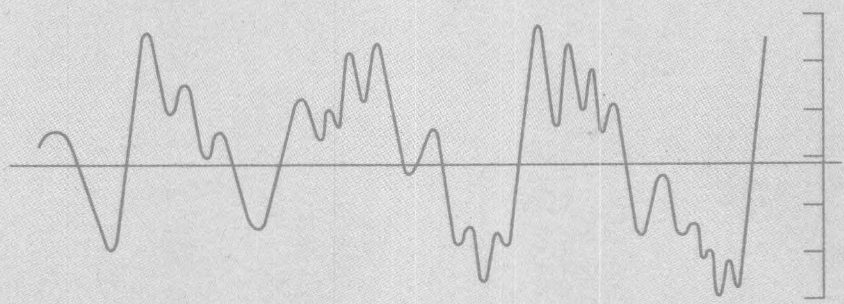
Proceedings of the U.S. Geological Survey Global Change Research Forum, Herndon, Virginia, March 18–20, 1991



U.S. GEOLOGICAL SURVEY CIRCULAR 1086

Cover Art. The artistically smoothed graph represents global temperature trends during the past 400,000 years as determined from fluctuations in oxygen isotope ratios in marine sediment cores. It indicates that warmer intervals, such as the present interglacial (the last 10,000 years), are rare and relatively short in duration. Intervals significantly warmer than today have not existed for more than 2.5 million years.

Proceedings of the U.S. Geological Survey Global Change Research Forum, Herndon, Virginia, March 18–20, 1991

Edited by JOHN A. KELMELIS and MITCHELL SNOW

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U.S. GEOLOGICAL SURVEY CIRCULAR 1086

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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Organizing an interdisciplinary meeting to review the diverse topics represented in global change research is not an easy task. It requires the concerted effort of a large number of people. Many arrangements must be made, schedules established, and activities coordinated. Budget and personnel restrictions mandate obtaining the best possible value for the resources expended.

It is a very fortunate circumstance that the USGS Global Change Research Forum was organized and orchestrated by Linda Stanley, who ably dealt with all the details, large and small. She was the real driver behind the Forum and without her it would not have happened. Scott Tilley was her able assistant. He helped with the thousands of details from contracts to condiments, from abstracts to accommodations. He did an outstanding job.

Mary Fischer and Hannah Sluss provided constant secretarial help, which is a difficult task given all the Committee on Earth and Environmental Sciences business and other activities constantly underway in the Assistant Director for Research's office. Mary Lefler graciously helped throughout the conference.

Thanks also go to the "Gang of 12" for providing the technical expertise and the leverage within the divisions to make the program as comprehensive as it was. The Forum participants deserve thanks for providing the many technical presentations and insightful discussions throughout the meeting. And thank you to all of the others, who, through my oversight, I have not mentioned. All of you have made the job of putting this Forum together very much easier.

John Kelmelis
Coordinator
USGS Global Change Research Program

Editor's Note: The submissions by non-USGS employees have not been cleared through the USGS Director's Review process and may not reflect USGS style.

CONTENTS

Acronym List

AAP average annual precipitation
AAT average annual temperature
ADI Arctic Data Interaction
AFFP average frost free period
AMS accelerated mass spectrometry
ARC Arid Regions Climate project
AVHRR Advanced Very High Resolution Radiometer

BAHC Biological Aspects of the Hydrologic Cycle
BATS Biosphere-Atmosphere-Transfer Scheme
BCNM Barro Colorado Nature Monument

CD ROM compact disk read-only memory
CEES Committee on Earth and Environmental Sciences
CNN Cable News Network
CNO California-Nevada-Oregon
CRREL (U.S. Army) Cold Regions Research and Engineering Laboratory (in Hanover, N.H.)

DCW Digital Chart of the World
DEM digital elevation model
DIC dissolved inorganic carbon
DOD Department of Defense
DOE Department of Energy
DRI Desert Research Institute
DSDP Deep-Sea Drilling Project

EDC EROS Data Center
ENSO El Niño-Southern Oscillation
EOF empirical othogonal function
EOS Earth Observing Satellite
EPA Environmental Protection Agency
ERBE Earth Radiation Budget Experiment
ESDD (USGS) Earth Science Data Directory

FAO (United Nations) Food and Agricultural Organization
FCCSET Federal Coordinating Council for Science, Engineering, and Technology

GCIP GEWEX Continental-Scale International Project
GCM general circulation model
GEWEX Global Energy and Water Cycle Experiment
GFDL Geophysical Fluid Dynamics Laboratory
GIS geographic information system
GISP II Greenland Ice Sheet Project
GISS Goddard Institute for Space Studies
GLIS Global Land Information System
GPS global positioning system
GSC Geological Survey of Canada

HCDN Hydro-Climatic Data Network
HCN Historical Climate Network
HDGEC Human Dimensions of Global Environmental Change

ICSU International Council of Scientific Unions
IGBP International Geosphere-Biosphere Program

IGCA International Global Atmospheric Chemistry Program
IGFA International Group of Funding Agencies
IGY International Geophysical Year
INSTAAR Institute for Arctic and Alpine Research
IPCC Intergovernmental Panel on Climate Change
ISSS International Society of Soil Sciences
IWG Interagency Working Group (on Data Management for Global Change)

JGOFS Joint Global Ocean Flux Study

LDGO Lamont-Doherty Geological Observatory, Palisades, New York
LEF Luquillo Experimental Forest (in Puerto Rico)
LTER long-term ecological research

MARS Mitigation and Adaptation Strategies
MHD magnetohydrodynamic
MLRA Major Land Use Resource Area
MMTS maximum minimum temperature system
MSS (Landsat)Multispectral Scanner

NAS National Academy of Sciences
NASA National Aeronautics and Space Administration
NATSGO National Soil Geographic data base
NAWQA National Water Quality Assessment program
NCAR National Center for Atmospheric Research
NCDC National Climate Data Center
NDVI normalized difference vegetation index
NHAT Northern Hemisphere air temperature
NOAA National Oceanic and Atmospheric Administration
NOS National Oceans Service
NRC National Research Council
NRSC National Remote Sensing Center (in Great Britain)
NSF National Science Foundation
NTIS National Technical Information Service

OCt Old Crow tephra
ODP Ocean Drilling Project
OMB Office of Management and Budget
OSTP Office of Science and Technology Policy

PAGES Past Global Changes
PC personal computer
PCAST President's Council of Advisors of Science and Technology
PMRW Panola Mountain Research Watershed
PNA Pacific North America
PNV potential natural vegetation
PRISM Pliocene Research, Interpretation, and Synoptic Mapping

RBV (Landsat) Return Beam Vidicon
RES radio echo sounding

SAR synthetic aperture radar
SCAR Scientific Committee on Antarctic Research
SI Smithsonian Institution
SiB Simple Biosphere model
SMMR Scanning Multichannel Microwave Radiometer
SO Southern Oscillation

SOI Southern Oscillation Index
SOWR sensitivity of water resources
SCS Soil Conservation Service
SOTER Soil and Terrain date base
SPECMAP spectral mapping
SSA single-spectrum time-series analysis
SST sea-surface temperature
STATSGO State Soil Geographic data base
STRI Smithsonian Tropical Resources Institute

TDR Time-domain reflectometry
TOGA Tropical Ocean-Global Atmosphere
TM (Landsat) Thematic Mapper

UCAR University Corporation for Atmospheric Research
UKMO United Kingdom Meterological Office
UNESCO United Nations Educational, Scientific, and Cultural Organization
USCGC U.S. Coast Guard Cutter
USDA U.S. Department of Agriculture
USGCRP U.S. Global Change Research Program
USGS U.S. Geological Surv3ey
USSR Union of Soviet Socialist Republics

WCRP World Climate Research Programme
WEBB (USGS Global Change Project of) Water, Energy, and Biogeochemical Budget
WGGC Working Group on Global Change
WOCE World Ocean Circulation Experiment

Proceedings of the U.S. Geological Survey Global Change Research Forum, Herndon, Virginia, March 18–20, 1991

Edited by John A. Kelmelis *and* Mitchell Snow

First General Session

Welcome and Introductory Remarks

Stephen Ragone, Assistant Director for Research
U.S. Geological Survey

Earth sciences information and understanding are essential components to solving many of society's problems. Within the last decade, the U.S. Geological Survey (USGS) has embarked on several programs to help solve such problems. Let me mention a few of them to establish the theme for this meeting.

A study that is representative of the kinds of programs the Survey has been getting into in the last 10 years is the investigation of contamination of the Kesterson National Wildlife Refuge. The USGS, along with other Department of the Interior bureaus, initiated a program to identify the nature and extent of irrigation-induced water-quality problems in the Western United States. Results of the program significantly contributed to the understanding of the location and factors affecting the occurrence of arsenic and selenium in the environment.

Those of you from California might be familiar with the earthquake insert that was included in the San Francisco Bay Sunday papers in September 1990. Recently, I visited my son who lives in the Marina District, and I was happy to see how valuable USGS information was to the public. This is another example of how Survey investigations can contribute to the well-being of society.

My research was formerly in the Toxic Waste Hydrology Program. The program just held its fifth technical meeting, which now draws 200 to 300 people. The program provides information about the fate of contaminants moving through surface and ground water. Such information is relevant to the mission of several Federal agencies—EPA, DOE, and DOD particularly—and to the States. This program has demonstrated how essential Earth-sciences information is to solving the point-source contamination problems facing our Nation today.

The Survey is also playing a major role in the President's agricultural initiative on water quality. As one of several Federal agencies, the Survey is studying what happens to agricultural chemicals after they have been applied to our farmlands. We're working arm-in-arm with USDA and EPA in the field in the Midwest, sharing our expertise and developing some understanding of the processes that move the chemicals. Such interagency partnership will lead to the development of farming practices for mitigating the effects of agriculture on water quality.

Finally, I want to mention the National Water Quality Assessment (NAWQA) program, which is just getting underway. NAWQA represents a major example of how the Survey is providing information that will help decisionmakers protect and enhance the Nation's water quality.

The U.S. Global Change Research Program provides the Survey an opportunity, once again, to demonstrate the importance of the broad disciplines that constitute the Earth sciences in addressing a major societal problem. The scope and scale of the Global Change Program make it unique. In this context, there is some good news and some bad news about the Global Change Program. The good news is that the Global Change Program is a highly visible, socially relevant, interdivisional, interbureau, interagency, interdis-

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ciplinary effort. The bad news is that the Global Change Program is a highly visible, socially relevant, interdivisional, interbureau, interagency, interdisciplinary effort. Although the program provides us an opportunity to demonstrate the relevance of the Earth sciences, its high degree of visibility and the broad social and political implications of the program may require some accommodations on our part. Researchers may encounter additional demands to show relevance or timeliness of the results of their studies. Researchers may be expected to demonstrate how well their work is coordinated with other researchers, not only within the Survey, but within other bureaus and agencies, and even internationally. These demands are not necessarily bad. It really is a matter of balance.

In the final analysis, however, the responsibilities of the researchers in the Global Change Program are simple. First and foremost, they are to carry on the tradition of excellent research. One of the things that the bureau and division technical managers have to do is ensure that the USGS research community remains a research community. The second responsibility is to keep in mind the larger overall technical picture in which our research is being conducted. Global change research is interdisciplinary research, and we have to ensure that the technical relevance of our work is conveyed outside traditional boundaries. Likewise, we have to be receptive to the research information becoming available to us from nontraditional sectors, including the political scientists and economists. Finally, we must remember the societal context in which the research is being conducted. We must strive to make the results of the research available as soon as possible and in a format that is useful to decisionmakers.

We also have to ask ourselves how best to get our job done. The fact is that there are not enough resources and people to do everything that we feel should be done under the banner of global change. Thus, the divisions and the bureau coordinators have a major responsibility to ensure that the research being conducted represents a balanced, integrated, efficient, and comprehensive effort, within the constraints of funding and staff.

This meeting will provide us with a conceptual framework for the research, and for the data collection and management activities that constitute the USGS Global Change Program. It will describe the major scientific and information issues that are being addressed, as well as the geographical context in which the research and data-collection activities are being conducted. As you look through the abstracts, you will see the seeds of some very exciting opportunities for research and for coordination between the people in this room and other researchers in the scientific community at large.

The charge to us this week is to listen to the presentations with a view to both their scientific relevance and their relevance to the U.S. Global Change Program. Constructive criticism is welcome. Identify the value of your research to others with regard to the kind of information you are obtaining, the type, scale, and intensity of data being collected, and how it might be used in other studies. Use the opportunity of this meeting to work with others to ensure that no essential understanding or data are missing.

The Committee on Earth and Environmental Sciences: Its Role in Federal Research

Dallas Peck, Director
U.S. Geological Survey

This meeting is a first. It's a mixture of people from different disciplines and different divisions working together on a very important program. I have hoped all along that this would be a program to bring together the different elements of the Survey and the Department of the Interior in a spirit of cooperation. This is a testament that we're making some progress. This could be a catalyst for making it happen.

It's particularly a pleasure to have the representatives from the other Interior bureaus. We're looking forward to working together with you through this program.

I look forward to hearing about your research and asking questions. It's important that we get to know each other so that we can develop teams and work together to solve problems. The need for cooperation and the importance of building and maintaining partnerships are key elements. Understanding the context within which your specific research fits means understanding what the whole program is all about.

I'm going to talk a little bit today about global change and then discuss the Committee on Earth and Environmental Sciences. I hope that's the last bureaucratic talk you'll hear. I'm looking forward to hearing some science for a couple of days—instead of budgets and bureaus.

We are scientists. We know the world changes. It was a little chillier 18,000 years ago than it is now. So we know that the climate changes in a natural sort of way. However, there are indications now that the environment, and particularly the climate, may be changing as a result of man's influence. We've been a rider on the train for all these millions of years, but now we have access to the train's steering mechanism.

The ozone hole over the Antarctic is a particularly good example of a phenomenon that seems to reflect the impact of man's activities. The same thing is true with the very famous curve indicating the increase in CO_2 at the summit of Mauna Loa. The Earth would be 30° cooler without the greenhouse gases, but CO_2 concentrations have increased 0.5 percent per year since 1958.

This fact summarizes why we're here. There's an increase in trace gases that may cause global warming and may change all sorts of things. That's going to have tremendous impacts on you and me and society as a whole. Changes in the Earth's climate, both natural and manmade, may have profound implications for the future of our Nation. They can affect our economic well-being, our competitive position in world markets, and the health and safety of our people. That same statement is true of the world as a whole.

Important decisions are going to be made nationally and internationally over the next few years. They're going to be poor decisions if we have a poor understanding of what's going on. So it's important to get that understanding. That helps provide a focus and a way to establish priorities.

A word that I like to use around town these days is "paradigm." It's the "in" word. But the message is more important than the word—that science is an integral part of the policy process in areas like global change.

The problem is that the global system is comprised of a variety of interactive parts: the atmosphere, the oceans, the solid Earth, and the land surface, including soils, water, and biota. There are so many complex interacting aspects of this that it's pretty hard to understand. We need a better understanding of these processes if we are to predict the consequent impacts of global change.

The carbon cycle is a good example of the uncertainties that we face. The flux related to man's activities is about 6 billion tons of CO_2. Now, of that, we don't know where 2½ billion tons goes. It may be in the oceans. It may be in the midlatitude biosphere, including the soils. We have to learn where the carbon is and understand the cycle a little better.

The Committee on Earth and Environmental Sciences, as well as the group of you here, is working to develop the science of global change—to make the observations, develop the understanding, and form a predictive understanding of global change—and then hand that information to policymakers. The Domestic Policy Council and the President, working through Allan Bromley, the present science adviser, will use our input for the policy decisions that will be made domestically and around the world.

The handoff will be made through the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). FCCSET has been in existence since 1976, but it was raised to prominence by Allan Bromley. Allan Bromley was the first science adviser to have cabinet-level status; in other words he's at the same rank as the Secretary of the Interior. Today FCCSET meets in the Roosevelt Room of the White House. Most of the chairmen are Assistant Secretaries, Under Secretaries, or Secretaries.

There are seven different committees, all of which have been very active. One of them is the Committee on Earth and Environmental Sciences (CEES). It was formed out of the old Oceans and Atmospheres Committee about 4 years ago. Tony Calio was the first director of CEES, and, for the last 3½ years, I've been chairman.

The work really gets done through a whole series of working groups. One of the most active and successful has been the Working Group on Global Change that Bob Corell heads. He's going to be talking to us later about that. Another very important one has to do with research on mitigation and adaptation strategies, the so-called MARS Subcommittee. That had been headed by John Kelmelis, but now it's headed by Gary Evanson of the Department of Agriculture. We have a number of other kind of important subcommittees tackling things like water resources, coastal oceans, and atmospheric sciences. The subcommittees under the committee have been very successful. We also interact informally with another very successful group, the Interagency Working Group on Data Management for Global Change headed by Tom Pyke of the National Oceanic and Atmospheric Administration (NOAA).

Why CEES? The basic point is that we need coordination. We need to identify what the gaps and missing elements are. We need to relate to international science programs. We need to coordinate with ourselves and with the policymakers. I think we've been successful in doing that.

One of the good things over the last year is that we have new active participants—the Department of Transportation and the Smithsonian. And the Department of Defense is a far more active participant than it has been in the past.

We have to maintain a partnership. That's a particularly important element of the success we've had in this program. We're all in it together, and we're all partners. We have to focus on the interdisciplinary science aspects as well as the international aspects. We have to do the planning and carry out the program at the same time. We have to guide the process with priorities. Setting those priorities and developing a good, crisp goal statement has been an important part of reaching this goal.

It has taken a lot of effort and a good partnership between the many Federal agencies to develop this program. We have moved very quickly. What might have taken 5 to 7 years, we carried out in about 18 months.

Through all the Federal agencies, we work with scientists at universities. In the Federal laboratories we also work with international programs like WOCE, the World Ocean Circulation Experiment, and TOGA, the Tropical Ocean-Global Atmosphere program.

We work with the National Academy Committee on Global Change to lay out the main science elements. Through the National Academy, we work with the International Geosphere-Biosphere Program of the International Council of Scientific Unions (ICSU). Along with the World Climate Research Program, it is the international analog of our domestic Global Change Research Program.

Our good working relationship with the Office of Management and Budget (OMB) is enormously important. Dr. Jack Fellows of OMB is a hydrologist and a good science partner in planning these programs. He has helped guide us and prepare documents. He has been very effective. Working with him in identifying budget priorities, we have moved the program's budget from somewhat over $100 million in 1989 to the President's request of almost $1.2 billion in 1992.

It is through the Office of Science and Technology Policy—through the present science adviser, Allan Bromley—that we reach into the Domestic Policy Council and other parts of the White House policy apparatus.

The CEES Federal research strategy for global change accompanied the President's budget in January 1989. Since then, we've prepared similar documents laying out the details of the program in far more detail, including the budget priorities.

In our original document, we laid out the research program goal—that is really important. It's something to focus on in our discussions today. There are a lot of aspects of the world, all the way from the core to the atmosphere, that have changed over its millions and billions of years. This program is to gain an understanding of the complex interactions that predict these changes so that we can establish a scientific basis for national and international policy formulation decisions.

Our objectives break down into three parts: documenting, observing, or monitoring; gaining understanding through research; and developing models—both conceptual models and predictive models—so we can predict what the implications and the impacts would be.

U.S. Global Change Research Program

Robert Corell, Assistant Director for Geosciences
National Science Foundation and Chairman,
Working Group of Global Change

I want to share some perspectives on the U.S. Global Change Research Program circa 1991, where we hope to go and what the forces are.

We are interested in the total Earth system. The U.S. Global Change Research Program is intended to cover a fairly broad spectrum of scientific interest. There would have been a propensity for us to focus on physical, biological, geological, and chemical sciences—the traditional parts of the natural sciences—but we've made an explicit reference to social processes because potential anthropogenic changes—changes the come from people—are what bring us to the table. We need to know more about the evolution of societies, about the way we invest our resources as a civilization, and about the way those investments affect our environment.

These concerns intermesh with an international and national policy framework. And we, in the Earth sciences, for the first time, at least from my perspective, have moved from the quietude of our laboratories to front and center. We're on the agenda at the Paris Economic Summit. Our science can no longer be done in the isolation that it was in the past. Science results now are placed on the policy tables of heads of state.

When Margaret Thatcher was the Prime Minister of Great Britain, she became interested in global change. She asked for, and received, briefings. Every 2 weeks she spent half a day sitting in Number 10 Downing Street with key scientists who tried to help her understand the driving scientific questions that make global change important to her nation and the other nations around the world. She became very, very knowledgeable about the subject. She would get into the questions of what's in the model and the roles of the various component parts and processes. That's a different level of interest by policymakers from what we've been exposed to throughout most of our professional lives.

Most of us gathered here, and certainly the Committee on Earth and Environmental Sciences (CEES), tend to be working on the scientific underpinning of global change, the processes in question. This research sits in a larger context, particularly in the Departments of the Interior, Energy, or Agriculture—what I call the Earth-based mission agencies. Those agencies have strong needs for understanding the impacts of global change on the terrestrial environment and the political outcome of these projected changes. It is that interaction between scientific research and policy information needs that must be well coordinated to help the policy process solve some major problems now and in the future.

If we're going to say something about how science fits into the policy process, we must separate out Earth-systems elements that are normal and natural—driven by the way the climate functions and has functioned over the millennia—from those elements that are induced by humans around the world. That will help us understand the changes that we can and cannot influence.

We've tried to drive the U.S. Global Change Research Program from fundamental scientific issues and questions. Yet, we are part of the policy process. Our job is to somehow link science and policy, to speak the language of policymakers. For example, when we talk about biogeotechnical processes, most people on Capitol Hill won't know what we are talking about. We must put that into a context that lets them understand that it has something to do with the carbon cycle and that the carbon cycle is important.

The U.S. Global Change Research Program is organized across government to bring together the resources of all of the participating agencies. We're hard pressed to find an agency of government that is not involved. The policy process is handled through the Domestic Policy Council, which consists of those members of the Cabinet who have domestic policy responsibility, augmented, in this case, by two science agencies that were not there before: NASA and NSF. At this time the research activities are conducted by DOC/NOAA, DOD, DOE, DOI, EPA, NASA, NSF, SI, and USDA.

PCAST, the President's Council of Advisors of Science and Technology, came into existence roughly a year ago. It is made up of people appointed by the President from outside the government. It is patterning its organization after the IGFA process, so there are direct clones in the CEES. Three members of the council have been designated as liaisons to CEES, and they are in fact expanding their membership to work more closely with us.

The U.S. Global Change Research Program has worked to build linkages between these groups. There are many examples demonstrating how this work is paying off. If you look at the 1991 economic report the President sent to Congress, you'll see, for the first time, a major section on the environment—written largely by the CEES community and our partner agencies around the government. This is an example of the results of the linkages among agencies that this program has created. These linkages are not perfect.

They need to be expanded, but the framework is there, and we seem, in my judgment, to have gotten off to a decent start.

I'd like to suggest that the United States has one of the best organized programs for global change research; it is, by a long shot, better organized than global change research programs in virtually any other country in the world. Our ability to use our organization, our structure, to get the job done for our people will be the true test.

Our program goal has three priorities: to support the broad U.S. and international scientific effort; to identify natural and human-induced changes; and to focus on interactions and interdisciplinary science. Nothing is in the U.S. Global Change Research Program unless it serves at least one of these priorities, and we hope it serves more than one.

The program is designed to evaluate the Earth system. To use a medical metaphor—to identify the Earth's vital signs. What makes it tick? We need to measure those key parameters and keep track of them over time. This should help to truly expand our knowledge of the critical processes, and that leads to a conceptual enhancement of understanding.

I think it's tremendously important that we all enhance our conceptual understanding of the Earth's life-sustaining functions; then we can worry about model development, prediction, or assessment. Without that fundamental knowledge, the programs to predict changes are likely to fall short of the long-term program goal. What is that goal? Ultimately, to help us better assess—if you will, predict—the future so that sound management and policy decisions can be made.

No matter what is done, human-induced variability must be separated from natural variability. Understanding must be enhanced so that there is some predictive capability. But trying to fit the U.S. Global Change Research Program into a framework has become controversial at times.

Nevertheless, the framework has been immeasurably helpful to us as we have tried to work our way through the budget process. It does have an impact on the actual budget. Budget policymakers who don't come from science—decisionmakers at the White House and Capitol Hill—understand that we have brought a priority process to bear and can better understand that the funding increases we request are being generated as part of a carefully crafted priority structure.

The framework is a living document. It should be changed. It's had a few modifications in the year and a half of its existence and will have more in the out-years.

Enough background. The program and the budget for fiscal year 1992, the one that is before the Congress, represents about a $230 million increase over the 1991 budget. That's a little less than a 25 percent increase. This virtually doubled the program since 1990.

What were the guiding principles used in developing the budget? What is the difference between the strategy of 1990 and the strategy of 1989?

In 1989, the agencies that make up CEES said to the Administration and the Congress, "We recommend that you wrap this program up in about 3 years with about a 60 percent increase each year. Thereafter, a committee of the agencies will manage those resources. Some programs will fade out and new programs will emerge as the objectives are amended." That was agreed to for 2 years.

The budget summit has forced us to rethink that approach. Instead of 50 to 60 percent increases, what we can expect is much less than that. It will be significant growth nonetheless.

In putting forth the 1992 budget, we were asked by the Office of Management and Budget (OMB) to take a good look at the long-range targets, timetables, and goals and objectives. The CEES is in the middle of developing these. It's a tough job to put milestones on a scientific research program, and yet we're spending over a billion dollars, and congressional and White House people want to know where that money is going, when the goals will be met, and what useful results will be produced as we proceed toward the goals. These are valid concerns.

This is not simply a climate program. The word "climate" is used frequently, because that's the topic that has the political clout at the moment. It's the topic people understand. Words like "greenhouse gases" are constantly in the newspaper. But we're concerned about more than just climate. We need to know how this planet ticks, what makes it function, what the controlling processes are. We are trying to ensure that over the long term we have the capacity to track how the earth functions. Because of the visibility of the climate aspects, we chose to highlight some of those things that will move us forward on the climate question a little more rapidly and slow down the growth of some of those other parts of the program. That is a fact; however, there is no less of a commitment to the other elements of the program over the long term. They will probably grow a little more slowly.

How did we decide that? We decided to introduce some new ideas. As most of you know, in the early work of the committee, we had to think about integration. We had to bring together the component parts, disciplines, and resources of people and ideas to eventually get an integrated view of the system. We ended up using the idea of the integrating theme, which moves us to truly integrating all of the component parts.

We chose to do three or four themes. These are the areas in which there was substantial budget growth. We lead with climate modeling and prediction as precursors to integrated persistent modeling. Modeling, prediction, and assessment provide an integrated force for working across the disciplines. This not only allows us to deal with what you might call a classical view of climate modeling from the physical perspective but also forces us to worry about the ethnogenic element—the biological and social sciences aspect.

It also forces us to ask questions about the past, about paleoclimate, and about fundamental Earth systems processes. That's our strategy. We think it will help us move toward our goals and will ensure a sound program in the long run.

There are also three additional focal points: global water and energy; global carbon; and ecological systems and population dynamics. Let me say a word or two about each of them.

- *Climate modeling and prediction*. The goal of this element is to develop improved predictive capability of the Earth as a global system and to enhance our capacity to predict global climate at regional levels.

  This is a very challenging objective. It is going to take years to meet it. But we think that setting that as a target, as a precursor to integrative Earth system modeling, is a desirable feature. It means getting at things like the climate process and all of its component parts. It also has implications for ocean science and the atmospheric research community.

  We see ourselves improving integrated predictive capability versus merely building the models. That has three implications: to make predictions, to support the assessment process on the science as well as the policy, and to provide input to improve our modeling capability.

  There are a number of key component parts that we're working on: to ensure that data sets fit into and feed the modeling process; to enhance process understanding so that the component parts are a more realistic picture of what's really taking place in the Earth's environment; and to increase computational capability not only in new machines but, more important, with algorithms to do the complex analysis more effectively and efficiently.

  It is estimated by the modeling community, not by CEES alone, that we need roughly three orders of magnitude of increased computer capacity. We will have that at our disposal within the next 5 to 8 years. That makes it possible to start conducting modeling at regional resolutions.

- *Global water and energy*. In my view, this is the first really truly integrated piece of scientific research that we are conducting across disciplinary, system, and scale boundaries. Its first expression, certainly not its only expression, is the Global Energy and Water Cycle Experiment (GEWEX) program.

  GEWEX is a world climate research program initiative. GEWEX was born conceptually a number of years ago but is now ramping up very rapidly. Its first major pilot staging program is for the continental United States.

  The international community decided that the continental United States provided a unique opportunity—we have a massive data set. It brings in the hydrologic cycle at the highest level of our conceptual notion of that idea. The international office for GEWEX is here in Washington. It is chaired by a U.S. scientist. So the United States has shown substantial leadership in developing this effort.

- *Carbon Cycle*. The carbon cycle is not just CO_2; it consists of all the carbon elements in the system. This has very strong biological implications. Many of the processes that move carbon around and sequester it have both terrestrial and oceanic biological implications.

  Our level of knowledge about the carbon cycle is remarkably poor. For at the moment, we can't account for 25 percent of the carbon sequestration process. Conventional wisdom is still that it's not in the ocean but somewhere in the terrestrial biosphere. Hardly a month goes by that *Nature* or *Science* or another major semi-popular journal doesn't address it. The science requirements here are really broad.

  The Earth sciences research community in general and USGS in particular have contributed significantly over time to paleostudies. These studies have helped set the groundwork for understanding the carbon cycle. We now need to expand that to understanding the large carbon cycling process in the terrestrial environment. This will be a valuable contribution.

- *Ecological system population dynamics*. The Department of the Interior has important resources and you here in USGS have unique abilities that allow the ecological system and population dynamics part of the program to expand because of your interest in the terrestrial system.

I would be irresponsible if I didn't say something about some of the other parts of the program. Those integrating areas that have substantial impact on the solid Earth processes, paleoclimate, and other Earth systems history issues are particularly important. I want to point out that we have asked the Academy to set up special panels to review these and other areas. We expect those reports out this year. They might substantially alter the out-year projections for our investment in research.

For the next 4 years, the overarching goal is establishing the program that will build an integrated system model with regional resolution. We think that that's going to come into being say by 2010. A companion to that modeling effort is a global observing system. The Earth Observing System (EOS) is not a global observing system. It is a research tool that allows us to get to the global observance. In the Earth sciences there are many observing systems. They have taken decades to put into place. Once stream gauges, for example, are in place, they're a vital part of evaluating how your science is doing and how your policy is functioning and can become part of a global observing system.

Those are the far, far distant goals and objectives. To reach them, we're going to be working in the early part of the program, first by building a sound scientific and programmatic footing in the early part of the 1990's—focusing on climate, moving toward predicting climate, and then integrating our Earth system modeling at increasingly finer resolutions until regional scale predictions can be made with a good understanding of their reliability.

In passing, I need to mention something about computer resources. As many of you know, there is a companion FCCST program in the advanced scientific community known as the High Performance Computing and Communications Program. The two are working side by side. CEES is worried about program-specific aspects of computing, and the high-performance computing initiative is concerned about the generic issue of computing resources. So that program, for example, is driving very hard toward massively parallel computer architectured software and the supporting hardware.

The people who are really working on that problem think they will have a crossover on vector-based computing—massively paralleled computing—in 2 years. That's significantly earlier than was originally anticipated. For us, that's exciting because when you start to think about massively paralleled computation, you start to think about two to three orders of magnitude more power. And that translates into resolution of the kind we need to meet our goal of predictions at the regional scale.

There are many problems that we're going to run on workstations or other computing resources as they exist today. This we'll continue. We're not done with vectorized, parallel, and Cray-like machines. But for certain problems there will be major improvements.

I also want to say a word about international cooperation. This is a complex picture, but it has a very simple message. Many of the component parts of the U.S. Global Change Research Program have global implications and therefore involve as many nations of the world as are willing to participate. In thinking about that, we've come up with a strategy for developing the ideas, the commitment, the resources, and the methods of implementation.

By and large, the CEES is relying on the scientific community to do the fundamental science. That involves scientists in government agencies and elsewhere but not through the CEES per se. So we rely heavily on the U.S. National Academy of Sciences (NAS). We rely heavily on the workshop processes that produce science plans and scientific implementation programs. But largely they're known through the International Council of Scientific Unions (ICSU) or its national equivalent, such as the NAS.

With respect to facilitating and implementing these programs internationally, we rely to a large measure on the intergovernmental bodies of the United Nations, such as the World Meteorological Organization or UNESCO, because they have the membership and the access to the international research community. And to do many of these terrestrial research programs, access to field programs requires participation from the international sphere.

Last summer we formed an international equivalent to CEES. It's called IGFA, the International Group of Funding Agencies for Global Change Research. It brings together the CEES-like bodies from around the world to coordinate to the best of our ability the timing of assets that are put on the problem so that we don't decide to put all our money in the United States on one set of programs while other countries make other decisions.

I want also to say a word or two about something that is very close to home but has broad international implications. At the White House conference last spring, the President invited other nations to join the United States in establishing regional research institutes that address regional and global research efforts. Since that time, there have been task forces appointed under the CEES. There's a special group now called the Working Group on International Programs and Development that has the responsibility to work with the Office of Science and Technology Policy (OSTP) and other bodies of the government to establish an institute for the Western Hemisphere. The first major expression of that will be a science-level planning meeting in Puerto Rico in mid-July. And within the 1992 budget, there are resources to kick this off in the Western Hemisphere.

If you would like to track the philosophy that is inherent in the U.S. approach to global change research, I urge you to read Report Number 15 of the International Geosphere-Biosphere Program [Global Change System for Analysis, Research and Training (START)] . It lays out the conceptual framework for these regional research institutes.

In summary, the U.S. Global Change Research Program presents the scientific community with some very substantial challenges: to reduce uncertainties about our understanding of how the planet ticks, to make predictions about what future environments are likely to be, and to reduce the uncertainty of our predictions—to give us the capacity to feed into the policy process. The long-term goal of CEES is to know about the Earth and what makes it function. Out of that knowledge, the other matters will fall into place.

U.S. Department of the Interior/U.S. Geological Survey Global Change Research Program

John Kelmelis, Coordinator,
USGS Global Change Research Program
U.S. Geological Survey

Thank you all for coming to the first USGS Global Change Research Forum. The term "forum" was chosen carefully. A forum is an open exchange of ideas, and it is ideas that make research happen; of course, funding money helps too. The forum is somewhat more structured than we'd like it to be. But structure is necessary so that as many research topics as possible can be presented in the short time we have available.

I hope that all of you here will take the opportunity to talk with other scientists and to make contacts across divisions and across disciplines to help with your research. Listen to the discussions on topics that are not your usual areas of interest; surprising new and innovative research efforts may result.

You might ask why the Department of the Interior is involved in a scientific research program that is often characterized as climate change research. And the answer is simple; it is stewardship.

The Department of the Interior is the steward of 500 million acres of managed and unmanaged lands and of natural resources in the United States that span the physical, biological, and social spheres, without which large segments of the population would suffer incredibly and without which large segments of the economy would crumble. It is imperative that we know how global change affects the management of that land and those resources and how those lands and resources will affect global change.

The U.S. Global Change Research Program is far more than climate change. While the climate change question is one of the major issues, other issues are critical as well—all are linked to the climate system, but all have causes and effects outside of the climate system. All are critical to policymaking, whether the climate is actually changing or whether it's merely varying.

These issues include, among many others, sea level rise; coastal changes; biodiversity and population dynamics; desertification; water availability, both quantitative and qualitative; and land use changes and their social and economic impacts. These are all areas in which the USGS and the rest of the Department of the Interior have scientific and management interest.

Since its beginning in 1879, the U.S. Geological Survey has conducted global change research. Of course, it was not called global change research at the time; that is new terminology. The USGS has had a long tradition of studying the Earth's past.

Studying the Earth's past is critical for mineral exploration, and one of the earliest charges of the Geological Survey was to inventory the mineral resources of the land.

Characterizing the present has been a basic staple of the USGS research since its inception. A monumental effort lasting more than a century has provided environmentalist and engineer alike with maps of the land's surface so that efficient and sound use could be made of our limited resources. We are only now beginning to realize how limited and fragile some of those resources are.

The processes that have changed the past to the present have also been studied since the Geological Survey's beginning. It is the basis of science to understand processes. It is only by understanding the many Earth processes that we can ever expect to make wise choices on the use of the resources or wise decisions on the hazardousness of a place.

All of this research has produced immense amounts of data. The USGS has learned how to manage that data for the benefit of all. The USGS is still learning and will learn more as research and operational activities produce new data, new types of data, and new demands for data. Responding to this challenge will expand our technology, our management capabilities, and even our philosophy of data management.

Thus, the USGS is unique in its expertise and desire to examine the past, characterize the present, and develop an understanding of the processes that have changed the past to the present—and that will change the present to the future.

The USGS, with our sister bureaus at the Department of the Interior, brings a unique perspective to the U.S. Global Change Research Program. It is the perspective of those who must manage the resources of our lands. We work at the scale of laboratory experiment, at scales at which managers must make decisions, and at global scales. These are not just spatial scales; they're temporal scales as well. Because of this, we have already achieved results that are useful to resource managers and to other scientists in the U.S. Global Change Research Program.

It is now our job to deliver results, not just make plans. And so a sample of our 1991 results includes the publication of the final report of the 3-year Delaware River Basin Sensitivity Study. This report will contain information on climate and weather scenario development; on hydrologic and water resources response to climate, both contemporary and potential future; on response to the Delaware estuary, both physical and chemical, to climate change; and potential changes in drought in the basin.

Also, a pilot study to estimate the sea surface temperatures in the North Atlantic Ocean for the Pliocene, the last time the Earth's climate was significantly warmer than at present, will be completed. The pilot study will demonstrate the capacity to reconstruct environmental conditions on a scale suitable for testing general circulation model simulations of warmer climates.

Digital files of global vegetation cover and global soils maps have been produced. Vegetation greenness and classification maps at national and continental scales will be developed. Initial efforts will concentrate on the United States and North America. This will help identify spacial and temporal boundaries of evapotranspiration and other biologic processes.

A prototype of the Global Land Information System will become operational. This system will provide a method to access metadata (information about information) for scientists seeking sources of information about the Earth's land surfaces. This will help scientists studying global changes and other topics to locate the existing terrestrial data they need to conduct their research.

During the next couple of days we will hear in much greater detail about these and many other accomplishments of the USGS Global Change Research Program and the progress in new and ongoing research efforts. These accomplishments are important. This is a program driven by stewardship, management, and policy needs, and many of those needs cannot wait until the ultimate question of whether, or by how much, climate is changing is answered.

The Committee on Earth and Environmental Sciences (CEES) Working Group on Global Change (WGGC) is developing a milestone chart at the moment. It shows a global climate model capable of reliable predictions as the ultimate goal. Producing such a model of the climate will probably take 30 to 40 years. To achieve that goal, many intermediate milestones must be met. Complicating the achievement of those milestones is the iterative nature of scientific advancement, with understanding in one field nourishing advances in the other.

Fitting into the effort are hundreds of small contributing programs that contribute pieces to the puzzle. No one agency, even focusing all of its efforts, can hope to accomplish this on its own; however, all of the agencies together contribute parts, which makes the entire project realizable.

If we were to carry the chart showing the milestones of the U.S. Global Change Research Program to the project level, the chart would be totally unintelligible. There would be tens of thousands of projects across many agencies over the life of the U.S. Global Change Research Program. Obviously, the chart will have to be updated frequently as new, and sometimes unexpected, results and interpretations occur.

We, the U.S. Geological Survey, are part of the overall national and international global change research effort, a valuable part without which I believe the effort would falter, if not fail. Our programs cut across six of the seven science elements outlined in the research plan of the U.S. Global Change Research Program. Of course, these programs focus on our areas of greatest expertise, making critical contributions to the interdisciplinary science elements of climate and hydrologic systems, biogeochemical dynamics, Earth systems history, and solid Earth processes. We're also active in the study of ecological systems and dynamics and in human interactions.

The U.S. Global Change Research Program has evolved from the former climate program established in 1979, 10 years before the U.S. Global Change Research Program started, to 11 elements funded at $28.2 million in fiscal year 1991. And in fiscal year 1992, the President's budget requests $32.5 million. The number of elements of the program will certainly fluctuate over the years as our understanding of portions of the Earth system increases and objectives of the U.S. Global Change Research Program are met. Fluctuations will also take place as the realities of the nation's budget affect programs all across government.

The programs currently funded span the interests of global change. Some are global in nature, such as interactions of climate and hydrologic systems, biogeochemical exchanges, paleoclimates, and land characterization. Others examine sensitive regions. These are sensitivity of water resources, coastal erosion and wetlands processes, volcano emissions, climates of arid and semiarid regions, and cold region studies. The land data and extramural grants programs provide broad support to the other work. I won't describe the details of these programs. You'll learn more of them throughout the meeting over the next few days.

When the programs of the other bureaus of the Department of the Interior are included, a broad-based study of the terrestrial system becomes apparent. It is imperative that any global change research effort we propose to do not only meet the needs of the U.S. Global Change Research Program but also provide useful input to the stewardship mission of the Department of the Interior, and we have to ensure that any proposals we make identify that input.

That our research will be applied to important problems of the day is in keeping with many years of performing basic research and data acquisition in support of policy decisions. I expect that results from our program will be useful long before the question about global change is ultimately answered.

I was told that I had to say something about the process by which decisions are made within the USGS on global change research, so bear with me. There's a round-table group. In fact, we meet around a round table in the Information Systems Division conference room every week. That group discusses all of the issues of the USGS Global Change Research Program.

That group is called the "Gang of 12." All of the divisions are represented, as are the Assistant Director's office for programs and the Assistant Director's office for research.

The Gang of 12 discusses each program element that is proposed and attempts to agree on a total package that can be supported by the divisions while meeting the overall goals of the U.S. Global Change Research Program, the Department of the Interior, and the USGS. We have an external panel of experts, most of whom are here at this forum. They help us with the review process. Also, we must attempt to assess the viability of the program in the Office of Management and Budget (OMB) and Congress.

In addition, the Committee on Earth and Environmental Sciences has developed the unique ability to generate phenomenal amounts of paperwork for the member agencies. And that's not really a negative statement. The work is necessary to build and run a complex program like the U.S. Global Change Research Program.

Much of the work is short turnaround—on the order of days, or even hours, and it's needed to keep the wheels of both the executive and legislative branches greased and responsive to the requirements as varied as the continued availability of Landsat data and the expansion of the terrestrial-based research in a program that is often conceived of as simply climate change by many outside of the research community.

The Gang of 12 helps provide the necessary responses and is constantly dealing with these short turnaround efforts. Exhausting as it is, it helps keep our fingers on the pulse of the program.

The program, as agreed upon by the Gang of 12, is presented to the division chiefs for their approval. And, of course, negotiations have to take place there. Then it's presented to the Director, who must weigh it against the other priorities within the bureau and within the Department.

Within the Department, there are two working groups: the Global Change Research Working Group, of which Steve Ragone is the Executive Director and to which I am the USGS representative, and the Policy Working Group, which is at the Assistant Secretary's level.

The Research Working Group acts for the Department much like the Gang of 12 acts for the USGS. It is through the Department's Global Change Research Working Group that programs are presented to the CEES.

Through a system of agency reviews, working group reviews, and specialist task group reviews, a balanced program is arrived at by the CEES. This includes suggesting increases in the types of research that are inadequately supported to meet the goals of the program and suggesting decreases in oversupported programs. Once the recommended balanced program is planned, it is proposed to the OMB.

There is another track as well, and that is through the normal budgetary process. There the research programs are presented to be included in the Department's budget request. Thus, there are two independent tracks. Both tracks lead to OMB; both tracks must be satisfied for the program to make it to the President's budget request to Congress, and then Congress must be satisfied. Members of the Gang of 12 often get involved at various levels of this process as well.

That's enough about process. It's science that we came here to talk about.

We will strive to maintain our tradition of objective scientific research while we step beyond our traditional disciplinary boundaries and make interdisciplinary, interdivisional, interagency, and international links to significantly expand our understanding of a changing world. Please participate, interact, exchange ideas, make new links among each other, and help make this forum and the U.S. Global Change Research Program one of the most dynamic scientific efforts that the USGS has ever engaged in.

Interagency Working Group on Data Management for Global Change

Eliot Christian
Information Systems Division
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The Interagency Working Group on Data Management for Global Change, usually known as simply the IWG, focuses on data needed for global change research, and its activities are as relevant to global change researchers as to data managers. Although its role is one of coordination, not implementation, the IWG does have a record of making things happen.

Through the IWG, the Federal research agencies help set the tone for global change science. As you know, global change research is not driven solely by the traditional agenda of the natural science agencies, and the Survey viewpoint needs to be actively expressed. The Survey does have a strong voice in the IWG, in part because the Survey's Land Data Management Program is second in size only to NASA's program.

In addition to influencing global change research on a broad scale, what the IWG does can affect your project on the operational level. For example, the IWG may influence how your proposal is evaluated, how easy it is for you to find other global change data and information, and what you might pay for data. If you let your needs and preferences be heard through the IWG, your research could benefit directly.

The U.S. Government efforts in global change research are focused through the Committee on Earth and Environmental Sciences, the CEES, chaired by Dallas Peck. A continuing theme of the U.S. Global Change Research Program is that data management is an integrating priority. That means it's crucial to the success of all of the other program elements.

The current IWG grew out of informal coordination in 1987 among Ray Watts of the USGS, Dixon Butler of NASA, and Francis Breatherton, then at the National Center for Atmospheric Research. Launched as an ad hoc group under the CEES, the IWG works closely and shares membership with the CEES Working Group on Global Change, especially its "Earth Systems Measurement and Data Management" task group and its "International Coordination and Development" task group.

To support its coordination role, the IWG today has a modest budget made out of contributions by the participating agencies—NOAA, NASA, EPA, NSF, Navy, and the Departments of Energy, Agriculture, State, and the Interior. With active interagency participation, the IWG has been effective in raising policy recommendations to the CEES and in tackling practical data management problems.

Now, you might be wondering why data management becomes such an issue in the global change context. Sure, the U.S. Global Change Research Program is big, but the technologies available for data management are still advancing explosively. Why don't we just scale up our current data management practices to handle global change data and information?

We all know that global change research will generate data in unprecedented volume and that researchers will need that data organized in many different ways. Although the sheer size of the data management problem presents a massive technical challenge, there are more basic reasons why global change data management requires a new approach.

The need for comparable data in very long time series requires that data be archived and documented well enough to be useful long after the original research, 20 years later at least. Also, global change research, as a program, is driven by public policy issues rather than purely scientific curiosity. This need for policy relevance implies a strong emphasis on interdisciplinary perspectives and on interagency projects.

The Survey's mission has always involved historical, interdisciplinary, and interagency data issues. Each of our mission programs has long established data management practices and its own coordination with other programs. However, global change research spans many programs, so the inconsistencies that exist become very troublesome. One striking example is the lack of an interagency agreement on how to document data to be useful over time and across science disciplines.

The IWG is now coordinating agency plans to resolve some of these major inconsistencies, including a framework for a global change data and information system. The concept of this system is evolving away from that of being a new supersystem that would bring together everything you'd want to know about global change—the major thrust is now to emphasize the prerogatives of the separate researchers and a very decentralized flow of information.

The original charge given to the IWG is very simple: to make it as easy as possible for the scientific community to access and use data needed to study global change. It should be clear here that the IWG is focused on the needs of the scientific community, not on helping data managers find new ways to do data management.

The National Science Foundation (NSF) continues to be a very active member of the IWG, and the Committee on

Geophysical Data of the National Academy of Sciences is a continuing source of scientific guidance. In fact, the IWG commissioned the Committee on Geophysical Data to document a U.S. strategy for global change data and information management. The strategy document is still awaiting official publication, but draft copies were widely reviewed and are in active use now.

The IWG also sponsored the University Corporation for Atmospheric Research, UCAR, to hold a 3-day forum on data management for global change. At that forum, the IWG met with 65 representatives of the scientific community to explore their perspectives on data management problems and possible approaches. Another forum is planned for later this year.

In addition to periodic meetings and forums, the IWG coordinates several ongoing activities and has supported pilot projects by member agencies. One ongoing activity is the development and operation of a global change master directory. This joint venture maintains a catalog of global change data sets across agencies and data centers.

There is also an ongoing IWG activity handling international exchange issues and another activity that looks at various agency mechanisms that are in use for ordering and billing for data products.

The IWG recently started a new activity to address data and information management standards issues, which includes informal and emerging standards. As chairman for that standards activity, I tried to draft a charter to encourage any level of input or participation from researchers and data managers. I look forward to working with many of you in this IWG standards activity.

The IWG sponsored the International Geosphere-Biosphere Program's Global Change Diskette Project, which focused on the need for cost-effective tools and data for developing countries. The project's PC-based geographic information system used Africa data sets such as vegetation cover. It's now being widely used for training in global change study techniques.

Another pilot project is the Survey's recently completed "Arctic Data Interactive." ADI serves as a prototype for an electronic science journal incorporating hypermedia techniques.

The IWG is always looking for additional pathfinder projects or other ideas. The general guidelines for proposals are that the project be short term, 1 to 2 years, and that it address data management problems of wide interest to agencies in the global change research community. To be appropriate to the IWG, the proposal ought to be outside of the normal responsibilities of any one agency so that IWG sponsorship is directed toward projects for which there is no other usual source. Please call me directly or go through your division channels if you would like to raise an idea to the IWG.

In the policy area, the IWG developed a set of seven principles of data management to be applied to the overall U.S. Global Change Research Program and to be used as criteria to evaluate project funding proposals. These principles were approved by the CEES and are receiving wide exposure internationally, throughout the Federal Government, and within agencies. The Global Energy and Water Cycle Experiment, GEWEX, has incorporated these principles as part of its science plan. And through division representatives, the Survey is seeking to apply these principles to all of its programs, not only global change research.

The two most relevant principles to researchers here are probably the principle of designating an archive for the data and the principle that data be made available as soon as they are widely useful. Now, setting a short time for exclusive use of data is probably a sensitive point. I would point out that for the Earth Observing System (EOS), the plan is that data will be available to all researchers at the same time as they are made available to the principal investigator.

Ultimately, these data management principles must be applied in actual projects. As you may know, an explicit data management plan is already required in applications for NSF grants. When global change project proposals are reviewed by the CEES, they are now evaluated in part on how the projects propose to address these principles.

In practice, the specific mechanisms you might use to manage project data can range from fairly simple to very complex. At the project description level though, expressing your data management plan ought to be very straightforward. So I'd like to take a look at what that would consist of.

Within a global change research project description, the data management plan should address these four points:

1. Identify—what data or information will be gathered or derived;
2. Document—how and where the data will be documented;
3. Archive—which established archive will house the data; and
4. Distribute—when and how the data will be made accessible.

The data management plan in a one-page project description might be stated in two or three sentences. For example, a complete data management plan might be written like this: "The primary data product is a derived data set produced by a computer model of global change. The data will be accessible at the USGS in Menlo Park when the model is published. It will be documented in the Earth Science Data Directory."

Another example might be: "This project will generate Arctic groundwater observations, which will become part of the USGS National Water Information System data base. Once the report has been published, the data will be identified in NAWDEX and referenced in the Global Change Data and Information System."

This second example also illustrates that project data management will often need to mesh with broader mission programs such as those that are managed at the division level. Please call me at any time if you'd like to talk about a project plan and how you can identify, document, archive, or distribute your project data.

Before I finish, I'd like to give you a feel for how you might envision the Global Change Data and Information System as a tool for your global change research.

Let's say you have an idea for a new global change research project. As you develop your project description, the Global Change Data and Information System shows you related projects already completed, in progress, or proposed. This information allows you to see opportunities for collaboration and to avoid unnecessary overlap with other projects.

The system also allows you to see the current research priorities as expressed in the overall U.S. Global Change Research Program plan, so you can tailor your project description to highlight its relevance. In writing your project description, you include a data management plan that tells how you will identify, document, archive, and distribute the project data. In this case, your new project data may not be part of an existing mission program, so you check with your Division's data management office to determine which established archive will house the data. The Global Change Data and Information System describes the procedures for requesting services from that data center and helps generate an electronic message requesting data archive services. The data center then responds with the electronic input form you will use to identify and document your data set.

The Global Change Data and Information System directory helps you to find or even browse through related data sets that may be useful in your project. Of course, once your own project is funded and completed, the system provides the mechanism for you to describe your project data so that they can be used by other researchers across agency and scientific discipline boundaries.

In summary, the Survey is working through the IWG to improve access to USGS data and information by outside global change researchers and access to outside sources by USGS global change researchers.

I hope you've seen that there are things afoot in the IWG that you may want to explore further or to influence. To the extent that you let me know what works for you, we can help the IWG shape the future for global change data management.

A Fragile Seam of Dark Blue Light

Jack Eddy, Director
Office for Interdisciplinary Earth Studies
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Some years ago, I met with a number of astronauts who were preparing to man the Spacelab module, which was to be carried on one of the space shuttle flights. In the group was a young German scientist named Ulf Merbold.

Later, after their successful mission, he had this to say about what he saw when he first looked down on the Earth from the vantage point of space: "For the first time in my life, I saw the horizon as a curved line that was accentuated by a thin seam of dark blue light, our atmosphere. Obviously, this was not the ocean of air I had been told it was so many times. I was terrified by its fragile appearance."

Science, in recent years, has focused more and more on the Earth as a planet, one that for all we know is unique—where a thin blanket of air, a thinner film of water, and the thinnest veneer of soil combine to support a web of life of wondrous diversity in continuous change. What is more, living and nonliving parts of the system are by nature entwined and interconnected.

"When one pulls up any part of it," wrote the naturalist John Muir, "he finds its roots entangled with all the rest." I think the mystic poet Francis Thompson may have said it better in 1893, when he wrote, "All things by immortal power, near or far, hiddenly, to each other linked are; that thou canst not stir a flower without troubling of a star."

I don't think anyone doubts these connections—least of all, any of you here. We're here for a global change research forum, a scientific enterprise that's driven by environmental concerns serious enough to have inspired the kind of scientific crusade that, as Bob Corell showed us, is going to extend halfway through the next century, and it's focused on impending global changes.

Yet the world is everchanging and always has. How do the modern changes rank in perspective? Ask yourself this question: What are the most drastic global changes that the Earth has known in its long history?

My own list, in the long run, would include probably first the acquisition of an atmosphere and the oceans; the birth and the spread of life; the repeated annihilations of life that seem to go on with the destruction of species, as at the boundary of the Cretaceous and the Tertiary 65 million years ago; and surely the drifting and gnashing of the continents that give us our present geography and all the action in geology today.

If asked to describe the most drastic global changes of the last 1 or 2 million years, I think I would put only two on that list: the recurrent ice ages that signaled a drastic change in the tempo of Pleistocene climate, and the rise of man, whose whole history has been played out in the shadow of the last of these. And from all of these, life has recovered, apparently through interactive processes that make it resilient to environmental change.

What about the last 100 years? What is the most drastic global change of this period? Although the Earth has warmed by 0.6°C, that global warming cannot qualify as a drastic change, nor can wars. It is surely, instead, the complete ascendancy of man on the planet, now numbering about 5 billion, or about 34 per square kilometer of the land surface of the Earth.

We get an erroneous impression of the crowding of the planet in our own country, a very large one, where the population of about 25 per square kilometer is significantly less than the world average. In China, where a quarter of the Earth's people live, the density of people is now 108 per square kilometer. In the United Kingdon and India, in the latter of which one-seventh of the Earth's population lives, there are over 200 people per square kilometer; in Japan and the Netherlands, there are over 300; in Taiwan, there are 513; and in Hong Kong, there are 5,000.

I think the marks of this many people are now on the planet: marks that were at first subtle and for millennia insignificant in any global view. But that is no longer the case and never will be.

We see them most easily at night, as in the montage of modern dark Earth views from space put together about 10 years ago by Woody Sullivan and already out of date. Only the curved arc of the aurora borealis that is seen there, caught by chance above Norway, is natural, a reminder of how the world was but a century ago.

The world at night is now so bright that cities on the northeast coast are indistinguishable in the glowing blur of a megapolitan BosWash. Puerto Rico is an island of light, as is the whole south of India and Southeast Asia, where so many now live and will live.

More than 1 percent of the Earth's surface is urban. More than 10 percent of the land surface is now under cultivation. More than 30 percent is today under active management for the purposes of mankind.

I think more pervasive and much more troubling in 1991 are the changes we have wrought in but the last seconds of geologic time in the essential chemistry of the planet. I don't think I need to tell any of you about it, about how permanent it is and about how when you drove here today, as I did, you put carbon dioxide into the atmosphere that will be here long after any of us in this room are on the planet.

Inadvertently, we have initiated, indeed, a global experiment whose ultimate outcome is at present unknown. And in so doing, we may have driven Ulf Merbold's fragile seam of dark blue light—in which is all of life—beyond its range of natural repair. Perhaps we have done this at a time when we must prepare the planet for a doubling of the present world population, most of it in the less developed world. The Earth is changing at a rate faster than it has ever known and at a time when a change in any part of it affects all the rest.

There's nothing new or particularly sinister about global change; it happens all the time. The Earth is a dynamic planet, as you all know and have seen. It is only in our minds that time or conditions are ever frozen and only our short lifetimes that make anything seem fixed. On repeated occasions, since man has walked upright, the planet has been held in the icy grip of major ice ages, as in the time of Cro-Magnon man, when all of Canada, on another continent, lay under 2 miles of ice for more than 20,000 years.

"The whole history of humankind," wrote the historian Norman Pounds, "has been lived in the shadow of an ice age." And in a world of global change.

When Columbus was a boy, the Earth fell again into a period of prolonged cold, called the Little Ice Age, that lasted for 400 years through the middle of the 19th century, when global temperatures dropped something less than 1°C. And the Earth recovered.

What is different today is the rate of anticipated change.

The Little Ice Age, so far as we know it, was characterized by a rate of change of about 0.5°C per century in global mean surface temperature. The rate of greenhouse warming in the most conservative models of climate is at least ten times faster, about 0.5°, not per century but per decade, which will drive the temperature, so far as we know, in 50 to 100 years to levels higher than any that have been reached in the last 30 million—since the early Tertiary Period.

There is something else that is new and, to me, troubling about these predictions of future climate change. It is the first time in human history that we, as individuals or a society, have been allowed to look clearly at the face of the future. Never before have we known tens of years in advance what awaits us, and it is a real experiment to see how society responds to being able to look ahead. It makes one wonder: Did God ever want us to be able to look ahead? Much of the responsibility of what we do about it rests with people like us and with organizations like the Survey.

Is all this I have told you another "cranberry crisis" that will soon go away? I don't think so. What makes it seem different to me is that now it's based on solid scientific information. And in a sense, it's now accompanied by a call from policymakers at the highest level.

The reason I decided to invest my life in this crusade 7 years ago was it seemed to me that these were problems that not only were real—and they bother me as they do all of you—but were only going to be made worse with time, that the pressures of population were always going to keep these problems before us.

Can we count on continued funding at the level that Bob Corell showed us today, or not? I think for sure we can. These problems are going to be there, and they're going to get worse. To me, that makes it a rather safe gamble of one's time, plus something we should all work toward.

It is a difficult problem for several reasons. To Senator Gore, the reasons were these: We deal with long-term problems in a short-term world. We deal with "uncertainties" that will always abound, as in the classic case of the association between tobacco and health. There will always be enough uncertainty there to make some people unsure even though the great weight of evidence is in another direction. We need to decide using incomplete information. There is a science fiction nature to the threat. And the options are expensive and socially revolutionary.

Still, I think the current level of national and international awareness of the problem still should amaze us; it does me.

In the past, there were only voices out of the wilderness. One of them was Andrei Sakharov, the Soviet dissident physicist who died in 1989. In the 1970's, when he was fighting a political system from within, he defined what he saw as the four threats to mankind, and he put them in the order of perceived danger. I think it's a pretty good list. The first was nuclear war; the second was hunger; the third was problems of the environment; and the fourth shouldn't surprise us coming from someone there: "the stultifying effects of mass culture."

The war danger seems to be passing. Hunger has always been there. And the environment will always be a major problem.

Today environmental consciousness worldwide has reached a peak unequaled in all the past. The notion of an endangered Earth, driven largely by concerns of ozone depletion and impending climate changes, has now appeared in almost everything we watch or read and is or has been high on the agendas of heads of state. In the last 4 years, global environmental concerns have taken the covers of all the major magazines, the titles of television series, and even an episode of "Saturday Night Live."

Global environmental change has been the subject of conferences called personally by the President of France, the Prime Minister of England, the President of the Soviet Union, the President of the United States, and even the Pope, in an encyclical issued a year ago at Christmas 1990. The Second World Climate Conference held in Geneva a few months ago focused the attention of an entire planet on impending problems of climate and global change.

I think we're ready to do something about it, and that's why you're here. The dilemma that we face is knowing what to do, which requires knowing how the system works.

A number of years ago, that bad boy of science, Wally Broecker, told me this story that now seems apt to describe the situation we have all felt when we're asked, as scientists, what we should do about all these problems.

Wally said it's not unlike being dropped down, totally uneducated, to take charge of a major oil refinery—and forget for a moment the fires of Kuwait, but think about a big working oil refinery. You're plopped down in the chair of the director—as the one who is supposed to know.

Then people start coming in your door and saying, "Something's wrong. The stuff that used to come out of the pipe down there on LE56 that used to be clear is now all black. There are continual fires breaking out over here on this side of the refinery, the electric power keeps failing, the heating doesn't seem to work, and the supply system seems to be breaking down."

As these problems come in, you would say, "Now, wait a minute; hold it. Show me the plans. Put the plans to the refinery on the table here, and we can track down what the problem is."

They look at you and say, "But we don't have any plans. We don't know how it works."

That is the situation with the Earth: we work here, but God never gave us the plans that go with the place. Moreover, we're like the guys in the refinery: we've got pipefitters and electricians and plumbers and welders, but we don't have any total system "refinerists," or whatever it would be. And we somehow, in a great hurry, have to find them, or make them, and in the meanwhile re-create the plans of a working system.

I think it *is* a crisis, and I think, as in the case of a city under siege, there is a need to organize and mobilize, if not to put out fires, at least to understand the nature and extent of the environmental threat.

What is it now that we must do? I have a personal list of six actions that seem to me imperative. As we talk about the program, you'll see that most of them are well covered in the program we are building, but here's my personal list.

- The first is to put the Earth in intensive care. We've got to monitor the vital signs of the planet. We must put in place, as fast as we can, systems to detect global changes in what are to our best knowledge the most vital signs. And we must continue to track them indefinitely into the future.

  This we owe to future generations, and it is a task neither started nor yet fully defined. What we now know best of long-term global changes concerns trace gas abundances and, to a lower level of certainty, surface temperatures. The scattered readings of other parameters now in hand are not enough to diagnose a system as complex and as interconnected as the Earth.

  And if you agree with me that this must be high on our list, that helps you understand why in a budget that's never big enough, but still big, for global change, so much of it goes to NASA.

  It's expensive business, but we've got to start doing it. And it's up to you and me as non-NASA persons to make sure that the vital signs that EOS and other space and nonspace systems monitor are the right ones.

  The challenge is to anticipate wisely, so that when the youngest among us are asked 20 years from now what vital parameters have changed in the last 20 years, we shall have given them the means to answer. I think it very sad that we didn't start that earlier and that the process is being delayed as much as it is now.

  You should ask yourself what you would put on the list, knowing we can afford to monitor only a limited number. The comparison with health is, I think, a pretty good one. We're like physicians in an intensive care ward, with a patient, just admitted, on whom we can put on only so many monitors. We have only suspicions as to what is wrong. What is it we should monitor? We've got to come to agreement on that, soon, and start. That was number one.

- Number two on my list is to begin a crash effort to recover the history of global changes. What happened the last time that temperatures reached the levels that we expect? How did the natural Earth respond to carbon dioxide and methane levels as high as we see them going now? I don't need to remind you, as people in the Survey, that that is the stock and trade of the geological sciences, who do it very well.

  It is also, I think, one of the great intellectual achievements that through such reading of natural diaries, we were able to recover the lost fact that there were once ice ages. Humans are very poor sensors of these changes as they happen, surreptitiously, in real time.

  It has always amazed me that we endured and forgot an ice age at a time when there were intelligent Cro-Magnon people walking around Europe and people in this hemisphere, yet nothing came down to us at all about it in legends. We have a story in the Old Testament about a flood and some other catastrophes that were probably local events, but nothing at all about a global ice age. I think we were designed to forgive and forget, which is good, but it makes us the worst possible detectors of gradual change.

  We must use whatever tricks we can to read nature's diaries, and we must do it faster than we are now. We know very little of past climate. There's now a debate, as you know, regarding the warming of even the last century. In a few months, a conference will convene in Japan to debate whether there was a Little Ice Age.

All that we know in good detail about the really long temperature history of the Earth and about the corresponding changes in atmospheric greenhouse gases comes from a number of ice cores that you can count on the fingers of one hand, and you wouldn't need all five fingers. These dangerously few cores have provided our only clues to how the Earth works as a biogeochemical system. Other records like them from other places are needed now for prediction and for the validation and testing of models.

In some cases we shall be doing something like what other scientists now call "salvage archeology."

Salvage archeology, as you know, comes in when, for example, the Corps of Engineers, which I think is about to put in a dam in southern Colorado, and archaeologists are called in to quickly dig up the past before it is forever lost. We face a similar call in the case of old-growth trees, which are going very fast, and a number of threatened lacustrine and other sedimentary records.

We must recognize that we have to work faster and to secure greater funding to recover the history of the past, which, in many cases, is no longer a subject of only academic interest. The world is watching and waiting and looking over our shoulders, depending on us as scientists to answer such questions as the phasing between past changes in carbon dioxide and surface temperature. Which comes first? How much of a lag is there, and why?

- The third imperative is to develop an Earth system science. I think we have started on that at last, and you've heard that talked about today. In doing this, we go against the grain of history. For 100 years, science has been specializing, going in exactly the opposite direction. In the courses of study that universities taught 100 years ago, for example, there were no detailed science subjects like today. Geology is a rather late invention, as are oceanography, hydrology, and atmospheric physics. It is our nature to specialize; we need those also who will bring it back together.

If you were to ask the Earth—if it could speak—"How is your biosphere today?" or "How is your geology?", it would say, "My *what*?"

It's all hooked indistinguishably together. These are artificial names that we have invented in order to study it or to grant diplomas, and we somehow have to find a way to look at the whole. This does not take from the need for continued, strong disciplinary studies, but we need to add to our agenda for research the study of system processes and of global processes.

- The fourth imperative is to begin now to develop Earth system models. Bob Corell gave us today a very visionary look into the next 50 years that called for the development of models and the need to get them in place so that we can begin to make reliable predictions. They will require the missing set of plans for the refinery.

I think the goal should be operable models, capable of tests within 10 years and capable of reliable prediction within 20. And, if this seems like a long time away—A.D. 2000 or 2010—think about how short a time ago 1980 or 1970 was. Usable models must include all coupled elements of the system. They will be crude at first—toy models, if you will—but I think we ought to get going on them with some speed.

- The fifth imperative is to put in place a global data and information system: a challenge in which the Survey has many roots and many present activities. The system must be one that makes environmental data, both past and current, available to everyone, instantly, among all fields of study. We must make it easy to ship biological data to meteorologists, to ship meteorological data to biologists, and to ship data between countries, even new ones like Lithuania.

Why is it necessary? Because the problems are interconnected and data connect disciplines. And because we need all the manpower we can get. And to accommodate, intelligently, a vast new stream of Earth system data.

We must also put an end to the concept of proprietary data, and that's a case where EOS is really leading the way. When I started out as an astronomer, it was the way you worked, that you got your own data and for a while, sometimes a long while, you kept it very close to your chest. Only then, and sometimes never, was it shared. Those days are passing.

Data and information systems may sound boring to some. A voice from the room today pointed out that data always comes up last and gets talked about last and funded last, and we somehow have to reverse that. Here is where our nation's big investment in the Earth Observing System may help us out, because that system is trying to put in place a global data and information system that can serve as an example.

- The sixth and last imperative is to enlist and train a new army of scientists who are needed to create the set of plans that God never gave us and to provide the responsible policy advice that will be called for ever more loudly in the future. Gene Rasmusson asked about that earlier today from the floor: Where are the people who are going to do this?

We must build a cadre of scientists and technicians needed to keep the promises that you and I have made through efforts in education at all levels. The challenge is to recruit and educate a new and larger generation of scientists to work in the environmental and related sciences and to make these challenging jobs attractive.

We must also involve, much more than we have, the talents of scientists from the undeveloped world. We must do this for three reasons. The first is that we need them. There aren't enough people if we don't involve them.

A second reason is that we need to know about their parts of the world, and we're not going to get that kind of information unless we involve those who live and work there.

The third reason, sometimes forgotten, is that to provide responsible policy advice that might make a difference in this world you cannot expect nations to respond or alter policy if they haven't been involved from the start.

In spite of past efforts, the present international effort at global change is at present still very heavily an activity of scientists of the Northern Hemisphere and Australia, leaving out about half the globe, and this must be redressed.

In particular short supply are regional and global ecologists and regional and global hydrologists. Another shortage I came across last week at an international meeting on past global changes are the people who model paleodata, who develop climate and other environmental models of the past. There are so few of them that if you get them, all three of them, at a meeting, then all the work stops.

It's not unlike the situation in the early days of radio astronomy—a new subdiscipline that burst upon the scene at the end of World War II—as a very exciting new field. It was so new that there was almost no one to work in it. The story was that whenever two radio astronomers got together, the first thing they did was to try to hire each other.

As I said earlier, we need hydrologists who work at scales larger than the watershed. And we need some kind of hermaphroditic scientists who can work with one foot in the natural sciences and the other in the social sciences, to address what is probably the biggest unknown in the whole system, which is the human element of global change.

How well does the U.S. Global Change Research Program (USGCRP) fit this list?

The good news is that much of what I've said is now being done.

For one thing, the U.S. Global Change Research Program that you heard described so well today by Dallas and by Bob Corell and others now stands as a "paradigm" to the world. It has set an example for many other countries. It has broken ground that we never thought possible several years ago. I think we should feel happy about the amount of funding that Congress has given us at a time when there are many competing demands.

I don't think we heard enough today, even from Dallas, who is such a big player in it, or Bob, about the tremendous achievements of the Committee on Earth and Environmental Sciences. The Committee is still not a perfectly happy family, of course, but its members have done what was never done before in bringing agencies together and in looking at each other's budget books. They are even finding ways to live with the hardest of all organisms to live with—which is the National Academy of Sciences—to try to work with the Committee on Global Change. These are tremendous accomplishments.

At the same time, there are still problems in our own U.S. program. One of them is that while there are lots of closet environmentalists out there, in academia and elsewhere, the reaction of much of the academic community is not altogether positive to an organized program of the sort that we're here cheering on tonight.

Their objections deal with fears of big science versus little science, a scientific psychosis that will probably never go away. We customarily get around that by saying we've got to do both and that, yes, not all science is going to be in the U.S. Global Change Research Program, not in any field. We may indeed take all the paleomodelers—all three of them—but there may be only a small fraction of the people in any field that will be working centrally in this, and there will still be room and money for a scientist's own individual investigations.

I think there's a general distrust of any program—I'll have to say it—that is run by the Feds. My God, you're going to let USGS and NASA and NOAA run this thing? So we have some more selling to do to show them how sage and trustworthy you all are. But that's out there.

There's also a danger of diffusion that worries me. Some research institutions I won't mention have developed unilateral initiatives, reinventing for their own ends, programs that we've organized, we've fought for, and we believe must be done collectively. They arise as a way to win without getting in the game or even suiting up. I look upon it as in a bicycle race where, yes, there's lots of them back there winding on us, but that's okay so long as we get to the needed end.

There's the question of sufficient manpower that I mentioned earlier and the question of adequate funding. Have we yet made the case to Congress about what we're doing in this program?

I was asked also to tell you about the international program in which the U.S. Global Change Research Program is a part and more than a part as an example and a leader. What's going on in the rest of the world?

The International Geosphere-Biosphere Program has been in the planning stages now for 8 years. Would you believe it? It is going into the implementation stage this year, in 1991. It now involves on the order of 50 nations, of which about 40 now have national committees for global change research like our own. Included are all the major countries of the world. China and the Soviet Union are very big players. The ones we've yet to bring on board are largely in Africa.

The IGBP is sponsored by the International Council of Scientific Unions and is now organized by a secretariat in the Swedish Academy of Sciences in Stockholm. Sweden now pays far more than its share of administrative costs; many other countries, including the United States, also contribute.

The IGBP now collaborates very closely with the World Climate Research Program, and that collaboration gets closer and closer all the time. Many of us wish that the two will someday merge into an international global change program that would have the climate elements of the World Climate Research Programme and the nonclimate elements of the IGBP working essentially together.

The core research projects that are now established in the IGBP define the way that that program will run. They comprise a federation of allied research projects that do a pretty close job of matching the major tombstones, if you will, in the U.S. Global Change Research Program: the major science priorities.

There are now five of those federated projects that together make up the IGBP. One of them is the International Global Atmospheric Chemistry Program, IGAC. It now has a core project office in Cambridge at MIT that is funded by the United States. It brings together a lot of international effort, and it fits in with the U.S. thrust toward biogeochemical dynamics.

The second core project is JGOFS, the Joint Global Ocean Flux Study. It has a core project office established in Germany, in Kiel, funded by Germany. It will look at the marine side of biogeochemistry. Problems of the carbon cycle are highlighted also in the 1992 U.S. Global Change Research Program.

The third of these projects, less known, just opened a core project office in the last year in Australia, in Canberra. It's the Global Change and Terrestrial Ecosystems project, which includes impacts on agriculture and forestry. It is a very close match to the U.S. priority element on ecological systems and dynamics.

The PAGES project will soon open a core office in Switzerland that we hope will be co-funded by Switzerland and the United States to look at past global changes, where that acronym—that very fitting acronym—comes from. It corresponds to the U.S. effort in Earth system history.

Biological Aspects of the Hydrologic Cycle, BAHC, is an IGBP core project that will introduce more biology, more life science, into what is now the Global Energy and Water Cycles Experiment (GEWEX) program of the WCRP. It has its core project office now in Berlin.

There are now in place five major international projects of the IGBP. They each rank as the equivalents of the World Ocean Circulation Experiment (WOCE), the Tropical Ocean-Global Atmosphere program (TOGA), GEWEX, and even the IGY, if you will; five of them are going, and a few others are under discussion. The really good news is that the IGBP is now closely associated with the World Climate Research Program, with strong connections to GEWEX, WOCE, and TOGA. I think it would be a good idea to band all these together even more formally.

The IGBP has also a built-in design to mesh with a third part of the international global change program that corresponds to the U.S. thrust in the human dimensions of global change; internationally, that will be taken care of by a separate program run by the International Social Sciences Council, called Human Dimensions of Global Environmental Change (HDGEC).

These three, IGBP, WCRP, and HDGEC, I think you'll see working closely together in future years, providing the international counterpart of the research activities that we will be working on in this country.

They have worked together already in laying out the newest step you heard Bob Corell talk about today: the establishment of regional research centers around the world, an effort meant largely to entrain the less developed countries into the job of monitoring global change, understanding it, modeling it, and handling the data.

That will be done if plans proceed as now envisioned by setting up global change research centers that will, in effect, divide the world into 14 parts. One will encompass northern South America, another southern South America. Others envisioned among them are the Caribbean, the Mediterranean, and the Arctic. One will encompass the Antarctic. You can figure out some of the rest.

In each of them there will be sited a regional research center. In each of them will be regional research sites that are linked to this center. The centers will intercommunicate and talk to each other and deal with the major elements of the international program.

That's a very fast and acronym-filled survey of what seems to me a very healthy sign that countries of the world are banded together, much like the United States is within, to tackle global change research. There is now as well an international funding organization for global change research that Bob Corell has put together to coordinate international funding for these activities. Indeed, if you are a scientist who is worried about big science versus little science, maybe you should be worried, but I think again when a city is under siege, as I think the Earth is, you needn't get too upset about that.

I'm going to end with a thought about the level of funding that is now going into the USGCRP, the time that's going into it, and something about the challenge.

The U.S. Congress has authorized, in an era of severe constraints, almost a billion dollars in fiscal year 1991 for focused research in this program, a number that's within a factor of three of what was envisioned a number of years ago when this program was first thought up. Indeed this year's $900 and some million is not yet enough for what must be done, but it's still a lot when measured in terms with which we're more familiar.

How does that compare with other big numbers that we may know about? The total world economic output, the sum of the gross national products of all countries, is now about $18 thousand billion, or $18 million million.

The gross national product of the United States is $5 thousand billion, more or less. The U.S. national debt is $3 thousand million: there's another big number for you. The President's budget for fiscal year 1992 is $1,450 billion, $218 billion of which is allocated to all of the things that you and I are interested in. The savings and loan bailout will cost us $100 billion.

I read in the *New York Times* the other day that the estimated Iraqi reparations to Kuwait are about $100 billion. The cleanup costs of U.S. nuclear plants also come in at that level. Star wars was estimated a couple of years ago at $41 billion. The annual U.S. foreign aid is $12 billion. The United States contributes $1.8 billion to the World Bank each year. The cost of a shuttle spacecraft is $1.2 billion. The U.S. Global Change Research Program is big enough to appear in such a list: the President's request for fiscal year 1992, as you know, is about $1.2 billion.

How is that to be spent? You probably know. Most of it goes to NASA for the simple reason that we've got to get the vital signs monitored, and it costs a lot to get instruments started and kept in place.

What about the international costs? The estimated annual budget for each of the core projects, when they get up to full speed, is on the order of $100 million per year. The estimated annual budget of a Regional Research Center, of the 14 I told you that might be established, is $10 million. We now put about $2 million into administering the international program.

The fiscal year 1991 budget for the USGCRP is around $950 million. How much is that?

Toward the close of a thought-filled book, *The Farther Shore*, Don Gifford puts such incomprehensible figures into a more personal perspective. If you or I were personally given the U.S. Global Change Research focused budget for fiscal year 1991 to spend on ourselves, and we were given that in the year that Christ was born, invested none of it, and spent it at the exorbitant rate of $1,000 a day through all the months and years of history that have since passed by, we would still have enough left today to last another 621 years. A billion dollars is a lot of money.

I think a more appropriate comparison may be found in the fractional increases granted to the program over the last 3 years, which confirms, to me, that Congress is ready to bring this program up to the visible level.

The point I should like to leave you last is that most of the work of the broad global change program lies ahead of us. Moreover, like Babe Ruth at the plate, we scientists have pointed to where, in deep center field, we're going to place a hit, inviting a world of watchers to see that it is done. Promised are not singles, or doubles, but home runs in the form of pragmatic assessments and predictions sufficiently specific to be of use to policymakers. It is a very big challenge that we have taken on; it will require a lot of challenging research across a broad front, a lot of innovation, a lot of new methods of doing things.

I think we have to keep the message heard that prudent decisions regarding the global environment require first that we know what, if anything, is changing and why. And that the cost of the focused research to provide updated answers to these very real questions is the most prudent investment one can make in the environmental future; that the rush to legislate, which is always the first resort of policymakers, cannot outdistance knowledge nor supplant the need for better understanding.

Support of the focused science that makes up the broad global change program needs to be sustained at a level in this country several times higher than today. In time, this investment in knowing must surely be acknowledged by those who govern as a necessary fee for living on a planet so benign.

The total international cost of the broad global change program, in the United States and all other countries, will probably reach the level of $5 to $10 billion per year, or roughly 0.05 percent of the world's present economic output, and that is a very small insurance premium.

I think we have to keep reminding ourselves and others that, as Bob Corell said today, global change is more, I would say *much* more, than climate change or global warming. Most would agree that the global changes that will strike the hardest blows on people or other living things in the next 20, 50, or 100 years will not be those of climate change.

If the world is in environmental extremis today, it is more through the rapidly changing chemistry of the air and soils and water, through the inexorable and wide-reaching pressures of urbanization and intensive agriculture and land use. Impacts of a changing climate driven by the enhanced greenhouse effect are not unlinked to these other concerns, and because of them they will become even more serious.

We must never tie the support that's needed to understand a changing planet to some expected unequivocal announcement that, "Aha, the Earth is warming, and it's fitting this predicted curve."

Although it is the most widely publicized facet of the problem, climate is also surely the most fickle. It can vary only surreptitiously. It will always be hidden from human perception behind masks of short-term extremes and local or regional weather that will always far exceed in magnitude any underlying trend.

Climate change can be seen only in retrospect. And if we take the past as a guide, it can be recognized best from the perspective of at least 100 years removed. We don't dare wait for that.

In spite of all that I have said about how good an organized program is and how we have to address global change through big science, I want to end with this quotation to remind us of reality. It comes from Samuel Langley, a name you know. He was an American scientist who died in 1909, and he was, among other things, president of the American Association for the Advancement of Science.

In his retiring address as president in 1889, he had this to say, which I always try to keep in mind if I get too excited about big programs: "We often hear the progress of science likened to the march of an army toward some definite end. But this, it has seemed to me, is not the way science usually moves, but only the way it seems to move in the view of the compiler, who probably knows almost nothing of the real confusion, diversity and retrograde motion of the individuals that comprise the body."

He went on to say that although this comparison is often used, the one he liked better for the march of science is that of a pack of hounds. In the long run perhaps, the pack catches its game, but in the course of the hunt, it nevertheless, behaves in a random fashion. When in doubt, each individual goes his own way, by scent, not by sight, some running back and some forward. In some times of doubt, the louder voiced members of the pack convince many to follow them, though when they do, it's nearly as often down a wrong path as down a right one. In other times of doubt, the entire pack has even been known to move off bodily on a false scent. Nevertheless, it still seems to get its game.

Second General Session

Earth System History and Global Change

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The Earth is constantly changing, and the geologic record contains the evidence of past climate change and the effects of change on Earth systems, including the biosphere. Climate varies naturally on time scales of decades to hundreds of thousands of years. Documenting and understanding the record of natural variability is very important for differentiating between natural changes and those that may be occurring because of man's activities.

Public concern about climate change is growing because man's activities are increasing the concentration of greenhouse gases in the Earth's atmosphere. But we know from the study of ice cores that atmospheric concentrations of CO_2 and other greenhouse gases have varied naturally in the past. Figure 1 shows a detailed record of oxygen isotope variations and CO_2 content of air bubbles trapped in the Greenland Dye 3 ice core. The oxygen isotope variations reflect changes in local air temperatures at the ice core site with more negative values representing colder temperatures. The CO_2 measurements reflect CO_2 content of the atmosphere. The analysis illustrates close correlation in the variability of CO_2 content of the atmosphere and air temperature and shows that significant changes occurred over time scales of decades to centuries. Further work is needed to determine if the CO_2 changes lead or lag the temperature changes. However, it is clear from this and from other ice core records, such as the 160,000-year record from the Vostok ice core in Antarctica, that both climate and atmospheric concentrations of greenhouse gases (CO_2 and CH_4) varied significantly and on relatively short time scales in the past. Understanding the causes and impacts of these past variations can help us understand and predict future change.

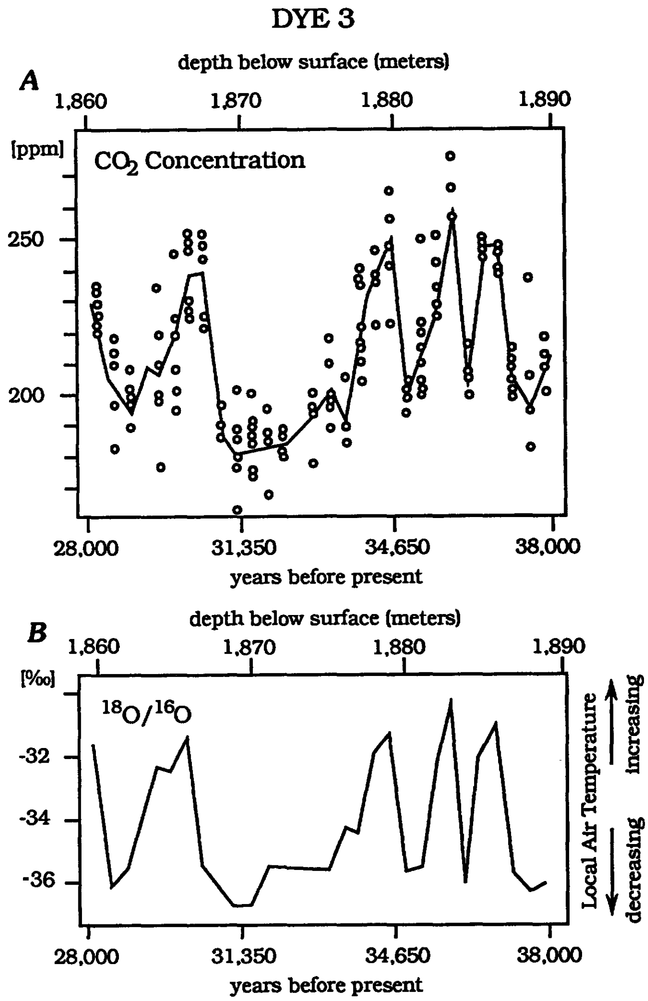

Figure 1. CO_2 and oxygen isotope values from a 30-meter section of Greenland Dye 3 ice core. The section from 1,860 to 1,890 meters below the top of the core represents about 10,000 years ranging from 28,000 to 38,000 years before present. Panel (*A*) shows concentrations of CO_2 measured from air bubbles trapped in the ice. Open circles give individual measurements. Solid line connects mean values for samples from the same interval of the ice core. More negative values indicate colder temperatures. Note close correlation between local air temperature and concentration of CO_2. Figure modified from Oeschger and others, 1985.

PALEOCLIMATE STUDIES

By studying the geologic record we can observe the response of Earth systems to climate change, gain insights into the mechanisms and causes of climate change, and determine links between different components of the climate system. We can use paleoclimate studies to build and refine climate models by testing the ability of climate models to hindcast the past. Specifically, our confidence in the ability of climate models to predict possible future changes will be increased if climate models can accurately simulate climates that actually occurred in the past.

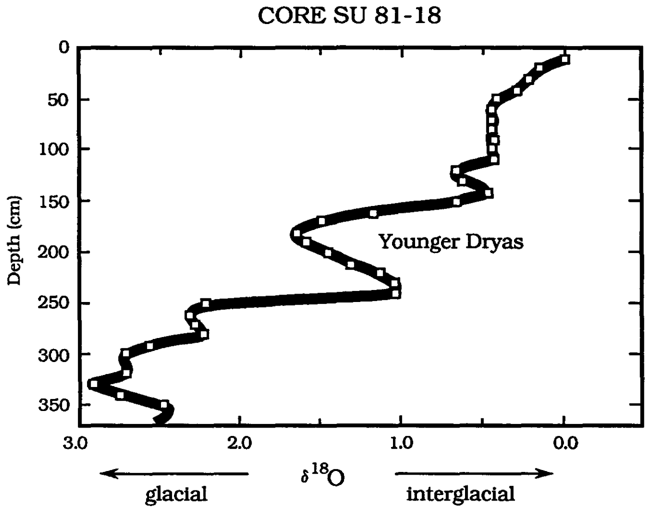

Figure 2. Oxygen isotope record from foraminifers in Core SU 81–18 taken off Portugal. The record represents the transition from glacial conditions at the bottom of the core to interglacial conditions at the core top. In this figure more positive values (heavy values) represent glacial conditions and more global continental ice volume whereas smaller values (light values) represent interglacial conditions and less global continental ice volume. Note rapid reversal toward glacial conditions that is labeled "Younger Dryas." The abrupt reversal of the transition to interglacial conditions, known as "Younger Dryas event," took place over a few decades. Figure taken from Fairbanks, 1989.

Providing information on past climates on the scale and scope needed to help understand and model future global change represents a major challenge to Earth historians. Substantial, coherent, and quantitative data sets are needed in a relatively short period of time. In order to meet the needs of global change research, resources have to be concentrated on well-selected problems and questions, and interdisciplinary approaches have to be more widely used. Recognizing the need for a more organized research effort, the National Research Council's committee on global change (National Research Council, 1990) has formulated a research plan for Earth system history that involves three major initiatives focused on the Holocene, on late Quaternary glacial-interglacial "cycles," and on longer term major climatic changes (discussed below). Investigations under this plan will explore both the conditions and the variability during these periods. In addition, particular attention will be placed on periods of abrupt transitions, which may provide insights into potential Earth systems responses to rapid changes and possible nonlinear responses to climate forcing anticipated over the next century.

The first NRC initiative is aimed at producing an integrated set of globally extensive records of the Holocene as a frame of reference for comparison of greenhouse gas induced warming. This initiative would essentially detail the natural variability of the current climate state, which must be known before anthropogenic changes can be identified with certainty. For example, average global temperature has varied by 1.0 to 1.5°C during the Holocene. Thus, the change of +0.5°C in global average temperature estimated for the last century is within the range of natural variability of the current climate state.

The second initiative is to understand glacial-interglacial fluctuations of the Quaternary. Special concerns in this initiative include delineating systems response to known orbital forcing, detailing interactions among different components of the climate system, and documenting instabilities in the climate system.

The third initiative is to examine system response to large changes. Primary concerns in this initiative include insights into warm climates, the development of paleoenvironmental data sets to test model simulations of different climate states, and the response of the biosphere to large perturbations.

As mentioned above, paleoclimate studies document a number of extreme states and abrupt transitions in the Earth's climate. We must be able to explain and model these extreme states and transitions in order to understand and make credible predictions of future changes. For example, at the end of the last major glaciation, rapid global warming was abruptly reversed at about 11,000 years ago, and large portions of the Northern Hemisphere returned to almost full glacial conditions within a time span of decades to a century (fig. 2). Then after a few hundred years, the climate again abruptly changed and rapidly warmed to the present interglacial climate. The abrupt reversal of global warming at about 11,000 years ago may be related to fundamental changes in deep-ocean circulation (Broecker, 1990), but the forcing and mechanisms for the change are still unknown. An example of an extreme warm event is provided by the Kap København Formation in Greenland. This unit contains wood and other plant remains that show that trees were growing at the northern tip of Greenland about 2 million years ago. The growth of trees at 82°N latitude indicates winter temperatures in northern Greenland 2 million years ago were 15° to 20°C warmer than present winter temperatures (fig. 3). Much additional work is needed to document the duration and geographic extent of the 2-million-year warming episode and understand the cause for this large climate perturbation.

Several common themes run through all three initiatives. These themes include (1) abrupt transitions, (2) climates of warm periods, (3) system response to known forcing, (4) biotic response to climate change, and (5) links between different components of the geosphere and biosphere with emphasis on the carbon cycle. These themes will guide the overall Federal global change research effort and provide the context for USGS investigations.

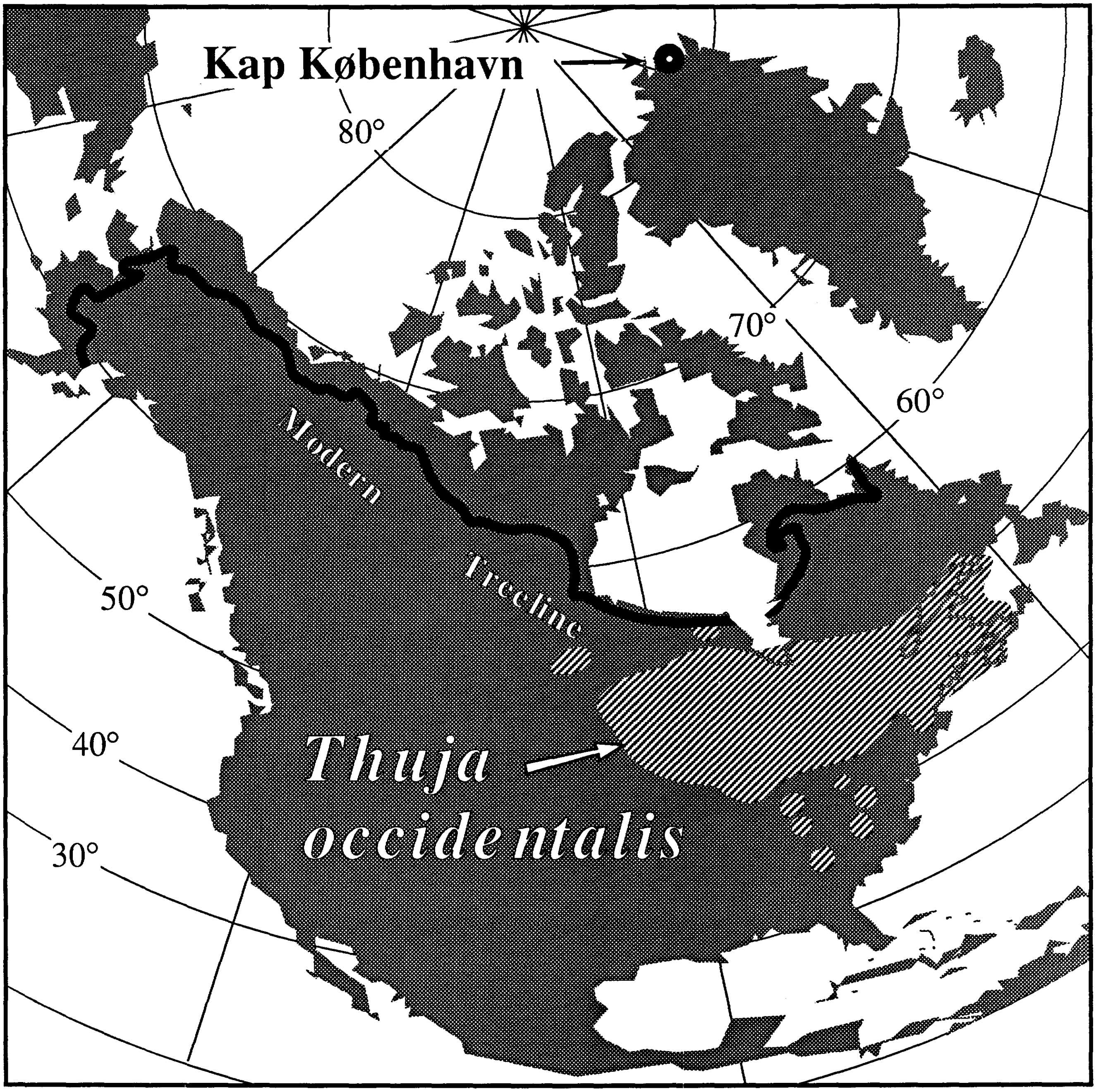

Figure 3. Location of Kap København at northern tip of Greenland, location of modern tree line, and modern distribution of *Thuja occidentalis*. Trees including *Thuja occidentalis* were growing at Kap København about 2 million years ago. This northward migration of the tree line suggests winter temperatures in northern Greenland 2 million years ago were 15° to 20°C higher, and precipitation was at least double modern values. Figure modified from Funder and others, 1985.

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Climate, Hydrology, and Water Resources

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Perhaps the most significant of all the effects of global climate change are those related to hydrology and water resources. Potential effects in the agricultural, forestry, and urban sectors, although of justifiable concern, are actually derivative problems stemming from the climate change effects on water availability. Clearly, potential changes in the distribution, quantity and quality of, and demand for water form one of the most central issues in the current worldwide efforts to understand and deal with climate change. Both nationally and internationally, a reliable water supply is an essential base for social, economic, and political stability.

The issue would be troublesome enough if it were merely a matter of estimating future hydrologic conditions. However, when considering water resources, it is also necessary to incorporate social and economic dynamics. During the first assessment of the Intergovernmental Panel on Climate Change (IPCC), scientists participating in the working group that investigated the potential impacts of climate change realized that producing an estimate of agricultural, water resources, human settlement, and other conditions extant within a climate that may exist 40 or 50 years in the future would be misleading at best and unrealistic at worst, unless estimates of concomitant social and economic conditions likely to exist in these future decades were also prepared. Thus, to acquire estimates of future water resource conditions appropriate for planning and policy formulation, consideration must be given to (1) physical changes likely to occur in the climate and hydrologic systems associated with both human-induced and nonhuman influences, (2) social and economic changes not affected by climate, and (3) social and economic changes that may occur in response to climate and that may, in turn, produce their own effect on the climate.

This presentation focuses primarily on the physical aspects of the linked climate-hydrology-water resources theme. This subject lies within the mission of the Geological Survey's Water Resources Division, and it is, in many respects, more tractable than those aspects associated with the dynamics of social and economic behavior. Two diverse components of the subject will be discussed: fundamental process research (including modeling) and the estimation of the sensitivity of water resources to climate variability and change.

We will look first at fundamental processes. For decades, hydrologists have begun seminars of broad hydrologic issues by considering the hydrologic cycle. Given the

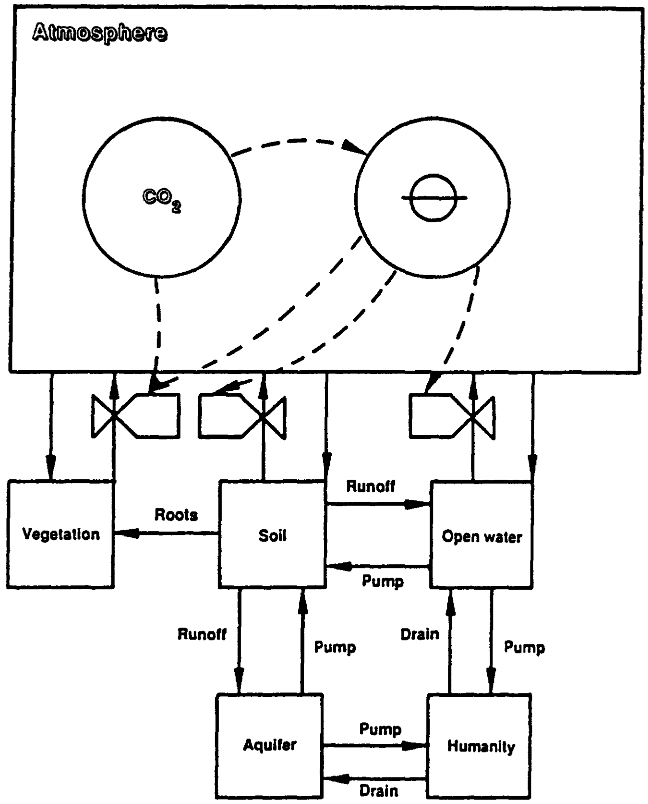

Figure 1. The global hydrologic cycle (Waggoner and Revelle, 1990).

theme of this forum, global change, it is equally appropriate to follow that tradition here. However, I will depart from the typical illustration of the hydrologic cycle (the block diagram showing land, ocean, and atmosphere, with snow, vegetation, and rivers) and use a more contemporary graphic that appears more like the plumbing in a water system (fig. 1). In this illustration, from Waggoner and Revelle (1990), the large rectangle at the top represents the water in the atmosphere. The smaller squares beneath the rectangle represent the water in vegetation, in the soil reached by roots, in the aquifers below, and in open bodies of water. The square marked humanity represents the water in ourselves, pipes, dishwashers, and so forth. Arrows represent the fluxes between reservoirs. Valves are placed on three fluxes to show that they are controlled by CO_2. Carbon dioxide directly affects transpiration from foliage by increasing it through faster photosynthesis and by narrowing leaf pores. Indirectly, CO_2 warms the air temperature,

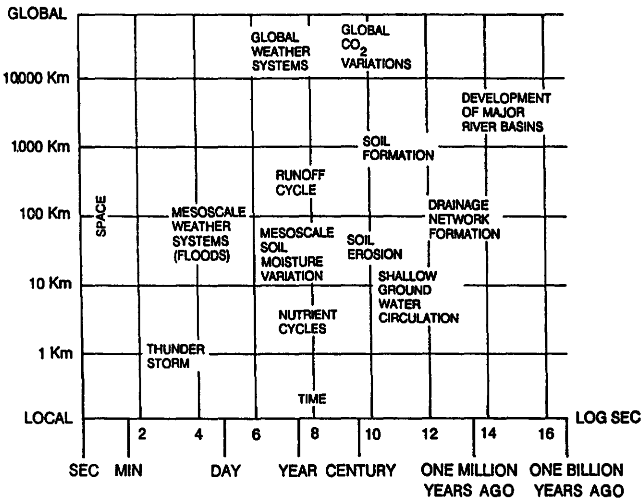

Figure 2. Spatial and temporal scales of selected atmospheric and hydrologic processes (National Research Council, 1991).

enhancing the evaporation from vegetation, soil, and open water. Faster evaporation, of course, decreases the water that runs off to bodies of water or into aquifers, increases pumping to irrigate soil, and even raises humanity's demands. The arrows from the atmosphere down to the vegetation, soil, and open water boxes represent the flux by precipitation. Water resources (in the context of human consumption and use) exist in the open water and aquifer boxes.

From this perspective, it is possible to begin defining critical climatic-hydrologic research needs in a global change context. Three of the most notable needs are presented here: improved process models, enhanced data collection, and coordinated field experiments and campaigns. Modeling and data collection are not independent processes. Ideally, each drives and directs the other. Better models illuminate the type and quantity of data that are required to test hypotheses. Better data, in turn, permit the development of better and more complete models and new hypotheses (National Research Council, 1991).

Clearly, model development and improvement have become pivotal aspects of the U.S. Global Change Research Program. The adequate parameterization of variables representing the terrestrial phase of the hydrologic cycle remains a major weakness of existing general circulation and mesoscale climatic models. As a recent report of the National Research Council (1988) notes,

> "Treatments of runoff in climate models do not adequately represent the realities of catchment-scale hydrology, such as the highly nonlinear, almost threshold, relationships between rainfall and runoff as well as the dependence on terrain, soil heterogeneity, and subgrid-scale statistical structures of rainfall patterns. . . . Improvements in modeling the linkages between surface hydrology and climate require better understanding of evapotranspiration from diverse terrestrial vegetation, other land covers, and lakes; infiltration of water through the unsaturated zone with consequent improved understanding of aquifer recharge; the conversion of precipitation to streamflow, including the role of topography at a variety of scales of catchment and storm patterns; and the processes of snow accumulation, transformation, redistribution, and melting."

Hydrologists have developed a number of finer resolution basin-scale models of hydrologic processes. It remains to be seen if these relatively successful basin-scale modeling efforts can simply be scaled up to work in the coarser atmospheric models. The usefulness of microscale knowledge of plant physics, soil physics, lake thermal structure, and other processes in estimating the required model parameters of a general circulation model (GCM), given the diversity of land characteristics in a given cell, is unknown. Approaches to modeling the land surface processes in the GCM's that account for the fact that moisture conditions within a grid cell are highly variable need to be explored. Finally, the importance of lateral movements of water on or beneath the land surface (either as ground-water flow or by diversion, storage, and application to the land in large irrigation projects) to the climate system has not been explored. The present GCM's assume that water moves only vertically between the land and the atmosphere or directly from the land to the oceans and that there is no spatial redistribution of moisture within the cell or between cells. The issue of scale is critical in any effort to model climatic and hydrologic processes, because the range of dynamics involved varies spatially from a point up to the globe and temporally from a second up to millennia (fig. 2).

Data also represent a major need in the climatic-hydrologic research arena. Advances in the atmospheric and hydrologic sciences are dependent upon the success with which investigators are able to integrate reliable, large-scale, long-term data sets (National Research Council, 1991). Such data are particularly needed to initialize, validate, and prescribe boundary conditions for the process models described earlier. The data sets required for these tasks are highly varied and include topography, land use and cover, vegetation, soil moisture, humidity, temperature, precipitation, wind velocity, and runoff.

It is also important to recognize that models are not going to provide answers to all of the questions associated with global change. Data need to be used for monitoring the global environment and for conducting diagnostic or retrospective studies. An example of such use is evident in the subdiscipline of hydroclimatology, where large-scale interactions between the atmosphere and the hydrosphere are determined by statistical associations. Hydroclimatology has both diagnostic and prognostic elements and is a strong complement to the deterministic process models of climate, especially with respect to processes for which the underlying physics are poorly defined.

This leads us to the third critical need, coordinated field experiments and campaigns. It is now generally accepted that further progress in the development of the needed parameterizations of land surface fluxes of energy and water in climate dynamics and hydrology must be based on new comprehensive experiments conducted, and with field data collected, at broader scales than those customary in the past (National Research Council, 1991). One of the most visible and comprehensive signs of the recognition of this need is the incipient Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Programme.

The goal of GEWEX is to determine global distributions of water and energy fluxes from observations and to compute their values from predicted atmospheric properties, for the purpose of quantifying the energetic processes of the Earth's climate system and the atmospheric forcing on the ocean, land, ice, and vegetation (World Climate Programme, 1990). The initial phase of GEWEX is focusing on the establishment of a GEWEX Continental-Scale International Project (GCIP) to study the water and energy budgets of an extensive geographical area of the earth for which there is a large volume of accessible data. The objectives of GCIP are (1) to determine the time/space variability of the hydrologic and energy budgets over a continental scale; (2) to develop and validate macroscale hydrological models, related high-resolution atmospheric models, and coupled hydrological-atmospheric models; (3) to develop and validate information retrieval schemes incorporating existing and future satellite observations coupled with enhanced ground-based observations; and (4) to provide a capability to translate the effects of a future climate change into impacts on water resources on a regional basis.

The Mississippi River basin has been selected as the GCIP study area. The meteorological and hydrological networks covering the continental United States, enhanced by new Doppler radars, wind profilers, and automatic weather stations being implemented as part of the upgrade of the U.S. observing network, provide the best opportunity for collecting the data sets essential for (1) the determination of precipitation, wind fields, and other climatic variables and (2) the validation of estimations based on remotely sensed data. Equivalent data sets are not likely to be available in other continental areas within the same time frame, that is, the mid-1990's.

The general strategy for implementing GCIP is illustrated in a time-phase schedule commencing in the early 1990's with a series of contemporaneous planning studies, proceeding through to a buildup observational period, and then to a full 5-year intensive observing period (fig. 3). The timing of the buildup period and start of the intensive observing period will be determined to some extent by the speed with which some of the new key observing systems planned for the Mississippi River basin can be implemented. Currently, it is estimated that the intensive observing period could begin around 1995 and continue through to the end of the decade, when it is anticipated that several new satellite-borne remote sensing systems will be in operation. Diagnostic, modeling, and water assessment studies will proceed throughout the life of GCIP, making use of each new data set as it becomes available.

We turn now to the second aspect of the climate, hydrology, and water resources theme to be addressed in this presentation, that is, the sensitivity of water resources to climate variability and change. Although a totally comprehensive analysis of the climatic effects on water resources requires consideration of numerous specific scientific issues, only a few of the most important ones are discussed here. One of the more critical and controversial issues relates to the use of climate scenarios. In order to estimate the hydrologic and water resource effects of climatic change, a regionally specific forecast of future climatic conditions is necessary. Precipitation, air temperature, cloud cover, wind speed, and humidity are the most important conditions. Unfortunately, reliable forecasts of regional climate changes are currently unavailable. In their absence, various approaches are used to develop "scenarios" of future climatic conditions. These include (1) hypothetical, or prescribed, climatic conditions; (2) general circulation model output; (3) recent historical analogs; and (4) paleoclimatic reconstructions (fig. 4; Gleick, 1989; Lins and others 1990).

Purely hypothetical scenarios have been widely used in recent years to assess the response of watersheds to future changes in climate. Frequently referred to as "what if" scenarios, this method of generating climatic values is easy to develop and apply and affords a useful means of testing the sensitivity of a watershed to a range of climatic conditions. In practice, the method involves prescribing, for example, a +2°C or +4°C temperature increase, along with a percentage change in precipitation, such as +5 or −10 percent. Admittedly, such scenarios may not be very realistic. They are valuable, however, in facilitating the study of the effect of a range of climatic values without specifying the likelihood of one set of conditions versus another. Thus, emphasis is placed on identifying under what combination of climatic conditions a water system experiences stress, as opposed to attempting to "forecast" future water system conditions.

A second type of climate scenario is based on the output from general circulation models (GCM's). Model-simulated atmospheric values, such as temperature and precipitation, are then used as input to hydrologic models. General circulation models are the most sophisticated class of climate models. They are detailed, time-dependent, three-dimensional numerical simulations that include horizontal and vertical atmospheric motions, heat and moisture

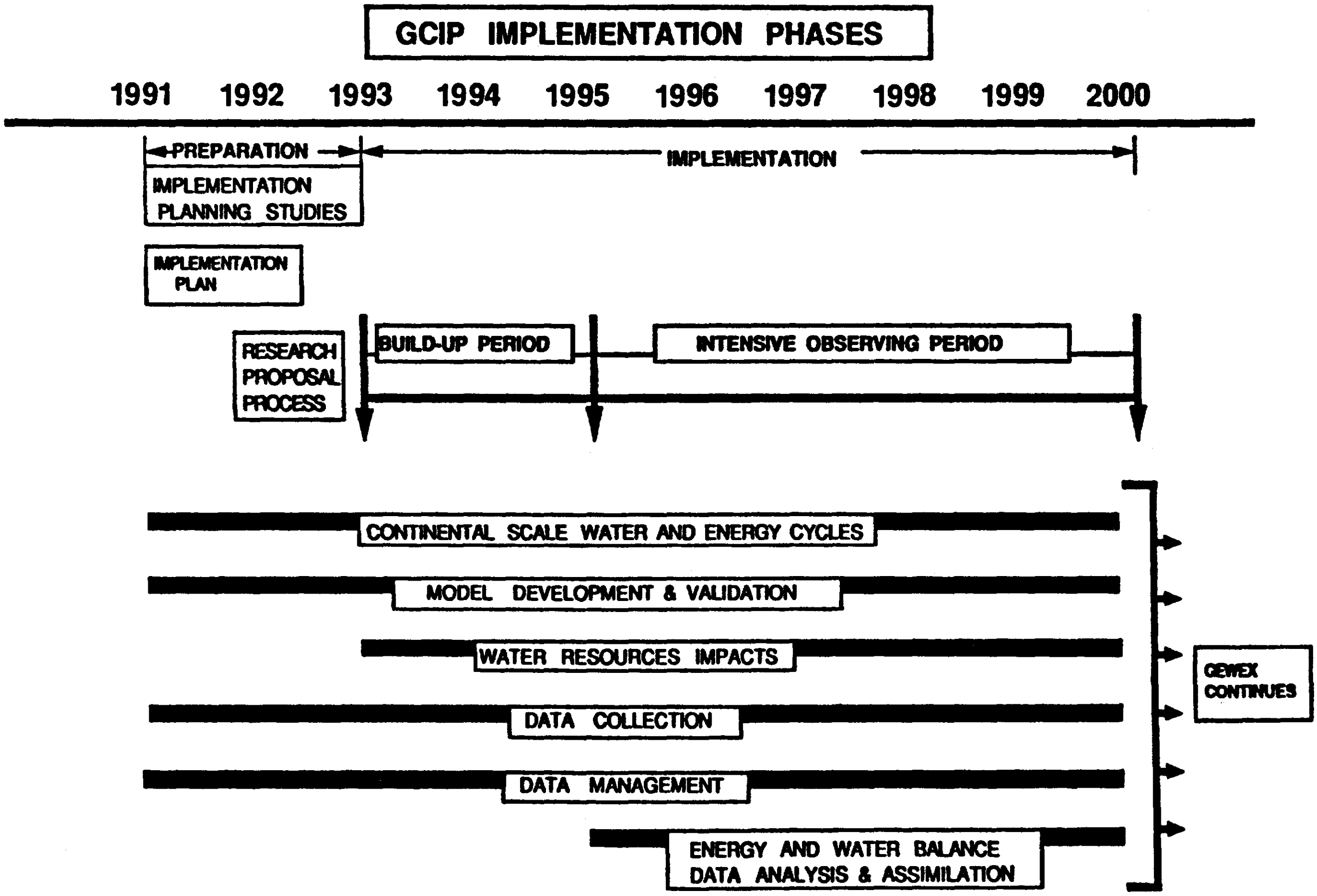

Figure 3. The GEWEX Continental-Scale International Project (GCIP) implementation phases.

exchanges, and interactions between the land, ocean, ice, and atmosphere (Manabe and Wetherald, 1980; Washington and Meehl, 1984; Wilson and Mitchell, 1987). Presently, GCM's provide the most comprehensive simulations of the climatic effects of increasing concentrations of greenhouse gases.

Despite their complexity, however, general circulation models suffer from two major limitations when used to provide data for evaluating hydrologic and water resources consequences of climatic change. First, the spatial resolution of GCM's, typically several degrees of latitude by several degrees of longitude (that is, hundreds of thousands of square kilometers), is too coarse to provide information detailed enough to be of hydrologic significance. Hydrologists generally focus on processes occurring at catchment scales (tens to hundreds of square kilometers). To be of use from a hydrologic perspective, therefore, GCM output must be disaggregated from the low-resolution grid scale to the more detailed high-resolution catchment scale. The development of methods for disaggregating GCM-generated estimates of precipitation and temperature is currently a very active area of research. A major contribution to this endeavor has recently been made by a team of Geological Survey investigators using a technique based on classifying weather pattern types affecting streamflow in the Delaware River basin (Hay and others, 1991). Weather types permit the identification of weather conditions associated with varying frequencies, intensities, and amounts of precipitation. Weather-type frequencies were used to stochastically simulate precipitation for Philadelphia and to produce estimates that statistically match observed precipitation. A new method was then developed that derives weather-type

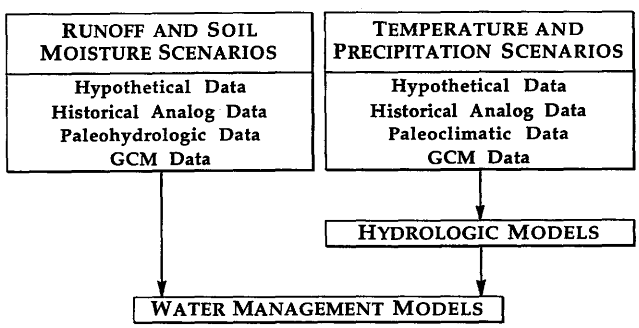

Figure 4. Methods for estimating the hydrologic and water resource impacts of climatic change (Gleick, 1989).

frequencies from GCM-generated climate change scenarios to simulate future precipitation.

Second, the parameterization of terrestrial hydrologic conditions in general circulation models is very rudimentary and typically does not provide regional simulations that are realistic enough for water resources planning. Parameterization refers to the expression of the statistical effects of various detailed, high-resolution (subgrid scale) transport processes in terms of the more coarse, low-resolution (grid scale) variables explicitly resolved by the model (Global Atmospheric Research Program, 1975). Because of the wide range of scales of interacting atmospheric processes in relation to the limited spatial resolution of GCM grid cells, it is technically and economically impractical to observe or explicitly calculate the effects of subgrid scale processes in detail. These subgrid processes are, however, extremely significant in their effects on climate, and it is necessary to relate their statistical effects to measurable or computable conditions at more general scales. Because the arbitrary specification of detailed effects does not accommodate full interaction with the broader scale resolvable state of the atmosphere, parameterization is required. As a consequence, the representation of many atmospheric and terrestrial conditions (such as evapotranspiration and soil moisture) in GCM's are generally poor and unrealistic.

Although general circulation models are internally consistent characterizations of the climate system, accounting for most of the important components and interactions, they are still very crude representations of the natural system and do not produce realistic forecast information at regional scales. It is very important to be cognizant of this fact when using GCM simulations of future climatic conditions to estimate potential future hydrologic conditions. Because GCM's produce quantitative estimates of future conditions, hydrologic analyses based on such estimates give the appearance of being more "realistic" than they may actually be. Readers of such reports must remember that the descriptions of "future hydrologic conditions" are only as good as the model predicted climatic conditions, and these are not very good at all.

A third method for producing scenarios of future climatic conditions, historical analogs, is based on the use of data from the recent observational record. This procedure involves searching for periods in recent history when climatic conditions were similar to those that are believed will accompany a doubling of atmospheric CO_2. In most regions, hydrologic conditions associated with these anomalous climatic conditions are known, so it is possible, therefore, to develop insights into the vulnerability of water systems to climatic change. The strength in this method is that it draws on human experience. On the other hand, this method has a serious weakness. In many regions, the magnitude of estimated changes in climate is greater than most natural historical variations. Thus, it may not be possible to find an appropriate analog in the systematic record or, if such a variation exists in the record, it is unlikely that it lasted for a long enough period of time to obtain a reliable (in the context of future conditions) estimate of its hydrologic effects (Karl and Riebsame, 1989).

The fourth method of producing scenarios of future climatic conditions is based on analyses of variations in climatic conditions over periods spanning millennia, as recorded in the geologic record. By observing such variations and attempting to identify periods that may be similar to future greenhouse conditions, that is, paleoclimatic analogs, it is possible to identify where significant changes in water availability may appear. Paleoclimatic scenarios are limited by several things, however, in their usefulness for evaluating the impacts of future climatic changes on hydrology and water resources (Gleick, 1989). First, the farther back in time one goes, the more difficult it becomes to recover hydrologic data. Second, the reasons for climatic fluctuations through geologic time may differ significantly from the human-induced changes anticipated in the coming decades. Third, because these paleoclimatic changes generally predate human activity, there is no evidence of how they might affect society.

Significantly, the ability to assess hydrologic and water resource impacts of climatic change is predicated on satisfying several important requirements. First, it is necessary to understand how hydrologic systems respond to meteorological and climatological conditions. Notably, the current capability for meeting this requirement is only fair. Second, one needs estimates of regional meteorological conditions attendant to a potential future climate. This is the "water supply" side of the impacts equation. From the preceding discussion of scenarios it should be clear that the ability to produce an accurate regional forecast of climatic conditions decades, years, or even months into the future is currently very poor. Third, estimates of the regional social and economic conditions likely to exist contemporaneously with a future changed climate are necessary. This is the "water demand" component of the impacts equation. As with climate forecasting, the current ability to accurately forecast regional social and economic conditions is poor. It is noteworthy that studies of the accuracy of socioeconomic forecasts in general, and water use forecasts in particular, have shown that the majority of such forecasts during the past 30 years have been substantially in error (Osborn and others, 1986).

Although in recent years there has been an increased interest placed on understanding how worldwide water resources would be impacted by long-term climate change, little attention has focused on the fact that our current understanding of how water resources respond to short-term climate variability is seriously deficient. Significantly, it is only by first improving our knowledge of the latter shorter term processes that it will be possible to answer questions associated with the former longer term process. Thus, increased understanding of relations between climatic variability and hydrologic response must be developed. Such work should include the development of methods for translating climate model information into a form that provides relevant data for watershed and water resource system models.

One of the most important outcomes of the Intergovernmental Panel on Climate Change (IPCC) Impacts Assessment (Tegart and others, 1990) was the recognition that physical and social scientific understanding is not yet at a level where water resources impact assessments are practical. Significantly, though, it is now feasible to identify river basin sensitivities to both climate and socioeconomic change. Clearly, such identification is essential to the development of reasoned and beneficial planning and policy-making activities.

Lins and others (1990) suggest that in the absence of a true impact assessment capability, a number of beneficial tasks should be undertaken in order to develop useful planning and policy formulation information. For example, improved analytical tools for characterizing climate effects on water resources and water resource systems can be developed. Considerable work has already been initiated in this regard. Also, techniques and tools specifically designed for planning and managing water resource systems assuming a nonstationary climate can be developed. Such methods are critical inasmuch as the traditional procedures for water resources planning unrealistically assume stationary climatic conditions. Moreover, water system managers can test and evaluate alternative operating procedures and rules for making their systems more robust (less sensitive) to climate variability and change. Having taken such steps as these, as regional climate and socioeconomic forecasts begin to improve, an adequate scientific and technical basis will then exist to define the effects of climate change on the physical hydrologic system as well as the issues of water demand and water use.

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Terrestrial Implications and Uncertainties in the Atmospheric Carbon Dioxide Budget

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Atmospheric CO_2 is one of the smallest carbon reservoirs in the global carbon cycle (fig. 1). Because of its relatively small carbon content, the atmosphere is very sensitive to changes in the larger carbon reservoirs with which it exchanges. This sensitivity spans a broad spectrum of time scales, depending on the rates of CO_2 exchange between the atmosphere and the other global carbon reservoirs (fig. 1). Of particular concern is the historical acceleration of CO_2 production caused by human consumption of fossil fuels and destruction of vegetation. These activities produce so much CO_2 that the potential greenhouse effect due to anthropogenic CO_2 is several times that due to any other greenhouse gas (fig. 2), even though CO_2 is not the most efficient greenhouse gas on a per-molecule basis. Accordingly, anthropogenic CO_2 has been the focus of most of the concern for potential global warming caused by an increase in the greenhouse effect.

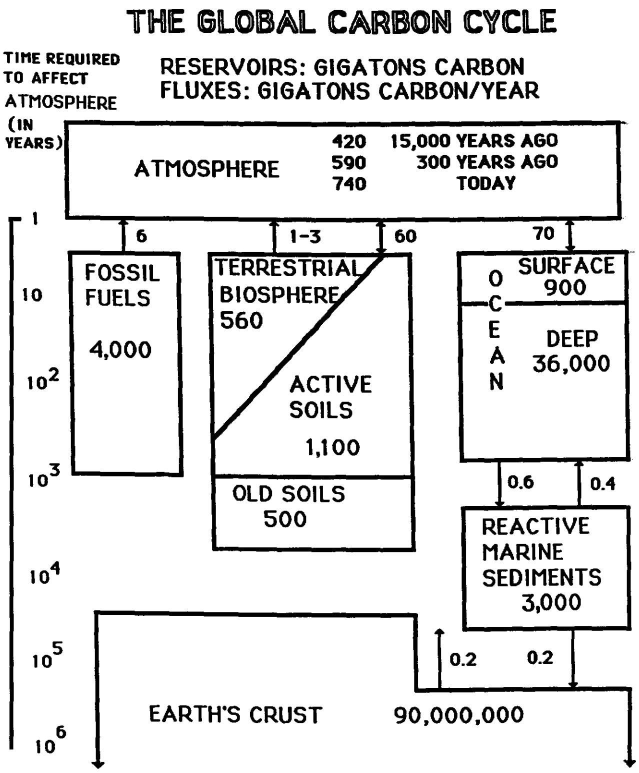

Figure 1. A representation of the principal reservoirs and fluxes in the global carbon cycle. Vertical placements relative to scale on left show approximate time scales required to affect atmospheric CO_2.

Table 1. Approximate historical budget for anthropogenic carbon dioxide for the years 1850 through 1990

[See text for sources of data. Uncertainties of sums are calculated as square-roots of sums of squares of individual uncertainties. Units: gigatons carbon]

Sources and sinks	GtC
Fossil fuels	220±25
Nonfossil sources	125±40
Total anthropogenic input	345±45
Ocean uptake	−135±25
Atmospheric increase (from 288 to 352 ppm)	−140±5
Net budget "imbalance" (terrestrial sink?)	70±50

Ironically, the increased research focus on CO_2 has not resolved one of the most fundamental questions: Where does the anthropogenic CO_2 go? It has long been known that the atmosphere retains only about half of the CO_2 produced by burning fossil fuels. The fate of the other half—and the fate of the CO_2 generated by the destruction of terrestrial vegetation—has been the most intensely debated topic among CO_2 researchers for decades. While it is clear that the oceans are capable of absorbing much of the "missing" CO_2, the absorption of CO_2 on land appears to be a necessary but very perplexing component in balancing the global CO_2 budget.

The most powerful constraint on the CO_2 budget of the last 250 years is provided by the historical record of atmospheric CO_2 concentrations. This record can be assembled from analyses of air trapped in polar ice cores (Neftel and others, 1985) and, since the late 1950's, monitored directly at sites remote from industrial areas (Keeling and others, 1989a). Industrial CO_2 emissions can be estimated from production statistics (Keeling, 1973; Marland, 1989). Emissions from vegetation and soils can be estimated from land use records (Houghton and Skole, 1990). Estimates of ocean uptake must be based on models that integrate simulations of air-sea gas transfer, seawater chemistry, and ocean circulation. A variety of ocean models indicate uptake of about 30 to 50 percent of added CO_2 (Sundquist, 1985; Siegenthaler and Oeschger, 1987). A CO_2 budget for the period 1850 to 1990 can be estimated (table 1) by subtracting the oceanic uptake and atmospheric increase from the sum of the fossil-fuel and nonfossil emissions. Although the uncertainties in the budget are large and

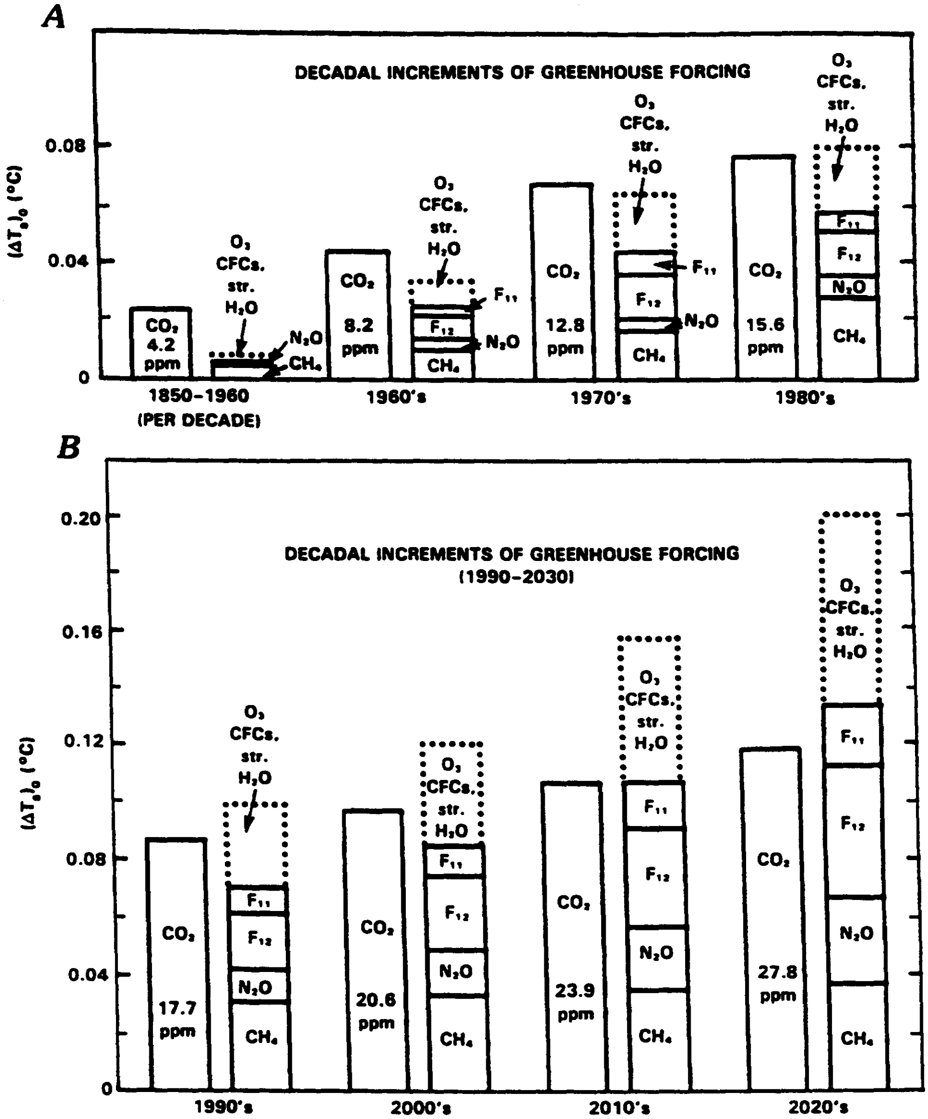

Figure 2. Incremental greenhouse forcings attributed to anthropogenic trace gases, by decade. These forcings do not include feedbacks of the global climate system, and therefore represent only a fraction of the total expected global temperature effect. Future forcings are based on a scenario of future gas emissions that assumes simple extrapolation of early 1980's growth rates. From Ramanathan and others (1985, Figure 15–22, p. 874). A. 1850–1980. B. 1990–2020.

difficult to quantify (table 1 assumes—arbitrarily—a sum-of-squares relationship among the uncertainties of individual terms), the net imbalance appears to require a significant terrestrial carbon "sink." The identity of this sink is unknown.

A similar imbalance is apparent in estimates of the annual CO_2 budget for recent years. Three estimates based on data from the 1980's are shown in table 2. Each estimate implies a terrestrial sink analogous to that inferred from table 1. Like the long-term historical budget, the annual CO_2 budget is affected by large uncertainties. For example, different estimates of the annual atmospheric CO_2 increase, such as those apparent in table 2, may be attributed to real interannual variations, which amounted to about ±25 percent (standard deviation) during the 1980's (Keeling and others, 1989b, table 6).

Table 2 also shows more significant uncertainties in the large discrepancy between the ocean CO_2 uptake estimate of Tans and others (1990), which is based on ocean surface CO_2 measurements, and the ocean uptake estimates of Keeling and others (1989b) and Watson and others (1990), which are based on ocean models. This discrepancy

Table 2. Three scenarios for annual carbon dioxide budgets from the 1980's

[The budget of Keeling and others (1989b, table 10, p. 352) is from their summary of mean annual fluxes as of January 1, 1980. The budget of Watson and others (1990, p. 13), which is part of the Scientific Assessment of the Intergovernmental Panel on Climate Change (IPCC), is their summary estimate for the decade 1980–1989. "Scenario 6" of Tans and others (1990, table 4, p. 1437) is based on atmospheric CO_2 data for 1981–1987 and ocean surface CO_2 measurements for 1972–1989. The net budget "imbalance" in each case is thought to represent terrestrial CO_2 uptake. units: gigatons carbon per year]

Sources and sinks	Reference 1	Reference 2	Reference 3
Fossil fuel burning.........	5.3	5.4±0.5	.3
Nonfossil sources..........	1.8	1.6±1.0	1.4
Atmospheric increase.......	−2.8	−3.4±0.2	−3.0
Ocean uptake..............	−2.2	−2.0±0.8	−0.7
Net budget "imbalance"	2.1	.6±1.4	3.0

Reference 1: Keeling and others, 1989b, 1980 scenario
Reference 2: Watson and others, 1990, IPCC scenario
Reference 3: Tans and others, 1990, "Scenario 6"

has direct implications for the terrestrial component of the CO_2 budget because the much smaller ocean uptake estimate by Tans and others requires a much larger terrestrial sink. Moreover, the location of the discrepancy can be specified by analysis of the latitudinal gradient of atmospheric CO_2 concentrations. Anthropogenic CO_2 accumulates in the Northern Hemisphere atmosphere more rapidly than it can be mixed southward (fig. 3). The resultant north-to-south atmospheric CO_2 gradient, combined with estimates of the rate of interhemispheric atmospheric exchange, constrains the rate at which CO_2 reaches the Southern Hemisphere via the Northern Hemisphere atmosphere. This constraint applies to a large fraction of anthropogenic CO_2 because nearly all of it is produced in the Northern Hemisphere.

Both Keeling and others (1989b) and Tans and others (1990) concluded from such calculations that there must be a large CO_2 sink in the Northern Hemisphere (table 3). Without such a sink, the buildup of CO_2 in the Northern Hemisphere would be much higher and the latitudinal gradient would be steeper. Table 3 shows that Keeling and others attribute this sink primarily to ocean uptake, whereas Tans and others attribute it mainly to terrestrial uptake. Both budgets are defensible: Keeling and others constrain their simulations using atmospheric ^{13}C as well as CO_2 data, while Tans and others do not use ^{13}C data. On the other hand, Tans and others show that the Northern Hemisphere ocean uptake suggested by Keeling and others does not appear to be consistent with the most extensive data set available for estimating net ocean surface CO_2 exchange. Both budgets suggest that the global biosphere is a net CO_2 sink, in spite of the significant quantities of CO_2 released by deforestation. The budgets differ in their estimates of the magnitude of this sink, particularly in the Northern Hemisphere.

Table 3. The latitudinal distribution of carbon dioxide uptake according to two of the scenarios summarized in table 2

[The specified equatorial latitude ranges are 15.65°N–15.65°S for Keeling and others (1989b) and 15°N–15°S for Tans and others (1990). Negative sign denotes net uptake from the atmosphere; positive sign denotes net release to the atmosphere. units: gigatons carbon per year]

Latitude and environment	Keeling and others, 1989b 1980 scenario	Tans and others, 1990 "Scenario 6"
Extratropical Northern Hemisphere:		
Ocean.......................	−2.6	−0.6
Biosphere....................	−0.5	−2.6
Total......................	−3.1	−3.2
Equatorial:		
Ocean.......................	1.4	1.3
Biosphere....................	0.3	1.0
Total	1.7	2.3
Extratropical Southern Hemisphere:		
Ocean.......................	−1.0	−1.4
Biosphere....................	−0.1	0.0
Total......................	−1.1	−1.4
All Latitudes:		
Ocean.......................	−2.2	−0.7
Biosphere....................	−0.3	−1.6
Total......................	−2.5	−2.3

Tables 1 through 3 illustrate the extent to which the atmospheric CO_2 budget remains fundamentally unresolved. Best estimates of both industrial-era and annual CO_2 budgets suggest a net imbalance equivalent to approximately 30 to 60 percent of the production of CO_2 from burning fossil fuels. The imbalance appears to require uptake of an amount of CO_2 approaching (in the industrial-era budget) or possibly exceeding (in some recent annual

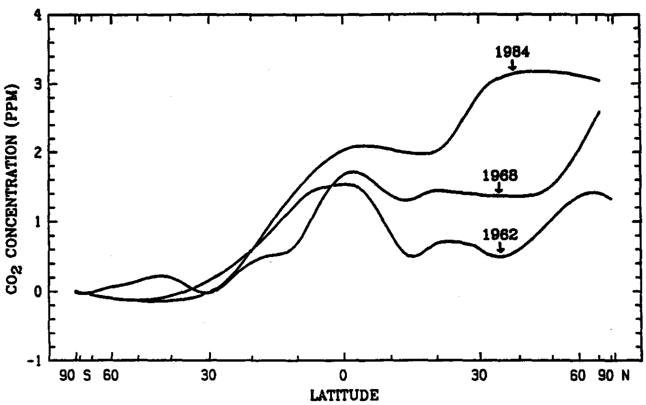

Figure 3. Seasonally adjusted atmospheric CO_2 concentrations vs. latitude for May 1984, January 1968, January 1962. The curves are cubic spline fits of data from ships and fixed-island and coastal stations. All curves are plotted as differences relative to the contemporaneous atmospheric CO_2 concentration at the South Pole. From Keeling and others (1989a, figure 32, p. 184).

budgets) the amount released from the biosphere by deforestation and other changes in land use.

The inference of a terrestrial CO_2 sink has persisted through decades of carbon-cycle modeling and research, yet the specific identity of this sink remains elusive. Efforts to balance the CO_2 budget by direct monitoring require determining small differences between large sources and sinks. For example, net terrestrial CO_2 uptake might be calculated from the difference between estimates of net primary productivity and heterotrophic respiration. These fluxes are more than an order of magnitude greater than the hypothesized net uptake. The resolution of such differences is inherently limited by uncertainties arising from spatial and temporal variability of large sources and sinks. Global monitoring of net CO_2 exchange with the biosphere is not yet feasible. The studies by Tans and others and by Keeling and others show how monitoring of oceanic and atmospheric CO_2 uptake may constrain net biospheric CO_2 exchange at least as accurately as direct monitoring of the biosphere. However, the history of CO_2 research suggests that atmospheric CO_2 budgets will not be widely accepted unless they can be related to specific identifiable CO_2 exchange processes.

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Land Data and Information Management

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Science—we'll use adjectives—it's interesting, it's exciting, it's challenging, it's rewarding, and it's important. Data management, it's...um, it's...well, it's important.

Our attitude truly has to change, and my attitude has. I don't know if I'm a scientist anymore, and I'm certainly not a data manager, but I do see the challenges. These challenges are evident to all of us as we do our research in a different context than we've done in the past.

Let me ask you five questions. Think about them.

First, are you sure, when you set out to do your research, that all the available data in your topical area or region are readily available to you? Are you sure that you can determine what data exist? Are you satisfied with the availability of current data?

Second, what makes you sure that you have access to all the data that might be available in your area of interest? Is there a chance that you know data are available, but you can't access the data?

Third, how about the information about the data you seek? This introduces a new term, "metadata," or information about data. Are you fully satisfied with the way the data that you seek from other sources are identified and characterized?

Fourth, how about your data? Are your data available to the science community? You'd probably say "Yes, my partner here works with me; the data are available." How about the metadata that describe your data so that this data could be more readily available to other scientists? I'm not talking about your close colleagues. If you are a geologist or a hydrologist, are your data available to a forester? a biologist? a social scientist? Are the data that you worked with and the metadata about the data readily available and documented in a manner so that someone in a totally different field of study can access and fully understand the data? Could someone in a different field acquire your data for their studies on Earth systems and global change?

Fifth, what about the mechanisms that you use to ensure that your data are available? These data can be in the form of reports or hand-recorded field information, or the data might be on floppy disk, hard disk, or magnetic tape. What mechanisms are you using to ensure that there's ready access—not necessarily to the results of your work but to the data?

Clearly, we are facing some serious challenges in the area of data and information management. The Survey is a partner in this national research program, and we must make a commitment together to improve our attitude toward data management.

The scientific objectives of the Nation's global change research program are to measure the health of the planet, to improve our understanding of Earth system processes, and to make predictions for the future. Furthermore, there is a commitment to have open access to much of the data, eventually all of that data, that contribute to carrying out these objectives.

Policies are emerging because of the importance of data management. One important policy is a commitment to data preservation, starting now. We have an early commitment to maintaining and preserving data.

A policy of easy access is also important—which gets back to my five questions. We need to pay more attention to data commonality in the area of data access. The way we, in our discipline areas of hydrology, mapping, and geology, exchange either data or metadata with scientists in other disciplines will lead to the establishment of data standards. Often, as researchers, we don't like to follow standards, but they are essential if we expect to provide data access with any degree of efficiency.

Another important policy is to make data available at the lowest possible cost so that researchers throughout the world can have access to this data without having to spend a large part of their research budget on acquiring the data.

These policies point to the fact that the way we manage our data now may be unacceptable. In a single discipline, we take a single data set, and we share it only with our closest colleagues. In the future, we must develop new techniques, new infrastructures, and new capabilities for handling increasingly large volumes of data. We used to talk about kilobytes of data, then megabytes, now gigabytes, and next is terabytes; it just kind of flows off the tongue. What is 1,000 terabytes? A petabyte. I really don't know how many that is. All I know is that it's a lot of those little hummers. These are the terms that we're starting to use as we look to the future.

We've started some new initiatives within the Survey in the last 12 to 18 months.

The first one on the list is Landsat data maintenance and conversion. I won't say too much about this job other that it's big, and, unfortunately, among NASA, NOAA, and the Survey, it has not been done very well.

The second initiative is called data set development. The purpose of this activity is to roll up our sleeves and get some experience with new and different types of data that are regional, continental, and global in scale.

The third initiative is to develop a global land information system—to help understand what's available, who has it, where it is, how to process it, how to get it into digital form, how to enter it into an information system, and maybe how to create some derivatives from it.

Let's take these new initiatives in ascending order.

The global land information system—here we're looking at a conceptual plan for building an information system but of a different type than we're accustomed to. Our plan is to look at the information systems within our own organization; to look at what NASA, NOAA, and EPA have done; and then to glean the good from each of these existing systems to conceive a land information system that deals with nontraditional types of data. I'm talking about metadata, an information system that contains metadata and only metadata but a system that contains different types of metadata and that has improved query, access, and network efficiencies.

The types of data that you would want in a global land information system would include land cover, terrain, soils, and satellite observations. Only in a few cases would the data actually reside in the Survey. Most often, the data would reside someplace else. But we have a congressionally mandated responsibility to conceive an information system that will provide access to a wide variety of data held by different organizations.

There are basically three levels of query in the global land information system, starting with a very general *directory*—like the Survey's Earth Science Data Directory and NASA's Master Data Directory—where someone can log into the system and say, "I'm interested in soils data of the world. What's available?" The directory could point to work done by the United Nations Food and Agricultural Organization (FAO), by the International Geosphere-Biosphere Program, or by the Soil Conservation Service. The directory gives quick, generalized information.

The second level of query is the *guide*, sometimes called a catalog. If you were searching for FAO soils data, you might ask "What is this data? How were the data acquired? What kind of instrumentation was used? How reliable are the data?" Answers to these questions are found in the guide.

Inventory information is contained in the third level of query. Here one can find the detailed parameters associated with the data and what geographic areas are covered. Instructions on how to access the data also are included in the inventory.

Anybody in the Survey or another government agency—and eventually anybody in the world—can log into the global land information system through INTERnet, ETHERnet, NASAnet, GEOnet, or other existing "nets." Connection to the information system can be made with a terminal, PC, or workstation, providing real-time access to the metadata files.

In some cases, the information system will be extended to include not just text files but also graphic displays, particularly with image data. When we are dealing with satellite images, often someone will want to know what the data look like. If there are clouds in the data, they will want to know where the clouds are located.

The satellite images can be sampled by selecting a portion of the total number of picture elements in the original image. The sampled data form a coarse resolution image that easily can be stored, retrieved, and displayed along with the metadata that describe the image. Thus, a person can perform searches by geographic area and then display the images of interest—taken during periods of high rainfall, snowfall, whatever—and actually see at least sampled portions of the image.

That's just a quick introduction to the first activity that is part of the new data management initiatives within the Survey.

The second data management initiative is called global data set development. Global data set development provides an opportunity to gain some experience with very large data sets. But first, we need to know who wants what. Who are these Earth system modelers, and what kind of data do they need? From the literature and from one-to-one conversations with modelers, we know that information about physical parameters, rates of processes, nominal classifications of the landscape, rates of change, and types of change is the kind of data needed, but at regional, continental, and global scales.

We searched for several global data sets.

The first was vegetation. What's the best vegetation data set available in the world? We didn't find much. Elaine Matthews, at the Goddard Institute for Space Studies, created a global vegetation map from a variety of sources. Part of our effort is to characterize that data, with her help, and to make sure that the data and the metadata are available in an information system like the global land information system I just described.

Another global data set describes the world's ecosystem. J.S. Olsen, J.A. Watts, and L.J. Alison have done this kind of work at Oak Ridge National Laboratories in Oak Ridge, Tenn. Again, interpretations were compiled using a variety of source material. Soils interpretations have been made by Leonard Zobler (Columbia University, New York, N.Y.) from the FAO's global soils map.

Global elevation data—this material goes way back if you track its original source—can be acquired from NOAA's National Geophysical Data Center in Boulder, Colo. These data are referred to as ETOPO5 and have 5-minute grid cell spacing, which is about the best we have of the entire globe.

Land use and land cover mapping are areas of expertise within the Survey. What's available of the world?

Probably the best product has been generated by the Soviets. We are working with the University of New Hampshire to convert the Soviet maps to digital form, to show the data in various map projections, to compile the attribute files after digitization, and to make the data available to the science community.

What about satellite data? One example of Earth observation data is that acquired from the polar-orbiting NOAA satellites using the Advanced Very High Resolution Radiometer. That sensor system provides data at about 1-kilometer resolution. Multiple passes are acquired each day across the country. These passes are mosaicked, geometrically corrected, and then registered on each successive day, one image after another. A normalized difference image is calculated to obtain an index of the condition of the vegetation or a measure of greenness—the difference between the red and the infrared channels, divided by the sum of the two, provides an index image that closely approximates the condition of vegetation occurring on the Earth's surface.

An interesting aspect to using satellite images for assessing vegetation condition is that it can be done in 1-week, 2-week, 3-week, or monthly intervals throughout an entire growing season with today's computer processing facilities. In fact, we're doing this on 12-year-old VAXes. It sometimes takes a long time, particularly to merge the vegetation index data with other data sets and to do more complex processing tasks, but these satellite data provide a new way of looking at the Earth and its temporal cycles.

Clearly, Earth observations from space will help us measure the health of the planet, especially when the satellite data are merged with other data sets that may or may not come from the Survey, such as elevation models, digital line graphs, major land use areas, land cover, ecoregions, and climatic zones.

We are doing everything in our power to identify data sources of the world and to make those data available to the science community. I'm excited about combining the technologies of satellite image processing and geographic information systems to develop a data base that can be used to characterize the landscape.

We now have an agreement with the Canadian government to expand this work from the conterminous 48 States to all of North America. We'll work with the Canadians on creating a comprehensive land surface characterization data base for the entire continent. And then, wouldn't it be nice if we could do this for the globe? I think this is within reach when we're talking about a long program of 15 to 20 years.

Part of this effort is to make these regional, continental, and global data sets available to the science community at the lowest possible cost. Right now, the time-sequence greenness data over the conterminous United States for the 1990 growing season, all of those multiple data sets, can go on five CD-ROM's. You can get three gigabytes of data for $160.

The preservation of Landsat data is the third data management initiative being addressed by the Survey. First of all, does the Earth science community care whether Landsat data are properly maintained? Some scientists do.

Scientists being trained in graduate school today—scientists who are going to reach their prime in 15 to 20 years—might want to know, for example, what Kuwait City looked like in January 1991 as the Iraqis pulled out. Using Landsat imagery, you can count between 600 and 1,000 fires burning out of control near Kuwait City. The science community, particularly the United Nations Environment Program, is worried about the impact these fires are having on the environment. They're worried about oil spills in the Persian Gulf. They're worried about disturbances to the desert varnish.

Preserving that data is difficult. If you think it's difficult to store your data on floppy disks or on hard disks, visit the Landsat data archive. Some of the data are on ½-inch tapes—tens of thousands of high-density tapes.

The first 400,000 scenes of Landsat data, acquired between 1972 and 1978, were delivered to us from NASA. There's no system available today that can even process these data. The computers built by NASA in the late 1960's to process these data are gone. The people of the United States have paid more than $1.5 billion to fly Landsats 1 through 5. More than 1 million Landsat scenes are archived at the EROS Data Center, 40 percent of which cannot come out of the plastic storage bags because the systems to process these data don't exist anymore. We're not even sure these data can be read.

Our priority activity is to preserve the most recent Landsat data—the thematic mapper data acquired since 1982.

The experience we are gaining with Landsat data will serve us well when managing satellite data acquired by future space systems, such as the planned Earth Observing System (EOS). The Survey is a partner with NASA for EOS. The EROS Data Center will be a distributed active archive center for land data acquired by EOS—which is another example of the Survey's commitment to a long-term program of data and information management.

In summary, the Survey is taking the subject of data and information management very seriously. In this presentation, I have touched on the global land information system as an example of a prototype system for managing information about data, called metadata. I have talked about data set development in support of climate change research, about the Landsat data preservation problem, and about the Survey's anticipated role in EOS. When carrying out current responsibilities associated with data management, we have found both challenges and rewards. But I think we do not need to change our attitudes. I've certainly changed mine.

Developing a Sound Basis for National Policy

Allan Bromley
Assistant to the President for Science and Technology

It is indeed a pleasure to be here with you in this first of the interdivisional workshops on the interagency U.S. Global Change Research Program. These last few years have represented a remarkable achievement in terms of coordinating and developing the program. The President and all of us in the Bush Administration are very much indebted to your director, Dallas Peck, for the leadership that he has provided.

A remarkable cross section of agencies, 19 in all, have been brought together—and I think it represents a first, both inside and outside of government—in a cooperative, collegial spirit to put together a program that represents something of which the nation can be proud. It is a coherent and integrated program rather than just a heterogeneous combination of 19 different programs that happened to boil up through 19 different agencies.

Those of you who have ever been involved in coordinating anything among quite independent agencies understand what an accomplishment this represents. Agencies have been convinced to go back home and recraft their programs so that they fit into a national program rather than furthering a particular private aim of somebody in the bowels of that particular agency. In the years ahead, the success of this program is going to depend critically on the efforts of a great many of our agencies working together with the same kind of cooperation, understanding, and, in fact, trust.

We will keep looking to the Geological Survey to provide the major leadership, not only in the overall program but in the special areas of hydrology, hydrologic systems, Earth systems history—particularly having to do with paleoclimates, paleohydrology, and paleoecology—solid Earth processes, land characterization, and land data management.

I want to take this opportunity to emphasize the importance that all of us back in the White House place on data management, because that's going to be one of the very key elements of your work in the years ahead. You're fortunate that the U.S. Global Change Research Program has at its disposal the EROS Data Center, and someday somebody is going to tell me exactly what the EROS Data Center contains. My misspent youth had enough Greek and Latin to make this a fascinating question.

One of the important things to keep in mind is that data management is a very real problem. When EOS–A is functioning as we expect it to function, it will deliver data equivalent to the entire Library of Congress every 4.8 days. Unless we have made some major steps in the high performance computing and communications program that is one of the President's initiatives this year, we will be swamped by all these data.

We have an opportunity, however, to develop our information-handling capabilities in parallel with the work that you're involved in. When the need arises, we'll be in great shape to digest, analyze, and present these huge amounts of data in fashions that use the remarkable ability of the human to sense patterns and to develop hypotheses based on graphical information.

A useful piece of information is that 75 percent of whatever fraction of your brain happens to be working is devoted to visual processes. I would not dare to guess at what that fraction is.

Visual processing is something that we have not taken nearly as much advantage of as we should have in the past. But with the new supercomputers that are now available to us, for the first time we can build the interface between vast amounts of data and human perceptions and analytic abilities in an entirely new way.

I don't think I need to tell anyone in this room that, over the past century and a little more, we have been engaged in what is unquestionably the largest unplanned experiment that our species has ever attempted on the planet.

We've altered the face of the Earth in irretrievable fashion by clearing forests, building cities, and converting wild lands to agriculture. We've changed the composition of the Earth's atmosphere; in fact, the carbon dioxide that we've put into our atmosphere represents the largest single impact that our species has had on the planet.

It is not surprising that we have now reached a point where we have to face the possibility that those changes can lead to unpleasant consequences. They may be large or small; we're not sure yet what their magnitude or timing might be. But it's clearly a global problem that can be addressed only at a global level with a vast amount of goodwill. And those of you who have been attending the meetings of the framework negotiating session just recently completed will recognize that we have some distance to go in developing goodwill in the international global change arena.

One of the things that would make our life vastly easier would be if there were any sort of clear, unequivocal understanding of the phenomena that we're dealing with. If, for example, it were possible to associate the warmer-than-average years of the 1980's with a greenhouse effect, then the policy decisions that we would have to make to respond to that effect would be vastly simpler than they are in the present situation, where it is far from obvious what is cause, what is effect, and exactly where we're headed.

It is also true that the global circulation models—the major computer models that we have come to depend on to predict the future of climate change—are not nearly as complete or as fine grained as we would like them to be or as they will need to be if we are to use them as the basis for sound national policy.

It is very important for us, as people making policy, to remind ourselves from time to time about what we do know about the system and what we do not know about the system. We know, for example—and none of this is going to come as great news to many of you in this room, but it's worthwhile simply listing some of these things—that for the past 100,000 years, global average temperatures and atmospheric carbon dioxide have risen and fallen together, at least on a large scale. We also know that the atmospheric loading of carbon dioxide has increased by about 25 percent since preindustrial times.

We have excellent measurements from the Mauna Kea equipment that allows us to average over much of the Pacific basin. We also know that other greenhouse gases, like the chlorofluorocarbons and methane, have increased much more rapidly. In the case of methane, we don't fully understand why this is happening, and our monitoring and measuring techniques are not as good as they might be.

We know, too, that the global circulation models predict an average surface temperature increase of between 1.5°C and 4.5°C for a doubling of the equivalent carbon dioxide loading. I say equivalent to take into account all of the greenhouse gases on a comprehensive equivalent basis.

Finally, I think most of you in the room and most scientists anywhere would agree that the average temperature of the planet has increased by somewhere between 0.3°C and 0.6°C over the past century.

Each of those statements is the result of hard-won evidence obtained by people like yourselves working in your own special fields. It's been difficult, and the most difficult part of all is the fact that there is still a tremendous number of uncertainties associated with many of these data. Let me mention just a few of them.

Regarding the warming of the last century, I think you would all agree that it is not scientifically possible to associate in an unambiguous way the warming that we believe we see with a specific greenhouse effect.

First of all, the behavior of the warming doesn't agree with what you'd expect from a simple greenhouse phenomenon. The systematic decrease in the global temperature from about 1940 to 1970 is certainly not something you would expect as you increase the flux of greenhouse gases into the atmosphere.

One of the things we have to keep in mind is that we know from our measurements that the global temperature does fluctuate. Either we could be observing a fluctuation, or a fluctuation could be masking a much larger increase, because of a greenhouse effect, than we have thus far seen. We have to find out which of these is the case.

Regarding the paleoecological connection between carbon dioxide and temperature, it is enormously important to be able to say with certainty which is the leading phenomenon. Does the temperature increase result because of an increase in carbon dioxide, or does the carbon dioxide result in an increase in temperature? Despite a number of claims that this question has been resolved, I think the jury is still out; we really do not know which is which.

As far as the general circulation models are concerned, remarkable progress has been made. It remains the fact, however, that of the six major global circulation models, three predict that if we were to double the equivalent greenhouse gases, the American Midwest would get hotter and drier, and the other three say it would get colder and wetter. That's the kind of fundamental scientific information that is extraordinarily helpful as you try to make policy decisions.

What we have to do, clearly—and one of the major challenges for you and the research program that you and the Committee on Earth and Environmental Sciences have pulled together—is to try to improve this regional predictive capability. In the absence of regional predictions, it's well nigh impossible to apply economics to the situation, and in the absence of economics it's extremely difficult to make sensible policy.

It's also a little startling to those who are not experts in the field to realize that over the past 18 months we appear to have lost a quarter of all the carbon in the global carbon cycle. As you well know, we have always thought and taken as an article of faith that 50 percent of the carbon dioxide that goes into the atmosphere is immediately absorbed by the oceans, leaving 50 percent in the atmosphere. Over the last 2 years, however, the actual measurements of carbon dioxide partial pressure in the Earth's oceans, primarily by U.S. and British ship instrumentation, have shown that the fraction is much nearer to 25 percent.

Where is the other 25 percent? There are many hypotheses. Perhaps the increased carbon dioxide has fertilized plant life in the temperate zones and the missing carbon is in the biomass in the temperate latitudes. We don't know, and it's something that we have to find out.

We also know that passive microwave radiometry from satellites has given us the ability to do precise temperature measurements from satellites over long periods. This is surprising, because I don't think anyone believed that the calibrations would remain fixed. Still, there are mysteries left even when we have these precise measurements. For example, the fact that the average global temperature, measured over the entire planet rather than in just a few isolated measuring locations, did not increase at all from 1979 to 1989, during a period of major increase in greenhouse loading, is a puzzle.

Another remarkable new development is the ideas that Broecker and his colleagues have produced to the effect that the global circulation in our oceans may not be as permanent as we have thought. There may be more than one stable configuration. A suggestion has been made, for example, that when the North American mid-continent sea broke into the Atlantic through the Saint Lawrence waterway, it flipped the circulation in a major way and turned off the Gulf Stream, producing fundamental changes in climate worldwide. We don't know whether that happened or not, but it's a fascinating idea and deserves a tremendous amount of additional study.

The last thing I would mention is that Intergovernmental Panel on Climate Change (IPCC) documents suggest that if we are to achieve the goals that the IPCC finds appropriate, we should make something like a 60- to 80-percent reduction in anthropogenic carbon dioxide emissions. That's going to make a significant difference in the ways we do business and live our lives. It bears emphasis, however, that the anthropogenic fluxes are slightly less than one-twentieth of the natural fluxes. A 2- to 3-percent change in a natural sink could therefore have the same overall effect as this 60-percent change in anthropogenic emissions. Conceivably, this could be done with much less turmoil and difficulty for our society. It obviously merits study.

But if anybody tells me he is about to grind up a battleship and sprinkle it around Antarctica, I'm going to be very uneasy until a number of bathtubs have been filled up with ground-up battleship to see just what else happens when you do this. It's a marvelous idea to fertilize and increase the level of biological material that, at least on the basis of our present information, we believe to be limited by the availability of iron. But it certainly needs some study before we plunge ahead. We have tended to take the approach in the past of "damn the torpedoes"—if there's a technology, let's implement it. We have learned that this can lead to some very unhappy situations.

Given all these uncertainties, how best can we, as a Nation, approach this issue of greenhouse warming? Obviously, this is an area where we are looked to by much of the rest of the world for leadership, although we have been accused of dragging our feet by some nations. We have been accused of not wishing to exert leadership. We have been accused of a great many things.

One of the most important things we can do is represented by the U.S. Global Change Research Program. Understanding the system a lot better than we do now is a major challenge. I think the coordinated multiagency program that Dallas and his colleagues have put together is something of which we can be proud. Since the President took the first program plan with him to the economic summit in Paris and delivered it to all the other heads of state, it has been considered a prototype for a proper national program in many fields of activity.

The program, as Dallas has spelled it out, has three fundamental objectives: to document the Earth's system through coordinated, integrated observations; to improve our scientific understanding on the basis of these data; and to develop the capability to predict what is going to happen both in the short-term and in the long-term and both in the global sense and in the regional sense.

We are, I hope, about to see major progress in the development of both the space-based and ground-based components of this program. Very large systems like EOS, the Earth Observing System, a key part of Mission to Planet Earth, get more press and more attention than do the equally important developments that are taking place on the surface. But it is only by putting both space- and surface-based activities together that we can hope to answer the fundamental questions.

I want to conclude by again complimenting the Committee on Earth and Environmental Sciences for the remarkable accomplishment that this U.S. Global Change Research Program represents. It is something that even a few years ago people would not have believed possible. It is something that business schools are talking about making into a case study. That's the ultimate measure of success.

The most important thing is the translation of good science, good technology, and good economics into good policy. That's the challenge for all of us in the Federal Government, and it's one toward which we're making progress.

It is a pleasure to have been here with you to ensure that you get your lunch and also to talk to you about the remarkable job that all of you have done. It's an activity of which you can be justly proud. No other nation has anything like the group of people who are represented in the room today. We count on you for a tremendous amount of the understanding on which we will build a very important part of our future.

The Receding Threat From Global Warming

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One popular and apocalyptic vision of the world influenced by increasing concentrations of infrared-absorbing trace gases is that of ecological disaster brought about by rapidly rising temperatures, sea level, and evaporation rates. This vision was developed from a suite of climate models that have since considerably reduced their estimates of prospective warming. Observed temperatures indicate that much more warming should already have taken place in the Northern Hemisphere and that night, rather than day, readings in that hemisphere show a relative warming. A high-latitude polar night warming or a general night warming would be either benign or beneficial. Further, a large number of plant species show both increased growth and greater water use efficiency under enhanced carbon dioxide.

An extensive body of evidence now indicates that anthropogenerated sulfate emissions are mitigating much of the warming and that increased cloudiness as a result of these emissions will produce primarily night, rather than day, warming. These observations could drastically alter the debate on global warming in favor of less interventionist policies.

Virtually all scientists directly involved in research on climatic change believe that the Earth will undergo some warming as a result of the increase in anthropogenerated emissions that absorb infrared radiation or enhance the "greenhouse effect." However, within certain broad limits, how much the world warms is irrelevant. Rather, the critical policy question is how the world will warm, because the real effect will be expressed by its regionality, seasonality, and distribution within the day-night cycle. As a result of these factors, there are now several compelling lines of evidence that indicate that the chance of an ecologically or economically disastrous global warming is becoming more remote. These findings are at considerable variance to what might be referred to as one vision of apocalyptic warming: global temperature change of approximately 4°C, pronounced sea level rise because of the melting of major areas of land ice and thermal expansion of water, and starvation and civil strife resulting from ecological chaos.

It is interesting to note that the 19th-century calculations of Arrhenius, which projected a net global warming of approximately 5°C for a doubling of carbon dioxide, are usually cited as an argument for the robustness of the apocalyptic vision, inasmuch as projected warming by much more complete general circulation climate models in the mid-1980's gave roughly the same answer. What was usually neglected in this citation is that Arrhenius also wrote, in the same paper, that the warming would be greater in winter than in summer, that it would tend to occur at the high latitudes (and therefore concentrate in polar night), and that a primary effect would be to diminish the temperature range between day and night—that is, that night temperatures would be those primarily affected. For reasons described below, this is hardly the formula for the climate disasters implied in the apocalyptic vision.

While that vision is accommodated by more lurid interpretations of the recent Intergovernmental Panel on Climate Change (IPCC) Policymakers Summary (1990), it is not even characteristic of the median range of climate impacts suggested in that report. Rather, that vision became prominent because of two synergistic events. The first was the publication of a generation of general circulation model (GCM) climate simulations in the mid- to late 1980's: These predicted a mean global warming of 4.2°C with winter warming of as much as 18°C for the North Polar regions (Hansen and others, 1984; Manabe and Wetherald, 1980; Mitchell, 1983; Schlesinger, 1984; Washington and Meehl, 1983). The second was the congressional testimony of June 23, 1988, that there was a "high degree of cause and effect" between current temperatures and human greenhouse alterations (Hansen, 1988).

Nowhere in that testimony, and to my best knowledge nowhere else, did NASA's James Hansen ever state that the anomalously warm summer of 1988 in the United States was caused by human alterations of infrared-absorbing trace gases. Nonetheless, the press and the public concluded otherwise: 70 percent of the respondents to a subsequent CNN (1988) poll agreed with the statement that the 1988 drought was in fact caused by "the greenhouse effect." There is little doubt that such unanimity in fact does reflect a commonly held vision.

In the light of that vision, we examine here the problems of (1) global and hemispheric temperature histories and trace gas concentrations, (2) artificial warming from urban heat islands, (3) high latitude and diurnal temperatures, (4) more recent climate models, (5) direct effects on vegetation of an increase in carbon dioxide, and (6) compensatory cooling from other industrial products. Also included at the end is a personal projection based on my interpretation of these findings.

TRACE GAS CONCENTRATIONS AND TEMPERATURE HISTORIES

Although there are several infrared-absorbing trace gases that have increased as a result of anthropogeneration, almost all of the current radiative forcing is associated with (in descending order), carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons. As a result of their infrared absorption and the concentration of these species in the lower atmosphere, an increasing, but very small, fraction of energy that would normally escape to space is redirected toward the Earth's surface, resulting in increased warming. The sensitivity of the current mean surface temperature is thought to be about 1°C for every additional w/m^2 of downward-directed radiation.

Continuous instrumental records of CO_2 concentration date from the late 1950's at Mauna Loa Observatory, where the 1958 annual average was 315 ppm. The concentration now is near 354 ppm. "Preindustrial" (circa 1800) concentrations were initially assumed to be in the range of 295 ppm (Schlesinger, 1982), giving a change between 1800 and the mid-1980's (level: 335 ppm) of 14 percent. Assuming that change alone accounts for a change in total radiative forcing of approximately 0.7 w/m^2, the observed warming of approximately 0.5°C in the last 100 years certainly seemed consistent with the changes in trace gases that were assumed in the early 1980's.

Since then, estimates of the background CO_2 concentration have dropped somewhat, and the calculated contributions by other anthropogenerated infrared-absorbing gases have increased dramatically. Initial ice-core studies gave a background of 270 to 290 ppm, with a most likely value of 279 ppm (Neftel and others, 1985). Another analysis obtained a lower bound of 260 ppm (Raynaud and Barnola, 1985). The Soviet/French work on the long Vostok core seems to corroborate the lower values (Lorius and others, 1987), which, if assumed to be 270 ppm, results in an anthropogenerated rise of 31 percent to date. This would increase the flux of downwelling radiation by approximately 1.5 w/m^2, which would have increased global mean temperature approximately 1.5°C if other factors were not either delaying or mitigating the warming.

Other greenhouse gases, notably methane, nitrous oxide, and the chlorofluorocarbons, have also increased considerably. The current climate forcing of methane is nearly 40 percent of the effect of increased CO_2 (Craig and Chou, 1982). The radiative effect of all of the non-CO_2 trace anthropogenerated greenhouse enhancers is approximately an additional 80 percent of that caused by a change in CO_2 alone. Thus the current effective CO_2 concentration is approximately 420 ppm, or 151 to 161 percent of the background range of 260 to 279 ppm. The IPCC (1990) corroborates this by stating that "greenhouse gases have increased since pre-industrial times...by an amount that is radiatively equivalent to about a 50 percent increase in carbon dioxide," which gives a current effective value of 390 to 420 ppm. By all calculations, we have already proceeded more than halfway to an effective doubling of the background CO_2 concentration.

While the citation is often made that the history of global temperature as "at least not contradictory to" the mid-1980's climate model projections (MacCracken and Kukla, 1985), those models produce an expected equilibrium warming for this trace gas change of approximately 2.5°C, while a least-squares fit of the entire set of Jones and Wigley global data gives a rise of 0.45 ± 0.10°C in the last 100 years (Balling and Idso, 1990). Further, virtually all of the warming of the northern hemisphere was prior to the major postwar emissions of the trace gases (Jones, 1988). This discrepancy is further compounded by the fact that the "water" (southern) hemisphere, which should warm up least and slowest, in fact shows the more "greenhouselike" signal.

Least-squares analyses of the Jones and Wigley global record demonstrate that fully 90 percent of the warming of the global record took place prior to 1945. At this time the actual CO_2 concentration was in the range of 307 ppm and the effective concentration was approximately 322 ppm. This is only one-third of the total forcing to date and implies that there has been very little warming during the period in which the majority of the radiative forcing has taken place.

Oceanic thermal lag may not in fact account for the difference. Wigley (1987) calculated, using liberal estimates of the lag, that the hemisphere should still have warmed 1°C (primarily after 1950), and the net global warming since then is in fact approximately 0.30°C. Sea surface temperature analyses of Bottomley and others (1990) and Oort and others (1989) demonstrate very little lag between that record and land readings.

URBAN HEAT ISLANDS AND LONG-TERM SITE BIAS

Localized warming related to urban buildup has long been recognized as a confounding factor in regional and global temperature analyses. While causes include changes in the surface energy balance, local wind flow, and amount of open sky, precise calculations on the various components of the "urban effect" are not available. However, Karl and others (1988) have found in the United States that the effect is statistically detectable at population levels of 2,500 and up, and Balling and Idso (in press) note the effect at population levels as low as 500. The temperature record is further confounded by the fact that exponential population increases suggest the urban warming bias should be of the same functional form as enhanced greenhouse forcing and will therefore contaminate the latest years of temperature measurement. In other words, it would be striking if the last years in the record weren't the warmest.

Karl and others (1988) have created a deurbanized "Historical Climate Network" (HCN) of 492 stations that have been checked for instrumental and location changes and adjusted for population. While this record applies only to the coterminous United States and is therefore not necessarily representative of global trends (that is, it shows a slow but unsteady cooling for much of the last 50 years), it serves as an important check on other global records because they can be compared over this limited region.

Karl and others found an artificial warming of 0.10 to .15°C in the global temperature records. Curiously, the bias appears greatest in the U.S. portion of the record. A similar analysis of an analogous Soviet Union record shows no overall urban bias (Jones, in press), although urban stations are in fact cooler than surrounding rural ones from 1953 to 1967. There is no difference between the two through 1980, and then there is some apparent urban warming after 1980. A similar negative urban effect is observed in the 1960's in mainland China (Wang and Karl, in press). It therefore seems that the global urban bias is currently not appreciably more than 0.10°C, but it should be noted that it will be more pronounced at the end of the record, which shows the warmest temperatures. Because of the urban effect, it appears that the true global warming during the last 100 years is 0.35 to 0.40°C.

Urban contamination compromises our estimates of historical temperature change. In an attempt to determine the reliability of the various long-term climate records, Spencer and Christy (1990) correlated satellite-microwave sensed temperatures with Karl's United States HCN and the hemispheric records of Jones and Wigley and the Hansen and others (1984) record that formed the basis of the June 1988 congressional testimony. The HCN is the most correspondent (R^2=0.77), Jones and Wigley's record was almost as reliable (R^2=0.72 and 0.66) for the Northern and Southern Hemisphere, while the NASA record of Hansen and Lebedeff in the Southern Hemisphere was much less reliable (R^2=0.27). This last record, which is the "warmest" of the global records, has the majority of its warming in that hemisphere. Spencer and Christy's (1991) temperature record from 1979 through 1990 shows a global trend of only +0.04°C/decade, and the coefficient of determination (R^2) between the U.S. HCN and the 1979–1990 data is now 0.86.

We calculated annual departures from the 1979 through 1990 mean period in the Jones and Wigley data set and subtracted from them anomalies in the Spencer and Christy data. When these are plotted as function of time (beginning in 1979), it is apparent that there is a dramatic relative warming of the Jones and Wigley data, compared to the satellite, in the Southern Hemisphere; no similar effect occurs in the Northern Hemisphere. The very high correlation between the satellite data and the U.S. HCN suggests that the measurements are accurate and therefore that there is a great deal of spurious warming in the recent Jones and Wigley data for the Southern Hemisphere. If this is the case, than global warming in the land-based records is much lower than 0.4°C, perhaps as low as 0.2°C.

An additional, and more insidious, problem may be introduced into long-term land-based climate records by a *general* site bias. Over what was the "developing world" of the late 19th century, the longest standing records have tended to originate at points of commerce. Because of the predominance of water power during that era, it is likely that the longest records are in fact at sites that are preferential for cold air drainage. Such locations may be buffered from nighttime warming.

Several attempts have been made to compensate for both population and general biases, usually involving temperatures in the free atmosphere. These can be determined from combinations of barometric readings and weather balloon ascents, and therefore cannot suffer from the urban effect on thermometers. Angell (1990), using the atmospheric layer from 850 to 300 mb, found a net warming of 0.24°C in the last 30 years after adjusting for El Niño warming and volcanic cooling. This is quite consistent with the global land record. A recent extension shows 1990 as the warmest year (by 0.04°), but this is not replicated in the Spencer and Christy data. The Spencer and Christy data correlated very well with Angell's data up to 1990.

Michaels and others (1990) used the depth of the bottom half of the atmosphere over North America back to the beginning of systematic balloon observations in 1948 and a statistical surrogate back to 1885 and concluded that the observed secular variability in surface temperatures calculated from this record was approximately three times larger than that measured from ground-based thermometers. The rise in the first half of the 20th century and the subsequent fall through the mid-1970's was in fact concurrent with that of the ground-based record, although the magnitude was again greater. Notably, the rise in early 20th-century temperatures calculated by this method (of 1.8°C) does not differ appreciably from the expected regional greenhouse warming calculated by GCM's for the next century. It is unknown whether this magnitude is related to noise in the statistical transfer functions between the cyclone frequency record used to calculate the 500 mb height from 1885 to 1948 or whether it truly reflects free-atmosphere temperature variability.

Weber (1990) also examined the same layer over the entire Northern Hemisphere since 1950 and found warming in the Northern Hemisphere tropics and subtropics but cooling in the higher latitudes, with no overall hemispheric warming or cooling between the 1950's and the 1980's. This signal is opposite what would be expected from most climate models that suggest enhanced high-latitude warming and minimal tropical warming.

HIGH-LATITUDE AND DAILY TEMPERATURE REGIMES

In the climate simulation of Manabe and Wetherald (1980), which is quite representative of the mid-1980's generation of climate models (Hansen and others, 1984; Manabe and Wetherald, 1980; Mitchell, 1983; Schlesinger, 1984; Washington and Meehl, 1983), the difference between 2× CO_2 and 4× at high northern latitudes is twice the difference between 1× and 2× (8°C), suggesting that for the currently effective 1.5× there should be considerable Arctic warming, even with oceanic thermal lag. Nonetheless, the Elsaesser and others (1986) compendium of temperature records indicates a rapid rise in Arctic temperatures prior to the majority of trace gas emissions and concurrent with the rise in the Northern Hemisphere average. In most records the rise is followed by a decline, from the 1930's to the mid-1970's, of similar proportion.

All general circulation climate models suggest that the polar warming will be magnified in winter. Nonetheless, there has been a substantial secular decline in winter temperatures over the Atlantic Arctic since 1920 (Rogers, 1989), and there has been no change in polar night temperatures at the South Pole—a station that surely has no urban warming or cold air drainage (Sansom, 1989). Kalkstein and others (1990) have documented that, although there has been no net warming of the North American Arctic, the coldest air masses, whose mean surface temperatures are approximately −40°, have warmed some 2°. Thus the most severe air mass in North America may be undergoing some mitigation that is consistent with an enhanced greenhouse.

The very negative vision of future climate is not supported by recent studies on daily temperature regimes. Karl and others (1988) examined maximum and minimum values from the U.S. HCN and found that the daily range (difference between the two) has declined precipitously since 1950 and is now two standard deviations below the mean for the century. In that record, maximum values have actually declined, while minimum values have risen. It is worth noting, however, that a measurement bias toward a lower daily range has recently been introduced by the replacement of the traditional mercury-in-glass thermometer with the electronic MMTS version, although the magnitude of the bias only explains about one quarter of the decline in range (R.G. Quayle, National Climate Data Center, Asheville, N.C., 28801, pers. commun.).

This behavior of the HCN is consistent with an enhanced greenhouse combined with the increases in cloudiness (of 3.5 percent) and reduced sunshine that have been documented across the coterminous United States (Angell, 1990). Weber (1990) has also documented a decline in sunshine in Germany and notes that the effect is enhanced in the mountains, which implicates stratocumulus—the low-altitude cloud type most effective at surface cooling—as the cause. Warren and others (1988) have also found increasing cloudiness at most marine locations around the globe, although the shipboard observations used are subject to substantial observer and scale biases. Nonetheless, the cloud type that shows the most increase is again the low-level stratocumulus and again in the Northern Hemisphere. The finding of a decline in ultraviolet radiation at the low elevations (Scotto and others, 1988), in combination with increased values at heights greater than 10 km (Bruhl and Crutzen, 1989), is also consistent with an increase in low-level cloudiness.

Subtraction of maximum and minimum temperature curves for the other Northern Hemisphere locations in the IPCC chapter on observed temperature (Folland and others, 1990) gives the same result: a considerable narrowing of the daily range since 1950 that is mainly a result of a rise in night temperatures. Rural data for the Soviet Union, not included in the report exhibit the same behavior (T.R. Karl, National Climate Data Center, Asheville, N.C. 28801, pers. commun.).

If anthropogenerated warming takes place primarily at night, the negative vision of future climate is probably wrong. Evaporation rate increases, which are a primary cause of projected increases in drought frequency (Rind and others, 1990), are minimized. The growing season is longer, because that period is determined primarily by low night temperatures. Finally, many plants, including some agriculturally important species, will show enhanced growth with increased moisture efficiency (Sionit, 1980) because of the well-known "fertilizer" effect of CO_2. Night warming also minimizes polar melting because mean temperatures are so far below freezing during winter that the enhanced greenhouse is insufficient to induce melting. Thus "how" the world has warmed already appears to be beneficial. If this is indeed the expression of the altered greenhouse, the Earth will have to reverse a course it has already embarked upon to get to an enhanced greenhouse disaster.

Curiously, none of the analyzed Southern Hemisphere temperature ranges are declining (Folland and others, 1990; T.R. Karl, National Climate Center, Asheville, N.C., 28801, personal communication citing doctoral dissertation of J. Salinger, University of East Anglia). Such an important interhemispheric differential in one of the prime components of diurnal energy could be very important, as the most likely cause would be an increase in Northern Hemisphere cloudiness with less change in the Southern Hemisphere. One prime candidate for causation is therefore anthropogenerated sulfate, which both reflects solar radiation directly and brightens clouds by serving as condensation nuclei. Anthropogenerated sulfide is produced in much lower volume in the Southern Hemisphere and has a residence time from days to months, so that very little diffuses from the Northern to the Southern Hemisphere.

MORE RECENT CLIMATE MODELS

An earlier generation of GCM's calculated a mean equilibrium warming for a doubling of atmospheric CO_2 of 4.2°C, with maximum warming of as much as 18°C during North Polar winter and less significant warming (approximately 2°) over tropical oceans (Hansen and others, 1984; Manabe and Wetherald, 1980; Mitchell, 1983; Schlesinger, 1984; Washington and Meehl, 1983).

Major shortcomings in these calculations included unrealistic ocean dynamics and ocean-atmosphere coupling, inadequate cloud paramaterization (prior to the ERBE analysis even the sign of the temperature forcing by the earth's cloud cover was unknown and debatable; it is now thought to be negative) (Ramanathan and others, 1989), and the usual use of stepwise (instantaneous) doubling of CO_2 rather than the low-order exponential increase that exists in the real world.

With a modified ice-water interaction between clouds, projected warming in the United Kingdom Meteorological Office (UKMO) dropped from 5.2° to 1.9°C (Mitchell and others, 1989). With a coupled ocean and climate general circulation model, the net warming in the National Center for Atmospheric Research (NCAR) model dropped to 1.6°C for 30 years after a shock doubling, compared to 3.7°C in an earlier equilibrium calculation (Washington and Meehl, 1989). Manabe and others (in press) reports a net equilibrium warming for a doubling with a coupled atmosphere-ocean model of 1.8°C, compared to 4.3°C in a more primitive version. The net warming projected for the Southern Hemisphere is approximately 1.0°C, with 2.5°C projected for the Northern Hemisphere. The observed behavior of the last 50 years—in which the Southern Hemisphere shows a more "greenhouselike" warming than the Northern Hemisphere—seems inconsistent with this model projection unless there has been some mitigation of Northern Hemisphere warming by other means (such as from sulfate aerosols) not included in the modeling process.

In each of these models, estimates of global warming for a doubling of CO_2 have been considerably reduced. The mean of these three runs is 2.0°C, down over 2° from the previous mean. This substantially reduced warming is calculated with either altered cloud or ocean parameters. It therefore seems logical that a combination of the two will produce even less net warming.

The NCAR calculation with the coupled land and ocean GCM for 30 years after a shock doubling shows that areas of warming of greater than 4°C have been dramatically reduced, and in fact there are no areas of warming in either hemisphere for June–August.

Because maximum warming in all GCM's tends to concentrate at high latitudes, use of this Mercator or related projections presents a highly distorted view of model results that serves to overemphasize areas of warming. In terms of actual area of the globe, on an annual basis, the area of greater than 4°C of warming in the illustrated model is less than 5 percent. Because almost all of that warming is confined to latitudes higher than 60° in the Northern Hemisphere, *virtually all of the strong warming is now projected for either twilight or night*, which is consistent with what has been observed in the U.S. HCN.

It is tempting to view the unanimity of these newer models as a sign of reliability, but that is not the case. In a version of the NCAR model that increases greenhouse gases by a realistic 1 percent per year (as opposed to the "shock doubling" used in the model cited above), calculations based upon its results show that the current land temperature should be 1.4°C above the 1950 mean (Washington and Meehl, 1989); in fact the rise has been on the order of 0.3°C. Thus, even the most conservative climate model appears to have grossly overestimated global land warming. This version also predicts very unrealistic regional temperatures for the current greenhouse enhancement. The distribution of December-February temperature in the 5-year average of years 26 to 30 in the 30-year transient run, roughly speaking, should be analogous to a 5-year aggregate in the period 1975–1985 (years 26–30 beginning in 1950). The most significant projected anomalies are the 2–4° warming of the northern half of North America and the 3–6° *cooling* of the North Atlantic. Neither occurred, although Atlantic temperatures may have dropped some. This projected cold anomaly does not appear in later years of this transient model (G.A. Meehl, National Center for Atmospheric Research, pers. commun., September 13, 1990).

THE RESPONSE OF VEGETATION TO AN INCREASE IN CO_2

It has long been known that many plants show increased growth rates when subjected to increasing concentrations of CO_2. In fact, this response may be an expression of plant evolution, inasmuch as virtually all terrestrial plant species evolved when the atmospheric CO_2 concentration was higher than it is today. Many plants show this enhanced growth at concentrations higher than 3,000 ppm, some 10 times greater than late-19th- century values. Ellsaesser (1990) has noted that, in the last ice maximum, the Earth's atmosphere was within 100 ppm of being unable to support plant life because of a lack of carbon dioxide. In fact, during the last 100 million years, the Earth has undergone a general cooling associated with a reduction in atmospheric CO_2 that has only been reversed by human industrial activity.

Enhanced atmospheric CO_2 appears to stimulate plant growth both by increasing the rate at which carbon is fixed and by increasing plant water use efficiency. Thus we can expect that plants of the 21st century, on the average, will grow more rapidly per unit of moisture consumed. If the climate of that era is going to be dominated by night warming—which will lengthen the growing season without substantially increasing the natural evaporation rate—we may therefore expect a profound "greening" of the planet.

Atmospheric CO_2 has increased some 33 percent since the Industrial Revolution. Is there any evidence that this greening has begun? Woodward (1987) has indicated that plant specimens from the British Museum collected in the mid- 19th century (prior to the major CO_2 input) have more stomata than members of the same species collected today. These are the pores through which gases exchange and are the major pathway for loss of moisture. This verifies laboratory experiments that demonstrate that plants grown under enhanced CO_2 have fewer stomata than those grown under ambient concentrations. Consequently, both laboratory and field studies indicate that plants have already become more water-efficient as a result of the increase in CO_2.

Several "real world" surveys also indicate that vegetative growth is accelerating as a result of the increase in carbon dioxide. The effect has been noted in montane species in the Western United States, in a virgin forest plot being carefully monitored by the Oak Ridge National Laboratory, and in the northern forests of Scandinavia (Idso, 1989). In all these studies the growth responses have been dramatic and appear to be unexplainable by any conventional weather variable. Further, they have occurred at a time when forest growth is ostensibly being retarded by acid precipitation. Thus, while the same mechanism that causes acid rain may be preventing a disastrous warming (see below), the same gas that could cause warming (CO_2) could be enhancing growth that more than compensates for any putative losses of forests to acid rain.

There is some other evidence for large-scale vegetation expansion. Brush surveys in the State of Texas indicate a change in the area infested by woody plants from 88 million acres in 1963 to 106 million in 1983. Idso (1989) quotes a 1988 study by Veblen and Markgraf concerning "a dramatic invasion of the (Patagonian) steppe by tree species...as well as many species of tall shrubs." This change has occurred in spite of purposeful deforestation by European settlers and without any demonstrable climate change.

In fact, these and other changes have prompted two rangeland specialists to comment that "an experiment assessing the consequences of increased CO_2 levels has already been conducted on a global scale, and we should consider the possibility that the recent increases in abundance of woody plants on rangelands is its most visible result" (Mayeux and Johnson, 1986).

COMPENSATORY COOLING FROM OTHER INDUSTRIAL PRODUCTS

It is clear that human activity, besides enhancing the greenhouse effect, also produces substances that can serve to counter that effect. These include particulates, which serve to scatter radiation, and sulfur dioxide, which when oxidized to sulfate can nucleate clouds.

Mayewski and others (1990) recently demonstrated that the anthropogenerated sulfate load in the Northern Hemisphere atmosphere now is equivalent to the maximum loading from the Tambora volcano, which has been associated with a 2°C cooling of short duration. Hansen and Lacis (1990) suggest that current global forcing from aerosols may be as much as 1.5 w/m^2. Because anthropogenerated sulfates are produced and reside primarily in the Northern Hemisphere, we may therefore be equaling or overcompensating for current greenhouse forcing (1.5–2.5 w/m^2, depending upon estimate) with actual negative forcing in the hemisphere that contains most of the world's population. Recent calculations by Charlson and others (1990) quantitatively demonstrate this phenomenon.

Idso (1990) recently compared Northern and Southern Hemisphere temperature histories and found a striking difference that appears to be associated with the onset of world industrialization after World War II. Beginning in the mid-1950's, Northern Hemisphere temperatures stopped rising at the rate that characterized the 20th century, while those in the Southern Hemisphere continue to rise at the rate that characterized the first half of this century.

In fact, if anthropogenerated sulfates were mitigating enhanced greenhouse warming, we would expect to see the following:

1. Night warming from an increase in both clouds and greenhouse forcing,
2. A counteraction of daytime warming by the greenhouse forcing because of an increase in clouds,
3. A decrease in daily temperature range,
4. Concentration of these effects in the industrial (northern) hemisphere, and
5. Enhanced brightening of low-level clouds near sulfate source regions.

Previous sections of this paper detail evidence for the first four. With regard to the fifth, Cess (1989) analyzed a limited set of satellite data and found an increase in brightness in ocean-surface stratocumulus that was heightened near the source regions of Asia and North America. The effect, in which reflectivity was increased by as much as 8 percent, persisted for thousands of miles downstream from the source regions. A "clean" swath of the South Pacific Ocean served as a "control" and showed no brightening. Finally, German and United States records showing a decrease in sunshine (Angell, 1990; Weber, 1990) and the diminution of ultraviolet radiation at low altitudes (Sansom, 1989) coupled with enhancement at high elevation (Kalkstein and others, 1990) argue for some type of increase in a low-altitude reflectant.

CONCLUSION

One apocalyptic vision of the world influenced by an enhanced greenhouse is that of ecological disaster resulting from rising temperature, evaporation rates, and sea level. Several lines of observational and model evidence show that this scenario is becoming increasingly improbable.

The Northern Hemisphere, which should warm first and most, shows little net change in the last half-century. Repeated measurements now show relative warming at night, which may in fact be beneficial. The amount of global warming is clearly less than it should be according to the earlier GCM's, given the fact that we are already halfway to an effective doubling of CO_2. The only high-latitude signal that seems consistent with a greenhouse alteration is a 2°C warming of air masses whose average surface temperature is approximately $-40°$, which is a slight modification of the air mass type that is most inhospitable in North America. Other anthropogenerated compounds may be mitigating the warming. New climate models partition almost all of the warming of more than 4°C to polar twilight or night, which will have a minimal effect on ice melting.

If this is the course the Earth has embarked upon in response to human insults of the atmosphere, that response is primarily benign. And if human sulfate emissions are indeed the cause of this benign greenhouse, what are the implications for environmental policy?

A PERSONAL PROJECTION

World population and the ambient CO_2 concentration are profoundly linked, with an explained variance of approximately 99 percent between the two variables over the last 200 years. Any attempt to forcibly change this linear relationship will therefore involve disturbance of a highly coupled system and is therefore not likely to be particularly successful.

I believe that both the observed and theoretical evidence for mitigation of greenhouse warming by anthropogenerated sulfates is compelling and that it certainly serves to explain several disparate measurements that seemed counter to a simple greenhouse enhancement. If this is indeed true, the dimensions of the policy debate on global change have changed dramatically.

Two arguments should now surface. One group will argue, as did Hansen and Lacis (1990), for an advanced timetable to drastically reduce or eliminate fossil-fuel combustion, because the much longer residence time of CO_2 means that a substantial warming pulse already has been hidden by sulfates and that that pulse will emerge soon after SO_2 emissions are reduced.

The counterargument will be that we may have inadvertently discovered a control technology against greenhouse warming. The acid-rain effects of that technology can be minimized by concentrating fossil-fuel-based power generation on the eastern margin of continents, while using nonfossil dense energy sources inland.

Is a sulfate-mitigated warming reason to limit fossil-fuel combustion immediately, or does it argue that coal, whose reserves can last for centuries, should continue as a primary fuel? The former point of view now acknowledges both economic and ecological disruption as usage is curtailed, while the latter viewpoint will continue to increase the CO_2 content to the atmosphere dramatically. Will we purposefully produce a significant near-term disruption, or will we hope that the intellectual capital generated by nondiminished economic activity will, over the next 200 years, provide a nondisruptive solution to the global warming problem? That is the environmental question of the 1990's.

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Third General Session

Pliocene Climates

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The PRISM (Pliocene Research, Interpretation, and Synoptic Mapping) project is an interdisciplinary, coordinated investigation of Pliocene climates. Knowledge of the climate and environmental conditions during this youngest of the sustained warm intervals in Earth history will be used to explore numerical model simulations of past warm climate episodes and to provide insights into the impact of such climates on the biota and other aspects of Earth systems. PRISM operates through three core projects, which focus on pelagic marine, ocean margin, and terrestrial records. PRISM members collaborate with researchers at the national and international levels (table 1) to increase expertise and geographic coverage. A steering committee provides overall planning and scheduling of activities.

PRISM has two principal objectives. The first is to construct a synoptic paleoclimate map of the Northern Hemisphere for a much warmer interval than today or the last interglacial. The components of the map will include

Table 1. PRISM External Collaborators

Group/Organization	Subject or Area
International	
Group/Organization	*Subject or Area*
Working Group VIII U.S.-Former Soviet Union Bilateral Agreement on Environment Protection, Institute of Geography, Moscow	Pliocene Reconstruction
Geological Survey of Canada	Canadian Arctic
University of Iceland	Pliocene, Iceland
Institute of Earth Sciences, Wales	Modern and Pliocene, NE Atlantic, SW Pacific
Shizuoka University, Japan	Late Neogene, W Pacific
Geological Institute, Moscow	Late Neogene, Bering Sea-Arctic Basin
Tongii University, China	Late Neogene, W Pacific
Smithsonian Tropical Research Institute (STRI), Panama	Late Neogene, Central America, Isthmus of Panama
National	
Group/Organization	*Subject or Area*
National Center for Atmospheric Research (NCAR), Boulder Goddard Institute for Space Studies, New York	Modeling
Institute for Alpine and Arctic Research (INSTAAR), Boulder University of Alaska, Fairbanks University of Massachusetts, Amherst	Late Neogene, Arctic
Lamont-Doherty Geological Obervatory Columbia University, Palisades	Late Neogene, Pacific
Northern Illinois University	North Atlantic
University of Maine	Oxygen/carbon isotopes
University of Oregon	Technique development
University of Florida	Pliocene, Florida
University of Texas, Austin	Pliocene, Gulf of Alaska
University of Delaware	Pliocene, Atlantic Coastal Plain
Ohio State University Byrd Polar Research Center	Antarctic ice volume changes

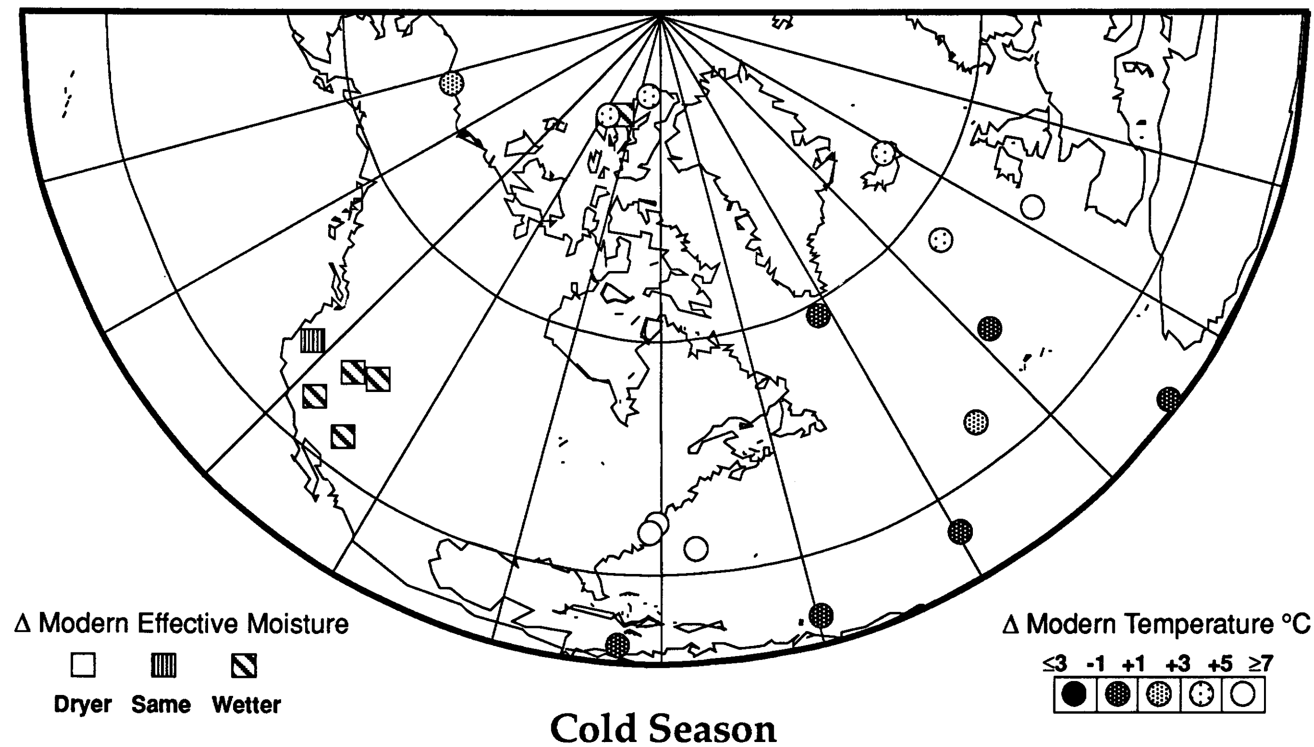

Figure 1. Environmental estimates from 3 million years ago.

estimates of precipitation, sea surface temperature, biota, and other aspects of Earth systems response to global warming. The reconstruction will provide a quantitative data set to calibrate and test numerical model attempts to simulate warmer climates. The reconstruction will be especially important for evaluating model simulations of regional-scale effects because current model simulations show gross differences on regional scales. The second PRISM objective is to document climate variability during the Pliocene with particular emphasis on the interval from 3.5 to 2.0 million years ago. This interval brackets the first major continental glaciation of the Northern Hemisphere at about 2.5 million years ago and represents a large, abrupt transition in Earth systems. Documentation of climate variability during the Pliocene will lead to better understanding of the mechanisms, forcing functions, and impacts of this major climate shift.

Initial PRISM activities include (1) delineation of Pliocene climate variation, (2) identification and evaluation of Pliocene records, (3) chronological refinement at key sections, and (4) development and refinement of techniques to quantify environmental parameters. A major warm episode at or about 3 million years ago is the first target for synoptic reconstruction. Estimates of sea surface temperatures (SST) and of precipitation for localities at 3 million years ago are shown on figure 1. Those results show that SST near the eastern coast of the United States, in the northeast Atlantic, and in the Arctic Ocean were much higher during this interval. SST in equatorial regions and off the southern tip of Greenland were similar to modern values. Precipitation was generally higher both in the Western United States and in the Canadian Arctic.

We tentatively conclude that the warming at 3 million years ago (fig. 1) involved increased transport of heat northward by the Gulf Stream and North Atlantic Drift. Sea ice must have been substantially reduced or even absent in large parts of the Arctic Ocean during this interval. Future work will involve testing and refining our preliminary interpretations by analyzing more sites to give broader geographic coverage to our reconstruction and by comparing our data to model simulations.

Desert Processes

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U.S. Geological Survey (USGS) research in deserts has traditionally been focused on understanding how certain types of sedimentary rocks (eolian sandstones) were built by wind in ancient deserts, because the structures formed by wind deposition have later influenced the migration of oil and gas. New demands on the USGS—to provide better understanding of the geological causes and effects of global change—require research into the role of desert processes, especially wind erosion, in changing land surfaces and resources in response to changes in climate or in human activity. The erosional effectiveness of wind varies very rapidly with changes in land surface climatology (precipitation, wind regimes, soil moisture, vegetation) and with human activity (farming, grazing, construction, war). Wind erosion provides an almost immediate signal of a changed environment in the form of deflating surfaces, migrating dunes, or dust emission, and it provides evidence of past episodes of aridity in the paleoclimatic records of dunes and of dust infiltrated into ice cores, lake and marine sediments, and soils.

Wind erosion has occurred episodically at least since the Cambrian on all continents on Earth. It also occurs on other planets (Mars and Venus). Wind erosion at present may remove as much as 1 billion tons of sediment (including soils) per year from North America. Saltating sand destroys crops, abrades property, and generates dust palls (aerosols) that affect the global radiation budget in ways that are still poorly understood, possibly even having feedback effects on climate. The recognition of eolian components in marine sediments, glacial ice, and soils worldwide has coincided with the perception, based on satellite tracking of dust storms, that wind is capable of transcontinental and even global transport of vast amounts of fine sediment. The sources, sinks, and rates of erosion and transportation of airborne sediment, past and present, are still poorly known. More reliable data are needed for inclusion in global climate models (GCM's), for forecasting adverse effects of wind erosion on vulnerable land surfaces such as the semiarid American West, for detecting and assessing variations in eolian activity that may be early warning signals of global change, and for calibrating paleoclimatic reconstructions.

Where, in the one-third of the Earth's land surface that is desert, should studies of global change be focused? The hyperarid core deserts are ideal "natural laboratories" in which to study wind processes unhindered by surface moisture and vegetation, but they are *not* the most critical areas in which to focus studies on the detection and societal consequences of global change. The key areas are the adjacent semiarid to subhumid regions, where climatic conditions are marginal and surfaces are inherently susceptible to wind erosion wherever they become destabilized. Eighty percent of the world's grazing lands and most of the irrigated farming are in these climate-sensitive transitional zones.

Vulnerability of the dry parts of the continental interiors to wind erosion is a global problem, exacerbated by the recent tendency to exploit these regions for grazing and farming. The result of this pressure has been "desertification"—the degradation and loss of biological productivity, whether due to climate change or human activity. The presently arid to subhumid regions in the continental United States and southern Canada, central Asia, central Australia, parts of central South America, southern Europe, central southern Africa, and the southern margin of the Sahara (Sahelian zone) all are surfaced largely with eolian materials (dunes and sand sheets or loess) deposited during Quaternary episodes of greater aridity. Their surfaces are now "fixed" to some extent by vegetation, but, like the Sand Hills of Nebraska, they remain chronically vulnerable to reactivation, "preconditioned" to remobilization by wind, given a return to greater aridity or removal of the native vegetation.

Although years of effort have been applied to studies of erosion and sediment transport by running water, only recently have we begun to define the basic geologic and climatic controls on erosion, transport, and deposition of sediment by wind under natural (field) conditions. Past neglect of wind as a geologic agent was due in part to the absence of reliable equipment capable of long-term monitoring in the abrasive, often difficult environments where eolian processes are most active; hence, most early studies of wind erosion relied on the collection and analysis of proxy data or on wind-tunnel experiments. Rates of wind erosion inferred from previous studies may be wildly inaccurate; preliminary results recently acquired by field instruments suggest that calculations derived from wind-tunnel experiments and theoretical considerations differ by an order of magnitude or more from calculations derived from field measurement under real conditions. The reason for this difference is that the standard wind-erosion equations are based on ideal conditions in wind tunnels and on certain characteristics of farm fields. These equations do not work well for natural surfaces with variable soil moisture and uneven topography or for different types of vegetation and surface sediments.

Systems now are in place to obtain field measurements of climatic and surface geologic conditions concurrently with real-time measurements of eolian sediment flux. Automated "Geomet" stations are presently operating in several types of desert sites in the American Southwest that range in climate from hyperarid to semiarid. Ground surface and atmospheric conditions recorded at these sites provide data on the "normal" climatic variability under which eolian processes are active and eventually will provide data for calculating rates and amounts of eolian sediment transport that actually occur under monitored sets of land surface/climatic conditions. Once the boundary conditions for modern eolian activity are more precisely defined, the modern analogs should be used to better calibrate models of the paleoclimatic conditions inferred from eolian deposits. In addition, the long-term Geomet records will provide a baseline of present climatic variability in areas typical of the American Southwest, against which future effects of changes in climate and human activity may be assessed.

Satellite Image Atlas of Glaciers of the World

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Of all the expected impacts of the predicted global warming on the geosphere and biosphere, the greatest potential for economic disruption of human population is by accelerated melting of glacier ice (net loss of global glacier volume) and a concomitant rise in sea level. The cryosphere (glacier ice, sea ice, snow cover, ground ice, and permafrost) is the most sensitive component of the geosphere to seasonal and longer term changes in global surface temperature. During the past two decades, satellite sensors have recorded variations in the areal extent of sea ice, snow cover, and glaciers. Only by using satellite sensing technology may systematic and repetitive regional and global measurements of changes in area or other remotely sensed characteristics of the cryosphere be accomplished.

The realization that one element of the Earth's cryosphere, its glaciers, was amenable to global inventorying and areal-change monitoring with Landsat images led to the decision, in 1978, to prepare an 11-volume U.S. Geological Survey Professional Paper 1386 (A–K), *Satellite Image Atlas of Glaciers of the World*, in which Landsat 1, 2, and 3 multispectral scanner (MSS) and return beam vidicon (RBV) images are used to inventory the areal occurrence of glacier ice on our planet within the spacecraft's orbital coverage (between about 81° north and south latitudes). Between 1979 and 1981, optimum Landsat images were distributed to an international team of 54 scientists (from 25 nations, representing 42 different institutions), who each agreed to author a section of the Professional Paper concerning either a geographic area or a glaciological topic. In addition to analyzing images of a specific geographic area, each author was asked to summarize up-to-date information about the glaciers within the area and to compare the present areal distribution of glaciers with historical information about their past extent (for example, from published maps, reports, and photographs). Because of the limitations of Landsat images for delineating or monitoring small glaciers in some geographic areas (for example, inadequate spatial resolution, lack of suitable seasonal coverage, or complete absence of coverage), information on areal distribution is sometimes necessarily derived from ancillary sources. Completion of the atlas by 1993 will provide an accurate regional inventory of the areal extent of glaciers on our planet within a relatively short time (1972 to 1982). This global "snapshot" or "benchmark" of glacier extent already is being used for comparative analysis with previously published maps and aerial photographs and with new maps, satellite images, and aerial photographs to determine the areal fluctuation of glaciers in response to natural or culturally induced changes in the Earth's climate. For example, sequential Landsat images have documented many major changes in the coastal regions of Antarctica.

Chapter A of the atlas is a general introduction, including a discussion of the physical characteristics, classification, and global distribution of glaciers. The next nine chapters, B through J, are arranged geographically and present glaciological information from Landsat and other sources of data on each geographic area: Chapter B, Antarctica (Swithinbank, 1988); Chapter C, Greenland; Chapter D, Iceland; Chapter E, continental Europe (except for the European part of the USSR); Chapter F, USSR, China, India, Nepal, Afghanistan, and Pakistan; Chapter G, Turkey, Iran, and Africa (Kurter and others, 1991); Chapter H, Irian Jaya (Indonesia) and New Zealand (Allison and others, 1989); Chapter I, South America; and Chapter J, North America. Chapter K presents related glaciological topics.

Sensitivity of Water Resources in the Delaware River Basin to Climate Change

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The U.S. Geological Survey began a study of the effects of climate change on water resources in the Delaware River basin in 1988. As part of this study, a hydrologic model of the basin was developed that included the operation of reservoirs and diversions. The basin hydrologic model was used to examine the sensitivity of water resources in the basin to prescribed changes in temperature, precipitation, and the stomatal resistance of plants to transpiration.

Results of simulations made using the model indicated that within the ranges of the prescribed changes in precipitation (−20 percent to +20 percent) and temperature (0 to +4°C), streamflow and reservoir contents were more sensitive to changes in precipitation than to changes in temperature. In contrast, irrigation demand was more sensitive to changes in temperature than to changes in precipitation. The results also indicated that all water-resource components of the basin were very sensitive to prescribed changes in the stomatal resistance of plants to transpiration.

Because of current reservoir operating rules, simulation results indicated that the New York City reservoirs are more sensitive to climate changes than are other water-resource components of the basin, such as streamflow at Trenton, N.J., and the position of the salt front in the Delaware River estuary. Storage in the reservoir system acts as a buffer to changes in unregulated streamflow caused by climate changes, and to changes in the upstream movement of the salt front in the estuary caused by sea-level rise.

Natural climate variability has a large effect on estimates of future hydrologic conditions in the Delaware River basin. The estimated effects of natural climate variability were as large as the modeled effects of the prescribed climate changes. Because natural climate variability causes such large changes in basin water resources, it could mask any effects of long-term trends in climate change.

INTRODUCTION

Scientists have estimated that increasing concentrations of atmospheric carbon dioxide (CO_2) may cause global warming and changes in temporal and spatial patterns of precipitation (Bolin, 1986; Lins, 1988). Some research also has shown that the stomatal resistance of plants to transpiration is increased in a CO_2-enriched atmosphere thereby decreasing transpiration rates (Idso and Brazel, 1984). Such changes in temperature, precipitation, and plant transpiration may have important effects on water resources.

In 1988, the Water Resources Division of the U.S. Geological Survey initiated an interdisciplinary study of the sensitivity of water resources in the Delaware River basin to climate change (Ayers and Leavesley, 1988). Certain aspects of the basin's water resources were of particular concern: (1) changes in streamflow, (2) changes in water storage in the New York City and other basin reservoir systems, (3) maintenance of prescribed minimum streamflow requirements, (4) the upstream movement of saline water in the Delaware River estuary caused by changes in freshwater inflows, and (5) changes in irrigation demand. This paper presents the results of a sensitivity analysis of the basins water resources to climate change.

THE DELAWARE RIVER BASIN

The Delaware River basin, which lies along the east coast of the United States, encompasses about 30,000 km^2 (fig. 1). The region has a humid, temperate climate with a mean annual temperature of about 12°C and a mean annual precipitation near 1,200 mm. Soils and topography vary considerably within the basin. Soils range from thick sandy-loam soils to thin clayey soils, and topography varies from low relief in coastal areas to the Appalachian mountains in the northern part of the basin.

The Delaware River basin provides water for an estimated 20 million people within and outside the basin (Albert, 1987). Water availability is enhanced by a system of reservoirs, wells, and diversions. Two large diversions out of the basin are through the New York City aqueduct system and the Delaware and Raritan Canal (D & R Canal) (fig. 1). Releases of water from the reservoirs are managed to maintain specified minimum flows at important points in the river. These minimum flows keep saline water downstream of important freshwater supplies.

The objective of the Delaware River basin study was to examine the sensitivity of the water resources in the Delaware River basin to climate change under existing water management policy and infrastructure.

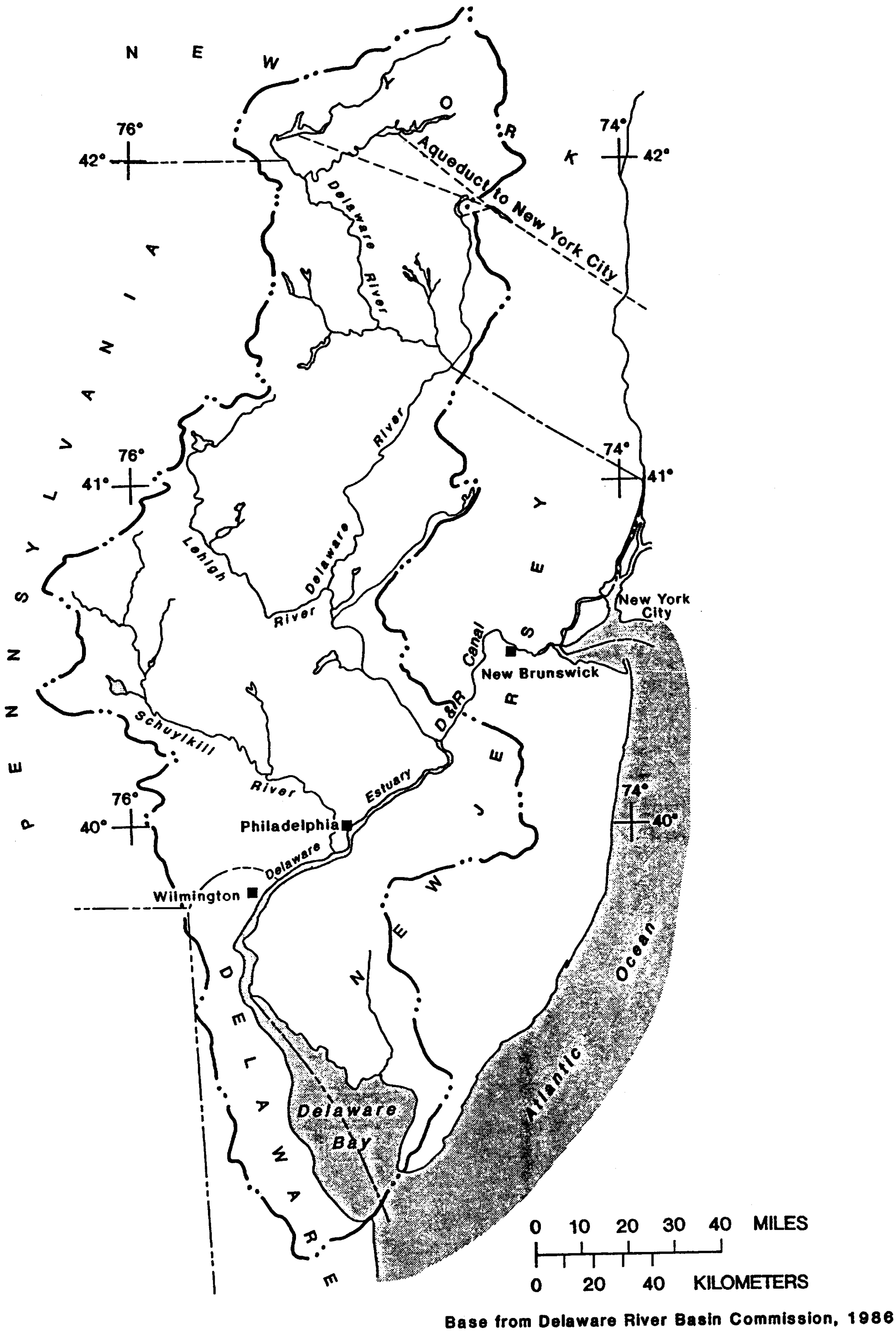

Figure 1. The Delaware River basin.

HYDROLOGIC MODEL OF THE DELAWARE RIVER BASIN

To examine the sensitivity of the water resources in the Delaware River basin to climate change, a hydrologic model of the basin was developed that included the existing management policy and infrastructure. The model was based on a monthly time-step water balance within the basin. The basin water-balance model was a modification of the Thornthwaite water-balance model, which is a water-budget bookkeeping procedure that accounts for soil moisture, evapotranspiration, water deficit, snowmelt, and surface runoff (Thornthwaite and Mather, 1955; McCabe and Ayers, 1989).

The basin water-balance model estimates unregulated streamflows based on climate inputs (monthly mean temperature and monthly precipitation) and a few simple parameters such as soil field capacity (see McCabe and Ayers (1989) for a detailed description of the water-balance model).

Unregulated streamflow estimates were made at several key nodes in the basin, such as the sites of reservoirs where critical management decisions are made. Basin operation rules then were applied at these key nodes and reservoir storage, regulated streamflow, and the position of the salt front in the Delaware River estuary were estimated for every time step in the simulation. The length of the time that the basin was in a state of drought for a given simulation was computed as the number of months when the simulated reservoir storage or regulated streamflow dropped below some specified level.

The basin water-balance model also was adapted to estimate annual irrigation demand as a function of temperature, precipitation, and soil characteristics. Irrigation applications were based on the soil-moisture content estimated by the model.

SCENARIOS OF CLIMATE CHANGE

General circulation models (GCM's) of the atmosphere commonly are often used to estimate the effect of increasing atmospheric CO_2 on climate. There is an inherent scale problem, however, in interpolating estimates from GCM's to areas the size of the Delaware River basin. GCM nodes are spaced on a grid about 4° of latitude by 5° of longitude. The size of the Delaware River basin measures only about 3° of latitude by 1° of longitude. Thus, the basin is smaller than the area outlined by four GCM modes, and estimates of climate conditions from such spatially coarse models for areas the size of the Delaware River basin are unreliable (McCabe and Ayers, 1989).

In an attempt to overcome the spatial incompatibility between GCM's and the Delaware River basin, surface weather patterns, such as frontal passages and high-pressure systems, simulated by GCM's were compared to observed weather patterns over the basin. The spatial size of weather patterns (about 10° of latitude by 10° of longitude) is large enough to be estimated reasonably by GCM's, and knowledge of weather-pattern frequencies and characteristics in and around the Delaware River basin allows for adequate estimates of temperature and precipitation.

GCM simulations of weather patterns (for both current and doubled-CO_2 conditions) were analyzed and compared to observed weather patterns [a detailed description of GCM weather-pattern analysis is given in Hay and others (1992)]. Although GCM-simulated weather pattern frequencies for current conditions matched well with observed weather-pattern frequencies, the weather-pattern frequencies computed for doubled-CO_2 conditions matched observed data equally well. Changes in weather-pattern frequencies from current to doubled-CO_2 conditions were hoped to be the primary driving force of changes in temperature and precipitation simulated by the GCM's; this would have provided a scale-appropriate means of estimating future temperature and precipitation without relying on GCM simulations of changes in precipitation and temperature. The GCM results indicated, however, little or no changes in weather-pattern frequencies from current to doubled-CO_2 conditions.

Given the inability to use weather patterns to generate appropriate climate-change scenarios for doubled-CO_2 conditions, and the lack of confidence in using GCM simulations directly, prescribed changes in precipitation and temperature were used in the analyses presented in this paper. The range in prescribed changes represented the range of GCM estimates of precipitation and temperature changes reported in the literature (Schneider and others, 1990).

Because of the speculation that increasing concentrations of CO_2 may increase the stomatal resistance of plants to transpiration, prescribed changes in a conceptual stomatal-resistance factor were included in the climate-change scenarios (Idso and Brazel, 1984; Rosenberg and others, 1990; Wolock and Hornberger, 1991). The range in prescribed changes in stomatal resistance reflect the range reported in the literature for doubled-CO_2 conditions (Rosenberg and others, 1990). In addition, prescribed increases in sea-level also were incorporated as a component of climate change. As temperatures increase with increasing concentrations of atmospheric CO_2, sea-level also is estimated to increase due to thermal expansion of the oceans as they warm, and due to the melting of glacial ice. Increased sea-level may have important effects on the position of the salt front in the Delaware River estuary and the intrusion of salt water into freshwater aquifers.

The prescribed temperature and precipitation changes were used with simple stochastic equations to generate multiple time series of temperature and precipitation that were subsequently input to the Delaware River basin hydrologic model. Temperature and precipitation time

Table 1. Median drought frequency[1] in the Delaware River basin derived from 50 30-year simulations for various prescribed changes in temperature and precipitation

Temperature Change[2]	Precipitation Change[2]				
	−20%	−10%	No Change	+10%	+20%
No change	79	29	6	1	0
2°C warming	90	50	13	3	0
4°C warming	96	70	29	7	1

[1] Drought frequency is defined as the percentage of months during a 30-year simulation the basin is in drought conditions based on contents of New York City reservoirs.

[2] Change from current mean annual temperature and precipitation (1895–1988).

Table 2. Annual irrigation demand (in millimeters) for various prescribed changes in temperature and precipitation based on 50 100-year simulations

Temperature Change[1]	Precipitation Change[1]				
	−20%	−10%	No Change	+10%	+20%
0°C warming	212	192	174	158	145
2°C warming	278	256	236	217	201
4°C warming	357	331	309	289	269

[1]Change from current mean annual temperature and precipitation (1895–1988).

series developed from the succhastic equations were used to study the effects of long-term transient changes in climate on water resources, as well as the effects of steady-state changes. The time series of temperature and precipitation estimates also were used to evaluate the effects of prescribed changes in temperature and precipitation on water resources amid natural climate variability. Even with prescribed long-term changes in precipitation and temperature, natural climate variability creates a wide range of climate conditions that potentially may occur.

RESULTS OF MODEL SENSITIVITY ANALYSES

Effects of Changes in Temperature and Precipitation

Streamflow and drought conditions (defined by streamflow or reservoir storage) were sensitive to the prescribed changes in precipitation and temperature. For example, the median drought frequencies derived from 50 30-year simulations for various climate changes are given in table 1. Drought frequency is the percentage of months during a 30-year simulation that the basin experienced drought conditions based on the contents of the New York City reservoirs. Drought occurred approximately 6 percent of the time for current climate conditions, but increased to 13 percent of the time for a warming of 2°C with no change in precipitation, and increased to 29 percent of the time for a warming of 4°C with no change in precipitation. For the 2°C warming scenario, drought frequency increased to 90 percent for a 20 percent decrease in precipitation, but decreased to 0 percent for a 20 percent increase in precipitation.

Within the ranges of precipitation and temperature changes used in this study, drought frequencies were more sensitive to precipitation changes than to temperature changes (table 1). Assuming a 2°C temperature increase, drought frequencies varied from 0 to 90 percent, depending on the assumed change in precipitation. In contrast, assuming a 10 percent decrease in precipitation, drought frequencies ranged from 29 to 70 percent, depending on the prescribed temperature change. The sensitivity of drought to precipitation, coupled with uncertain GCM precipitation estimates for a CO_2-enriched atmosphere, made the estimation of CO_2 effects on drought difficult.

Irrigation demand estimated by the basin model also was sensitive to the prescribed changes in temperature and precipitation (table 2) based on 50 100-year simulations. The estimated annual irrigation demand was 174 mm for current climate conditions, 236 mm for a warming of 2°C with no change in precipitation, and 309 mm for a warming of 4°C with no change in precipitation. Annual irrigation demand was 278 mm for a 2°C warming combined with a 20 percent decrease in precipitation, and 201 mm for a 2°C warming combined with a 20 percent increase in precipitation.

Within the prescribed ranges of precipitation and temperature changes, irrigation demands were more sensitive to temperature changes than to precipitation changes (table 2). Assuming a 2°C temperature increase, annual irrigation demand varied from 201 to 278 mm, a range of 77 mm depending on the change in precipitation. In contrast, assuming no change in precipitation, irrigation demand varied from 174 to 309 mm, a range of 135 mm depending on the prescribed temperature change. Temperature has a strong effect on soil moisture and irrigation demand through its effect on potential evapotranspiration.

Sensitivity analyses also indicated that increases in temperature can affect the timing of streamflow in areas where winter snow accumulation and spring snowmelt are currently important components of the annual water budget. Increased temperatures cause a greater proportion of winter precipitation to fall as rain, and therefore allowed more of the available precipitation to run off during the winter and reduced the snow accumulation and the snowmelt runoff during spring.

The various water-resource components of the Delaware River basin differed in their degree of sensitivity to climate change due, in part, to the current management policies practiced in the basin. Drought as defined by the contents of the New York City reservoirs was more sensi-

Table 3. Effects of prescribed changes in temperature and precipitation on changes in water-resource components based on 50 30-year simulations

Change in temp.[1] Change in precip.[1]	No change No change	+4°C No change	+4°C −10 percent
Percentage of time in drought (based on stream flow at Trenton, N.J.)	3	9	20
Percentage of time in drought (based on contents of New York City reservoirs)	8	30	73
Position of salt front (river mile)	75	77	79

[1]Change from current mean annual temperature and precipitation (1895–1988).

tive to changes in precipitation and temperature than was drought as defined by streamflow at Trenton, N.J. (table 3). Similarly, the position of the salt front in the Delaware River estuary was less sensitive to changes in climate than was drought as defined by the contents of the New York City reservoirs. This difference in sensitivity resulted because the New York City reservoirs are the primary mechanism used to maintain minimum flows in the Delaware River, and to maintain the position of the salt front below river mile 100 where water is withdrawn from the river by the city of Philadelphia, Penn. Storage in the reservoir system acts as a buffer to changes in unregulated streamflow caused by changes in temperature and precipitation. If requirements of reservoir releases from the New York City reservoirs are reduced, then the sensitivity of the various water-resource components changes. For example, if target flow requirements are reduced, reservoir storage in the New York City reservoirs becomes less sensitive to climate changes and the position of the salt front in the Delaware River estuary becomes more sensitive (table 4).

Table 4. Model simulations of the percentage of time New York City (NYC) reservoir storage is at zero (less than 1 percent of storage capacity) and the salt front in the Delaware River estuary is at or above river mile 100 for a 4°C increase in mean annual temperature (1895–1988) and a 10 percent decrease in mean annual precipitation (1895–1988), and for various reductions in required reservoir releases (target flows)

	Reduction in target flows (percent)						
	0	10	20	30	40	50	60
Percentage of time NYC reservoir storage reaches zero	4.0	3.0	2.0	1.5	1.0	0.5	0.0
Percentage of time salt front reaches river mile 100...........	0.0	0.0	0.0	0.0	0.5	2.0	5.0

Table 5. Percentage of time the New York City (NYC) reservoir storage reaches zero (less than 1 percent of storage capacity) and the position of the salt front in the Delaware River estuary reaches river mile 100 for a 4°C increase in mean annual temperature 1895–1988) and a 10 percent decrease in mean annual precipitation (1895–1988), and for various prescribed upstream shifts in the mean monthly position of the salt front

	Prescribed upstream shift in mean monthly position of salt front				
	miles kilometers	0 0	5 8	10 16	15 24
Percentage of time NYC reservoir storage reaches zero		4	5	6	6
Percentage of time salt front reaches river mile 100..............		0	0	2	5

Effects of Sea-Level Rise

The effects of potential sea-level rise on the water resources of the Delaware River basin were examined by prescribing shifts in the mean monthly position of the salt front in the Delaware River estuary and observing changes in the percent of time New York City reservoirs reached zero storage (less than 1 percent of storage capacity) and the percent of time the salt front reached river mile 100. Model results indicated that even for large increases in temperature and decreases in precipitation large upstream shifts in the mean monthly position of the salt front only caused the salt front to reach river mile 100 a small percentage of the time (table 5). For example, a shift in the mean monthly position of the salt front 10 miles (16 km) upstream resulted in the salt front reaching river mile 100 only 2 percent of the time for a 4°C increase in temperature and a 10 percent decrease in precipitation. To produce a 10 mile (16 km) upstream shift of the salt front would require a sea-level rise of almost 1 m, which is more than twice the current estimates of sea-level rise for doubled-CO_2 conditions (Robin, 1986; Titus, 1986).

The percentage of time the New York City reservoirs reached zero storage increased as the mean monthly position of the salt front was shifted upstream because current operating rules require releases from the reservoirs to maintain the salt front below river mile 100.

Potential effects of sea-level rise on salt-water intrusion into coastal aquifers also was considered. Examination of coastal aquifers along northern Delaware indicated that the location and extent of inundation caused by sea-level rise has a great effect on salt-water intrusion into many aquifers along the Delaware River basin. Inundation causes saline water to move inland past silty confining units and to more readily intrude into the aquifer. The lack of detailed topographic maps (with a 30 to 50 cm contour interval) and

Table 6. Effects of prescribed changed in temperature, precipitation, and stomatal resistance on annual irrigation demand (in millimeters) based on 50 100-year simulations

A. No change in temperature [1]

Change in Precipitation[1]	Change in Stomatal Resistance		
	No Change	+20%	+40%
No change.....	174	91	26
−10%.........	192	103	32

B. +2°C increase in temperature [1]

Change in Precipitation[1]	Change in Stomatal Resistance		
	No Change	+20%	+40%
No Change	236	133	48
−10%.........	256	149	58

[1]Change from current mean annual temperature and precipitation (1895–1988).

Table 7. Range of drought frequency[1] derived from 50 30-year simulations of current climate conditions and conditions resulting from prescribed changes in temperature and precipitation[2]

[T, current mean annual temperature (1895–1988); P, current mean annual precipitation (1895–1988)]

Climate scenario	Drought frequency (percent) 0 10 20 30 40 50 60
Current climate	-------------->
T+4°C	---------------------->
T+4°C, P−10%	---------------------------------->
T+4°C, P+10%	-------------->
P−10%	---------------------------->

[1]Drought frequency is defined here as the percentage of months during a 30-year simulation the basin is in drought conditions based on contents of New York City reservoirs.

[2]Change from current mean annual temperature and precipitation (1895–1988).

detailed description of the silty confining units limited research of this problem. At this point, because the intrusion of salt-water into many aquifers along the Delaware River are sensitive to the location and extent of inundation, reasonable estimates of the effects of sea-level rise on salt-water intrusion into coastal aquifers along the Delaware River are not possible.

Effects of Changes in Stomatal Resistance

The results of the sensitivity analyses performed in this study indicated that the water resources of the Delaware River basin were very sensitive to changes in stomatal resistance, and that changes in stomatal resistance could offset the effects of increases in temperature and decreases in precipitation (table 6). With a 2°C increase in temperature and no change in precipitation, annual irrigation demand was 236 mm, an increase of 62 mm over estimated current irrigation demand (174 mm) (table 6). With increases in stomatal resistance of 20 and 40 percent, however, annual irrigation demands were 133 and 48 mm, respectively, which represented decreases of 41 and 126 mm from the estimated current demand (174 mm) (table 6). The reduction in transpiration caused by increased stomatal resistance more than offset the increase in potential evapotranspiration resulting from increased temperature.

In a similar manner, increases in stomatal resistance offset decreases in precipitation. With no change in temperature and a 10 percent decrease in precipitation, annual irrigation demand was 192 mm, an increase of 18 mm over estimated current annual irrigation demand (table 6). With increases in stomatal resistance of 20 and 40 percent, annual irrigation demands were 103 and 32 mm respectively, which represented decreases of 71 and 142 mm from the estimated current demand (table 6). Even for a 2°C increase in temperature and a 10 percent decrease in precipitation, annual irrigation demand was less than estimated current demand when stomatal resistance was increased (table 6).

Effects of Natural Climate Variability

Natural climate variability was a major factor affecting the estimation of the effects of climate change on water resources in the Delaware River basin. For a given expected future climate, natural variability created a wide range of climate conditions that potentially may occur. The range in climate conditions that may be realized due to natural variability can mask the effects of long-term changes in temperature and precipitation. Table 7 gives a range of drought frequencies due to natural climate variability for several climate-change scenarios. Each scenario had a suite of possible drought frequencies; for instance, drought frequency ranged from 1 to 20 percent for current climate conditions and from 4 to 36 percent for a 4°C increase in temperature and no change in precipitation. The overlap in these distributions implies that natural climate variability can mask the effects of estimated long-term climate changes. Even if accurate estimates of long-term changes in mean temperature and precipitation can be made, a wide range of drought frequencies is possible because of natural short-term variability in precipitation and temperature.

SUMMARY AND CONCLUSIONS

A hydrologic model of the Delaware River basin was developed that included the operations of reservoirs and diversions based on current management policy and infrastructure. The basin hydrologic model was used to examine the sensitivity of the water resources in the basin to climate change. Because of a large amount of uncertainty in estimates of climate change by GCM's, a range of prescribed changes in climate was used.

Changes in streamflow and reservoir contents were more sensitive to changes in precipitation than to changes in temperature within the ranges of prescribed changes in temperature and precipitation used in the study. In contrast, changes in irrigation demand were more sensitive to changes in temperature than to changes in precipitation. The water resources of the Delaware River basin also were very sensitive to changes in stomatal resistance of plants to transpiration, which may offset the effects of increases in temperature and decreases in precipitation.

The current infrastructure and reservoir operating rules cause the various water-resource components of the basin (for example, New York City reservoir storage, streamflow at Trenton, N.J., and the position of the salt front in the Delaware River estuary) to have differing sensitivities to climate changes. By changing the reservoir operating rules, the sensitivity of the various water-resource components to climate changes can be altered.

The potential effects of climate change on water resources in the Delaware River basin are uncertain for several reasons. First, GCM estimates of the effects of increasing CO_2 on regional precipitation are unreliable, and basin water resources are very sensitive to changes in precipitation. Second, the basin water resources are sensitive to assumptions about the effects of CO_2 on stomatal resistance of plants to transpiration. Finally, the effects of natural climate variability are as large as those due to the prescribed temperature and precipitation changes. Natural variability in precipitation and temperature, therefore, may mask the effects of long-term climate trends on water resources.

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A Strategy for Large-Area Land Characterization: The Conterminous United States Example

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We need an accurate descriptive and quantitative understanding of the characteristics of the land surface to derive parameters needed in global and mesoscale climate models.

An inspection of the characteristics of global land data sets shows that we do not have consistent, comprehensive data bases of vegetation conditions at spatial resolutions required for the next generation of global climate models.

The Matthews land cover data base is considered the best global vegetation, land cover, and land use data base (Matthews, 1983). The Matthews data base was assembled from approximately 70 vegetation maps and 40 land use maps covering portions of the globe—augmented where necessary with Landsat imagery. The result is a representation of the Earth's land surface characteristics at a spatial resolution of 1° of latitude by 1° of longitude. Although this is the best data base for representing the global land surface, there are inconsistencies in the data set because of the difficulty of consolidating the more than 110 source maps with different classification systems, interpretation methods, and accuracy levels into a single global coverage.

Considering the growing importance of mesoscale or regional land process models, we must begin building land characteristics data bases that provide a more detailed look at spatial patterns of the landscape. We must also start assessing a broader range of land surface characteristics if we are to contribute data to models that adequately address biosphere, atmosphere, and hydrosphere interactions.

To address this problem, U.S. Geological Survey staff at the EROS Data Center (EDC) initiated an investigation in late 1990 to develop a large-area land characterization to start filling the gaps caused by unavailable or inadequate land surface data.

Remote sensing can help solve this problem. For example, the National Center for Atmospheric Research recently concluded that normalized difference vegetation index (NDVI) data provide a better definition of both what is on the land surface and where the boundaries of different land cover types are than other global data sets (Henderson-Sellers and others, 1986). NDVI data are derived from Advanced Very High Resolution Radiometer (AVHRR) data collected onboard National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. NDVI measures several land surface properties including primary production, leaf area, evapotranspiration, canopy resistance, and surface heat flux. In its basic form, however, NDVI is difficult to interpret and incorporate directly into existing models.

Our large-area land characterization research is focused on the development of methods for classifying remote-sensed data such as 1-kilometer (km) resolution AVHRR imagery to produce large-area land characteristics data bases. We are developing a prototype data base for the conterminous United States that can be evaluated as an alternative to current data sets.

Our experimental methods and prototype product definition are guided by several design considerations that were developed at the onset of the research:

- The methods must be repeatable over large areas. In most cases, the larger the area the more complex the analysis will be.
- Significant seasonal, ecological, and cultural variations in the landscape must be dealt with.
- The procedures must be efficient even with large data volumes. This requires simple rather than elaborate, complex approaches. If, for example, it takes several years to map land cover for a small part of the Earth's surface, the value of the results will be greatly reduced.
- Data of varying quality must be usable. Some source materials will be reliable, some inaccurate. We need methods that will use the strengths of various types of data in order to create a single integrated data base of land characteristics.
- The results must have the flexibility to be tailored to a range of applications. The user community for large-area land characteristics data bases includes the environmental monitoring and land management communities, in addition to global change scientists.

Figure 1 illustrates the conceptual approach we are using to produce the land characteristics data base. Our analysis is based on a combination of remote sensing and other multisource Earth science data in an integrated classification framework. A time series of 1-km NDVI data provides a means to classify land cover based on the seasonal characteristics of vegetation communities. Other climate, elevation, and ecosystem variables are used to stratify selected remote sensing derived classes into homogeneous categories.

The prototype land characteristics data base contains both spatial and attribute components. The spatial component is a set of seasonally distinct land cover regions, which

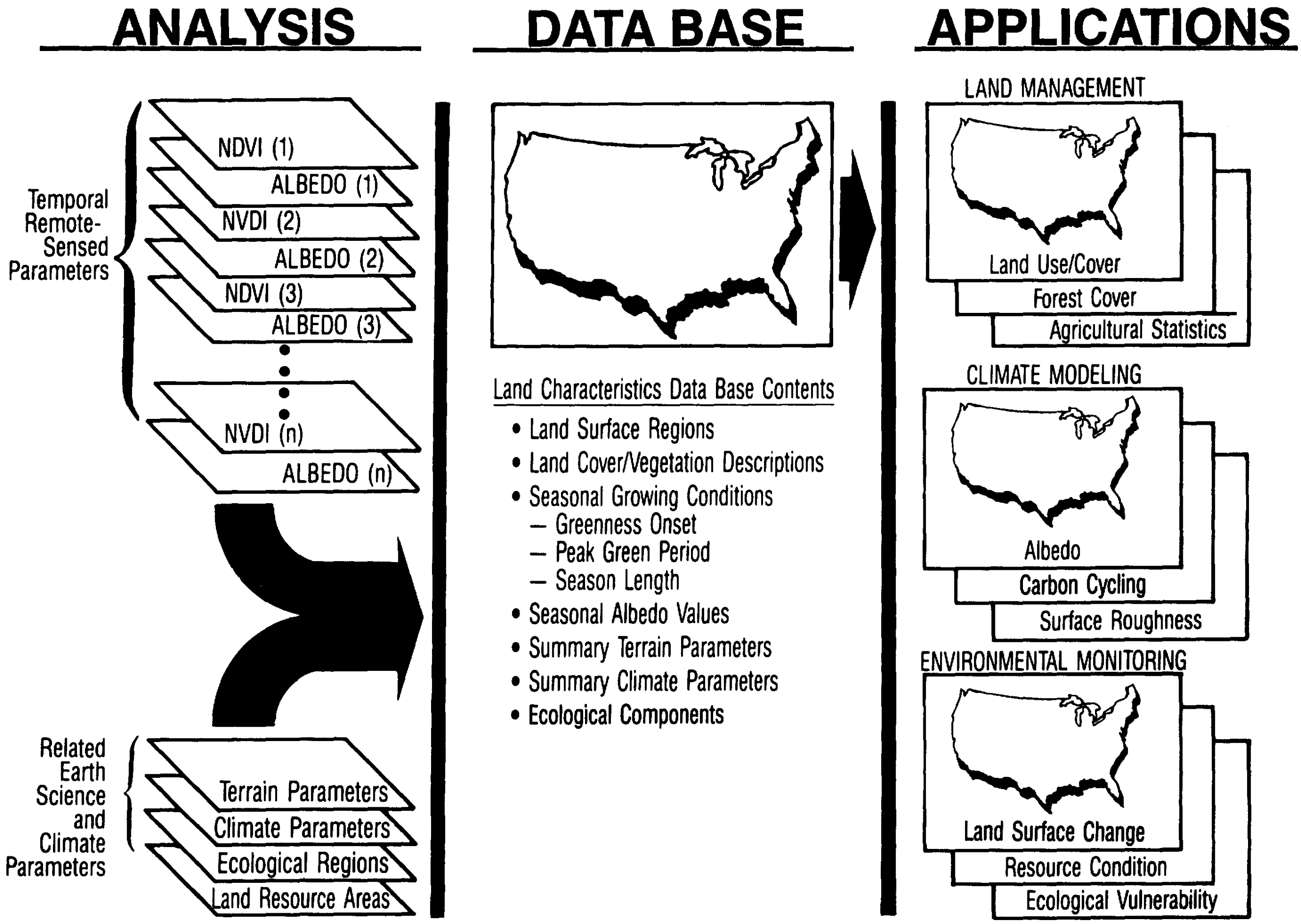

Figure 1. Conceptual framework for large-area land characterization research.

are consistent in their floristic composition and their physiognomic characteristics. (The density and height of the communities are constant within the regions.) Equally important, however, is that each region has consistent seasonal characteristics, so that we can look at the temporal variations in factors such as leaf area or albedo.

Each region is described in terms of land cover and vegetation components (community composition and life form). Also included are quantitative biophysical data pertaining to seasonal parameters of land cover (onset of greenness, peak green period, duration of green period, and relative biomass amounts). Additional properties, such as physical measures of albedo, evapotranspiration, primary production, and leaf area index, may be added to the data base as research defining acceptable procedures for their calculation are completed.

Finally, the data base includes summary site characteristics that describe the local context of each region. These site characteristics include the ecological setting, terrain characteristics, and climate conditions of the various regions.

Collectively, the regions and attributes data base must be flexible enough to be tailored to a variety of applications. We can view this as a spreadsheet of land parameters that can be translated or interpreted to yield variables or classes of data needed for specific models or applications. This may include production of land cover maps, or perhaps the spatial distribution of carbon. Our strategy is to provide enough descriptive and quantitative detail so that users have a dynamic source of needed data.

The data required to produce the land characteristics data base are based largely on remote sensing and, in particular, AVHRR data from the NOAA polar-orbiting series of satellites. The NDVI transformation derived from AVHRR provides a useful means for looking at the seasonality of land cover and permits classification of the different vegetation communities that form land cover regions.

Various characteristics of AVHRR data make this type of data useful for understanding global vegetation patterns. AVHRR data provide an appropriate resolution (approximately 1 km) over the entire globe. A single AVHRR scene is about 2,600 km wide. The AVHRR

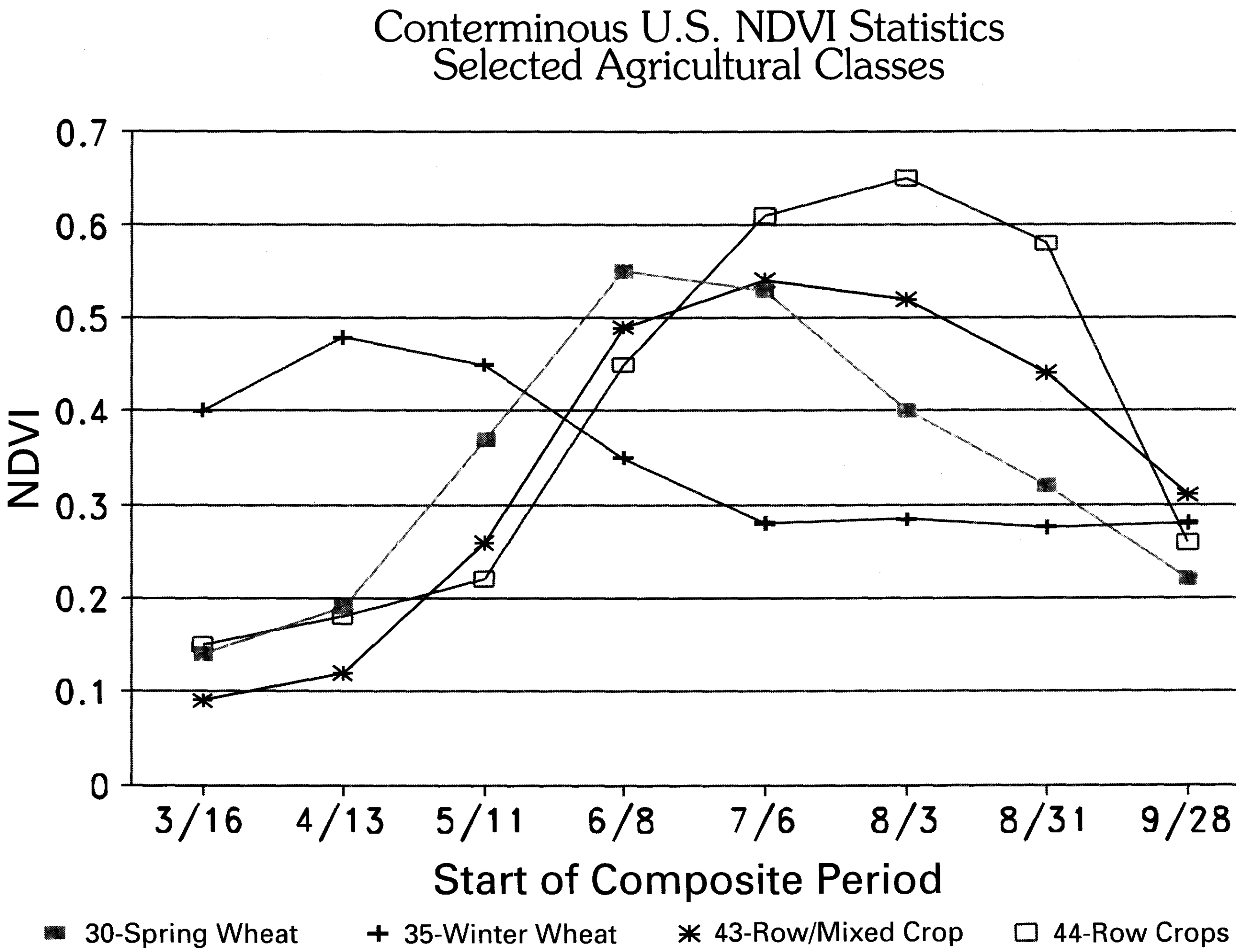

Figure 2. NDVI temporal characteristics for selected agriculture and range land cover clases.

sensor views the same land area every day. With two operational satellites, we receive imagery of the Earth twice a day. This provides data about landscape conditions at any given date. When we accumulate the daily observations and use simple transformations like NDVI, we can get a good picture of the patterns of vegetation dynamics.

The NDVI is considered sensitive to differences in standing green biomass. Thus, over time, it provides a profile of annual vegetation phenology (Justice and others, 1985). For the conterminous United States, EDC is producing NDVI composites every 2 weeks (Eidenshink and others, 1991; Sadowski, 1990). The NDVI composites for 1990 show patterns of greenness caused by changes in regional temperatures and precipitation.

NDVI data for March through October 1990 were processed using image classification techniques to identify the seasonally distinct land cover regions in the United States. We overlaid 17 biweekly AVHRR greenness images of the conterminous United States, creating eight sequential monthly composites. These composites were evaluated using unsupervised classification methods to segment the data into seasonally distinct land cover regions.

Figures 2 and 3 illustrate the relationship between temporal NDVI values and selected land cover types. The graphs display selected classes and the NDVI means from the eight monthly composites. Because NDVI time-series data capture the seasonality of vegetation, the data are diagnostic of the form and the floristic characteristics of vegetation communities found across the country.

The NDVI curve for rangeland in figure 2 (class 5) represents the Basin and Range region of the United States. If we assume that the value of 110 is the approximate start of green-up, we can infer that this class represents cool-season vegetation with low primary production. Therefore, through a convergence of evidence, we can interpret this category as representing sagebrush steppes with cool-season grasses.

The curve for class 30 represents North Dakota. The start of the growing period is in April, and the peak of green is in June. This phenology of vegetation development leads

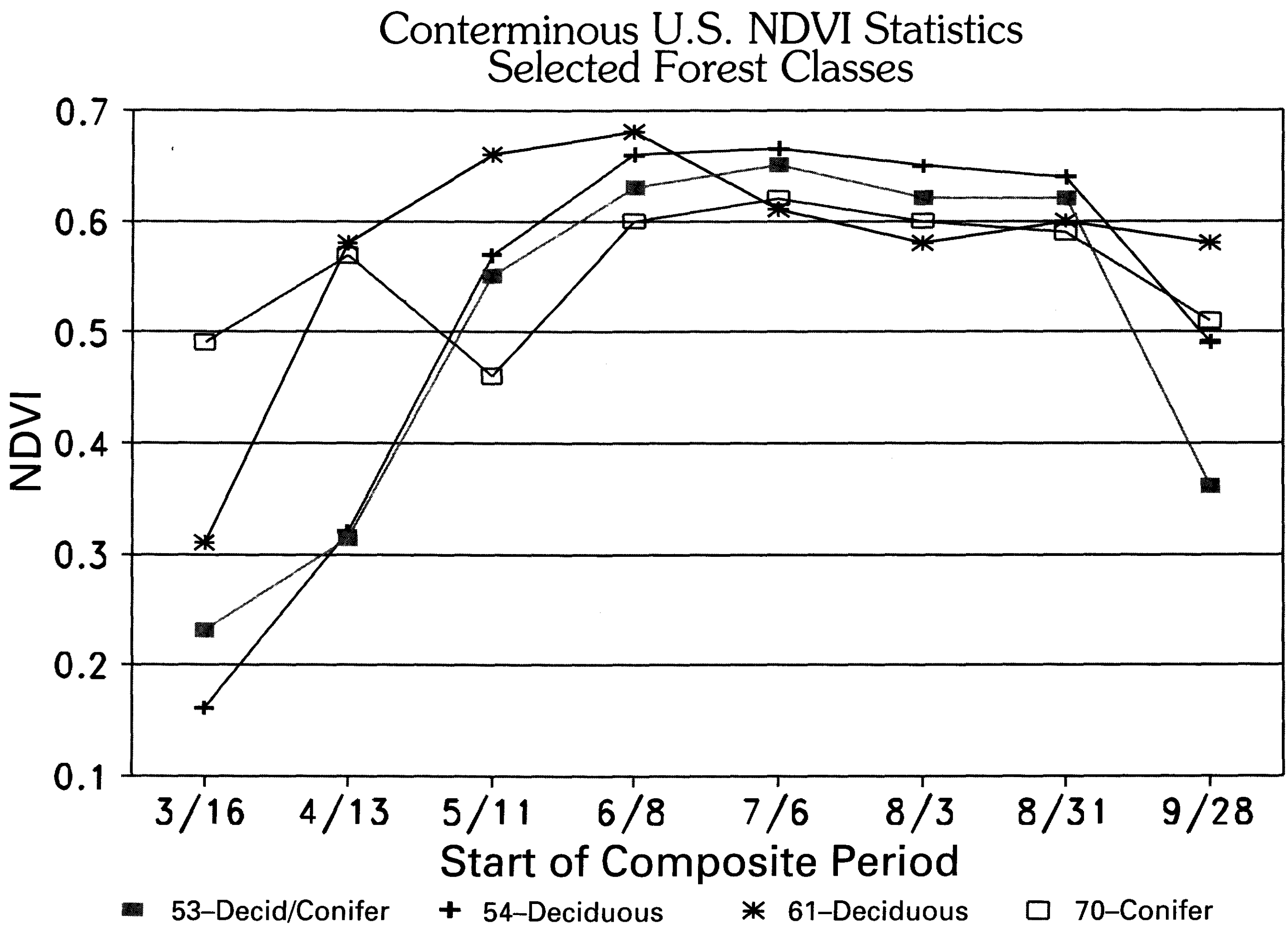

Figure 3. NDVI temporal characteristics for selected forest land cover classes.

to the conclusion that this class represents a spring wheat region.

Class 44 displays a later start and peak of greenness and a higher overall amount of greenness (or relative biomass). The shapes of the curves for classes 30 and 44 are similar, but their seasonal traits are different. We can interpret class 44 as row crops, and in particular, corn and soybeans in the corn belt.

Figure 3 displays greenness curves for several types of forest vegetation. Class 53 represents northern hardwood regions of Minnesota, Wisconsin, and Michigan (maple, birch, and beech) and has a late green-up. Class 61 represents oak and hickory forests in southern Appalachia and in the Boston Mountains, the Ozarks, and the Ouachita Mountains. Although both classes represent deciduous forests, they are in separate classes because of different timing of green-up and green-period duration.

Class 70 is found in the Pacific Northwest and is composed of conifer forest types (fir, spruce, hemlock, and cedar). Note the dip in greenness in early May—an example of the impact of clouds and haze on NDVI. In this case, the high amount of atmospheric interference was a diagnostic characteristic that aided in the interpretation of this class.

Finally, class 69 represents a mixed forest community in the southern United States, a combination of oak, hickory, and southern pine.

This classification is the starting point and represents our results to date. Even though we can identify many significant land cover relationships, there are several classes that correspond to multiple, disparate land cover types. We are currently in the process of improving these classes through the incorporation of multisource data.

An important tool in understanding our preliminary classes is the Major Land Resource Area (MLRA) data base produced by the Soil Conservation Service. The MLRA's include descriptive information that helps calibrate the contents of the classes.

For class 30, found primarily in North Dakota, we see that about 60 percent of the class falls in three MLRA's: Central Black Glaciated Plains, Central Dark Brown Glaciated Plains, and Red River Valley of the North (fig. 4). The land use attributes for the three MLRA's indicate that

Class	30	Name	Central Black Glaciated Plains
Percent	24.5	Land use	Dryland Wheat/Small Grains (70 percent); Range/Woodland (25 percent)
		Elevation	300–600m
		Topography	Level to Undulating Till Plains/ Kettles, Kames, Moraines
		AAP	400–500mm
		AAT	4–7°C
		AFFP	120–140 Days
		Soils	Borolls
		PNV	Natural Prairie (Wheatgrass, Needleandthread, Needlegrass)
Class	30	Name	Central Dark Brown Glaciated Plains
Percent	17.3	Land use	Dryland Spring Wheat (65 percent); Range/Grazing
		Elevation	500–600m
		Topography	Rolling Till Plains with Kettles, Kames, Moraines, Lakes
		AAP	350–425mm; Majority in Growing Season
		AAT	1–7°C
		AFFP	110–130 Days
		Soils	Borolls
		PNV	Natural Prairie (Wheatgrass, Needleandthread, Needlegrass)
Class	30	Name	Red River Valley of the North
Percent	17.2	Land use	Dryland S.Wheat/S.Bean/Potato/ Beet/Corn (80 percent); Wooded (10 percent)
		Elevation	200–300m
		Topography	Nearly Level Glacial Lake Plain
		AAP	475–550mm; Majority in Growing Season
		AAT	2–7°C
		AFFP	105–135 Days
		Soils	Aquolls
		PNV	Natural Prairie (Bluestem, Switchgrass); Oak/Elm

Figure 4. Major land resource areas and their characteristics found in class 30.

dryland spring wheat makes up about 70 percent, 65 percent, and 80 percent, respectively, of the three MLRA's. This suggests that class 30 likely has dryland spring wheat as the dominant land use. In addition to providing an indication of dominant land use, the MLRA data bases give a profile of other characteristics such as terrain conditions, precipitation, temperature, and annual frost-free periods that help interpret seasonally distinct land cover regions.

Digital elevation data also provide insights into land cover characteristics. Elevation has a significant impact on vegetation and land cover and, thus, can be used both to understand vegetation types and to divide regions represented by two or more land cover types into homogeneous classes. For example, several similar classes are found both in the southwestern United States and in the northern Rocky Mountains. In the southwest, the vegetation is desert grassland with biomass production in midsummer following July rainfall. In the Rocky Mountains, the vegetation is alpine tundra; here temperature (as influenced by elevation) controls the production of biomass. This is an example where decision rules based on elevation can sort similar classes into separate seasonally distinct land cover regions.

We are developing decision rules for using such ancillary variables as elevation, climate, MLRA's, and ecosystems to stratify the mixed classes into homogeneous land cover classes. We will then complete the development of the descriptive and quantitative attributes for each of the final regions. The attributes will serve as spreadsheets of characteristics that correspond to different, seasonally distinct land cover regions. Derivatives from the land characteristics data base will include maps of seasonal parameters (onset of greenness, peak green period, duration of green period, and NDVI). We also plan to provide linkages to existing land cover classification systems (such as the USGS Anderson system), so that continental patterns of land cover can be better understood.

Our immediate plans are to solicit critical reviews of our prototype work. We will then improve and test the methodology in different environments (such as Arctic regions). Ultimately, we plan to expand our work to include all of North America. Our goal is to develop a prototype data base containing the detail users need to tailor data to their specific application.

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Breakout and Poster Sessions

A Distributed Visualization Modeling Environment for Methane Flux

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An interactive, distributed modeling environment for the analysis of methane flux at local and regional seasonal scales is under development. The modeling environment will use distributed processing and visualization technology to provide the tools to develop an ecosystem model for arctic Alaska. A collaborative effort with National Aeronautics and Space Administration (NASA) was established to develop the model, whose descriptions of methane fluxes, environmental parameters, and temporal dynamics are based on quantitative surface and satellite remotely sensed observations.

A distributed modeling capability will allow near real-time control of model simulations and analysis of both input and output data. The application of visualization techniques for analysis will exploit the inherent power of the human visual system. The interactive nature of the modeling environment will enhance understanding of the many variables that control methane emission rates. System development will involve the design and implementation of a prototype flux model on the NASA Ames Research Center supercomputer. Model control, visualization, and analysis activities will be handled by a high-performance graphics workstation. The system will be designed as a distributed workstation application that can run the actual model on the supercomputer. Visual tools, such as time-series animation and 3-D perspective transformations, will be developed to convey critical elements, spatial patterns, and interactions among the environmental variables contributing to methane emission. Land surface characterization parameters required by the model will be generated from remotely sensed data. Digital data sets of vegetation and land cover, elevation and its derivatives, thaw depth, water depth, soil temperature, precipitation, and leaf area index will be used.

Long Climatic Records From Sediment Cores in Western North America: Results and Prospects

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Most of the continuous Quaternary paleoclimatic records now available from North America span the past 10,000–20,000 years; only rarely do records span more than 100,000 years. Few deposits east of the Cordilleras are suitable for long-term climate records, but many sedimentary basins of considerable antiquity are present in the western part of the continent. Previous work by the USGS has described long records at Clear Lake (130,000 years ago), Searles Lake (about 3.2 million years ago), and Tulelake (3 million years ago), all in California.

The USGS is well positioned to pursue other long records in Western North America by virtue of its institutional stability and access to drilling equipment. Sediment cores represent a significant investment and require proper curation. Parallel studies of particular cores demand careful systematic core sampling and sample tracking. A good model exists in the DSDP/ODP core library system; we are implementing a similar system for cores from continental sites. We also plan to adopt the Deep-Sea Drilling Project/Ocean Drilling Project (DSDP/ODP) practice of recovering many cores while reserving detailed studies for the best ones.

Many suitable sites for long climate records in western North America have been identified. Further work will begin in 1991 in south-central Oregon, where several sites will be cored to obtain at least 100 thousand year records that can be correlated with marine cores taken from the Gorda Rise. Some of these records should also include older sediments. The tephra record should be well preserved in at least some of these sites, allowing direct links to the marine record and permitting study of phase relationships between marine and continental climate records. We also hope to recover a detailed and continuous record from deposits at a forested site that is correlative with deep-sea oxygen-isotope Stage 5. This will allow comparison with the pollen record from Clear Lake.

Work planned for 1992 includes recovery of a long core from Fort Yukon, Alaska, which should provide a record of climatic change spanning several million years at high latitudes. Other prime candidates for long cores are Mono Lake and Owens Lake. Studies of these cores will involve both academic and USGS researchers from many disciplines.

Continuous continental climate records spanning 10^5-10^6 years will permit us to assess aspects of global change that are not accessible through studies of only the past 20,000 years, including the nature of transitions from interglacial to glacial periods and the character of jumps between modes of long-term behavior. Neither abrupt climatic changes nor long-term modal shifts are well understood as yet (particularly as they affect continental records), but such understanding may be of critical importance for evaluating how the climate system could change in response to anthropogenic forcing.

Transects of Long Climatic Records

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Long climatic records (more than 100,000 years) are as yet relatively rare from continental environments. Each such record provides a history of the climate at a particular site through time, but a detailed understanding of the dynamics of the climate system through time will require study of multiple sites distributed across major climatic boundaries of regional significance.

The scarcity of long records from continental environments results in part from the lack of suitable deposits in many parts of the world. In the extensional tectonic regime of the Western United States, however, closed basins are common enough to permit strategic selection of sample sites for long records. A nested sampling strategy will permit independent evaluation of various factors whose effects cannot be separated at single sites.

Here I describe a potential California-Nevada-Oregon (CNO) transect of long records across major regional climatic boundaries in the northwestern Great Basin, extending from the ancient lake basins of the upper Feather River drainage north of Lake Tahoe to the Malheur Basin of east-central Oregon. The boundary zone between regions dominated by Pacific vs. continental airmasses passes through the middle of this transect. Because the volcanoes of the southern Cascades have produced many Quaternary tephra layers in this area, detailed correlations between cores will be possible.

Among the factors that can be studied over long-time intervals within the context of the CNO transect are the positions of major airmass boundaries through time, vegetation behavior of the eastern vs. western sides of the Sierra Nevada, behavior of drainage basins at several different latitudes, paired studies of neighboring pluviated vs. unpluviated basins, and studies of the filling of pluvial lakes through multiple cores within a given pluvial system.

Prospects are good for recovering suitable cores from many sites along the CNO transect. Detailed studies may not be appropriate for all cores, but each will contribute to a regional stratigraphic framework that can later be extended to cover much of the Western United States.

Late Cenozoic Climates of Alaska and Yukon: A Joint U.S. Geological Survey–Geological Survey of Canada Global Change Research Project

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U.S. Geological Survey

This interdisciplinary paleoclimate research project involves scientists from the USGS, Geological Survey of Canada (GSC), Agriculture Canada, and several universities in Canada and the United States. Its objectives are (1) to improve understanding of the history of climate and environments in Alaska and Yukon during the past 17 million years; and (2) to improve late Cenozoic biostratigraphic and chronologic frameworks needed to interpret the surficial and subsurface geology of Alaska and northwest Canada. The research specialties involved in the project include sedimentology, stratigraphy, isotope geology, paleomagnetism, palynology, paleobotany, paleoentomology, and paleopedology.

The project began with a joint USGS-GSC planning workshop held in Menlo Park, Calif., in November 1989. The first joint field season was carried out in August 1990, when a team of nine scientists studied and sampled Miocene fossil-bearing deposits exposed along the valley walls of the Porcupine River in northeastern Alaska. Preliminary results indicate that between about 17 to 15 million years ago the climate of interior Alaska was far more temperate and substantially less continental than is today's rigorous subarctic climate. During middle Miocene time, forest vegetation included taxa such as *Pinus, Tsuga, Metasequoia, Abies, Ulmus, Pterocarya, Carya, Ilex,* and *Diervilla.*

None of those taxa grow in interior Alaska today. The second field season will be held in June–July 1991 in interior Alaska and northern and central Yukon. The 1991 field season will involve a team of 12 scientists, and field objectives include examination and sampling of deposits of Miocene, Pliocene and early Quaternary age. In 1992 the project will attempt to obtain a ca. 350 m sediment core from Yukon Flats in interior Alaska. If successful, the drilling effort will provide a rare opportunity to obtain a nearly continuous record of late Cenozoic climate and environmental changes in interior Alaska. The information derived from this project will contribute significantly to understanding how past global climate changes have behaved at high latitudes in the Northern Hemisphere. General circulation models suggest that global warming is most dramatic in those regions.

Sustainable Development: Focus for Department of the Interior Global Change Human Interactions Experiment

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U.S. Geological Survey

A Department of the Interior collaborative experiment is proposed to illustrate how a regional sustainable-development approach might help mitigate future disasters and, at the same time, maintain a healthy regional economy and promote interactions with other regions. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet theirs" and "development that takes account of social and ecological factors as well as economic ones" by the World Commission on Environment and Development and the International Union for Conservation of Nature and Natural Resources, respectively.

Experiments in Colorado, California, and Alaska would be based on collaboration among groups sharing regional concerns and responsibilities. Scenarios would be developed to determine how those concerns could be integrated into specific resource management decisions. Teams would comprise three components: research, management, and a regional observatory.

The research component would consider models of land-use change processes, their environmental and socioeconomic consequences, and efficacy of various adjustment strategies. The management component would examine land management policies and actions of the Interior bureaus, other Federal agencies, and State and local governments in relation to a sustainable-development model. The regional observatory component would monitor and interpret trends by collecting or inventorying relevant data bases, such as land-use/land-cover and land-capability data bases.

Liaison would be maintained with other global change programs; for example, in Colorado, the Long-Term Ecological Research sites program, the proposed new Colorado Man and the Biosphere regional site program, the emerging University of Colorado Global Change program, and the prospective National Science Foundation Long-Term Regional Research Sites program for global change/human interactions.

Using Spatial Statistics to Improve Estimates of Regional Methane Emissions From Tundra Ecosystems

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G.P. Livingston and R.E. Rossi, TGS Technology, Inc.

Spatial statistical methods, in particular geostatistics, are used to estimate quantities when data are not regularly sampled and to estimate the errors of interpolation for each point. Remote sensing technology, geostatistics, geographic information systems, and in situ approaches are integrated to modify estimates of midsummer methane emissions from tundra ecosystems on the North Slope of Alaska that are being made in a companion project sponsored by NASA. Based on ground coordinates of sampling sites and recorded methane emissions, geostatistical analysis has been used to test underlying sampling assumptions. Spatial interpolation and random simulation techniques are being used to generate methane emission and error surfaces. Using geographic information system analysis, the scientists will combine data on error surfaces with data on vegetation strata derived from Landsat multispectral scanner classifications, and with calculated strata emission means and variances, to produce flux estimates adjusted for sampling locations. Analysis is underway at three scales: Local—small areas about the size of a single multispectral scanner pixel (50 m^2); Meso—the land portions of the Beechey Point and Barrow 1:250,000-scale quadrangles; and Regional—the entire 196,000 km^2 of the North Slope. These analyses use tundra methane flux measurements from Prudhoe Bay, Point Barrow, and other Alaskan sites along the coastal plain and in the foothills of the Brooks Range.

Reconstructing Climate of the Great Basin for the Past 25,000 Years: Completed and Ongoing Research

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During the last few years a study of arid regions' climate has been undertaken to understand the magnitude and timing of changes that occurred in the hydrologic balance of the Great Basin during the past 25,000 + years. The Arid Regions Climate (ARC) project also has attempted to suggest hypotheses of climatic change that explain variation in the size of Great Basin lakes and glaciers and the timing of ground-water recharge. Our current hypothesis follows the suggestion of Ernst Antevs that, during an Ice Age, the polar jet stream (a source of increased precipitation and decreased evaporation) is located over the American Southwest during the entire annual cycle. In an effort to test the efficacy of the jet-stream hypothesis, numerical simulations of the effects of the introduction of (1) a jet-stream climatology, (2) ice cover, and (3) lake-effect processes on lake-size have been performed (see abstract by S. Hostetler).

In addition, we have been testing the ability of various sediment-based chemical parameters (e.g., carbonate chemistry, mineralogy, and stable-isotope content) to serve as proxy indicators of lake-size change. Ongoing research includes extension of the lake-size chronology of the western Lahontan basin through integrated studies of outcrop and cores from various altitudes in the Pyramid and Winnemucca Lake subbasins. This interdisciplinary research effort is being jointly conducted by members of the Geological Survey's Water Resources and Geologic Divisions, the academic community (University of Colorado, University of California—Berkeley, University of California—Davis, Western Washington State University, Calgary University, University of New York—Binghamton, Kent State University, Imperial College, University of Michigan, University of New Mexico, and Columbia University) and other research institutions (INSTAAR, NCAR, LDGO, NOAA, DRI). In addition to extending the chronology of Lake Lahontan, this study will test methodologies of paleolake-size determination. Members of the project will also attempt to formulate an optimal set of sampling and analytical procedures for the determination of lake-size change in large closed-basin lake systems common to the Great Basin.

From Fire to Flood: Pacific Climate and Southwestern Watershed Management

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Fire and flood regimes integrate weather phenomena over space and time and thus offer a less equivocal measure of climatic variability than point rainfall. Pacific climate, specifically the Southern Oscillation (SO), exerts a strong influence in the Southwestern United States, where fires and floods are primary concerns of watershed management. Two diagnostic studies are presented in which climatic effects were considered to improve forecasts of large fires and to challenge indiscriminate use of standard methods for estimating flood frequencies.

Ponderosa pine forest is the predominant vegetation in the upper watersheds of the Rio Grande and Colorado River basins. Due to a policy of suppression, fire regimes in these forests have shifted from frequent (2- to 10-year intervals) surface fires in early historic times to occasional stand-replacing crown fires in the modern era. Such large fires cannot only yield large sediment pulses in critical watersheds, but they also can affect local and global climates by injecting greenhouse gases and aerosols into the midlatitude troposphere. The climatologies of these fires are only now being linked to large-scale and highly variable features of the climate system such as the Southern Oscillation. Fire scar and tree growth chronologies (1700 to 1905) and fire statistics (since 1905) from Arizona and New Mexico show that large areas burn after dry springs associated with the high phase of the SO (La Niña). Because fire regimes lag teleconnections one or more seasons, the relation between SO and fires could have forecasting value and thus important implications for both fire and watershed management (Swetnam and Betancourt, 1990).

Flood-frequency analyses typically yield inconsistent results for rivers in southern Arizona, a phenomenon commonly attributed to watershed changes (urbanization of floodplains, channel evolution, etc.) rather than climate; however, climatic effects are manifested by dramatic differences between flood-frequency estimates for different storm types, for different time periods, and for El Niño conditions. For example, on the Santa Cruz River at Tucson, increasing flood magnitudes since 1960 were accompanied by a shift in annual flood seasonality, with more floods occurring during fall and winter. This shift reflects greater meridionality in the upper air westerlies and more frequent El Niño conditions after 1960. Questions are raised about the validity of standard methods of flood-frequency analysis in regions where mixed populations of floods affect flood magnitude and frequency (Webb and Betancourt, 1992).

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Soil Interpretations for Global Change Modeling and Impact Assessment

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Global soil data bases are being developed from source maps at three scales for use in assessing global change. These will initially be used for evaluating the storage and dynamics of water and carbon in the soil. The data bases will be adapted for use as inputs to general circulation models of the atmosphere and for assessing the impacts of alternative scenarios of climate change and human activity on agriculture and forestry. Physical, chemical, and biological changes in soil as a global natural resource will also be evaluated. Soil scientists in the Soil Conservation Service, the Environmental Protection Agency, the National Aeronautics and Space Administration, and the International Society of Soil Science are collaborating on the interpretations.

An initial set of interpretations will be developed for a digitized and edited global soil map at 1:25,000,000 scale. The polygons are being classified to the suborder level of soil taxonomy and according to soil temperature regime. The initial interpretations will be completed within 6 months.

More detailed interpretations will be developed for a digitized and edited global soil map at 1:5,000,000 scale. The polygons are being classified to the great group level of soil taxonomy, with the two most important great groups being indicated for each polygon. The soil temperature regime is also encoded. By relating the soil taxonomy to other data bases that contain information on soil properties, a more rigorous definition of the soil properties on a global scale is possible. The additional data bases include the State Soil Geographic (STATSGO) and the National Soil Geographic (NATSGO) data bases in the United States, which are linked to the Soil Interpretations Record. Data bases from field and laboratory analyses of soils (pedons) will be used worldwide. Maps of slopes and surface texture can be produced at the present time. Additional data base connections and interpretations will be completed within 1 to 3 years.

Participation in international efforts to develop global soil data bases and derivative maps at the 1:1,000,000 scale includes testing proposed data base structures in a geographic information system. Maps have been developed for the North American test site of the Soil and Terrain (SOTER) digital data base of the world. The effort at the 1:1,000,000 scale is longer term and will require extensive international coordination.

A 3-Million Year Terrestrial Climate Record and the Variable Character of the Marine-Terrestrial Climate Connection

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The 3-million year paleolimnological diatom record from Tule Lake, northern California, reflects climatic changes that relate to the interaction of continental ice sheets and low-pressure air systems in the North Pacific. This record clearly defines the transition from warmer and equable Pliocene climates to "Pleistocene-style" climates of high variability. Lacustrine variation occurred largely as a result of changes in effective moisture and seasonality of precipitation.

In the Pliocene and the warm intervals of the early Pleistocene, algal productivity was dominated by *Aulacoseira*, a diatom that prospers in warm, freshwater lakes. Glacial climates in the late Pliocene, 2.6 to 2.4 million years ago, caused a decrease in effective moisture; but cooler climates allowed freshwater marshes to persist throughout the year in this region. After 900,000 years ago, marsh environments, reflected by an abundance of *Fragilaria* species, recurred at about 100-thousand year intervals, approximately coinciding with the even-numbered marine oxygen isotope stages.

During the Mid-Brunhes Climatic Event, recorded as reduced dust flux in the North Pacific, Tulelake became very shallow and alkaline to saline, perhaps as low thermal gradients and weak wind systems failed to deliver sufficient moisture to northern California.

Late Pleistocene climatic changes at Tulelake are of different character than those that occurred earlier, possibly reflecting different circulation patterns in the Pacific Ocean as observed in marine diatom records.

Arctic Ocean Winter Polynya Zones During 1978–87

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Per Gloersen, National Aeronautics and Space Administration

The Scanning Multichannel Microwave Radiometer (SMMR), which operated on board the Nimbus-7 satellite from October 1978 to August 1987 (the longest interval of observation ever accomplished by a satellite-borne passive microwave instrument), obtained continued sequential synoptic observations of the entire Arctic sea ice cover every 2 days during all weather and solar illumination conditions. This unique, almost decade-long data set gives the first reliable information on the distribution and size of polynya zones (areas of reduced ice concentration due to the creation of leads, parallel-sided cracks, and amorphously shaped openings) that occur throughout the Arctic Ocean during winter. The occurrence of large polynya zones during winter is of great significance for the arctic heat balance because the flux of heat and water vapor through a given area of open water is 2–3 orders of magnitude greater than through the ice. The SMMR record shows that an average of 0.17×10^6 km^2 of open water, about 2.4 percent of the area of the Arctic Ocean, occurs throughout each winter. Thus, the polynya fluxes dominate the heat and vapor exchanges between the Arctic Ocean and its atmosphere. During the SMMR period, large ($>10^4$ km^2) polynya zones formed in various parts of the ocean throughout each winter. The distribution patterns of the polynya zones vary interannually, but there are three mesoscale areas where they repeatedly occur: (1) southern Beaufort Sea adjacent to the Alaska coastline; (2) north of zone 1, centered along 82° north; and (3) Chukchi Sea along the transpolar drift stream. Most polynya events are remarkably persistent, lasting for periods of several weeks to several months. Because it is doubtful that wind forcing can maintain open polynyas for such lengthy periods, it is postulated that they are driven by ocean forces, namely relatively stationary surface water divergence patterns formed by upwelling associated with tides or internal waves.

Global Change Data Management

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The interdisciplinary, interagency, and international aspects of global change studies, together with their long-term view, pose unprecedented challenges to the data management community. Traditional land data management practices are inadequate to bridge the tremendous volumes of historical and future global change observations and scientific understanding. The majority of global change observations required by researchers are acquired by spaceborne sensors; however, existing satellite data are in immediate jeopardy because of deteriorating storage media, and data inquiries cannot be made easily because index and catalog systems are outdated or do not exist. An example is Landsat data, which provide the longest and most consistent global record of the Earth's condition; however, Landsat data are being lost because magnetic storage tapes are deteriorating and processing systems to retrieve some of the data are inoperable or unavailable.

Current data management problems will be compounded in the future unless improved technologies are applied now. The acquisition rate and volume of land-related data to be collected by satellite systems in the 1990's and beyond will increase enormously, and effective data management systems must be in place. For example, the National Aeronautics and Space Administration's Earth Observing System program alone will generate more than 10,000 terabytes of data over 15 years. Data from current and future U.S. and international satellites, in addition to the ground-based data stored at numerous locations, must be available to global change research programs. Data directories, catalogs, and inventories, linked by communications networks, are needed to help identify and order data. Capabilities to develop, process, and distribute land data sets are needed to ensure that the data are readily available in user-compatible formats. Meeting these data management requirements is essential to an integrated, comprehensive long-term program of documenting the Earth system on a global scale.

The U.S. Geological Survey's global change data management activities began in fiscal year 1990. Current efforts are concentrated in three areas: (1) Land Data Directory, Catalog, and Inventory Systems Development, to provide on-line systems containing land information and data to the global change science community, with interfaces to the Global Change Data and Information System; (2) Landsat Data Maintenance and Conversion, to convert Landsat data to a stable storage medium and improve Landsat data processing capabilities; and (3) Data Set Development, Processing, and Distribution, to develop and implement techniques for organizing, producing, and making available land data sets.

Late Cenozoic Arctic Climatic Change

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This investigation began in fiscal year 1990 and initially was composed of two parts. The objective of Part I was to establish the character and chronology of major late Cenozoic climatic changes in northern Alaska. This part of the investigation was terminated after the first year of funding. Fortunately the research was founded on a solid base of geologic mapping and associated stratigraphic, geomorphic, geophysical, geochemical, and paleontological studies carried out over the past 15 years that facilitated several significant accomplishments from this single year of work: (1) Stratigraphic and paleomagnetic studies with J.W. Hillhouse (Branch of Western Regional Geology) determined an age of 2.48 million years ago for the Pliocene Bigbendian marine transgression of northern Alaska. Knowing the age of this high sea level event is important for the synoptic reconstruction of Pliocene warm intervals, which is an integral part of the National Global Change Research Plan. Also, determining the age of the Bigbendian transgression permitted calculation of a generalized ground temperature for the past 2.48 million years using measurements of the extent of amino acid diagenesis in the shells of Bigbendian mollusks. The calculated ground temperature is about −15°C, which suggests that permafrost has been present nearly continuously since the Bigbendian transgression. (2) Stratigraphic and palynological studies with R.E. Nelson (Colby College) determined that Arctic Slope vegetation during the Pliocene Colvillian marine transgression, which occurred sometime between 3.0 and 2.48 million years ago, was boreal forest or spruce-birch woodland with scattered pine and rare fir and hemlock. Climate was much warmer than at present and slightly warmer than during the succeeding Bigbendian transgression, which was characterized by an absence of permafrost and sea ice. (3) Results from oxygen-isotope analyses by J.F. Whelan (Branch of Isotope Geology) show that marine mollusk shells from deposits of the last two eustatic high sea level events along the Beaufort Sea coast, which include the last interglacial highstand (125,000 years ago), have higher $\delta^{18}O$ values than modern shells. Our initial interpretation is that this enrichment in part indicates less extensive summer sea ice than occurs during modern summers. Continuing this research could provide information regarding the response of the Arctic Ocean to warming during the last interglacial, which is one goal of the Earth System History element of the National Global Change Research Plan.

The objective of Part II, which began this fiscal year, is to determine the details of climatic change on the Alaskan arctic slope during the latest glacial-interglacial cycle through a multidisciplinary study of ancient eolian-dominated sedimentary systems. Emphasis will be placed on the warm period that peaked about 10 or 9 thousand years ago as a possible analog for a phase of the warming that is expected to result from the buildup of anthropogenic greenhouse gases in the atmosphere. Research will concentrate on eolian sand, interdunal lake sediments, and loess on the western part of the Arctic Coastal Plain, because studies have demonstrated that these now-stabilized eolian sediments and their intercalated paleosols are sensitive indicators of climatic change, and that they formed over the latest glacial-interglacial cycle. This research will include morphological and sedimentological studies that can provide information about wind directions, surface moisture conditions, and snow cover; studies of fossil lacustrine ostracodes by R.M. Forester (Branch of Paleontology and Stratigraphy) that will indicate water temperature-hydrochemistry-climate relations; measurements of oxygen isotopes in fossil and active ice wedges by D.E. Lawson (U.S. Army Cold Regions Research and Engineering Laboratory) that can provide paleotemperature information; and pollen analyses by R.E. Nelson that will show changes in vegetation through time. This research will link climatic change to physical processes on the Earth's surface in the climatically sensitive Arctic, which are goals of the Earth System History and the Solid Earth Processes elements of the National Global Change Research Plan.

"Cool" vs. "Warm" Winter Precipitation and its Effect on Surface Hydrology in the Western United States

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In this study, the winter precipitation in the Western United States is stratified into "warm" and "cool" groups, which are decided on the basis of regional temperature anomalies. Consideration of the temperature in association with the precipitation may provide a means for better identifying distinct precipitation-bearing atmospheric circulation types. Temperature has an impact on surface hydrology: when storms are cool they deposit more precipitation as snow than when they are warm. Finally, an investigation of historical winter variations of precipitation/temperature should be useful in discriminating natural climate fluctuations from possible future global warming effects.

Local anomalies and their spatial patterns of pertinent variables were composited for the four categories (cool/wet, warm/wet, cool/dry, warm/dry) at selected watershed regions. Variables considered include atmospheric circulation, precipitation, temperature, streamflow, and snow water content. Although the cases entering the composites are chosen on the basis of the precipitation and temperature in a specific basin, the anomalies of all of these variables extend well beyond the basin; often the centers are fairly remote, and there are opposite-sign teleconnections downstream. Characteristic monthly atmospheric circulation anomaly patterns occur for each of the two wet categories. The cool/wet pattern has great southward meridional flow of cold air into the eastern Pacific, while the warm/wet pattern is dominated by strong southerly displaced zonal flow over the eastern North Pacific basin. Circulation patterns of individual storms from the cool/wet and warm/wet classes confirm that the storms themselves, not simply the intervening between-storm periods, produce those circulation anomaly patterns, and thus exert a major influence on the surface temperature as well as the precipitation during these months.

Concerning runoff, the impact of temperature as well as the timing of precipitation during the water year is illustrated by compositing the monthly temperature and precipitation according to the late spring fraction of annual streamflow in rivers flowing out of California's Sierra Nevada mountains. A relatively late peak in streamflow is favored by later winter and spring precipitation and cool winter and spring temperatures, while a low fraction of spring/early summer streamflow is produced by heavy early winter and light spring precipitation and warm winter and spring temperatures.

The cool vs. warm classification also provides insight into anomalously dry spells as well as wet cases along the West Coast. While the circulation for both the cool/dry and warm/dry categories along the West Coast is dominated by high pressure anomalies near and upstream of a watershed, the pattern for the cool/dry case is displaced farther to the northwest, inducing a southward penetration of cold air from the Gulf of Alaska and the interior of North America to the coastal regions. The hydrological warm dry case appears to have the harshest impact on water supplies in the West, as evidenced by anomalies of snow water content and streamflow.

Data Management Planning

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This session will include practical guidance on writing a data management plan into a research project description—describing how the researcher will identify, document, archive, and distribute the project data. Specific information will be provided on using the USGS Earth Science Data Directory (ESDD) as a means for documenting USGS data sets. Those entries in the ESDD relevant to global change are forwarded to the Global Change Master Directory. Sponsored by the Interagency Working Group on Data Management for Global Change, the Global Change Master Directory catalogs global change data sets across agencies and science disciplines. This session will demonstrate a personal computer version of the Global Change Master Directory and provide information on access to the online version.

Climatic Change Inferred From Borehole-Temperature Measurements

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Analysis of meteorologic records indicates that the global temperature of the Earth has increased ~0.5°C during the past century. Presently it is unknown what fraction of the observed warming is due to the anthropogenic greenhouse effect and how much is simply a natural recovery from previous cooler temperatures. The meteorologic records that could be used to help resolve this issue are scarce before the onset of major industrialization (~1870 A.D.), and instrumental records remained very sparse well into this century for remote polar and desert regions; however, the temperature changes that have occurred at the Earth's surface during the past few centuries are effectively stored in the ground in the form of subsurface temperature transients. Paleosurface temperatures can be determined from precise measurements of these temperature transients by using appropriate mathematical techniques. This method is applicable wherever ground-water flow is absent, such as in regions of thick permafrost, in "tight" rock formations within equatorial and temperate zones, and in ice sheets. The determined paleosurface temperatures can be used to extend the existing meteorologic records back several centuries and to supplement them in regions where spatial coverage is currently poor.

Thus far, our principal result is that the solid-earth surface of Arctic Alaska has warmed 2 to 4°C during the past 50 to 100 yr. This conclusion is based on an analysis of numerous subsurface-temperature profiles obtained throughout Arctic Alaska. Only two weather stations in the region have maintained records longer than 30 years, and both stations are on the coast, where they are subject to strong maritime influences. Should this warming trend continue, it will have a major effect. Models indicate that the Arctic Ocean will become ice free during the summer if temperatures increase 4 to 5°C above present levels, thus affecting the meridional temperature gradient that drives weather systems in the Northern Hemisphere. In addition, accelerated drainage of water from thaw lakes and low-center polygons may occur, owing to degradation of ice wedges, allowing the tundra to become drier. The flux of the "greenhouse" gas methane from the tundra is highly sensitive to water availability within the tundra's active layer.

We continue to improve our equipment and mathematical techniques to determine paleotemperatures with greater "temporal" detail. These improved techniques will first be applied to Arctic Alaska to improve our understanding of this critical region. Available contemporary climate records (weather, tree ring, etc.) are being compiled and satellite data (Landsat, AVHRR) are being assessed to aid our interpretations. During the next 2 to 5 years, we will attempt to acquire and analyze precision borehole-temperature profiles from the Southwestern United States, Siberia, Greenland, and Antarctica to determine the magnitude of climatic changes in these regions on a timescale of decades to centuries.

Interrelations Between Gas Hydrates of Northern Alaska and Atmospheric Methane

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Atmospheric methane, a potential greenhouse gas, is increasing at such a rate that the current concentrations (≈1.7 ppm) will probably double in the next 50 years. Many researchers have suggested that destabilized gas hydrates may be contributing to this build-up in atmospheric methane. Little is known about the geologic or geochemical nature of gas hydrates, even though they are known to occur in numerous arctic sedimentary basins. Because gas hydrates occur close to the Earth's surface in arctic regions, they are affected by surficial changes in temperature; thus, destabilized gas hydrates may be sources of atmospheric methane. Under the present climate regime, the gas hydrates of the nearshore continental shelf may be the most vulnerable to change. Because of the abundance of available geologic data, our research has focused on assessing the distribution of gas hydrates within the onshore regions of northern Alaska. Our onshore gas hydrate studies are being used to develop geologic analogs for potential gas hydrate occurrences within unexplored areas, such as the thermally unstable nearshore continental shelf.

The primary goal of this project is to assess the relation between methane hydrate and global climate change. To reach this goal, the project has been divided into a series of three subprojects: (1) gas hydrate distribution, (2) gas hydrate composition, and (3) gas flux characterization. These subprojects have been designed so that deliverable products will be generated throughout the project. Each subproject has a distinct series of tasks and objectives. Within subproject 1, all available industry well-log and seismic data are being studied in order to determine the distribution of gas hydrates in the onshore and nearshore areas of northern Alaska. Subproject 2 deals with the characterization of the chemistry of the delineated gas hydrate occurrences. The primary source of data for this subproject has been our ongoing geochemical well sampling in the oil fields of the Prudhoe Bay area. Subproject 3 will include onshore and offshore geochemical surveys, with the first onshore survey scheduled for the summer of 1991. Proposed work under subproject 3 will also include the establishment of gas-flux monitoring stations, which should enable us to directly measure the rate of gas flux from decomposing gas hydrates.

Stratigraphy of Climatic Change in Large Lakes

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The sedimentary sections beneath large lakes potentially provide detailed records of past environmental changes in their respective basins. Large lakes contain varied and complex depositional environments. Paleoenvironmental reconstructions require that these complexities be deciphered so that climatic influences can be separated from other influences, such as faulting or mass wasting. On the other hand, the diversity of environments within large lakes is also an advantage for reconstructing past conditions, in that some part of the lacustrine system responds to almost any kind of environmental change. Finally, some large lakes, such as Lake Baikal, offer significant advantages over smaller bodies of water because they contain both short, high-resolution sedimentary records and long, continuous records.

The physical stratigraphy of lacustrine deposits commonly reflects climatic and limnologic changes. In addition, the stratigraphy and chronology of lake sediments form the framework for the paleontologic, isotopic, and geochemical methods that attempt to reconstruct past conditions. High-resolution seismic-reflection profiles provide a method for studying the sedimentary framework and evolution of lacustrine sequences. Seismic profiles document major events such as glacial advances, water-level changes, and fault displacements, as well as outlining sedimentary environments and facies distributions. Cores located on the basis of the seismic-reflection data provide verification of the stratigraphy and the raw materials for sedimentological, geochemical, and paleontologic analyses aimed at paleoenvironmental reconstructions. In Lake Michigan, for example, sediment texture and magnetic properties show a direct relation to Holocene lake-level changes, and ostracode assemblages and stable isotopes clearly reflect external climatic conditions.

An essential component of either synoptic or time-series reconstructions of past conditions is adequate chronologic control of sedimentary records. For the late Quaternary, radiocarbon dating is by far the most common chronologic method applied to lake sediments; however, traditional radiocarbon methods commonly yield problematic ages, partly because of their sample-size requirements. Detrital material older than the lake sediments contaminates many organic carbon samples, and disequilibrium between the lake waters and the atmosphere is problematic for carbonate samples. The small samples required by AMS radiocarbon methods permit separation of discrete carbon and carbonate fractions, producing more abundant and more accurate ages. We have successfully dated sediments in Lake Michigan that were previously described as unsuitable for radiocarbon dating.

Large, integrated, multidisciplinary studies of lake sediments, including stratigraphy, sedimentology, geochronology, paleontology, and geochemistry, offer an important way of reconstructing past climates and environments. This is particularly true for lakes such as Lake Baikal, which contains a long record of conditions in a region whose paleoclimate is virtually unknown.

Rates of Holocene Climate Change—Evidence From Varved Lake Sediments

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Varved Holocene sediments in Elk Lake, near the present forest-prairie border in northwestern Minnesota, provide a high-resolution (annual) record of climate change for the last 10,400 years. This region of the northeastern Great Plains is situated at a climatic "triple junction" between Pacific, arctic, and Atlantic-Gulf air masses and is particularly sensitive to climate change. The middle Holocene, between 8,500 and 4,000 years ago is often called the "altithermal" or "hypsithermal" implying increased temperature. This period in Minnesota is documented by an expansion of prairie vegetation; but this steppe-like environment was probably cold—similar to the prairies of the central provinces of Canada today. Climate-sensitive mineral, geochemical, and biological components in the sediments of Elk Lake show that the development of the prairie period was asymmetrical with a gradual beginning and an abrupt end. This dry period was punctuated with shorter-term, cyclic fluctuations in climatic conditions with periods of several hundred years and abrupt (decadal) transitions. A longer, distinctly moister and cooler interval occurred between 5,400 and 4,800 years ago. Pollen, diatom, and oxygen-isotope data from Elk Lake sediments indicate cooler conditions during the last 2,800 years, possibly reflecting the neoglacial period of arctic and alpine glacier expansion that culminated in the "Little Ice Age" between A.D. 1450 and 1850.

Varve Chronology or ^{14}C Dating—Which Do You Believe?

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Paleoclimate records from two very different environments, Elk Lake, Minn., and the Black Sea, have been calibrated using annual sediment laminae (varves). Radiocarbon dating of sediments from these two varve sequences produces ages that are too old, and this calls into question the use of ^{14}C chronologies in nonvarved lacustrine and marine sequences.

Radiocarbon dates of organic carbon from a core from Elk Lake are consistently older than the varve-count chronology, probably because of systematic incorporation of dead carbon (as bicarbonate) in the organic matter of the core. For example, the base of the laminated sequence was dated by varve enumeration as 10,400 years and by ^{14}C as 11,380 years. Assuming that varve years are true calendar years, the atmospheric ^{14}C age for each sample can be determined using a tree-ring calibration curve. The difference (Δ) between the measured ^{14}C age and the atmospheric ^{14}C age is a measure of the amount of old carbon in bicarbonate ions in Elk Lake water that were derived from leaching of calcareous glacial drift. In general, values of Δ decrease exponentially with decreasing age: leaching of calcareous drift decreased through time after an initial postglacial "pulse" of dissolved-carbonate carbon from freshly exposed glacial flour.

The Black Sea was a large, stratified (meromictic) lake during the Pleistocene when sea level was below the 50-m sill depth connecting the Black Sea with the Mediterranean Sea. As postglacial sea level rose, the Black Sea began to fill with Mediterranean Sea water. Increased salinity permitted the invasion of the marine coccolithophorid *Emiliania huxleyi*: Holocene sediments in the Black Sea contain distinctive white laminae composed of the calcite remains of *E. huxleyi*. The white, carbonate-rich laminae alternate with dark laminae composed of organic matter and clay to form varves. The date of the first invasion of *E. huxleyi* into the Black Sea, is 1,633 years ago by varve count and 3,200 years ago by AMS ^{14}C. These radiocarbon dates are suspect, however, because of the problem of reworked and (or) detrital carbonates and refractory organic carbon derived from the surrounding land masses. A ^{14}C balance for the Black Sea (J.W. Murray, University of Washington, written commun., 1991) shows that the surface waters of the Black Sea are highly depleted and that carbon fixed by plankton and the resulting organic carbon flux has an apparent age of 1,400 years.

Multiscale Characterization of Land Cover Complexity in Colorado

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Global change research requires a basic understanding of land surface processes and the applied management of land information. Research was initiated to develop the ability to organize and integrate data not only from different scales (meters to megameters) but also from different dimensional realms (point, raster, and vector). These multiscale descriptors of complexity can be used to analyze and classify land-cover types on a global scale.

The objective of this research is to determine how topography, directly and through climate, influences the spatial distribution of vegetation by exploring such questions as:

- How does the spatial complexity of topography vary with location?
- How does vegetation respond to differences in elevation?
- Where is terrain aspect an important determinant of precipitation?
- What is an appropriate scale for mapping vegetation biomass predicted from temperature change?

The test area is a 1,024- by 1,024-km region centered on Colorado, containing topographic data from a digital elevation model, greenness values from the Advanced Very High Resolution Radiometer satellite, point observations for temperature and precipitation, and an ecological zone polygon coverage. These data are examined at multiple scales using a C-language program that links remote sensing images with statistical analysis through the use of image pyramids. The variables are subjected both to multiscale analysis of variance, which characterizes overall spatial autocorrelation, and to multifractal analysis, which measures spatial complexity for given values and locations within the data. Regression analysis then is used to link the variables in a path structure reflecting presumed causal order. Results are rendered for a range of scales, but geographic information system vector coverages also will be produced.

Preliminary results indicate that the use of lower resolution data can save resources such as computer time and storage space; however, the research also shows that scale is a significant determinant of results, because with higher resolution data, location, not elevation, has the greater influence on vegetation. An important goal of this research is to visualize and map spatial data that will be technically reliable as well as useful to the global change research and policy community.

Description of Interdecadal Trends in Surface Temperatures of the Sierra Nevada and Gunnison River Areas Using Singular-Spectrum Analysis

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Modification of observed climate variables from selected periods within the historical record is one way of synthesizing climate-change scenarios. Climatologically interesting periods can be identified for this use on the basis of climatic trend analyses at regional scales. This strategy is being applied as part of Sensitivity of Water Resources (SOWR) studies of the Sierra Nevada of California and Nevada and Gunnison River of southwestern Colorado. Long-term trends in surface-air temperatures have been identified for the conterminous United States as a whole and in the vicinity of the SOWR studies. The method used was singular-spectrum time-series analysis (SSA) of spatial empirical-orthogonal functions (EOF) applied to monthly averages of daily mean temperatures in the United States for the period 1910–1988 (data from Karl and others, 1988). Spatial EOF analysis allows identification of large-scale variability, and SSA permits decomposition of selected temporal components of that variability (Vautard and Ghil, 1989).

Globally the average of observed surface-air temperature has risen by about 0.5°C this century (Folland and others, 1991), but corresponding warming is not evident in observations over the conterminous United States. The present analyses show that the temperature, on an interdecadal scale, in the United States as a whole warmed about 0.4°C during 1915–1935 followed by a slow, usually oscillatory decline or stasis until the mid-1970's and some warming since. Trends since 1935 are more site specific than the general warming before. The trend for the United States as a whole can be identified in simple area-weighted means or in the first spatial EOF (which represents 39 percent of the variability). The trend suggests oscillations with up to 60-year periods, rather than monotonic warming.

Regional reconstructions suggest that the best example of interdecadal warming in the Sierra Nevada region is the period 1915–1935 (the rise was about 0.3 of the standard deviation of local temperatures with seasonal variations removed). On this time scale, temperatures in the Sierra Nevada have been fairly stable since about 1940. In southwestern Colorado, the 1915–1935 warming was similar; temperatures after 1935 have been weakly oscillating with about a 25-year period. In Colorado, the 1960's show a slight decade-long cooling; the period since about 1973 shows a slight warming. These trends can be contrasted with a trend characterized by dramatic warming and cooling rates since 1935 in the Delaware River basin (a previous SOWR study region).

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Pliocene Marine Climate Records

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We have documented the character and variability of Pliocene marine climate records in the North Atlantic region as part of the PRISM (Pliocene Research, Interpretation, and Synoptic Mapping) investigation of Earth system response to global change. Sea-surface temperature (SST) estimates based upon quantitative analysis of planktic foraminifer faunas in North Atlantic deep sea cores show that high-frequency, low-amplitude variability related to orbital forcing was superimposed on long-term changes that delineate intervals within the Pliocene that were both warmer and cooler than today. One warm interval, centered at 3 million years ago, is the basis for a synoptic view of the North Atlantic Region. SST estimates from this interval show little to no warming in the tropical regions, whereas mid- to high-latitude areas show moderate to strong warming. SST estimates for the last interglacial (isotope stage 5e) show a similar pattern but warming during the last interglacial was not as pronounced as the middle Pliocene warming. Results indicate that Pliocene warming was amplified at higher latitudes, which is generally consistent with the regional pattern of global warming predicted by GCM equilibrium 2× CO_2 simulations. The pattern of Pliocene SST estimates suggests warm intervals of the Pliocene involved increased transport of heat northward by the Gulf Stream and North Atlantic Drift.

Climate, Lakes, and Ostracodes

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Lacustrine parameters such as water temperature, major dissolved ion (solute) composition, and conductivity are coupled to climate parameters on a regional scale. For example, lake parameters in a region with a cold-wet climate are different from those in a region with a warm-dry climate. Climate is a product of regional air masses that interact with surface water in predictable ways, coupling climate with limnology. The lake-climate linkage may be defined with multivariate techniques and may be portrayed with surfaces that plot gridded data from lakes on climate axes or vice versa.

Lacustrine ostracodes, which are microscopic crustaceans with calcite valves, are sensitive indicators of physical and chemical lake parameters. Ostracode occurrences define species-specific regions on surfaces created from those lake parameters that are coupled to climate. Modern ostracodes often range through the Pliocene, so a modern ostracode-to-climate calibration could offer climate reconstructions for the past 5 million years.

The ostracode-lake-climate relationship will be calibrated along climate gradients to maximize information with a minimum number of samples. The lake-climate relationship is illustrated using published data from the Itasca transect, a well studied climate-evaporation gradient in the upper midwest. The ostracode-lake-climate relationship is illustrated using unpublished data collected by Alison Smith (Kent State Univ.) from the same area.

The Effect of Climate Change on the Hydrology of Glacier Regions

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The general shrinkage of glaciers in the century has significantly contributed to the streamflow from glacier-covered regions. In 1977, the amount of water produced by glacier wastage in the Columbia River was worth over $18 million (Tangborn, 1980). The retreat of alpine glaciers worldwide accounts for one-fourth to one-half of the observed rise in sea level; therefore, understanding how variations in the extent of glacier cover affect water resources is an important first step in evaluating the effect of climate change on the hydrology of glacier-covered regions.

The long-term effect of glaciers on streamflow is to reduce streamflow variability from that observed in nonglacial basins. Glaciers naturally regulate streamflow by storing water as ice during cold periods and releasing water during warm periods. Basins with about 36 percent of the area covered by glaciers have the minimum variation in runoff. Runoff from glaciers is energy limited rather than mass limited like a seasonal snowpack. As the fraction of glacier cover increases, peak basin runoff shifts from May to late July.

In order to link the known effect of glaciers on streamflow to climàte change and the contribution of alpine glaciers to sea level changes, we must first be able to predict annual mass change with elevation for an individual glacier and extrapolate these changes to glaciers in the surrounding region. From these results, runoff from the glacier-covered region can be estimated. Once these processes are defined, runoff models can use results from mesoscale or global scale climate models to examine the response of glaciers and glacial runoff to different climatic scenarios.

Currently, the U.S. Geological Survey has designated three benchmark glaciers (two in Alaska and one in Washington State) on which intensive measurements of weather, runoff, and glacier mass change and extent are being made. Low-level monitoring of other glaciers in the region will indicate how mass changes in each benchmark glacier relate to mass changes in the surrounding glacier-covered region. These three benchmark glaciers do not adequately cover the range of glacier distribution in the United States and Canada. To increase this coverage I propose more benchmark glaciers be added to the U.S. Geological program.

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Report of a Workshop on the Correlation of Marine and Terrestrial Records of Climate Changes in the Western United States

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The eastern Pacific Ocean, dominated by the North Pacific High, the Aleutian Low, and the Western United States Low, generates the weather and climate of the Western United States and has an effect on the entire Northern Hemisphere. Changes in the positions and strengths of the atmospheric cells through time had a profound influence on the climate of the Western United States. The California Current is a large heat sink that extends along the western U.S. coast from about 50°N south to Baja California. This belt of cold surface water modulates the coastal climate of Western North America, but the strength and position of the California Current are direct responses to the atmospheric pressure cells. The history of the California Current is unknown, but it has responded to ENSO (El Niño-Southern Oscillation) events, as shown by historic records as well as from varves in marine sediments.

Although there are numerous terrestrial paleoclimate records available from the west coast, very few are high-resolution records (10 to 1,000 years) that contain the uninterrupted history for the late Quaternary, or even for the Brunhes. Moreover, there are very few long, high-resolution marine records from the Pacific borderland of the United States. None have been obtained with modern recovery technology (e.g., hydraulic piston cores), and none of them are calibrated by an independent, accurate chronology (e.g., magnetostratigraphy, tephrochronology). Finally, there are very few convincing physical or temporal ties between Quaternary paleoclimate records in the marine and terrestrial records of this region.

A workshop was held at Pájaro Dunes, Watsonville, Calif. in January 1991 as part of the USGS Climate Change Program to organize and coordinate a project to correlate marine and terrestrial paleoclimatic records from the Western United States and eastern North Pacific Ocean. The focus of the project is to develop detailed, high-resolution paleoclimatic records of the last 130,000 years, with as many climate proxy variables as possible, and a time resolution of 1,000 years or less. The workshop convened a group of experts from the USGS and the academic community to (1) prioritize potential sites to be immediately cored in the Western United States and the eastern North Pacific Ocean, (2) review and discuss the best stratigraphic correlation and dating techniques to apply to these cores, (3) identify the preferred methods and equipment for obtaining the proposed terrestrial and marine sections, and (4) discuss the logistics of sampling and developing a data base.

The priority terrestrial sites include Upper Klamath-South Cascades, Mono Lake, Calif., Owens Lake, Calif., Tulare Lake, Calif., and Ruby Marshes, Nev. The priority marine sites include Gorda Ridge, seamounts off California, the central California continental margin, and laminated sediments in basins off southern California and in the Gulf of California. The most promising stratigraphic techniques include paleomagnetic intensity stratigraphy, tephrostratigraphy, and oxygen-isotope stratigraphy. Terrestrial coring will be accomplished by conventional drilling, but the marine coring requires a new, state-of-the-art, coring system, such as the French Stacor.

Assessing the Human Impact of Global Change in Western United States and Alaska

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Human populations and their occupation of the land are both a cause and an effect of global change. Three regions have been selected to study the dynamics of this relationship between man and nature: northern California, Colorado, and arctic Alaska. The present-day patterns of land use and land cover will be used as bases for mapping ecological and economic factors such as primary productivity, biomass, biological diversity, economic productivity, employment, and population. A model of the present-day state of land resources dynamics will be built. Variables in this model will be altered to test the impacts in these regions of various global change scenarios. Areas that are especially sensitive to these changes will be highlighted on resulting digital data maps and interactive displays. Policymakers will be able to distinguish critical areas and examine mitigation strategies before serious damage is done.

Role of Volcanic Emissions in Global Change

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Past work suggests that volcanic emissions play an important role in global change. Volcanic emissions have been invoked as forcing agents for global change throughout geologic history. Several investigators of modern-day climate change have shown statistically significant temperature decreases following large subaerial eruptions of the 19th and 20th centuries. Little is known, however, of the compositions and emission rates of chemically and radiatively active gases and aerosols emitted from volcanoes during quiet periods, and even less is known about emission rates during eruptions. The lack of information concerning the chemistry and volumes of gases emitted by volcanoes during both eruptive and quiescent degassing is one of the chief impediments to progress in understanding the relationship between volcano emissions and global change. Volcanic emissions are, nevertheless, expected to be a significant factor in global change policy issues. Of particular concern is the role that volcanic emissions may play in complicating and modifying global change that may result from anthropogenic forcing. Thus, research on volcanic emissions is needed to provide a scientific basis for developing policy on global change. Indeed the U.S. Global Change Research Program has identified volcanic emissions as potentially important agents of global change, and as early as 1989 it recommended the study of volcanic emissions: "The role of subaerial and submarine volcanism in contributing radiatively important gases, aerosols, heat, and fluids that influence the composition of the atmosphere and ocean will be quantified."

This presentation is intended to provide an overview of the research initiated in fiscal year 1991 in the Branch of Igneous and Geothermal Processes on the role of volcanic emissions in global change. The principal research problems, objectives, approaches, and plans will be outlined. The main objectives of the research are to increase data, improve monitoring capabilities, and enhance understanding concerning the compositions and emission rates of gases released by erupting and quiescently degassing volcanoes. The plan is to pursue these objectives over the next several years by (1) using currently available techniques to build data bases on the emission rates and compositions of volcanic gases; (2) applying new technology to improve volcanic emission monitoring capabilities; (3) participating in experiments to calibrate space-based satellite sensors capable of imaging volcanic gas emissions; and (4) using mass balance models to better constrain the emissions of volcanic systems on a global scale, and to better constrain their contributions to the biogeochemical cycles of carbon, sulfur, and halogens. Various elements of the plan will be illustrated with specific examples of projects underway in fiscal year 1991 to acquire data on the compositions and emission rates of volcanic gases and of secondary aerosols derived from volcanic gases at erupting and quiescently degassing volcanoes. A brief summary of the preliminary results of sulfur-emission studies at Redoubt Volcano, Alaska, will be presented, time permitting.

REFERENCE

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Climatic and Paleo-Oceanographic History of the Canada Basin, Arctic Ocean

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The sediments that fill the deep basins and drape the isolated ridges of the Canada Basin contain a detailed record of the climatic and oceanographic environments that reigned in the north polar region from the equable conditions of the Albian to the harsher conditions of the Quaternary. Marine geologic studies on Northwind Ridge and the Beaufort Sea continental slope and rise of the Canada Basin from USCGC *Polar Star* in 1988 and 1989 indicate that a large part, and probably most, of this record can be recovered with piston cores located on the basis of seismic reflection profiles obtained from ice breakers. Using these data we hope to document the interrelated history and character of middle Cretaceous to Holocene climatic and oceanographic conditions in the north polar region, which has been especially sensitive to, and strongly affected by, climatic change. The detailed marine (and complementary terrestrial) sedimentary record that is available in the Canada Basin and its environs is also thought to contain valuable insights into the physical processes that drove global change, and will provide a base line for understanding future changes.

Preliminary results from Northwind Ridge include the recovery of three cores with benthic foraminifera-bearing middle Albian dark gray shale from the foot of the ridge, which is the oldest sediment so far recovered from the Arctic Basin. Nine cores from the ridge crest and eastern slope contain as many as 12 cycles of interleaved glacial and interglacial deposits that paleomagnetic data suggest represent the last 1 million years of glacial history. The interglacial sequences are dark brown, foraminifera-rich muds with ice-rafted clasts, whereas the glacial events are gray mud lacking ice-rafted clasts and marine fossils. Faunal and textural analyses suggest the Canada Basin was completely ice covered during glacial intervals. Interglacial intervals brought an abrupt influx of coarse-grained sediment to the basin from melting icebergs and foraminifera were abundant. Sedimentation rates on Northwind Ridge ranged up to 9mm per thousand years, and perhaps in places as high as 20mm per thousand years. These high rates result in expanded sedimentary sections that allow distinct glacial/interglacial events to be defined. Three short intervals of reversed polarity in one core, which all fall within glacial intervals, may support suggestions by other workers that a genetic link between ice ages and geomagnetic field behavior may exist.

Ten cores from the slope and rise of the eastern Beaufort Sea have sampled an as yet undated section of Neogene (and Paleogene?) strata, and both condensed and ponded Quaternary sections with multiple glacial/interglacial cycles. Detailed lithostratigraphic, paleontologic, paleomagnetic, isotopic, and chemical studies of both the Northwind Ridge and Beaufort Sea cores are in progress or are planned by a team of USGS and outside investigators.

The Effect of Changes in Data Resolution on Hydrologic Response

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The problem of water balance and the timing of the flow of water through drainage basins has been studied for many years, but it has never been of greater importance than it is now. The current studies, which suggest global climate change, predict possible changes in both temperature and precipitation in the next few decades as a result of man's activities. Although there is debate over the exact effect of these activities, most agree that there will be warming of the globe as a result of changes in the composition of the atmosphere. The result may affect the temporal and spatial distribution of precipitation, in addition to the amount. If this is the case, an understanding of the movement and distribution of water on a regional basis will be of even more importance than it is now.

This project will study the changes in the predicted flow of water through a drainage basin resulting from changes in the resolution of the input data. The runoff predictions will be generated by using the Precipitation-Runoff Modeling System and data from a geographic information system (GIS). Data describing the physical characteristics of the basin will be entered into the GIS, integrated and manipulated to meet the requirements of the model, and then output to run the model.

The manipulation will include the creation of data sets for the basin at a series of resolution levels by generalizing the raster data base. The model will then be used to predict daily flow values for the basin. A comparison of the values at each resolution will be performed by using spatial and statistical techniques to determine the difference between the flow values for generalized basins and the original basin calculations.

Coral Fluorescence as an Index of Runoff in South Florida

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Some corals contain seasonal growth bands, like tree rings, that chemically and physically record aspects of their environment (climate) as they grow. Cores from large corals, greater than 2 m in diameter, contain records of at least monthly resolution that may be several centuries long. Corals living adjacent to continental areas record aspects of continental runoff and air temperature as part of the environment in which they grow.

Fluorescent coral skeletons from the Florida Keys may serve as a proxy for rainfall or runoff. Excitation by short-wave ultraviolet light results in a yellow fluorescence that occurs in bands conformable with coral growth bands. Fluorescence apparently results from the incorporation of organic acids derived from soils of nearby land areas during times of high runoff. Intensity of fluorescence is recorded through time in the growing coral and shows strong correlation with flow from drainage canals in south Florida after 1900. ^{18}O of the aragonite skeleton in coral is determined by coral growth rate and by temperature and isotopic composition of seawater. Growth variability may be minimized by sampling procedures. Through careful comparison between fluorescent and ^{18}O records, it may be possible to extract a temperature record from corals in south Florida. Although the ^{18}O "paleothermometer" is complicated by water of variable isotopic composition originating from the Everglades and Florida Bay, corals growing in different environments may record signatures either of runoff, precipitation, or Gulf Stream water mass. Hence, coral fluorescence provides a salinity index that, when used in conjunction with ^{18}O, may allow a refined climate proxy to be extracted from coral cores.

Seawater Temperature and Coral Bleaching in the Florida Keys: No Relation to Global Warming. . .Yet

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Coral bleaching is a natural phenomenon during which corals lose their color and photosynthetic symbionts (zooxanthellae) in response to stress. Bleaching is known to occur in response to rapid changes in salinity, light, temperature, nutrients, pollutants, exposure to air, and disease. Prolonged bleaching can be fatal, but corals often recover from bleaching events of several weeks or longer. During the 1960's and early 1970's bleaching was rarely reported, perhaps because of the small number of divers making observations at that time. During the last decade, reports of bleaching in the Caribbean, Bahamas, and Florida during late summer months have become widespread. Recent bleaching occurrences have been speculatively attributed to summer thermal stress and linked with global warming.

The U.S. Geological Survey maintained thermographs at several sites in the northern Florida Keys between 1975 and 1988. Temperature records generally show strong correlations between sites (correlation coefficients [r]>0.95) suggesting that water temperature may be predicted throughout the Florida Keys by using a few long-term thermograph sites. These records also show that temperatures at shelf-edge sites are dominated by the Florida Current and inshore sites are dominated by air temperature. The temperature records also demonstrate that seawater in the Keys was warmer in the 1980's than during the late 1970's. Bleaching events reported for the Florida Keys in 1979, 1983, and 1987 did not occur during times of widespread, high water temperatures. Compared to a ten-year average, 1979 and 1983 were about average years. The year 1987 was warm, but not extreme, although September was an unusually warm month. The summers of 1981, 1982, and 1986 were extremely warm, but bleaching was not reported for those years.

Water temperatures at Hen and Chickens Reef show some correlation (r=.7) with Northern Hemisphere air temperature (NHAT), although the variation in water temperatures is greater than the variation in air temperatures by a factor of about three. This is not a total coincidence because Hen and Chickens is situated in an area of the shelf where the primary forcing of water temperature is air temperature. The reef is at a high latitude (for reefs, at 25°N), and it is affected by a mixture of climate processes: frontal systems characteristic of northern latitudes in the winter and westerly trades more characteristic of southern latitudes in the summer. It is not surprising that there might be some correlation between Northern Hemisphere air temperatures and water temperatures at this locality. This correlation poses the possibility that if NHAT continues to rise, seawater temperatures will follow, perhaps at an accelerated rate, with lethal consequences for many species of corals common in the Florida Keys; however, it seems unlikely that past bleaching events in the Keys can be directly linked to global warming.

The Old Crow Tephra: A Stratigraphic Marker for the Last Interglaciation in Alaska?

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A recent fission-track age determination of 140,000 years ago, plus or minus 10,000 years, for the Old Crow tephra of Westgate and others (1983) (OCt) seems to indicate that it was deposited before the last interglacial maximum (oxygen-isotope substage 5e). The OCt has now been recognized at 11 sites in Alaska, and its stratigraphic placement at nine of these sites is well defined. The stratigraphic record at some sites seems to confirm deposition of the OCt before the last interglaciation, but data from other sites challenge this widely accepted age relationship.

At Birch Creek and Halfway House in central Alaska, the Old Crow tephra occurs within a paleosol that probably formed under forested conditions and that could represent substage 5e. At Fairbanks and at the Palisades of the Yukon on the other hand, the tephra occurs within silt that clearly underlies a conspicuous organic horizon that may have formed during substage 5e. Three sites in the Koyukuk Valley show comparable variations. At Ky-11, the tephra lies between the lower two of three horizons that exhibit spruce-pollen peaks; at Ky-12, peat with spruce wood occurs in loess 2 m above the tephra; at the Hogatza Mine the tephra overlies a peat rich in spruce pollen that indicates forest about as extensive as that of the present day.

The OCt also has been reported at two sites in western Alaska. At Imuruk Lake, it coincides with a minor spruce-pollen maximum 1.5 m below a major zone of spruce pollen that indicates forest limits beyond those at present. In the Holitna lowland, the tephra occurs below an extensive organic horizon that appears to represent interstadial rather than interglacial conditions.

At four of the sites discussed above (Palisades, Fairbanks, Ky-12, and Holitna lowland), the OCt clearly occurs below an organic horizon or spruce-pollen peak that represents a distinctive warm interval; but at three other sites (Birch Creek, Halfway House, and Hogatza Mine) it occurs within or just above an equally conspicuous paleosol. Multiple paleosols or spruce-pollen maxima at Birch Creek, Halfway House, Ky-11, and Imuruk Lake form complex records that make correlations with substage 5e uncertain. These multiple organic horizons suggest that no single buried forest bed or spruce-pollen peak at any site can be assumed to represent a unique "last interglacial maximum."

The varying stratigraphic positions of the OCt probably were not caused by multiple volcanic eruptions. No locality has yet been identified with more than one OCt, and geographic distribution and tephra geochemistry also are consistent with a single depositional episode. Alternatively, the OCt may have been deposited during an early warm phase of the last interglaciation when residual glaciers were still present, loess deposition was active locally, and soils and organic horizons formed elsewhere. High-resolution uranium-series ages show that the sea-level maximum associated with the last interglaciation lasted from about 132,000 to 120,000 years ago. An appropriate time for the diverse environments indicated by the OCt is just prior to this high sea-level event, perhaps about 135,000 years ago, plus or minus 5,000 years ago. This age estimate is consistent with the younger part of the time interval suggested by the recent fission-track age determination cited above.

REFERENCE

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Nutrient and Carbon Dynamics in Soil Systems

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Terrestrial soils currently contain about twice as much carbon as the atmosphere. Most global models for soil carbon rely strictly on the present-day association of soil-carbon budgets and climate/vegetation classes. Our goal is to understand the processes that control fixation and oxidation of soil carbon and to develop an approach that encompasses the spatial and temporal variations of such processes.

We are developing a simulation of soil as a CO_2 sink during the retreat of the Laurentide Ice Sheet as an illustration of the dynamics of soil carbon. Upon deglaciation, fresh deposits act as substrates for vegetation and begin accumulating carbon as plant colonization and succession proceed. The rate of terrestrial carbon fixation over the past 18,000 years is dependent on (1) the rate of ice retreat, (2) the spatial distribution of soil types, and (3) the rate at which carbon accumulates during the development of each soil type. Most soil types appear to accumulate carbon exponentially, in which rates of CO_2 fixation typically decline by about two orders of magnitude after 1,000 to 10,000 years of deglaciation. Spatial variation of rates among soil types also appears to vary by about 2 to 3 orders of magnitude within any given age-span. One notable exception is peat soils, which have carbon accumulation rates at least 10 times higher than any other soil type.

Based on the dynamics of ice retreat and soil development in the Laurentide region, we hypothesize that (1) the rate of carbon fixation by soils was greatest at around 8,000 years ago, and (2) subsequent declining rates of carbon fixation were caused by both the exponential decrease in soil carbon accumulation and the deceleration of ice retreat. We further suggest that the decline in carbon fixation with time in a given soil type is probably determined by the combined influences of decomposition dynamics, climatic change, nutrient availability, and soil hydrology. These factors play crucial roles in the dynamics of the terrestrial carbon budget.

Estimation of Precipitation Patterns in the Delaware and Gunnison River Basins

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A method has been developed that uses weather-type analysis as a tool for disaggregating general circulation model predictions into spatial scales useful for water-resource studies. The method has been applied to the Delaware River basin to predict the effects of doubling atmospheric carbon dioxide from general circulation model output on precipitation patterns in the region. This study indicates that changes in regional precipitation patterns under double- atmospheric, carbon-dioxide conditions result primarily from changes in the weather characteristics within a weather type, rather than from changes in the weather-type frequencies.

In the Gunnison River basin, orographic precipitation events dominate the winter season and convective precipitation events dominate the summer season. A convective precipitation model will be developed, and it will be used in conjunction with an existing orographic precipitation model, both being driven by a stochastic weather-type generator. Topographic parameters such as elevation, aspect, and slope will be quantified at several scales using a variety of discritization techniques for use in precipitation modeling. Precipitation patterns will be modeled based on relations among weather types, topographic parameters, and measured precipitation.

Lake Baikal, Southeastern Siberia: Prospects for Paleoclimate Research

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Located just north of the Mongolian border in southeastern Siberia, Lake Baikal is the deepest (~1,600 m) and volumetrically the largest (23,000 km^3) lake in the world. The sedimentary section preserved beneath the lake is believed to be more than 5 km thick and spans more than 25 million years. Lake Baikal is an especially promising site for paleoclimate research because of its high-latitude location (52° to 56° N) and the extreme continentality of the climate in southeastern Siberia. Also, whereas Baikal's drainage basin was glaciated during the last ice age, the lake itself was not glaciated because of relative dryness. Marked variations in sedimentation rates (<10 to 100 cm per 1,000 years), exposure, and thickness allow sampling both very long records and shorter high-resolution records. These include full glacial cycles (100,000 years), the last glacial-interglacial transition (10,000 years), and short-term events like the younger Dryas (1,000 years) and the Little Ice Age (100 years).

In 1990 the U.S. Geological Survey and the University of South Carolina, in conjunction with other U.S. universities, the Soviet Academy of Sciences, and the Russian Academy of Science, began a 5-year multidisciplinary paleoclimate study of Lake Baikal. This work is applying micropaleontologic, isotopic, geochronologic, sedimentological, and geochemical methods to reconstruct a Quaternary climate record for southeastern Siberia. Reconnaissance coring and high-resolution seismic profiling were begun in summer 1990. Gravity and box cores were collected at six sites in the lake and more than 600 km of seismic profiles were obtained, the first such data to be obtained on Baikal using satellite navigation (GPS). This work will be expanded in 1991 and 1992 with the collection of 10 m piston cores and an additional 2,500 km of high and mid-resolution seismic profiling. In early 1992 the Soviet Ministry of Geology will begin drilling from the ice at water depths of up to 800 m with anticipated recovery of cores up to 100 m in length.

Geomagnetism and Climate

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The Earth's magnetic field provides a coupling mechanism whereby particle radiation energy from the Sun gets directed into the Earth's environment. The Sun emits a continuous stream of charged particles or plasma known as the "solar wind.' The geomagnetic field shields us from this deadly radiation, and the interaction of this plasma with the geomagnetic field sets up a magnetohydrodynamic (MHD) generator that deposits a million megawatts of power into the ionosphere and upper atmosphere causing atmospheric heating, altering atmospheric chemistry, and giving rise to the familiar auroral lights. During magnetic storms, this rate can increase several orders of magnitude. As the number of eruptions on the Sun (such as solar flares, which emit huge quantities of plasma) increase and decrease over the 11-year sunspot cycle, greater and lesser amounts of energy are injected into the Earth's environment, particularly in the polar regions where weather systems frequently originate.

Many correlations are known to exist between climate and the sunspot cycle, and between the Earth's magnetic field and climate patterns. Droughts in the High Plains region of the United States have roughly followed the double-sunspot cycle (22 years) since 1820. Temporal variations of magnetic field intensity and temperature have been found to be inversely correlated over periods of 500,000 years. Atmospheric vorticity (a measure of stormy weather conditions) increases 3 to 4 days after a magnetic storm. Relationships have been found between the diurnal range of total ozone and geomagnetic activity. Furthermore, an electric field potential, averaging about 400,000 volts, extends from the Earth's surface up through the troposphere where weather occurs. The weather environment can thus be characterized as a highly charged, spherical capacitor with a leaky dielectric, embedded in a time-varying magnetic field. Yet a focused effort to understand the dynamics and underlying physical mechanisms responsible for the correlations between the geomagnetic field and climate has never been made.

The Geomagnetism/Climate Interaction research program is seeking to identify and explain the various processes by which the geomagnetic field influences weather and climate. Near-real time regional and global magnetic field models are being developed. Simplified theoretical simulations will be studied to establish general characteristics of particle movements from the upper atmosphere down through the troposphere under the influence of the Earth's electromagnetic system. The effects of atmospheric heating and alterations in atmospheric chemistry will have to be identified, and efforts will be made to incorporate geomagnetic field models into current and future climatological models.

Modeling the Late-Pleistocene Paleohydrology of the Great Basin

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Models of lake temperature and evaporation, lake ice, lake level, and regional climate have been used to link the record of lake level in the Lahontan and Bonneville basins to past changes in synoptic-scale atmospheric circulation (the position of the polar jet stream) and regional scale climatic features (lake-atmosphere feedbacks). Results from experiments using the lake thermal and lake-level models indicate that repositioning of the polar jet stream during the late Pleistocene could have been the primary factor in controlling large magnitude changes in the level of Lake Lahontan 15,000 to 12,000 years ago. The simulations indicate evaporation was reduced (relative to present) by ~42 percent to 758 mm a^{-1} under a jet-stream related climatology. Given an evaporation rate of 758 mm a^{-1}, precipitation rates 76 percent greater than the present-day mean (170 mm a^{-1}) and discharge rates 280 percent greater than the present-day mean (2.7 km^3 a^{-1}) were necessary to simulate the highstand of Lake Lahontan 13,000 years ago. Results of lake thermal simulations indicate that ice could have formed on Lake Lahontan for ~4 months per year, leading to a ~55 percent reduction in annual evaporation rates (relative to present). With this rate of evaporation, the historical maximum 1983 rates of precipitation (300 mm a^{-1}) and discharge (6.5 km^3 a^{-1}) would have maintained the highstand of Lake Lahontan. The NCAR mesoscale model of climate (MM4) was used in modeling experiments to investigate the hypothesis that lake-effect precipitation was a component of the hydrologic balances of Lakes Bonneville and Lahontan during the late Pleistocene. Results from the experiments indicate that lake-atmosphere feedbacks could have led to lake-effect precipitation that helped to maintain the lakes at their pre-highstand levels 20,000 to 15,000 years ago. Lake-effect precipitation generated by the lakes also could have been delivered to regions downwind from the lakes.

Large-Area Digital Elevation Data and Their Derivatives

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Digital elevation models (DEM's) are raster representations of land surfaces. Terrain information such as slope, watershed boundaries, and drainage networks that can be derived from DEM's is integral to models of the hydrologic cycle because the characteristics of the terrain surface largely determine surface water flow and air flow. Global change issues that use models of the hydrologic cycle include seawater infiltration, snow cover, surface and ground water supplies, crop yields, extent of wetlands, sedimentation, and chemical transport.

The lack of DEM's is noticeable when inventorying large-area data sets. This lack was documented in a National Aeronautics and Space Administration Topographic Working Group report published in 1988. Continental DEM coverage is generally limited to the 5-minute resolution coverage provided by the ETOPO5 DEM data set distributed by the National Oceanic and Atmospheric Administration. The Digital Chart of the World (DCW) effort by the Defense Mapping Agency to digitize 1:1,000,000-scale contours by the end of calendar year 1991 will provide improved digital contour data for much of the world; however, the DCW plan will not necessarily include the generation of DEM's from those contours. Some parts of the Earth have incomplete raster elevation data and digital contour and point elevation data at varying resolutions. These data could be combined for large areas, using surface generation capabilities to interpolate contours and points to a gridded format where necessary. The U.S. Geological Survey has begun assembling a North American data set in this manner, providing a DEM of use to a wide community of modelers. North America was selected because many promising source data sets were identified and because North America is being used as a test continent for many global change studies.

An important characteristic of the new North American data set will be hydrologic integrity. Preliminary investigations show that the digital methods developed at the Geological Survey to extract hydrologic information (depressional storage, slopes, aspects, flow directions, drainage networks, and watersheds) from digital elevation data can produce meaningful parameters for models of the hydrologic cycle even at cell sizes of 1 km.

Research is in progress to study the effect of DEM source and resolution on model parameterization. For example, slope calculations are sufficiently sensitive to DEM cell size to affect surface water model results adversely. Normalization procedures are needed to mitigate the effects of DEM characteristics on model results.

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Satellite Passive Microwave Observations of Snow Conditions in the Upper Colorado River Basin

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Satellite passive microwave observations from the Scanning Multichannel Microwave Radiometer (SMMR) provide a unique synoptic record of snowpack properties in the Upper Colorado River Basin from 1979 to 1986. These all-weather observations provide synoptic snow cover information as well as an index of snowpack water equivalent for the entire drainage. For the 8-year period, the SMMR observations show that the mean maximum snowpack covered 74 percent of the basin. The minimum coverage was 35 percent, in 1981, and the greatest coverage was 99 percent, in 1979. Furthermore, the time series of snow cover show that the maximum for each year may be as short as 24 days or take place as an extended plateau for as long as 3 months. The annual maximum of the spatially integrated satellite observed brightness temperatures provides an index of basin water equivalent that correlates with the annual discharge ($r^2=0.4$), and shows behavior similar to that of the snowpack extent. This correlation improves when digital elevation data are used to characterize the basin ($r^2=0.65$). Hence, this study combines the small-scale elevation data with the mesoscale SMMR observations to investigate the basinwide snowpack characteristics and the hydrology of the basin.

Planar Pattern of Delayed Postglacial Uplift in New England: A Datum for Measuring Late Glacial Sea-Level Changes

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A multiple regression analysis of the elevations of ice-marginal glaciomarine deltas no younger than about 14,000 years ago shows an extremely close fit to a tilted flat (equipotential gravitational) surface that rises 0.836 m/km to the N27.5°W. The postglacial uplift pattern of these glaciomarine deltas in coastal New England from northeastern Massachusetts into southwestern Maine is very similar to that previously recorded for glaciolacustrine deltas of similar age from inland areas of New England. These patterns indicate that both areas are part of the same postglacial crustal uplift block, and that little or no eustatic sea level change occurred between approximately 15,000 and 14,000 years ago, during which time the margin of the late Wisconsinan Laurentide ice sheet retreated from Boston, Mass., into southwestern Maine. A different elevation trend is shown by several slightly younger glaciomarine deltas a short distance north in Maine, where the slope rises 0.91 m/km to the N35°W. The difference in trend suggests that soon after the ice margin reached Maine, eustatic sea level rose rapidly, nearly 7 m during the time the ice margin retreated 10 to 15 km, which may have taken only 200 years.

Our new data not only confirm the delayed postglacial uplift model previously described for western New England, but also indicate that little or no eustatic sea level change occurred during a substantial period of early deglaciation. However, shortly after the retreating ice margin reached southwestern Maine, sea level began to rise rapidly, while uplift continued to be delayed. Postglacial uplift in the region appears to have begun between 14,000 and 13,300 years ago, before the retreating ice margin reached eastern Maine.

Permafrost and Gas Hydrates as Possible Sources of Atmospheric Methane at High Latitudes

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The United Nations Intergovernmental Panel on Climate Change has identified permafrost and gas hydrates as important high-latitude methane sources on the basis of minimal quantitative information. Permafrost and gas hydrates are associated in two distinct high-latitude settings: (1) on shore, where the permafrost is continuous and the zone of gas-hydrate stability ranges in subsurface depth from about 200 to 1,200 m; and (2) on the nearshore Continental Shelf, where relict permafrost has persisted since times of lower sea level when the present inundated shelf was exposed to very cold subaerial temperatures. Three studies that consider methane occurrence in examples of these settings are reported here: (1) The current release of methane from gas hydrates on the Continental Shelf was estimated at about $3–5\times10^{12}$ g/yr, on the basis of the inferred distribution of methane in permafrost-associated gas hydrates and the transgression history of the Arctic Ocean during the Holocene. (2) Hydrocarbon-gas compositions were measured in 17 surface-sediment samples collected through the ice cover of Harrison Bay. This bay is offshore from an area of known gas-hydrate occurrence on the North Slope of Alaska. Geophysical surveys indicate the presence of offshore permafrost and of gas anomalies in the sediment. No major methane anomalies were detected in these surface sedimentary deposits, and deeper sampling is required to test more completely this nearshore region. (3) The gas composition of ground ice in permafrost was measured at two sites near Fairbanks, Alaska. In the air of a tunnel, where permafrost is subliming, methane concentrations were about 13 ppmv, whereas outside the tunnel, methane concentrations were only 1.7 ppmv. An ice sample from the tunnel contained 0.036 mL of methane per liter of melted ice. At the second site, near the University of Alaska campus, samples from a short core of permafrost contained as much as 6 mL of microbially derived methane ($\delta^{13}C$=L74 ‰) per liter of melted ice. These preliminary results indicate that (1) gas hydrates may currently contribute methane to the atmosphere and (2) shallow ground ice can contain varying amounts of methane at low concentrations and thus be a high-latitude source of methane.

Paleoclimate Reconstructions From Alaskan Ice Records: Teleconnections Between Pacific–North American (PNA), Reverse PNA, and El Niño–Southern Oscillation (ENSO) States

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We propose to reconstruct a detailed, high-resolution climate record from glacier ice recovered in southern Alaska that will emphasize the annual to most recent millennial time scale. Our results will be compared with records covering the same time span from lake varves of North-Central United States, coral records from central Florida, and the ENSO record both from the Quelccaya Ice Cap and sediment records from the Santa Barbara channel of southern California. While much is known from the continental ice sheets of Greenland and Antarctica, little comparable information is available from Alaska, where ice contains a climate record that is influenced by the northern Pacific Ocean. This same influence dominates all of North America. Volcanism in Alaska provides air circulation information through tephra layers of known source and age. We propose collection of ice core samples at a site(s) satisfying the following criteria: (1) location above the glacial equilibrium line (1,000–2,100 m), (2) presence in ice of an appropriate signal of annual cycles without frequent or major melting events, (3) existence of a polar to subpolar glacial regime, (4) confinement of ice by broad and simple bedrock topography to minimize complications from flow deformation, and (5) presence in ice of traceable horizons of volcanic products that also are suitable for age determinations. The proposed continental records from Alaska are critical to any global program of climate change.

Four complementary disciplines will be applied to the study of ice cores obtained. These include (1) study of the stratigraphic, structural, and petrofabric properties of the ice samples (J. Fitzpatrick), (2) study of occluded, adsorbed, and clathrated gas in ice and snow (firn gas) as indicators of changing greenhouse and other atmospheric gases (G. Landis), (3) study of metals as indicators of oceanic, continental, and volcanic exhalation materials in ice and snow samples (T. Hinkley), and (4) study of stable isotope variations in snow and ice samples as indicators of surface temperatures, climatic weather patterns, accumulation rates, and post accumulation modifications to ice (R. Rye). Evaluation of our proposed ice core site at Churchill—Bona in the Wrangell—St. Elias Range is planned for June of fiscal year 1991. Additional ice is available from GISP II (Greenland), Byrd core (Antarctica), Dunde (China), and Quelccaya (Peru) for correlation with Alaskan ice records obtained after fiscal year 1992.

HCDN (Hydro-Climatic Data Network): A U.S. Geological Survey Streamflow Data Set for Climatological Analysis

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Our research objective is to characterize the temporal patterns of streamflow variation over this century, at several spatial scales—watershed to meso- to continental—and to contrast this variation with that of concurrent meteorological conditions. To do this, it was necessary to assemble a suitably large data set of long discharge records that also satisfied certain other criteria. Not only must the discharge records in this data set be of good quality, with respect to minimal measurement errors, but also the watersheds that the streams drain need to have been relatively free of anthropogenic influences or at least have been consistent in the nature and degree of the anthropogenic activity over the period of record. The minimal requirement for such analysis is that the average monthly flow values should be relatively free of regulation by human controls, either overt or unintentional.

The U.S. Geological Survey has had a program of systematically gaging streamflow in the United States and its Trust Territories that began in 1888 with the measurement of the flow of the Rio Grande River at Embudo, N. Mex. At present, records for over 10,000 sites, many currently gaged but also many now discontinued as gaging sites, are stored in the USGS WATSTORE data base. We worked with USGS district data specialists in each State to select those records or portions of records of average daily discharge that are consistent with the criteria we delineated above. We have identified approximately 1,700 records of essentially unregulated and measured (not estimated) streamflow throughout the United States and its territories. Because of their utility to a broad range of climate studies, there is great interest in this collection of records, not only among other Federal agencies, but also among academia and private industry. Consequently the discharge data, along with auxiliary watershed and statistical characteristics, will be made available from the U.S. Geological Survey in both printed and electronic form.

Stochastic Analysis of $\delta^{18}O$ and $\delta^{13}C$ Time Series Found in a Continuous 500,000-Year Climatic Record From Great Basin Vein Calcite

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DH-11, a 36-cm long core of vein calcite, was retrieved from Devils Hole, Nev. It was dated using both alpha-counting and mass-spectrometric (MS) techniques for both the ^{230}Th-^{234}U and the ^{234}U-^{238}U methods. The relationships between age and distance from the free face of the core were statistically indistinguishable for the two methods, within the respective method's level of precision. Given the greater precision afforded by MS, an age-distance relationship was established based only on the 21 MS–dated samples. The core was found to span the period from approximately 60,000 to 570,000 years ago, with an average growth rate of 0.7 mm per thousand years. The light stable isotopes, $\delta^{18}O$ and $\delta^{13}C$, were analyzed concurrently for 285 samples taken at set intervals down the length of the core. In the resulting time series, the $\delta^{13}C$ excursions generally precede those of $\delta^{18}O$, so that if the series is shifted uniformly in time by 7 thousand years, the linear correlation between the two can be increased from $r=-0.58$ to -0.75. The range of the normalized $\delta^{13}C$ time series is slightly larger than that for $\delta^{18}O$. During full glacial times, the normalized $\delta^{18}O$ values are more extreme than those of $\delta^{13}C$, whereas during the transition into an interglacial period as well as during the first portion of that interglacial, the $\delta^{13}C$ values are more extreme.

Spectral analysis of the DH-11 stable isotope time series indicates robust peaks (in order of decreasing power) at 93, 40, 25, 22.8 and 17 thousand year cycles for the $\delta^{18}O$ series and at 91, 40, 23, 28 and 18.2 thousand year cycles for the $\delta^{13}C$ series. No evidence is found of the 100 thousand year cycle widely reported in the marine literature. The pattern of temperature variation through the last interglacial period, as inferred from the DH-11 core, is consistent with that found for the Vostok ice core, both in timing and duration. Both records are more consistent with the earliest high sea level stands indicated by recent redating of coral reef terraces from the Huon Peninsula than is the SPECMAP series, which was calibrated on the basis of the Milankovitch theory of climate change. These results pose a challenge to the theory.

Water, Energy, and Biogeochemical Budgets in the Luquillo Mountains, Puerto Rico

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The Luquillo mountains in eastern Puerto Rico are the U.S. Geological Survey research site for the study of biogeochemical and geomorphic processes that control the movement and transformation of water, energy, nutrients, and bedrock weathering products in the earth-surface environment. Two areas in the mountains are being studied (1) the 11,300 hectare U.S. Forest Service-administered Luquillo Experimental Forest, and (2) the Rio Grande de Loiza basin, an agriculturally developed watershed undergoing urbanization and industrialization. The four principal research elements of the Water, Energy, and Biogeochemical Budget program (WEBB) in Puerto Rico are (1) Biogeochemical Budgets: Water, energy, ionic, nutrient, sediment, and gas budgets will be calculated in two micro-watersheds instrumented with meteorologic, soil, hydrologic, and ground-water monitoring equipment. (2) Physical and Chemical Weathering Processes in Undeveloped Watersheds of Contrasting Lithology: Chemical-weathering and mass-wasting processes in micro-watersheds within two dominant geologic terranes (volcaniclastic and quartz diorite) will be compared. In addition, the effects of landslides on biogeochemical cycling in each region will be assessed by a temporal evaluation of physical, chemical, and mineralogic variation found in landslides of varying dates of occurrence. This element will enable the development of models to describe the hillslope hydrology and landform evolution. (3) Comparison of Developed and Forested Watersheds: Paired basins will be selected and gaged in the adjacent Rio Grande de Loiza watershed. Budgets of all aqueous constituents in flux (Ca, Mg, Na, K, Si, NH^4, HCO^3, Cl, SO^4, NO^3, NO^2, Br, F, PO^4, and dissolved organic carbon) will be compared and contrasted in developed and forested basins of similar lithology. Gas-flux differences between the two areas will be evaluated using chamber techniques and the results related to land-use differences. (4) Reservoir and Agricultural Pond Gas Fluxes: Most soils contain methanotrophic bacteria that consume methane faster than methane is produced at anaerobic microsites in the soil matrix. Methane is normally produced in significant amounts only in the sediments of shallow, standing water. In Panama, the bacteria in one hectare of shallow pond or lake produce approximately the same amount of methane as the soil bacteria in 400 hectares of pristine forest consume. To calculate a budget for methane in northeastern Puerto Rico, methane production in selected reservoirs and agricultural ponds will be determined using bubble collectors.

Investigation of Climate-Hydrology Interactions Using Coupled Atmospheric and Hydrologic Models

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Investigations of the interactions of climate and hydrology over a range of spatial and temporal scales are being conducted using field experiments and selected atmospheric and hydrologic models. These investigations address the spatial and temporal distribution of meteorologic variables, including precipitation, temperature, and solar radiation, and the interaction of these variables with the spatial distribution of basin characteristics such as topography, soils, vegetation, and geology. Field data will be used to develop and test a system of serially coupled atmospheric and hydrologic models for use in investigating atmospheric and hydrologic processes and process interactions. A modular modeling system is being developed to support the hydrologic modeling components of these studies. The system will accept distributed inputs from a range of atmospheric models and will be used to simulate distributed water- and energy-flux processes over a basin. Biogeochemical processes will be added to the system using current process understanding and the results of other interdisciplinary research studies.

One investigation is focused on climate-hydrology interactions in complex mountainous terrain where snow is the major form of precipitation. An orographic atmospheric model that simulates the interactions of topography and air-mass flux to provide the spatial and temporal distribution of precipitation and air temperature will be coupled to a distributed-parameter watershed model. Nodal output of the orographic model, at length scales of 2.5–10 km, will be used to provide precipitation and temperature inputs for the watershed model. The orographic model will be coupled to a mesoscale atmospheric model that can in turn be coupled to a general circulation model. Initial test sites include the Gunnison River basin in Colorado; the Carson, Truckee, and American River basins in Nevada and California; and several basins in Oregon and Washington.

A second investigation is focused on climate-hydrology interactions where rainfall is the major form of precipitation. Spatial and temporal measures of rainfall provided by doppler radar will be used to (1) investigate and develop techniques to disaggregate atmospheric-model outputs to generate smaller scale convective rainstorms for basin-scale applications, and (2) develop improved hydrologic models for runoff and water-balance simulation. Initial test sites are selected basins in the Colorado Front Range between Fort Collins and Denver.

Land Characterization Using Remotely Sensed Data and Artificial Neural Networks

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General circulation models currently use very simple descriptions of the land surface as input. The estimation of those land surface characteristics may be improved through the generalization of regional data bases. Information derived from existing land use and land cover data bases will begin to meet these needs, but these data bases are no longer current in many areas. The methods that use satellite imagery and statistical classification techniques provide information more quickly, but the use of neural network-based techniques for this type of mapping will provide more accurate land cover data as well.

Artificial neural networks, state-of-the-art techniques for pattern recognition and image data classification, are computer simulations that, to a limited extent, model a network of interconnected simple biological neurons. These networks can be trained for land characterization. Neuron interconnection weights and network configuration interact to generate partitions in multispectral feature space. A multilayer, feed-forward network configured with two internal layers of neurons is recommended for improved multispectral classification of remotely sensed image data.

By using multispectral data as input, artificial neural networks can be trained in such a way that the neuron weights, and hence the network function, create a desired input-to-output classification. Back propagation of an error signal can adjust network weights. The performance of neural network classifiers can be superior to conventional statistical classification techniques when data include spatial or textural information. Incorporating a 3- × 3-pixel neighborhood about each multispectral data point suggests that the network performs a spatial filtering process. Preliminary research shows that spatial and multispectral data integration via neural networks can be used for land characterization.

Biogeochemical Cycling of Carbon and Related Elements in Estuarine Wetlands

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The combined effect of increasing greenhouse gases, carbon dioxide, methane, and chlorofluorocarbons, is projected to cause a global warming of 1 to 3°C over the next century. The effects of this warming on the biosphere and geosphere are complex, because of the interdependence of many biogeochemical processes. Warming effects may be enhanced or decreased, that is positive or negative feedback, as a result of the interdependence of these processes. Methane is an important greenhouse gas to consider in these feedback loops, because it absorbs radiation more effectively than CO_2 and with increases of atmospheric CH_4 of 1 percent annually, biogeochemical processes that influence CH_4 emissions may have a dramatic cyclical feedback on global warming. Global warming is projected to cause a sea level rise of 0.5 to 1.5 m in less than 100 years. Coastal fresh and marine wetlands will be influenced spatially through creation and loss of wetlands and chemically through conversion of fresh water to brackish or saltwater marshes. Coastal wetlands are very important contributors to the global carbon cycle because of their high biological productivity, storage of organic carbon, and emissions of CO_2 and CH_4. In order to develop predictive models for the carbon cycle as regards to global change, it is paramount that we understand the processes that control CH_4 emissions in coastal wetlands where immediate influences of sea level rise may be detected.

We will study the spatial and temporal variability in the components of the carbon cycle, including greenhouse gas emissions and carbon storage, in fresh, brackish, and salt water marshes in Louisiana coastal wetlands. In addition, we will relate carbon cycling in these environments to other interrelated processes such as sulfur and trace metal cycles. To accomplish this, we will examine physicochemical characteristics of marsh sediments and interstitial waters, carbon, nitrogen, and sulfur stable isotope systematics of sediments and biota, and sediment CH_4 gas emissions. We will also study core material from offshore Louisiana in order to look for fresh to brackish water transitions during the Holocene wetland losses and compare chemical characteristics of ongoing wetlands processes with the chemical signatures displayed in the geologic record. Results of these studies will be compared with other studied sites described in the literature in order to examine the global variability of these processes. The biogeochemical process information gained from these studies is important to model and forecast effects of global change.

Monitoring the Dynamics of the Antarctic Coastline With Landsat Images

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The extent of advance or retreat of ice shelves and glacier tongues along the Antarctic coastline is known only for a few well-studied areas; yet to properly assess changes induced by global climatic variations, the entire coastline should be monitored. This problem is important because climate-induced changes in the area and volume of polar ice sheets may severely affect the Earth's densely populated coastal regions; melting of the West Antarctic ice sheet alone would cause a sea-level rise of 3.5 m.

An extensive set of Landsat images covering Antarctica was acquired in the early to middle 1970's. Recently a program to obtain new Landsat images over the Antarctic coastal region was initiated by an international consortium of the Scientific Committee on Antarctic Research (SCAR). These later views of the scenes imaged earlier will permit the monitoring of coastal changes. Our pilot study showed that the images, after scanning, digitizing, and registration, can be manipulated by image-processing techniques, so that the extents of shelf ice, glaciers, and open water or seasonal ice can be compared, and the changes mapped and quantified. Our study also showed that many crevasse patterns in the floating part of outflow glaciers retain their identity over as much as 15 years, so that the patterns may be registered digitally by using a computer interactive display or optically by using a stereoscope. From the registered points, the translational movement can be calculated, giving an extensive velocity profile of the glaciers. For example, 70 points on the Stancomb-Wills Glacier and Glacier Tongue, eastern Weddell Sea, Queen Maud Land, yielded velocities ranging from 950 m per year near the grounding line to 1,200 m per year at 100-km distance seaward from this line. The statistical error of the measurements along individual flowlines was determined to be 3 to 5 percent. This glacier and ice tongue have moved exceptionally fast. Similar measurements are possible for most outlet glaciers in Antarctica, and we have identified about 20 sets of presently available paired Landsat images for further analysis.

Monitoring coastline changes and obtaining a baseline of current glacier velocities will significantly improve our understanding of the present Antarctic environment and its sensitivity to future changes in global climate.

Glacier Growth and Shrinkage Related to Climate Variations and Nonclimatic Factors in Alaska

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At a time when the effects of climate variations are the focus of global change research, it is important to separate the influences of climate on glaciers from those of other processes. Proxy climate signals in glacier behavior can be ambiguous because changes in either temperature or precipitation can produce growth or shrinkage, and such changes can be mixed with signals from geologic, hydrologic, and glaciologic processes. Glacier growth (volume increase) can result from either decreased melting or increased snowfall, or from non-climatic factors such as protection by landslide rock debris, reduction of water depth at glaciers ending in water, or recovery after a surge. A tidewater glacier, Hubbard Glacier for example, is growing and may continue its advance for another 60 km for a millennium as it moves a protective terminal moraine down Yakutat Bay. At the same time, Columbia Glacier is shrinking as it calves into deep water behind a moraine it recently abandoned, and retreats rapidly. We do not know if the total volume of these glaciers is changing because their advances and retreats are asynchronous and the rates are unequal. Glaciers on volcanoes and those carrying ash deposits from eruptions can also behave somewhat independently from climatic forcing.

Wolverine Glacier, 60.4°N latitude in Alaska, responds primarily to climate, and it experienced a period of growth from 1976 to 1988. Observations of the glacier show that variations in winter snowfall exert the primary control over its annual ice volume changes. When the glacier grows, the mountainous region experiences increases of air temperature and precipitation that generally take place at temperatures colder than −5°C at the altitude of the glacier in midwinter. Thus, the warming fails to convert snowfall at the glacier to rain. Summer temperatures and melting are relatively steady. Cold, dry winters have returned since 1989, and the glacier is again shrinking. Sea surface temperatures in the Gulf of Alaska and the position of the Aleutian Low have influenced these fluctuations. Thus, Wolverine Glacier currently tends to grow when its climate varies toward a warmer and wetter state. Several global climate models predict warming of winter temperatures and increases in precipitation at high latitudes with increasing concentrations of greenhouse gases.

These results support the hypothesis that high-latitude glaciers and polar icecaps could grow as climate warms, while low-latitude glaciers shrink; however, Wolverine Glacier is located about 200–600 km west of the primary glacierized region in North America (58–62°N), so our results may not apply to the behavior of these other glaciers. Studies of glaciers in this region are required to investigate the transfer of results from present research sites to the main mass of glacier ice in North America.

Oversimplified ideas of global climate change can produce ambiguous or incorrect predictions of glacier and ice sheet response; therefore, estimates of glacier behavior and runoff from climate model scenarios require that attention be given to seasonal patterns of both temperature and precipitation, as well as the altitude distribution of glacier ice in each geographic region. These interactions with climate can also be mixed with responses caused by variable boundary conditions, ice flow instabilities, and oceanic and geologic processes. This combination of processes explains why different glaciers in the same region are often observed to be both growing and shrinking.

Photogrammetry and Global Change

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Photogrammetry is the process of using images in a quantitative way, both spatially and spectrally, and provides engineering integrity for cartography and geographic information systems. This process is concerned with sensor geometry and calibration, map projections and geometric transformations, data registration and resampling, and, in general, all the processes that affect image geometry and spectral reliability from the time of acquisition to the product.

Global change studies use images from weather and Earth resource satellites with visible, infrared, microwave, and radar sensors. Images from aerial photographs and other aircraft-borne sensors also are used. Eventually the image data are combined and analyzed and entered into spatially referenced data bases in geographic information systems that are used for modeling.

The Advanced Very High Resolution Radiometer (AVHRR) Antarctic Image Map, scheduled for printing in August 1991, is an example. This satellite image map, the first of the entire continent, was prepared with the cooperation of the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS) in the United States and the National Remote Sensing Center (NRSC) in Great Britain. The data were supplied from the NOAA satellites; the image mosaic was assembled by the NRSC. The map will be printed by the USGS.

This image map required digital image processing and mosaicking and the use of digital cartographic data to achieve registration on the Polar Stereographic projection. Landsat images were used to correct the coastline by eliminating seasonal ice, and the result will be the most consistent and reliable coastline of the continent at this scale (1:5,000,000). The printing process for one visible and two infrared bands will require several innovations. The image will also be available in digital form.

Continental Hydrology and Global Climate

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The hydrology of the continents helps determine the global climate. The hydrosphere and the atmosphere are tightly coupled because of the role of water in the radiation and heat budgets of the atmosphere. Future progress in global hydrology and climate dynamics will require interdisciplinary analyses of the dynamics of this coupled system. In recognition of these basic scientific factors, the U.S. Geological Survey (USGS) research project, "Continental Hydrology and Global Climate," was established in August 1988. The objectives of the project are (1) to develop improved models of the global climate system by improving their representation of land-surface hydrology, and (2) to develop an improved understanding of the global hydrologic cycle and its coupling with global climate. Much of the research uses the numerical climate model of the Climate Dynamics Group at the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration, located on the campus of Princeton University in Princeton, N.J. This is a transient, three-dimensional mathematical model of the global atmosphere, including dynamics, radiation, the hydrologic cycle, and interactions with the oceans and the continents. It is the subject of model development, and one of the tools for studying coupled dynamics. Supporting theoretical work is also performed using other numerical models and analytical techniques.

As a result of this research, it has been shown that the current parameterization of continental hydrology in the GFDL climate model permits excessive evaporation, at the expense of runoff, for a given atmospheric forcing. The causes of these errors have been identified and corrected. Furthermore, in preliminary analyses of coupled land-atmosphere sensitivity experiments, it has been shown that the excessive evaporation leads to increased precipitation (hence increased evaporation) and to decreased potential evaporation (hence decreased evaporation). The atmosphere thus provides positive and negative feedbacks on errors in evaporation. We have conducted a study of the effects of an erroneous definition of potential evaporation rates in climate models on the computed surface water and energy balance of the continents. In this study, we have shown that potential evaporation produced by many climate models is excessive, and that the calculated values of summer soil moisture in the midlatitudes are too low. When the corrected scheme is applied, the estimates of potential evaporation and soil moisture in the GFDL climate model are much closer to those based on observational data. Progress has also been made on the fundamental hydrologic problem of simple analytical descriptions of evaporation. A general non-linear solution of the combination problem describing evaporation from a wet surface has been derived. It has been used to show that the standard linear solution consistently underestimates evaporation. It has also provided the basis for a new look at the old problem of equilibrium evaporation, or evaporation under conditions of full mutual adjustment of land surface and atmosphere. It has been concluded that equilibrium evaporation is much more common than suggested by the literature.

Glacier Monitoring for Global Change—Three Case Studies

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The purpose of glacier monitoring is to document changes in glacier systems, focusing on changes in position, areal extent, and volume. Equally important is deciphering the recent history of the glacier system and documenting the chronology of change. Data for glacier monitoring come from the following: field observations, surface measurements, radio echo sounding (RES), remote-sensing (aerial photography, synthetic aperture radar (SAR) and satellite photography) and spectral imagery, published and manuscript maps and charts, and direct and proxy evidence of former glacier positions (trim lines, moraines, radiometric dating, lichenometry, and dendrochronology).

In 1984–1985, Mendenhall Glacier, which has retreated for more than two centuries, experienced a minor readvance. The advance triggered changes in the glacier's drainage, resulting in an order-of-magnitude increase in the glacier's rate of retreat. Annual field visits, combined with analysis of ground and aerial photography, were used to document the sequence of events involved in the accelerated retreat and to document that the retreat was not a manifestation of global warming.

Field observations, measurements of suspended-sediment-load, RES, and analysis of aerial photography, satellite imagery, and 80-year-old topographic maps were used to determine that Bering Glacier has retreated 8 km during this century. Retreat has formed a lake and resulted in the sediment starvation and rapid erosion of the beach separating the lake from the Gulf of Alaska. Continued beach erosion could result in Bering glacier icebergs entering the Gulf, where they could be a threat to shipping, including tanker traffic from Prince William Sound. RES determined that Bering Glacier occupies a fiord basin extending well below sea level and that several hundred cubic kilometers of the glacier could ultimately become icebergs.

SAR of the Malaspina Glacier reveal ice-surface morphological features that mimic bed morphology and provide insights into the glacier's Neoglacial history. Identification of the position of the end moraine of the adjacent Hubbard Glacier, under the Malaspina, provides constraints on when the Malaspina expanded to its present position. Photography, extending back to 1895, and satellite imagery document stagnation of the glacier's margin and surges. RES determined that Malaspina also occupies a fiord basin extending well below sea level.

Monitoring Land Surface Responses to Social and Economic Pressures in Sahelian Africa

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The climate of Sahelian Africa is characterized by marginal rainfall for crop production and by extreme variations in seasonal and annual precipitation; therefore, current agricultural production often is not sufficient to feed the local population. In addition, social and economic pressures result in land degradation, which threatens agricultural and renewable natural resources. Technical assistance programs have been implemented to protect local populations from short-term effects that often result in famine. Many programs strive to establish conservation projects and implement policies of sustainable development.

Time-series remote-sensed data, which estimate vegetation conditions, are available from the National Oceanic and Atmospheric Administration polar-orbiting satellites for all of Sahelian Africa. The data are produced for crop condition assessments and as an early warning indicator of potential famine. They are also used for monitoring grasshopper and locust habitats to prevent plagues that threaten crops. The purpose of this research is to develop a procedure for time-series monitoring of short- and long-term land surface changes and trends with vegetation index image data that can be used in conjunction with other resource and monitoring data.

Definitions of the best resource stratifications and the most sensitive parameters from time-series greenness data for monitoring change are being investigated. Socioeconomic and natural resources data have been entered into a data base that defines and tests stratifications from a variety of resource-based land potentials. Because large volumes of statistics must be derived from the spatial data base, pattern recognition approaches are being developed and tested for computer-assisted data extraction. Senegal is being used as the test case because considerable socioeconomic, climatic, and natural resources data are available from prior projects. Current and potential human carrying capacity and total monetary value derived from rainfed agricultural crop production provide basic information to address the impact of change.

Quantification of Information Contained in Outputs of General Circulation Models

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Mathematical models that generate scenarios containing no temporal correspondence to time series of actual occurrences are difficult to evaluate. One such class of models consists of atmospheric general circulation models (GCM). The lack of paired observations in the time series makes standard statistical methods either invalid or ineffective in testing the validity of a GCM. One approach to resolving this quandary is the use of a relative information measure, which is based on the uncertainties contained in the histograms of aggregations of both the model output and the data base. Each interval of each histogram is analyzed, from a Bayesian perspective, as a binomial probability. For the data-based histogram, the reciprocal of the sum of the variances of the posterior distributions of probability in each interval is denoted as its information content. For the model-based histogram, the reciprocal of the sum of the expected mean squared errors of the posterior distributions in each interval likewise is its information content. The expected mean squared error, which accounts for potential biases in the GCM, is computed as the expectation of the squared differences between the data-based and the model-based posterior distributions for each interval. The ratio of the information content of the model-based histogram to that of the data-based histogram is the relative information of the model.

A 5-year monthly precipitation time series for January at a single node of the current version of the Community Climate Model, including the Biosphere Atmosphere Transfer Scheme, contains 8.9 percent of the information in the most recent 30 years of data in the Climatological Data Set assembled by the National Climate Data Center (NCDC). If the 5-year simulation were extended, its relative information content could be expected to approach 14.5 percent. For July monthly precipitation, the 5-year simulation contained 11.2 percent of the information of NCDC data base and had a limit of 18.1 percent for extremely long simulations. Aggregation of two adjacent cells at the same latitude showed some improvements in relative information, but longitudinal aggregation with two additional adjacent cells degraded relative information to less than either the one- or two-cell levels.

Application of this approach to several GCMs is planned for the near term, while longer-term plans are for the development of monitoring strategies for climate change to be based on the information measure.

Late Quaternary Sea Level History of the Pacific Coast of North America: A Detailed Record of the Last Glacial/Interglacial Cycle

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Marine terraces are common on the Pacific coast of North America from Washington state to southern Baja California. Such terraces form during stillstands of sea on tectonically stable coasts, and during rises of sea level on uplifting coasts, when the rate of sea level rise matches the rate of tectonic uplift. Thus, marine terraces provide a detailed record of sea level high stands if they can be dated accurately. Our investigations have shown that solitary corals are far more common in west coast marine terrace deposits then previously thought and we have generated about 80 new $^{230}Th/^{234}U$ ages from terraces along the coast from Bandon, Ore., to Cabo Pulmo near the southern tip of Baja California. The two most frequent ages are ~125,000 and ~80,000 years ago, which correspond to ages from the last interglacial period that have been reported for emergent coral reef terraces on tropical island coasts such as Barbados, Haiti, and New Guinea. These ages agree well with times of high solar radiation at high latitudes when global ice volumes would be minimal, and as such, our data agree with the Milankovitch, or orbital- forcing theory of climate change; however, our results show that sea level at 80,000 years ago was much closer to present than data from Barbados and New Guinea indicate.

Stable isotope analyses of marine terrace mollusks can be used to infer ocean paleotemperatures. We analyzed mollusks from a number of terraces dated 125,000 and 80,000 years old along the west coast from Oregon to Baja California. Results indicate that on open coasts (as opposed to protected embayments), ocean temperatures were 2.0–2.5°C cooler than present at ~125,000 years ago and were 3.0–5.5°C cooler than present at ~80,000 years ago. The cooler-than-present temperatures at 125,000 years ago can be explained by warmer land temperatures, which would in turn increase the strength of alongshore winds, which would enhance upwelling and result in cooler near-shore waters.

In certain places in southern California and Hawaii, calcareous eolianites overlie the 125,000 and 80,000 year old marine deposits and are separated from them by a paleosol. Contemporary beaches are too small and too low in calcareous sand to have provided the source sands for these eolianites; however, offshore shelf sediments in these areas have abundant calcareous sand and would provide a ready source of sediment for calcareous eolianites if exposed during a sea level low stand. We hypothesized that these eolianites were deposited from wind-transported calcareous sand derived from shelf sediments that were exposed during glacially-lowered sea levels. The eolianites contain secondary carbonate rhizoliths (root casts) that can be dated by uranium-series methods. Results indicate that eolianites were deposited during two intervals, between ~80,000 and ~50,000 years ago, and again between ~27,000 and ~14,000 years ago. These intervals agree well with solar radiation minima in high latitudes when we would expect glacial ice volumes to be at a maximum and sea levels to be at a minimum. Thus, eolianites may be excellent glacial markers.

History of Desertification on the Great Plains: A Holocene History of Eolian Sand Movement

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Our goal in this project is to develop a detailed Holocene climatic history of the Great Plains using the geologic record of eolian sands. The Great Plains region is an area that is highly sensitive to climatic changes. It is characterized at present by a subhumid climate in its eastern part and a semiarid climate in its western part. One characteristic of the region is extreme year-to-year variability in rainfall, based on climate records of the last 100 years or so. This short-term variability is superimposed on trends of longer duration and the Great Plains droughts of the 1910's, 1930's, and 1950's are dramatic examples of such variability. On yet a longer timescale, the middle Holocene Altithermal interval (8,000 to 5,000 years ago) and the late Holocene (3,500 to 1,500 years ago) were periods of extreme warmth and dryness on the Great Plains (and elsewhere). During the Altithermal, temperatures may have been as much as 2°C warmer than present, and precipitation was drastically reduced over a period of as much as 3,000 years.

The increases of carbon dioxide and other greenhouse gases in the atmosphere have led climate model investigators to predict that significant global warming may take place within the next century. Midlatitude continental interiors, such as the Great Plains, are areas where dramatic warming and decreased precipitation are predicted to occur. In fact, the middle Holocene Altithermal interval has been cited by climate model investigators as one of the best analogs to a predicted 21st century warming and drying.

An understanding of the potential for future climatic change on the Great Plains is critical economically. The region is one of the most important in the United States for crops, cattle, and ground water resources. What is needed are data on the areas of the Great Plains that would be most susceptible to economic loss due to precipitation reductions under a 21st century warming and drying. The best method to determine which areas are most susceptible to desertification in the future is to look at which areas were most susceptible to such changes in the past.

Eolian sands are attractive deposits for paleoclimatic reconstruction on the Great Plains for a number of reasons. Eolian sand is highly sensitive to climatic change because stabilizing vegetation on such deposits in semiarid regions cannot tolerate significant reductions in precipitation. Research conducted to date indicates that there is a history of repeated eolian sand movement in the Holocene. Dune morphology and stratification, and isotopic and geochemical fingerprinting of sand source areas allow reconstruction of paleowind patterns, which in turn provide the basis for atmospheric circulation models and air mass distributions. Our ultimate goal is to produce a detailed Holocene history of eolian sand movement on the Great Plains that will allow reconstruction of drought history, paleowind patterns, and probable atmospheric circulation patterns.

The Global Land Information System

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The Global Land Information System (GLIS) provides scientists with a single, interactive source of information and access to data pertaining to the Earth's land surface that can be used in continental- and global-scale Earth science and global change studies.

The GLIS can be characterized as a metadata system containing both descriptive information about data sets and associated functions that allow scientists to assess the potential utility of data sets, determine their availability, and place online requests for related data products. The data set information in GLIS is maintained in three levels of granularity and detail: the directory, guide, and inventory. The directory contains high-level, summary descriptions of entire data sets. The data set guides contain detailed descriptions of entire data sets, including such information as sensor specifications, extent of coverage, processing history, data quality, and product availability. Data set inventories contain detailed information about individual data set entities, such as a Landsat scene or an Advanced Very High Resolution Radiometer (AVHRR) pass, and provisions for temporal-, spatial-, and parameter-oriented queries of the inventories. The GLIS also offers several graphic tools and services such as geographic coverage presentations and data set visualizations, including a digital image browse capability. A GLIS prototype will be available for user access in May 1991 and will contain references to a variety of regional, continental, and global land science data sets, including an inventory of AVHRR data held by the U.S. Geological Survey's EROS Data Center and an inventory of the old Landsat Multispectral Scanner (MSS) data recently freed of exclusive-rights restrictions by the commercial Landsat operator, EOSAT. A fully operational GLIS, planned for 1992, will include an inventory of worldwide holdings of AVHRR data, an operational AVHRR image browse capability, references to newly developed source and derivative global land data sets, and a complete inventory of worldwide holdings of Landsat Thematic Mapper (TM) and MSS data. A Landsat TM image browse capability is planned for 1993.

Methane in Mono Lake, California

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Mono Lake is a hypersaline, alkaline closed-basin lake. The basin was formed 1×10^6 years ago by subsidence and was soon followed by regional volcanism. Volcanism still persists in the basin. Normally, the lake is monomictic and displays a winter turnover. During the El Niño winters of 1982 and 1983, sufficient freshwater was released into the lake to induce meromixis, which persisted until November 1988. Our investigations focused on the identification, formation, oxidation, and outward flux of methane from the lake during and after meromixis.

The picture of methane in the lake is complicated by several factors. The most significant feature was the presence of three discrete sources (Oremland and others, 1987; GCA 51:2915). Two sources were associated with constant-flow gas seeps emanating from a natural gas deposit beneath the lakebed. These widely distributed seeps were characterized by stable isotopes and hydrocarbon abundance indices to be of two distinct flavors: bacterial origin and thermogenic origin. Radiocarbon content of the dissolved methane in the lake revealed it to be of recent bacterial origin (i.e., a comparable age as the lakewater DIC). The seeps, however, were essentially radiocarbon "dead," indicating an age of 720,000 years. Lake sediments have methanogenic activity (for example, Kiene and others, 1986; AEM 52: 1037; Oremland and G. King, 1989, Microbial Mats: 180). This methane originates in the sediments, and it is enriched in carbon-12; however, when it diffuses into the bottom water, it becomes depleted in carbon-12 because of anaerobic bacterial oxidation. The lake's surface waters, however, are supersaturated with methane in the atmosphere, and an outward flux of the gas has been measured (Miller and Oremland, 1988; GBC 2:269). Fluxes ranged from 0.4 to 201 μmoles m^{-2} h^{-1} during meromixis (1985–1987).

Factors associated with water-column stability influenced the extent and nature of methane release from the lake to the atmosphere. Anoxic bottom water increased from premeromixis value of 8 μM to 60 μM by January 1988. This value represented the difference between sediment flux plus water-column storage minus oxidation and outward flux. Complete water-column mixing (November 1988–September 1989) resulted in the loss of more than 1×10^7 moles of methane from the lake, most of which escaped to the atmosphere and bypassed oxidation by bacteria. Methane concentrations in the air on and around the lake were significantly above ambient (1.7 ppm) at several locations. Highest values (2.4 ppm) were associated with sites at Paoha Island, as well as two locations on the lake's northern shores. Future efforts will be directed toward determining the seasonal trends of these anomalies as well as their source(s).

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Assessment of Effects of Potential Climate Change on the Hydrology of the Gunnison River Basin

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A study has been initiated in the Gunnison River drainage basin, Colorado, to improve the understanding of water-resource sensitivity to the effects of potential climate change. The Gunnison River provides a substantial portion of water to a complex water-resource system and provides an opportunity to develop techniques useful in assessing the sensitivity of the water resource to changes in climate. The study has been divided into the following categories: (1) climate scenarios, (2) streamflow modeling (watershed and routing/accounting models), (3) water use and water rights, and (4) effect on dependent processes.

The objectives of the climate-scenario category are to describe the existing climate regime; develop alternative climate scenarios for use in sensitivity analyses; and define reasonable climate scenarios with an hypothesized climate change. The streamflow-modeling category will provide streamflows for various climate scenarios. This category has two major components, watershed or small drainage-basin modeling, and streamflow/reservoir routing through the main channel and large tributaries. Watershed modeling will be used primarily on small, upland drainage basins where snow accumulation and melt processes are important. Output from these models will provide the input to downstream accounting and routing models used in water-resource system management. In the third category, existing water use/water rights will be identified so the effect of the altered water-resource system can be assessed. Changes in climate and resulting changes in streamflow might have significant effects on dependent processes such as the quality of water or sediment transport. The objective of the dependent–processes category is to identify the changes in streamflow–dependent processes. There is considerable interest in identifying the streamflows needed to maintain existing channel morphology in the main channel of the Gunnison River.

The Panola Mountain Research Watershed: Hydrologic and Biogeochemical Process Research, A Watershed Approach

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The Panola Mountain project was initiated in fall 1984 to address several scientific issues of the acid rain phenomenon. One objective of the project was to investigate terrestrial processes that control streamwater chemistry with emphasis on studying those constituents that control the acid-base chemistry. Results of this research contributed to a major goal of the National Acid Precipitation Assessment Program: the prediction of watershed response to acidic atmospheric deposition. Predictive hydrochemical models require a mechanistic understanding of the controls on water chemistry. Much of this understanding was provided by intensive interdisciplinary watershed studies, which were conducted worldwide. Results from these studies and from the modeling efforts indicate that the processes controlling streamflow generation are not clearly understood. Consequently the genesis of water quality along hydrologic pathways, particularly those contributing to streamflow, also is not clearly understood. In order to understand how changes in climatic variables will affect water quality genesis, it will be necessary not only to research the biogeochemical mechanisms but also to investigate the role of hydrologic pathways in controlling streamflow generation.

The Panola Mountain Research Watershed (PMRW), a 41-hectare drainage, is in the Southern Piedmont physiographic province, 25-km southeast of Atlanta, Ga. PMRW lies within the Southern Plains ecoregion, the largest ecoregion within the conterminous United States, and it contains soils representative of those covering 98 percent of the physiographic province. It also contains both dominant forest types of the ecoregion, southern hardwood and loblolly pine. Rainfall moves rapidly through PMRW (it takes 30 minutes from maximum rainfall intensity to peak flow at the basin outlet); therefore, it was necessary to characterize the water chemistry on short time intervals. Field-data collection for the first 3 years focused on event sampling, resulting in one of the most extensive databases available from small watershed studies in the United States.

The research objectives for the PMRW under the U.S. Geological Survey's Global Change Project of Water, Energy, and Biogeochemical Budgets (WEBB) are (1) to investigate processes that control the movement and solute composition of water along hydrologic pathways in a forested Piedmont watershed, and (2) to investigate the processes controlling soil solution chemistry. The approach for the first objective will focus on catchment (41 ha) soil solution chemistry and subcatchment (10 ha) scales. The second objective will focus on the plot scale. The research for the first objective is concerned with which soil solutions and how much of each soil solution gets to the stream. The research for the second objective seeks to determine the chemical evolution of these solutions and predict their evolution through time in response to factors such as land-use management and vegetation changes. The research will expand our knowledge of biogeochemical processes in the unsaturated zone. The soils research will be conducted primarily at the plot scale with supporting laboratory experiments, and it will complement the soil physics done at the plot scale needed for the first objective. Methods development is a necessary part of this research because so many soil chemical properties are operationally defined. For example, the validity of using environmental isotopes of water for tracing flowpaths is to be addressed, as well as the isotopic evolution of precipitation as it travels through the watershed.

Climatic Variability in the San Francisco Bay Estuarine System

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Understanding natural and human-caused variability in the historic records from our bays and estuaries is essential before better predictions of future changes can be made. The San Francisco Bay system is one of the most important estuaries on the west coast. Records extending back to the early 1900's show that the San Francisco Bay system has marked variations in both its physical and biological elements. While human factors played a role in modifying the characteristics in the bay over long periods of time, the interannual fluctuations in the bay have been dominated by short term climate effects. These climate variations include changes in the atmospheric circulation patterns, the precipitation levels in central California and particularly in the Sierra Nevada, and the discharge into the estuary in the spring and early summer from the Sacramento and San Joaquin River system. Such variations also must have a strong geological and biological signal.

An interesting refinement on the well-known influence of climate control on the magnitude of fresh water supply to the bay is the effect of the exact timing of runoff events. This region has a strong annual cycle caused by winter precipitation in the cool season, causing rain in the bay and snow in the Sierras and dry conditions in the warm season. The runoff of the snowmelt in the spring and summer may be either accelerated or delayed in response to anomalous air temperature patterns during spring. Atmospheric circulation in winter largely determines whether the year is wet or dry, and atmospheric circulation in spring largely controls the early (warm) or late (cool) timing of the fresh water release of the Sierra snow pack. Four scenerios (wet warm, wet cool, dry warm, and dry cool) produce characteristic modes of variability in the river basin, estuary, and coastal ocean over a broad spectrum of time scales including monthly and longer. The response of surface salinity (SS, a conservative property, or nearly so, for fresh water) shows that both the magnitude and timing of fresh water flows (delta flow) affect the bay. For example, in a warm spring, snowmelt is early and more rapidly depleted so that the summer delta flow is relatively low and late summer SS is relatively high. It is crucial to recognize these springtime effects of the atmospheric circulation before one can discriminate between the natural variability and artificial effects (such as the artificial late spring reductions in delta flow caused by agricultural impoundments, diversions, and consumption). The artificial effects can mimic a warm spring scenario in the river basin and estuary but not in the coastal ocean.

Phosphate and Trace Metals in Cenozoic Phytoplankton: A Signal of Changing Ocean Chemistry

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Marine primary productivity is limited by the availability of PO_4^{3-} and NO_3^{1-} in the current ocean, which is virtually fully oxic. Their concentrations simultaneously approach zero in surface waters because the PO_4^{3-}:NO_3^{1-} ration (1:15) of their uptake by phytoplankton equals their availability in upwelling deep seawater. Under less oxic conditions, this balance might not have been maintained owing to (1) the fast recycling rates of PO_4^{3-} and NO_3^{1-} between the photic zone and the deep ocean reservoir, (2) their short residence times in the ocean of a few 10's of thousands of years, and (3) their totally different sources and sinks within the ocean. As plankton adjust their composition in response to the chemistry of their environment, taking up luxury amounts of nutrients that are in excess of a single "limiting" nutrient, a change in the PO_4^{3-}:NO_3^{1-} ratio of past oceans could be reflected by differences in the PO_4^{3-} content of phytoplankton of different ages.

Changes in the seawater concentrations of bioreactive trace elements might also be reflected by their concentrations in plankton. The export of many trace elements from the fully oxic ocean today is largely via the accumulation of organic detritus on the sea floor. Under less oxic conditions this might not have been the case. For example, Cr is reduced under conditions of denitrification from CrO_4^{2-} to Cr^{3+} and precipitates as $Cr(OH)_3$. Other factors being the same, its concentration in seawater would have been less during times when the O_2 of the deep ocean was lower than it is today, caused by its continued removal from surface water by organisms and by an accelerated removal rate from the deep ocean inorganically.

We propose to examine the P and metal contents of individual tests of planktonic organisms that cover the time period middle Tertiary to present. Preliminary work by us and others has demonstrated the feasibility of such analyses by secondary ion mass spectrometry.

Potential Effects of Climate Change on the Surface-Water Resources of the Carson, American, and Truckee River Basins

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The U.S. Geological Survey (USGS), as part of its Global Change Research Program, is investigating the potential effects of climate change on the water resources of the Carson, American, and Truckee River basins. These basins, located in western Nevada and central California, are adjacent and on opposite slopes of the northern Sierra Nevada. The American River drains to the west and to the Pacific Ocean. The Carson and Truckee Rivers drain to the east into the Great Basin. Hydrologic differences between east and west draining basins are a focus of the investigation. Climate scenarios are being developed initially by extrapolating historical records of climatic extremes and ultimately by using general circulation model predictions. These scenarios will be applied to deterministic watershed models to evaluate sensitivities and to simulate responses of basin-scale hydrologic processes to climate change. Basin characteristics are being determined with remote-sensing techniques and geographic information systems. The project complements a parallel investigation by the U.S. Bureau of Reclamation to study the possible effects of climate change on water supply and demand, system management, and operating criteria. The USGS project will involve concurrent research in linking large-scale circulation to local watershed models, and in the use of remote-sensing and GIS techniques to define land-surface characteristics and hydrologic processes in mountainous terrain.

Development of Land Data Sets for Studies of Global Climate Change

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The U.S. Geological Survey has begun a major initiative to organize, produce, and distribute land data sets that will support the land data requirements of the global change science community. Satellite image data sets, produced from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer sensors, will be developed to provide repetitive, synoptic coverage of regional, continental, and global land areas. These data sets, integrated with related land data and supplemented by coregistered Landsat data sets, will enable scientists to quantify fundamental land surface attributes that are needed to model land surface processes, to detect and monitor land surface change, and to map land cover. These well-structured, consistent land data sets will form the historical record of land observations prior to the era of the National Aeronautics and Space Administration's Earth Observing System sensors.

Use of Ash Layers in the Reconstruction of Earth System History: Correlation and Age Calibration of High Resolution Stratigraphic-Climate Records in the Oceans and on Land

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Projections of future variability in the Earth's physical environment, climate, and ecosystems can be made from studies of Earth-system history that provide baseline data on past natural conditions. Records of past conditions need to be precisely dated and correlated among sites on various time and space scales to determine whether past climate-induced changes are local, regional, or global and to determine the timing and rates of these changes. Correlations of past climate records between marine and terrestrial sites are particularly important in such studies. The oceans contain a relatively continuous, homogenous, and generally correlatable record of climatic changes. The variation of past faunal and floral assemblages provides information on past physical conditions, and the associated oxygen-isotope signal provides a record of volumetric changes in the world's oceans through time. By contrast, the records obtained on land tend to be much more fragmented, and often reflect a much more complex response to changes in climate forcing. This response often is controlled by local factors as well. In order to understand how and why these variations exist, and how past climate changes correlate in time and space, we need to identify precise reference time-horizons by which marine- and land-based records can be correlated.

For the past 20 years, we have been identifying and dating widespread volcanic ash layers that provide correlation and age control for stratigraphic sequences on land and in the oceans. Our efforts have focused on Pliocene and Quaternary sections along the Pacific borderland of the Western United States. For the past 7 years we have also studied the Indian Ocean borderland of East Africa. First we find and sample macroscopic tephra layers (volcanic ash or tuff layers) or disseminated volcanic particles in exposed stratigraphic sequences or in cores. We describe the petrography of the tephra and separate and analyze the volcanic glass to provide characteristic chemical "fingerprints" by which a tephra layer can be identified. Many of the widespread tephra layers we have studied are now numerically dated. New layers that we find are dated by the appropriate method. Compositions of new tephra samples are compared to our data base of about 2,500 previously analyzed samples, and the best matches are identified. Finally, we establish correlations among sections by a combination of chemistry, petrography, other independent age data, and characteristic stratigraphic sequences among tephra layers.

Our current focus is correlating and dating high-resolution marine-land site transects spanning an age range of at least the last 130,000 years within the Pacific borderland of the Western United States, a large region containing a variety of ecotones. These tephrostratigraphic correlations complement magnetostratigraphy (for example, as at Tulelake, Calif.) and provide a stringent test on other age control and correlations, regardless of the precision with which the tephra layers are dated.

Water, Energy, and Biogeochemical Budgets at Sleepers River, Danville, Vermont

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In cold-temperate regions, the annual cycle of snow accumulation and snowmelt may undergo dramatic shifts in response to climatic change. Forecasting the effects of such shifts requires a more broadly based understanding of water, energy, and biogeochemical budgets (WEBB). To this end, a joint global change research project by the U.S. Geological Survey (USGS) and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), under the USGS WEBB program, was recently initiated at Sleepers River Research Watershed, a 112-km^2 upland basin in rural northeastern Vermont. Sleepers River was selected as the research site because of its 30-year hydrologic and energy data base. The project will draw on the expertise of the USGS on hydrological and biogeochemical processes, cold-regions hydrology, and the engineering problems of field instrumentation in a cold-region environment.

Core data will be collected at a minimum of two headwater hillslopes (from ridge to stream channel) representing forested and agricultural (pasture) land usage. Vertical and lateral patterns of water movement will be studied by a network of time-domain reflectometry (TDR) soil-moisture probes installed in soil pits along a downslope transect (ridgetop to stream). Water will be collected from the unsaturated and saturated zones to study the chemical evolution of soil water as it moves toward the stream. Spatial and temporal patterns of major solute chemistry and carbon- and oxygen-isotope ratios will be coupled with water-flux data to identify the dominant hydrologic flow paths and biogeochemical reaction pathways. Determinations of trace gas fluxes also will be made in the soil pits. The response of the soil thermal regime to incoming surface energy and geothermal flux will be investigated by simultaneous measurements of soil-temperature profiles and energy fluxes. The research approach will use new technical and theoretical tools to test hypotheses—for example, the use of carbon-isotope ratios to assess the contribution of carbonate weathering to alkalinity. The core information at the hillslope scale will be evaluated from the larger-scale perspective to determine the relative importance of hydrochemical processes as basin size increases.

Baseline Studies for Monitoring Global Climate Change in the Arctic Environment: A Remote Sensing-Spatial Data Base Approach

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In 1989 the U.S. Geological Survey's EROS Data Center Alaska Field Office established a 10-year monitoring program based on remote-sensed and other digital spatial Earth science data bases to support global climate change studies in arctic, subarctic, and boreal regions of Alaska. The monitoring program is designed to support studies and models of Earth system processes at landscape, ecosystem, and regional scales. These site and regional models will improve parameter estimates for circumpolar and global climate change models. A major component of the project focuses on research elements associated with the spatial integration of widely varying sources of Earth science data and multiplatform, multitemporal sources of remote-sensed data for land surface characterization. Site-specific information will be correlated through collaborative studies with regional and hemispheric level data bases for broad scale extrapolations and predictions.

Establishment of a monitoring program for the arctic and subarctic regions will be accomplished by addressing the following goals:

1. Establish eight study sites within Alaska that sample unique ecosystems with a high potential for change.
2. Compile a comprehensive archive of remote-sensed and automated Earth science data bases for designated sites.
3. Develop baseline data bases and maps from which to document change in the biological and physical components.
4. Identify and develop data analysis and data integration techniques for detecting and monitoring change.
5. Establish a program for acquisition and integration of new data from existing and future satellite systems.
6. Use geographic information system technology to develop parametric and nonparametric models to study and predict ecosystem change.
7. Correlate site and ecoregion level data with statewide and circumpolar data for broad scale modeling.

A key element of the project includes the development of an ecological regionalization map of the entire circumpolar arctic and subarctic regions through collaborative efforts with the Environmental Protection Agency and Environment Canada.

Sulfur Isotope Geochemistry of Paleoclimate Change in Lake Baikal, Siberia

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Lake Baikal, located in the Baikal Rift of southeastern Siberia, is the deepest and most ancient freshwater lake in the world. The lake has accumulated an estimated 5 km of sediment over the last 30 million years and potentially contains the longest and most complete record of climate change in central Asia. Perturbations in climate affect vegetative cover, precipitation, and runoff, and they can strongly influence the lake's circulation, vertical mixing, and nutrient dynamics. These fluctuations have a direct effect on lacustrine productivity, redox conditions, and sulfur transformations in lake sediment, and they may be recorded as down-core variations in sulfur forms and sulfur isotopic compositions. For example, warmer average temperatures may inhibit lake overturn and thus lead to lower primary productivity, stagnant bottom-water conditions, and formation of ^{34}S-enriched pyritic sulfur.

As part of a large program of joint U.S.-Russian research on the paleoclimatology and paleolimnology of Lake Baikal, we examined the abundance and isotopic composition of the major forms of sulfur in sediment cores from the lake. In the initial phase of this study, samples were analyzed from cores (<5 m in length) from two very different sedimentary environments within the lake: a site near the Selenga delta that has a relatively high deposition rate, and a site on the Academician Ridge with a low deposition rate. Overall the sulfur content of the sediment ranges from 0.02 to 0.55 wt. percent, consisting of 0.01 to 0.03 wt. percent organic sulfur, zero to 0.03 wt. percent monosulfide sulfur, and zero to 0.52 wt. percent disulfide (pyritic) sulfur. Sulfur isotopic ratios ($d^{34}S$) have a 47 per mil range, from −3.7 to +43.3 per mil, reflecting large variations in the abundance of dissolved sulfate in the lake's bottom water and the rate and extent of sulfate reduction in the sediment. The patterns of sulfur geochemistry at the two sites examined are significantly different, caused by differences in sedimentation and redox conditions. These differences underscore the importance of distinguishing between lake wide and local or basin-specific changes in paleolimnology when attempting to interpret how this large and diverse lake responded to climate change.

Examination of Biogeochemical Processes in Tropical Watersheds of Puerto Rico and Panama

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Research is concentrated on investigations of nutrient cycles, gas exchange, and weathering and erosion processes in small watersheds in northeastern Puerto Rico at the Luquillo Experimental Forest (LEF), and in central Panama at the Barro Colorado Nature Monument (BCNM). The LEF is the site of a recently initiated project funded under the Water, Energy, and Biogeochemical Budgets (WEBB) Program of the U.S. Geological Survey's Water Resources Division (WRD) and run through the Caribbean District Office of WRD. The LEF is readily accessible to researchers and is amenable to a complex research program. It is a region that climatologically and geologically resembles typical tropical environments more than any other area within U.S. territory. The BCNM includes Barro Colorado Island and surrounding mainland peninsulas in Gatun Lake, the largest artificial lake in the Panama Canal basin. The BCNM is under the stewardship of the Smithsonian Tropical Research Institute (STRI), which presently shares funding for the work.

Sampling is organized using a quasi-nested-basin approach. Micro-watersheds have been selected on contrasting lithologies [Puerto Rico—quartz diorite, basaltic volcaniclastics; Panama—andesite and basaltic volcaniclastics]. The micro-watersheds are used to identify and characterize processes in detail. Larger watersheds are used for the hydrologic and chemical budgets, because the spatial distribution of agricultural development and of many important hillslope processes, such as landslides, is sufficiently patchy and uneven that it is impossible to select representative micro-watersheds. In Puerto Rico, the larger watersheds are contrasted with geologically matched nearby watersheds that have been agriculturally developed. In Panama, the Panama Canal Basin, which has a detailed 80-year hydrologic record, is used as the reference watershed. Paired sites within the Panama Canal basin are used to determine the effects of development.

The primary objective of the studies of weathering and erosion is to use long-term chemical sampling and physical monitoring to characterize the processes that control the distribution and transport of major, important-minor, and nutrient elements (Al, C, Ca, Cl, F, Fe, Ge, H, K, Mg, Mn, N, Na, O, P, S, Si, Sr, Ti, Zr) through soils, downslope, and out of the watershed. Phenomena of interest to global-change research include the fixation, storage, and export of carbon and nutrients as related to biogeochemical and geomorphic processes within the watersheds. The experimental design permits comparison between natural and developed environments. The exchange of methane and carbon dioxide with the atmosphere is being examined for different types of environments (forests, swamps, lakes) in light of variations in hydrologic conditions. The soil-gas work in Panama is now completed and is among the first studies to quantify the seasonality of methane emission in tropical habitats.

Developing Land Surface Characterization Requirements for Water and Energy Exchange Models

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The goal of this research is to enhance our understanding of the types and characteristics of geographic data that are required for numerical models of water and energy exchange processes at the land surface-vegetation-atmosphere interface. The focus is on biospheric modeling of the diurnal variations of the land surface energy balance, including the partitioning of net radiation into sensible and latent heat components. Such models depict the dynamic interactions between the free atmosphere and the biosphere at the land surface (i.e., radiative energy, momentum, moisture, and heat exchanges within the soil-plant-atmosphere-system). The Biosphere-Atmosphere-Transfer-Scheme (BATS) and the Simple Biosphere Model (SiB) are two examples of this type of land surface parameterization under development for global change models. Heterogeneous land surface characteristics, including terrain (elevation, slope, and aspect) and vegetation (type, morphological structure, and physiological attributes), are major factors in determining the behavior of these interactions. Furthermore, incomplete understanding of processes, temporal dynamics, and multiple scales complicate the characterization of surface roughness, albedo, and stomatal resistance.

Preliminary tasks are to (1) assess, evaluate, and document the geographic data requirements for first generation models and more complex biospheric models, in part through comprehensive literature review and input from expert modelers, and (2) gain further insight into spatial data requirements by conducting a demonstration project within the complex terrain and heterogeneous landscape environments of Colorado and other, less challenging, regions to investigate multiscale sensitivity analyses, spatial integration methods, and statistical aggregations for biospheric models such as BATS. Other advanced dynamic models as tools for land surface characterization will also be studied through collaborative projects.

Simulations based on appropriate zero-dimensional modeling as well as coupled modeling for multiscale regions within typical global change model cells will be based on global data sets and U.S. Geological Survey spatial data products, including cartographic data as well as derived data sets from Landsat and the NOAA polar orbiting satellite's Advanced Very High Resolution Radiometer (AVHRR). Requirements for new thematic products, accuracy, scale/resolution, and role of derivative products will be studied. Initial multiscale tests on land cover and digital elevation model/solar insolation modeling within the Montrose and Limon, Colo., quadrangles are underway.

Consumption of Atmospheric Methane in Unsaturated Soils

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Recent increases in the atmospheric concentration of methane have been attributed to culturally induced increases in global sources as well as to diminution of natural methane sinks. The overall global methane mass balance is not completely defined; extensive field research is required to adequately quantify source and sink terms. Consumption of atmospheric methane by soil bacteria is the most important terrestrial methane sink, accounting for as much as 10 percent of the total global sink (tropospheric photo-oxidation accounts for the majority of the remaining sink); however, there is relatively little quantitative information about the temporal and spatial distribution of methane consumption by soil systems. Likewise, there is a general lack of knowledge of the edaphic, hydrologic, and thermal controls on the consumptive process.

We established a network of locations for measurement of soil methane fluxes in the Central and Western United States. This network encompasses a wide range of conditions of soil temperature, moisture content, and nutrient availability. It includes locations along altitudinal and vegetational gradients in the Mojave Desert-Great Basin transition zone in Nevada, in the southern Rocky Mountains in Colorado, and in tallgrass prairie in Kansas. An objective of our study is to characterize the temporal and spatial heterogeneity of methane consumption by relating consumption rates to easily measured soil conditions such as surface temperature and soil-moisture content. In addition, field investigations focus on determining the bounds on consumption that are defined by environmental extremes, and on determining the alteration of methane consumption rates caused by cultural disturbance. Measurements at the Nevada site are intended to characterize methane consumption for high temperature, low moisture content, and low nutrient content conditions; likewise, flux measurements through snowpack at the Colorado site characterize the effects of sustained low temperatures. Paired measurements at the Konza Prairie Natural Resource Research Area in Kansas compare and contrast undisturbed prairie grassland with prairie that has been converted to agriculture. Effects of biomass burning, agricultural chemical applications, and crop cover have also been investigated at that location.

A Monthly Water Balance Model to Study Possible Impacts of Climate Change in the Delaware River Basin

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The Delaware River is an important source of water for about 20 million people both within and outside the basin. When storage in the New York City Reservoir System in the upper part of the basin falls below specified levels, drought warnings or drought emergency conditions are declared, and water use is restricted. The frequency with which drought emergency conditions are in effect is termed "drought risk." Drought risk, under present climate and rules of operation, is estimated by running 50 years of monthly temperature and precipitation values through a basin model that simulates the operation of reservoirs and diversion canals in the basin. The 50 years of synthetic temperature and precipitation values are created by generating serially- and cross-correlated random residuals from historic monthly means. The basin model uses a modified Thornthwaite water-balance model to convert temperature and precipitation to natural runoff values.

Conditions associated with climate change are introduced by modifying historic monthly mean temperature and precipitation and rerunning the basin model. The modifications of the historic means are determined by the difference in single and double atmospheric carbon dioxide runs for three general circulation models (GCMs): the Goddard Institute for Space Studies (GISS) model, the Geophysical Fluid Dynamics Laboratory (GFDL) model, and the Oregon State University (OSU) model. The change in estimated drought risk caused by doubling atmospheric carbon dioxide levels varies greatly depending principally on the precipitation characteristics of the GCM chosen. Similar changes in flow at Trenton and the position of the salt front in the Delaware estuary were observed in the model runs.

Paleobotanical Evidence of Population Dynamics and Paleoclimatic Fluctuations

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Palynological and plant-macrofossil studies provide evidence of changes in population sizes, community structures, and range boundaries that occurred in response to long-term climatic changes. Paleobotanical investigations illustrate the sensitivities of individual species to climatic variations, and they permit assessments of amplitudes of change, response rates, and linearity of the responses of these taxa. Synoptic-scale maps of vegetation and other paleoclimatic proxy data for selected past-time slices provide insights into large-scale changes in climatic circulation. These maps can be compared with mapped output from numerical general circulation model (GCM) simulations to validate model depictions of past climates and to evaluate the credibility of these models in the prediction of future climates. Multivariate analyses of modern vegetation-climate relationships provide quantitative estimates of temperature, precipitation, and seasonality from fossil records. These quantitative relationships can also be used with numerical climate model simulations to estimate the past and future distributions of species and ecosystems.

Our initial focus has been on the Western United States, where several factors have made it difficult to establish the modern relationships among plant distributions and climatic parameters. These include the complex physiography and climate, the sparse coverage of weather stations, and the paucity of species-distributional information. To circumvent these problems, an equal-area grid of 30-year means of January, July, and annual temperature and precipitation values was produced by regionalized regression equations. Distributions of selected modern plant taxa were delimited by digitizing outlines from published range maps. Probability surfaces generated from these climate and vegetation data were used to illustrate the modern relationships among species distributions and climate variables. Current research objectives include using this methodology to estimate climatic conditions during the Pliocene across North America.

Some Anticipated and Measured Responses of Glaciers to Global Change in Alaska

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The linkage between glaciers and climate and the role that glaciers play in the hydrologic cycle are imperfectly known. Global temperature increases are expected to cause surface melting at higher elevations on glaciers worldwide. At first, most of the increased surface melt at high elevations will be refrozen within glaciers as internal accumulation. Runoff modelers need to recognize how the process of forming internal accumulation will decrease and delay the runoff derived from increased surface melting.

A small sea-level rise could cause several large glaciers in Alaska to begin drastic retreats. A rise that is inconsequential to most human activities could increase erosion along the narrow beaches that presently separate Malaspina, Bering, and other glaciers from attack by the waters of the Gulf of Alaska. Recent ice-penetrating radar measurements show that the potential retreat of Malaspina Glacier is 45 km and of Bering Glacier, 50 km. A small sea-level rise also increases the potential for retreat of a few actively calving glaciers. The threatened glaciers are sea-calving glaciers that are near their extended positions.

Long-term studies of glacier mass balance and runoff from Wolverine and Gulkana Basins, Alaska, show that recent increases in glacier ice storage are associated with increased basin runoff and increased total precipitation. This is contrary to the accepted relation in which ice storage increases are assumed to be withheld from unchanged total precipitation, which would reduce basin runoff. At Wolverine Glacier, a measured increase in the mean annual temperature has been associated with increases in both ice storage and basin runoff. The direct relation among mean annual temperature, ice storage, and runoff is not expected to hold for all glaciers, nor for these glaciers, as temperature continues to rise. Because the areal extent and temperature range over which the direct relation applies is undefined at this time, the sign of its effect on global sea level is undetermined. An important implication of this work is that in the absence of precipitation and ice storage change assessment, the reason for changes in basin runoff are ambiguous.

Our plans are to (1) extend the long-term records of glacier mass changes and climate data at existing study sites for use in empirical and theoretical assessment of the glacier/climate relation; (2) increase the mass balance and climate sampling density and coordinate the expanded effort with Canadian and other agency colleagues for use in improving and ground-truth checking GCM results; (3) improve understanding of relation between changing glacier mass and the hydrologic cycle; and (4) recognize uniquely glacier processes and bring them to the attention of the global circulation modeling community.

Banded Corals as Indicators of Tropical Pacific Paleoclimate

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The Hawaii District of the U.S. Geological Survey's Water Resources Division has recently started a project using massive corals of the genus *Porites* as indicators of paleoclimate. The goal of this project is to establish a climatic record that augments and predates recorded meteorologic and oceanographic observations at sites in the tropical Pacific basin. Specifically, we plan to use growth bands of massive corals as environmental recorders of rainfall and surface seawater temperature over the past several hundred years.

Geochemical variations in the calcium carbonate skeleton of actively growing massive corals can be correlated with environmental conditions in the surrounding seawater at the time of skeletal deposition. Furthermore, both annual and daily growth bands in such corals can be used to establish a chronology analogous to well-known studies using tree rings. This chronology can be combined with variations in skeletal composition to reconstruct specific environmental conditions at a particular time. For example, historic records of surface seawater temperatures have been constructed using variations in the ratio of oxygen isotopes ^{16}O and ^{18}O.

Several workers have recently demonstrated that massive corals may record fluctuations in river discharge by incorporating dissolved organic molecules into the skeletal matrix. These molecules fluoresce upon exposure to ultraviolet radiation, and the intensity of fluorescence is proportional to the volume of river discharge. We plan to use this attribute to reconstruct river discharge records for volcanic islands in the tropical Pacific, starting with the Hawaiian Islands. We also plan to obtain a record of water temperature using stable isotopes of oxygen.

Our program is in the early stages of development. To date, we have acquired and field tested an underwater drill rig capable of coring corals. We currently are engaged in choosing sites in the Hawaiian Islands for intensive field work, and arranging analytical facilities for the preparation and analysis of cores. In collaboration with other workers, we plan to establish a record of rainfall and surface seawater temperature over the past several hundred years.

An Investigation of the Water, Energy, and Biogeochemical Budgets of Loch Vale and Other Rocky Mountain Watersheds

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The interaction of climatic change with water, energy, and biogeochemical budgets will be most pronounced in watersheds that have biotic communities at the limit of their tolerance to climatic conditions. One such class of watershed is the alpine/subalpine/montane watersheds typical of the Rocky Mountains. Minor shifts in climate can markedly alter boundaries of community structure that define transitions in the watershed processes. Because such boundaries are especially well defined in these watersheds, and because such watersheds are widespread throughout the Rocky Mountains and other great mountain ranges worldwide, they are a critical element in understanding the most immediate effects of climatic change on watershed processes and the feedback of watershed processes to climate.

There are three topics in which there is a critical lack of understanding of watershed processes in the alpine/subalpine/montane watersheds of the Rocky Mountains: (1) processes controlling the flow path and flux and water; (2) processes controlling the energy balance and chemistry of snowpacks; and (3) processes controlling weathering and biogeochemical budgets. The basin and chemical characteristics of the Loch Vale watershed in Colorado are similar to alpine and subalpine watersheds throughout the Rocky Mountains. Such watersheds are among the most extensive of unaltered ecoregions in the Nation. Thus, understanding of processes that affect such watersheds is very likely to be transferable.

Some Recent Advances in Statistical Analysis of Spatial Random Processes

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Spatial variability of inputs to basin-scale hydrologic models is an important consideration for evaluating uncertainty in the output from such models. Data often consist of widely scattered measurements of inputs, such as precipitation, that are subsequently used to generate values over a fine grid of locations throughout the basin. Spatial random processes provide a convenient framework for generating model inputs on a fine spatial scale, conditional on widely scattered observations, and possible concomitant information such as digital elevation data. This presentation reviews some recent computational advances in fitting rational two-dimensional spectra to unequally spaced observations. PC-based FORTRAN programs have been written for selecting a model, estimating parameters, and using the model for interpolation. A data set consisting of snowpack measurements from western Colorado is used to demonstrate the methods.

Hydrologic and Biogeochemical Budgets in Temperate Lakes and Their Watersheds, Northern Wisconsin

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The Wisconsin Water, Energy, and Biogeochemical Budgets (WEBB) study area is in the Northern Highlands region of northern Wisconsin. The region is a rich mosaic of glacier-formed kettle lakes interspersed in a complex, low-relief topography. The study area includes seven lakes that, for the past 10 years, have been the site of the University of Wisconsin–Madison, North Temperate Lakes Long-Term Ecological Research (LTER) project. The Wisconsin WEBB project addresses some of the critical gaps in the understanding of hydrologic processes that control water and biogeochemical budgets in the lakes.

The overall objective of the Wisconsin WEBB investigation is to understand processes underlying the responses of hydrologic, biological, and chemical systems in the study area to climate variations and human activities. The initial funding supports two research elements, (1) rainfall/streamflow/ground-water recharge processes, and (2) surface and ground water interactions. The objectives of the first element are to investigate the partitioning of precipitation into quick-response streamflow and ground-water recharge, and to develop predictive capabilities for the streamflow generation and recharge processes. The objectives of the second element are to identify geochemical processes that control the flux of important chemical species at the sediment-lake interface, and to investigate the influence of stream and ground-water flow on the solute budgets and hydraulic residence time of Trout Lake.

The approach for the first research element involves a combination of isotope sampling and moisture accounting. Three sites have been chosen initially: one streamflow/ground-water recharge site and two upland ground-water recharge sites (one in an open area and one under the forest canopy). Water samples will be collected from the stream, piezometers, and lysimeters before, during, and after precipitation events. Several rain gages in the study area will provide instantaneous precipitation intensities and water for composite isotope samples. A complete climatological station will be installed to provide support data. It complements an existing climatological raft run by the North Temperate Lakes LTER project. One emphasis of the sampling is investigation of processes controlling the isotopic evolution of precipitation as it moves through the soil.

The approach for the second research element involves fine-scale sampling at the sediment/lake interface of Trout Lake and monitoring surface water contributions of water and solutes to Trout Lake. The fine-scale sampling will use a variety of techniques, including membrane equilibrators, core squeezing, microprobes, and seepage-meters. Carbon dioxide and methane production rates for sediment extracts will be used to identify critical processes. Whole water and filtered samples for nutrients and major ions for all tributary streams and the outlet from Trout Lake will be used to assess the importance of stream sources to solute budgets. Techniques for estimating the hydraulic residence time distribution for Trout Lake will be explored.

Assessment of the Potential Effects of Climate Change on Salinity Intrusion in Delaware Bay

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The purpose of the Delaware River basin study is to improve knowledge of the response of the basin's water resources to potential climate changes. Details of the objectives and an overall study plan are found in Ayers and Leavesley (USGS Open-File Report 88–478, 1988). The study described here is a subset of the broader study and is focused primarily on salinity intrusion in the Delaware River. Given changes in freshwater discharge into the Delaware River as determined from the larger study, and given probable sea-level rise estimates, the purpose here is to calculate the distribution of salinity within Delaware Bay and River. This salinity distribution will then be used to assess saltwater intrusion into aquifers adjacent to the estuary.

The approach adopted for this study is comprised of two parts, an analysis of existing physical data in order to derive a basic understanding of the salt dynamics and the numerical simulation of future conditions based on this analysis. The data of interest include stage and salinity data from USGS and the Delaware River Basin Commission, and tide, salinity, and current meter data from NOAA/NOS. From these data, rates of the various salt transport processes can be calculated, such as those of horizontal residual transport, tidally induced dispersion, and transport from the estuarine circulation. Knowledge of these rates and their changes as a function of changing conditions is an essential input to the numerical simulations.

There are two important constraints in the model: it must resolve the spatial scales important to the salt dynamics, and it must be sufficiently efficient to allow extensive sensitivity studies. This has led to a three-dimensional model that uses harmonic decomposition in time and irregular finite elements in space (Walters, CSR, 1992a). These equations are coupled to the advection-diffusion equation for salt so that density-gradient forcing is included in the momentum equations. Although the study described here is still in progress, the model has reproduced sea-level variations and the three-dimensional structure of tidal and residual currents very well. In addition, the study has addressed the effects of a 1-m rise in mean sea level on hydrodynamics. Remaining work will focus on salt dynamics (1992b).

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Synoptic-Scale Climate and Mass Balance Interactions in Western North America

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The mass balance of glaciers depends on the seasonal variation in precipitation, temperature, and insolation. For glaciers in Western North America, these meteorological variables are influenced by the large-scale atmospheric circulation over the North Pacific Ocean. The purpose of this study is to gain a better understanding of the relation between mass balance at glaciers in Western North America and large-scale atmospheric effects at interannual time scales, as well as the behavior of longer-term cumulative changes in glacier volume. This study differs from most other mass balance studies in that the objective is to investigate large-scale similarities between glaciers using exploratory data analysis, rather than to examine the relation between mass balance at a single glacier, and local and nonlocal forcing.

This study is an extension of a previous study (Walters and Meier, AGU Monograph 55, 1989) that used empirical orthogonal function (EOF) analysis to bring out the large-scale similarities and differences in glacier behavior as recorded in the mass balance time-series. Once the EOF extraction is finished, the mode amplitude time-series are correlated with climatological variables such as averaged-sea level pressure, 700 mb height anomalies, Pacific North America (PNA) index, and Southern Oscillation Index (SOI). Some of these correlations are more successful than others. The procedure above emphasizes the interannual variability in the data sets. In order to examine longer period changes, the filtered interannual variations and the cumulative balances are searched for trends and patterns.

The first (largest) mode in the EOF analysis contained 60 percent of the variance, and it was strongly related to fall and winter atmospheric pressure patterns; the second mode contained 20 percent of the variance, and it was related to a summer pattern where high temperatures caused relatively high ablation. Both glacier balances and EOF's show strong correlations with large-scale variations in seasonal 700 mb height anomalies and sea-level pressure, and weaker correlations with Southern Oscillation Index and Pacific North American index. These results support the conclusion that the largest modes in the EOF analysis have succeeded in capturing the synoptic-scale similarities in the data sets, and that the response of the individual glaciers is more highly dependent on the large-scale atmospheric conditions than local-scale meteorological differences.

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Modeling the Spatial Distribution of Solar Radiation Incident on the Land Surface

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Solar radiation incident at the land surface drives several important environmental processes, such as evapotranspiration, photosynthesis, and atmospheric heating. Work is underway to quantify the terrain-dependent component of spatial variability, couple it to mesoscale meteorological and other process models, and quantify the effects of terrain-induced radiation variability on process aggregation (spatial integration), especially in mountainous regions.

Major terrain geometric factors to consider are

- orientation of local slope with respect to solar position;
- shadowing of terrain from direct (refraction-path) solar radiation; and
- horizon obscuration by local and surrounding terrain, which diminishes sky view and reduces diffuse radiation.

The first step in developing spatially accurate models of incident solar radiation is to separate terrain geometric effects from solar direction and atmospheric transfer effects. In 1990, J. Dozier and J. Frew of the University of California at Santa Barbara developed an efficient algorithm for deducing horizons along terrain profiles; computer codes are now being developed to apply their method repeatedly across two-dimensional digital elevation models (DEM's) at numerous azimuths. For each point on the DEM, the software will compute horizon vertical angle as a function of azimuth and sky-view solid angle. The former is needed for computing shadowing (given solar azimuth and elevation), and the latter is used to compute reductions in diffuse radiation. The algorithm is structured for coupling to either a data- or a model-based specification of atmospheric direct and diffuse radiative transfer.

Relations Between Upper-Air Flow Patterns, Climate, and Hydrologic Variability in the Red River of the North Basin in North Dakota, South Dakota, Minnesota, Manitoba, and Saskatchewan

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The Red River of the North drains about 290,000 km^2 in the United States and Canada. The Red River of the North and some of its tributaries are international streams that are managed in accordance with provisions of the 1909 Boundary Waters Treaty between the United States and Canada. CO_2-induced climate change could have an adverse effect on streamflow regimen, and changes in streamflow regimen could create difficult interstate and international legal problems.

The purpose of this study is to investigate the hydrologic response of the Red River of the North and its tributaries to past climatic anomalies. The objectives of the study are to (1) analyze 50-kPa atmospheric pressure height and 50- to 100-kPa atmospheric thickness patterns for the northern hemisphere associated with extreme wet and dry periods in the Red River of the North basin during 1947–89; (2) assess differences between upper-air patterns that accompany wet and dry periods; (3) statistically compare surface climate variables to upper-air flow patterns and streamflow of the Red River of the North and its tributaries during wet and dry periods; and (4) assess circulation controls that lead to anomalies in upper-air flow patterns associated with wet and dry periods.

A review of 200 years of flood information on the Red River of the North at Winnipeg indicates that several major floods during the 1800's were larger than any floods that occurred during 1947–89. Streamflow data from the main-stem gaging stations on the Red River of the North indicate that low-flow conditions during the 1930's were more extreme than during 1947–89. Although the upper-air data (1947–89) can be used to describe the relations indicated in the objectives, the results may not be complete because they may not represent the most extreme climatic conditions that have occurred during the last 200 years.

Preliminary analysis of the 50-kPa anomalous pressure patterns for December–January indicates that extreme dry periods are associated with the amplification of a high pressure ridge over western North America that brings dry, adiabatically heated air into the Red River of the North basin. In contrast, analysis of anomalous pressure patterns indicates that extreme wet periods are associated with amplification of a trough over western North America that brings moisture-laden air from the southern and central United States into the Red River of the North basin.

Arctic Data Interactive: Demonstration of a Hypermedia System

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In May 1988, the U.S. Geological Survey, in cooperation with the Interagency Working Group on Data Management for Global Change, established a program with representatives from the Arctic research community to facilitate data management. The Arctic was selected as the focus for a data management project because (1) climatic models suggest that the Arctic will be one of the first areas to respond to changing climate, (2) the magnitude of environmental change will be greater in the Arctic than on other areas of the Earth's surface, and (3) the Arctic scientific community is a relatively small and organized group willing to enhance access to data and information. A key activity that the U.S. Geological Survey has undertaken is membership in the Arctic Environmental Data Directory Working Group, which is sponsored by the Interagency Arctic Research Policy Committee. The working group is composed of representatives from Government agencies and academia. One of the goals of the working group is to facilitate access to Earth science data and information for the Arctic and hence improve dissemination. As a first step, the working group developed the Arctic Environmental Data Directory, which contains more than 350 references to

Arctic data sets maintained by U.S. Government agencies and other institutions. To meet the data management goals of the Arctic research community, the working group has undertaken a pilot study known as the Arctic Data Interactive (ADI) to design an integrated information product that will be published using compact disc read-only-memory (CD ROM) technology. The ADI prototype will include the following multimedia elements:

- Arctic Environmental Data Directory
- Bibliographic information
- Full text of research reports and (or) short papers (including illustrations)
- Selected Arctic data sets

The project entails developing a prototype computer system that includes a mix of textual, numerical, and spatial data and possibly related software for data analysis. The data will be in standard formats to facilitate use with other applications software such as spreadsheets, graphics, and image processing.

The design of the ADI prototype is based on the concept of hypermedia technology. Hypermedia is defined in the computer and information science literature as a software environment for developing nonsequential database-management systems. Hypermedia techniques provide the capability to create associative links between structured and unstructured information that may include data, text, graphics, imagery, and sound. Hypermedia systems are also characterized by a user interface that incorporates icons (graphic representations) and multiple windows on a computer monitor.

Carbon Dioxide Contributions of the Terrestrial Biosphere to the Global Carbon Cycle

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The terrestrial biosphere plays an important role in the global carbon cycle. Since the middle of the 19th century, large amounts of carbon dioxide (CO_2) have been released into the atmosphere from the burning of fossil fuels, deforestation, and other man-induced effects. Since 1958, accurate measurements of CO_2 in the atmosphere have been made from several locations around the world. The level of CO_2 in the atmosphere has increased from approximately 285 parts per million (ppm) in the preindustrial age to over 345 ppm today. Of the total CO_2 released daily into the atmosphere, about 60 percent remains there and about 40 percent is either absorbed by the oceans or by the biosphere. A great deal of uncertainty exists regarding this latter 40 percent. During the same period in which CO_2 has been added to the atmosphere, the total area of the world's forests has been reduced. The tropical forests are continuing to be destroyed at a rapid rate and this reduction in biomass will have long-term implications for the global carbon cycle.

To predict the consequences of continued fossil fuel use, deforestation, and other terrestrial changes, complex global models of the carbon cycle have been developed. Data that are used in these models include rates of fossil fuel use, rates of absorption and transmission of carbon, area measurements of various vegetation types, estimates of future land-use changes, estimates of historical land uses, and the effects of increased CO_2 on plant growth.

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