for alternatives to seismic surveys		X				
Process for assessing the effects of multiple activities (for example, seismic) on marine mammals, information available for decision making	X	X				
Information on duration of deflection, on individual as well as populations, when/if marine mammals return after deflection		X				
Ability to access information about where and when proprietary seismic activities take place to access the impacts on bowhead whales, both on individuals and populations		X				
Information on the physiological effects of noise	X	X				
Baseline information about how animals use habitats			X	X		
Impacts on marine mammals by spills/leaks			X			
Population dynamics of species (birth, growth, death) and sensitivities to disturbances at these life stages, behavioral changes			X	X		
Behavioral changes of animals and impacts these changes have on humans who depend on them			X			
Data that reflect trends and variability in species baseline			X			
Ability to identify differences between adaptation from climate change and seismic activity			X			
Information on state-of-the-art seismic activity for on-ice and in-water use (what it is and how it is used)			X			
Data on functional relationship between seismic technology use and marine mammals			X			
Data on the thresholds for seismic impacts to marine mammals			X			
Cascading effects of impacts to marine mammals resulting from impacts to other species			X			

Table A–1. Input received during the five facilitated expert consultations and the North Slope Public Session.—Continued

Issue topics and detailed input	Industry session	North Slope session	Federal session	Non-regulatory session	State session	North Slope public session
Marine mammals and noise—Continued						
Efficacy of monitoring and mitigation efforts of seismic activities (180/190 Criteria)	X		X		X	
Sensitivity to noise and variation in time and space				X		
Cumulative impacts, acute and chronic, time and space				X		
Chronic effect at drilling structure				X		
Unique behavioral patterns in the Arctic				X		
Synthesis of existing science				X		
Unique acoustics in Arctic				X		
Cumulative impacts to behavior from industrial activities (not just noise)				X		
Ambient noise mapping				X		
Avoidance capabilities of wildlife				X		
Habituation potential				X		
Predictive models for wildlife impacts and climate change impacts to species				X	X	
Baseline environmental contaminant level for marine mammals					X	
Creation of a marine mammal co-association to help monitor and study the cumulative impacts on the marine mammals						X
Ability to detect marine mammals during the seismic activity						X
Plankton and noise						X
Ocean bathymetry/seafloor relief data for both Chukchi and Beaufort Seas from coast line to 200 mile area for NSB						X
Cumulative impacts						
Lack of updated guidelines on how cumulative impact activities for EISs are written and used (sufficiency and applicability)	X	X		X		
Outcomes of cumulative impact assessments are not functional for intended purposes	X	X			X	
Lack of clear indicators and standards for cumulative impact analysis, inconsistencies between agencies, how science is incorporated	X	X			X	
Coordinated effort among industry to reduce impacts (for example, sharing seismic equipment/data)	X				X	
Efforts to integrate current cumulative impacts data into industry planning	X					
Cumulative impacts of exploratory drilling on food availability, breeding, behavior, predator/prey relationships, and contaminant levels		X	X			X
Functional relationship between existing/historical data management decision-making needs		X				

Table A–1. Input received during the five facilitated expert consultations and the North Slope Public Session.—Continued

Issue topics and detailed input	Industry session	North Slope session	Federal session	Non-regulatory session	State session	North Slope public session
Cumulative impacts—Continued						
Access to information on activities in Russia and Canada that effect cumulative impacts on animals exposed at multiple locations along migratory routes or over multiple years		X				
Ability to link onshore and offshore activities in cumulative impacts assessment		X				
Connection between cumulative impacts on species and on human subsistence/traditional (cultural) uses and social structure		X			X	
Information on drilling muds, discharges and what effects it might have on subsistence food sources		X				
Meaningful analysis of impacts to human health		X				
Attribution of impacts and thresholds (impacts for oil production versus other sources) (thresholds for unacceptable impacts to species)			X			
Data on functional relationships between risk factors			X			
Lack of data to run integrated multi-variant models of cumulative impacts			X			
Cumulative effects: linking spatial and species Bayesian models			X			
Waste management				X		
Amount of scientific information on cumulative impacts			X	X		
Consideration of the time and space scales that cumulative impacts are assessed				X		
Relationship between technology and cumulative impacts				X		
Risk assessment/technology changes of various development scenarios				X		
Terrestrial/marine interaction				X		
Uncertainty in development levels and potential development, unlikely scenarios included in decision making				X	X	
Unknown mitigation efforts to respond to cumulative impacts					X	
Inability to identify independent and cumulative impacts				X	X	
Public perception of cumulative impacts					X	
Not equally weighing positive and negative outcomes					X	
Cumulative impacts of on-land infrastructure for OCS exploration, damage to the tundra, and abandonment of infrastructure with end of exploration						X
Sea currents and winds will carry the spilled oil all over the Arctic, chain reaction destruction of the food chain						X
Increased shipping in OCS resulting in black carbon/soot emissions-cumulative impacts ocean acidification, chemical sink						X
Permitting is issued on individual bases and does not account enough for multiple activities						X
Disposals of all leases–total of all permits issued						X

Table A–1. Input received during the five facilitated expert consultations and the North Slope Public Session.—Continued

Issue topics and detailed input	Industry session	North Slope session	Federal session	Non-regulatory session	State session	North Slope public session
Other concerns						
Social impacts with new development; income, population, lifestyle, way of life, lack of privacy					X	X
Effectiveness of mitigation acts					X	
Efficiency of mitigation acts					X	
Utilize traditional knowledge, western science alone is a fraction of knowledge of what the Iñupiat know						X
Are studies being conducted to look at the socioeconomic effects on the people of the NSB?						X
Publicize all findings from ALL study groups						X

Table A–2. Information-Consideration Grid to organize science and issue needs used in the U.S. Geological Survey Arctic Outer Continental Shelf (OCS) Team's facilitated expert consultation sessions.

[This information was used to consider science sufficiency as illustrated in figure A–1]

How important is issue XX in your decision making associated with oil and gas leasing, development, and policy topics?				
Not a consideration	**Minimally important**	**Moderately important**	**Important**	**Critically important**
	Some consideration, but as an ancillary topic, not enough to result in accommodation in project design or policy topic	One of several main issues considered in project design or policy topic	One of a few issues that are considered in decision outcomes	Foundational to determining decision outcomes
0	1	2	3	4

Please assess the body of scientific information status for issue XX				
None	**Minimal body**	**Moderate body**	**Good body**	**Robust**
No information available at all	Information with high uncertainty or very limited in scope, scale, or applicability to Arctic OCS	Body of information expanding but with notable insufficiencies, functional in most cases	Good body of information across most aspects of issue with limited uncertainty, data gaps may exist for minor elements	Robust information directly applicable to Arctic OCS decision making
0	1	2	3	4

Table A–3. Example of science questions and assessment of sufficiency for one of the expert consultation sessions, the non-regulatory session.

[Information-Consideration Grid scores (see table A–2) for four respondents are provided; however, for some issues, not every respondent provided a score. General judgment of sufficiency is based on the definitions provided in table A–2 and placement of the score within the Grid Graphic (see figure A–1). Scores that fell generally within red and orange zones of the graphic were placed as a gap. Often individuals differed either in the value of the topic to their decision making or to their opinion about status of the body of scientific information on the topic. These are listed as "variable" responses in Sufficiency column]

Issue/gap	Information-Consideration Grid Score Importance, Information Status	Sufficiency
Climate change		
Unknown biological response to climate change (models), adaptability	2,2; 3,1; 4,1; 3,1	Gap
Adequacy of physical models for climate change	1,2; 3,2; 4,1; 3,3	Variable
Baseline data for biological systems (spatial and temporal)	3,2; 4,2; 4,1	Gap
The ability to link larger models to near shore processes/response (down scale)	0,1; 2,2; 3,1; 2,1	Variable
Use of existing technology/resources to understand climate change in the Arctic	2,3; 2,1; 2,2	Variable
Predictability of refugia in time and space	1,1; 4,1; 4,0; 2,1	Gap
Relationship between water chemistry and environmental change due to climate change	0,1; 2,2; 1,2; 1,1	Reassess
Human use response to climate change (for example, ship traffic, noise, hunting patterns, fishing, subsistence)	0,1; 3,2; 4,1; 4,2	Gap
Relationship between subsistence use and changing environmental conditions	1,2; 2,2; 4,1; 2,2	Variable
Relationship between human cultural changes and changing environmental conditions	0,1; 2,2; 2,1; 1,2	Reassess
Oil-spill response		
Detection and tracking	4,2; 4,1; 4,0; 4,1	Gap
Mechanical response	4,2; 4,2; 4,1; 4,2	Gap
Risk assessment	2,1; 4,2; 4,1; 4,2	Gap
Ice management (includes subcategories)	4,2; 4,1; 4,1	Gap
Non-mechanical response options	3,2; 3,1; 4,2	Gap
Ecosystems and human response to spill	4,2; 4,1; 4,1; 3,2	Gap
Impacts of spill response on ecosystems and human systems	4,1; 3,1; 2,1; 3,2	Gap
Capacity assessment	3,1; 4,3; 4,2; 4,2	Variable
Trajectory assessment/models	3,1; 4,0; 3,2	Gap
Fate and effects of spill	4,2; 4,1; 4,1; 3,1	Gap
Baseline for damage assessments	3,3; 3,1; 4,1; 4,1	Gap
Pre-identification of sensitive areas	2,3; 4,1; 4,1; 3,1	Gap
Sensitivity mapping and response planning	3,3; 4,1; 4,1; 3,1	Gap
Planned response options	3,3; 3,2; 2,2	Good
Protocols and standards (damage assessment, restoration)	3,2; 2,1; 3,1	Gap
Information availability	4,2; 3,1; 4,1	Gap

Table A–3. Example of science questions and assessment of sufficiency for one of the expert consultation sessions, the non-regulatory session.—Continued

Issue/gap	Information-Consideration Grid Score Importance, Information Status	Sufficiency
Marine mammals and noise		
Location/tracking (habitat use)	4,1; 4,1; 3,3	Variable
Sensitivity to noise and variation in time and space	4,2 ; 3,2	Gap
Cumulative impacts, acute and chronic, time and space	4,0; 4,2, 4,0; 4,1	Gap
Chronic effect at drilling structure	3,1; 4,1; 2,2	Gap
Unique behavioral patterns in the Arctic	3,2; 2,1; 2,2	Gap
Modeling wildlife impacts	3,1; 4,1; 2,1	Gap
Synthesis of existing science	4,1; 4,1; 4,2	Gap
Unique acoustics in Arctic	2,1; 1,1	Reassess
Relationship between changes in behavior and changes in sensitivity	3,1; 1,1	Variable
Cumulative impacts to behavior from industrial activities (not just noise)	3,1; 4,1; 3,1	Gap
Ambient noise mapping	2,0; 2,1	Gap
Avoidance capabilities of wildlife	3,1; 2,1; 2,1	Gap
Habituation potential	2,1; 2,1	Gap
Cumulative impacts		
Waste management	2,3; 2,1; 2,2	Variable
Amount of scientific information on cumulative impacts	4,1; 4,0; 4,1	Gap
Methods to conduct cumulative impacts assessments (sufficiency and applicability)	3,2; 4,1; 4,1	Gap
Knowledge of individual impacts	3,2; 3,1; 2,1; 3,2	Gap
Consideration of the time and space scales that cumulative impacts are assessed	3,1; 4,1; 4,2	Gap
Relationship between technology and cumulative impacts	1,1; 2,1; 3,2	Variable
Risk assessment/technology changes of various development scenarios	1,1; 4,1; 3,0; 2,1	Variable
Infrastructure development scenarios related to oil/gas development	1,1; 3,1; 4,0; 4,1	Variable
Terrestrial/marine interaction	2,2; 3,1; 4,1; 1,2	Gap
Uncertainty in resource condition	3,1; 2,1; 2,1	Gap
Uncertainty in development levels and potential development	3,1; 4,0; 3,1	Gap

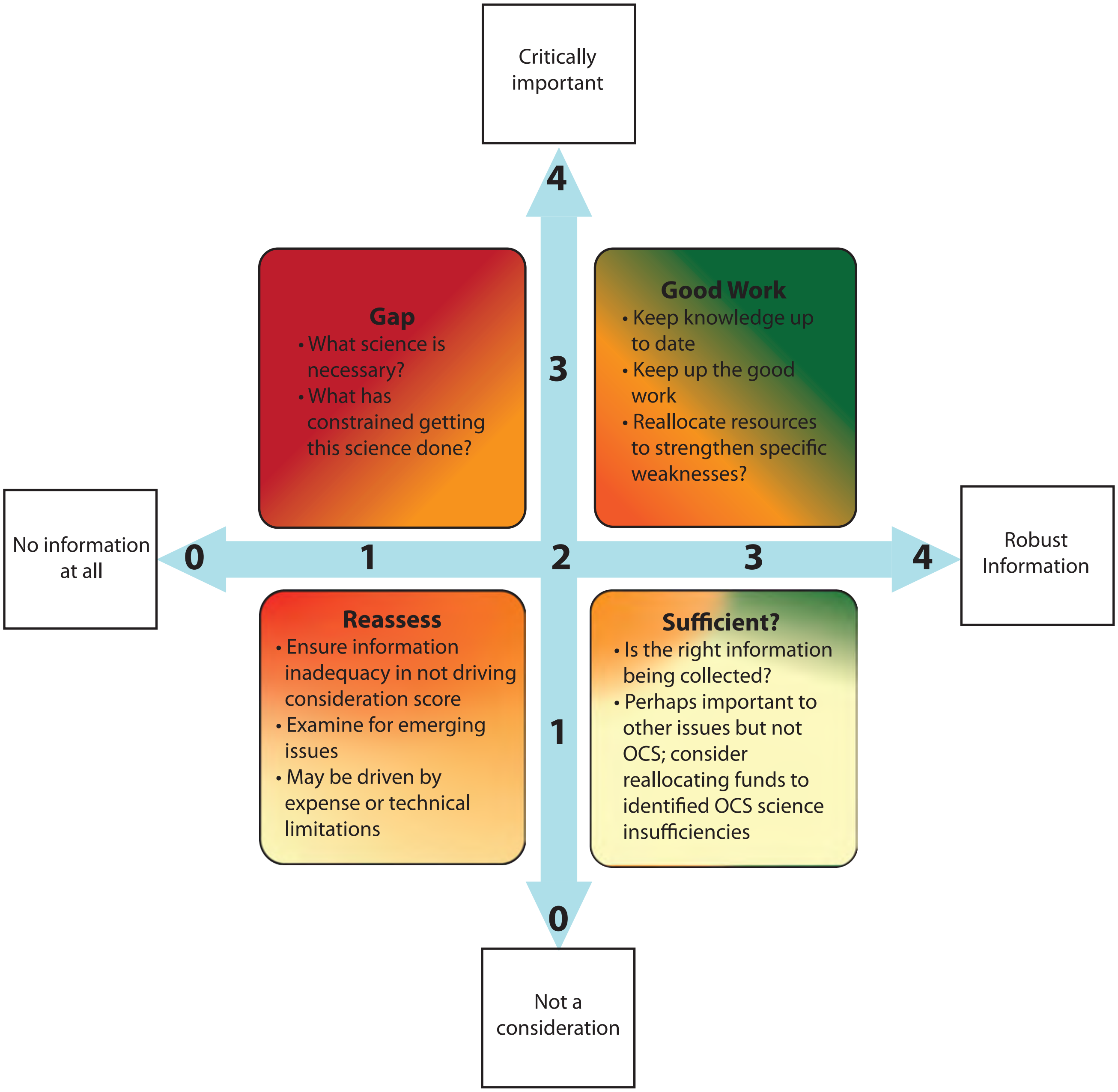

Figure A–1. Grid tool used in the first series of structured consultations sessions. *Y*-axis represents the importance of an issue to an individual's decision making associated with oil and gas development. *X*-axis represents the participant's view of the status of the body of scientific information for that issue. When scores (see table A–3) generally fell within a red or orange portion of the grid, the topic was considered a gap.

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Appendix B. Science Workshop

As part of our series of expert consultations the USGS Outer Continental Shelf (OCS) Team participated in the January 2011 Alaska Marine Science Symposium in Anchorage, Alaska, to gain focused input from the science community on key topics that had arisen during our assignment. The USGS OCS Team participated in the Symposium's Poster Session to interact with participants and held a 3 hour facilitated technical workshop to obtain scientific input on areas of critical and fruitful investigation or approaches informative to the science gap analysis. The discussions were centered on four overarching scientific questions on topics that were consistently mentioned during our other expert consultations or in our literature assessments and that cross-cut the issues that are the focus of our science gap analysis (fig. 1–4). These topics were:

- What weather and oceanographic data are immediately needed to improve spill risk assessments, response planning, and spill response; what approaches are recommended to obtain such data?
- What supplements to agency monitoring and approaches to integrated ecological monitoring are needed for improved development impact assessment, including spill assessment (Natural Resource Damage Assessment, recovery, and restoration) efforts.
- Given gaps in spatial and temporal understanding of resources, how (methods, approaches) can the extensive industry site-specific monitoring be coupled with synoptic governmental efforts to improve broader scale understanding.
- What are the important differences in the physical and ecological conditions of the Beaufort and Chukchi Seas that need to be clearly understood to address the Secretary's commitment to OCS exploration in the "right place/right time."

The participants were provided background on the USGS OCS Team's assignment, context for each of the questions, and several discussion starter questions. They then were asked to self-select one of the four break-out groups to participate in. After 45 minutes of facilitated discussion, groups were disbanded and participants self-selected another break-out group to participate in. In this second series of discussions, participants started with the materials developed by the first group and continued discussion. At the end of these discussions, each break-out group reported out to the full workshop. Input from those break-out groups is summarized in appendix tables B–1 and B–2.

The following includes the materials that were provided to Symposium participants at the poster session in preparation for the January 21, 2011 USGS-sponsored 3-hour workshop.

Break-Out Topic One: What weather and oceanographic data are needed immediately to improve spill risk assessments, response planning, and spill response; what approaches are recommended to obtain such data?

Framing the Topic: Information, assumptions, and predictions of weather, ice, currents, and other physical oceanographic data occur throughout pre-decisional documents and implementation plans for oil and gas development. Such information and its uncertainty influence infrastructure design and placement decisions; spill risk probability determination; modeled spill trajectories and predicted ecological outcomes; and spill contingency planning, response gap estimates, and real-time spill response. The importance of these data to sound decision making is acknowledged and reflected in ongoing study efforts. For example, a recent Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)-sponsored product by Weingartner and others (2010a) provides recommendations on physical oceanography studies for the Beaufort Sea. New technologies also are being assessed in BOEMRE- and industry-funded efforts as in Potter and Weingartner (2009) or Weingartner and others (2010b) who examine the use of a high-frequency radar system to map surface currents for improved spill trajectory models and spill response planning and how viable such systems are in partially ice-covered waters. However, what the potential fate and effect of oil might be from an accidental spill, the level of risk to be tolerated, and the sufficiency of science informing these topics remain points of discussion and disagreement among vested parties.

In this break-out group, we would like to know what is going well and needs to continue, what is a good start and needs enhancement, what has not been addressed and should be and WHY. In the latter two cases, we would appreciate your understanding of how proposed increases in existing efforts or new data would inform the decision process.

Discussion Starter Questions:

1. Are there proven technologies and sampling regimes that should be expanded temporally or spatially, or initiated? If so, how might that happen?
2. Logistics in the Arctic are challenging. Are there alternate technologies that should be investigated or whose use can be enhanced to obtain sufficient metocean data to support effective spill assessment, planning, and response?
3. The Arctic is not a static system, but is undergoing climate-driven change. What data collections and approaches should be considered to improve our ability to understand and forecast key weather and oceanography information to improve risk analyses over the multi-decade horizon of leasing decisions?
4. Are there different data needs or approaches that should be considered for the Chukchi Sea versus Beaufort Sea and vice versa?
5. What are some "low hanging fruit" opportunities, if any, that could be considered immediately?

References Documents: (intended only as examples of a few study efforts)

Potter, R., and Weingartner, T., 2009, Surface circulation radar mapping in Alaskan coastal waters: Beaufort Sea and Cook Inlet: Final Report OCS Study MMS (BOEMRE) 2009-049.

Weingartner, T., Pickart, R., and Johnson, M., 2010a, Recommended physical oceanography studies in the Alaskan Beaufort Sea: Final Report OCS Study MMS (BOEMRE) 2010-018.

Weingartner, T., Winsor, P., Potter, R., and Statscewich, H., 2010b, Chukchi Sea surface currents: accessed March 31, 2011, at http://www.ims.uaf.edu/hfradar/.

Break-Out Topic Two: What supplements to agency monitoring and approaches to integrated ecological monitoring are needed for improved development impact assessment, including spill assessment (NRDA, recovery) efforts?

Framing the Topic: : Information and assumptions about the status and trends of ecosystem components occur throughout pre-decisional documents and implementation plans for oil and gas development. Such information and its uncertainty influence estimation of potential ecological impacts in Oil Spill Risk Assessment Models by providing likely resource intersections based on spill trajectory models. Spill contingency planning incorporates best understanding of ecologically sensitive areas to be protected during response. Status and trends in distribution, demographics, physiological condition, and the like provide the foundation for assessing damage under the National Resource Damage Assessment (NRDA) process and later inform restoration strategies, recovery goals, and progress towards those goals. In addition, experience from the 1989 *Exxon Valdez* Oil Spill restoration effort demonstrates the need for understanding of individual species to be coupled with a more holistic ecosystem framework in which to assess and judge recovery. Cumulative effects analyses also examine species and community perspectives. There is significant investment to develop improved species and system's knowledge. Various Federal and State agencies have ongoing mission-specific population-level sampling. The BOEMRE's Environmental Studies Program also funds key work across a wide spectrum of ecological components informative to the OCS planning process. Examples range from traditional knowledge as reported in Quakenbush and Huntington (2009) and satellite telemetry (Alaska Department of Fish and Game, 2010) collected to provide a broader understanding of single species such as bowhead whale, to studies of species groups such as shorebirds (Powell and others, 2009) to integrated biomonitoring/bioaccumulation sampling for nearshore areas (Neff, 2010). However, what the potential ecological consequences might be from oil and gas infrastructure or an accidental spill, the level of risk to be tolerated, and the sufficiency of science to inform these topics remain points of discussion and disagreement among vested parties.

In this break-out group, we would like to know what is going well and needs to continue, what is a good start and needs enhancement, what has not been addressed and should be and WHY. In the latter two cases, we would appreciate your understanding of how proposed increases or new data would inform the regulatory decision process.

Discussion Starter Questions:

1. Are there proven technologies and sampling regimes that should be expanded temporally or spatially, or initiated? If so, how might that happen?
2. Many different monitoring, population, and ecosystem studies and sampling efforts are ongoing within the BOEMRE, other Federal and State agencies, and academic and non-governmental organization communities within the Arctic OCS, both specifically to inform oil and gas development decisions and with other goals, informative to OCS decision making. Are there science frameworks or modeling approaches that might be fruitful to bring knowledge from such sources together in a transparent way to better inform annual study priority setting and determination of progress towards filling data gaps?
3. Logistics in the Arctic are challenging. It may not be feasible to sample all populations and communities of interest at the desired intensity to reduce uncertainty. Are there alternate metrics that could be added to existing population survey efforts as surrogates for population status?
4. The Arctic is not a static system, but undergoing climate-driven change. What data collections and approaches should be considered to improve our ability to understand and forecast key population and ecological functions to improve cumulative effects and risk analyses over the multi-decade horizon of leasing decision?
5. Are there different data needs or approaches that should be considered for the Chukchi Sea versus Beaufort Sea and vice versa?
6. What are some "low hanging fruit" opportunities, if any, that could be considered immediately?

References Documents: (intended only as examples of a few study efforts)

Alaska Department of Fish and Game, 2010, Satellite tracking of Western Arctic Bowhead Whales: Alaska Department of Fish and Game (ADFG) Final OCS Study BOEMRE (MMS) 2010-033.

Neff, J., 2010, Continuation of the Arctic nearshore impact monitoring in the development area (cANIMIDA) - Synthesis, 1999–2007: Final Report OCS Study BOEMRE 2010-032.

Powell, A., Taylor, A., and Lanctot, R., 2009, Pre-migratory ecology and physiology of shorebirds staging on Alaska's North Slope: OCS Study MMS (BOEMRE) 2009-034.

Quakenbush, L., and Huntington, H., 2009, Traditional knowledge regarding Bowhead Whales in the Chukchi Sea near Wainwright, Alaska: Final Report OCS Study MMS (BOEMRE) 2009-063.

Break-Out Topic Three: Given gaps in spatial and temporal understanding of resources, how (methods, approaches) can extensive industry site-specific monitoring be coupled with synoptic governmental efforts to improve broader scale understanding?

Framing the Topic: There are inherent uncertainties in estimates of undiscovered oil and gas resources and in economic conditions that define when and where development may occur as a result of a leasing program. From 5-year Lease Sale Plans through specific sale EIS documents, estimates of environmental effects must rely on assumed exploration and development scenarios. The question often asked is—how is what we know, at the scale we know it, applicable to environmental assessments. How much confidence should we have in that understanding.

In this break-out group, we would like to discuss your thoughts on mechanisms that could be considered to gain greater knowledge and improve scales of inference through strategic linkages of project or scale-specific studies or process studies by industry, academia and others with larger scale synoptic efforts.

Discussion Starter Questions:

1. What are the types of site-specific studies underway today? Process studies? Broader scale synoptic efforts?
2. Are there mechanisms in place to facilitate linkages among different scaled studies? If not, what would you like to see?
3. Could modeling and process study design approaches, such as those in the North Pacific Research Board-National Science Foundation Bering Sea Integrated Ecosystem Research Project, be fruitful to Arctic OCS decisions? Are there other such ecosystem-based "tactical" efforts that could be examined?
4. What are some "low hanging fruit" opportunities, if any, that could be considered immediately?

Break-Out Topic Four: What are the important differences in the physical and ecological conditions of the Beaufort and Chukchi Seas that need to be clearly understood to address the Secretary's commitment to OCS exploration in the "right place/right time."

Discussion Starter Questions:

1. Consider the other Break-out Topics (1) metocean data, (2) monitoring information, and (3) addressing scales of inference. Is there a difference in sufficiency or importance of specific science between the Beaufort and Chukchi Seas that need to be highlighted?
2. Are there particular ecological areas that need focus?
3. Are there unique socioeconomic considerations between the planning areas for which different science attention is warranted?

Table B–1. Listing of science concerns expressed by participants at the technical workshop held at the Alaska Marine Science Symposium on January 21, 2011, in Anchorage, Alaska.

Science concerns	Topic 1: Meteorological-ocean data needs	Topic 2: Monitoring efforts	Topic 3: Scaling issues
Climate down scaling has to be used to develop ranges of parameters not to expect precise results	X		
Distributed Biological Observatory (DBO)	X	X	X
DBO done on an ongoing basis where drilling may take place	X		
Make physical oceanographic models accessible to researchers, public, and oil-spill response. Combine on single interface (Alaska Ocean Observing System site?)	X		
Comprehensive ecological monitoring of subsurface phytoplankton, benthic ecology, substrate, diversity, production, ice seal stock, beluga stock, prey structure, cod, euphausiids, copepods, and identify biology	X	X	
Trace material flow through the ocean, including river melt water and sediment transport	X		
Monitoring for real-time met-ocean data and water-level observations	X		
Make sure ocean circulation data keep up with depth of oil exploration	X		
Ice thickness, scale of measurements needed, scale of time observations, ice gouging, met-forcing affects on ice-floe movement	X		
Understanding of the variations of the ocean from lease block to lease block	X		
Develop an incentive for public data (build and update database), publish raw data as it is collected, up-to-date data in GIS	X	X	
Make sure ocean/atmosphere models account for extreme events	X		
Coast Guard and oversight of spill cleanup	X		
Improve efficiency and collaboration between industry, academia, and government agencies including disciplines not used to collaborating	X	X	
Establish on-going consistent monitoring strategies done in a broad integrated manner that provides ability to quantitatively measure/predict impacts	X	X	X
Interactive online research assets map showing where instruments in field season exists, need to show this same information historically	X		
Determine when equipment cannot be deployed due to wind, waves, fog, cold, darkness	X		
Ranking of environmentally sensitive areas especially nearshore and shoreline, changes to priority protection sites based on projects	X	X	
Trajectory modeling particularly in ice conditions	X		
Physical oceanography effects on infrastructure seasonally and during storm events	X		
High resolution circulation patterns around sensitive areas, subsurface current information, seasonal variability of currents	X		
Greater focus on effects of potential submarine pipelines and onshore support facilities		X	
Fish species lists are slowly being developed, but population, total numbers, distribution, genetics, movement, and ice association are missing		X	
Effects of natural gas/methane on subsurface species		X	
Effects of gas blowout at depth		X	

Table B–1. Listing of science concerns expressed by participants at the technical workshop held at the Alaska Marine Science Symposium on January 21, 2011, in Anchorage, Alaska.—Continued

Science concerns	Topic 1: Meteorological-ocean data needs	Topic 2: Monitoring efforts	Topic 3: Scaling issues
Characterization of biological aspects of Barrow Canyon and other unique features that may be considered exempt from lease sales or need data at a higher resolution	X	X	
What compartment is the Chukchi/Beaufort biomass in during various seasons, years?		X	
National Resource Damage Assessment (NRDA) Process: how does monitoring relate, integration of historical and contemporary data, develop training [Shoreline Cleanup Assessment Technology (SCAT)], subsistence considerations in Bering Sea	X	X	
Conduct experiments including test spill with dye tracer, spill recovery methods, oil in water and oil in ice	X	X	
Consult with Norway and United Kingdom for their risk assessment and safety case planning as well as research on oil/ice interactions	X	X	
Local residents may be interested in working on compromises that determine right time/right place		X	
Use of models and datasets not representative of Arctic conditions may lead to incorrect conclusions and decisions		X	
Increase coordination for planning, lease sales, mitigation measures, permitting, on-going monitoring, and rehabilitation including oil-spill response		X	
Food web cycles are lacking adequate description especially low in food web, annual variability, and potential to disrupt these systems		X	
Develop oil vulnerability index for species in Beaufort/Chukchi		X	
Give emphasis for site-specific studies to sites located in areas likely to be effected, that is, lease areas		X	
Concern for cultural and resource impacts from development, need socio-economic baseline		X	
Better framing in terms of temporal/spatial – percent chance of occurrence		X	
First assess relative abundance/importance then prioritize areas for more in-depth studies		X	
Pair oceanographic observations with biological		X	
Data need for restoration of Arctic Ocean systems and populations		X	
Regular surveying of local communities for changes they are seeing		X	
How will we know the baseline data are representative given the potential changes occurring already due to climate change		X	
Marine mammal range extensions and response to ecosystem variability		X	
Incorporation of Alaska Ocean Observing System data into biological studies, especially for food web/prey structure/energy flow		X	
Continued development of autonomous underwater vehicles (AUVs) and unmanned aircraft, augment acoustic recorders with sensors to capture biological activity and develop new technologies to increase monitoring capabilities	X	X	
How is oil breakdown effected by dispersants in ice and ice-free environments		X	

Table B–1. Listing of science concerns expressed by participants at the technical workshop held at the Alaska Marine Science Symposium on January 21, 2011, in Anchorage, Alaska.—Continued

Science concerns	Topic 1: Meteorological-ocean data needs	Topic 2: Monitoring efforts	Topic 3: Scaling issues
Effects of oil containments and dispersants to the ecosystem, what is the adaptation of organisms to the oil		X	
Long-term carbon assessment in water [for example, chromophoric dissolved organic matter (CDOM)] as baseline assessment, seawater chemistry, locate natural seeps	X	X	
Successful monitoring of Boulder Patch (Beaufort) year-round could be considered for other significant habitats – (Chukchi?)		X	
Community-based monitoring and assessment as a framework for determining current status and future trends, include local communities for on-the-ground response	X	X	
Pre-identify in-state resources with appropriate and current training, publish roster at least within planning, response, and government and industry		X	
Pre-identify mechanisms to distribute response-related research funding		X	
Address unique Arctic logistical issues regarding chain of custody, such as sample storage/handling issues		X	
Pre-identify the process by which monitoring and sampling would be temporarily expanded or initiated		X	
What processes control the marine system, use this to help determine what to measure and monitor		X	
Scale at which things vary on benthos is much shorter than in water column		X	
Consider health impact, assessment and linking (and social parameters) human health with the ecosystem		X	
Necessary to identify what regions of the Arctic are important habitat for particular species		X	
Need migration/movement not just population for risk analysis		X	
More studies needed in microbiology (bacteria), bioremediation		X	X
Consider shifting baselines during monitoring programs and comparison to baselines		X	
Distinguish between monitoring of potential impacts of 'regular' operations versus those from 'spill' scenarios and monitor species recovery after a hydrocarbon release		X	X
Standardized studies need to be done to calculate locally meaningful correction factors for things like marine mammal density estimates.		X	
Gaps are seasonal, lacking early season and over winter so monitoring should include seasonal components, for example, winter oceanographic monitoring for circulation		X	X
Synthesis and integration of existing information including observations, model data, fate and effects of spilled oil, dispersant use, ecological data and baseline data	X	X	X
Under Ice system monitoring (including seasonality) = huge productivity	X	X	
Ice-edge tracking (underway; relationship to ecosystem)		X	
Species adaptation capability/capacity		X	
Expand buoy array		X	X

Table B–1. Listing of science concerns expressed by participants at the technical workshop held at the Alaska Marine Science Symposium on January 21, 2011, in Anchorage, Alaska.—Continued

Science concerns	Topic 1: Meteorological-ocean data needs	Topic 2: Monitoring efforts	Topic 3: Scaling issues
Transparency, quantitative/qualitative		X	
Recognize different monitoring needs/platforms/suitability to meet needs of the questions posed, proactive monitoring design		X	
Need time-sensitive sites (transect) that are spatially placed to capture upstream and downstream work			X
Transport models that incorporate key physical and biological parameters			X
Nested site selection			X
What is the type/discipline of ecosystems data received to understand that ecosystem			X
Longer comparable data sets from existing spatially distributed sampling stations, replicate Outer Continental Shelf Environmental Assessment Program (OCSEAP) studies		X	X
Fisheries—epibenthos abundance and distribution, species composition, ecological process, habitat association			X
Opportunistic opportunities to collect data and explore/analyze existing			X
Broader scope oceanographic understanding is needed for better understanding of smaller scale			X
Tiering of information/studies is an important technique			X
Do more research about planning to respond to oil spills in ice-infested Arctic waters, burning oil in ice, identify areas for pre-positioned protection	X		X
Propagation of sound through oceans			X
Passive acoustic monitors for mining data from other sounds			X
Seismic data – through water column			X
Spatial and temporal variability of ecology			X
Ecological asset inventory			X
Indices for keystone species			X
Model verification – especially validation			X
Process (in addition to coordination) for defining “sufficiency” across spectrum of data/understanding, different for different levels of activity		X	X

Table B–2. Differences in Beaufort and Chukchi Seas as noted by participants at the technical session held at the Alaska Marine Science Symposium on January 21, 2011, in Anchorage, Alaska.

Chukchi Sea
Cumulative impacts – shipping
Less infrastructure in place
Wave height, cold (affects weathering and clean up), visibility, wind driven leads
More complex, topographically, Barrow Canyon
Shoal habitat (Hanna and Harold)
Bering Sea influence; nutrients and carbon
Shallow sea with oil resource far offshore in deep water
Sea bottom very productive, hot spots
More shelf and areas of interest for exploration are ice free longer
Most development areas beyond coastal subsistence use areas
Spring whaling, seal hunting on shear ice, walrus and seal hunting in pack ice
Development farther offshore, greater risk?
More historical and ongoing work
Primarily ship provided transport, shorter transit from south, no road access
Walrus haulouts changing due to changing ice, modeling of walrus distribution
Critical feeding areas for migrating birds
Point Lay, Point Hope – very traditional village lifestyles
Beaufort Sea
Cumulative impacts – oil and gas in Canadian Beaufort
Ice-driven leads, land-fast ice
Current OSC exploration, more infrastructure
Nutrients and carbon from upwelling and shore, more complex circulation
Beaufort gyre influenced, longer sea ice in summer, river influenced
Deep sea with oil resource in shallow water
Flat shelf, sea bottom mostly barren, ice gouging, active gouging zone
Dissolved organic carbon terrestrial carbon utilization
Perhaps more viable, trending towards less ice cover
Lots of overlap between subsistence and development
Fall whaling, cisco/white fish
Importance of cod, 96 percent of fish abundance and biomass, keystone species
Need synthesis of existing data (census of marine life)
Multi-modal, road access to Prudhoe Bay, cargo aircraft, access to small vessels, used to heavy equipment, longer ship transport times
Much more subsistence, but perhaps not as traditional lifestyles

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Appendix C. Structured Decision Making for Energy Exploration and Development Decisions on the Arctic Outer Continental Shelf

By Sarah J. Converse

Background

Decisions facing the Department of the Interior (DOI) on behalf of the Federal Government about whether and where to permit oil and gas exploration and development on the Arctic Outer Continental Shelf (OCS) are challenging. The challenge arises primarily as a function of four characteristics. First, there are complex and potentially competing objectives associated with a diverse stakeholder contingent (for example, energy development, marine mammal protection, oil-spill prevention). Second, there are a wide variety of different decision alternatives available to the decision maker, including many possible combinations of temporal and spatial structures in development permitting. Third, there is an unknown array of decisions required of other agencies resulting from each possible oil and gas development decision alternative that could be selected by the DOI. Fourth, as demonstrated by the analyses outlined in the chapters of this report, there exists a great deal of complex information as well as substantial uncertainty about the potential effects of development on the myriad resources of management interest.

Structured decision making (SDM; sensu Clemen, 1996; Possingham and others, 2001; Williams and others, 2007) is the application of decision science to assist decision makers in the process of making decisions, and is especially important and applicable in the case of decisions that are both important (that is, high stakes) and challenging. SDM rests on the idea that decisions can be made more effectively (that is, more likely to lead to attainment of management objectives) if a structured analysis is conducted. This analysis consists of deconstructing decisions into their component parts, analyzing each part, and synthesizing the parts into a decision framework that can produce direct recommendations to decision makers about which decision is most likely to lead to attainment of management objectives. More generally, engagement in a formal decision-analytic process helps the decision maker to develop the fullest possible understanding of the complexities of the decision, such as decision objectives, tradeoffs, uncertainties, and risks.

Structured decision making is not appropriate in all cases. The use of the process requires that a decision maker can be identified and that the management objectives (potentially multiple and competing) of that decision maker can be articulated. In addition, the set of decision alternatives under consideration must be known or knowable, and there must be an ability to make predictions about how different alternatives would impact the objectives of interest; such predictions can arise from data or from expert judgment and may (and often do) involve substantial uncertainty. Finally, and most generally, the process requires transparency in development of all decision components.

Value of Structured Decision Making

A formal decision-analytic process can help most specifically by producing a recommended course of action most likely to lead to attainment of management objectives. More generally, however, the process is useful for informing a decision maker about the complexities of the decision. For instance, the process is useful in helping the decision maker to develop a clear articulation of the management objectives, to contemplate tradeoffs, to be aware of uncertainty and integrate risk attitudes into the decision (that is, the degree of risk the decision maker is willing to accept in order to obtain some potential benefit), and to develop a sense of what information is available and what uncertainties are relevant. When used appropriately, formal decision processes are designed to lead to decisions that are (Runge and others, 2009):

- Transparent—SDM is designed to produce transparency in the decision-making process, to remove the “black box” aspects of decision making, such that decisions can be understood and communicated.
- Explicit and Able to be Documented—The transparency required by the SDM process results in decision processes that are explicit in their treatment of decision components, which results in decisions that can be effectively documented within an administrative record.
- Deliberative—SDM encourages careful deliberation about the various components of the decision-making process. This is expected to lead to better decision outcomes because deliberation encourages more thorough identification of management objectives and tradeoffs, a wider search for creative decision alternatives, more complete use of scientific information in developing predictions of decision outcomes, and more thorough articulation of important uncertainties and risks in the decision.

- Robust—SDM recognizes that uncertainty and risk influence decision making. As such, SDM is designed to produce decision processes that fully recognize the type and magnitude of uncertainty and risk; such decision processes are designed to produce recommendations that are robust to the uncertainty and risk that exist; that is, decision processes that are most likely to lead to attainment of management objectives.

Stakeholders and Structured Decision Making

Within the public policy realm, consideration of the values of stakeholders is of paramount importance in framing decisions. In the U.S. Department of the Interior Adaptive Management Technical Guide, engagement with stakeholders is identified as the first step of the adaptive management process, which itself is recognized as a structured decision-making process (Williams and others, 2007). Stakeholders have multiple roles in developing decision processes, and should be effectively engaged in the development of each component of the process. Perhaps most critically, the objectives of stakeholders must be understood and integrated. The decision maker, in public policy decisions, has ultimate responsibility for understanding and articulating stakeholder objectives, and for weighing tradeoffs between competing objectives of diverse stakeholder groups. As such, we assume herein that the values of stakeholders are included as they are understood by and embodied in the objectives and tradeoffs of the decision maker.

Components of Structured Decision Making

Structured decision making consists, most basically, of deconstructing decisions into their component parts, analyzing the individual components, and synthesizing the components into an integrated decision framework that is designed to lead to recommended courses of action. As such, decision analysts recognize that every decision involves a consistent set of components (for example, Hammond and others, 1999). These components are:

Decision Problem.—The decision problem is a clear statement of the decision that is to be made. It includes information on the factors prompting the decision, the identity of the decision maker, the particular decision to be made, the spatial and temporal scope of the decision, the timing of the decision, and whether the decision will be repeated through time or is a one-time decision.

Objectives.—The objectives are the things that the decision maker wants to achieve in the context of the particular decision. They are representations of values, policy, and stakeholder objectives guiding the decision maker. In decision analysis, it is often useful to differentiate between fundamental and means objectives. Fundamental objectives reflect ultimate statements of values—in essence, the most basic values of the decision maker. Means objectives, by contrast, are objectives the decision maker would like to achieve because they are themselves means to achieving the fundamental objective(s). For example, if a fundamental objective, in the context of the OCS energy exploration and development decision, is to maintain the tourism value of the Arctic system, a means objective may be to minimize the construction of energy development infrastructure in critical viewsheds.

Alternatives.—The decision alternatives are the comprehensive set of alternative management actions available to the decision maker. The alternatives will depend on the particular decision to be made, and may have many elements (for example, spatial and temporal components).

Model.—The system model and predictions component is the component most familiar to scientists. This component encompasses all information available about the implications of different decision alternatives on the management objectives. That is, science in a decision-making context serves to link our decision alternatives to our objectives, such that we can make predictions of the form, “if we take action ‘a’, the result in terms of a given management objective will be ‘b’.” More specifically, we often make such predictions in a probabilistic framework, because we have substantial uncertainty about the functioning of complex systems.

Optimization.—The tradeoffs analysis, or optimization, is the final step necessary in identifying an optimal decision, and involves searching among the proposed set of decision alternatives for the option that is most likely to lead to the attainment of management objectives. In many cases, this means weighing tradeoffs among competing objectives. In addition, some decisions involve an additional component.

Monitoring and Feedback.—Monitoring and feedback are applicable when decisions are repeated through time. In these cases, monitoring data can be used to assess whether management objectives are met, to measure the state of the system for informing state-dependent decisions (that is, where the decision that one takes depends on some aspect of on-the-ground conditions), and to reduce uncertainty about how the system responds to management (Lyons and others, 2008). These monitoring data can then be used to update predictions about system responses to management, thus facilitating improved decision making through time (Nichols and Williams, 2006).

Prototyping of a Decision Framework

With the input of the U.S. Geological Survey (USGS) OCS Team, the broad outline of a decision framework to inform the DOI Arctic OCS energy exploration and development decision was developed. This framework was developed as an example of a more fully articulated framework that could be developed with the input of the decision maker or delegates. That is, this decision framework is both incomplete and not assumed to represent the true aspects of the decision as understood by the decision maker; instead it is intended as an illustration. This simple prototype demonstrates the basic process of SDM and how it could be applied to synthesize and analyze science and policy information to inform Arctic OCS energy exploration and development decisions.

Decision Problem.—The national strategy for energy and economic security defines the intent by the Administration to open certain OCS areas to exploration, set aside those areas deemed inappropriate for development, and increase oil and gas exploration in some frontier areas. The Arctic OCS is identified as one of the most promising frontier areas for consideration because of its high potential of oil and gas resources, a substantial portion of the global potential. This is evidenced by the fact that oil and gas leases already exist in the Arctic OCS. It also is an environment containing substantial ecological and social resources of high spatial and temporal complexity. Within this area, there exist federally mandated conservation requirements within the context of the National Environmental Policy Act, International treaty, and Endangered Species Act regulations. The DOI holds authority for decisions on energy exploration and development in the Arctic OCS.

There are two decisions facing the DOI—one short term and one long term. The short-term decision involves deciding what to do with current Arctic OCS leases that are on hold. The long-term decision involves deciding when and where to permit exploration, development, and production of oil and gas resources in the Arctic OCS; that process is nested within ongoing and repeated revision of the OCS 5-year planning process. There are decisions made at each stage (exploration, development, and production) that can be seen as linked decisions (that is, decisions made at one stage influence the decision alternatives available at the subsequent stage), and there are substantial stakeholder concerns related to the linked nature of these decisions. Concern in the conservation community is based on the perception that once exploration begins, it is inevitable that production will occur; the energy industry is concerned that any one of these linked stages can result in termination of exploration and development prior to production.

There are disparate stakeholders with vested interests and substantial influence through the congressional, judicial, and regulatory processes whose views must be considered and incorporated into the decision. Industry has made significant investments in the Arctic OCS. Other stakeholders include the subsistence community (who have invested generations in the region and whose culture is tied to the marine environment), the general public (who have a stake in the biodiversity, remoteness, the domestic energy resource, and the lease revenue), and the conservation community (who have a stake in the biodiversity and ecological function of the Arctic). Federal agencies with stakes in the decision include the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) (regulatory authority over leases), the National Oceanic and Atmospheric Administration (NOAA) (regulatory authority over listed species), and the Coast Guard (ultimately responsible for spill response and safety).

There is substantial scientific uncertainty about the impacts of energy exploration and development on resources of interest. The DOI has recognized this uncertainty and has tasked the USGS with describing the state of scientific knowledge in order to inform decisions regarding the Arctic OCS; results of the USGS analyses are described in the chapters of this report. In addition, the linked nature of these decisions does have the effect of allowing monitoring data to inform future steps in the decision process, indicating the importance of well-designed and well-executed monitoring plans.

4.

Objectives.—The USGS OCS team developed a draft objectives hierarchy consisting of fundamental objectives grouped in thematic areas, and linked to means objectives. This objectives hierarchy is expected to represent at least some of the objectives of the DOI in the context of the Arctic OCS energy exploration and development decision, but it is not expected to be a complete or necessarily accurate set of the DOI's objectives. The objectives are illustrated graphically in figures C–1 through C–3 and also are provided below. First tier elements are thematic areas (that is, groupings of fundamental objectives). There were three thematic areas identified: human communities, ecosystem values, and economic vitality. Second tier elements are fundamental objectives, of which 10 were identified. Third tier elements are means objectives.

The identified objectives are as follows:

1. Maintain Values of Human Communities
    a. Protect Human Health and Maintain Human Safety
    b. Protect and Maintain Subsistence Communities
        i. Maintain Populations of Subsistence-Hunted Species
        ii. Maintain Culturally Critical Components of Subsistence Hunting
    c. Meet Trust Responsibilities to Native Communities
2. Maintain Ecosystem Values
    a. Protect and Maintain Ecological Function
    b. Protect and Maintain Biological Diversity
        i. Maintain Populations of Endangered Species
        ii. Maintain Populations of Marine Birds
        iii. Maintain Populations of Marine Mammals
        iv. Maintain Populations of Fishes
    c. Protect Wilderness Values and Experience
3. Maintain Economic Vitality of Region
    a. Meet Energy Production Targets
    b. Meet Lease Revenue-Generation Targets
    c. Provide Employment Opportunities
    d. Maintain Tourism Value

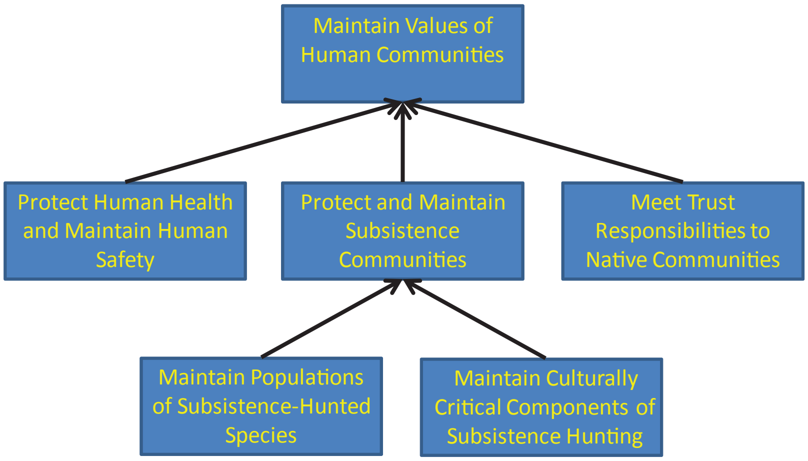

Figure C–1. Objectives hierarchy for the "Maintain Values of Human Communities" theme.

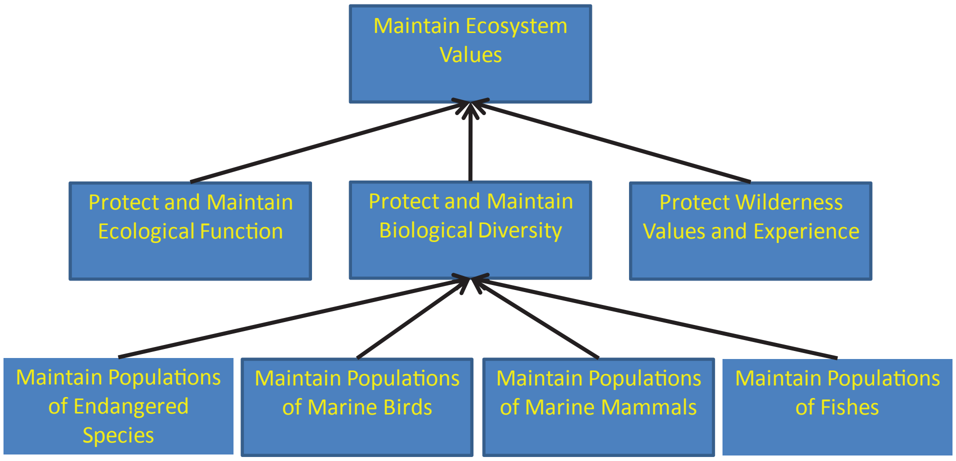

Figure C–2. Objectives hierarchy for the “Maintain Ecosystem Values” theme.

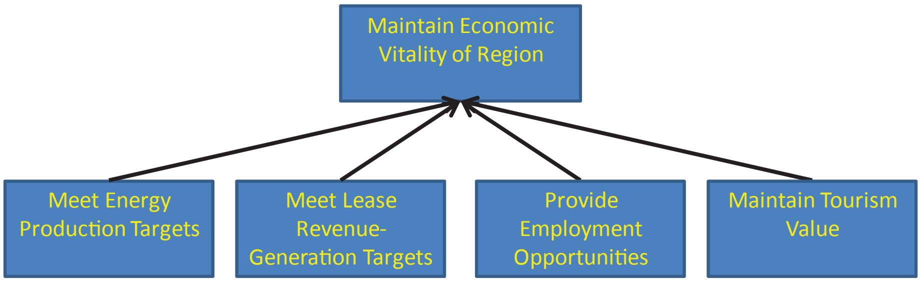

Figure C–3. Objectives hierarchy for the “Maintain Economic Vitality of Region” theme.

Alternatives.—Decision alternatives will involve different spatial and temporal patterns of permitting. Spatial aspects include the particular blocks opened for permitting, such as whether to allow drilling inside the current exclusion area or to expand the exclusion area, and the physical location of permitted sites within permitted blocks, including the allowable proximity to resources of spatial interest. Temporal aspects include the timing of exploration and production activities within a permitted area (for example, drilling could be staggered through time) and whether to impose seasonal constraints on activities. Additional aspects include which mitigation measures to mandate (for example, such as constraints on the density and spacing of drill sites). Decision alternatives will be defined by various combinations of different spatial and temporal patterns of permitting, both with and without mandates for various mitigation measures.

Models.—The modeling stage is the stage during which scientific information is used to develop predictions of the impact of decision alternatives on the various management objectives. We note, however, that building predictive models can only commence after the preceding elements of the decision process are fully understood (that is, the decision problem, objectives, and decision alternatives).

To build predictive models, we would begin by developing conceptual models that link components of the system through logical relationships; these logical relationships are described in narrative form throughout the chapters of this report. Conceptual models must demonstrate links between alternatives and objectives, so the basis for predictions about the impacts of decision alternatives on objectives can be made. Development of conceptual flow diagrams is a useful precursor to development of quantitative predictions. An example can be seen in figure C–4, linking the spatial location of permitted sites to the objective of maintaining populations of marine mammals.

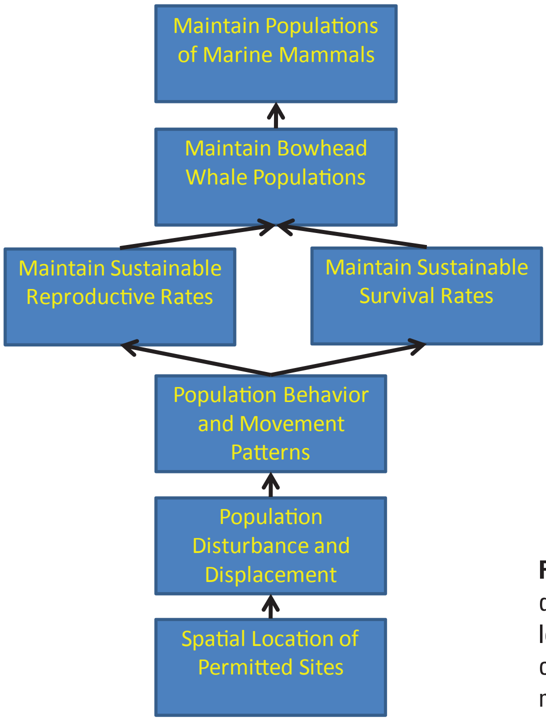

Figure C–4. An example logical flow diagram linking actions (the spatial location of permitted sites) to an objective (maintain populations of marine mammals).

Once such conceptual models are developed, they can be used to form the basis of quantitative predictions. Separate predictive models are needed for each of the fundamental objectives, where outputs of the models will be in units related to the objective (for example, for the objective "maintain populations of marine mammals," models for each species of interest would produce output in the form of numbers of individuals or probability of population viability). These models will make predictions, then, of the impact of each decision alternative on each of the identified management objectives.

One appropriate quantitative modeling tool for at least some of the objectives may be Bayesian Belief Networks (Marcot and others, 2006), which are graphical models that allow for propagation of uncertainty via conditional dependencies between model components. These are probabilistic models that frequently can be developed even with sparse scientific information. Much of the scientific information necessary to build the predictive models of interest may be in the form not of data but of expert knowledge. In this case, techniques for expert elicitation could be used to capture this information in a fashion appropriate for building quantitative models (Meyer and Booker, 1990; Ayyub, 2001).

Optimization.—Once predictions are made about the impact of each decision alternative on each management objective, a wide variety of formal techniques can be used to search among the decision alternatives to identify the optimal decision alternative. Given the complexity and multi-objective nature of the OCS energy exploration decision, it is likely that Multi-Criteria Decision Analysis (MCDA; Keeney and Raiffa, 1976) will be the source of appropriate optimization techniques. In multi-objective decisions, optimization consists of making tradeoffs among multiple objectives. That is, certain alternatives will perform best on some objectives, while different alternatives will perform best on other objectives. The task, then, is to consider these tradeoffs.

A variety of methods are available for tradeoff analysis in MCDA, but frequently the techniques involve developing, in concert with the decision maker or delegates, weights on objectives and then normalizing and summing the predicted outcomes across alternatives to develop "scores" for each alternative, where the alternative with the highest score is identified as the preferred alternative. A necessary final step, then, is sensitivity analysis to evaluate the impact of any uncertainty on the model predictions or the objective weights to inform the decision maker if the decision is highly sensitive to these elements. Sensitivity analyses may suggest places for improvement in the decision framework before final recommendations are developed.

Capacity for Structured Decision Making and Requirements of the Process

Capacity for supporting decision-analytic processes exists both within USGS and in academic and non-profit settings around the United States. Recommendations for conducting decision analysis include:

1. Designate a team coordinator who can act as the decision maker's representative in the decision-analytic process. The team coordinator should have an accurate understanding of the decision maker's objectives (which will integrate the objectives of stakeholders as described above).

2. The team coordinator should work directly with the decision analyst(s) to form a team consisting of experts with relevant knowledge on the different components of the decision, as well as relevant legal and administrative matters.

3. The decision analyst(s) should work with team members in a workshop setting to develop an initial sketch of the elements of the decision (this is known as rapid prototyping the decision framework).

4. Individual team members can then work individually to further develop different components of the decision framework, for example, complete development of relevant predictive models. This individual work should be done in close coordination and with regular input from other members of the team.

5. A final workshop may be held during which the final tradeoffs analysis can be conducted. This, paired with appropriate sensitivity analyses, can be used to complete the report on the decision-analytic process.

Summary Recommendations: Formal decision-analytic methods are useful for supporting decision making in challenging settings with multiple objectives, complex sets of available decision alternatives, and substantial uncertainty and risk. Using the collective knowledge of the USGS OCS team, we developed a Structured Decision Making framework as an example of what could be developed to inform decisions about energy exploration and development in the Arctic OCS. Although development of such a framework would require input of the decision maker or delegates in order to accurately represent management objectives and tradeoffs, we present this example to illustrate the process as well as the potential utility of SDM in this setting, wherein adoption of SDM could facilitate a more robust, transparent, and deliberative decision. We encourage careful consideration of SDM as a useful process in the Arctic Outer Continental Shelf energy exploration decision setting.

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Appendix D. The *Exxon Valdez* Oil Spill Experience: Lessons Learned from a Cold-Water Spill in Sub-Arctic Waters

By Dede Bohn

Background

The March 24, 1989 *Exxon Valdez* Oil Spill (EVOS) was not related to oil and gas development activities, but was the result of the grounding of the tanker *Exxon Valdez* on Bligh Reef in Prince William Sound, Alaska, while outside of normal traffic shipping lanes to avoid icebergs. This accident was the largest oil spill in U.S. waters until the *Deepwater Horizon* spill of 2010. The lessons learned from the spill are included here for the purposes of highlighting Alaska-based experience ranging from spill response through Natural Resource Damage Assessment components that can help inform the U.S. Geological Survey (USGS) Arctic Outer Continental Shelf (OCS) Team assignment.

Most of the oil from the grounding of the *Exxon Valdez* was spilled in the first 6 hours as approximately 10.9 million of the 53 million gallons of North Slope crude oil aboard leaked into the water. Within 2 months, the spread of this oil had impacted more than 1,300 discontinuous miles of the 9,000-mi long coastline in the Prince William Sound and the Gulf of Alaska region (fig. D–1). Less than 1 of the 1,300 mi of oiled beaches was accessible by road (Hunt, 2009). Exxon was not prepared for a spill of this magnitude, nor was its pipeline service company and responder Alyeska, nor the Federal or State governments (Skinner and Reilly, 1989). Efforts were made to remove oil from the water, and included booms to collect oil, test areas of burning, surface dispersants to break up the oil into smaller concentrations, and mechanical skimming to remove oil on the surface. Once the oil had reached shorelines, chemical cleaners, hot water and high pressure, and manual removal by shovels, human hands and absorbent materials were used (Alaska Department of Environmental Conservation, 1993). For the past 20 years, the $900 million in civil settlement funds paid by Exxon have supported restoration, monitoring and research activities in the spill-impacted area (*Exxon Valdez* Oil Spill Trustee Council, 2011b).

The OCS Arctic evaluation and planning effort for oil development can benefit from the EVOS experience through two aspects: (1) improvements in oil-spill prevention and response made as a result of the EVOS, which have enhanced our protection capabilities; and (2) lessons learned from the EVOS, which can inform better preparedness and protection.

Improvements in Spill Prevention and Response Triggered by the EVOS Have Enhanced Our Preparedness

Significant progress has been made in oil-spill prevention and response as a direct consequence of lessons learned from the EVOS, applicable to both its spill area as well as spills elsewhere. Some of these improvements better prepare the OCS Arctic planning effort, and are listed below. The Federal Oil Pollution Act of 1990 (OPA 90), passed by Congress in response to the EVOS, established a procedure for assessing natural resource damages and establishing liability, and designates specific Federal, State and Tribal Government officials to act as trustees on behalf of the public to recover damages from the responsible parties to restore injured, destroyed, or lost natural resources. The OPA 90 also added "oil" to the other hazardous substances covered by the Comprehensive Environmental Response, Compensation, and Liability Act of 1980. In the EVOS area itself, specific advances include:

- Alyeska Pipeline Service Company (established in 1970 to oversee the Trans Alaska Pipeline System, and Exxon's first responder to the EVOS), now spends more than $60 million annually under the Ship Escort/Response Vessel System (SERVS) created in 1989, to plan, prepare, and enhance oil-spill prevention and response measures in Prince William Sound.
    - Alyeska oversees oil spill contingency plans such as those required by the State of Alaska for all tankers traveling in Prince William Sound, which must include scenarios for open-water, nearshore, and shoreline responses and support operations.

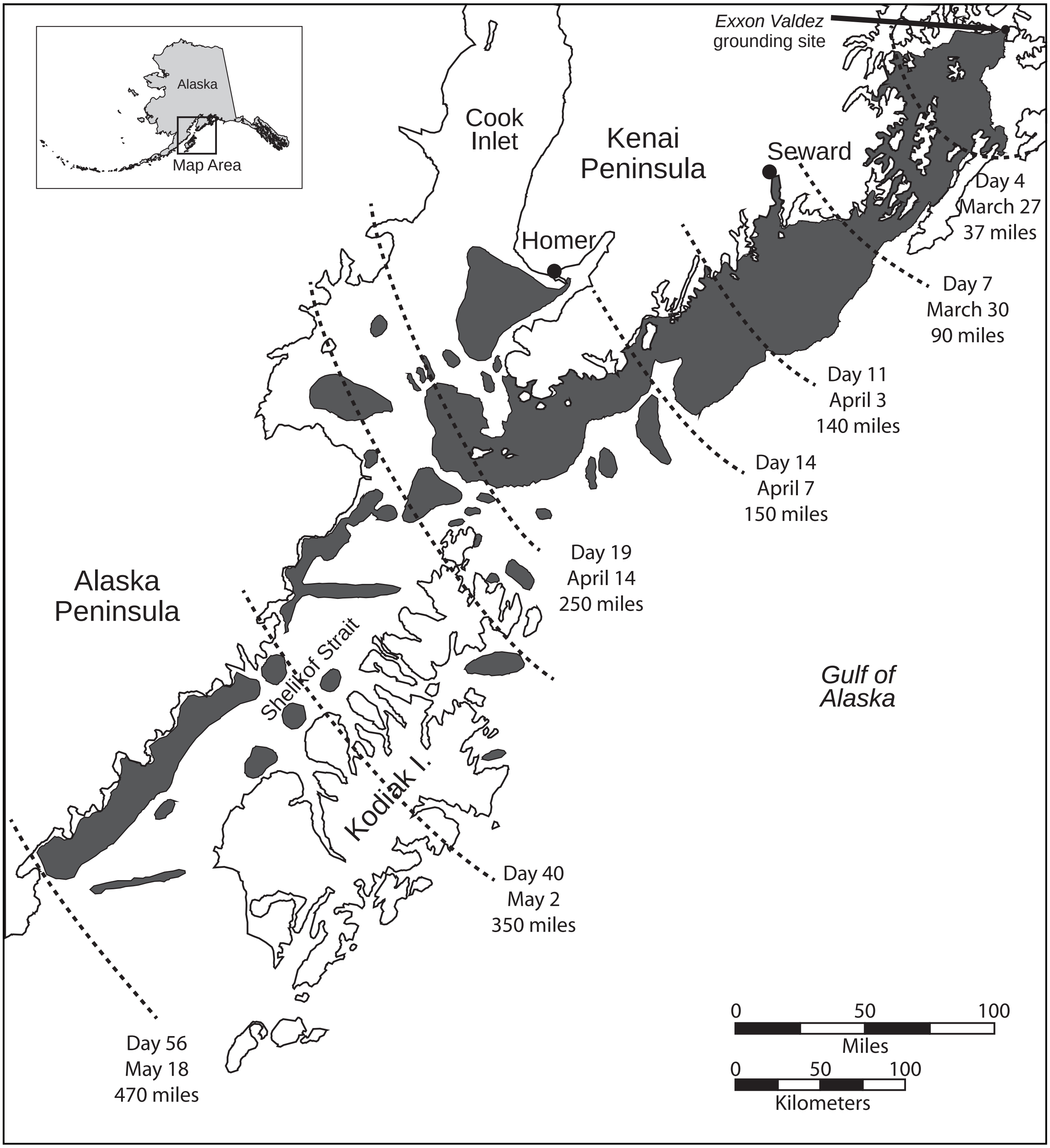

Figure D–1. Within 8 weeks after the spill, wind and currents had distributed the oil from the site of the accident at Bligh Reef in Prince William Sound into the Gulf of Alaska areas of Cook Inlet, Kodiak Island, and the Alaska Peninsula, a maximum distance of 470 miles. Source: 1993 State On-Scene Coordinator's Report (Alaska Department of Environmental Conservation, 1993).

- Under Aleyska's SERVS program:
  - The design of skimming systems to separate and remove oil from the surface of water has been improved and is now 10 times greater than it was in 1989.
  - Seven barges, capable of holding 818,000 barrels of oil, have been made available in Prince William Sound. At the time of the spill, even if oil could have been collected, there was no holding facility.
  - Forty miles of containment boom is available in Prince William Sound, seven times as much as in 1989.
  - Dispersants are stockpiled for use and application systems via helicopters, airplanes, and boats have been designated.
  - Contingency planning for spills in Prince William Sound, held annually, must include a scenario for a spill of at least 12.6 million gallons.
- The U.S. Coast Guard, via satellite, has expanded the area where it monitors for icebergs and other potential hazards in the paths of tankers transporting oil across Prince William Sound.
- Two, rather than one, escort vessels now accompany and, if needed, assist each tanker while it is in the Sound, as directed by an executive order from the Alaska Governor soon after the EVOS.
- At the State level, a dozen new laws for oil-spill prevention, response, and oversight were passed by the Alaska Legislature between April 1989 and May 1990, including: (1) enlarging the State's emergency oil and hazardous substance response fund to 50 times its previous size; (2) revisions to the oil-spill prevention, response, contingency plan regulations; and (3) increased liabilities and penalties for polluters.
- Congress enacted legislation requiring double hulls on all oil tankers by 2015, including those traveling in Prince William Sound. A U.S. Coast Guard study estimated that, had the *Exxon Valdez* been double-hulled at the time of the spill, the amount of oil spilled would have been reduced by more than one-half (*Exxon Valdez* Oil Spill Trustee Council, 2011b).
- The OPA 90 established two oversight and monitoring programs, one in Prince William Sound, and one in Cook Inlet, to foster partnership of industry, government, and local communities in overseeing the environmental compliance for crude oil terminals (Cook Inlet Regional Citizens Advisory Council, 2011; Prince William Sound Regional Citizens' Advisory Council, 2011).
- The Oil Spill Recovery Institute, established by Congress in the OPA 90 after the spill, is charged with identifying and developing the best available techniques, equipment and materials for responding to oil spills in the Arctic marine environment and to complement Federal and State damage assessment efforts. The Institute is actively conducting research and educational and demonstration projects to carry out its mission, and is mandated through September 2012 (Prince William Sound Science Center Oil Spill Recovery Institute, 2011).

Planning for Preparedness in the Arctic OCS Region: Lessons Learned from the EVOS

Below we list in *italics* some of the lessons learned from the EVOS, which have bearing on the potential strengths and weaknesses of the scientific and technical understanding for Arctic OCS activities. Following each lesson is an explanation of the EVOS activities that comprised it.

Oil-Spill Response

Move quickly and be prepared to contain the oil to keep the situation from worsening.

The extent of injuries to natural resources and services resulting from a spill depends on the circumstances of the incident and the prevailing environmental conditions. Although the weather was calm for the first 3 days after the EVOS, Alyeska Pipeline Company, the designated first responder under the Prince William Sound contingency plan, had few pieces of equipment available and ready for use. In addition to Alyeska's contingency plan, National, regional, and local plans mandated by Federal regulation also had been developed, but the plans were not coordinated, had not established a response command hierarchy for responding to a spill, and lacked specific measures to address such problems as how to address spills in remote areas (Skinner and Reilly, 1989).

- Lightering, the process of unloading the remaining oil from the damaged tanker, took 11 days until the seepage of oil could be stopped. Underwater divers had located holes in 11 of the ship's holding tanks. (Skinner and Reilly, 1989).
- Only two skimmers and little or no containment boom were deployed initially (Skinner and Reilly, 1989).
- A small initial test burn successfully consumed 12,000 to 15,000 gal, but further tests were thwarted due to stormy weather (Skinner and Reilly, 1989).

- There were not enough dispersants available, nor enough vessels and equipment ready to deploy the dispersants. An initial trial application on the first day of the spill failed because of a lack of mixing energy (wind) and a later trial was inconclusive (Skinner and Reilly, 1989).
- A severe winter storm with wind gusts up to 73 mph arrived the evening of March 26 quickly dispersing the oil into patches, which spread to beaches up to 40 mi south of the site of the accident, at the same time temporarily grounding the response vessels.
- Eventually the oil reached as far as 470 mi away, to Chignik, on the Alaska Peninsula. Because the escaped oil was so widespread, it was necessary to continue cleanup efforts for four summers. Some oil lingers today, and cleanup efforts for it remain underway.

Spill response should aim to prevent oil from reaching streams, fine sediment beaches, and estuaries.

- Oil persisted in the sediments of streams, mussel beds, and estuaries, contaminating natal and nursery fish habitats for several years (Moles, 2001).

Damage and Injury Assessment

Fate of the oil, and thus the potential and nature of subsequent environmental effects, depends on a complex interaction of variables at the time of the spill, including chemistry, weather, shoreline characteristics, currents, temperature, and season.

- Estimates on the fate of the spilled oil are (Wolfe and others, 1994):
    - 20 percent evaporated,
    - 50 percent biodegraded either where it was deposited or in the water column,
    - 14 percent was recovered or disposed during the trial burning and dispersant treatments,
    - Less than 1 percent remained in the water column,
    - 2 percent remained on intertidal shorelines, and
    - About 13 percent remained in subtidal sediments, mostly as highly weathered residues.
- Within days, a winter storm had widely dispersed the oil slick both on the surface and subsurface of the seawater; oil droplets in the water column reached depths of at least 75 ft (Short and Harris, 1996); some mousse formed as the oil churned and mixed with water, and some tar balls formed as a result of evaporation (Payne and others, 1996).
- Wind, tide, and currents continued to redistribute the oil for at least 2 months, as shown in figure D–1.
- Spring tides were nearly 18 ft, stranding some oil high on shorelines, giving rise to a "bathtub ring" which was protected from wave action, resulting in no further dispersal (Spies, 2007).
- The total number of animals killed by the spill is unknown. The carcasses of more than 35,000 birds and 1,000 sea otters were found after the spill, but since most carcasses sink, this is a minimum estimate of the actual loss. The EVOS Trustee Council estimates are: 250,000 seabirds, 2,800 sea otters, 300 harbor seals, 250 bald eagles, up to 22 killer whales, and billions of salmon and herring eggs (*Exxon Valdez* Oil Spill Trustee Council, 2011c).
- Biologically, the end of March is particularly stressful for organisms because they have nearly depleted their stored energy and are beginning migration and reproduction cycles and the added impact of being oiled or having oiled prey takes a big toll. The populations of plankton and herring, which form the base of the food chain supporting much of the wildlife, were hard hit because the spring plankton bloom had just begun, and Pacific herring were entering the nearshore habitat of Prince William Sound in order to spawn. All age classes of herring and a significant portion of spawning habitats were contaminated by oil, and subsequently, lesions and elevated hydrocarbon levels were documented in some adult herring (Rice, 2010).

Emphasize preplanning: develop and maintain a regularly updated scientific sampling or biological response plan.

- Develop assessment approaches that do not require extensive baseline data, such as ecosystem models that identify pathways and processes at risk to oil injury; increase the accuracy of these models by running the models with parameters gleaned from pre-spill biological samples so that a baseline condition can be better established, and perturbations tested pre-spill. Monitor populations that can serve as surrogates for others, such as monitoring harlequin ducks as a surrogate for benthic-feeding birds (See, 2001).
- Develop a multi-species integrated approach to test mechanisms limiting recovery; an example in the nearshore environment included a study focused on the invertebrate-feeding sea otter and harlequin duck combined with the fish-feeding river otter and pigeon guillemot seabird (Peterson and Holland-Bartels, 2002).
- Pre-plan coordination and designate trained staff; maintain a scientific sampling or biologic response plan. Otherwise, collections can be haphazard, and data and specimens can be lost and unreported, inaccurate, and incomplete. Plan for a central data clearinghouse (See, 2001).

Obtain a geochemical signature of the spilled oil; not all of the oil encountered on the beaches of the spill area was sourced from the Exxon Valdez accident.

- Some of the oil residues found on some of the Prince William Sound shorelines were chemically distinct from the spilled oil (Kvenvolden, 1993).
- Flattened tar balls found throughout the northern and western parts of the Sound had carbon-isotopic and biomarker signatures of oil products used in Alaska before 1970, and are thought to have been created when storage facilities ruptured during the 1964 Alaska earthquake (Kvenvolden, 1995).

Cleanup

Cleanup was slow to get started, but eventually involved more than 11,000 workers. The combination of the presence of such a large workforce and its supporting infrastructure on sensitive coastal areas, coupled with effects from cleanup approaches, resulted in confounded impacts to the environment.

Detrimental effects of shoreline cleanup methods are complex and sometimes oversimplified.

- High-pressure, hot-water washing of the Prince William Sound shorelines effectively removed stranded oil, but damaged flora and fauna directly and indirectly, and received much public criticism, which caused it to be discontinued. Studies from the EVOS were among the first to document these impacts (Mearns, 1996).
- Response methodologies continue to include the high-pressure, hot-water washing techniques, but the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration now gives greater weight to evaluating the complexities and competing interests and the environmental tradeoffs before these methodologies are used (National Oceanic and Atmospheric Administration Office of Response and Restoration, 2011).

Restoration

A number of factors affected the ability of agencies to assess damage, define restoration goals, and judge progress towards those goals. Main among these was the lack of pre-spill data for potentially damaged natural resources and (or) the lack of current data. While, for example, significant data were available for seabirds and their prey, such data were collected in the 1970s prior to a decadal oceanic regime shift, which brought in different oceanic temperatures and salinities, resulting in changes to the food web, which triggered restructuring of the biological communities (Anderson and Piatt, 1999). Thus, the use of available pre-spill data such as seabird colony population surveys and demographic information as a pre-spill data set upon which to judge damage or recovery was confounded (Piatt and Anderson, 1996).

The United States Government and the State of Alaska settled their claims against Exxon Shipping Company and Exxon Corporation on October 9, 1991, with a settlement agreement comprised of a criminal plea agreement and fine of $150 million, criminal restitution for injuries to fish, wildlife, and land for $100 million, and a $900 million civil settlement fine. A Memorandum of Agreement between the Federal and State governments established the *Exxon Valdez* Oil Spill Trustee Council to manage the $900 million civil settlement for restoration activities. The Council is comprised of three Federal and three State Trustees.

Define restoration objectives and strategies to achieve the goal of recovering the oil spill area ecosystem.

- Since the EVOS, the OPA 90 Natural Resource Damage Assessment (NRDA) regulations have established that the restoration goal is achieved when the injured natural resources and services have returned to the condition they would have been, had the spill not occurred.
- In the 1994 EVOS Restoration Plan, some recovery objectives specified a return to pre-spill conditions or to stable or increasing population trends, which did not account for stressors other than oil, which became increasingly important as time went by.

Injury assessment of natural resources is complicated by a lack of pre-spill data and compounded by natural variation and will always involve uncertainties.

- In lieu of applicable pre-spill population data, animal carcass counts, a crude and minimal measure, had to be used in order to measure the extent of damages. Actual losses were higher than counted because some carcasses sank or were never discovered. For example, research studies have estimated the actual loss of the seabird murre population at 40 percent of its pre-spill level, or a loss of 250,000 murres, compared with the carcass recovery of 21,000 (Piatt and Ford, 1996). Such extrapolations are highly sensitive to the “observed versus not observed” ratio applied to calculate total loss, which in turn is affected by weather conditions that hamper the ability to make observations.
- Sources of uncertainty in assessing both the short- and long-term damage following a spill include variability in the available population estimates, lack of pre-spill data, ongoing changes to the ecosystem as a result of changing climate and other natural factors, emergence of new effects (for example, new contamination arising from contact with lingering oil), difficulty establishing causation (an unequivocal cause-and-

effect relationship between the biological resource and the oil), and comparing studies of differing spatial and temporal scales (Integral Consulting, Inc., 2006).

- Additional measures and approaches to measure damage in lieu of contemporary pre-spill baselines proved essential to developing an understanding of system recovery. Recovery status has been determined by evaluating the initial magnitude of oil impacts to a population through carcass counts, comparing the population demographics between oiled and unoiled areas, comparing the health of biological community members from oiled and unoiled areas, measuring to determine continued exposure to lingering oil through biomarker or tissue concentrations, establishing the persistence of sublethal or chronic injuries, evaluating the intrinsic ability of the population to recover, and accounting for other stressors from natural or anthropogenic sources (*Exxon Valdex* Oil Spill Trustee Council, 2006).

Track the status of recovery by updating the status of injury through monitoring.

- A list of natural resource and human service injuries caused by the EVOS helped guide the Restoration Plan adopted by the EVOS Trustee Council in 1994. The listings include the recovery status of individual species as well as sediments, subtidal and intertidal communities, commercial fishing, subsistence, recreation and tourism, archeological resources, and designated wilderness areas. The list has been instrumental to the EVOS Trustee Council in prioritizing the expenditure of public restoration funds received from the civil settlement with Exxon, ensuring that money was expended on resources needing attention. As restoration has proceeded and recovery statuses have changed, the list has been updated and re-published in 1996, 1999, 2002, 2006, and 2010. The list serves to track and document the status of recovery of the oil spill area; as of 2010, 2 resources have not recovered (Pacific herring, pigeon guillemots), 10 resources are recovering (Barrow's Goldeneyes, black oystercatchers, clams, designated wilderness areas, harlequin ducks, intertidal communities, killer whales, mussels, sea otters, sediments), 10 resources have recovered (archeological resources, bald eagles, common loons, common murres, cormorants, Dolly Varden fish, harbor seals, pink salmon, river otters, sockeye salmon), 3 resources are very likely recovered (cutthroat trout, rockfish, subtidal communities), and the recovery status of 2 resources (Kittlitz' and Marbled Murrelets) is unknown (*Exxon Valdez* Oil Spill Trustee Council, 1994, 2006, 2010).

Use an ecosystem perspective; examine food chains, and use ecosystem models to pinpoint pathways and processes at risk to oil injury. Do not ignore lower trophic levels.

- Multi-disciplinary, multi-species approaches increased the power to detect and evaluate recovery: the Sound Ecosystem Assessment project evaluated factors affecting productivity of Pacific herring and pink salmon; the Nearshore Vertebrate Predator program addressed factors affecting the recovery of four indicator species; and the Alaska Predator Ecosystem Experiment evaluated the productivity and recovery of seabirds based on the availability of forage fish (*Exxon Valdez* Oil Spill Trustee Council, 2011b). Recovery also will involve complex interactions, such as those associated with the dynamics of both microbial communities and food webs, which will cascade changes up to the largest predator.

Oil can remain toxic in the environment a surprisingly long time; oil degradation rates depend upon localized conditions (Michel and Esler, 2010, and citations therein).

- Some oil has persisted more than 2 decades in unexpected amounts and in toxic relatively unweathered forms, buried in the subsurface intertidal area of approximately 50 discontinuous beach sites, which put together, total a shoreline length of about 1.5 mi.
- The beaches with persistent oil have an upper, highly permeable layer and a lower layer of low permeability where the oil has remained trapped, physically protected from disturbance, oxygenation, and photolysis.
- The oiling history (high, medium, low) of the beaches, surveyed after the spill and again in 2001 and 2008, is one important indicator of predicting where oil persists.
- Biodegradation of the oil has been limited by a low concentration of dissolved oxygen as well as a nutrient concentration too small to sustain oil-consuming microorganisms. Bioremediation projects are being undertaken in 2011, 22 years after the spill.

Some of the lingering oil has been bioavailable to wildlife and has induced chronic exposure in nearshore species (Michel and Esler, 2010, and citations therein).

- Organisms that use the intertidal zone were severely impacted by initial oiling and cleanup and continued to show adverse impacts from continued exposure such as reduced survival rates and diminished populations. Studies have addressed and documented exposure to lingering oil in birds (harlequin ducks, Barrow's Goldeneyes, black oystercatchers, pigeon guillemots), sea otters, and fish (masked greenlings and crescent gunnels).
- Some harlequin ducks and sea otters in the nearshore environment have continued to exhibit signs of exposure to oil through 2006 and 2009, as measured through elevated oil biomarkers in blood and tissues or in gene expression. Studies are ongoing and awaiting the results of laboratory analyses of the most recent harlequin duck samples collected in March 2011 to see if oil exposure continues.

Long-term chronic exposure is now recognized as a major component of injury and may equal or exceed acute effects (Peterson and others, 2003).

- Effects of the EVOS have revised the paradigm for assessing ecological risks of oil in the ocean. Previously, it was assumed that acute mortality is the main impact to a population, but EVOS research has shown that chronic, delayed and indirect long-term risks and impact play a much larger role than previously envisioned. Risk assessment models that project biological injury need to be updated from treating species independently to instead provide for interacting variables.
- A delay in population reduction was caused, for example, by ingestion of oiled prey, by lower survival rates for harlequin ducks in the winters following the spill due to cumulative stress from encountering the lingering oil, and by damage to fish over time through oil exposure which increased embryo mortality and deformity and resulted in poor predator avoidance and low growth rates.
- Recovery was postponed as cascades of indirect effects, such as a food shortage of forage fishes as well as a reduction of high-quality forage fish prey reduced seabird populations of murres, puffins, and pigeon guillemots. Animal communities may experience delayed recovery depending on complex interactions, and communities may not soon return to their original configurations. For example, a loss of experienced breeders in seabird colonies disrupted the phenology of breeding for several years, imperiling late-fledging young, such as murres. On rocky shorelines, indirect interactions resulting from oiling and loss of the ubiquitous rockweed plant cover, as well as grazing and predatory gastropods, are thought to have delayed the recovery process for a decade or more, while opportunistic barnacles colonized the open rock spaces and disrupted the food chain.
- Injury to seabirds, mammals, fish, and invertebrates continues long term through chronic exposure from ingesting contaminated prey and through foraging in oiled sediments, and through disruption of reproduction. Long-term exposure of fish embryos to weathered oil has had population consequences through indirect effects on growth, deformities, and behavior (Rice, 2010, and citations therein).

Oil effects can be subtle, indirect, and long term.

- Long-term monitoring and research have been essential in identifying the full impacts of the spill, as evidenced particularly for sea otters and harlequin ducks. The EVOS Trustee Council has sponsored a multitude of projects to monitor the recovery of injured species, and final reports can be found on their website (*Exxon Valdez* Oil Spill Trustee Council, 2011b) as well as throughout the published literature. Long-term monitoring of the recovery of the nearshore environment, where patches of toxic oil still linger, is one such project which is ongoing, and which is being considered for 5 to 20 additional years of funding by the EVOS Trustee Council at its August 2011 meeting.
- Some injuries cannot be determined until years later, such as the significant long-term biological effects of lingering oil; studies are currently in progress for harlequin ducks and sea otters.
- Delays in the recovery of bird and mammal predators of fish and invertebrates resulted from chronic and indirect effects, such as the loss of their habitat due to oiling or cleanup activities and the subsequent spread of opportunistic species, such as algae or small intertidal fishes, which inhibited the return of the original fish and invertebrate food sources (Peterson, 2000).

- Sublethal exposures to oil caused mortalities due to compromised health, growth, or reproduction; for example, long-term exposure of the black oystercatchers that foraged on heavily oiled shores, documented up to 3 years post-spill, showed reduced breeding and smaller eggs than those that bred in unoiled areas; higher chick mortality occurred in areas where their diet consumption had included oiled mussels; and the oystercatcher parents gathering prey on oiled shores fed chicks more to achieve less growth than those on unoiled shores, at a higher energetic cost (Peterson and others, 2003).
- The acute, initial loss of killer whales following the spill has had a long-term impact on the recovery of the ecosystem because the species is long-lived with low reproductive rates, and, as the predator at the top of the food chain, significantly affects the structure of the ecosystem (Rice, 2010).
- Pacific herring, a primary forage fish for many seabird and marine mammals, still have not recovered. Despite numerous studies, the causes of this phenomenon are not well understood, but appear to include disease, predation, and poor recruitment (the survivability of juveniles) (*Exxon Valdez* Oil Spill Trustee Council, 2010).

Not much real (that is, direct) restoration can be done; so instead the environment must be restored.

- Lost services, such as commercial and sport fishing, recreation and tourism, and subsistence are assumed to be restored when the species upon which they were based are restored (*Exxon Valdez* Oil Spill Trustee Council, 1994).
- To date, because direct restoration opportunities are few, the $900 million civil settlement funds received from Exxon and managed by the EVOS Trustee Council have been allocated 24 percent to research, monitoring, and direct and indirect restoration; 37 percent to habitat protection and acquisition; 22 percent reimbursements for assessments and response; and 17 percent in an investment trust fund to increase the amount of funds available for future studies (*Exxon Valdez* Oil Spill Trustee Council, 2011b).
- Natural recovery was selected under the 1994 EVOS Restoration Plan as the preferred alternative for restoration, and research and monitoring were directed at tracking the status of recovery (*Exxon Valdez* Oil Spill Trustee Council, 1994).
    - Because natural recovery over the past 20 years has failed to remediate the 50 beach segments identified recently with the most significant persistent oil, bioremediation projects using oxygenation and nutrient enrichment techniques are being tested by the EVOS Trustee Council in 2011 as a way to clean up the remaining oil (*Exxon Valdez* Oil Spill Trustee Council, 2011a).
- Habitat acquisition to promote natural recovery of spill-injured resources, especially on lands under imminent threat of development, has been a significant and well-received component of the EVOS restoration program, and could be an effective tool elsewhere. As of 2006, the Council has protected more than 630,000 acres of habitat, including more than 1,400 mi of coastline and more than 300 streams valuable for salmon spawning and rearing (*Exxon Valdez* Oil Spill Trustee Council, 2010).

A Reopener clause, part of the 1991 legal settlement between Exxon and the State and Federal governments, provided for unanticipated injury.

- Some of the long-term injury from the spill was not identifiable initially, but has been established since, under research funded by the EVOS Trustee Council. Under the oil spill Reopener clause in the 1991 litigation settlement with Exxon, on August 31, 2006, the Federal and State governments submitted a demand letter to Exxon to pay up to $100 million for additional restoration work for the recovery of a population, habitat or species suffering a substantial loss or decline from an injury that could not have been known or reasonably anticipated on the date of the settlement. The plan focuses on the restoration of sites where lingering toxic oil persists (U.S. Department of Justice, 2006). Studies assessing the linkage of injury from the lingering oil to damage at the population level, particularly in sea otters and sea ducks, which inhabit the nearshore environment where the lingering oil occurs, are ongoing, and their outcome will help inform the Reopener claim. Trustee Council-sponsored research is underway to continue to identify lingering oil site locations, factors limiting the degradation of the oil, and to test pilot projects to remediate the pockets of lingering oil. Negotiations between the governments and Exxon to address this claim remain underway since September 2006.

Prepare for conflicting studies.

- Exxon Corporation has continued to fund its own damage assessment studies, and the resulting conclusions have consistently contrasted with those funded by the EVOS Trustee Council. The studies have differed in concept, statistical rigor, and choice of study sites and those differences have led to differing conclusions (Spies, 2007; Rice, 2010).

- Sampling design begets conclusions: Despite having common goals, four studies on the impact of the spill on intertidal biota involved different sampling efforts, analytical methodologies, and the choice of biological response variables that led to differing conclusions. Two of the studies were funded by Exxon Corporation, one by the EVOS Trustee Council, and one by the NOAA Hazmat program (Peterson and others, 2001).

Summary Points for the OCS Oil Planning Team Effort

Prevention is the principal defense against oil spills. Preparedness is the next best thing, with the caveat that no two oil spills are the same. Full recovery from the *Exxon Valdez* oil spill has not yet occurred, 22 years later. Keeping oil from reaching shorelines, where it is difficult to treat, may remain in a toxic form in the subsurface for up to 22 years—as in the EVOS—and takes an enormous toll on the food chain, must be a top priority in spill response. Not all species are equally affected, and not all species recover at the same rate. Initial wildlife mortalities from the EVOS were extreme, and likely understated due to lack of pre-spill population data and the difficulty in recovering carcasses. Studies of the long-term environmental and health effects on wildlife of acute and chronic exposure to oil have yielded surprising findings emphasizing the magnitude and complexity of the long-term impact. The effects of chronic oil exposure, delayed impacts, and sub-lethal impacts on growth, development, and reproduction have caused decreases at the population level; this finding is significant. An ecosystem-approach, allowing for the effects of indirect and cascading reactions, is imperative in evaluating restoration.

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Appendix E. Arctic Marine Synthesis—Data Sources and Data Quality

The "Arctic Marine Synthesis: Atlas of the Chukchi and Beaufort Seas" by Audubon Alaska and Oceana (Smith, M.A., 2010, Arctic Marine Synthesis—Atlas of the Chukchi and Beaufort Seas: Audubon Alaska and Oceana, Anchorage) represents an emergent approach about data quality and sufficiency. Before the creation of this effort few others had assembled broad-scale information for this area. This broad synthesis utilizes spatial data from more than 100 sources plus literature and reports from another 400 sources, resulting in 44 thematic maps that cover six categories for the Chukchi and Beaufort Seas: Physical Oceanography, Water Column and Benthic Life, Fish, Birds, Mammals, and People. A listing of maps, data sources, and data quality ratings compiled from this synthesis is shown in table E–1.

Table E–1. Listing of maps, data sources, and data quality ratings as compiled from "The Arctic Marine Synthesis: Atlas of the Chukchi and Beaufort Seas" by Audubon Alaska in partnership with Oceana (Smith, 2010).

[**Good:** provides a complete geographic picture of the resource or species; data are consistent and of decent quality for mapping at the scale used (1:5,000,000); this rating does not indicate that fine-scale, project level data are available; **Fair:** provides a partial geographic picture of the resource or species; data are variable, some portions of the map are represented by reliable, high-quality data and data for other portions of the map are outdated, opinion-based, or missing data altogether; some key features, such as concentrations areas, may be missing. **Poor**: provides an incomplete geographic picture of the resource or species; information is missing, outdated, or deficient, but it is the best known data available (Smith, M.A., 2010, Arctic Marine Synthesis—Atlas of the Chukchi and Beaufort Seas: Audubon Alaska and Oceana, Anchorage)]

Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Physical Oceanography		
Project Area	Good	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Alaska State Geospatial Data Clearinghouse. 2008. Base data. GIS shapefiles. <http://www.asgdc.state.ak.us/>. Accessed June 2008. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Johnson, G.W., A.G. Gaylord, J.J. Brady, M. Dover, D. Garcia-Lavigne, W.F. Manley, R. Score, and C.E. Tweedie. 2009. Arctic Research Mapping Application (ARMAP). CH2M HILL Polar Services, Englewood, Colorado. <http://www.armap.org>. Accessed January 2010.
Bathymetry	Good	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Alaska State Geospatial Data Clearinghouse. 2008. Base data. GIS shapefiles. <http://www.asgdc.state.ak.us/>. Accessed June 2008. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Chukchi Sea shoals. GIS feature class (based on AOOS 2009).
Ecoregions	Good	Piatt, J.F., and A.M. Springer. 2007. Marine ecoregions of Alaska. Pages 522–526 in Long term ecological change in the Northern Gulf of Alaska. R. Spies, editor. Elsevier, Amsterdam. <http:/www.absc.usgs.gov/research/NPPSD/marine_ecoregions.htm>. Accessed July 2008. Nowacki, G., P. Spencer, T. Brock, M. Fleming, and T. Jorgenson. 2001. Ecoregions of Alaska. GIS shapefile. USGS, Reston, Virginia. World Wildlife Fund. 2009. Terrestrial ecoregions. GIS shapefile. <http://www.worldwildlife.org/science/ecoregions/item1267.html>. Accessed November 2009.
Ocean Circulation	Fair	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Ocean circulation. GIS feature class (based on Weingartner et al. 2005; Weingartner 2006; MMS 2007; University of Alaska Fairbanks, Institute of Marine Science 2009). MMS (Minerals Management Service). 2007. Chukchi Sea Planning Area, Oil and Gas Lease Sale 193 and seismic surveying activities in the Chukchi Sea final environmental impact statement. U.S. Department of the Interior, MMS, Alaska OCS Region, Anchorage, Alaska. University of Alaska Fairbanks, Institute of Marine Science. 2009. Chukchi Sea circulation. Digital map. <http://www.ims.uaf.edu/chukchi/>. Accessed March 2009. Weingartner, T. 2006. Circulation, thermohaline structure, and cross-shelf transport in the Alaskan Beaufort Sea. Report OCS Study MMS 2006-031. MMS. Weingartner, T., K. Aagaard, R. Woodgate, S. Danielson, Y. Sasaki, and D. Cavalieri. 2005. Circulation on the north central Chukchi Sea shelf. Deep Sea Research Part II: Topical Studies in Oceanography 52:3150-3174.

Table E–1. Listing of maps, data sources, and data quality ratings as compiled from “The Arctic Marine Synthesis: Atlas of the Chukchi and Beaufort Seas” by Audubon Alaska in partnership with Oceana (Smith, 2010)—Continued

[**Good:** provides a complete geographic picture of the resource or species; data are consistent and of decent quality for mapping at the scale used (1:5,000,000); this rating does not indicate that fine-scale, project level data are available; **Fair:** provides a partial geographic picture of the resource or species; data are variable, some portions of the map are represented by reliable, high-quality data and data for other portions of the map are outdated, opinion-based, or missing data altogether; some key features, such as concentrations areas, may be missing. **Poor**: provides an incomplete geographic picture of the resource or species; information is missing, outdated, or deficient, but it is the best known data available (Smith, M.A., 2010, Arctic Marine Synthesis—Atlas of the Chukchi and Beaufort Seas: Audubon Alaska and Oceana, Anchorage)]

Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Physical Oceanography—Continued		
Sea Ice Dynamics	Fair	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Chukchi Sea shoals. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Landfast ice (≥3 months per year). GIS feature class (based on National Ice Center 2008). Audubon Alaska. 2009. Monthly sea ice concentration (≥50 percent based on monthly median from 2003–2007). GIS raster dataset (based on National Ice Center 2008). Audubon Alaska. 2009. Recurring leads and polynyas. GIS feature class (based on Stringer and Groves 1991; USFWS 1995; Carmack and MacDonald 2002; Eicken et al. 2005). Carmack, E.C., and R. MacDonald. 2002. Oceanography of the Canadian shelf of the Beaufort Sea: a setting for marine life. Arctic 55:29-45. Eicken, H., L.H. Shapiro, A.G. Gaylord, A. Mahoney, and P.W. Cotter. 2005. Mapping and characterization of recurring spring leads and landfast ice in the Beaufort and Chukchi seas. OCS Study MMS 2005-068. MMS, Anchorage, Alaska. Hearon, G., D. Dickins, K. Ambrosius, and K. Morris. 2009. Mapping sea ice overflood using remote sensing: Smith Bay to Camden Bay. Report prepared by DF Dickins Associates, Coastal Frontiers Corporation, Aerometric, and University of Alaska, The Geophysical Institute, for U.S. Department of Interior, MMS, Alaska OCS Region. National Ice Center. 2008. National Ice Center Arctic sea ice charts and climatologies in gridded format. GIS datasets. F. Fetterer and C. Fowler, editors. National Snow and Ice Data Center, Boulder, Colorado. National Snow and Ice Data Center. 2010. Monthly sea ice extent. GIS shapefile. <ftp://sidadscolorado.edu/DATASETS/NOAA/G02135 shapefiles/>. Accessed January 2010. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. Stringer, W.J., and J.E. Groves. 1991. Location and areal extent of polynyas in the Bering and Chukchi seas. Arctic 44, Supplement 1:164-171. USFWS. 1995. Habitat conservation strategy for polar bears in Alaska. USFWS, Anchorage, Alaska.
Sea Floor Substrate	Poor	Carmack, E.C., and R. MacDonald. 2002. Oceanography of the Canadian shelf of the Beaufort Sea: a setting for marine life. Arctic 55:29-45. Dunton, K.H., E. Reimnitz, and S. Schonberg. 1982. An Arctic kelp community in the Alaskan Beaufort Sea. Arctic 35(4):465-484. Horowitz, W.L. 2002. Evaluation of sub-sea physical environmental data for the Beaufort Sea OCS and incorporation into a geographic information system (GIS) database. OCS Study MMS 2002 017. <http://www.mms.gov/itd>. Accessed June 2009. Mohr, J.L., N.J. Wilimovsky, and E.Y. Dawson. 1957. An Arctic Alaskan kelp bed. Arctic 19:45-54. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington.

Table E–1. Listing of maps, data sources, and data quality ratings as compiled from “The Arctic Marine Synthesis: Atlas of the Chukchi and Beaufort Seas” by Audubon Alaska in partnership with Oceana (Smith, 2010)—Continued

Good: provides a complete geographic picture of the resource or species; data are consistent and of decent quality for mapping at the scale used (1:5,000,000); this rating does not indicate that fine-scale, project level data are available; **Fair:** provides a partial geographic picture of the resource or species; data are variable, some portions of the map are represented by reliable, high-quality data and data for other portions of the map are outdated, opinion-based, or missing data altogether; some key features, such as concentrations areas, may be missing. **Poor**: provides an incomplete geographic picture of the resource or species; information is missing, outdated, or deficient, but it is the best known data available (Smith, M.A., 2010, Arctic Marine Synthesis—Atlas of the Chukchi and Beaufort Seas: Audubon Alaska and Oceana, Anchorage)]

Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Physical Oceanography—Continued		
Sea Surface Temperature	Good	Audubon Alaska. 2009. Average yearly mean sea surface temperature, May–October, 2004–2008 GIS raster dataset (based on Feldman and McClain 2009). Feldman, G.C., and C.R. McClain. 2009. Ocean color web, aqua MODIS, NASA Goddard Space Flight Center. N. Kuring, S. Bailey, and W. April, editors. <http://oceancolor.gsfc.nasa.gov/>. Accessed June 2009.
Observed Climate Change	Good	Halpern, B., S. Walbridge, K. Selkoe, C. Kappel, F. Micheli, C. D’Agrosa, et al. 2008. A global map of human impact on marine ecosystems. Science 319:948-952. National Snow and Ice Data Center. 2010. Monthly sea ice extent. GIS shapefile. <ftp://sidadscolorado.edu/DATASETS/NOAA/G02135 shapefiles/>. Accessed January 2010.
Water Column and Benthic Life		
Chlorophyll-*A*	Good	Audubon Alaska. 2009. Average seasonal mean chlorophyll-a, May–October, 2004–2008. GIS raster dataset (based on Feldman and McClain 2009). Feldman, G.C., and C.R. McClain. 2009. Ocean color web, aqua MODIS, NASA Goddard Space Flight Center. N. Kuring, S. Bailey, and W. April, editors. <http://oceancolor.gsfc.nasa.gov/>. Accessed June 2009.
Net Primary Productivity	Good	Audubon Alaska. 2009. Mean yearly sum of net primary productivity, 2003–2007. GIS raster dataset (based on Behrenfeld and Falkowski 1997; Oregon State University 2009). Behrenfeld, M.J., and P.G. Falkowski. 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceanography 42:1-20. Oregon State University. 2009. Ocean productivity. GIS datasets. <http://www.science.oregonstate.edu/ocean.productivity/index.php>. Accessed April 2009.
Zooplankton	Poor	NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.
Benthic Biomass	Fair	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Benthic biomass. GIS raster dataset (based on Grebmeier et al. 2006; Shelf Basin Interaction 2008). Grebmeier, J.M., L.W. Cooper, H.M. Feder, and B.I. Sirenko. 2006. Ecosystem dynamics of the Pacific-influenced northern Bering and Chukchi seas in the Amerasian Arctic. Progress in Oceanography 71:331-361. Shelf Basin Interaction. 2008. Benthic samples. Microsoft Access database. <http://www.eol.ucar.edu/projects/sbi/all_data.shtml>. Accessed July 2008.

Table E–1. Listing of maps, data sources, and data quality ratings as compiled from "The Arctic Marine Synthesis: Atlas of the Chukchi and Beaufort Seas" by Audubon Alaska in partnership with Oceana (Smith, 2010)—Continued

Good: provides a complete geographic picture of the resource or species; data are consistent and of decent quality for mapping at the scale used (1:5,000,000); this rating does not indicate that fine-scale, project level data are available; **Fair:** provides a partial geographic picture of the resource or species; data are variable, some portions of the map are represented by reliable, high-quality data and data for other portions of the map are outdated, opinion-based, or missing data altogether; some key features, such as concentrations areas, may be missing. **Poor**: provides an incomplete geographic picture of the resource or species; information is missing, outdated, or deficient, but it is the best known data available (Smith, M.A., 2010, Arctic Marine Synthesis—Atlas of the Chukchi and Beaufort Seas: Audubon Alaska and Oceana, Anchorage)]

Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Water Column and Benthic Life—Continued		
Opilio (Tanner or Snow Crab)	Poor	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Opilio crab. GIS feature class (based on NOAA 1988; Paul and Paul 1997; NOAA and MMS 2008). NMFS (National Fisheries Management Service). 2005. Final environmental impact statement for essential fish habitat identification and conservation in Alaska. NOAA National Marine Fisheries Service, Alaska Region, Anchorage. NOAA (National Oceanic and Atmospheric Administration) and MMS. 2008. Cruise report for the 2008 Beaufort Sea Survey, July 27–August 30, 2008. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. Paul, J.M., and A.J. Paul. 1997. Reproductive biology and distribution of the snow crab from the northeastern Chukchi Sea. American Fisheries Society Symposium 19:287-294.
Fish		
Capelin	Poor	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Johnson, S. 2008. Capelin counts from beach seine surveys near Barrow, 2004–2008. Excel spreadsheet. NOAA, Juneau, Alaska. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.
Pacific Herring	Poor	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.
Saffron Cod	Poor	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Saffron cod. GIS feature class (based on NOAA 1988; NOAA and MMS 2008; Wilson 2009) Geological Survey of Canada. In review. Environmental atlas of the Beaufort coastlands. <http:/gsc.nrcan.gc.ca/beaufort/fisheries_e.php>. Accessed January 2010. NOAA (National Oceanic and Atmospheric Administration) and MMS. 2008. Cruise report for the 2008 Beaufort Sea Survey, July 27–August 30, 2008 NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NMFS (National Fisheries Management Service). 2005. Final environmental impact statement for essential fish habitat identification and conservation in Alaska. NOAA National Marine Fisheries Service, Alaska Region, Anchorage. Wilson, Bill, NOAA. 2009. Personal communication with Melanie Smith, Audubon Alaska. 25 June.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Fish—Continued		
Pink Salmon	Poor	ADFG. 2009. Anadramous waters catalog. GIS shapefile. AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.
Chum Salmon	Poor	ADFG. 2009. Anadramous waters catalog. GIS shapefile. AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.
Birds		
Yellow-Billed Loon	Fair	Audubon Alaska. 2009. Yellow-billed Loon. GIS feature class (based on USFWS 1992-2008; Schmutz 2002-09; Drew and Piatt 2003; Fair, 2009; Schmutz 2009). BirdLife International. 2009. Important Bird Areas. GIS feature class Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. Fair, J. 2009. Personal communication with M. Smith/Audubon Alaska. 18 December. Schmutz, J. 2009. Yellow-billed Loon satellite telemetry locations 2002-09. Alaska Science Center, USGS, Anchorage. Schmutz, J./USGS. 2009. Personal communication with M. Smith/Audubon Alaska. June. USFWS. 1992–2005. Density polygons (based on USFWS Eider breeding population survey and USFWS Arctic Coastal Plain aerial breeding pair survey). USFWS. 1992–2006. Eider breeding population survey. USFWS. 1992–2008. Arctic Coastal Plain aerial breeding pair survey. USFWS. 1998–2003. Arctic Coastal Plain molting sea duck survey. USFWS. 1999–2001. Beaufort Sea nearshore and offshore waterbird aerial survey. USFWS. 1999–2007. Common Eider survey. USFWS. 2003–2004. Arctic Coastal Plain Yellow-billed Loon survey. USFWS. 2005–2007. Western Alaska Yellow-billed Loon survey. USFWS. 2007. Yellow-billed Loon (Gavia adamsii) fact sheet. May. USFWS, Alaska Region, Anchorage.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Birds—Continued		
Red-Throated Loon	Fair	Audubon Alaska. 2009. Red-throated Loon. GIS feature class (based on Portenko 1981; Flint et al. 1984; USFWS 1992-2008; Barr et al. 2000; Schmutz 2000-09; Drew and Piatt 2003; Ridgely et al. 2007; Schmutz 2009). Barr, J.F., C. Eberl, and J.W. Mcintyre. 2000. Red-throated Loon (Gavia stellata). In The birds of North America Online. A. Poole, editor. Cornell Lab of Ornithology, Ithaca, New York. <http://bna.birds.cornell.edu/bna/species/513>. Accessed June 2009. Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. Flint, V.E., R.L. Boehme, Y.V. Kostin, and A.A. Kuznetsov. 1984. A field guide to birds of the USSR. NJ: Princeton University Press, Princeton, New Jersey. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington. Portenko, L.A. 1981. Birds of the Chukchi Peninsula and Wrangel Island (translated from Russian). Published for the Smithsonian Institution and the National Science Foundation, Washington, D.C. Amerind, Springfield, Virginia. Ridgely, R.S., T.F. Allnutt, T. Brooks, D.K. McNicol, D.W. Mehlman, B.E. Young, et al. 2007. Digital distribution maps of the birds of the Western Hemisphere, version 3.0. NatureServe, Arlington, Virginia. Schmutz, J. 2009. Red-throated Loon satellite telemetry locations, 2002-09. Alaska Science Center, USGS, Anchorage. Schmutz, J./USGS. 2009. Personal communication with M. Smith/Audubon Alaska. June. USFWS. 1992–2005. Density polygons (based on USFWS Eider breeding population survey and USFWS Arctic Coastal Plain aerial breeding pair survey). USFWS. 1992–2006. Eider breeding population survey. USFWS. 1992–2008. Arctic Coastal Plain aerial breeding pair survey. USFWS. 1998–2003. Arctic Coastal Plain molting sea duck survey. USFWS. 1999–2001. Beaufort Sea nearshore and offshore waterbird aerial survey. USFWS. 1999–2007. Common Eider survey. USFWS. 2003–2004. Arctic Coastal Plain Yellow-billed Loon survey. USFWS. 2005–2007. Western Alaska Yellow-billed Loon survey.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Birds—Continued		
Spectacled Eider	Fair	Audubon Alaska. 2009. Important Bird Areas. GIS feature class. Audubon Alaska. 2009. Spectacled Eider. GIS feature class (based on USFWS 1992-2008; Larned et al. 1995; Larned and Tiplady 1997; Larned 1999; Petersen et al. 1999; Petersen et al. 2000; Drew and Piatt 2003; Petersen 2009). BirdLife International. 2009. Important Bird Areas. GIS feature class. Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. Larned, W.W. 1999. Ledyard Bay survey. August. USFWS, Anchorage, Alaska. Larned, W.W., and T. Tiplady. 1997. Late winter population and distribution of Spectacled Eiders (Somateria fischeri) in the Bering Sea, 1996–97. October. USFWS, Anchorage, Alaska. Larned, W.W., G.R. Balogh, and M.R. Petersen. 1995a. Distribution and abundance of Spectacled Eiders (Somateria fischeri) in Ledyard Bay, Alaska, September 1995. November. USFWS, Anchorage, Alaska. Larned, W.W., G.R. Balogh, and M.R. Petersen. 1995b. Late winter distribution of Spectacled Eiders (Somateria fischeri) in the Bering Sea, 1995. September. USFWS, Anchorage, Alaska. Larned, W.W., J.I. Hodges, and M.R. Petersen. 1995c. Distribution and abundance of Spectacled Eiders (Somateria fischeri) in Mechigmenskiya Bay, Chukotka, Russia, September 1995. November. USFWS, Anchorage, Alaska. Larned, W.W., M.R. Petersen, K. Laing, R. Platte, and J.L. Hodges. 1995d. Progress report: location and characteristics or Spectacled Eider molting and wintering areas, 1993-94. February. USFWS, Anchorage, Alaska. Petersen, M./USGS. 2009. Personal communication with M. Smith/Audubon Alaska. July. Petersen, M.R., J.B Grand, and C.P. Dau. 2000. Spectacled Eider (Somateria fischeri). In The birds of North America online. A. Poole, editor. Cornell Lab of Ornithology, Ithaca, New York. <http:/bna.birds.cornell.edu/bna/species/547/articles/introduction>. Accessed June 2009. Petersen, M.R., W.W. Larned, and D.C. Douglas. 1999. At-sea distribution of spectacled eiders: A 120-year-old mystery resolved. Auk 116:1009-1020. USFWS. 1992–2005. Density polygons (based on USFWS Eider breeding population survey and USFWS Arctic Coastal Plain aerial breeding pair survey) USFWS. 1992–2006. Eider breeding population survey. USFWS. 1992–2008. Arctic Coastal Plain aerial breeding pair survey. USFWS. 1999–2007. Common Eider survey. USFWS. 2008. Critical Habitat portal: Spectacled Eider Critical Habitat. GIS shapefile. <http://criticalhabitat.fws.gov/crithab/>. Accessed August 2008.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Birds—Continued		
Steller's Eider	Fair	Audubon Alaska. 2009. Steller's Eider. GIS feature class (based on USFWS 1992-2008; Fredrickson 2001; Drew and Piatt 2003; Ridgely et al. 2007; Martin 2009). BirdLife International. 2009. Important Bird Areas. GIS feature class. Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. Fredrickson, L.H. 2001. Steller's Eider (Polysticta stelleri). In The Birds of North America online. A. Poole, editor. Cornell Lab of Ornithology, Ithaca, New York. <http://bna.birds.cornell.edu/bna/species/571>. Accessed February 2009. Martin, P. 2009. Steller's Eider satellite telemetry locations 2000-02. USFWS, Fairbanks, Alaska. Martin, P./USFWS. 2009. Personal communication with M. Smith/Audubon Alaska. June. Ridgely, R.S., T.F. Allnutt, T. Brooks, D.K. McNicol, D.W. Mehlman, B.E. Young, et al. 2007. Digital distribution maps of the birds of the Western Hemisphere, version 3.0. NatureServe, Arlington, Virginia. USFWS. 1992–2006. Eider breeding population survey. USFWS. 1992–2008. Arctic Coastal Plain aerial breeding pair survey. USFWS. 1998–2003. Arctic Coastal Plain molting sea duck survey. USFWS. 1999–2007. Common Eider survey.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Birds—Continued		
King Eider	Fair	Audubon Alaska. 2009. King Eider. GIS feature class (based on NOAA 1988; USFWS 1992-2008; Larned et al. 1995; Dickson et al. 1997; Larned 1999; Dickson and Gilchrist 2002; Drew and Piatt 2003; Ridgely et al. 2007; Oppel 2008; Oppel 2009; Oppel et al. 2009).
		Audubon Alaska. 2009. Important Bird Areas. GIS feature class.
		Dickson, D.L., and H.G. Gilchrist. 2002. Status of marine birds of the southeastern Beaufort Sea. Arctic 55, Supplement 1:46-58.
		Dickson, D.L., R.C. Cotter, J.E. Hines, and M.F. Kay. 1997. Distribution and abundance of King Eiders in the western Canadian Arctic. In Occasional paper number 94. D.L. Dickson, editor. Canadian Wildlife Service, Edmonton, Alberta.
		Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage.
		Larned, W.W. 1999. Ledyard Bay survey. August. USFWS, Anchorage, Alaska.
		Larned, W.W., G.R. Balogh, and M.R. Petersen. 1995a. Distribution and abundance of Spectacled Eiders (Somateria fischeri) in Ledyard Bay, Alaska, September 1995. November. USFWS, Anchorage, Alaska.
		Larned, W.W., G.R. Balogh, and M.R. Petersen. 1995b. Late winter distribution of Spectacled Eiders (Somateria fischeri) in the Bering Sea, 1995. September. USFWS, Anchorage, Alaska.
		Larned, W.W., M.R. Petersen, K. Laing, R. Platte, and J.L. Hodges. 1995d. Progress report: location and characteristics or Spectacled Eider molting and wintering areas, 1993-94. February. USFWS, Anchorage, Alaska.
		NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.
		Oppel, S. 2008. King Eider migration and seasonal interactions at the individual level. Dissertation, University of Alaska Fairbanks, Fairbanks, Alaska.
		Oppel, S./University of Alaska Fairbanks. 2009. Personal communication with M. Smith/Audubon Alaska. September.
		Ridgely, R.S., T.F. Allnutt, T. Brooks, D.K. McNicol, D.W. Mehlman, B.E. Young, et al. 2007. Digital distribution maps of the birds of the Western Hemisphere, version 3.0. NatureServe, Arlington, Virginia.
		USFWS. 1992–2005. Density polygons (based on USFWS Eider breeding population survey and USFWS Arctic Coastal Plain aerial breeding pair survey).
		USFWS. 1992–2006. Eider breeding population survey.
		USFWS. 1992–2008. Arctic Coastal Plain aerial breeding pair survey.
		USFWS. 1998–2003. Arctic Coastal Plain molting sea duck survey.
		USFWS. 1999–2001. Beaufort Sea nearshore and offshore waterbird aerial survey.
		USFWS. 1999–2007. Common Eider survey.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Birds—Continued		
Common Eider	Fair	Audubon Alaska. 2009. Common Eider. GIS feature class (based on Drew and Piatt 2003; USFWS 1992–2008; NOAA 1988; Kendall 2005). Audubon Alaska. 2009. Important Bird Areas. GIS feature class. Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. Kendall, S.J. 2005. Surveys of breeding birds on barrier islands in the Arctic National Wildlife Refuge, 2003–2004. USFWS, Arctic National Wildlife Refuge, Fairbanks, Alaska. Larned, W.W., M.R. Petersen, K. Laing, R. Platte, and J.L. Hodges. 1995d. Progress report: location and characteristics or Spectacled Eider molting and wintering areas, 1993-94. February. USFWS, Anchorage, Alaska. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. USFWS. 1992–2008. Arctic Coastal Plain aerial breeding pair survey. USFWS. 1998–2003. Arctic Coastal Plain molting sea duck survey. USFWS. 1999–2001. Beaufort Sea nearshore and offshore waterbird aerial survey. USFWS. 1999–2007. Common Eider survey. USFWS. 2005–2007. Western Alaska Yellow-billed Loon survey. USFWS. 2008. Beringian seabird colony catalog. Microsoft Excel spreadsheet.
Long-Tailed Duck	Fair	Alexander, S.A., D.L. Dickson, and S.E. Westover. 1997. Spring migration of eiders and other waterbirds in offshore areas of the western Arctic. In King and Common eiders of the western Canadian Arctic. D.L. Dickson, editor. Occasional Paper Number 94. Canadian Wildlife Service, Edmonton, Alberta. Audubon Alaska. 2009. Important Bird Areas. GIS feature class. BirdLife International. 2009. Important Bird Areas. GIS feature class. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington. Portenko, L.A. 1981. Birds of the Chukchi Peninsula and Wrangel Island (translated from Russian). Published for the Smithsonian Institution and the National Science Foundation, Washington, D.C. Amerind, Springfield, Virginia. USFWS. 1992–2005. Density polygons (based on USFWS Eider breeding population survey and USFWS Arctic Coastal Plain aerial breeding pair survey). USFWS. 1992–2006. Eider breeding population survey. USFWS. 1992–2008. Arctic Coastal Plain aerial breeding pair survey.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Birds—Continued		
Ivory Gull	Poor	Audubon Alaska. 2009. Ivory Gull. GIS feature class (based on Portenko 1981; Benter 2009). Benter, B./USFWS. 2009. Personal communication with M. Smith/Audubon Alaska. 21 August. Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. Mallory, M.L., I.J. Stenhouse, G. Gilchrist, G. Robertson, J.C. Haney, and S.D. Macdonald. 2008. Ivory Gull (Pagophila eburnea). In The birds of North America Online. A. Poole, editor. Cornell Lab of Ornithology, Ithaca, New York. <http://bna.birds.cornell.edu/bna/species/175>. Accessed June 2009. Portenko, L.A. 1981. Birds of the Chukchi Peninsula and Wrangel Island (translated from Russian). Published for the Smithsonian Institution and the National Science Foundation, Washington, D.C. Amerind, Springfield, Virginia.
Kittlitz's Murrelet	Poor	Arctic Ocean Diversity. 2009. Kittlitz's Murrelet known nest locations in Alaska (based on Day et al. 1999). <http://www.arcodiv.org/Database/Birds_datasets.html>. Accessed June 2009. Audubon Alaska. 2009. Important Bird Areas. GIS feature class. Day, R.H., K.J. Kuletz, and D.A. Nigro. 1999. Kittlitz's Murrelet (Brachyramphus brevirostris). In The birds of North America online. A. Poole, editor. Cornell Lab of Ornithology, Ithaca, New York.<http://bns.birds.cornell.edu/bna/species/435>. Accessed January 2010. Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. Ridgely, R.S., T.F. Allnutt, T. Brooks, D.K. McNicol, D.W. Mehlman, B.E. Young, et al. 2007. Digital distribution maps of the birds of the Western Hemisphere, version 3.0. NatureServe, Arlington, Virginia. USFWS. 2009. Kittlitz's Murrelet nesting areas. USFWS, Anchorage Field Office.
Northern Fulmar	Fair	Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. USFWS. 2008. Beringian seabird colony catalog. Microsoft Excel spreadsheet.
Short-Tailed Shearwater	Fair	Drew, G.S., and J.F. Piatt. 2003. North Pacific pelagic seabird database, version 1.0. Alaska Science Center, USGS, Anchorage. Larned, W.W. 1999. Ledyard Bay survey. August. USFWS, Anchorage, Alaska. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.
Seabird Colonies	Fair	USFWS. 2008. Beringian seabird colony catalog. Microsoft Excel spreadsheet.
Important Bird Areas	Fair	Audubon Alaska. 2009. Important Bird Areas. GIS feature class. BirdLife International. 2009. Important Bird Areas. GIS feature class. Bird Studies Canada and Canadian Nature Federation. 2004. Important Bird Areas of Canada database. Bird Studies Canada, Port Rowan, Ontario.

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Mammals		
Polar Bear	Fair	ADFG. 1997. Most Environmentally Sensitive Area (MESA) Data. GIS shapefiles. Habitat and Restoration Division. Amstrup, S.C., G.M. Durner, I. Stirling, and T.L. McDonald. 2005. Allocating harvests among polar bear stocks in the Beaufort Sea. Arctic 58:247-259. Kalxdorff, S. 1997. Collection of local knowledge regarding polar bear habitat use in Alaska. Technical report MMM 97-2. USFWS, Marine Mammal Management, Anchorage, Alaska. Kochnev, A.A., V.M. Etylin, V.I. Kavry, E.B. Siv-Siv, and I.V. Tanko. 2003. Traditional knowledge of Chukotka Native peoples regarding polar bear habitat use. Prepared for U.S. National Park Service by The Chukotka Association of Traditional Marine Mammal Hunters, The Alaska Nanuuq Commission, The Pacific Fisheries Research Center (Chukotka Branch). McDonald, L.L., and D.G. Robertson. 2000. Polar bear maternity den surveys in the Russian Arctic: development of protocols and standard operating procedures. Western EcoSystem Technologies, Cheyenne, Wyoming. MMS. 2008. Bowhead whale aerial survey program. Microsoft Access database. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington. North Slope Science Initiative. 2008. Polar bear locations. GIS shapefile. <http://www.gina.alaska.edu/projects/nssi-catalog>. Accessed October 2008. Stishov, M.S. 1991. Results of aerial counts of the polar bear dens on the Arctic coasts of the extreme Northeast Asia. In Polar bears: proceedings of the tenth working meeting of the IUCN/SSC Polar Bear Specialist Group. S.C. Amstrup and O. Wiig, editors. October 25-29. Sochi, USSR. USFWS. 2009. Polar bear proposed critical habitat. GIS shapefiles. USFWS (U.S. Fish and Wildlife Service) and MMS. 1994. Conservation plan for the polar bear in Alaska. June. USFWS, Anchorage, Alaska. USGS (U.S. Geological Survey). 2002. Confirmed polar bear den locations, 1919-2002. GIS shapefile. Biological Resources Division.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Mammals—Continued		
Arctic Fox	Poor	Audubon Alaska. 2009. Arctic fox. GIS feature class (based on Pelletier 2000; Nowacki et al. 2001; Patterson et al. 2007; Pamperin 2008; Northwest Territories Environment and Natural Resources Wildlife Division 2009; IUCN 2009). IUCN (International Union for Conservation of Nature). 2009. Arctic fox (Alopex lagopus) range map. Species Survival Commission Canid Specialist Group.<http://www.canids.org/species/Alopex_lagopus.htm>. Accessed June 2009. Northwest Territories Environment and Natural Resources Wildlife Division. 2009. Arctic fox distribution. Digital map. <http://www.nwtwildlife.com/NWTwildlife/foxes/arcticfox/distribution.htm>. Accessed June 2009. Nowacki, G., P. Spencer, T. Brock, M. Fleming, and T. Jorgenson. 2001. Ecoregions of Alaska. GIS shapefile. USGS, Reston, Virginia. Pamperin, N.J. 2008. Winter movements of Arctic foxes in northern Alaska measured by satellite telemetry. University of Alaska Fairbanks. Patterson, B.D., G. Ceballos, W. Sechrest, M.F. Tognelli, T. Brooks, L. Luna, et al. 2007. Digital distribution maps of the mammals of the Western Hemisphere, version 3.0. NatureServe, Arlington, Virginia. Pelletier, B.R. 2000. Environmental atlas of the Beaufort coastlands. Geological Survey of Canada. <http://gsc.nrcan.gc.ca/beaufort index_ephp>. Accessed June 2009.
Pacific Walrus	Fair	ADFG (Alaska Department of Fish and Game). 1986. Alaska habitat management guide. Division of Habitat, Juneau, Alaska. AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Chukchi Sea shoals. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Pacific walrus. GIS feature class (based on NOAA 1988; MMS 2008). MMS. 2008. Bowhead whale aerial survey program. Microsoft Access database. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. Robards, M., A. Kochnev, and S. Deming. 2007. Sharing knowledge about Pacific walrus. Published map.
Ribbon Seal	Fair	AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Angliss, R.P., and R.B. Outlaw. 2008. Alaska marine mammal stock assessments, 2007. U.S. Department of Commerce. Report Technical Memo NMFS-AFSC-180. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Boveng, P.L., J.L. Bengtson, T.W. Buckley, M.F. Cameron, S.P. Dahle, B.A. Megrey, J.E. Overland, and N.J. Williamson. 2008. Status review of the ribbon seal (Histriophoca fasciata). U.S. Department of Commerce, NOAA. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Mammals—Continued		
Spotted Seal	Fair	ADFG. 1997. Most Environmentally Sensitive Area (MESA) Data. GIS shapefiles. Habitat and Restoration Division. AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Angliss, R.P., and R.B. Outlaw. 2008. Alaska marine mammal stock assessments, 2007. U.S. Department of Commerce. Report Technical Memo NMFS-AFSC-180. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Spotted seal. GIS feature class (based on NOAA 1988; ADFG 1997; Rugh et al. 1997; Lowry et al. 1998; Eningowuk 2002; NOAA 2002; Oceana 2008). Eningowuk, J. 2002. Spotted seal (based on local and traditional knowledge). Lowry, L.F., K.J. Frost, R. Davis, D.P. DeMaster, and R.S. Suydam. 1998. Movements and behavior of satellite-tagged spotted seals (Phoca largha) in the Bering and Chukchi seas. Polar Biology 19:221-230. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington. Oceana. 2008. Spotted seal. GIS feature class (based on local and traditional knowledge). Rugh, D.J., K.E.W. Shelden, and D.E. Withrow. 1997. Spotted seals, Phoca largha, in Alaska. Marine Fisheries Review 59:1-18.
Ringed Seal	Fair	ADFG (Alaska Department of Fish and Game). 1986. Alaska habitat management guide. Division of Habitat, Juneau, Alaska. Angliss, R.P., and R.B. Outlaw. 2008. Alaska marine mammal stock assessments, 2007. U.S. Department of Commerce. Report Technical Memo NMFS-AFSC-180. AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Ringed seal. GIS feature class (based on NOAA 1988; Harwood and Stirling 1992; MMS 2008). Bengtson, J.L., L.M. Hiruki-Raring, M.A. Simpkins, and P.L. Boveng. 2005. Ringed and bearded seal densities in the eastern Chukchi Sea, 1999–2000. Polar Biology 28:833-845. Frost, K./Retired biologist. 2010. Personal communication with M. Smith/Audubon Alaska. 3 January. Harwood, L.A., and I. Stirling. 1992. Distribution of ringed seals in the southeastern Beaufort Sea during late summer. Canadian Journal of Zoology 70:891-900. MMS. 2008. Bowhead whale aerial survey program. Microsoft Access database. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Mammals—Continued		
Bearded Seal	Fair	Angliss, R.P., and R.B. Outlaw. 2008. Alaska marine mammal stock assessments, 2007. U.S. Department of Commerce. Report Technical Memo NMFS-AFSC-180. AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.htm>. Accessed February 2009. Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009). Audubon Alaska. 2009. Bearded Seal. GIS feature class (based on NOAA 1988; Bengtson et al. 2005; Angliss and Outlaw 2008; MMS 2008; Boveng 2009). Audubon Alaska. 2009. Chukchi Sea shoals. GIS feature class (based on AOOS 2009). Bengtson, J.L., L.M. Hiruki-Raring, M.A. Simpkins, and P.L. Boveng. 2005. Ringed and bearded seal densities in the eastern Chukchi Sea, 1999–2000. Polar Biology 28:833-845. Boveng, P./NOAA Alaska Fisheries Science Center. 2009. Personal communication with M. Smith/Audubon Alaska. June. Frost, K./Retired biologist. 2010. Personal communication with M. Smith/Audubon Alaska. 3 January. MMS. 2008. Bowhead whale aerial survey program. Microsoft Access database. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington.
Bowhead Whale	Fair	ADFG. 2009. Summary maps of fall movements of bowhead whales in the Chukchi Sea. <http://www.adfg.alaska.gov/static/home/about/management/wildlife/management/marinemammals/pdfs/bow_move_chukchi_sea.pdf>. Accessed February 2009. Audubon Alaska. 2009. Bowhead whale. GIS feature class (based on North Slope Borough 2003; ADFG 2009; Quakenbush 2009). Moore, S.E., and K.L. Laidre. 2006. Trends in sea ice cover within habitats used by bowhead whales in the Western Arctic. Ecological Applications 16(3):932-944. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington. Noongwook, G., H.P. Huntington, and J.C. George. 2007. Traditional knowledge of the bowhead whale (Balaena mysticetus) around St. Lawrence Island, Alaska. Arctic 60:47-54. North Slope Borough. 2003. Bowhead whale subsistence sensitivity. (The map incorporates data from Moore and Reeves 1993 and Richardson 1999.) In Barrow, Alaska: North Slope Borough. Department of Planning and Community Services, Geographic Information Systems Division. Oceana. 2008. Bowhead whale. GIS feature class (based on local and traditional knowledge). Quakenbush, L./ADFG. 2009. Personal communication with M. Smith/Audubon Alaska. February.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
Mammals—Continued		
Beluga Whale	Fair	ADFG. 1997. Most Environmentally Sensitive Area (MESA) Data. GIS shapefiles. Habitat and Restoration Division. Angliss, R.P., and R.B. Outlaw. 2008. Alaska marine mammal stock assessments, 2007. U.S. Department of Commerce. Report Technical Memo NMFS-AFSC-180. Huntington, H. P., and the communities of Buckland, Koyuk, Point Lay, and Shaktoolik. 1999. Traditional knowledge of the ecology of beluga whales (*Delphinapterus leucas*) in the eastern Chukchi and northern Bering seas, Alaska. Arctic 52:49-61. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas. NOAA. 2002. Environmental sensitivity index, version 3.0. NOAA, Seattle, Washington. Suydam, R., and ADFG. 2004. Bowhead whale feeding areas. *In* North Slope Borough. 2006. North Slope Borough Area Wide Comprehensive Plan. Barrow, Alaska.
Gray Whale	Fair	Angliss, R.P., and R.B. Outlaw. 2008. Alaska marine mammal stock assessments, 2007. U.S. Department of Commerce. Report Technical Memo NMFS-AFSC-180. Audubon Alaska. 2009. Gray whale. GIS feature class (based on NOAA 1988; MMS 2008). MMS. 2008. Bowhead whale aerial survey program. Microsoft Access database. NOAA. 1988. Bering, Chukchi, and Beaufort seas coastal and ocean zones strategic assessment data atlas.
People		
Energy Development and Protected Areas	Good	Alaska Center for the Environment. 2009. Oil and gas infrastructure. GIS geodatabase. Alaska Department of Natural Resources. 2008. Surface holes. GIS shapefile. Alaska Department of Natural Resources. 2009. Oil and gas leases. GIS shapefile. Alaska Oil and Gas Conservation Commission. 2009. Oil and gas wells. GIS shapefile. Alaska State Geospatial Data Clearinghouse. 2008. Base data. GIS shapefiles. <http://www.asgdc.state.ak.us/>. Accessed June 2008. Audubon Alaska. 2009. MMS program areas, 2010–2015. GIS feature class (based on MMS 2009). BLM. 2008. Oil and gas infrastructure. GIS shapefiles. ESRI. 2009. StreetMap premium: North America. GIS feature class. MMS. 2009. Draft proposed Outer Continental Shelf (OCS) oil and gas leasing program, 2010–2015. January. World Wildlife Fund. 2009. Arctic-wide human infrastructure. GIS geodatabase. World Wildlife Fund. 2010. Protected areas in eastern Russia. GIS shapefile.
Human Impact	Good	Alaska Department of Natural Resources. 2008. Surface holes. GIS shapefile. Halpern, B., S. Walbridge, K. Selkoe, C. Kappel, F. Micheli, C. D'Agrosa, et al. 2008. A global map of human impact on marine ecosystems. Science 319:948-952.

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Map title	Data quality rating (Good, Fair, Poor)	Data sources for individual maps
People—Continued		
Predicted Climate Change	Fair	Audubon Alaska. 2009. Predicted climate change: increase in air temperature at surface, mean for June - August, 2000–2009 versus 2090 2099. GIS raster dataset (based on NCAR 2009; SNAP 2009). NCAR (National Center for Atmospheric Research). 2009. Global CCSM data: Scenario A1B –ensemble average for air temperature at surface. GIS shapefile. Geographic Information Systems (GIS) Initiative. <http://www.gisclimatechange.org/CCSMDownloadWizard.htm>.Accessed March 2009. SNAP (Scenarios Network for Alaska Planning). 2009. A1B GCM dataset: air temperature – 5-model composite. GIS raster dataset. <http://www.snap.uaf.edu/downloads/alaska-climate-datasets>. Accessed March 2009.

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Holland-Bartels and Pierce— An Evaluation of the **Science Needs to Inform Decisions on Outer Continental Shelf Energy Development in the Chukchi and Beaufort Seas, Alaska**—Circular 1370