State of the Earth's Cryosphere at the Beginning of the 21st Century: Glaciers, Global Snow Cover, Floating Ice, and Permafrost and Periglacial Environments—

INTRODUCTION—CHANGES IN THE EARTH'S CRYOSPHERE AND GLOBAL ENVIRONMENTAL CHANGE

By RICHARD S. WILLIAMS, JR.

With a section on INTENSIFICATION OF THE GLOBAL HYDROLOGIC CYCLE
By THOMAS G. HUNTINGTON

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

Edited by RICHARD S. WILLIAMS, JR., *and* JANE G. FERRIGNO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1386–A–1

The activities of the more than 7.0 billion human beings on Earth today [in 2012], almost 2 billion more people added since 1998, when the first chapter, A, Antarctica, was published, and the demands that those activities place on Earth's renewable and non-renewable resources are producing changes throughout the Earth System that are geographically widespread and that can be measured. In particular, reductions in the areal and (or) volumetric extent of the four elements of the Earth's cryosphere—glaciers, global snow cover, floating ice (sea, river, and lake), and permafrost—seem to have accelerated toward the end of the 20th century, as analyses of satellite data and field observations have documented. The global hydrological cycle is exhibiting significant variability, especially in the geographic distribution and intensity of precipitation, the availability of water resources, prolongation of periods of drought, and perhaps even an increase in the intensity of hurricanes. Of particular importance is the melting of glacier ice on land, because the newly liquid water is a major contributor to increases in streamflow in glacierized regions and to the ongoing rise in global sea level.

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INTRODUCTION—CHANGES IN THE EARTH'S CRYOSPHERE AND GLOBAL ENVIRONMENTAL CHANGE IN THE EARTH SYSTEM

By RICHARD S. WILLIAMS, JR.[1]

Introduction

In the late 1970s, the U.S. Geological Survey (USGS) began a three-decade-long international effort, in association with more than 100 U.S. and foreign scientists, to identify and analyze Landsat images in order to establish a global baseline of glaciers against which earth scientists could compare future changes in area quantitatively. The results of this effort have been and continue to be published in the 11 chapters [volumes] of USGS Professional Paper 1386.

The present Chapter A, "State of the Earth's Cryosphere at the Beginning of the 21st Century: Glaciers, Global Snow Cover, Floating Ice, and Permafrost and Periglacial Environments," is the introductory chapter for the Professional Paper 1386 series, Satellite Image Atlas of Glaciers of the World (Williams and Ferrigno, 2005).

The other 10 chapters in USGS Professional Paper 1386 are about specific geographic areas: the Antarctic ice sheet (Chapter B), the Greenland ice sheet (Chapter C), Glaciers of Iceland (Chapter D), Glaciers of Europe (Chapter E), Glaciers of Asia (Chapter F), Glaciers of the Middle East and Africa (Chapter G), Glaciers of Irian Jaya, Indonesia, and New Zealand (Chapter H), Glaciers of South America (Chapter I), Glaciers of North America (Chapter J), and Glaciers of Alaska (Chapter K). Chapter A provides comprehensive scientific assessments of changes in the four elements of the Earth's cryosphere (glaciers, snowcover, floating ice—sea, lake, and river—and permafrost) within the context of changes in the Earth System (figs. 1, 2).

The other 10 chapters, which describe the distribution of glacier areas in each of the glacierized regions of the world and are authored by one or more authors, fulfill two goals. The first goal was to create a baseline record of glaciers in each glacierized region during the 10-year period, 1972–1981, based on analysis of optimum Landsat images (no cloud cover, minimum seasonal snow cover) acquired by the Multispectral Scanner (MSS) and the Return Beam Vidicon (RBV) sensors on Landsat 1[2] (1972–1978), Landsat 2 (1975–1982), and Landsat 3 (1978–1983). The second was to invite the work of authors knowledgeable in each glacierized region to document the scientifically accurate historical record of past changes in glacier area. For the chapters fulfilling the second goal, one of which is not yet published (Chapter D, Glaciers of Iceland), the authors were able to extend that goal by including

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[2] Until the launch of Landsat 2 on 22 January 1975, Landsat 1 retained the original name given by the U.S. Geological Survey, ERTS 1 (Earth Resources Technology Satellite 1).

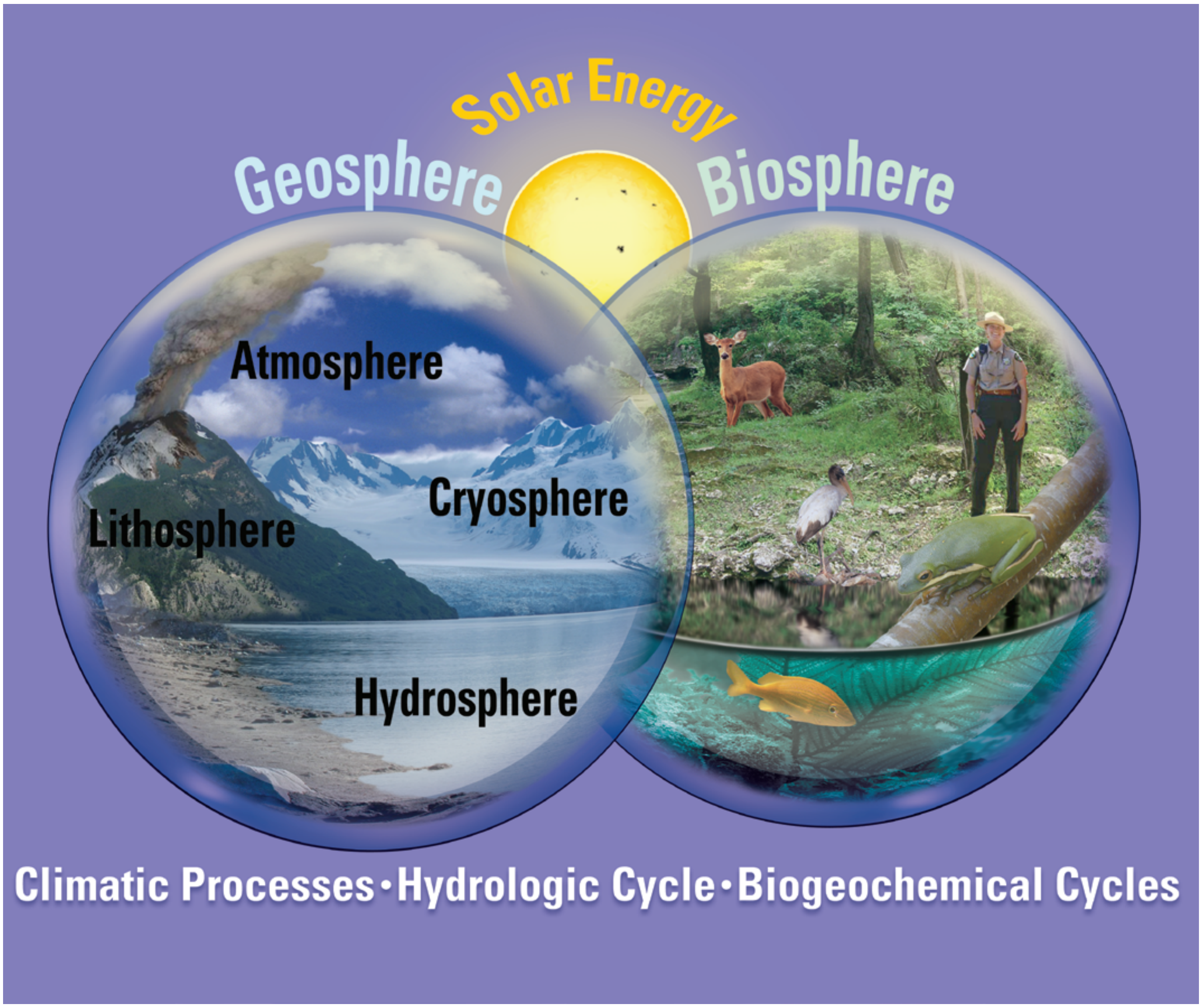

Figure 1.*—Conceptual diagram of the Earth System showing the four subcomponents of the geosphere (lithosphere, atmosphere, hydrosphere, and cryosphere), the biosphere (terrestrial and marine), climatic processes, hydrologic cycle, biogeochemical cycles, and solar energy. Designed by Jim Tomberlin, U.S. Geological Survey.*

Figure 2.*—Fractal snowflake diagram of the Earth's cryosphere showing its four elements: glaciers, snow cover, floating ice, and permafrost. Designed by Jim Tomberlin, U.S. Geological Survey.*

analyses of selected images from sensors on Landsats 4, 5, and 7, especially Thematic Mapper (TM) images from Landsats 4 and 5 and Enhanced Thematic Mapper (ETM+) images from Landsat 7, and images from sensors on other U.S. satellites, such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor designed and built by Japan on the EOS AM (Terra) spacecraft, and on satellites from other nations.

This introductory chapter differs from the other 10 chapters in providing globally comprehensive scientific assessments of changes in the four elements of the Earth's cryosphere: glaciers, snow cover, floating ice (sea ice, and lake and river ice), and permafrost (fig. 2). These changes span three to four decades from the 1970s into the first decade of the 21st century. Assessments of permafrost depend on direct field observations to monitor changes in area of continuous, discontinuous, and sporadic permafrost in high-latitude and high-altitude environments within the larger area of periglacial environments, but assessments of the other three elements of the cryosphere are based on analyses of images from various sensors on Earth-orbiting satellites.

For the Earth's *glaciers*, the first medium-resolution images [picture elements (pixels) of 80 meters (m)] (ERTS 1/Landsat 1)[2] were acquired in 1972, yielding more than 30 years of record. Degraded ETM+ images are still being acquired by the Landsat 7 spacecraft. For *global snow cover*, the assessments are based on images from 1966 to 2005 (40 years of record), with images still being acquired (in 2012). For *sea ice*, the analysis uses the 25-year record from 1978 to 2003, with images still being acquired (in 2012). For *lake ice* and *river ice*, analyses are of various satellite images and field-based observations during the 20th century into the early 21st century.

In the late 1970s, the original justification for preparing USGS Professional Paper 1386 A–K series (Satellite Image Atlas of Glaciers of the World) was to use Landsat Multispectral Scanner (MSS) and Return Beam Vidicon (RBV) images to determine the distribution of glacier area on Earth, but the scientific objectives for this introductory chapter were broadened to include an assessment of all four elements of the Earth's cryosphere. The reason for doing so was to show the changes taking place in each element of the cryosphere in response to the interval of pronounced regional warming and average warming globally that began in the 1990s and has not ceased.

Changes in the Earth's cryosphere are especially powerful indicators of global environmental change, because they vividly signify a change in regional and global climate by reducing the area or volume of glaciers, reducing the duration (and depth) of snow cover, seasonally reducing the areal extent and thickness of sea ice and shortening the duration of lake ice and river ice, and reducing the area of permafrost. Chapter A addresses the question of what we know at the beginning of the 21st century based on what we have learned about changes in glaciers, snow cover, floating ice (sea, lake, and river ice), and permafrost/periglacial environments during the past three to four decades. Assessment of changes in the first three elements of the Earth's cryosphere is primarily based on analysis of data from sensors on Earth-orbiting satellites. Assessment of the fourth element is primarily based on field observations.

Although the ocean holds 97 percent of the Earth's water, glaciers, which hold 2.15 percent, are the second largest reservoir of water (table 1) in the hydrologic cycle of the Earth System. The volume of glacier ice on land and its interchange with the ocean are directly related to the rise and fall of global

Table 1.—*Reservoirs of water worldwide*

[Values in thousands of square kilometers (10^3 km^2) except as noted; NA, not applicable; modified from Shiklomanov, 1993]

Water bodies	Distribution area	Volume	Global reserves (percent)	
			Total water	Freshwater
Oceans and seas	361,300	1,338,000	96.5	NA
Ground water	134,800	23,400	1.7	NA
Freshwater		10,530	0.76	30.1
Soil moisture		16.5	0.001	0.05
Glaciers and permanent snow cover	16,227	24,064	1.74	68.7
Ground ice/permafrost	21,000	300	0.022	0.86
Water reserves in lakes	2,058.7	176.4	0.013	NA
Fresh	1,236.4	91	0.007	0.26
Saline	822.3	85.4	0.006	NA
Water in swamps	2,682.6	11.47	0.0008	0.03
Water in rivers	148,000	2.12	0.0002	0.006
Water in biomass	510,000	1.12	0.0001	0.003
Atmospheric water	510,000	12.9	0.001	0.04
Total water reserves	510,000	1,385,984	100	NA
Total freshwater reserves	148,000	35,029	2.53	100

(eustatic) sea level. That 2.1 percent of water sequestered in glaciers represents a maximum potential rise in sea level of 75.6 m: 7 m from the Greenland ice sheet, 68 m from the Antarctic ice sheet and 0.6 m from non-ice sheet glaciers.

The Landsat images, which provided global coverage of land and shallow seas between lat 81° N. and lat 81° S., first became available on 23 July 1972. Our designation of the 10-year period 1972 to 1981 as the baseline for the analysis of Landsat 1, 2, and 3 images for a comprehensive global study of glaciers was, in retrospect, extremely propitious from several perspectives. Most importantly, the 1970s were a cooler interval of time in the Earth's regional and global climates. After the end of the "Little Ice Age" (Grove, 1988) in the late 1800s, global-average climate became warmer, interrupted by occasional cooler intervals. By the mid-1990s, after a 2-year period of global cooling following the explosive eruption of Mount Pinatubo, Luzon, Republic of the Philippines, in June 1991 (Robock and Oppenheimer, 2003), the global warming resumed. The cooler period during the 1970s to the mid-1990s contrasts sharply with the markedly warmer interval following the mid-1990s. The rapid warming of the Earth's climate has been clearly manifested in the four elements of the cryosphere, especially in the accelerated reduction in area and thickness of sea ice in the Arctic (Perovich and others, 2008; Zhang and others, 2008), in the thinning and recession of most of the world's non-ice-sheet glaciers, and in the increase in duration of seasonal melting on the Earth's second largest ice sheet, the Greenland ice sheet. The Arctic is especially sensitive to a warmer climate because of the presence of ice in the form of permafrost, floating ice (sea, lake, and river), non-ice-sheet glaciers, the Greenland ice sheet, and snow cover, all of which are subject to reduction in area and volume when surface temperatures are higher than 0°C.

In this chapter and in the other 10 chapters, the term 'glacier' refers to "A mass of snow and ice continuously moving from higher to lower ground…", the definition given by Armstrong and others (1973).

Part A-2 of this chapter discusses the different types of glaciers, from the largest (ice sheets) to the smallest (mountain glaciers). These studies and those in the next two parts [A-3 (Global Snow Cover) and A-4 (Floating Ice)] use satellite data.

Part A-3 concerns Global Snow Cover. The duration of snow cover, especially in the spring in the Northern Hemisphere, has been reduced by about 5 percent during the recent two decades, 1988–2008, when compared to the annual extent for the two decades between 1967 and 1988 [see also Intergovernmental Panel on Climate Change (IPCC), 2007a, b].

Part A-4 discusses Floating Ice, both sea ice and freshwater ice. The shrinkage in area of sea ice in the Arctic Ocean has been dramatic (Carroll, 2008). September 2007 marked the least area of sea ice cover (~4.1×10^6 square kilometers (km^2)), about 41 percent less than the ~7×10^6 km^2 average minimum for the period 1979 to 2003 (see Plate 1 and topical "Supplemental Notes" in the pocket at the end of this chapter). For lake and river ice during the same period, the interval between fall freeze up and spring breakup has shortened.

Part A-5 (Permafrost and Periglacial Environments) requires ground observations and measurements. The vast area of permafrost in Alaska, Canada, Russia, Europe, and central Asia is also undergoing warming and thawing (Brown and Romanovksy, 2008). The vital importance of satellite observations to monitoring and measuring glaciers, global snow cover, and floating ice, three elements of the Earth's cryosphere, was noted in a recent National Research Council (2008) report: Earth Observations from Space: The First 50 Years of Scientific Achievements:

> "No other single technological development has revolutionized cryosphere research as much as satellite observations…Understanding changes to ice sheets, sea ice, ice caps, and glaciers is important for understanding global climate change and predicting its effects. In particular, "shrinking ice sheets" and their contribution to sea-level rise were identified as the third most significant "Breakthrough of the Year" for 2006.

Evolution of Earth System Science, Post–World War II

Emergence of New Technologies

In 1945, Vannevar Bush, director of the Office of Scientific Research and Development, who reported only to the President of the United States, prepared a report to President Harry S Truman, "Science—The Endless Frontier (Bush, 1945). The report laid the groundwork for expanding federal support for science, including establishing new scientific agencies or restructuring existing agencies to become scientific agencies. All of these "new" scientific institutions were destined to make major contributions to the rapid growth of technology and science during the next three decades and beyond: National Science Foundation (NSF, 1950–present), National Aeronautics and Space Administration (NASA, 1958–present), and Environmental Science Services

Administration (ESSA, 1965–70, the predecessor agency to the National Oceanic and Atmospheric Administration (NOAA, 1970). In addition, the National Academy of Sciences (established in 1863) was given the authority to commission and publish reports that various committees of the National Research Council prepared (Hutchinson and Williams, 2007).

The 25-year period from the end of World War II to the early 1970s was a time of important technological advances by the United States (and by other nations) and the new scientific agencies were quick to exploit them. The human population (expanding from 2.5 billion in 1950 to 3.6 billion by the early 1970s) was beginning to leave a measureable imprint on the entire Earth System (Ehrlich, 1968), although this is not the first time that the activities of human beings have been implicated in such extensive change: during the late Pleistocene and early Holocene Epochs, human beings hunted entire species of animals to extinction (Diamond, 1997; Martin, 2005). A hypothesis by Ruddiman (2005) suggests that farming activities during the "Stone Age" had already begun to alter the composition of the Earth's atmosphere, increasing its concentration of methane and carbon dioxide.

In the early 1960s, Rachel Carson (1962) sounded the alarm in her influential book "Silent Spring" about the impact of the heedless and widespread dispersal of synthetic chemicals on wildlife and on human well-being. Of special concern to her, a biologist, were the insecticide dichlorodiphenyltrichloroethane (DDT) and other pesticides, which remain undissolved throughout the Earth's liquid water (hydrosphere) and in soils and shallow-water sediments (lithosphere), posing a danger to wildlife and human beings. Carson had left her position as a research biologist with the U.S. Fish and Wildlife Service (U.S. Department of the Interior) a decade earlier in order to devote full time to writing; she had already been recognized as a gifted author for her book "The Sea Around Us" (Carson, 1951). "Silent Spring" is "still regarded as the cornerstone of the new environmentalism movement" (Matthiessen, 2007, p. 15; Lytle, 2007). More importantly, her work documenting how human activity has had major impacts on ecosystems by our use of long-lasting poisonous hydrocarbons and organophosphates raised public awareness. She became a mentor to later generations of scientists who used the results of their scientific research to document the increasingly negative impact of human activity on the entire Earth (Matthiessen, 2007). R. Buckminster Fuller (1969) called the planet "Spaceship Earth" a "closed system" that received energy only from the Sun and thereby laid the theoretical foundation for what would eventually be called the Earth System (fig. 2). The Norwegian scientist Arne Næss (1973) contributed the concept of "Deep Ecology," arguing for the interconnectedness of all life forms, the intrinsic value of each, and the recognition that the expanding human population was having a deleterious impact on all living organisms.

On 20 July 1969, the U.S. space program succeeded in landing two astronauts on the Moon, perhaps the greatest technological achievement of the 20th century. Another technological achievement of the 1960s was the U.S. Department of Defense's development of reconnaissance satellites in its Corona Program. More than 100 satellites in the KH ("Keyhole") series (1–4) were launched between August 1960 and May 1972 (McDonald, 1997). With the creation of the Corona Program, the U.S. Geological Survey (USGS) was assigned the federal responsibility for establishing a classified facility in Building E-1, Newton Square, Reston, Va. to serve as a data and analysis center for Corona (and for Argon and Lanyard) photographs. With their high-level security clearances, USGS scientists and other federal-agency scientists were given access to Corona data and to classified ancillary data to use for various environmental studies, such as preparing land-use and land-cover maps. Not until February 1995 were Corona (Argon and Lanyard) data formally declassified. More than two years later, on 26 November 1997, the entire collection of Corona, Argon, and Lanyard imagery was released to the public by the National Reconnaissance Office (NRO), and the data, more than 2 million feet of film in 39,000 film cans, were archived at the USGS EROS Data Center, Sioux Falls, S.Dak. [*http://www.nro.gov/Corona/facts.htm*].

Stuart L. Udall, Secretary, U.S. Department of the Interior and concerned environmentalist (Udall, 1963); William T. Pecora, Director, USGS, and first director, Earth Resources Observation Systems (EROS); and William A. Fischer, second director of the EROS Program—all knowledgeable about the Corona Program—established the EROS Program and proposed unilaterally to design, construct, and launch the first Earth Resources Technology Satellite (ERTS 1). It would be the first civilian satellite capable of systematically and repetitively (every 18 days) recording images of the Earth's land and shallow-sea areas at medium spatial resolution (80-m pixels). The EROS Data Center in Sioux Falls, S.Dak. would archive and distribute the data (Johnson, 1968). The visionary idea of these three men, including their altruistic motto for the ERTS Program, "For the Benefit of All Mankind," eventually led to a partnership with NASA's Goddard Space Flight Center. ERTS 1 was placed in orbit on 23 July 1972, and represents another outstanding accomplishment of the U.S. space program.

The 1970s also saw two more major achievements by NASA. The Viking 1 and 2 orbiters of Mars, and the successful landing of two landers on the surface of Mars, revealed a "desert planet" with many landforms similar to those on Earth. In 1977, either or both of the two Voyager spacecraft, 1 and 2, successfully imaged Jupiter, Saturn, Uranus, and Neptune and their numerous moons, providing extraordinary new information about the four "gas giants" and, especially, about the diversity of landforms and other processes on their moons, including significant volcanic activity on Io, one of Jupiter's four Galilean moons.

Soon after ERTS 1 was launched on 23 July 1972, scientists who had been using stereoscopic, vertical aerial photographs in their field research quickly realized that the medium-resolution (80-m pixel) ERTS 1 MSS images provided a unique and heretofor unavailable opportunity to measure and monitor in a time-lapse fashion (cloud-cover permitting) changes occurring on the land and in the shallow-sea regions of the Earth, whether they be the result of natural processes or of anthropogenic (human) activities. Several compilations of research studies by government, academic, and industrial scientists, which NASA funded, confirmed that ERTS (Landsat) images now offered an opportunity for field scientists to expand their studies beyond local interests to regional and even global dimensions. The technical and engineering achievement of the ERTS/Landsat series of spacecraft (Landsat, 1, 2, 3, 4, 5, and 7), which had been acquiring images on a regular basis since 23 July 1972, provided field scientists with an unparalleled archive of images of the Earth's land areas and shallow seas. Electromechanical difficulties with the ETM+ sensor on Landsat 7 on 31 May 2003 truncated nearly 31 years of internationally admired success in continuity of image acquisition.

The first field scientist to use Landsat images to study a specific type of landform on a global basis, in this case aeolian landforms (dunes and sand seas), was the USGS geomorphologist and aeolian-landform specialist, Edwin

D. McKee. His pioneering "A Study of Global Sand Seas" (McKee, 1979) led the way for other field scientists to study changes in landforms, land cover, and land use from a global perspective, whatever their topic in the field-based geosciences and biosciences might be.

In addition to designing, building, launching, and operating most of the past and present Earth-orbiting satellites to acquire image and other satellite data for measuring changes in the Earth System that would be amenable to measurement by satellite sensors, NASA worked with other institutions to fund many of the atlases of satellite observations of global environmental change. The first atlas was compiled by Williams and Carter (1976) "ERTS-1: A New Window on Our Planet," based on research funded by NASA; Short and others (1976) compiled the second atlas, "Mission to Earth: Landsat Views the World." The third atlas was "Geomorphology from Space. A Global Overview of Regional Landforms" (Short and Blair, 1986), which included a chapter on "Glaciers and Glacial Landforms" (Williams, 1986). M.D. Cross (n.d.) published a series of "paired" Landsat images (three in the case of Mount St. Helens) to show changes that human activity and natural processes caused on the Earth's surface. The USGS Earth Resources Observation and Science (EROS) Data Center later developed a Web site populated by sequential Landsat images and ancillary data showing changes on the Earth's surface [*http://www.earthshots.usgs.gov*].

Gurney and others (1993) published an "Atlas of Satellite Observations Related to Global Change"; Williams and Hall (1993) included a chapter in the atlas on glaciers; other elements of the cryosphere were also covered. In 2005, the United Nations Environment Programme (UNEP, 2005), in association with NASA, the USGS, and the University of Maryland, published "One Planet. Many People. Atlas of Our Changing Environment," well illustrated with numerous satellite images as beautiful as they were informative. In 2007, King and others (2007) published "Our Changing Planet. The View from Space;" Hall and Williams (2007) included a chapter on glaciers and other elements of the cryosphere.

The last three of these volumes all contain the word "change" in their titles: the reference is to global environmental change, not solely to climate change. The distinction is a critical scientific one, emphasizing that all three volumes were addressed from an Earth System perspective (Rasool, 1988). A more recent book, "Earth Observation of Global Change: The Role of Satellite Remote Sensing in Monitoring the Global Environment" (Chuvieco, 2008), reemphasized the value of studying the world for the first time, from the truly global perspective attained using data from Earth-orbiting satellites, both polar-orbiting (Landsat and NOAA) and geostationary (NOAA), with particular reference to monitoring changes in the cryosphere (National Research Council, 2008). Clearly, the scientific analysis of images and other data acquired by Earth-observation satellites (National Research Council, 2008; Tatem and others, 2008) has contributed to a better understanding of changes in the Earth System that result from natural and from anthropogenic processes. Williams (1991) stated that the Landsat series of spacecraft was the key space-based component that supported the U.S. Global Change Research Program in the 1990s. In 2009, after a hiatus of 6 years, the importance of having a fully operational Landsat system to repetitively record changes on the Earth's surface is still extremely important. Without access to such data, scientists are severely handicapped in studying changes on the Earth's surface in response to changes in the Earth System.

Thanks, in large part, to the Landsat image archive, another revolutionary change was taking place in how scientists perceive the Earth—not as a series of individual systems, but rather as a holistic, interrelated, interactive series of systems, now referred to as the Earth System (fig. 1). Concurrently with these major technological and conceptual advances in the field sciences, the Earth's human population increased from 3.7 billion in 1970 to 4.8 billion in 1985, and it exceeded 6 billion by the start of the 21st century; in mid-2009, it had reached 6.8 billion.

The Developing Global Perspective

The first Earth Day was celebrated in April 1970, and it is now celebrated each year on 22 April. In December 1972, the launch of Apollo 17 was the final mission of the Apollo Program, the last landing on the Moon for at least the next 40 years (through 2012). Apollo 17 yielded two important results. Astronaut Harrison H. ("Jack") Schmitt, a geologist and former member of the USGS staff, took the famous photograph of the fully illuminated hemisphere of the Earth ("Full Earth") (fig. 3) during the trip from Earth to the Moon, possible only because of the nighttime launch of the spacecraft. The photograph became an international iconic symbol, including inclusion on the "unofficial" flag of Earth Day. Jack Schmitt's time on the lunar surface was devoted to collecting samples of the most scientifically important rocks that were lying on the surface or from outcrops.

By the late 1970s and early 1980s, many scientists studying various aspects of the Earth System became convinced that environmental change was having a global impact on all systems and began to publish studies of changes they observed. Scientists with the British Antarctic Survey at Halley Station on the Antarctic Peninsula measured a marked decline in the ozone layer in the Earth's upper atmosphere. In response to the implications of these scientific findings and of ozone depletion (National Research Council, 1989), the United Nations Protocol on eliminating the production and emission of chlorofluorocarbons (CFCs) was approved in Montréal in 1987. Charles F. Keeling had begun his measurements of carbon dioxide (CO_2) concentration in the Earth's atmosphere in 1958 at an observatory on Mauna Loa, Hawaii. During the next decade of CO_2 measurements, the sawtooth pattern of seasonal fluctuations was soon discovered to be superimposed on a continuing upward trend, which eventually became known as the "Keeling Curve" (fig. 4) (Keeling, 2008). The analysis of a 160,000-year record of atmospheric CO_2 from the Vostok ice core from "Dome C" in Antarctica revealed that glacial intervals had a CO_2 concentration of about 180 parts per million (ppm); interglacial intervals had a CO_2 concentration that peaked at 280 ppm (fig. 5) (Barnola and others, 1987). By the late 1980s, the atmospheric concentration of CO_2 was 350 ppm. Clearly, the 350 ppm concentration of CO_2 was well above (25 percent higher than) natural-background variability. Most atmospheric scientists considered human activities, especially the combustion of fossil fuels, to be the most likely source of the elevated CO_2 in the Earth's atmosphere (Hansen and others, 1981). Other scientists measured a concomitant increase in methane (CH_4) (Pearman and Fraser, 1988), another "greenhouse gas."

On 23 June 1988, James E. Hansen, an atmospheric scientist and Director of NASA's Goddard Institute for Space Studies at Columbia University, testified before a committee of the U.S. Congress that "the Earth was getting warmer" and that "with a high degree of confidence we could associate the

Figure 3.—*Photograph of the Earth, taken by geologist/astronaut Harrison H. (Jack) Schmitt in December 1972 during the Apollo 17 mission to the Moon. National Aeronautics and Space Administration (NASA) photograph no. 72-HC-928, courtesy of NASA Public Information Office, Washington, D.C.*

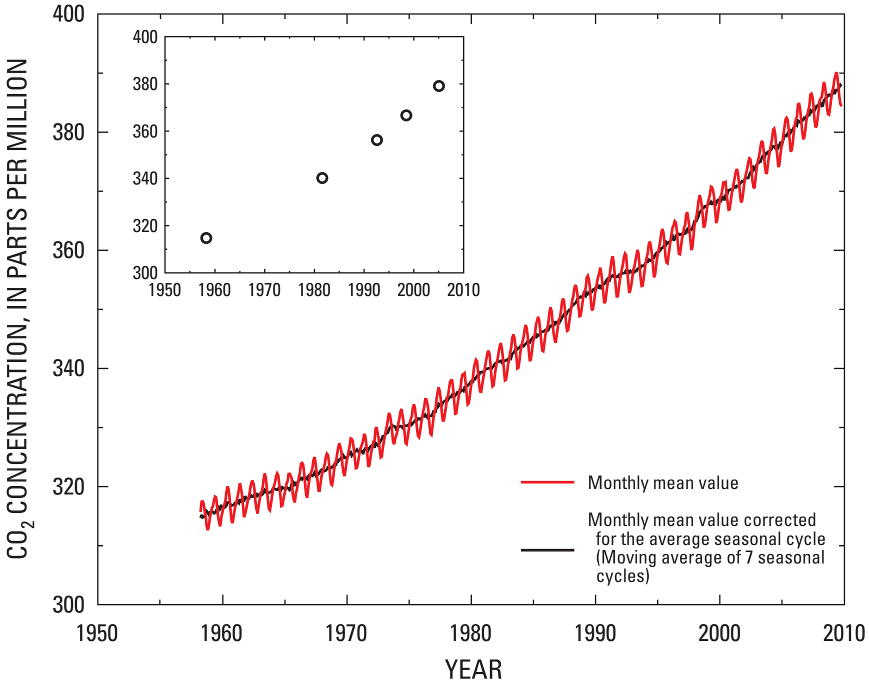

Figure 4.—*Graph of the "Keeling Curve," the instrumental record of the measurement of the concentration of carbon dioxide (CO_2) in the Earth's atmosphere at the Mauna Loa Observatory, Hawaii from 1958 (313 ppm) to 2009 (390 ppm). From figure at National Oceanic and Atmospheric Administration (NOAA) Web site: [*http://www.esh.noaa.gov/gmd/ccgg/trends/co2_data_mlo.html*].*

warming and the greenhouse effect" (Kerr, 1989, p. 1,041; Schneider, 1989). In additional testimony to the U.S. Congress in 1989, Hansen said that the "greenhouse effect" would cause "drought intensification at most middle- and low-latitude land areas" (Kerr, 1989, p. 1,041).

Even before these bold statements by a senior NASA scientist, the U.S. and international scientific communities had begun to seriously address the problem of human impact on climate and on the entire Earth System. George M. Woodwell, Gordon J. MacDonald, Roger Revelle, and C. David Keeling, in a report to the U.S. Council on Environmental Quality (Woodwell and others, 1979), discussed the critical problem of the increase in concentration of CO_2 in the atmosphere and the warming of global climate. NASA led the way in the early 1980s (see also, Ward and others, 2009) by convening a workshop of 50 scientists in Woods Hole, Mass., on "Global Change: Impacts on Habitability. A Scientific Basis for Assessment" (Goody, 1982). A follow-up report by the National Aeronautics and Space Administration (1983) addressed the key science issues. The National Academy of Sciences/National Research Council also convened a workshop in 1983 on the International Geosphere–Biosphere Programme (IGBP) in order to define the constituents of a study of global change (National Research Council, 1983). In the mid-1970s, the National Research Council (1975) published a report on the topic of climate change, a precursor to the broader topic of global change. In 1986, a follow-up report addressed the initial priorities for an IGBP study, "Global Change in the Geosphere-Biosphere" (National Research Council, 1986). Frank Press, President of the National Academy of Sciences, testified in 1987 before the Senate Subcommittee on Science, Technology, and Space with reference to the IGBP:

> Clearly an effort of this scope and magnitude presents a rather awesome challenge to science and to the institutions of science. It presents, as well, a challenge to our political system. Our task is to study and come to understand

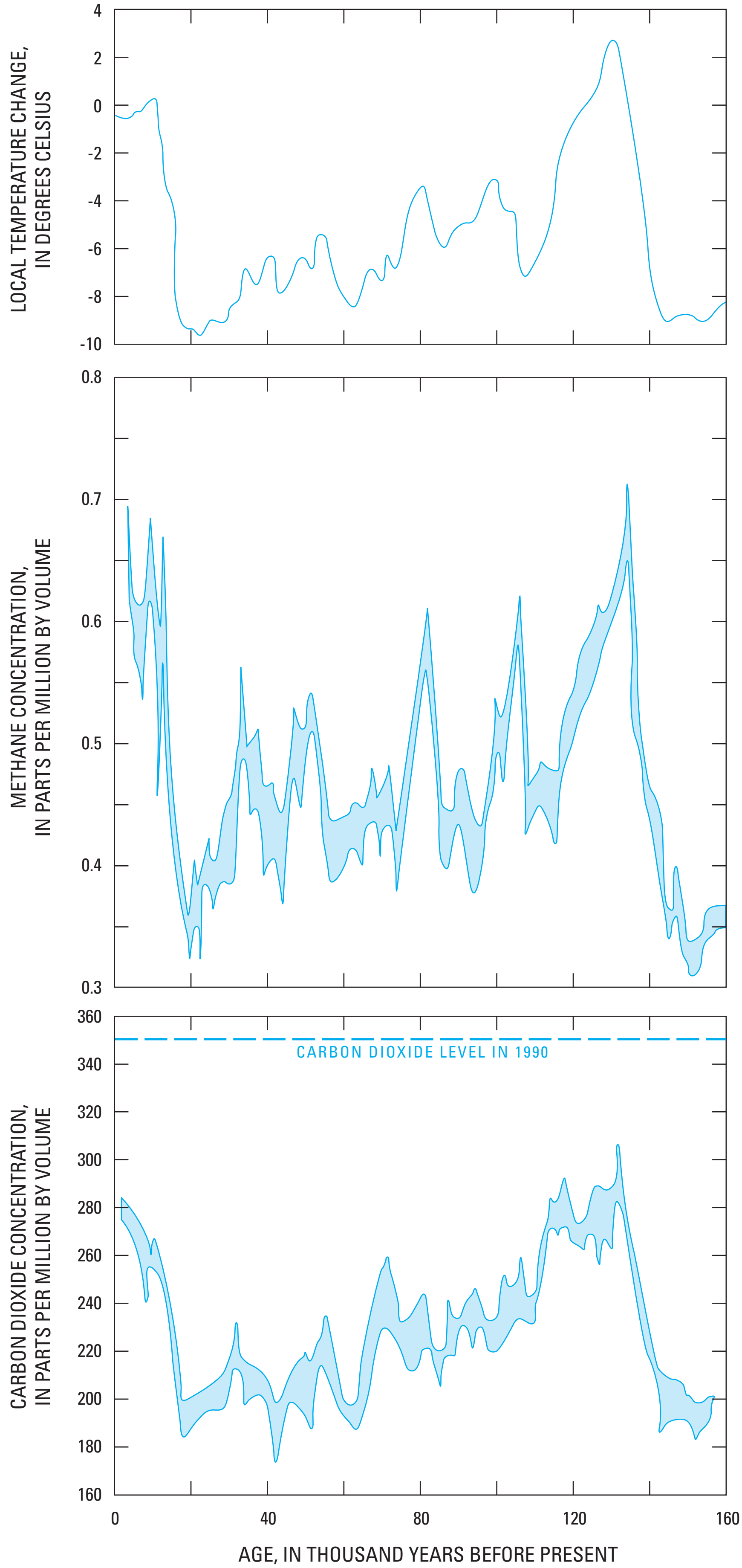

Figure 5.—*Graphs showing fluctuations of temperature, concentration of methane (CH_4), and concentration of carbon dioxide (CO_2) in ice core from Vostok, Dome "C," Antarctica for the last 160,000 years. Modified from figure 4.4 in Houghton (1997, p. 54).*

> changes in the global environment over periods of years to decades. We will need a network of satellite observations too extensive to be mounted by even the richest single nation. We will need in-situ observations and studies in the many national territories and exclusive marine zones. We will need virtually unprecedented cooperation in exchanging data. We will need to marshall freely and effectively the intellectual contributions of scientists from all countries. And we will, above all, need to maintain this effort unabated over fairly substantial time periods. This inescapable requirement or decades-long commitment to international scientific cooperation presents an unprecedented challenge to the political systems of the modern world.

In 1987, NASA published the Ride Report (Ride, 1987), "NASA Leadership and America's Future in Space: A Report to the Administration," written by a task force chaired by the astronaut Sally K. Ride, a physicist, and the first American woman to orbit the Earth. The Ride Report recommended that NASA focus the space program on four objectives:

- Mission to Planet Earth
- Exploration of the Solar System
- Outpost on the Moon
- Humans to Mars

Francis P. Bretherton, chair of NASA's Earth Systems Science Committee, was lead author of the Committee's 1988 report, "Earth System Science—A Closer View—A Program of Global Change" (Bretherton, 1988). The Special Committee for the IGBP published their report on global change (1988). Also, in 1988, Robert W. Corell, Associate Director for the Geosciences, NSF, chaired a new federal interagency, science committee, the U.S. Global Change Research Program (USGCRP), to coordinate research and budgets among seven agencies: National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Energy (DOE), USGS (U.S. Department of Interior), Environmental Protection Agency (EPA), NASA, NSF, and the U.S. Department of Agriculture. The integrated USGCRP would address research efforts in seven broad topics: climate and hydrologic systems, biogeochemical dynamics, ecological systems and dynamics, earth system history, human interactions [with the Earth System], solid-earth processes, and solar processes. The first integrated budgets of the agencies involved were submitted by the President to the U.S. Congress in FY1989; in FY1990 (prepared in July 1989), the President submitted a booklet supplementing the budget and reporting on the U.S. Global Change Research Program (U.S. Global Change Research Program, 1989). Similar reports were thereafter published each year. In 1990, the National Research Council published a report by its Committee on Global Change: "Research Strategies for the U.S. Global Change Research Program" (National Research Council, 1990). In 1992, the National Research Council (1992) published a report on the human dimensions of global environmental change. In 2001, the USGCRP addressed the importance of the global hydrologic cycle (Hornberger and others, 2001).

In May 2001, the Bush Administration requested that the National Academy of Sciences prepare a review of the 3d Assessment Report of the Intergovernmental Panel on Climate Change and recommend research priorities that would reduce uncertainties in climate-change science. The National

Academy of Sciences/National Research Council responded quickly with a report, "Climate Change Science: an Analysis of Some Key Questions" (National Research Council, 2001). Only one month later, however, on 11 June 2001, as part of a Climate Change Research Initiative (CCRI), the Bush Administration ordered a redirection of the interagency USGCRP, renaming it the "U.S. Climate Change Science Program."

The new name emphasized "Climate Change," a new research program that would focus only on one aspect (climatic processes) of the Earth System, rather than on the entire Earth System under the broader scientific and conceptual umbrella of global environmental change that the U.S. Congress had been funding (for example, the USGCRP). As early as 1988, S.I. Rasool, NASA's Chief Scientist for Global Change, had already raised the issue of the important scientific distinction between climate change and global change (Rasool, 1988). One effect of the change of name and of program emphasis was to reduce the importance of the role in global change of the activities of more than 6 billion humans, because global environmental change includes changes to the Earth System caused by deforestation, by construction of dams on major river systems, and by impact on global ecology (Southwick, 1996), a far more inclusive study than that of uncertainty about climate change science alone.

The narrowing and reorientation of the U.S. program of research in global environmental change ran counter to the study of the Earth as a holistic system. The World Meteorological Organization (WMO) and the United Nations Environment Programme had established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC was instructed to determine the magnitude of the impact of human activity on climate change. As of 2008, IPCC has published four assessment reports based on peer-reviewed scientific literature. The first Assessment Report was published in 1990 (Houghton and others, 1990) and included a "Summary for Policymakers"; an additional supplementary report was published in 1992 (Houghton and others, 1992). Three other Assessment Reports were published in 1995, 2001, and 2007. Several thousand scientists have been involved in the authorship, editing, and technical (peer) reviews of the reports written by three working groups that addressed the Physical Science Basis of Climate Change; Impacts, Adaptation, and Vulnerability; and Mitigation.

In October 2007, the Norwegian Nobel Committee awarded the 2007 Nobel Peace Prize jointly to the IPCC and to Albert [Al] Gore, Jr. (Gore, 2008) "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change." Former Vice President Gore, a journalist by profession and former U.S. Senator, had devoted much of his public service since the 1980s to informing the public and decisionmakers of the need to take action that would halt and reverse the negative impact of human beings on the Earth System. Two of his many books, "Earth in the Balance," (Gore, 1992) and "An Inconvenient Truth. The Planetary Emergency of Global Warming and What We Can Do About It" (Gore, 2006a), were efforts to improve the public understanding of the implications of global environmental change. The latter book was made into a motion picture, "An Inconvenient Truth. A Global Warming" (Gore, 2006b), which won an Oscar for "Best Documentary Feature Film" at the 80th Annual Academy Awards in February 2008.

Global Environmental Change

One goal of scientists involved in research on global environmental change is to determine the natural range of variability of the phenomena they are studying in order to determine unequivocally the point at which the observed change falls below or overshoots the expected range. David Keeling's measurements of CO_2 concentration in Earth's atmosphere at Mauna Loa, coupled with analyses of glacier-ice cores, established the fact that the atmospheric concentration of CO_2 is now [2009] 390 ppm (fig. 4), 30 percent greater than the uppermost range of its natural variability (172 to 300 ppm) (fig. 5) during the past 800,000 years.

Global environmental changes can be either natural changes in the Earth System (Williams, 1996) or changes caused by human modification of the Earth System. Climate change can be of short duration or long duration, and its onset can be slow or sudden (National Research Council, 2002). A short-duration natural change in climate, for example, atmospheric cooling, can be caused by a major explosive volcanic eruption, such as the Toba eruption in Indonesia about 70,000 years ago, the eruption of Mount Pinatubo in 1991 (Robock and Oppenheimer, 2003), or that of Tambora in Indonesia in 1815, which caused an estimated drop of 4°C globally the following year (Ward, 1989, p. 111), such a severe global impact that most crops in New England failed, and 1816 was known as "the year without a summer" (Newson, 1998, p. 24; Ward, 1989, p. 108–111). Such a natural event is an example of short-duration climate cooling, an "inevitable surprise" from the natural Earth System. Briffa and others (1998) examined the impact of numerous explosive volcanic eruptions on summer temperatures of the Northern Hemisphere from 1400 to 2000 C.E.; they found that the atmospheric cooling effect usually lasted only one year but that some impacts of the eruptions were of longer duration. These long-duration changes in climate present us with the challenge of "avoiding dangerous climate change" (Schnellnhuber and others, 2006). The annual increase in greenhouse gases drives long-duration changes and leads to a warmer climate globally, even though some changes may be less severe regionally (Intergovernmental Panel on Climate Change, 2007a).

Changes caused by human modification of the Earth System include conversion of land cover from forest to agriculture (grasslands or croplands), construction of dams on rivers, changes in the composition of the Earth's atmosphere resulting in climate change, and so on. In 1816 the Earth's human population was approaching 1 billion. In the editors' lifetimes, the global population has tripled (from 2.2 billion in 1938 to 6.8 billion in 2009), and it will probably exceed 9 billion by 2050.

There is growing concern by most natural scientists that the activities of the rapidly expanding human population (Erhlich, 1968; Ehrlich and Holdren, 1971; Bartlett, 1994; Cohen, 1995a, b; Meyer, 1996; Swerdlow, 1998; Hall and Day, 2009) are having measurably severe impacts on all of the terrestrial and marine environments of the Earth (Pimentel and others, 1997).

The impact of human population on the Earth was recognized as a cause for concern as early as the 18th century (Malthus, 1798). Hardin (1968) in "Tragedy of the Commons," a widely read paper in Science, discussed the growing problem of the increase in human population and the finite limit and (or) uneven geographic distribution of resources; Hardin later extended and updated his 1968 paper (Hardin, 1993; Kennedy, 2006). In 1975, Meadows and others (1975) presented their concerns about the limits to growth. In the decade of the 1990s, many scientists (Ehrlich and Ehrlich, 1990; Pimentel and others, 1994, 1997) and the National Geographic Society (Swerdlow, 1998) addressed the impact of population growth on food supplies, natural resources (especially water (de Souza, 1993; Pimentel and others, 1996; Rennie, 2005)), and the Earth's environment. Cohen (1995a, b) addressed the key question: How many people can the Earth support? Some scientists have suggested that the impact of human beings on the Earth System has now reached such a large magnitude that the Holocene Epoch should be said to have ended and the Anthropocene Epoch to have already begun (Steffen and others, 2004). "Anthropocene" was a term proposed by the Dutch chemist Paul Crutzen, awarded the Nobel Price for his work on depletion of ozone in the upper atmosphere (Kolbert, 2006).

Scientific Consensus on Climate Change

By 2004, a solid consensus of scientists involved in research on climate change accepted "the reality of anthropogenic climate change" (Oreskes, 2004, p. 1,686), although many scientists studying climate change and the increase in CO_2 in the Earth's atmosphere had already reached the same conclusion at least two decades earlier (Woodwell, 1978; Woodwell and others, 1979; Abrahamson, 1989). Oreskes (2004) further noted that the American Meteorological Society, the American Geophysical Union, and the American Association for the Advancement of Science had published statements supporting that conclusion. The publication of the two Arctic Climate Impact Assessment reports (Arctic Climate Impact Assessment [ACIA], 2004, 2005) established another scientific consensus of Arctic scientists: field observations and measurements and analysis of satellite data confirmed that the entire Arctic region was warming rapidly. In 2006, NOAA began to publish an annual State of the Arctic Report/Arctic Report Card (Richter-Menge and others, 2006, 2007), and Collins and others (2007) published an article to elucidate the physical science of climate change that provided additional support for the conclusion of warming in the Arctic.

Conclusions of the Arctic Climate Impact Assessment Project and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

The principal findings of the ACIA Project are (University of Alaska Fairbanks, 2004):

> In Alaska, Western Canada, and Eastern Russia average winter temperatures have increased as much as 4 to 7°F (3–4°C) in 50 years, and are projected to rise [another] 7–13°F (4–7°C) over the next 100 years.
>
> Arctic sea ice during the summer is projected to decline by at least 50 percent by the end of this century with some models showing near-complete disappearance of summer sea ice. This is very likely to have devastating consequences for some arctic animal species such as ice-living seals and for local people for whom these animals are a primary food source. At the same time, reduced sea ice extent is likely to increase marine access to some of the region's resources.
>
> Warming over Greenland will lead to substantial melting of the Greenland ice sheet, contributing to global sea-level rise at increasing rates. Over the long term, Greenland contains enough melt water to eventually raise sea level by about 23 feet (about 7 meters).
>
> In the United States, low-lying coastal states like Florida and Louisiana are particularly susceptible to rising sea levels.

> Should the Arctic Ocean become ice-free in summer, it is likely that polar bears and some seal species would be driven toward extinction.
>
> Arctic climate changes present serious challenges to the health and food security of some indigenous Peoples, challenging the survival of some cultures.
>
> Over the next 100 years, climate change is expected to accelerate, contributing to major physical, ecological, social, and economic changes, and the Assessment has documented that many of these changes have already begun.

In addition, Arctic Climate Impact Assessment (2004, p. 12–13) specifically addressed four elements of the cryosphere in the context of trends in Arctic climate:

> Melting glaciers, including the Greenland ice sheet: Glaciers throughout the Arctic are melting. The especially rapid retreat of Alaskan glaciers represents about half of the estimated loss of mass by glaciers worldwide, and the largest contribution by glacial melt to rising sea level yet measured. The area of the Greenland ice sheet that experiences some melting has increased about 16% from 1979 to 2002. The area of melting in 2002 broke all previous records.
>
> Declining snow cover: Snow cover extent has declined about 10% over the past 30 years. Additional decreases of 10–20% by the 2070s are projected, with the greatest declines in spring.
>
> Retreating summer sea ice: The average extent of sea-ice cover in summer has declined by 15–20% over the past 30 years. This decline is expected to accelerate, with the near total loss of sea ice in summer projected for late this century.
>
> Diminishing lake and river ice: Later freeze-up and earlier break-up of river and lake ice have combined to reduce the ice season by one to three weeks in some areas. The strongest trends are over North America and western Eurasia.
>
> Thawing permafrost: Permafrost has warmed by up to 2°C in recent decades, and the depth of the layer that thaws each year is increasing in many areas. Permafrost's southern limit is projected to shift northward by several hundred kilometers during this century.

The Arctic Climate Impact Assessment (2004, p. 13) also addressed the impact of melting of glaciers (including the Greenland ice sheet) in the Arctic on rising sea level and on the the coastal regions of the Arctic.

> Rising sea level: Global and arctic sea level has risen 10–20 centimeters in the past 100 years. About an additional half meter of sea-level rise (with a range of 10 to 90 cm) is projected to occur during this century. The increase in the Arctic is projected to be greater than the global average. The slope of the land and whether the coastline is rising or falling also affects the relative sea-level rise in each location.

By 2007, the scientific findings of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007a) were released to the public. As did the ACIA report, the IPCC report highlighted significant changes in all four elements of the Earth's cryosphere, especially in the Northern Hemisphere, and it too focused on rising sea level from melting of glaciers (and thermal expansion of sea water). The IPCC report on observed changes in climate and their effects on the cryosphere entitled its conclusions "Climate Change 2007: The Physical Science Basis—Summary for Policymakers" (Intergovernmental Panel on Climate Change, (2007b, p. 5–10). Here are some excerpts:

> Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.
>
> Eleven of the last twelve years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850).
>
> Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.

Average Arctic temperatures increased at almost twice the global average rate in the past 100 years. Arctic temperatures have high decadal variability, and a warm period was also observed from 1925 to 1945.

Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decreases in glaciers and ice caps have contributed to sea level rise (ice caps do not include contributions from the Greenland and Antarctic ice sheets).

Satellite data since 1978 show that annual average Arctic sea ice extent has shrunk by 2.7 [2.1 to 3.3]% per decade, with larger decreases in summer of 7.4 [5.0 to 9.8]% per decade.

Antarctic sea ice extent continues to show inter-annual variability and localized changes but no statistically significant average trends, consistent with the lack of warming reflected in atmospheric temperatures averaged across the region.

Temperatures at the top of the permafrost layer have generally increased since the 1980s in the Arctic (by up to 3°C). The maximum area covered by seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900, with a decrease in spring of up to 15%.

Global average sea level rose at an average rate of 1.8 [1.3 to 2.3] mm per year over 1961 to 2003. The rate was faster over 1993 to 2003: about 3.1 [2.4 to 3.8] mm per year [Sea level rose from a combination of steric increase in volume (due to thermal expansion) and melting of glacier ice on land.]

Paleoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 m of sea level rise.

In 2007, the United Nations Environment Programme published a comprehensive book, "Global Outlook for Ice and Snow" (Eamer, 2007). Also, in 2007, the World Climate Research Program (World Meteorological Organization) published a "Cryosphere Theme Report" (Key and others, 2007) to foster increased international cooperation in monitoring changes in the four elements of the cryosphere. Collins and others (2007) published an article to elucidate the physical science of climate change.

The IPCC Fourth Assessment Report (International Panel on Climate Change, 2007a) and Schlesinger and others' (2007) interdisciplinary study on human-induced climate change (Schlesinger and others, 2007) provided very strong evidence of the anthropogenic cause of climate change. Rosenzweig and others (2008, p. 353) concluded "that anthropogenic climate change is having a significant impact on physical and biological systems globally and in some continents." John Houghton (2008, p. 737), directly involved in the first three IPCC Reports, noted that "climate change is increasingly recognized as one of the most serious threats to humankind."

Donald Kennedy, editor-in-chief of Science, titled his editorial for a 2007 issue of Science (v. 317, no. 5837) "Climate: Game Over" (Kennedy, 2007, p. 425). Earlier in 2007, Richard A. Kerr, a journalist for "Science", referenced the IPCC Fourth Assessment Report in the title of his article, "Scientists Tell Policymakers We're All Warming the World" (Kerr, 2007, p. 754–757). Ruddiman (2008, p. 87) noted that "…scientific findings continue to confirm that we are in an unprecedented period of warming." Dessler and Parson (2006) reviewed the science and politics of global climate change, especially the "contentiousness" of the issue among nonscientists and paradoxically among many scientists in disciplines unrelated to the study of the Earth's climate, past, present, and projected future.

Changes in Sea Level with Fluctuations of the Earth's Glaciers

In the late 1990s, NASA scientists discovered that the southern part of the Greenland ice sheet was thinning (Krabill and others, 1999). An article in National Geographic (Appenzeller, 2007), with field photographs by James Balog, discussed the accelerated melting of the southern part of the Greenland ice sheet. By 2008, many scientists were focusing their field observations and (or) their analyses of satellite images and of other satellite data on the accelerated surface melting of the Greenland ice sheet (Hall and others, 2008; Perkins, 2008a; Witze, 2008; Tedesco and others, 2008). On the basis of the results of the Arctic Climate Impact Assessments' (ACIA) (2004, 2005); the record-setting reduction of sea-ice area in the Arctic Ocean in September 2007 (4.28×10^6 km^2) (NSIDC Notes, 2007; Stroeve and others, 2008)—significantly less (39 percent) than the 25-year average of approximately 7×10^6 km^2) (Parkinson and Cavalieri, this chapter); and the numerous scientific studies of accelerated melting of the Greenland ice sheet, an editorial in "Nature" (2008, p. 78) forcefully stated that "The Arctic—particularly Greenland—needs to become a major focus of research for years to come."

In the context of documented changes in the Earth's cryosphere, the greatest impacts of these fluctuations on human activity are: (1) the projected rise in sea level from melting glaciers (Warrick and others, 1993) that will: (a) inundate low-lying coastal regions, especially densely populated river deltas, such as the broad delta of the Ganges in Bangladesh, (b) submerge islands, such as the Tuamotu Archipelago of atolls in French Polynesia, and (c) penetrate coastal aquifers turning them brackish and eventually saline; and (2) melting and disappearing of glaciers in high-mountain regions, such as the Andes (Economist, The, 2007a) and the Himalaya (Barnett and others, 2005), will affect the consumption and hydropower generation of water and will cause a decline in the downstream availability of water for human use for agriculture.

Changes in the Global Hydrologic Cycle

Regional and global changes in the hydrologic cycle (fig. 1) (Huntington, Intensification of the Global Hydrologic Cycle section in this chapter; Vörösmarty and others, 2004; Stocker and Raible, 2005; Previdi and Liepert, 2008) will have the greatest impact on human beings and on other terrestrial fauna, flora, and other organisms (Rennie, 2005). Changes in precipitation (Zhang and others, 2007; Lambert and others, 2008), especially prolonged periods of drought (Kunzig, 2008; Levi, 2008; MacDonald and others, 2008), and variations in streamflow (Milly and others, 2005) will dominate, although there will be significant geographic variability.

According to Vörösmarty and others (2004), human activities are already transforming the global water system. Changes in the hydrologic cycle in the western United States during the last half of the 20th century have been well documented by Barnett and others (2008). Several scientists have concluded that water is already in crisis (Postel, 1992; Gleick, 1993). Pearce (2006) concluded that water is "the defining crisis of the twenty-first century." William E. Easterling, Dean, College of Earth and Mineral Sciences, Pennsylvania State University, stated, "Water will be in the twenty-first century what oil was in the twentieth century" (Easterling, 2008, written commun.).

The Earth System

Introduction

From the early 1970s to the beginning of the 21st century, major national and international scientific research programs were established, including the International Geosphere-Biosphere Programme (National Research Council, 1983, 1986) and the U.S. Global Change Research Program (1989) (National Research Council, 1990), to study changes in the Earth System and the growing impact of human activities on all of its components (Detwyler, 1971; Myers, 1984; Silver and DeFries, 1990; Gore, 1992; Pimentel and others, 1994; Vitousek and others, 1997; Harrison and Pearce, 2000; Klesius, 2002; Turco, 2002; Williams, 2002; Speth, 2004; Steffen and others, 2004; Cowie, 2007). These research programs, never before undertaken on such a scale, were precipitated by the development of the concept of an Earth System (fig. 1), in which the geosphere (lithosphere, atmosphere, hydrosphere, and cryosphere), the biosphere, climatic processes, the biogeochemical cycles, and the hydrologic cycle are considered to be interrelated and interactive.

The Earth System (fig. 1) has two primary components: the geosphere and the biosphere. The geosphere has four subcomponents: lithosphere (solid Earth), atmosphere (gaseous envelope), hydrosphere (liquid water), and cryosphere (frozen water); each of these subcomponents can be further subdivided into elements: for example, the oceans are an element of the hydrosphere. The biosphere (living organisms) contains about 100 phyla organized into 5 (more recently considered to be 8) kingdoms of lifeforms (Margulis and Schwartz, 1988). Human beings, belonging to the kingdom Animalia, are but one species of the estimated 20 million to 100 million species of the biosphere (Wilson, 2002a). Scientists have named only about 2 million species to date; however, an Encyclopedia of Life (EOL) Project was launched in 2008 to catalogue all living organisms on Earth. The Harvard biologist E.O. Wilson envisioned this ambitious effort, which uses the World Wide Web (Internet) as an interactive medium through which scientists and others contribute information about species [*http://www.eol.org*].

Human beings are in constant interaction with the Earth System, the components and subcomponents of which follow the fundamental principles of physics, chemistry, biology, and geology. These principles can be construed as functioning in terms of processes, including climate processes, and of cycles, including biogeochemical cycles and the global hydrologic cycle. In 2009, human beings numbered 6.8 billion worldwide, currently increasing annually by approximately 80 million, and projected to reach a total of approximately 9 billion by 2050, according to the U.S. Census Bureau [*http://www.census.gov/ipc/www/idb*]. Human societies have technological capabilities for altering all aspects of the Earth System directly or indirectly, and human use of renewable and nonrenewable resources that are sustained by climatic processes, biogeochemical cycles and the hydrologic cycle, puts us in seemingly inevitable competition with all other organisms. Figure 1 is a schematic view of the Earth System modified somewhat from a conceptual model developed by Dixon Butler at NASA in the early stages of its Earth Observing System (EOS) Program.

The natural variability of components and elements of the Earth System can be determined only by establishing long time-series records of key variables. A time series may be established by direct field observations and measurements of phenomena or processes (for example, by sampling concentrations of CO_2 in the Earth's atmosphere (fig. 4)) or by indirect measurements (for example by analyzing images from airborne and (or) satellite remote sensing of the area of glaciers, or through analysis of records of past climates). Analyses of cores from glaciers have enabled glaciologists to directly measure the composition of the atmosphere as it existed during the last several hundred thousand years (figs. 4, 5) giving scientists an unambiguous distinction between natural variability of the atmosphere and the variability caused by human activity.

Establishment of baseline records of key variables that provide unambiguous indicators of climate and environmental change is also important, such as the project that the USGS has undertaken with glaciers. In collaboration with more than 100 scientists, USGS scientists have used Landsat Multispectral Scanner (MSS) images to establish a 10-year (1972–1981) global baseline of the areal extent of glaciers in all of the Earth's glacierized regions (Williams and Ferrigno, 2007). The existing Landsat image database, other existing satellite-image databases, laser-profilometer data from ICESat, gravity data from the tandem GRACE satellites, and future satellites with a suite of different sensors provide scientists the opportunity for establishing global baseline records of other key variables that are amenable to monitoring and measurement with satellite remote sensing instruments.

Terrestrial and marine sediments, glacier-ice cores, and tree rings, among other elements of the Earth System, contain direct or (proxy) indirect records of climates and environments in the geologic past, climates that were warmer (Pliocene Epoch) and cooler (Pleistocene Epoch) than during the present Holocene Epoch. Establishing the range of natural variability of key environmental and climate indicators also requires careful deciphering and analysis of the geologic record.

To say that all parts of the Earth System are interactive and interrelated is to say that change in one will likely result in change in one or more others (Williams, 1996). This is the basis for concern that present day global warming is likely to lead to rapid change in the Earth System (National Research Council, 2002), with consequences that are now unpredictable and with a magnitude that is now unknown. The world's most knowledgeable earth scientists are now convinced that global warming is caused primarily by the continuing increase in carbon dioxide (CO_2) in the Earth's atmosphere, now (2009) at 390 parts per million (ppm) and currently increasing at the rate of 2 ppm a^{-1}, which is 30 percent higher than the maximum range of natural variability during the last 800,000 years. A glacial interval has a minimum carbon dioxide concentration of approximately 172 ppm; an interglacial interval, such as that the Earth is currently in, has a maximum of approximately 300 ppm. The range of natural variability is based on analyses of glacier ice-cores from Antarctica and of instrumental records, beginning in 1958, on Mauna Loa, Hawaii, by the atmospheric chemist C. David Keeling (fig. 4). The most recent report by Working Group 1 (The Physical Science Basis) of the Intergovernmental Panel on Climate Change (2007a) concluded, with a high level of scientific confidence, that the warming of the atmosphere, the warming of the upper layers of the oceans (hydrosphere), the accelerated melting of glacier ice in the cryosphere and the concomitant rise in global sea level (an interaction between the hydrosphere and cryosphere through the hydrologic cycle) are caused primarily by the increase in CO_2 and other "greenhouse gases" (interaction of atmosphere and biogeochemical cycles). Will the global warming that causes changes in one or more components and subcomponents of the Earth System be a smooth or an abrupt change, a slow and steady change, or sudden change (National Research Council, 2002; Climate Change Science Program, 2008)? In 2001, the USGCRP had published a scientific plan for future research on the global hydrologic cycle (Hornberger and others, 2001). Cook and others (2008) concluded that significant impact from global warming is likely to be an alteration in the hydrologic cycle: changes in regional patterns of precipitation (for example, regions of prolonged drought); changes in availability of fresh water to human beings and to other organisms; and reduction in volume of glacier ice, the meltwater from which will be added to the ocean, resulting in a more rapid rise in sea level (Steffen and others, 2008). The sea level is currently rising at 3 to 4 mm a^{-1} (Intergovernmental Panel on Climate Change, 2007c).

The color photograph of the Earth (fig. 3) permits the components of the Earth System (fig. 2), the four subcomponents of the geosphere: lithosphere (deserts in northern and southern Africa and in the Middle East, two diverging tectonic plates along the Red Sea), hydrosphere (oceans and lakes), atmosphere (clouds), and cryosphere (Antarctica and its continent-wide cover of glacier ice, the largest of the two remaining ice sheets on Earth); and the biosphere (tropical rainforest in central Africa around the Congo River basin) to be "visualized". The presence of water throughout the Earth System in its three phases (solid, liquid, and gas) makes the Earth unique among all the planets and moons in the Solar System. On the Earth, water appears as a gas in the form of water vapor in the atmosphere; as liquid water in the hydrosphere (oceans; lakes, rivers, and groundwater aquifers), lithosphere (soil), and biosphere (organisms); and as frozen water in the cryosphere. There is a dynamic hydrologic cycle in the Earth System. Because water covers 70 percent of the Earth's surface, Planet Earth would better be called "Planet Water."

Geosphere

The geosphere contains four interactive components: lithosphere, atmosphere, hydrosphere, and cryosphere, each of which is further divided into elements. The lithosphere, 4.6 billion years old, was the first component of the Earth System to form by condensation of particulates from the solar nebula and by accretion of planetoids and other solid objects. Next to form was the atmosphere, the composition of which has changed, and continues to change, over geologic time. The hydrosphere formed next. Only when the Earth became cool enough, with high mountain ranges and (or) continental plates in the high-latitude (polar) regions, did a cryosphere form.

Lithosphere

The lithosphere is the solid Earth, from its surface to its core. From a human perspective, the lithosphere is the dynamic surface of the Earth that is continually changing in response to natural processes taking place in the geosphere and the biosphere. Volcanic activity modifies the Earth's surface by covering it with lava flows and by depositing tephra (ash and other airborne particulates). Explosive volcanic activity can also depress temperatures in the atmosphere worldwide for a year or more (Robock and Oppenheimer, 2003), as happened after the Mount Pinatubo eruption in 1991. The eruption of Tambora (in Indonesia) in 1815 caused a pronounced global cooling. The following summer, crops in New England failed, and snow fell during the summer months (Strothers, 1984; Ward, 1989; Newson, 1998), so that 1816 was known as "the year without a summer."

Severe storms, such as tornadoes and hurricanes (typhoons), are natural processes that occur on or near the Earth's surface and cause irreparable damage. River floods can cause severe erosion and deposition of sediment along flood plains. Glaciers slowly erode and modify the Earth's surface, eventually depositing vast amounts of sediment downstream from their termini. Earthquakes can either uplift or depress the Earth's surface in limited regions. When earthquakes occur on the sea floor, they (and submarine landslides and volcanic eruptions) often cause seismic sea waves called tsunamis, which can flood coastal regions.

Human beings have made, and continue to make, profound changes on the Earth's surface through small- and large-scale engineering projects, including building roads, constructing malls and buildings, and conducting mining operations (Hooke, 2000). In 2004, the area of impervious surfaces (paved roads, parking lots, buildings) in the United States was 112,610 km^2, slightly smaller than the area covered by the State of Ohio (116,534 km^2) (Elvidge and others, 2004). Erosion of fertile topsoil is another impact from agricultural activities (Pimentel and others, 1995). Soil is being eroded from croplands faster than natural soil-forming processes can replace the loss: 2.5 cm (1 in) of soil requires 200 to 1,000 years to form, but it can be lost in a decade. In the United States, the loss is 17 times faster than natural restoration (Pimentel and others, 1995). If the soil and other sediments that have been eroded are not deposited in reservoirs behind dams, they are transported downstream into the ocean (Syvitski and others, 2005). Fifty percent of Iowa's fertile topsoil has been washed away during the past 150 years, requiring more use of nitrogen fertilizers to sustain productivity (Pimentel and others, 1995). According to the Agency for Toxic Substances and Disease Registry, more than 33,000 hazardous waste sites that contaminate soil and water resources have been identified in the United States [*http://www.cdc.gov/mmwr/preview/mmwrhtml/00016025.html*] .

Atmosphere

The Earth's atmosphere contains about 78 percent nitrogen, 21 percent oxygen, and 0.93 percent argon; the remaining 0.07 percent is made up of 0.04 percent carbon dioxide (CO_2), methane (CH_4), and other gaseous compounds. The amount of water vapor is variable but generally averages about 1 percent. Water vapor, CO_2, and CH_4 are the principal naturally occurring "greenhouse gases." These greenhouse gases maintain an average global temperature at the surface (15°C) that makes Earth far warmer than would be expected considering its distance from the Sun. Water-vapor content in the atmosphere column varies seasonally and regionally; CO_2 and CH_4 have varied over geologic time by processes not yet completely understood.

From analyses of ice cores extracted from the Antarctica and Greenland ice sheets, we know that both CO_2 and CH_4 were reduced in the atmosphere (to about 172 ppm for CO_2) during ice age temperature minima. During interglacials, atmospheric concentrations of CO_2 and CH_4 increased (to about 300 ppm for CO_2) (fig. 5). The concentration of CO_2 in the atmosphere at the start of the Industrial Revolution (ca. 1750) was 280 ppm. In 2009, the concentration of CO_2 is 390 ppm, about 39 percent higher than at the start of the industrial revolution. The 2009 concentration is also 30 percent higher than the 300 ppm recently measured in a 3.2-km-long ice core from Vostok and EPICA "Dome C" in Antarctica that recorded CO_2 in the atmosphere for the past 800,000 years. About 670,000 years ago, a low concentration of 172 ppm was recorded during a period of 3,000 years (Lüthi and others, 2008; Perkins, 2008b). Analysis of the same ice core from Antarctica indicates that during the past 800,000 years, CH_4 varied between 350 parts per billion (ppb) during glacials and 800 ppb during interglacials. In 2005, the concentration of CH_4 in the Earth's atmosphere was 1,770 ppb (Loulergue and others, 2008). The current (2009) concentration of CH_4 exceeds the natural level by more than 120 percent. Brook and others (2008) discuss the potential for abrupt changes in CH_4.

Human activities are producing changes in the Earth's atmosphere; the introduction of aerosols, soot, and other microscopic particles from industrial operations and from power generation alter the amount of solar energy that reaches the Earth's surface. The airborne particles and aerosols are suspected as the cause for the increase in respiratory problems in older people and for the increase in cases of asthma (Fennelly, 1979). The current quantities of "greenhouse" gases (carbon dioxide, methane, nitrous oxides) that enter the atmosphere upset the Earth's dynamic equilibrium. Climate warming is one signal of this disequilibrium. Twenty years ago many scientists recognized the negative implications of global environmental change (Malone and Roederer, 1985; Mungall and McLaren, 1991) and of global warming (Abrahamson, 1989; Kerr, 1989); the number of scientists that have continued to do so since then have increased to the point of reaching consensus (Houghton, 1997; Oreskes, 2004).

Hydrosphere

The hydrosphere (liquid water) and the dynamic hydrologic cycle are unique subcomponents of the Earth System. The hydrosphere consists of four elements: oceans; surface water: lakes, rivers, and streams; soil moisture; and groundwater. Earth is the "Water Planet."

The largest reservoir of water on our planet is the oceans, which contain 97 percent of the total volume. Glaciers contain 2.15 percent. Rivers and lakes, soil moisture, and groundwater constitute only 1 percent of Earth's water (see table 2, p. 404, in Williams and Hall, 1993, and table 1) Dynamic ocean currents transport energy, nutrients, and marine organisms throughout the water that covers nearly three-quarters of the surface of the Earth. Marine organisms are also transported and dispersed by humans intentionally and unintentionally, such as in the ballast tanks of ships (Ruiz and others, 2000).

The current (2009) human population of 6.8 billion is now consuming about 50 percent of the freshwater resources of the Earth (Raven and others, 1998). Reports of water shortages worldwide are increasing (Postel, 1992; deSouza, 1993; Gleick, 1993). Large engineering projects, such as China's Three Gorges Dam, have dammed almost all of the Earth's major rivers, forming large reservoirs for generation of hydroelectric power and for water supplies and irrigation. Globally, more than 45,000 large dams have been constructed (Klesius, 2002); such dams trap sediment, reduce water volume and velocity downstream, and are barriers to migrating fish, such as salmon, which, in the absence of fish ladders, can no longer reach upstream tributaries to spawn. Many agricultural regions, such as the Great Plains of the United States, depend on large withdrawals of groundwater, so groundwater tables are declining in these regions. Meltwater from glaciers is an important source of water for generating hydropower (in Switzerland, Norway, and Iceland, for example) and for human consumption downstream from glaciers in high mountain areas, such as the Himalaya and the Andes.

Because of the vital importance of water to meet human needs (personal, industrial, and agricultural), surface water and groundwater are heavily impacted by human activities (Hornberger and others, 2001; Intergovernmental Panel on Climate Change, 2007c). Water quality is degraded when surface runoff contains chemicals such as agricultural herbicides and pesticides, fertilizers, animal wastes from feedlots, mining waste, and airborne deposition of heavy metals from powerplants; and water is depleted in quantity, especially from deep groundwater aquifers in arid and semiarid regions, by diversion and damming of river systems, dredging of harbors and navigable waterways, and so on. Runoff transports into the ocean the agricultural chemicals in river systems, such as the Mississippi–Atchafalaya River Basin. Nitrogen and phosphorus reduce oxygen in marine waters of the Gulf of Mexico, creating seasonally recurring zones of hypoxia ("dead zones") (Boesch and others, 2009).Wetlands (hydrosphere and biosphere) have been markedly reduced in areal extent worldwide. Two rivers that were formerly tributaries to the Aral Sea in central Asia have been diverted in order to support cotton production. The Aral Sea has shrunk so much in area and volume that it no longer is one of the Earth's largest lakes, according to the National Geographic Society (2005). Once the Earth's fourth largest lake, it now ranks tenth (Kotlyakov, 1991; Pearce, 2006; Micklin and Aladin, 2008).

Cryosphere

The cryosphere (fig. 2) is frozen water (ice). The four elements of the cryosphere are glaciers, snow, floating ice on the sea and on lakes and rivers, and frozen ground (permafrost). Ice is part of the hydrologic cycle that remains sequestered (stored) until it melts, except for loss due to sublimation (change in phase from solid to gas without going through a liquid state). The cryosphere is a dynamic part of the Earth System (pl. 1) and is highly sensitive to global and seasonal changes in temperature when the temperature of Earth's surface becomes greater than 0°C. Today the cryosphere is located primarily in high latitudes (polar regions) or on high mountains where the annual mean temperature is low enough to permit the ice to persist from year to year. The temperate regions sustain ice during the winter months in the form of snow, lake ice and river ice, and frozen ground, but such ice disappears by spring or early summer. At higher latitudes and on high mountains, snow pack can persist from one year to the next if the summers are cool. Over time, glaciers form or expand during prolonged cool periods. During the last 100 years most non-ice-sheet glaciers have been in recession (retreating), and some glaciers that appeared on old maps no longer exist (Sigurðsson and Williams, 2008). Polar sea ice expands significantly during the winter months and shrinks during the summertime, so there are great annual changes in the ice-covered area of polar seas. Permanently frozen ground (permafrost) exists as areas of discontinuous (southern margin) and continuous permafrost over the northern polar regions in North America, at high elevations in Asia, in other areas such as islands in the Arctic and Antarctic, and in the higher elevations of the Andes.

Glaciers are the dominant component of the cryosphere, waxing and waning throughout the history of Earth in response to changes in global climate, latitudinal position of the continents, and latitudinal position and elevation of mountain ranges. Glaciers can modify the Earth's surface through erosion and deposition of a variety of landforms (Williams, 1986). At present, glaciers cover 15.8 million square kilometers (km^2) of Earth's land surface, and the volume of ice they contain is 33 million cubic kilometers (km^3) (see table 1, p. 403, in Williams and Hall, 1993; and table 2 in Part A–2 (Glaciers) of this chapter). The water that comprises glacier ice is derived from the oceans. About 75 m (245 ft) of potential global sea-level rise is stored as glacier ice on land. When the latest glacial was at its maximum, about 20,000 years ago, sea level was 125 m lower than it is today (Fairbanks, 1989).

The Antarctic and Greenland ice sheets and the colder temperatures produced in continental air masses in polar regions have a profound effect on the Earth System. They create conditions for global climate processes through exchange of energy between the polar and the tropical regions via atmospheric and oceanic circulation (Hornberger and others, 2001).

The human impact on the cryosphere is indirect. Human activities have contributed to global warming, especially warmer and longer summers, and that in turn is responsible for the observed global reduction in area and volume of the smaller non-ice sheet glaciers, especially tropical glaciers (Gramling, 2007), for hastening the seasonal reduction in area and thickness of sea ice in the Arctic Ocean, for reducing the amount and seasonal duration of snowfall (shorter winters), and for accelerating the melting of permafrost (Brown and Romanovsky, 2008; Economist, The, 2009). Human activities are also responsible for the second most important source of global warming: emissions of black carbon and other aerosols into the atmosphere have increased the melting of snow pack, glaciers, and Arctic sea ice by deposition of black carbon (Alley, 2007; McConnell and others, 2007; Ramanathan and Carmichael, 2008). Scientists continue to find evidence that human modification of the global climate is closely correlated with warming of the polar regions (Intergovernmental Panel on Climate Change, 2007a, b; Gillett and others, 2008; Monaghan and Bromwich, 2008).

Biosphere

Biologists estimate that 3.6 to 100 million marine and terrestrial species constitute the biosphere of the Earth today (Wilson, 2002a, p. 14). They further categorize these approximately 100 phyla into five kingdoms: single-celled prokaryotes; nucleated single-celled eukaryotes; and the three multicellular kingdoms (fungi, plants, and animals) (Margulis and Schwartz, 1988). The present profusion of life on Earth began with simple, single-celled organisms about 3.75 billion years ago (Leakey and Lewin, 1995, p. 15). A great diversity of marine life developed by about 600 million years ago. The Earth's flora and fauna have undergone divergent evolutionary paths and five major extinction episodes since multicellular life first appeared. Leakey and

Lewin (1995) cite the current rate at which species are going extinct as the "Sixth Extinction." Extinction means that a species is gone forever (fig. 6). Species diversity in the biosphere has a definite geologic and geographic bias (MacArthur and Wilson, 1967; Wilson, 1992; Swerdlow, 1999a, b). For example, there are more tree species in 10 hectares of a tropical rain forest in Borneo than in the entire North American temperate and subarctic forests. Restriction of species to a specific geographic location (endemism) is related to prolonged geographic isolation, as in the case of the diverse marsupial fauna of Australia or of the unusual flora and fauna of Madagascar. Biologists can in part explain the present-day geographic distribution of terrestrial flora and fauna and the degree of endemism that each biogeographic province represents through their dispersal by migration or through the seemingly capricious movement of crustal plates. Other factors include past changes in sea level, in episodes of mountain building, and in changes in regional climate, among others.

The biosphere is at greatest risk from human activities (Myers, 1999; Williams, 2000a, b, 2002; Walther and others, 2002; Wilson, 2002a, b; Root and others, 2003; Novacek, 2007; Rosenzweig and others, 2008); overharvesting of selected marine (fish stocks) and terrestrial (old-growth forests) species in turn also impact other species that depend on ecosystems in equilibrium (Cowie, 2007). Alteration of habitat, especially fragmentation into smaller and smaller areas of once continuous tropical rainforests or specialized ecosystems, and the introduction of a diverse mix of chemicals into ecosystems, such as the artificial hormones, antibiotics, and pesticides that organisms ingest (Vitousek and others, 1997), also cause great risk. Doney (2006) discussed the impact of changes in pH in ocean water ("ocean acidification") on the capability of organisms, such as foraminifera, to form tests (calcareous shells). Ships transport marine microorganisms (Ruiz and others, 2000) and other marine organisms between ports in ballast water.

Rachel Carson was one of the first scientists to recognize the negative impact of pesticides on bird fauna, especially the thinning of eggshells in many species of raptors (eagles, hawks, osprey) (Carson, 1962). Birds still remain among the most negatively impacted species on Earth. Young (1994) reviewed the status of 10,000 different species of birds, concluding that 1,600 species are threatened with extinction and that 5,000 species are in decline

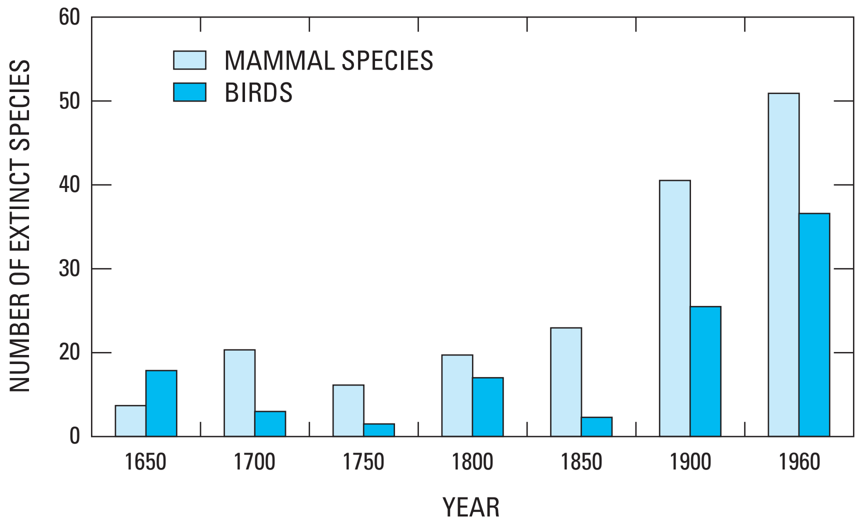

Figure 6.—*Global rates of extinction for birds and mammals during 1650 to 1960. From Figure 3.51 in Steffen and others (2004, p. 118).*

(fig. 6). The International Union for Conservation of Nature (IUCN) issued an updated "Red List" [The IUCN Red List of Threatened Species; see *http://www.iucnredlist.org/*] of threatened species in 2008, with particular emphasis on mammals, terrestrial and marine. Out of a total of 5,487 known species of mammals, scientists studied 4,651 species and found that 1,139 (nearly 25 percent) are under the threat of extinction. At least 76 species of mammals have become extinct since 1500 (Schipper and others, 2008).

Unlike extinction, which means "gone forever," extirpation of a species means that it has been eliminated from parts of its natural geographic distribution but is still present in restricted areas. Geographic areas such as isolated oceanic islands have a high percentage of endemic species present only in that limited area. Such species are at the greatest risk of extinction. Hawaii, the Galápagos Islands, and Madagascar have high endemism of their flora and fauna, all of which have adapted to specialized ecological niches. This specialization makes them exceptionally vulnerable to extinction when human activity introduces alien (nonnative) species from other geographic areas (Office of Technology Assessment, 1993; Stevens, 1993; Vitousek and others, 1996; Westbrooks, 1998; Pimentel and others, 2000; Pimentel, 2002).

Earth System Processes and Cycles

The interactive components and subcomponents of the Earth System follow the fundamental principles of physics, chemistry, biology, and geology, which include processes, such as climate processes, and cycles, such as biogeochemical cycles and the global hydrologic cycle.

Climate Processes

Climate processes are exceptionally dynamic, interacting with all of the components and subcomponents of the Earth System and with the Earth's hydrologic cycle and biogeochemical cycles. The Sun is the dominant source of energy for climate processes in the Earth's atmosphere and hydrosphere (liquid water). The amount of energy that the Earth's atmosphere, hydrosphere, and lithosphere receive varies latitudinally throughout the year because of the tilt of the Earth's axis and the seasonal change in tilt of the Northern and Southern Hemispheres (away from the Sun in the Northern Hemisphere in winter and toward the Sun in the Northern Hemisphere in summer).

The atmosphere and the hydrosphere (oceans) are interactively coupled to produce the great variability in climates worldwide. The latitudinal redistribution of solar energy from the equatorial to the polar regions and the rotation of the Earth on its axis are the source of the zonal circulation of the atmosphere, the movement north (and south) of tropical air masses and the movement south (and north) of polar air masses, the formation of storms along frontal boundaries between these latter two, the formation of hurricanes, and the circulation of warm and cold currents in the oceans.

The composition of the Earth's atmosphere, especially the percentage of "greenhouse gases" [for example, water vapor (including cloud cover), CO_2, CH_4, and so on]; the effect of the Antarctic and Greenland ice sheets (cryosphere) on ocean and atmospheric temperature; amount of seasonal snow cover and sea ice (cryosphere), which changes the albedo (reflectivity) of the Earth's surface [oceans (hydrosphere) and land (lithosphere)]; change in output of energy from the Sun; change in vegetative cover (biosphere) resulting from deforestation (change in albedo); and increased production of methane (CH_4) from the increase in area covered by rice paddies (biosphere) can all contribute to change in climate. Some changes in climate are natural, such as the "Little Ice Age," which occurred from about the early 1400s to the late 1800s, when the Earth's glaciers (cryosphere) advanced worldwide (Grove, 1988). The coldest interval during the "Little Ice Age" coincided with the "Maunder Minimum," from 1645 to 1715, when sunspot activity was minimal, suggesting that a decrease in solar energy had also occurred (Hammond, 1976).

Human impact on climate processes is both direct and indirect. As the climate becomes warmer, largely due to the increase in carbon dioxide and methane in the atmosphere (Intergovernmental Panel on Climate Change, 2007a), tropical air masses and oceans are expected to generate more intense storms (Elsner and others, 2008) when cold and drier high-pressure systems come in contact with hot and more humid high-pressure systems along frontal boundaries (because of the greater temperature differential, giving rise to more intense low-pressure traveling cyclones, thunderstorms, and tornadoes). Such conditions may also generate more intense hurricanes (Webster and others, 2005; Mann and Emmanuel, 2006; Trenberth, 2007; Elsner and others, 2008; Mooney, 2008). More events of high-intensity rainfall would produce more frequent and more severe floods.

Biogeochemical Cycles

"Biogeochemical cycles" refer to the movement of elements and molecules through the Earth System as a consequence of the interactions among organisms (biosphere) and the geosphere (lithosphere, atmosphere, hydrosphere, and cryosphere), which involve various chemical and geochemical processes. The study of complex biogeochemical cycles is critically important to achieving a better understanding of human impact on the Earth System. Many types of biogeochemical cycles move through the geosphere and biosphere at various rates and volumes and have various resident times in the components and subcomponents of the Earth System. They include carbon (C) (Houghton, 2003; Sundquist and Visser, 2003), nitrogen (N) (Galloway, 2003; Gruber and Galloway, 2008), sulphur (S) (Brimblecome, 2003), phosphorus (P) (Ruttenberg, 2003), and oxygen (O) cycles (Petsch, 2003) among others.

The biogeochemical cycle most in the news is the carbon (C) cycle, especially the movement of CO_2 through the Earth System. Carbon is of course present in all lifeforms, past and present. From a geological perspective, it is sequestered (stored) in coal deposits, hydrocarbons (oil and natural gas), and in vegetation, soils, and lacustrine (lake) and sea-floor sediments in the form of carbonates, such as $CaCO_3$ (Sundquist and Visser, 2003). Carbon is either moving through or sequestered in various components and subcomponents of the Earth System and, under natural conditions, is in dynamic equilibrium (Houghton, 2003). Carbon dioxide is not currently in equilibrium in the Earth's atmosphere because of human activities (Woodwell and others, 1978). Deforestation and burning of forests, coal, oil, and gas are releasing more CO_2 into the atmosphere than vegetation (biosphere) is removing and than soil (lithosphere) and the oceans (hydrosphere) are absorbing. Concurrent warming of the oceans decreases the capacity of water to absorb CO_2, further upsetting what was the dynamic equilibrium that existed before the beginning of the industrial era in the late 1700s. Carbon dioxide in the atmosphere is now 30 percent higher than its natural atmospheric variability of 172 ppm (0.00172 percent) during glacials ("Ice Ages") and its natural atmospheric variability of 300 ppm during interglacials, such as the current one (fig. 4).

Human activities are directly impacting the principal biogeochemical cycles—carbon, nitrogen, sulphur, and phosphorus—all of which are normally in dynamic equilibrium with the other subcomponents of the geosphere (except the cryosphere) and the biosphere. During the past 200 years, large amounts of CO_2 and CH_4 have been accumulating in the Earth's atmosphere. Carbon dioxide continues to increase at 2 ppm a^{-1} (Perkins, 2008) and so is on track to exceed 400 ppm by 2015. The high production of ammonium fertilizers has caused the amount of nitrogen entering the nitrogen cycle to rival the natural production of nitrogen in the Earth System (Kinzig and Socolow, 1994; Smil, 1997; Capone and others, 2006; Galloway and others, 2008). The most visible signs of this overload of nitrogen are contaminated groundwater and eutrophication of lakes and coastal bays, thereby diminishing the biodiversity in such ecosystems; contamination of surface water by runoff from animal feedlots (Galloway and others, 2008); and deposition from the atmosphere into the Earth's oceans (Duce and others, 2008).

Hydrologic Cycle

Of all the Earth cycles and processes that constantly interact with the Earth System, the most important to human beings, other fauna, flora, and other organisms is the hydrologic cycle (Jakosky, 1999) (fig. 7). The hydrologic cycle is the complex process through which water in its three phases (solid, liquid, vapor) moves through all components and subcomponents of the geosphere and biosphere. The physical and chemical properties of the water molecule make it unique as a substance. Physically, it has a high specific heat, meaning that it retains and loses thermal energy slowly. The movement of water through the Earth System also transports and releases energy: as water changes its phase from solid to liquid, from liquid to gas, and from solid to gas (sublimate), its thermal energy is stored (endothermic); changes in phase in the opposite direction release energy (exothermic).

The hydrologic cycle transports liquid water (after oceans and lakes evaporate it and after it is precipitated on land as rain or snow) by runoff of surface water (rivers and streams); by subsurface movement of groundwater (subsurface aquifers); by movement of water through animals, plants (evapotranspiration), and other organisms, and thus through the soil; it stores water in reservoirs of the ocean, rivers, and lakes and sequesters it in glaciers (cryosphere). The oceans contain 97 percent of the Earth's water, and glaciers store 2.15 percent. Therefore, only 1 percent of the Earth's water remains for surface water, ground water, soil moisture, and so on. Only 1 percent of the Earth's water sustains most lifeforms on the Earth (table 1).

The long-term exchange of glacier ice with the oceans determines global (eustatic) sea level. In response to variations in the volume of glacier ice on the continents, sea level has repeatedly risen and fallen within a range of about 200 m between glacials and interglacials (fig. 8). Approximately 20,000 years ago, for example, sea level was about 125 m lower than at present. If all of the present glacier ice were to melt, sea level would rise an additional 75 m. During

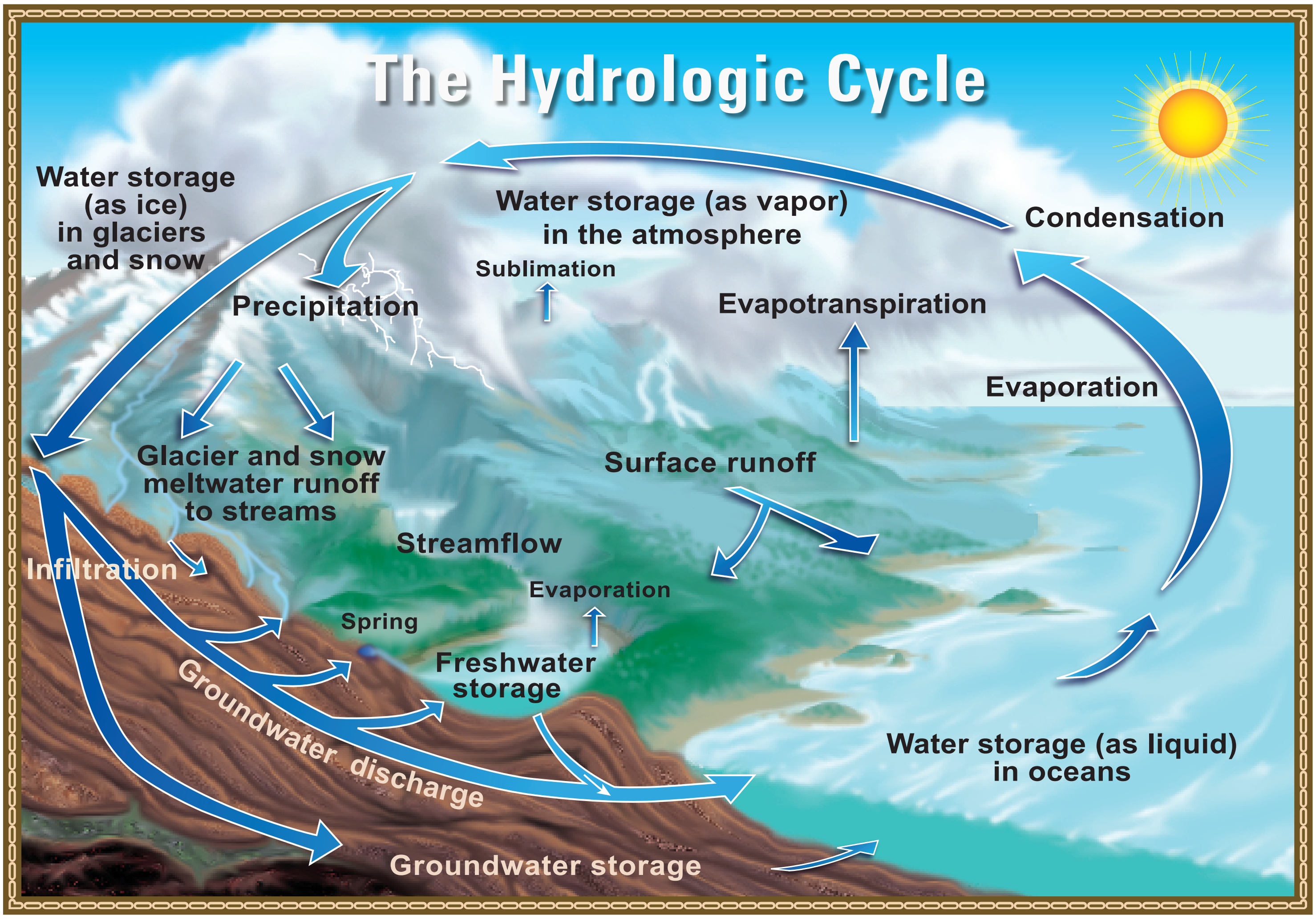

*__Figure 7.__—Conceptual diagram of the hydrologic cycle modified from U.S. Geological Survey Web site: [*http://ga.water.usgs.gov/edu/watercycle.html*].*

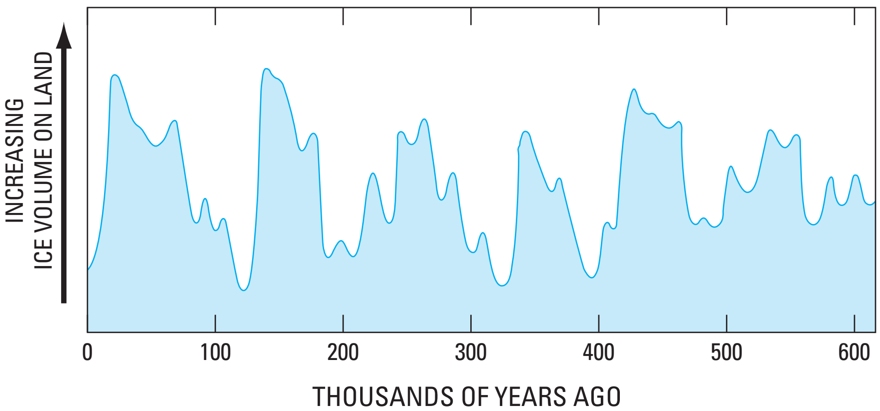

__Figure 8.__—Graph showing fluctuation in glacier ice volume on the Earth's land areas during the last 600,000 years [through six glacials (lower sea levels) and interglacials (higher sea levels)]. Maximum volume of glacier ice on land drops sea level approximately -125 m below today's sea level; minimum volume of glacier ice on land, with maximum carbon dioxide concentrations in the Earth's atmosphere of about 280 ppm, raises sea level approximately 6 to 7 m. Modified from figure in Houghton (1997, p. 55)

the 20th century, eustatic sea level rose at the rate of about 0.3 m per century. Under conditions of global warming, an acceleration in the melting of glaciers can be expected. The result would be a rise in global sea level.

Human impact on the hydrologic cycle is indirect through climate processes, but it is direct through altering the flow volume (discharge) of rivers, in altering the area of lakes (Aral Sea and Lake Chad, for example) and of wetlands, in increasing the depth of the groundwater table, in decreasing soil moisture, and in increasing evaporation and evapotranspiration from plants. All these changes occur through elements of the hydrosphere. The change in the volume of glacier ice is indirect (global warming). The loss in volume of glaciers through accelerated melting will cause a transfer from one reservoir of the hydrologic cycle (glacier ice) to another reservoir (oceans), producing a rise in global sea level. For human beings who live on islands, deltas, and low-lying coastal plains, the rise in sea level is of growing concern (Hansen, 2004).

Figure 9 shows the areas of the Pacific, Atlantic, Arctic, and Indian Oceans and of the Southern Ocean around the continent of Antarctica, and it shows the areas of the 11 seas (total 361,491,000 km^2). Figure 9 also shows the area of large continents (geologically large "islands") and small islands (total 148,647,000 km^2) on the Earth's surface, the total area of which at present is 510,066,000 km^2 (National Geographic, 2005, p. 136). Today, in short, 29.1 percent of the Earth's surface is land, and 70.9 percent is water (pl. 1). During a glacial interval, maximum glacier ice is on land. The lower sea level significantly changes the entire ratio of land area (37 percent of Earth's surface) to ocean area (63 percent of Earth's surface) (pl. 1). If no glacier ice were on land, the land area would shrink to 25 percent and the area of the oceans would increase to 75 percent (pl. 1). During the last interglacial interval (about 130,000 years B.P.), much of the Greenland ice sheet melted (Koerner, 1989). Glacier ice was nevertheless present at the higher elevations of Greenland, because glaciologists have found marine isotope stage (MIS) 5e ice (dating from approximately 119,000 to 124,000 years B.P.) and even MIS 6 ice (from approximately 130,000 to 190,000 years B.P.) in ice cores obtained from drilling at the summit of the Greenland ice sheet, even though disturbed stratigraphy characterizes the lowermost 10 percent of the ice core (Landais and others, 2003). Such a loss of glacier ice in Greenland would contribute to a rise in sea level of at least 6 m (Williams and Hall, 1993).

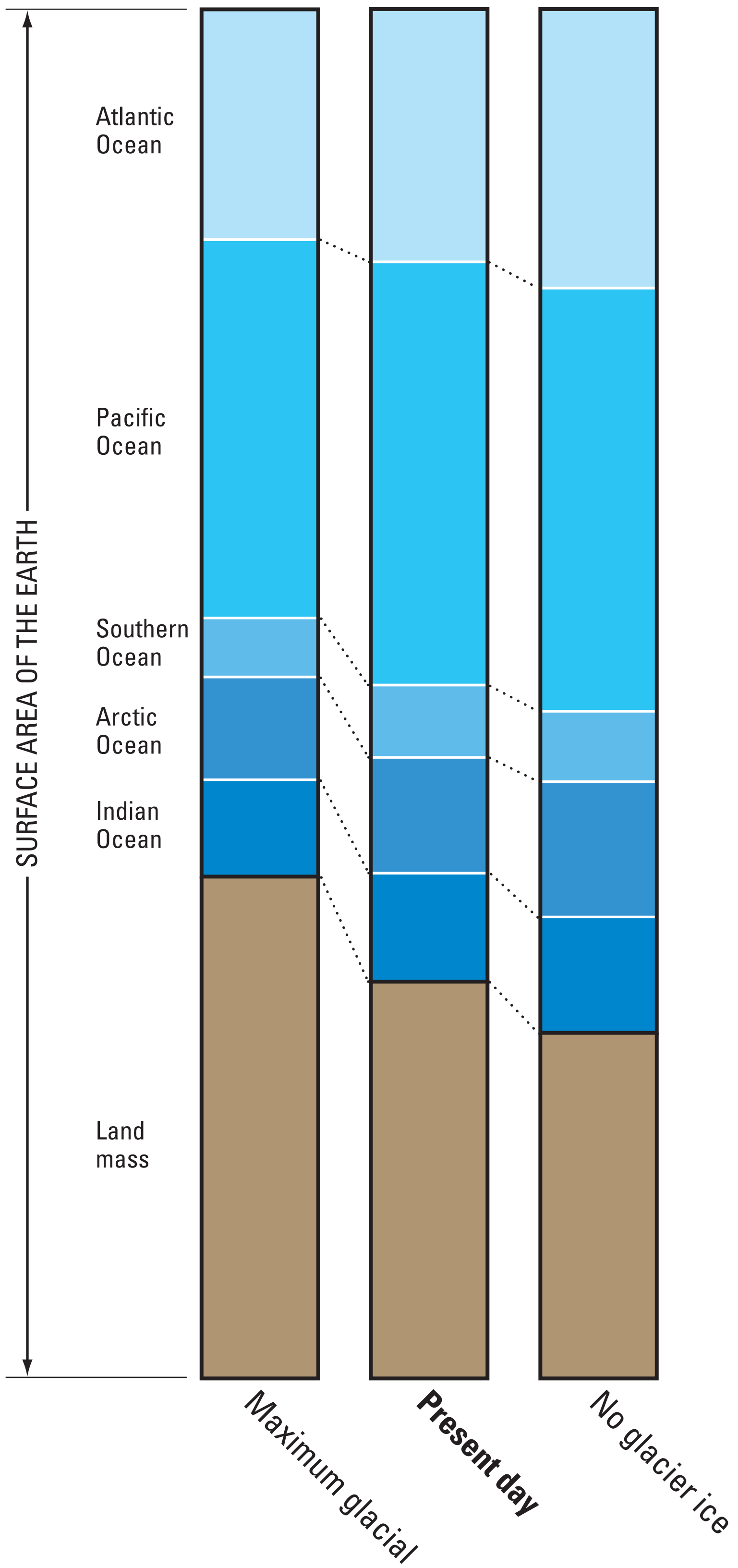

Figure 9.—*Three bar graphs showing percentages of land mass versus 5 major oceans at maximum glacial (land, about 37 percent), present day (land, 29.1 percent), and no glacier ice on land (land, about 25 percent). Between maximum glacier ice on land and no glacier ice on Earth, the land area fluctuates between 37 percent and, 25 percent, respectively.*

Intensification of the Global Hydrologic Cycle, *by* Thomas G. Huntington

Abstract

Among the more important questions in hydrology are whether there will be an intensification of the hydrologic cycle if the climate warms in the future; and, if so, what the nature of that intensification will be. Considerable interest in these questions arises because an intensification of the hydrologic cycle would likely lead to changes in the availability of water resources; an increase in the frequency and intensity of tropical storms, floods, droughts, and other extreme events; and an amplification of warming through feedback from water vapor. This section briefly reviews the current state of science regarding historical trends in hydrologic variables, including precipitation, runoff, tropospheric water vapor, soil moisture, glacier mass balance, evaporation, evapotranspiration, and length of the growing season. Although data are often spatially and temporally incomplete and regional analyses are varied and sometimes contradictory, the preponderance of evidence supports the hypothesis of an ongoing intensification of the hydrologic cycle. In contrast to these trends, however, the empirical evidence to date does not consistently support an increase in the frequency or intensity of extreme events during the period of observational record.

Introduction

There is a general consensus that evaporation and precipitation will likely increase if global climate warming continues. Such increases form the basis of the hypothesis that one of the major consequences will be that the global hydrologic cycle intensifies (or accelerates) (DelGenio and others, 1991; Loaiciga and others, 1996; Trenberth, 1999; Held and Soden, 2000, 2006; Arnell and others, 2001). It is well established that surface air temperature and precipitation over land increased during the 20th century (Folland and others, 2001; Alexander and others, 2006; Trenberth and others, 2007; Wentz and others, 2007). Results from recent simulations with ocean atmosphere models based on the Intergovernmental Panel on Climate Change (IPCC) IS92A midrange emission scenario (Legget and others, 1992) indicate that global mean temperature of surface air will increase 2.3°C, and that global mean precipitation, evaporation, and runoff will increase 5.2 percent, 5.2 percent, and 7.3 percent, respectively, by the middle of the 21st century (Wetherald and Manabe, 2002). Other climate models also predict increase in global precipitation and evaporation in the 21st century (Boer and others, 2000; Dai and others, 2001).

Because global temperature increased considerably over the 20th century, especially since the 1970s (Jones and Moberg, 2003), it is reasonable to ask whether trends in hydrologic variables and related indicators are consistent with an intensified global hydrologic cycle during that period. Consistency among indicator variables would greatly strengthen confidence in projections of the potential vulnerability of water resources that future climate warming could cause. Some aspects of an intensified hydrologic cycle pose potential threats to at-risk populations. More frequent occurrence of extreme events such as major tropical storms, floods, and droughts can affect human welfare directly through catastrophic damage or indirectly through adverse effects on crop productivity. Such threats are likely to occur disproportionately in developing countries that have the fewest resources for mitigating them and for adapting to their consequences (Arnell and others, 2001; Manabe and others, 2004).

Several lines of evidence can be used to assess the hypothesis of a warming-induced intensification of the global hydrologic cycle. The analyses of trends that this section reviews were done at differing spatial and temporal scales that are not directly comparable among studies or variables. In spite of these limitations, synthesizing the results from numerous studies can provide insight into how the global hydrologic cycle responded to past increases in temperature and how it may respond to future such increases. The purpose of this brief review of the evidence from time-series analyses of several hydro-climatic variables is to assess whether systematic changes in these variables occurred in the 20th century. Some of this information was summarized in the IPCC Third and Fourth Assessment Reports (McCarthy and others, 2001; Trenberth and others, 2007) and in Huntington (2006), but many more recent reports are now available that, taken together, provide a more comprehensive picture. IPCC reports include analysis of changes in precipitation, stream runoff, frequency and intensity of extreme events, atmospheric water vapor, cloudiness, pan evaporation, and soil moisture. Newly published insights address hydrologic and climatic change from a global perspective (Bates and others, 2008), including continental runoff, changes in ocean salinity, El Niño Southern Oscillation (ENSO), glacier mass balance, evaporation, and evapo-transpiration (ET). In addition, a growing body of research on hydrologic and phenological indicators confirms that the length of the growing season increased substantially during the 20th century, suggesting that hydrologic change has affected ET, at least in humid regions.

Trends in Hydrologic Variables

Precipitation

On a globally averaged basis, precipitation over land (excluding Antarctica) is estimated to have increased by 9 to 24 mm (1–3 percent) during the 20th century (Dai and others, 1997; Hulme and others, 1998; New and others, 2000). Another recent global study of land area during the period 1901 to 2003 found increases in maximum amounts of 1- and 5-day precipitation and in the number of very wet days (Alexander and others, 2006).

Regional variations are highly significant. For example, zonally averaged precipitation increased by 7 to 12 percent between lat 30° and 85° N. compared with a 2-percent increase between lat 0° and 55° S., and it has decreased substantially in some regions (Folland and others, 2001; Trenberth and others, 2007). Groisman and others (2004) reported increases in precipitation over the conterminous United States during the 20th century, with most of the increase confined to spring, summer, and fall. Increases in precipitation have been reported for most of China (Ye and others, 2004; Liu and others, 2005). Brown (2000) found systematic increases in winter (December through February) snow water equivalent over North America, averaging 3.9 percent per decade from 1915 to 1992. Increases in winter snow accumulation were also reported in Russia from lat 60° to 70° N. and from long 30° to 40° E. during 1936 to 1983 (Ye and others, 1998); Canada, north of approximately lat 55° N. (Karl and others, 1993; Zhang, Hogg, and Mekis, 2001); Greenland (Johannessen and others, 2005; Thomas and others, 2006); and, from 1992 to 2002, in East Antarctica (Zwally and others, 2005). Ye and others (1998) estimated snow water equivalent from measured snow depth using a ratio of 10:1 for snow volume to water volume. The large increases in snow depth (4.7 percent per decade) and the relatively small sensitivity to temperature of the ratio suggest that any error in using a fixed ratio would not alter the results significantly (Ye and others, 1998). Furthermore, the fact that the observed temperature of surface air generally increased over this region during most of this period suggests that snow density likely increased, making the fixed ratio over time a conservative estimate. These reports are consistent with the Clausius-Clapeyron relationship, that increasing winter temperatures result in increased precipitation, depending on the slope of the relationship between snowfall and temperature (Davis and others, 1999).

Human activities that increase the atmospheric presence of sulfate, mineral dust, and black carbon aerosols have the potential to affect the hydrologic cycle through suppressing rainfall in polluted areas and through reducing the solar irradiance reaching the Earth's surface (Ramanathan and others, 2001; Liepert and others, 2004; Wild and others, 2004). The primary mechanism for suppressing rainfall is that aerosols increase concentrations of nuclei around which water in clouds condenses and reduce the mean size of cloud droplets, resulting in less efficient coalescence into raindrops (Ramanathan and others, 2001). These effects are thought to be responsible for drier conditions in the north and wetter conditions in the south of China (Menon and others, 2002). Aerosol-induced reduction in solar irradiance reaching the Earth's surface could reduce surface evaporation and consequently could reduce precipitation, thus damping the hydrologic cycle (Ramanathan and others, 2001; Wild and others, 2004). Under conditions of decreased evaporation over land, precipitation can increase over land only if there is a corresponding advection of moist air from the oceans to the land (Wild and others, 2004). Whether the overall effects of aerosols will be primarily a spatial redistribution of precipitation that affects only polluted areas or a more general weakening of the water cycle is uncertain. On the one hand, there is evidence that solar irradiance reaching the Earth's surface has been reduced during the last 50 years (Stanhill and Cohen, 2001), which is consistent with the potential for a damping of the water cycle. On the other hand, the evidence for increasing precipitation, evaporation, and runoff over many regions during the same time period suggests that aerosols have not resulted in a widespread detectable damping of the hydrologic cycle, at least to date. More recent analyses indicate that trends in aerosol effects on solar irradiance have reversed in recent years and that the Earth is now brightening (Wild and others, 2005), thereby reversing the damping effect of aerosols on the hydrologic cycle (Andreae and others, 2005).

The eruption of Mount Pinatubo in 1991 resulted in a large injection of sulfur dioxide into the lower stratosphere. The sulfur dioxide was oxidized to sulfate particles (aerosols) that increased atmospheric albedo and remained in the atmosphere for more than one year. The sulfate aerosols resulted in a decrease in absorbed solar radiation, air temperature, and water vapor content of the atmosphere (Soden and others, 2005; Trenberth and Smith, 2005). These changes in the Earth's radiation budget have been associated with global decreases in precipitation and continental runoff (Trenberth and Dai, 2007), indicating that cooling was associated with a dampening of the global hydrologic cycle.

Runoff

In regional studies, increases in precipitation have been associated with corresponding increases in runoff in river basins in the conterminous United States (Lins and Slack, 1999; Groisman and others, 2001; McCabe and Wolock, 2002) (fig. 10) and in some large river basins in South America (Berbery and Barros, 2002; Garcia and Mechoso, 2005). In Canada, by contrast, increasing temperature with almost no change in precipitation resulted in no change in annual streamflow from 1947 to 1996 for most regions (Zhang, Harvey, and others, 2001). One striking exception is the Winnipeg River Basin where precipitation and runoff have increased markedly (St. George, 2006). The basins studied in North America were selected because of minimal human perturbations to the hydrologic cycle. Typical criteria for selecting basins exclude basins where consumptive use, land-use changes, streamflow transfers or diversions, and (or) significant management of reservoir levels could influence flow (Slack and Landwehr, 1992; Harvey and others, 1999).

Increases in precipitation and runoff have been shown to be quite variable among different regions (Karl and Riebsame, 1989; Keim and others, 1995). Recent reports indicate increasing annual streamflow in Arctic rivers (Lammers and others, 2001; Peterson and others, 2002; McClelland and others, 2004; McBean and others, 2005) and in western Russia (Georgievskii and others, 1996) (fig. 11). Precipitation increased, snowfall decreased, and runoff decreased or did not change during the latter half of the 20th century in the Tien Shan in northern Eurasia (Aizen and others, 1997); the decrease in runoff may be associated with decreasing meltwater from receding glaciers (Aizen and others, 1997; Khromova and others, 2003). There have been no globally extensive studies on trends in streamflow from minimally affected basins. Uncertainty remains about whether increasing ET could offset increasing precipitation and the melting of ice and permafrost, ultimately resulting in decreased freshwater inputs to the Arctic Ocean (Anisimov and others, 2001).

An analysis of trends in continental runoff from major rivers worldwide from 1910 through 1975 found that runoff increased about 3 percent (Probst and Tardy, 1987). A re-analysis of these trends during 1920 to 1995 in which data were reconstructed to fill in missing records confirmed an increase in world continental runoff during the 20th century (Labat and others, 2004). Labat and others (2004, p. 631 and p. 641) conclude, "…this contribution provides the first experimental data-based evidence demonstrating the link between the global warming and the intensification of the global hydrologic cycle." In a recent global land surface modeling study, Gerten and others (2008) reported that during 1901 to 2002 global river discharge increased by 30.8 $km^3 a^{-2}$, equivalent to 7.7 percent, due primarily to increasing precipitation. In contrast to these findings, Dai and others (2009) reported no increase in global river discharge.

It is evident that temporal trends in river discharge are variable among regions and that the long-term global trend is not clearly identified (Bates and others, 2008). Human alterations, including irrigation, dam building, changes in land cover, and extraction of groundwater, affect river discharge (Vörösmarty and Sahagian, 2000) but are of minor importance on a global scale compared with precipitation and evapotranspiration (Gerten and others,

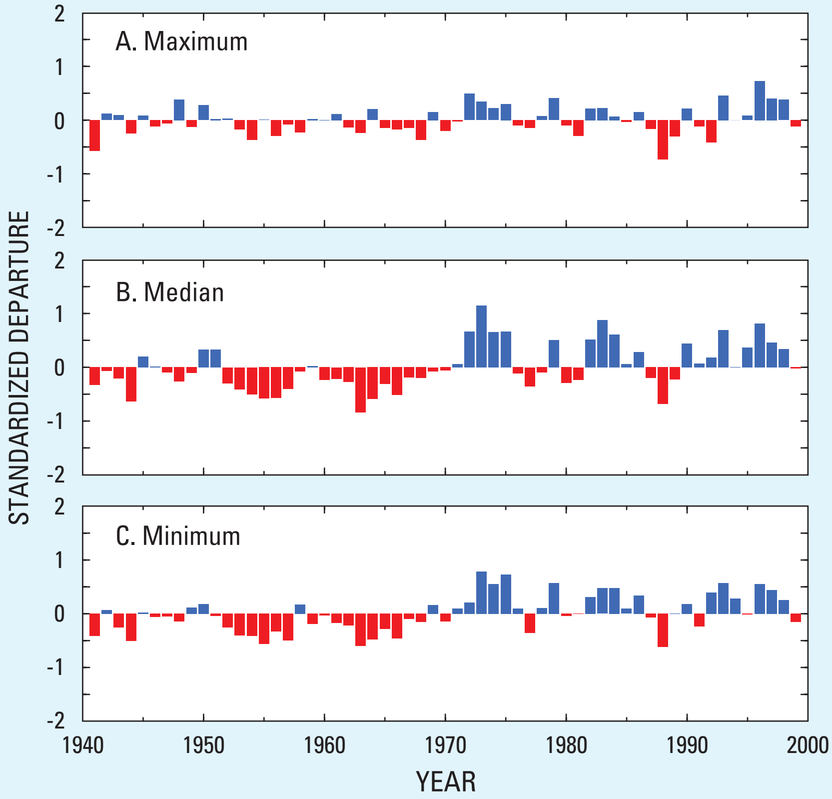

Figure 10.—*Mean standardized departures of annual maximum, median, and minimum daily streamflow for 400 sites in the conterminous United States (1941 to 1999). Modified from McCabe and Wolock (2002).*

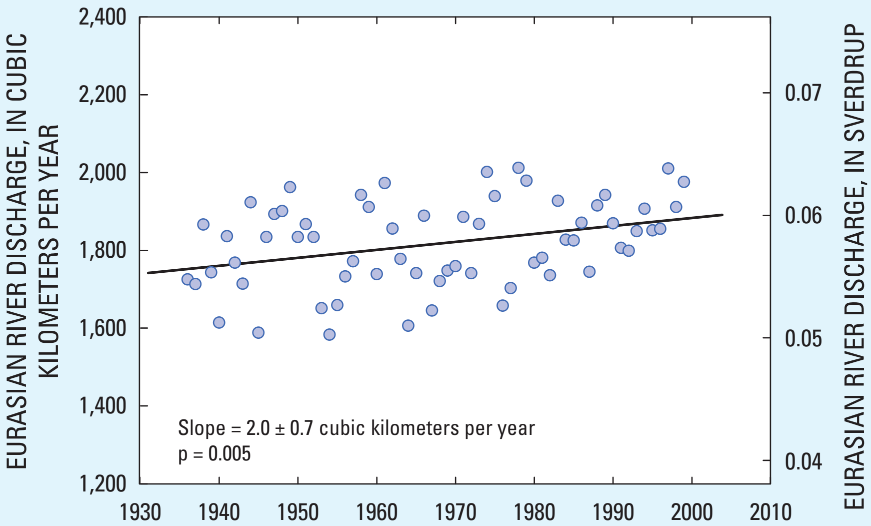

Figure 11.—*Trend in combined annual discharge from the six largest Eurasian Arctic rivers (1936 to 1999). Figure modified from Peterson and others (2002); reproduced with permission.*

2008). In some regions climate warming may cause increasing precipitation and compensating increases in evaportranspiration that result in no increase in river discharge. These increases in precipitation and evapotranspiration can contribute to an increase in the rate of precipitation recycling (Dirmeyer, and Brubaker, 2007) that itself is evidence for an intensification of the hydrologic cycle.

These results for major rivers, in conjunction with independent reports of increasing runoff from many smaller rivers in the northern hemisphere, constitute possible evidence for an intensification of the hydrologic cycle as being associated with global warming. These increases in runoff are consistent with the results of modeling studies, suggesting that runoff is likely to increase in high latitudes and in many equatorial regions but likely to decrease in the middle latitudes and in some subtropical regions as a result of differential responses to climate warming in different regions (Alcamo and others, 1997; Arnell, 1999; Manabe and others, 2004; Milly and others, 2005; Gerten and others, 2008). A modeling and observational analysis of the Arctic Ocean freshwater budget for the period 1950 through 2050 is consistent with an acceleration of the Arctic hydrological cycle: freshwater inputs to the ocean from net precipitation increased and will continue to do so, as did river runoff and net ice melt, which will also continue to do so (Holland and others, 2007). Decreases in runoff could occur as increases in evapotranspiration outweigh increases in precipitation.

Human alterations of land use, such as conversion of forest to agricultural land, may increase some proportion of runoff from rivers (Vörösmarty and Sahagian, 2000). In other cases, abandonment of agricultural land and subsequent reforestation could result in decreases in runoff. Human alterations to the hydrologic cycle can be extreme. For example, flood-prevention measures can reduce peak flows; consumptive use and evaporation from impoundments can reduce flows; and conversion of native vegetation to agricultural or developed land can decrease ET and can increase runoff. Runoff in major river basins includes the effects of both climatic variation and human alterations, making it difficult to differentiate the cause of changes in discharge in the basin. In addition, some part of the increase in runoff from river basins that contain permanent ice and snow is likely attributable to the melting of glaciers and of permafrost rather than to increased precipitation (see, for example, Kulkarni and others, 2003; McClelland and others, 2004; Yang and others, 2004). McClelland and others (2004) concluded that increasing precipitation was the most viable explanation for the increasing discharge from Arctic rivers.

The Mississippi River Basin has had well-documented increases in precipitation and runoff during the latter half of the 20th century. The mean annual discharge from the Misissippi River basin from 1949 through 1997 was 187 mm a^{-1} and during this period it increased by 0.85 mm a^{-1}, or 22 percent (Milly and Dunne, 2001). During this same time period, mean annual precipitation was 835 mm a^{-1}, an increase of 1.78 mm a^{-1}, or 10 percent (Milly and Dunne, 2001). During this same time period, mean annual evapotranspiration was 649 mm a^{-1} an increase of 0.95 mm a^{-1}, or 7 percent (Milly and Dunne, 2001). Human alterations to the hydrologic cycle in the Mississippi River Basin during the 20th century have been comparatively small, and increases in consumptive use that cause a decrease in runoff dominated them (Milly and Dunne, 2001). Two of the more significant changes in the Mississippi River Basin in the 20th century are the abandonment of cultivated farmlands and their conversion to forest or pasture, particularly in the southeastern part of the basin (Clawson, 1979; Wear and Greis, 2002), and the construction of numerous large dams. Both of these changes would have decreased runoff. Increasing precipitation and runoff in the Mississippi River Basin from 1949 through 1997 is consistent with an intensification of the global hydrologic cycle.

Increases in ET have also been inferred from another recent analysis of long-term data for the hydrologic budget in major river basins in the conterminous United States. Area-weighted average precipitation and runoff both increased during 1950 to 2000 in three large and five smaller river basins in the conterminous United States (Walter and others, 2004). Changes in storage were not measured but were considered to be minor over this period. Walter and others (2004) concluded that because precipitation increased substantially more than runoff increased, ET had likely increased at a rate of 1.04 mm a^{-1} during 1950–2000 (fig. 12). Similar analyses for the La Plata River Basin in southeastern South America are consistent with increasing ET (Berbery and Barros, 2002). The hydrologic budget for most of Canada indicates generally decreasing streamflow (Zhang and others, 2001a; Déry and others, 2005; Déry and Wood, 2005; Rood and others, 2005) but increasing or unchanged precipi-

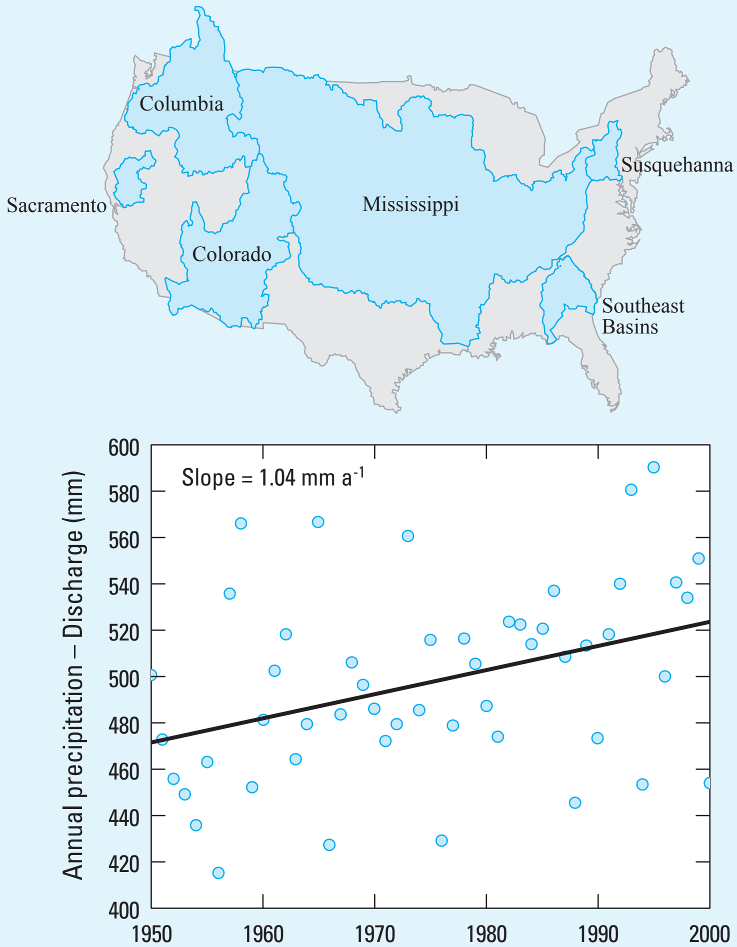

Figure 12.—*Trend (1950 to 2000) in the difference between annual precipitation and annual stream discharge for selected major river basins in the United States: Mississippi, Columbia, Colorado, Susquehanna, Sacramento, and Southeast Basins. Data were area-weighted averaged. Figure modified from Walter and others (2004); reproduced with permission. [mm, millimeters; mm a*$^{-1}$*, millimeters per year']*

tation (Zhang and others, 2000; Gagnon and Gough, 2002; McBean and others, 2005). Taken together, these analyses suggest that ET has increased over much of Canada.

Human alterations of the landscape have had large effects on trends in runoff from some river basins. Consumptive use has greatly decreased flow from some rivers, such as the Syr Darya and Amu Darya, which drain into the Aral Sea in Central Asia (Vörösmarty and Sahagian, 2000), and from the Huang He (Yellow River) in China (Chen and others, 2003). Construction of dams can have short-term effects on streamflow as reservoirs fill, and such construction has longer term effects if evaporation losses are high. The net annual effects of reservoirs on the global hydrologic cycle are diminishing, however, because the rate of construction of large reservoirs has declined markedly in recent decades (Avakyan and Iakovleva, 1998).

Water Vapor

In spite of substantial regional variation in the data and uncertainty because of missing data, there is evidence for an increase in water vapor at the Earth's surface over most northern latitudes (greater than lat 30° N.), with the exception of Greenland and northeasternmost Canada, during 1975 to 1995 (New and others, 2000; Rinke and others, 2009). Dai (2006) reported trends of increasing annual mean specific humidity over the surface of the globe between lat 60° S. and lat 75° N. for 1975 to 2005. Willett and others (2008) reported increased specific humidity at the Earth's surface from lat 60° N. to lat 4° S. of 0.11 and 0.07 g kg^{-1} per decade from 1973 to 2003. Studies using radiosonde measurements have also reported increases in lower-troposphere water vapor beginning in 1973 in the Northern Hemisphere (Zhai and Eskridge, 1997; Ross and Elliot, 2001); more recently, Special Sensor Microwave Imager (SSM/I) measurements have been used to extend this record (Trenberth and others, 2005; Wentz and others, 2007), further supporting recent increases in lower troposphere water vapor content. Deficiencies in the data, large interannual and regional variations, the relatively short-term nature of the data, and the association of these trends with ENSO and sea-surface temperature suggest great caution in making inferences about long-term trends (Trenberth and others, 2005).

Minschwaner and Dessler (2004) report that recent satellite measurements also indicate trends towards increasing water vapor in the tropical (lat 20° S. to lat 20° N.) upper troposphere (UT) (above 215 mb) during 1993 to 1999 that were consistent with model predictions. However, these researchers concluded that models based on the assumption of constant relative humidity overestimate the feedback from warming-induced water vapor. Their data indicate that the relation between UT humidity and sea-surface temperature within the convective regions of the tropical oceans lies between the cases of constant mixing ratio (specific humidity) and those of constant relative humidity.

Cloudiness

Cloudiness increased from the 1940s to 1990 over many continental regions of the United States, over mid-latitude Canada, Europe, Australia, and over the former Soviet Union (Dai and others, 1999). Recent assessments, consistent with Dai and others (1999), show continuing increases in cloudiness in many continental regions of the United States, over mid-latitude Canada, western Europe, Australia, and over the former Soviet Union, but they indicate decreases in cloudiness over China, Italy, Central Europe, and possibly over certain ocean regions (Trenberth and others, 2007). Large interdecadal variability in cloud cover has been reported, including a decrease in cloud cover over global land areas (lat 60° S. to lat 75° N., but excluding the United States and Canada where cloud cover trends were increasing) from the late 1970s to the mid 1980s, followed by a gradual increase (Trenberth and others, 2007). The long-term trend remains uncertain (Folland and others, 2001). The diurnal temperature range (DTR) is strongly and inversely related to cloudiness (Dai and others, 1999) and DTR decreased over most global land areas during the latter half of the 20th century (Easterling and others, 1997). Given the strong relation between cloudiness and DTR, the long-term downward trend in DTR suggests that cloudiness increased during the same period. Increases in cloudiness that result in significant decreases in solar radiation could decrease ET and thereby damp the hydrologic cycle, thus constituting a negative feedback.

Severe Weather

Considerable emphasis has been placed on testing whether the frequency or intensity of extreme weather events (for example, hurricanes, typhoons, floods, and droughts) has changed in recent decades. "Global losses reveal rapidly rising costs due to extreme weather-related events since the 1970's" (Rosenzweig and others, 2007, p. 110). The trend is primarily attributable to increasing population and infrastructures in coastal areas exposed to natural hazards, but insurance companies and the international reinsurers that underwrite them have expressed serious concern about their potential for increased liability for claims involving weather-related natural disasters, if climate warming results in increasing frequency or intensity (or both) of severe weather (Berz, 1999). Increases in precipitation in the higher precipitation quantiles have been observed in regional studies (Dai and others, 1997; Hulme and others, 1998; Folland and others, 2001; Groisman and others, 2004; Trenberth and others, 2007). Increases in precipitation intensity with increasing mean annual surface air temperature for a fixed precipitation amount have also been reported (Karl and Trenberth, 2003).

Observed 20th-century increases in precipitation, particularly in higher precipitation quantiles (for example, Groisman and others, 2004), may have increased the frequency of flooding. However, a review of the empirical evidence to date does not consistently support an increase in the highest flow quantiles globally (Kundzewicz and others, 2005) or in the United States (Lins and Slack, 1999; Douglas and others, 2000; Vogel and others, 2001; McCabe and Wolock, 2002), Canada (Zhang and others, 2001a), Scandinavia (Hyvarinen, 2003; Lindstrom and Bergstrom, 2004), or Central Europe (Mudelsee and others, 2003; Brázdil and others, 2006). In contrast with these studies, Milly and others (2002) reported that the frequency of floods with discharges exceeding 100-year levels from 29 basins larger than 200,000 km^2 increased substantially during the 20th century. Milly and others (2002) also stated that their conclusions were tentative and that the frequency of floods having return intervals shorter than 100 years has not changed.

Several time-series analyses of tropical storms have found no evidence for an increase in frequency (Easterling and others, 2000; Folland and others, 2001; Solow and Moore, 2002; Chan and Liu, 2004; Elsner and others, 2004; Vecchi and Knutson, 2008; Landsea and others, 2010), intensity (Free and others, 2004), or duration of the storm season (Balling and Cerveny, 2003) during the 20th century. Yet, other recent analyses have reported increases in storm frequency and intensity. For example, Emanuel (2005) reported increasing destructiveness of tropical cyclones in recent decades. Webster and others (2005) evaluated data on the intensity of tropical cyclones and on the number of tropical cyclones and cyclone days during the past 35 years; they found a large increase in the number and proportion of hurricanes reaching categories 4 and 5 on the Saffir-Simpson scale, the categories of which range from 1 (least intense) to 5 (most intense). Hoyos and others (2006) showed that the trend of increasing numbers of category 4 and 5 hurricanes for 1970 to 2004 is directly linked to the global trend in rising sea-surface temperature. Klotzbach (2006) recently analyzed trends in global tropical cyclone activity during 1986 to 2005 and reported a positive upward trend in tropical cyclone intensity and longevity for the North Atlantic basin and a considerable negative downward trend for the Northeast Pacific but no net trend in global activity. Curry and others (2006) reviewed the evidence for a linkage between climate warming, increasing sea-surface temperature, and an increase in hurricane intensity; they reported substantial evidence to support the hypothesis that warming has resulted in increasing sea-surface temperature and that the number of more intense hurricanes has increased since 1970. The state of science on this issue might be best summarized by the World Meteorological Organization's "Summary Statement on Tropical Cyclones and Climate Change" released in December 2006: "Though there is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone record to date, no firm conclusion can be made on this point." [*http://www.wmo.ch/pages/prog/avep/tmrp/documents/iwtc_summary.pdf*]

From 1900 to 1995, large, multiyear-to-decadal variations in the percentage of land area undergoing severe drought or receiving surplus moisture were observed; however, secular trends were small (Dai and others, 1998). After the late 1970s, the combined percentage of areas with severe drought or moisture surplus expanded, resulting from increased extent of either the drought area (for example, in the Sahel, eastern Asia, and southern Africa) or of both drought and wet areas (for example, in the United States and Europe) (Dai and others, 1998, 2004). For a given value of ENSO intensity, the response in areas affected by drought or by excessive wetness was more extreme after 1970 (Dai and others, 1998). The frequency of average-strength ENSO events appears to have increased during 1877 to 1999, and it also appears to be positively related to surface air temperature (Hunt, 1999; Herbert and Dixon, 2002). In a global analysis, Dai and others (2004) concluded that the proportion of the land surface characterized as "very dry" (Palmer Drought Severity Index (PDSI) <3.0) has more than doubled since the 1970s and that global "very wet" areas (PDSI >3.0) has declined slightly since the 1970s. An increase in the proportion of land area in drought since the 1970s is also reported by Burke and others (2006). These changes are highly variable among regions and are attributed to both ENSO-induced decreases in precipitation and warming-induced increases in evaporation; however, the changes are consistent with increasing risk of more frequent and more intense drought over some regions (Dai and others, 2004).

Soil-moisture content increased during the last several decades in parts of Eurasia (Robock and others, 2000) and in much of the continental United States during the 20th century (Andreadis and Lettenmaier, 2006). Recently, Sheffield and Wood (2008) reported a weak increase in global soil moisture for the period 1950 to 2000. This upward trend has occurred simultaneously with an upward temperature trend that would otherwise (in the absence of increased rainfall) be expected to decrease soil moisture. In this case, increases in precipitation are thought to have more than compensated for increased losses due to ET (Robock and others, 2000). In addition to indicating an intensification of the global hydrologic cycle directly, increases in soil moisture indicate the potential for increasing ET and, hence, for an indirect intensification of the global hydrologic cycle.

Glacier Mass

Most subpolar and mountain glaciers are declining in mass throughout the world in response to warming (Dyurgerov, 2003; Oerlemans 2005). Dyurgerov (2003) has shown that seasonal changes in mass balance of about 300 mountain and subpolar glaciers are increasing in amplitude (fig. 13),

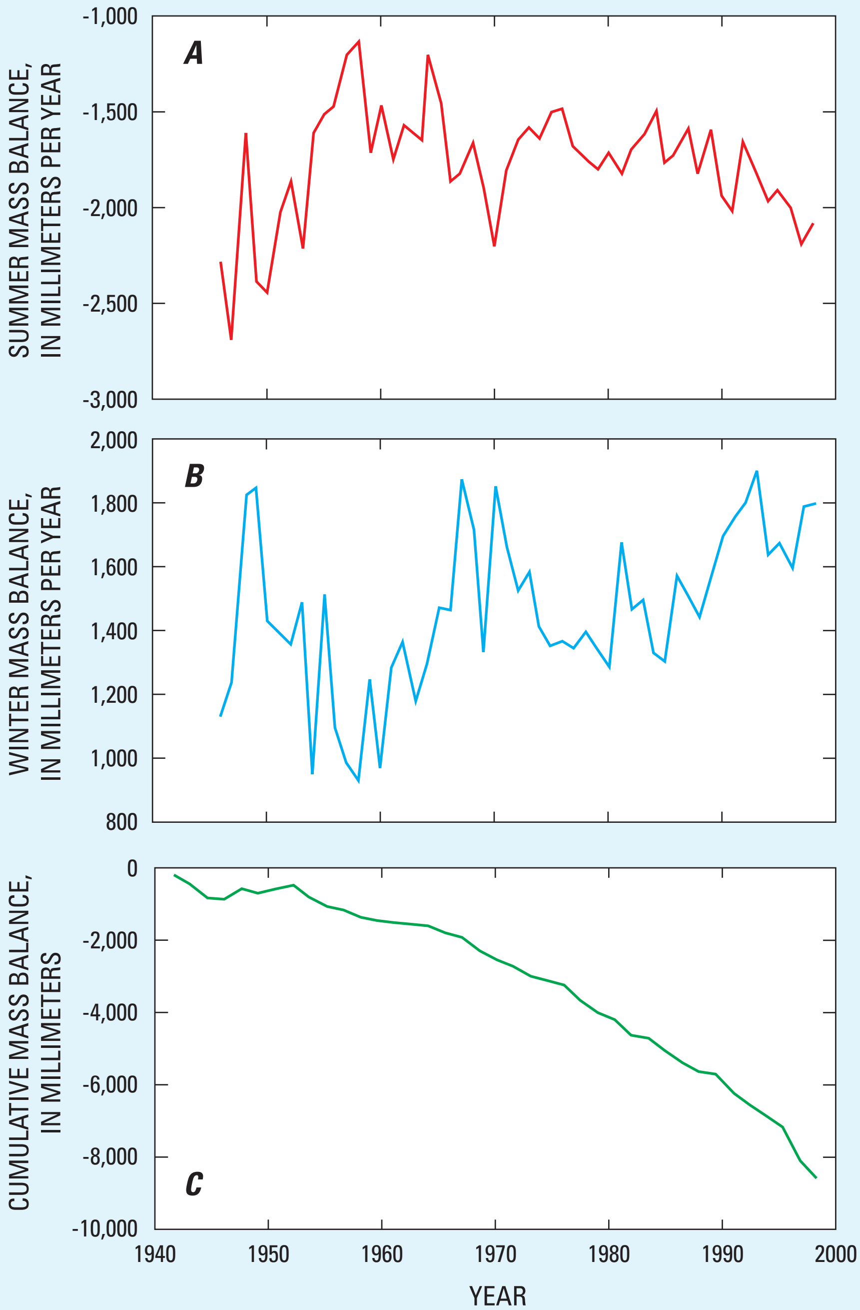

Figure 13.—*Trend in seasonal [**A**, summer; **B**, winter] and [**C**] cumulative mass balances for about 300 mountain and subpolar glaciers, not including the Greenland and Antarctica ice sheets. Figure based on Dyurgerov (2003).*

providing further evidence for a recent intensification of the global hydrologic cycle. Summer decreases in glacier mass balance are related to increasing air temperatures, and wintertime increases in glacier mass balance are related to increases in snowfall (Dyurgerov, 2003). The combination of these seasonal changes in glacier mass balance indicates that, under the current climatic regime, the rates of glacier melting and of snow accumulation on glaciers have increased.

Trends in Evaporation and Evapotranspiration

Evaporation and evapotranspiration (ET) are central to the global hydrologic cycle, and long-term measurements of their annual rates would be excellent indicators of the intensity of the global hydrologic cycle. Both parameters, however, are difficult to measure: to date, only a few dozen sites monitor ET in the world, and the period of record is quite short. Evidence for likely sensitivity of forests to lengthening of the growing season can be seen in the eddy covariance EUROFLUX data (Aubinet and others, 2002) and FLUXNET data (Law and others, 2002). The leaf-initiation date in beech was a significant variable in explaining interannual variability in net ecosystem exchange of CO_2 (Aubinet and others, 2002). FLUXNET data are generally consistent with a positive relation between growing-season temperature and actual ET (measured as net exchange of water vapor) (Law and others, 2002). Other indirect approaches for estimating evaporation and ET, or variables directly related to ET, can provide insight into the likely trends in these variables.

Decreases in pan evaporation have been observed over most of the United States and the former Soviet Union between 1950 and 1990 (Peterson and others, 1995). Such decreases are generally thought to be inconsistent with observed trends toward increasing temperature and precipitation. Taken together, these trends offer an "evaporation paradox" (Brutsaert and Parlange, 1998). Several analyses have indicated, however, that decreasing pan evaporation is consistent with increasing surface warming and an acceleration of the global hydrologic cycle (Brutsaert and Parlange, 1998; Golubev and others, 2001; Roderick and Farquhar, 2002; Brutsaert, 2006). Various mechanisms have been suggested to explain the apparent paradox. For example, it has been suggested that decreases in solar irradiance (resulting from increasing cloud cover and increasing concentrations of aerosols) and decreases in diurnal temperature range would cause the observed decrease in pan evaporation (Peterson and others, 1995; Roderick and Farquhar, 2002). Brutsaert and Parlange (1998) concluded that increasing concentration of water vapor resulting from a warming-induced increasing ET would inhibit pan evaporation. Golubev and others (2001) reported trends in increasing ET (measured empirically by means of massive weighing lysimeter data) and in decreasing pan evaporation during the period following World War II to 1990 at most sites in the former Soviet Union, where long-term data were available. Golubev and others (2001) concluded that the observed opposing trends supported the mechanism proposed by Brutsaert and Parlange (1998). The issue of whether trends in pan evaporation indicate an intensification of the global hydrologic cycle is not fully resolved (Ohmura and Wild, 2002), but the analyses of Brutsaert and Parlange (1998), Golubev and others (2001), and Brutsaert (2006) support an increase in ET.

Possible trends in evaporation over the oceans and their relation to precipitation and runoff have been addressed indirectly by use of salinity time-series data. Salinity in the upper 500- to 1,000-m depth increased significantly between 1955 to 1969 and 1985 to 1999 along a transect in the western basin of the Atlantic Ocean at latitudes between lat 40° N. and lat 20° S. (Curry and others, 2003) (fig. 14). Curry and others (2003) also reported systematic freshening poleward of these latitudes. The salinity increase was spatially coherent with measured warming of the sea surface. For lat 24° N. (the salinity maximum), the evaporation-minus-precipitation (E–P) anomaly averaged 5 cm a^{-1} during the 40-year period. The increase in E–P could be a result of either (1) an increase in evaporation with a decrease or no change in precipitation or (2) an increase in precipitation with a decrease or no change in evaporation. Sea-surface warming over the same region and time period suggests an increase in net evaporation that is consistent with predictions derived from the Clausius-Clapeyron equation and with possible changes in the hydrologic cycle (Curry and others, 2003).

Increases in salinity have also been reported in some subtropical regions of the Pacific Ocean (Wong and others, 1999; Boyer and others, 2005) and in the Mediterranean Sea (Roether and others, 1996; Béthoux and others, 1998). Wong and others (1999) concluded that the salinity changes observed in the Pacific Ocean were consistent with a "strengthening" of the water cycle during an average 22-year period from the middle to late 1960s to the middle to late 1980s. Boyer and others (2005) largely confirmed the trends reported by Curry and others (2003) for the Atlantic, and they reported increasing

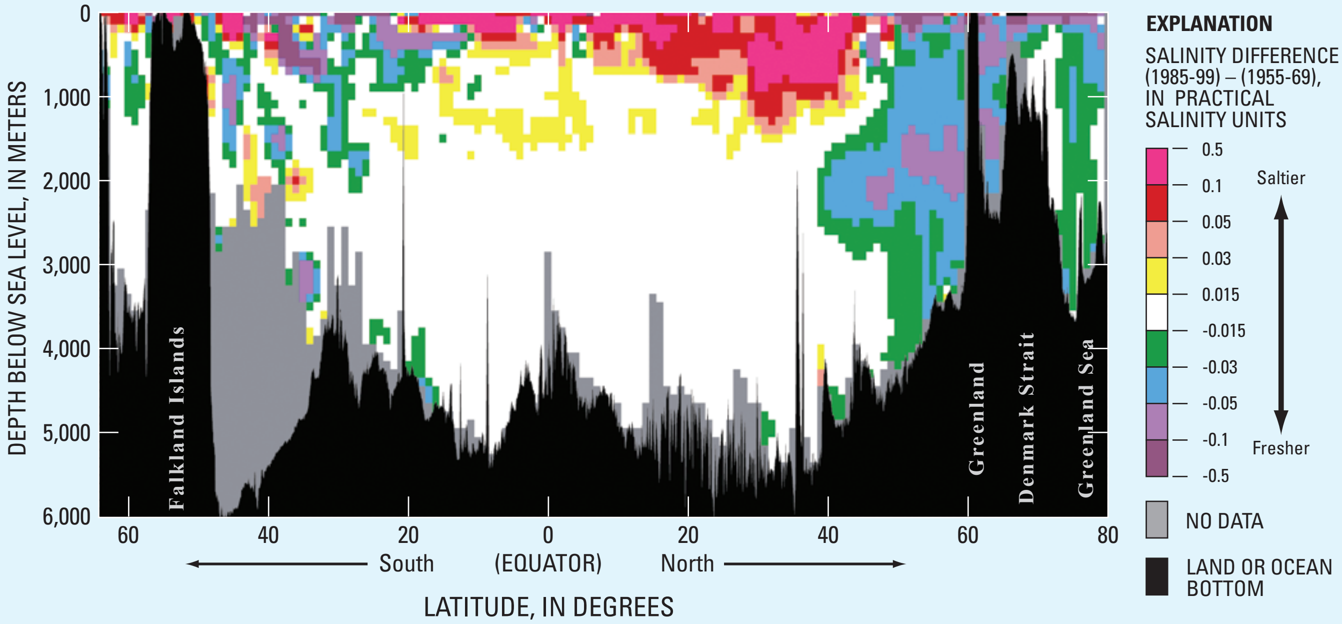

Figure 14.*—Salinity difference (1985 to 1999) minus (1955 to 1969), by depth, along a western Atlantic Ocean meridional transect from lat 80° N (Fram Strait) to lat 64° S (Antarctica). Figure based on and updated from Curry and others (2003).*

salinity for the Indian Ocean. However, the findings of Boyer and others (2005) for the Pacific Ocean contrast with those of Wong and others (1999). For the Pacific Ocean, Boyer and others (2005) found no trends in the tropics or in the Northern Hemisphere subtropics but did find evidence for increasing salinity in the Southern Hemisphere subtropics; they also found general freshening at higher latitudes. Béthoux and others (1998) attributed increases in salinity in the Mediterranean Sea to anthropogenic factors (reduced freshwater inputs and more saline inputs via the Red Sea), reductions in precipitation, and warming-induced increases in evaporation.

There is substantial evidence for a lengthening of the growing season throughout the Northern Hemisphere that is consistent with the concurrent trend in global warming. For northern temperate humid climates, the lengthening of the growing season is consistent with an overall increase in ET, because the period for active transpiration is longer and warmer (White and others, 1999). A recent increase in the length of the growing season was inferred from an advance in the timing of the spring seasonal drawdown in concentrations of atmospheric CO_2 (Myneni and others, 1997; Hicke and others, 2002; Fang and others, 2003; Zhou and others, 2003). That drawdown was coincident with an advance in the timing of the "onset of greenness" (inferred from NOAA advanced very high-resolution radiometer (AVHRR) satellite data showing the normalized difference vegetation index) in northern temperate regions (Myneni and others, 1997). Advances in the timing of many plant and animal phenological events in the Northern Hemisphere (Menzel and Fabian, 1999; Schwartz and Reiter, 2000; Walther and others, 2002; Parmesan and Yohe, 2003; Schwartz and others, 2006) strongly point to increases in length of the growing season.

Substantial increases in growing-season length have also been inferred in regional studies from temperature records (Cooter and LeDuc, 1995) and in reports of killing frosts (Baron and Smith, 1996). Fitzjarrald and others (2001) reported an advance in the timing of the spring decrease in the Bowen ratio in the eastern United States, indicating earlier leaf emergence and rapid increase in transpiration rate. Trends in high-northern-latitude freeze and thaw cycles for soil have been studied by use of satellite data from the Scanning Multichannel Microwave Radiometer and Special Sensor Microwave/Imager (Smith and others, 2004). In North America, Smith and others (2004) reported a trend toward longer growing seasons in evergreen conifer forests and in boreal tundra during 1988 to 2002. They also found earlier thaw dates in tundra and in larch biomes over Eurasia; however, trends toward earlier thaw dates in Eurasian larch forests did not lead to a increase in length of the growing season because of parallel changes in timing of the fall season (Smith and others, 2004).

Increases in growing-season length are also inferred from a variety of hydrologic and climatologic variables that are correlated with earlier spring warming: for example, earlier spring snowmelt runoff (Leith and Whitfield, 1998; Cayan and others, 2001; Zhang, Harvey, and others, 2001; Yang and others, 2002; Hodgkins and others, 2003; Cunderlik and Burn, 2004; Hodgkins and Dudley, 2006), earlier river ice-out (Dudley and Hodgkins, 2002; Huntington and others, 2003; Hodgkins and others, 2005), earlier lake ice-out (Magnuson and others, 2000; Hodgkins and others, 2002; Duguay and others, 2006), lengthening of the frost-free season (Easterling, 2002; Frich and others, 2002), and decreases in the extent of spring snow-cover across the former Soviet Union and China (Brown, 2000) and in the Swiss Alps (Scherrer and others, 2004).

Historical trends in North American snow-cover extent (SCE) are more uncertain. Long-term trends (1915–97) for North America for March and April showed increases in SCE, although the differences were not significant; but March and April SCE decreased rapidly after 1980 (Brown, 2000). Brown (2000) also reported widespread and significant trends toward earlier disappearance of snow cover throughout Canada during 1955 to 1977 and significant declines in April snow-water extent over North America during 1915 to 1997. There is also evidence that the ratio of snow to total precipitation has changed in some regions. Huntington and others (2004) showed that this ratio decreased in March in the New England region of the United States during 1949 to 2000. Knowles and others (2006) reported a decrease in this ratio in the western United States during 1949 to 2004. Karl and others (1993) reported a decrease in the ratio of snow to total precipitation for Canada south of lat 55° N. but no trend for Canada north of that latitude. Zhang and others (2000) reported an overall increase in the ratio for Canada, however, with significant downward trends occurring mostly during spring in southern Canada.

Increasing length of the growing season is the expected response to warmer air temperatures in spring and fall in temperate regions where the growing season is confined to the period when air temperatures remain above freezing. Transpiration is greatly reduced during the dormant season, and in humid regions of the eastern United States modeled ET increases as the length of the growing season increases (Eagleman, 1976). Mean annual ET, estimated from measured precipitation minus runoff, increases at a rate of about 3 cm $° C^{-1}$ in eastern North America (Huntington, 2003). Thus, if moisture is not limited, any extension of the growing season will increase total annual ET, thereby intensifying the hydrologic cycle.

Summary and Conclusions

Substantial uncertainty regarding trends in hydroclimatic variables remains because of differences among regions and in subsequent responses among variables and because of major spatial and temporal limitations in data. Quasi-decadal cycles for large-scale atmospheric circulation patterns such as the El Niño Southern Oscillation, North Atlantic Oscillation, and Pacific Decadal Oscillation complicate the interpretation of shorter term trends. Gaps in spatial coverage are large for some hydrologic indicators; therefore, trends in such areas are unknown. The risk in assuming that trends in these areas are comparable to those measured in other related areas is that the observed trends may simply represent regional redistribution rather than true global intensification. In spite of these uncertainties, the observed trends in most of the variables are consistent with an intensification of the global hydrologic cycle during part or all of the 20th century at scales of regional to global land area (table 2).

Consistency in response among multiple variables lends observational support for theoretical arguments and for predictions based on global circulation models that warming will likely result in further increases in evaporation and precipitation. The theoretical hydrologic response to a warming-induced

Table 2.—*Summary of trends in hydroclimatic variables, including primary period of record considered, and scale of trends (regional or global).*

[R, regional land area; G_f, global land area; —, insufficient data; ✓, trend of variable applies to time interval. Other sources for these data are most of the studies cited in this chapter]

Variable	20th century	Latter half of the 20th century	Predominant trend, regional or global
Precipitation	✓	varies	Uptrend (R, G_f)
Runoff	✓	✓	Uptrend (R, G_f)
Tropospheric water vapor	—	✓	Uptrend (R)
Cloudiness	—	✓	No change
Storm frequency and intensity	—	✓	No change
Floods	✓	✓	No change/uptrend (R)
Droughts	—	✓	Uptrend (R)
Soil moisture	—	✓	Uptrend (R)
Seasonal glacier mass balance	—	✓	Increasing (G_f)
Pan evaporation	—	✓	Downtrend (R)
Actual evaporation	—	✓	Uptrend (R)
Length of growing season[1]	✓	✓	Uptrend (R)
Length of growing season[2]	—	✓	Uptrend (R)

[1] Based on records of temperature or of agricultural killing frost.

[2] Based on satellite-derived normalized difference vegetation index (NDVI) often referred to as "onset of greenness."

intensification, as manifested in an increasing frequency and intensity of storms, floods, and droughts (Knutson and Tuleya, 1999; Tuleya and Knutson, 2002; Karl and Trenberth, 2003), is not consistently supported by the analyses to date. Because of the long-term intervals between returns and the stochastic nature of the occurrence of major storms, floods, and droughts, however, substantially more time may be required before a change in the frequency of these extreme events can be assessed. The lack of consistent trends in the frequency and intensity of major storms during the 20th century should not be taken as evidence that further warming will not lead to such changes in the future, particularly because the rate of warming in the 21st century is expected to be several times that in the 20th century (Meehl and others, 2007).

A critical question in understanding hydrologic response to ongoing and projected climate warming is whether evaporation, precipitation, and atmospheric water content will scale with the Clausius-Clapeyron relation, increasing by 7 percent per degree Kelvin, or at a significantly lower rate of 1–3 percent as climate models predict (Allen and Ingram, 2002). Recent satellite observations over the last two decades have suggested that the sensitivity may be closer to the Clausius-Clayeyron relation (Wentz and others, 2007).

On balance, the weight of evidence is consistent with an ongoing intensification of the global hydrologic cycle and emphasizes the need for improving our capabilities to monitor and predict the consequences of changing hydrologic regimes. Future improvements in spatial resolution and longer periods for collecting data, combined with enhanced understanding of complex feedbacks involving water, will reduce current levels of uncertainty. Primary hydrologic feedbacks include increases in atmospheric water vapor that result in more trapping of heat, changes in cloudiness and in the properties of clouds that can increase or decrease surface warming, and changes in snow cover and in surface melting of snow and ice that influence albedo and therefore the radiative balance (Abdalati and Steffen, 1997; Karl and Trenberth, 2003; Hall and others, 2004).

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Conclusions

The 21st century will be one of unprecedented changes to the Earth System because the rapidly increasing human population and its attendant activities are increasingly impacting this complex system. Anthropogenic climate change (Ruddiman, 2005) will continue to affect all components, processes, and cycles in the Earth's System. Continued warming will produce significant changes in the Earth's cryosphere. By the beginning of the 21st century, changes in the Earth's cryosphere were receiving increased attention, in the context of global environmental change (Key and others, 2007; Slaymaker and Kelly, 2007) and of climate change (Hansen, 2004), 30 years after work had begun on the Satellite Image Atlas of Glaciers of the World (Ferrigno and Williams, 1980).

Schellnhuber and others (2006) discussed ways of avoiding climate change. Melillo (2007) considered climate change to be the grand challenge for all of us in the 21st century. Hanson and others (2008) addressed the question of the optimal ("maximal") concentration of CO_2 in the atmosphere, concluding that it must not rise above 350 ppm.

Our earliest records of global temperature date to 1880; since then, geographically dispersed temperature records have been available in sufficient quantity to assess trends, as in figure 15, a graph of the Earth's temperature for the period 1880 to 2008. NASA's Goddard Institute for Space Studies (GISS) noted that the 8 warmest years of record shown in the graph have occurred since 1998, the 14 warmest since 1990 (McCarthy, 2008, p. 60).

A warmer Earth means a smaller cryosphere, both areally and volumetrically. Glaciers are melting; sea level is rising. How fast the Earth's glaciers, especially the Greenland ice sheet, will melt and how fast the sea level will rise are open questions. No matter what answers we may find, however, anthropogenic climate change will likely lead to a late Holocene Epoch interval that will be warmer than the end of the last interglacial (fig. 16) when most of the Greenland ice sheet melted (Koerner, 1989), resulting in a 6 m rise in sea level. The world's two great ice sheets—covering Greenland and the Antarctic—are indeed losing ice to the oceans and losing it at an accelerating pace. Researchers do not understand why the massive ice sheets are proving so sensitive to an as-yet modest warming of air and ocean water. The future of the ice sheets is still rife with uncertainty, but if the unexpectedly rapid shrinkage continues, low-lying coasts around the world—including New Orleans, southern Florida, and much of Bangladesh—could face inundation within a couple of centuries rather than millennia. Unless the increase in CO_2 can be stopped and reversed to less than 300 ppm, there will be a rise in sea level of at least 6 m in the future. Overpeck (1996, p. 1,821) concluded that "Major warm climate surprises of the type apparent in the Holocene interglacial paleoclimatic record may be our biggest worry in the years to come."

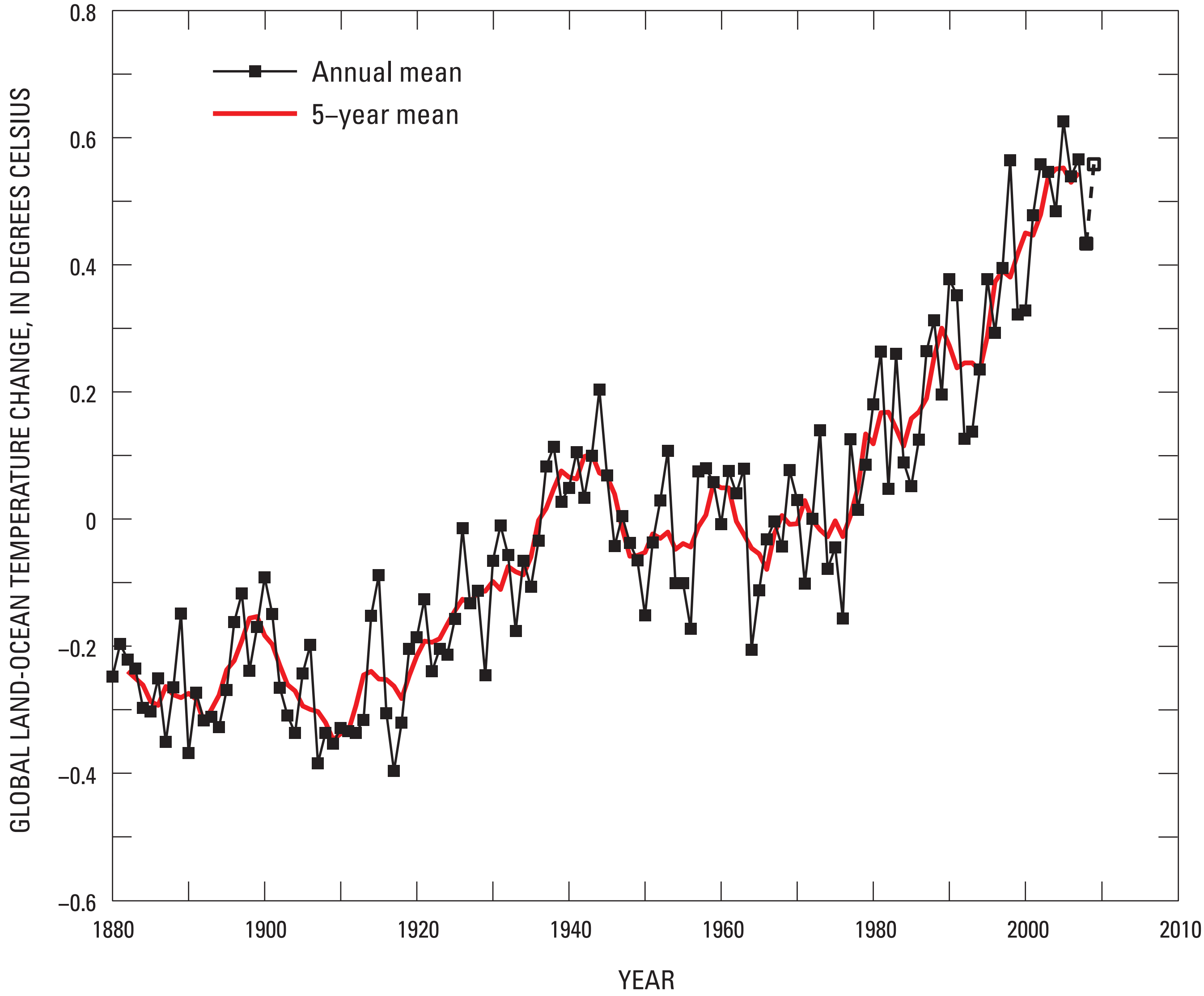

Figure 15.*—Graph of global annual surface temperatures from 1880 to 2007, relative to the annual mean temperature and 5-year mean temperature. Graph is based on data compiled by National Aeronautics and Space Administration Goddard Institute for Space Studies at* http://data.giss.nasa.gov/gistems/graphs/ *(see also McCarthy, 2008, p. 60).*

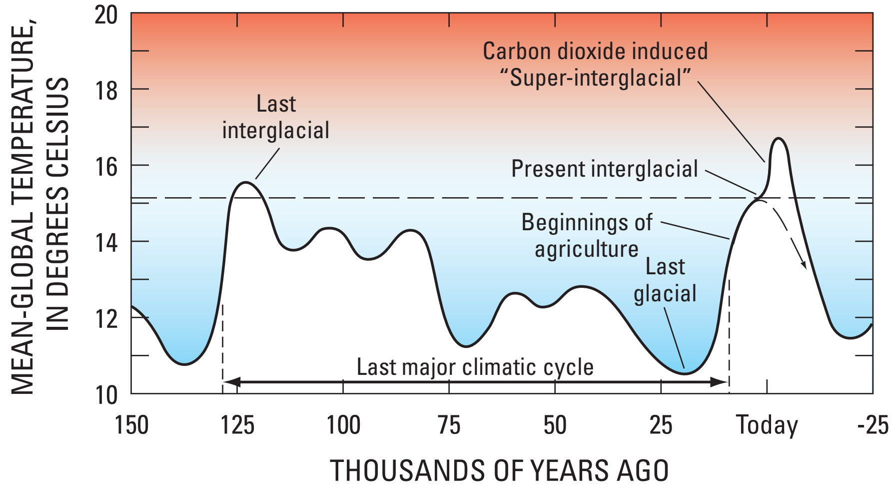

Figure 16.*—Graph of mean global temperatures for the last 160,000 years, and theoretical projection 25,000 years into the future, showing an enhanced "global warming" at the end of the Holocene Epoch (interglacial) before the start of the next glacial. Modified from Imbrie and Imbrie (1979, p. 186).*

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