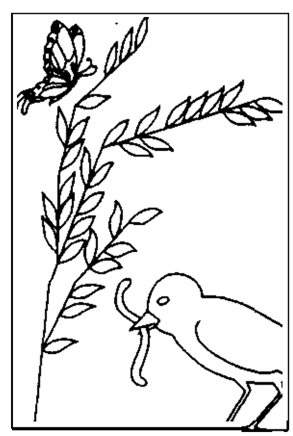
A Primer on Climate Change and Natural Resources 2

This chapter summarizes the current state of knowledge about climate change and describes the interaction of climate variables with natural systems. Background information key to understanding the impacts described in each of the resource chapters (coasts, water, agriculture, wetlands, preserves, and forests) is included here. This chapter illustrates the range of effects climate change could cause across systems and at different spatial and temporal scales.

Human activities have increased the rate at which greenhouse gases--carbon dioxide (CO_2) methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs--are building up in the atmosphere. This increase is likely to lead to changes in climate that could have significant effects on natural systems. The first-order effects of a buildup of greenhouse gases-increasing average temperature, rising sea level, and changes in precipitation and evapotranspiration--can be estimated with some confidence at the global scale. Global average temperature may increase about 2 OF (1 'C) by 2030 and sea level is predicted to rise by about 8 inches (20 centimeters)[1] in the same period; precipitation and evapotranspiration globally will also increase.

As scientists consider smaller spatial scales, their certainty about these effects decreases. Some midcontinent regions are likely to become warmer and drier rather than warmer and wetter, for example, but not enough is known yet about climate change on a regional scale to be confident about the direction and magnitude of changes. A decade or more of research will be needed before such precision is available. Second- and third-order effects, such as changes in individual plants and animals or whole ecosystems, are utimately the impacts that humans care



[1] To convert inches to centimeters (cm), multiply by 2.540,To

about. These changes in the natural and managed systems that societies depend on have socioeconomic consequences and result in costs or benefits.

Plants and animals are more immediately affected by extreme events, such as droughts, floods, or storms, than they are by changes in the long-term averages of climate variables. However, individuals may not be able to tolerate sustained changes in average temperature and precipitation. Such conditions might, for example, lead to increased vulnerability to pests, disease, and fires. Repeated stress will adversely affect not only individuals but also populations and species, potentially resulting in altered ecosystem ranges and composition.

As the climate changes and average temperature increases, the extremes experienced by ecosystems will change as well. The hottest temperatures may be hotter than previously experienced; the coldest temperatures may not be as cold as they are now. Ultimately, temperature shifts may alter the geographic range of species and ecosystems. Climate change may also benefit some plants and animals. Certain plants, for example, may derive benefits from the rising concentration of CO_2 in the atmosphere, which can act like a fertilizer. Higher temperatures could enable some plants and animals to increase their geographic ranges.

Ecosystems are always changing and would continue to do so without climate change. However, projected rates of change in temperature exceed the estimated rates for the past 15,000 years, which averaged about 2°F(1°C) per 1,000 years; under a changing climate, temperatures could rise 3 to 8 OF (1.5 to 4.5 °C) over the next century. These changes may be too rapid to allow forest ecosystems to migrate with the changing climate. Atmospheric concentrations of CO_2 are changing 30 to 100 times faster than shown in ice-core records, which go back millennia. Natural ecosystems are more vulnerable to climate change than are managed ones, such as farms and plantation forests, because active measures--irrigation, replanting, and fertilizing, for example are much more difficult to undertake in natural areas.

U.S. FISH AND WILDLIFE SERVICE

Many animals, such as this Rocky Mountain coyote, require large expanses of remote and undisturbed habitat to sustain populations. Human disturbance or fragmentation of habitat leads to declines in prey populations and vegetation cover. Affected species can migrate, decline, or alter their food sources.

Many natural systems are already degraded by pollution and geographic fragmentation. Additional human-caused stress may lead to undesirable changes in the values and functions of natural systems from which humans now benefit. ‘Uner stress, natural systems of plants and animals tend to breakup and reformulate in new systems with different species or mixes of species” (21). The total change in an ecosystem depends not only on its sensitivity to climate change, but also on the system’s absolute sensitivity to a variety of other changes that influence soil and water chemistry or habitat fragmentation (21).

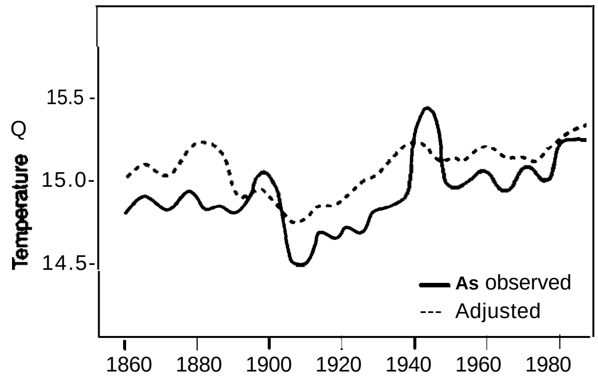
HOW DO WE KNOW CLIMATE IS CHANGING?

The Earth’s average temperature has increased 0.8 OF (0.45 ‘C) over the past 100 years, with an uncertainty range of +/-0.27 °F (+/-0.15 °C). The broad range reflects many inaccuracies introduced in the 100-year land-based temperature record by recording temperatures in cities (which tend to be warmer than rural areas),[2] using different instruments over time, and inadequate and changing spatial coverage.

Because the climate system is so inherently variable, it takes a long time to detect trends. Besides greenhouse gases, urban ozone, decreases in stratospheric ozone, increases in acidic air pollution, volcanic aerosols, and the solar cycle are all likely to have influenced the observed global temperature record. For example, the sum of all known greenhouse gases emitted to the atmosphere to date should have increased the heat-trapping capacity of the atmosphere by 2.1 watts per square meter (W/m*). However, over the past few decades, other forces could have counteracted as much as 50 percent of the effect by cooling the earth. Urban air pollution (e.g., soot and acid aerosols) could have offset the warming by up to 24 percent, ozone depletion by CFCS, 10 percent, and increased cloudiness by 20 percent. Although these cooling effects temporarily mute the greenhouse effect, they do not negate it, so net warming is expected. Simultaneously, solar irradiance (the output of the sun) may have enhanced the greenhouse effect by 14 percent.

Other naturally occurring events can confound the temperature record, too, such as the 3- to 7-year occurrences of El Niño. Volcanic eruptions (such as El Chichon in 1982 and Mount Pinatubo in 1991) can more than offset the entire greenhouse effect temporarily (for 2 to 4 years).[3] Recent satellite temperature measurements taken over a 12-year period show no warming trend (84). This satellite record cannot be used to refute global Warming for three reasons: 1) the record of measurements is over too short a period; 2) two major volcanic eruptions occurred during that period (Chichon and Pinatubo), followed by a several-year cooling due to the particles they injected into the atmosphere; and 3) the satellite

Figure 2-l—Long-Term Global Temperature Record



NOTE: Global average temperature from raw observations (solid line) vs. data adjusted for known biases (dashed line). Lack of data quality and contlnuity has led to an undesirable level of uncertainty about these records. To convert °C to °F, multiply by 1.8 and add 32.

SOURCE: T.R. Karl, 'Missing Pieces of the Puzzle," in: Research and *Exploration,* Spring 1993, pp. 235-49.

does not measure the near-surface temperature of the earth; rather, it integrates a 6,500-yard (6,000-meter) swath of the atmosphere (48).

Despite all the confounding factors, the long-term temperature record shows warming that is consistent with that calculated by the general circulation models (GCMS) (44) (see fig. 2-1 and box 2-A). The observed 0.8 OF rise is within—but at the low range of--the 0.7 to 2.0 OF (0.4 to 1.1 °C) that models predict. The warming is not "statistically significant' '-that is, it is not outside the range of normal variability. The unequivocal detection of a climate change signal from such complicated records requires at least another decade of measurements (44). The nine warmest years since 1891 were all in the 1980s and early 1990s (6). Several ancillary pieces of evidence consistent with warming, such as a decrease in Northern Hemisphere snow cover, a simultaneous

2 Bias due to "the heat island effect' is likely to be less than 0.1 °F (0.05 'C), or less than 10 percent of the observed temperature increase (43).

3 For example, Pinatubo injected 25 million tons (23 billion kg) of sulfur dioxide 15 miles (25 km) into the stratosphere; the cooling caused by reflectivity of those particles should offset the warming from greenhouse gases for 2 years until the particles settle out of the atmosphere.

Box 2-A–What the Models Tell Us: GCMs and Others

To describe how the climate system operates and to predict how changes in the composition of the atmosphere will affect climate, scientists have developed models known as general *circulation models* (GCMs). GCMs are composed of mathematical equations that describe the physical climate processes and interrelationships, including seasonal changes in sunlight, global air currents, evaporation and condensation of water vapor, and absorption of heat by t he oceans. The models incorporate basic physical principles (such as the conservation of energy and mass) and empirical evidence from observations of how the climate system seems cooperate (such as statistical equations describing t he humidity and temperature at which clouds generally form). The four major GCMs have generated somewhat different predictions about how climate might change largely because they use different empirical evidence and starting assumptions and incorporate different sets of climate variables. Even models that agree on global averages may predict different regional distrbutions because they have different ways of accounting for small-scale climate processes.

The differences in climate change predictions from the various major climate models have drawn considerable attention. So, too, has the fact that observed changes in global average temperature have been lower than initial estimates. Many models have predicted that based on the increases of human-generated greenhouse gas emissions (particularity carbon dioxide (CO_2) emitted during fossil fuel combustion) over the past century, global temperatures should already have increased by 0.5 to 2.0 ‘F (0.3 to 1.0 °C). Measurements of warming to date suggest that global average surface-air temperatures have increased approximately 0.5 to 1.0‘F (0.3 to 0.6 °C)--on the low end of the predicted range (45).[1]

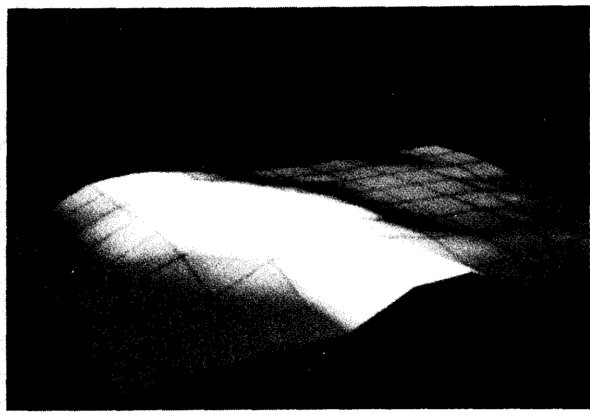
That global warming appears to be proceeding more slowly than predicted maybe due to difficulties in distinguishing short-term climate patterns from long-term trends, as well as to the complex and incompletely characterized interactions, of oceans, clouds, and air pollution with weather and climate (44, 92). Natural variations in weather (e.g., rainfall and temperature) occur over years or decades, which may mask longer-term (century and millennium) climate patterns for many years (63). In addition, oceans have an enormous capacity to absorb heat which may delay atmospheric warming for some time (81, 66). Clouds also play an important but uncertain role in moderating planetary climate. Depending on their composition and location, clouds may either cool the planet by reflecting incoming solar radiation or warm it by contributing to the greenhouse effect so it is not clear whether, in the aggregate, they contribute to or somewhat offset global warming (1, 66). Finally, global warming may be offset somewhat in the Northern Hemisphere because some human-generated pollution (particularly sulfur aerosols) may actually exert a cooling effect: when converted to sulfate particles in the atmosphere, they reflect incoming solar radiation (44, 66).

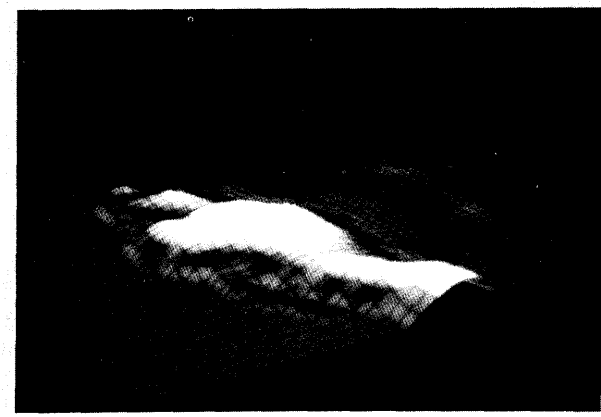
Generalities and uncertainties

GCMs paint the following general picture of global climate change. Average global air temperatures will increase. With increased temperatures will come an increase in average global precipitation because warmer air causes faster evaporation, speeding up the rate at which water vapor becomes available for aloud formation and precipitation. Increased temperatures will cause the water in oceans to expand (water expands as it warms above 39 OF (4 °C)), and as ocean volume increases, sea levels will rise. Sea level rise may be moderated if increased

[1] Global-average temperature statistics are compiled from historical temperature measurements from weather stations around the world. Accurate interpretation of historical temperature data Is complicated and controversial because changes in measurement techniques and locations over the past century make the data difficult to compare. Data analysis is further complicated by the urban “heat island effect”—local warming in areas with many buildings and paved surfaces that tend to trap heat-which has raised temperatures at some monitoring stations, reflecting changes in local climate apart from any potential global changes. The estimated temperature change reported here was a consensus figure developed by the Intergovernmental Panel on Climate Change (IPCC) that attempts to account for both the changes In measurement and the confounding effects of data from urban areas.

temperature and water-holding capacity of the air lead to more snow at the poles, which may cause arctic ice sheets to grow thicker in the near future; on the other hand, warmer temperatures could cause parts of the Greenland and Antarctic ice sheets to melt, causing even more sea level rise. Beyond these generalities, significant uncertainties remain about regional impacts, rates of change, and feedbacks. Regional predictions are quite murky, and they are the ones that are most important to individual resources and human societies. A variety of factors, including local or mesoscale effects of hills, and vegetation boundaries, are important in determining regional climate. GCMs cannot at present incorporate features this small (see the figure in this box) because spacing between grid points is between 150 and 800 miles (250 and 1,000 kilometers)[2] (94). Because models differ in how they treat these physical features and because the current generation of models is only beginning to incorporate the modeling of ocean currents and aloud cover, it is not surprising that the major GCMs differ markedly in predicting regional changes in precipitation, soil moisture, and other hydrologic variables. For example, certain models predict that precipitation will increase in some regions white others suggest that it will decrease (83). The range (and therefore uncertainty) in model output for soil moisture and runoff is even greater than it is for precipitation (49).





NOTE: Models cannot yet incorporate regional features adequately because grid sizes are too large. The smaller the grid size, the more complex and time-consuming each model run becomes. The top figure shows how a 480-km grid can obscure important geologic features. The bottom figure shows what the topography of the United States looks like with a 120-km model grid. The degree of resolution in the bottom figure is typical of present global weather prediction models.

SOURCE: National Center for Atmospheric Research.

Most climate modelers agree that precipitation is most likely to increase at high latitudes and that the water-holding capacity of the atmosphere (cloudiness) will be largest in low to midlatitudes (30). In the midcontinent areas, especially in summer, evapotranspiration may outstrip precipitation, and thus soil moisture and runoff would decrease. The potential for more-intense or longer-lasting droughts would therefore increase. Some scientists (78) suggest that GCMs (because of their lack of realistic land-surface models) understate the potential for the intensification of summertime drought in low to midlatitudes. If current trends in greenhouse gas emissions continue, they predict the frequency of severe drought in the United States would be expected to increase dramatically, with effects becoming apparent sometime on the 1990s (78).

A second likely regional consequence of global warming is that it will lead to changes in the type and timing of runoff. Snowmelt is an important, source of runoff in most mountainous areas. Warmer temperatures in such

2 To convert miles tokilometers, multiply by 1.609.

(Continued on next page)

Box 2-A–What the Models Tell Us: GCMs and Others-(Continued)

areas would cause a larger proportion of winter precipitation that now falls as snow to fall as rain. Thus, the proportion of winter precipitation stored in mountain snowpack would decrease. Winter runoff would increase, and spring runoff would correspondingly decrease. During times when flooding could be a problem, seasonal changes of this sort could have a significant impact on water supplies because adequate room in reservoirs would have to be maintained (53), and thus some early runoff would probably have to be released.[3]

Uncertainty surrounds predictions of the rate at which climate change may proceed. Most assessments of climate change have assumed that it will proceed gradually and continuously until the climate reaches some new equilibrium (21). These assessments attempt to characterize what the climate might eventually be like when the equivalent of doubled CO_2 has been reached; relatively few studies have examined the intermediate, or transient climate stages. However, a few suggest that the change may not linear and gradual. For example,the capacity of the oceans to absorb heat may delay warming for sometime, but there maybe some threshold after which ocean heat absorption slows and a relatively rapid warming of air temperatures follows (81)-or proceeds in steps in a series of punctuated equilibria (relatively rapid change for a short time followed by a period of relative stability), so transient climate stages might be important (15).

Uncertainties also arise from lack of knowledge about potential climate feedbacks--that is, processes that occur in response to global warming that either augment or diminish the effect in complex and interacting ways. For example, at warmer temperatures, the atmosphere can hold more water vapor, which is a powerful greenhouse gas, and this will magnify warming. On the other hand, some portion of the additional water vapor could form into clouds, which can, depending on their size, shape, and distance from the Earth's surface, reflect solar radiation and either amplify or offset some of the warming. The role of ice and snow in climate systems has not yet been quantified, and it is not clear whether it will prove to be an additional feedback. Warming in the polar regions will likely melt some portion of the polar ice caps, reducing the extent of land and ocean covered by them. Ice and snow are more reflective than either land or water; reducing the amount of ice and snow will allow both land and sea to absorb more heat= In addition, sea ice tends to insulate the ocean; when the ice is not present the ocean may release heat to the atmosphere more readily. Both processes could add to the warming cycle, so that as the atmosphere becomes warmer, it triggers various additional processes that will make it warmer still (66).

Other feedbacks may, however, counteract warming. For example, some scientists point out that vegetation may grow better in an atmosphere with higher concentrations of CO_2 Increased plant growth could allow plants to take up more carbon from the atmosphere, potentially acting as a brake to greenhouse warming (61).

Despite the uncertainties attached to climate change predictions, there are many areas of agreement on the global, and even some regional, outlines of change. The effects on ecosystems and natural resources are more uncertain. Even if models could now generate accurate regional and local climate predictions, scientists do not yet have the theoretical knowledge to predict with confidence how ecosystems will react to the predicted climate changes—and how ecosystem response will translate into impacts on natural resources and on the people who depend on them. And they are further still from being able to forecast how or whether systems could adapt

3 The California Department of Water Resources has estimated, for example, that if average temperatures warm by5'F (3 'C), winter snowmelt runoff would increase, but the average April-July runoff would be reduced by about 30percent (M. Roos, Chief Hydrologist, California Department of Water Resources, personal communication, 1992).

SOURCES: Intergovernmental Panei on Climate Change (IPCC), World Meteorological Organization, and United Nations Environment Program, C//mate *Change:* The *IPCC Scientific Assessment,* report prepared for IPCC by Working Group 1, J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds.) (Cambridge, England: Cambridge University Press, 1990); Intergovernmental Panel on Climate Change, World Meteorological Organization, and United Nations Environment Program, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment,* report prepared for IPCC by Working Group i, J.T. Houghton, B.A. Callander, and S.K. Vamey (eds.) (Cambridge, England: Cambridge University Press, 1992); U.S. Congress, Office of Technology Assessment (OTA), *Changing by* Degrees: *Steps* to *Reduce Greenhouse Gases,* OTA-O-42 (Washington, DC: U.S. Government Printing Office, February 1991).

decrease in Arctic sea ice, continued melting of alpine glaciers, and a rise of sea level (48), have also been corroborated.

WHAT CAUSES CLIMATE CHANGE?[4]

The Earth's atmosphere is a natural greenhouse. Sunlight passes through the atmosphere and strikes the Earth, and as the planet warms and radiates heat, a large share of the heat is trapped by gases in the atmosphere, primarily CO_2 and water vapor. Although these gases make up only 0.25 percent of the atmosphere by volume, they are responsible for increasing the average temperature of the Earth from O OF (the temperature it would be without these natural greenhouse gases) to 59 oF. The evolution of such an atmosphere offered the appropriate conditions for the development of life on Earth. Humans have added more CO_2 and other greenhouse gases (CH_4, N_2O, and CFCS) to the atmosphere over the past 100 years. These gases effectively trap the heat that would normally be radiated from the earth into space. Instead, heat is reflected back to the Earth, and both the surface and the lower atmosphere get warmer-causing global warming. This greenhouse effect is illustrated in fig. 2-2.

An international panel of scientists was established in 1988 to assess potential climate change and its impacts. This Intergovernmental Panel on Climate Change (IPCC) includes more than 50 countries, and operates under the aegis of the World Meteorological Organization and the United Nations Environment Program. IPCC issued a report in 1990 and an update in 1992 (44, 45) that represent the best scientific assessment to date about climate change and its causes. IPCC scientists agree on the basic atmospheric mechanisms that make the planet a greenhouse. They also concur that human activities, such as burning fossil fuel, deforestation, and agriculture, have increased the rate at which greenhouse gases are emitted to the atmosphere, and that the concentrations of those gases in the atmosphere are increasing.

WHAT CHANGES IN CLIMATE ARE PREDICTED?[5]

■ Carbon Dioxide and Other Greenhouse Gases

In contrast to measurements of temperature and precipitation, which do not reveal clear trends, measurements of greenhouse gases show significant, steady increases over the past century.[6] For example, the concentration of atmospheric CO_2, the most important greenhouse gas (other than water vapor), has been systematically monitored since 1958 at the Mauna Loa Observatory in Hawaii.[7] It has been increasing steadily for the past 35 years. Data from air bubbles in ice cores show that preindustrial atmospheric CO_2 concentrations were 280 parts per million (ppm); in 1990, the concentration had increased by more than 25 percent to an annual average of 353 ppm and is increasing at 0.5 percent per year (see fig. 2-3, lower data points). Seventy to 90 percent of the CO_2 added to the atmosphere today (about 8

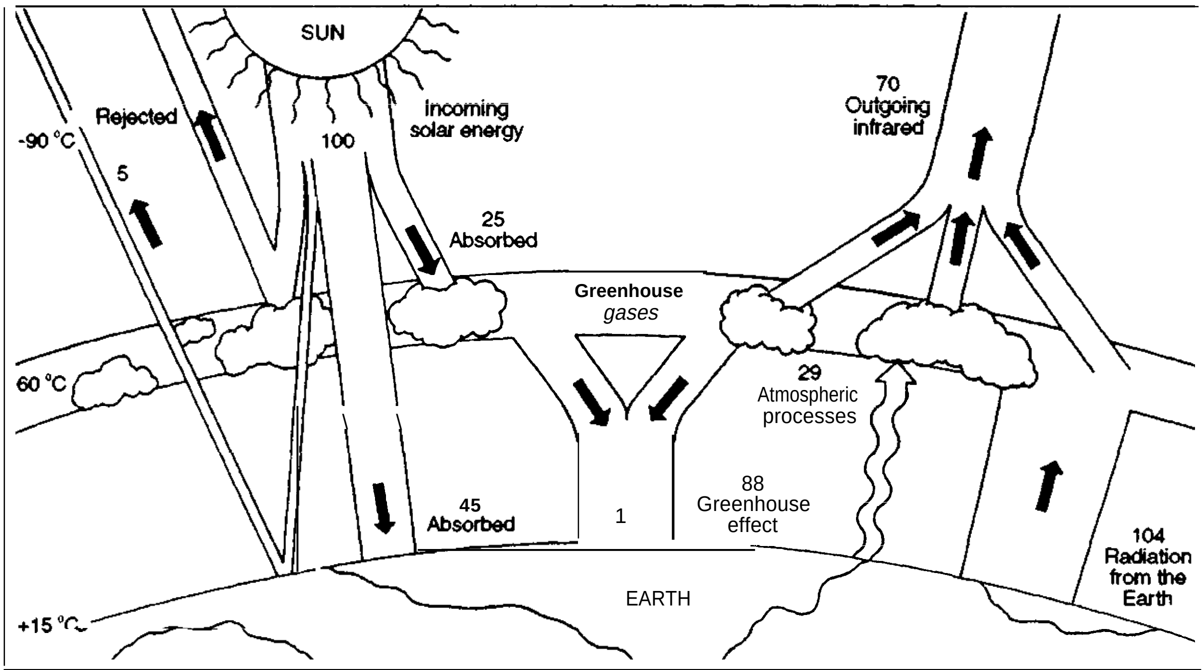
[4] This section briefly summarizes the mechanisms and the greenhouse gases that contribute to the greenhouse effect. For a more detailed treatment of climate change, see chapter 2 of OTA'S previous report on climate change, *Changing by Degrees* (88). That report also examines how the United States and other countries could reduce emissions that contribute to climate change.

[5] The predictions given throughout this section are based on an equivalent doubling by 2025 to 2050 of greenhouse gas concentrations from preindustrial levels. In addition, the predictions refer to a future *equilibrium climate*—that is, one in which the climate has finished changing and the climate system has arrived at a new balance—rather than the *transient climate*, or intermediate stage, that occurs as climate change is underway. Scientists debate whether the climate will reach anew equilibrium or whether we are instead entering an era of continuous change. Equilibrium may not be reached for centuries. (J. Mahlman, Director, Geophysical Fluid Dynamics Laboratory, Princeton University, July 28, 1993, at a briefing sponsored by the World Resources Institute and the National Oceanic and Atmospheric Administration.)

[6] For a more detailed discussion of the emissions and effects of greenhouse gases, see reference 88.

[7] CO_2 is responsible for about 70 percent of the radiative forcing (heat trapping) caused by greenhouse gases in the 1980s.

Figure 2-2—The Greenhouse Effect



NOTE: Radiation flows are expressed here as a percent of total incoming or outgoing energy. Incomlng solar radiation is partially reflected back into space (30 percent) and partially absorbed by the atmosphere, ice, oceans, land, and biomass of the Earth (70 percent).The Earth then emits *radiant energy back* into space. The "greenhouse effect" refers to the trapping of some of the radiant ● nqy the Earth emits by atmosphere gains, both natural and anthropogenic. As a result of this effect, the Earth's surface and lower atmosphere warm.

SOURCE: U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases, OTA-O-482* (Washington, DC: Government Printing Office, February 1991).

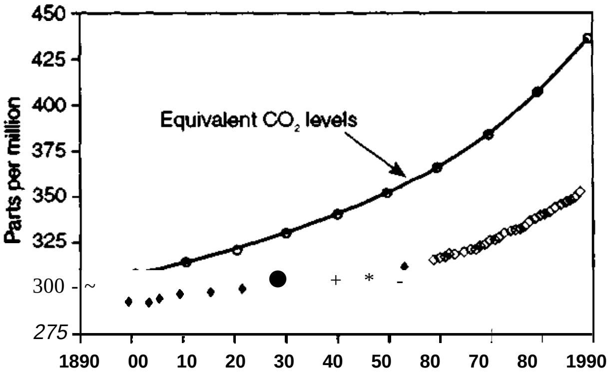
to 9 billion tons, or 7 or 8 trillion kilograms, of carbon each year) is due to the burning of fossil fuels--coal, oil, and natural gas; the remainder is attributed to deforestation. IPCC notes that under a "business-as-usual" scenario, the concentration of $C0_2$ could rise as high as 800 ppm-nearly triple the preindustrial level—by the end of the next century (44). If world emissions were frozen at 1990 levels, CO_2 concentrations would still rise to 400 ppm by about 2070 (see fig. 2-4),[8] and temperatures would continue to rise about 0.4 OF (0.2 'C) per decade for many decades.

Increases in the atmospheric concentrations of the greenhouse gases CH_4, N_2O, and CFCS have also been documented and can be linked to anthropogenic emissions. As the upper line in figure 2-3 shows, these gases effectively augment the greenhouse effect caused by CO_2. Sources of CH_4 emissions include rice paddies, domestic animals (cattle and sheep), natural gas production and delivery, coal production, and landfills (44). CH_4 concentrations increased about 1 percent per year between 1978 and 1987 (from 150 to 168 parts per billion (ppb)). Recently, this increase has slowed to 0.5 percent per year; the cause of this slowdown is unknown (45).

Atmospheric concentrations of N_20 began a rapid ascent in the 1940s and increased at 0.2 to 0.3 percent per year during the mid-1980s, with current concentrations at about 310 ppb. Ice-core

[8] Given that developing countries currently use one-tenth the energy of the developed world and their usage is increasing 6 to 10 percent per year, this later scenario is unrealistic (88).

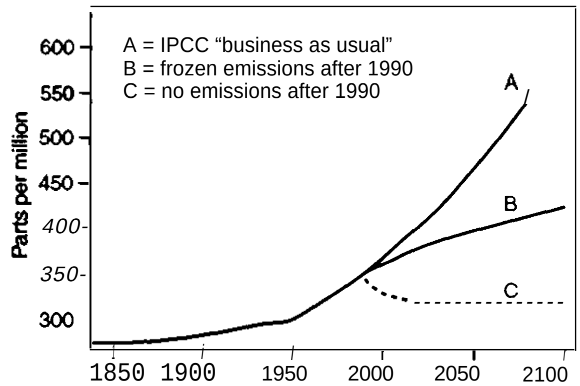
Figure 2-3-Measured and Equivalent CO_2 Concentrations in the Atmosphere



NOTE: The lower points represent atmospheric concentrations of CO_2 from Antarctic ice-core data (1890 to 1950, shown as diamonds) and from recent Mauna Loa observations (1 958 to 1990, shown as stacked squares). "Equivalent CO_2 levels" are shown by the connected circles; this is the additional effect caused by various trace gases (methane, nitrous oxide, and chlorofluorocarbons) expressed In CO_2 equivalents.

SOURCE: R.C, Balling, 'The Global Temperature Data," In: Research & *Exploration, vol.* 9, No. 2, Spring 1993, p. 203.

Figure 2-4-Expected CO_2 Concentrations in the Atmosphere According to Various Emissions Scenarios



SOURCE: M. Heimann, "Modeling the Global Carbon Cycle," paper presented at the First Demetra Meeting on Climate Variability and Global Change, Chiandiano Therme, Italy, Oct. 28-NOV. 3, 1991.

data show preindustrial concentrations of 285 ppb, which had been relatively stable for 2,000 years. Anthropogenic sources appear to be responsible for about 30 percent of N_2O emissions[9]—prirnarily from nylon production, nitric acid production, and the use of nitrogenous fertilizers.[10]

CFCS are humanmade chemicals used primarily for refrigeration and insulation. A worldwide treaty (the Montreal Protocol signed in 1987 and augmented by several subsequent amendments) will eliminate use of these chemicals by the end of the century. The concentration of CFCS in the atmosphere had been increasing at 4 percent per year in the 1980s. These chemicals cause ozone depletion worldwide and the Antarctic ozone hole. Given world action to phase out CFCS, the ozone hole is expected to close in 70 years. CFCS are greenhouse gases and trap heat, but because they also destroy ozone (another greenhouse gas), the net warming from CFCS is approximately zero (45).

Temperature

IPCC predicted that global average temperature would increase at a rate of 0.5 °F (0.3 °C) per decade, amounting to a 5.4 °F (3.0 °C) increase by 2100. Box 2-B summarizes the IPCC findings. Although the global average temperature has increased about 0.80 °F (0.45 °C) over the past 100 years, a warming of 1.4 to 4.0 °F (0.8 to 2.2 °C) is expected as an eventual result of the greenhouse gas concentration increases of the past century (this estimate does not include any warming from future emissions).

[9] J. Mahlman, Director, Geophysical Fluid Dynamics Laboratory, Princeton University, personal communication Aug. 27, 1993.

[10] However, the sum of all known anthropogenic and natural sources is still insufficient to explain rates of atmospheric increase (45).

Box 2-B–Highlights of the IPCC Scientific Assessment of Climate Change

IPCC is certain that:

- There is a natural greenhouse effect that already keeps the Earth warmer than it would otherwise be.
- Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases.

IPCC calculates with confidence that:

- Atmospheric concentrations of the long-lived gases (carbon dioxide, nitrous oxide, and the chlorofluorocarbons) adjust slowly to changes in emissions. Continued emissions of these gases at present rates, would cause increased concentrations for centuries ahead.
- The long-lived gases would require immediate reductions in emissions from human activities of over 60 percent to stabilize their concentrations at today's levels; methane would require a 15 to 20 percent reduction.
- The longer emissions continue to increase at present day rates, the greater reductions would have to be for concentrations of greenhouse gases to stabilize at a given level.

Based on current model results, IPCC predicts that:

- Under the IPCC "business-as-usual" scenario,[1] the global mean temperature will increase about 0.5°F(0.3°C) per decade (with an uncertainty range of 0.4 to 0.9 °F per decade), reaching about 2°F (1 'C) above the present value by 2025 and 5 OF (3 'C) before the end of the 21st century.
- Land surfaces will warm more rapidly than the ocean, and high northern Iatitudes will warm more than the global mean in winter.
- Global mean sea level will rise about 2 inches (6 cm) per decade over the next century, rising about 8 inches (20 cm) by 2030 and 25 inches (65 cm) by the end of the 21st century.

All predictions are subject to many uncertainties with regard to the timing, magnitude, and regional patterns of climate change, due to incomplete understanding of:

- sources and sinks of greenhouse gases,
- clouds,
- oceans, and
- polar ice sheets.

The IPCC judgment is that:

- Global sea level has increased 4 to 8 inches (10 to 20 cm) over the past 100 years.
- Global mean surface air temperature has increased by about 0.80 OF (0.45°C) (with an uncertainty range of 0.5 to 1.0 °F (0.3 to 0.6 'C) over the past 100 years), with the five globally averaged warmest years occurring in the 1980s.
- The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus, the observed temperature increase could be largely due to natural variability y; alternatively, this variability and other human factors (such as aerosol air pollution) could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.

[1] This scenario assumes that few steps are taken to reduce greenhouse gas emissions. The atmospheric concentration of CO_2 would double (over preindustrial levels) by about 2060, but the effective CO_2 concentration (the cumulative effect of all trace gases) would double by about 2030.

SOURCES: Intergovernmental Panel on Climate Change (IPCC), Climate Change: *The Scientific Assessment* World Meteorological Organization and U.N. Environmental Program (Cambridge, England: Cambridge University Press, 1990); Intergovernmental Panel on Climate Change (IPCC), *1992 IPCC Supplement*, World Meteorological Organization and United Nationa Environment Program (Cambridge, England: Cambridge University Press, 1992).

Greenhouse gas concentrations in the atmosphere will have effectively doubled[11] relative to their preindustrial values by 2030 (44, 45). Changes in global temperature will affect global patterns of air circulation and wind, possibly changing the frequency or pattern of convective storms. Some research suggests that a warmer sea surface may lead to a longer cyclone season with more-intense storms. To date, however, evidence on whether storm frequencies will change is inconclusive (81).

On the regional level, average temperatures are expected to increase more in the higher latitudes (in the Arctic and Antarctic), particularly in late fall and winter. In the northeastern part of North America under a doubled CO_2 climate, for example, warming could reach 14OF(8'C) during the winter (44), and average annual temperatures could increase as much as 18 OF (10 'C) in some high-latitude areas (81). In addition, summer warming in the middle latitudes, including much of the United States, could be greater than the global average, potentially reaching 7 to 9 °F (4 to 5 'C) in the Great Lakes area (45). In the tropics, however, temperature increases are likely to be less than the global average, and will vary less from season to season. Figure 2-5 (top) shows changes in the average annual, winter, and summer temperature ranges predicted for different regions of the United States used for studies performed for the Environrnental Protection Agency (EPA) (94). Regional temperature predictions such as these are accompanied by only a medium level of confidence, but the predictions are likely to improve within the next decade (8 1).

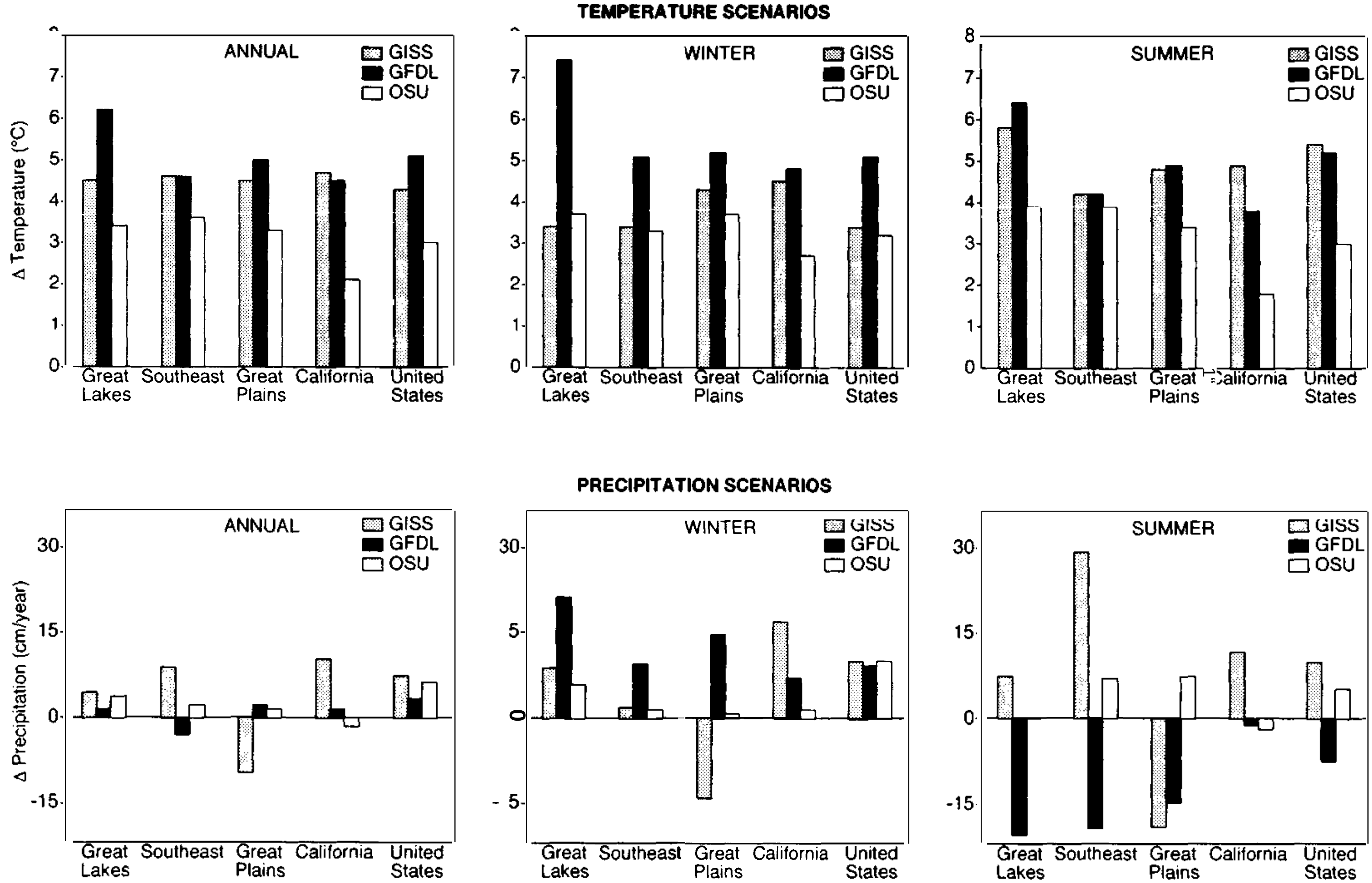
Precipitation

Worldwide, average precipitation is expected to increase by 7 to 15 percent under a doubled CO_2 atmosphere. Regional changes will be much more variable, with estimated increases of 20 to 40 percent in some locations (e.g., coasts), and decreases of up to 20 percent in other areas (78, 94). The seasonal distribution and form of precipitation are likely to change. In regions where precipitation increases, a significant share of the increase may come during the winter; in some locations, more winter precipitation will come in the form of rain than snow (81). Although researchers are fairly confident about the predicted rise in average global precipitation, they are much less confident about regional precipitation because of the many uncertainties surrounding small-scale climatic processes. Figure 2-5 (bottom) shows EPA's predicted average annual, winter, and summer precipitation patterns for different regions of the United States (94).

Natural climate variability is great relative to the expected changes in climate variables. Hence, separating the signal of climate change from the noise of natural variability is difficult. One statistical analysis of climate data from the southeastern United States indicates that if average rainfall increased 10 percent, there would be only a 7 percent chance of detecting that trend after 25 years; even a 20 percent increase in rainfall could only be detected with a 65 percent probability after 50 years (63). More concretely, it is difficult to know whether the recent 6-year drought in the western United States is a rare but possible outcome of natural climate variability, an early indication of climate change, or a return to the average climate after a long particularly wet spell. Longer climate records are needed to distinguish among these various possibilities. It is unlikely that researchers will be able to resolve the uncertainties to develop better predictions for another decade or two (81).

[11] The equivalent doubling of CO_2 refers to the point at which the combined total of CO_2 and other greenhouse gases, such as CH_4, built up in the atmosphere have "a radiative effect equivalent to doubling the preindustrial value of carbon dioxide from about 280 ppm to 560 ppm" (81). The full warming associated with that amount of greenhouse gases may be delayed by ocean warming: "The large heat capacity of the oceans will delay realizati"on of full equilibrium warming by perhaps many decades. This implies that any specific time when wc reach an equivalent CO_2 doubling . . . the actual global temperature increase may be considerably less [than 2 to 5°C]. However, this 'unrealized warming' will eventually occur when the climate system's thermal response catches up to the greenhouse-gas forcing.'

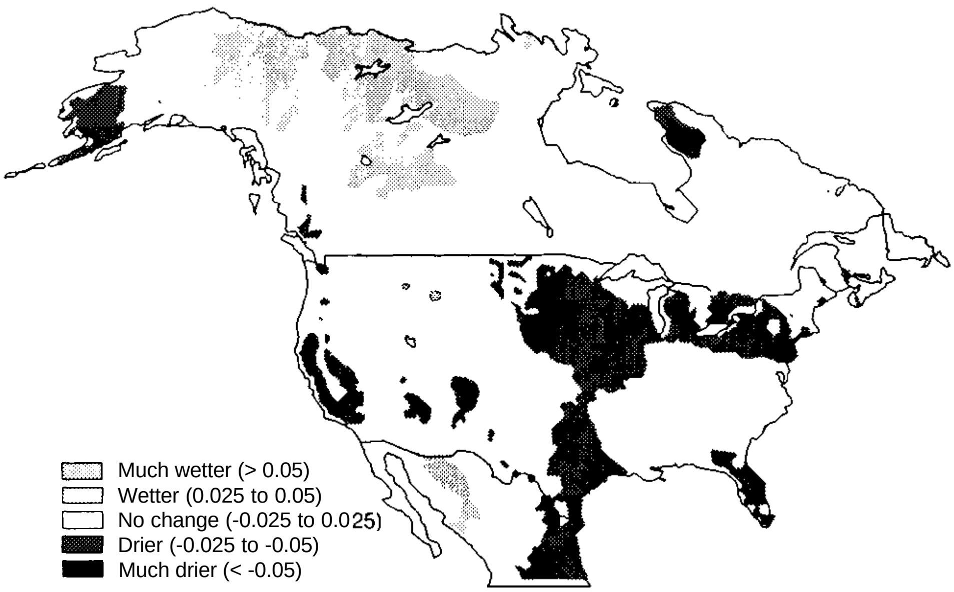
Figure 2-5—GCM-Estimated Changes in Temperature and Precipitation from a Doubling of CO_2



NOTE: GISS=Goddard Institute for Space Studies; GFDL=Geophysical Fluid Dynamics Laboratory; OSU=Oregon State University. To convert °C change to °F, multiply by 1.8; to convert centimeters to inches, multiply by 0.394.

SOURCE: U.S. Environmental Protection Agency (EPA), *The Potential Effects of Climate Change on the United States*, EPA-230-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. EPA, 1989).

Figure 2-6-Potential Soil-Moisture Changes Under the GISS Climate Change Scenario



NOTE: Numbers represent the degree of drying or wetting, calculated as the change in the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET). This ratio is an index of plant-moisture stress, indicating moisture availability relative to moisture demand. GISS-Goddard Institute for Space Studies.

SOURCE: P.N. Halpin, "Ecosystems at Risk to Potential Climate Change," contractor report prepared for the office of Technology Assessment, June 1993.

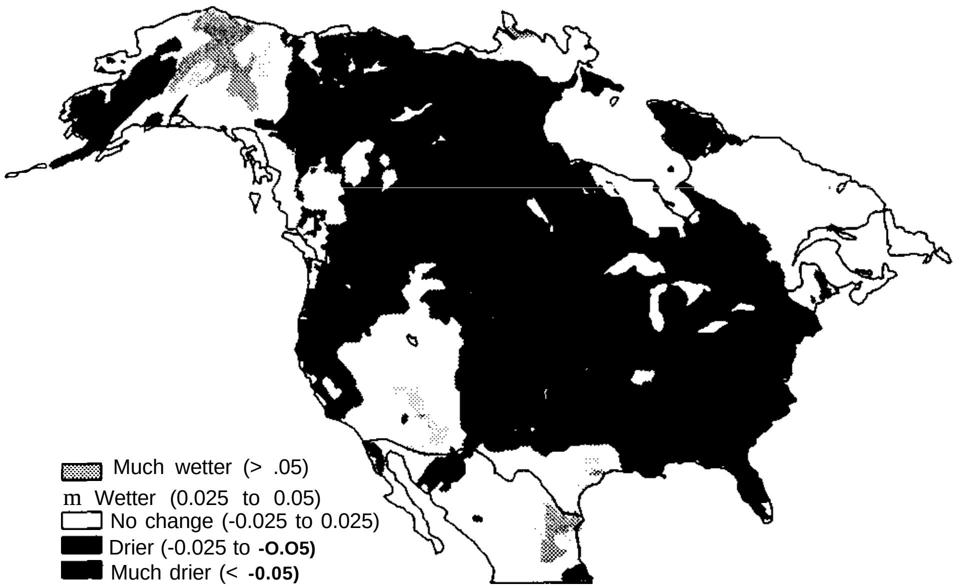
Moisture

Despite overall increases in precipitation, soil *moisture* is predicted to decrease in many mid-continental regions. Soil moisture, which is generally more important for vegetation than is total precipitation, may decrease for two reasons. First, the rate at which moisture evaporates from the soil surface and from plants (evapotranspiration) would increase as temperatures rise. The increased evaporation rates may cause soil to lose moisture at a faster rate than is supplied by the increased precipitation, particularly during the summer. Second, the manner in which added precipitation arrives can affect soil moisture by changing runoff patterns. There are limits to how much soils can absorb at once.[12] For example, sandy soils allow for relatively quick percolation of water through the soil column and into surface- and groundwater systems. However, the percolation rates of clay soils are slow. If increased precipitation comes in a few large storms rather than being evenly distributed over the year, more of it may run off rather than remain in the soil. Thus, increases in average annual precipitation will not necessarily lead to increases in soil moisture and could be accompanied by drier conditions.

Figures 2-6 and 2-7 identify areas of the United States that may face significant changes in soil moisture based on the climate changes projected

12 The ability of soils to retain water varies considerably according to soil composition (the proportion of sand and clay the soil contains) and organic-matter content. In general, sandy soils with little organic material, such as those in central Florida, have a low capacity for water storage. Soils with more clay and a higher organic content, characteristic of the Midwest, can generally retain more water (13).

Figure 2-7—Potential Soil-Moisture Changes Under the GFDL Climate Change Scenario



NOTE: Numbers represent the degree of drying or wetting, calculatad as the change in the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET). GFDL-Geophysical Fluid Dynamics Laboratory.

SOURCE: P.N. Halpin, "Ecosystams at Risk to Potential Climate Change," contractor report prepared for the Office of Technology Assessment, June 1993.

by two GCMS. An index. of soil moisture was calculated as the ratio of available moisture to potential moisture demand (calculated as the ratio of actual evapotranspiration to potential evapotranspiration) .13 White areas in the maps indicate regions of no significant change in the moisture index, dark shading indicates areas of drying, and lighter shading shows areas that become relatively wetter. The Goddard Institute of Space Studies (GISS) scenario (fig. 2-6) produces a mixed result, with large areas of moderate drying intermixed with patches of wetting in the Southeast and northern Rocky Mountain States. The Geophysical Fluid Dynamics Laboratory (GFDL) scenario (fig. 2-7) provides the most extreme outcome for North America, with significant drying across the eastern and central United States and along the Pacific Coast.

Sea Level

IPCC predicts that global average sea levels will rise by around 2 inches (6 cm) per decade for the next century, in contrast to the historic rate of 0.4 inches (1 cm) per decade that occurred since the end of the 19th century. By 2030, IPCC predicts that sea levels will have risen by around 8 inches (20 cm), with a total rise of 26 inches (65 cm) expected by the end of the century (44).

Sea level rise will result from the expansion that occurs as water warms. Oceans will also be

13 Calculated for the Office of Technology Assessment by P. N. Halpin (34). *Evapotranspiration is the* loss of water from the land surface resulting from both evaporation and plant transpiration. Potential *evapotranspiration is the* amount of water that would be lost if there were never a shortage of soil moisture. *Actual evapotranspiration is the actual* amount of water released to the atmosphere (reflecting precipitation and limited availability of soil moisture).

affected by the melting of ice in polar regions. The area of sea ice and seasonal snow cover will also diminish (42). It is likely that ice on the margins will melt more quickly in warmer waters. This result could change the mix of fresh and saline waters in high-latitude seas, and could further change ocean circulation patterns.

Sea level may increase more along some coasts and less along others because sea level rise depends not only on whether the oceans are rising but also on whether adjacent land masses are rising or sinking. Some coasts are sinking as soils are compressed; others are rising due to tectonic forces or as they gradually rebound from the weight of glacial ice that burdened them during the last ice age.[14] Mississippi River Delta in the Gulf of Mexico is subsiding, leading to relatively rapid rates of land loss, while much of the West and the Alaskan coasts are experiencing tectonic uplift and glacial rebound. Thus, the relative sea level rise and the associated land loss is predicted to be greater along the Gulf Coast (as well as in parts of Florida's Atlantic Coast and the South Atlantic States) than along the Pacific Coast. The interaction of sea level rise, altered waves and currents, and storms could lead to greatly increased erosion on sandy coasts and barrier islands (77; see vol. 1, ch. 4).

HOW WILL CLIMATE CHANGE AFFECT NATURAL RESOURCES?

Climate interacts with ecosystems at every level, from the individual to the landscape, throughout the energy and nutrient cycles, and on time scales ranging from seconds to centuries. The effect of climate can be direct, through the action of temperature, evapotranspiration, and sunlight, and indirect, through variables such as wind, cloud cover, ocean currents, and the chemical composition of the atmosphere. For example, photosynthesis rates are affected by the amount of sunlight striking a plant's leaves, which is determined by cloud cover, which in turn is determined by such climatic factors as temperature, evaporation, and wind. Similarly, global temperature affects the amount of precipitation and runoff, which in turn affects the transport of nutrients on land and through wetlands; ocean currents, which are also strongly affected by global temperatures, carry nutrients through marine systems. Indeed, over the long term, climate both shapes the physical landscape and determines where various ecosystems can exist (see fig. 2-8). Climate change of the predicted magnitude is not unprecedented, but scientists who warn of the potential harms of human-induced climate change point out that past global warming and cooling occurred over centuries and millennia rather than decades (see fig. 2-9).[15]

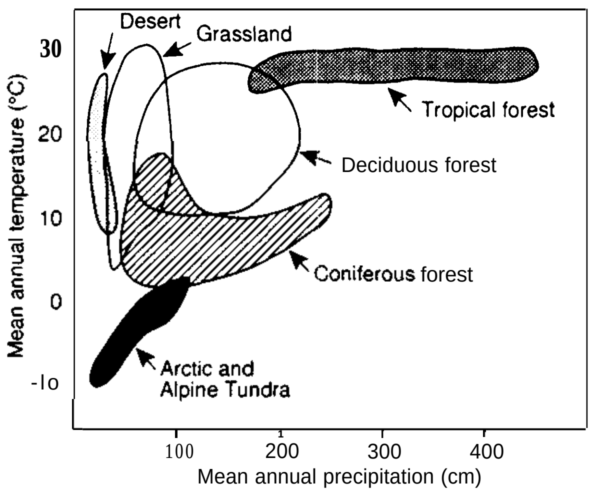
▮ Direct Climate Impacts

Climate is often defined as the long-term "average weather. ' Likewise, predictions for climate change characterize changes in the Earth's average annual temperature. However, individual plants and animals respond to events on small temporal and spatial scales. Variability is usually more important than annual totals or averages. The seasonal distribution of precipitation and temperature, the form precipitation takes (whether rain or snow), extreme events such as droughts or floods, climate-generated fire cycles, late spring frosts, and early fall freezes are all significant factors in determiningg the survival and productiv-

14 Land in delta areas often subsides. Sediment from upland areas loosely packs layers at the river delta where the river meets the ocean; as sediment accumulates over time, it gradually grows heavier and compresses the underlying layers, so the delta land mass sinks relative to the ocean. Coastal land may also subside in areas where offshore oil and gas extraction or pumping of water from coastal aquifers, has hollowed out underground spaces that are gradually compacted by the masses of land and water above. Much of the northern part of the North American continent is still slowly rising as it rebounds from the weight of glaciers that covered it during the last ice age and is situated on a tectonic plate that is being lifted as the adjacent plate slides beneath it; both processes may cause sea levels on the western and Alaskan coasts to appear lower relative to the coastal land mass.

15 Although recent ice-cover analysis suggests that climate may have shifted several degrees in a decade or less over regions of Greenland.

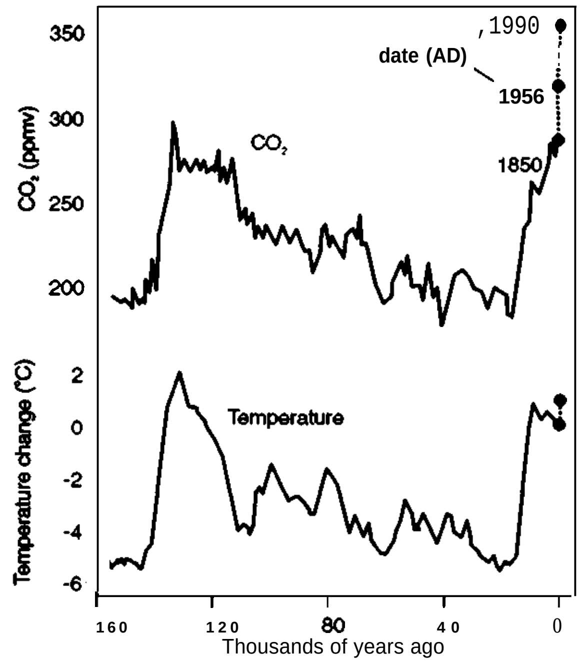
Figure 2-8--Approximate Distribution of the Major Biotic Regions



NOTE: Based on mean annual temperature and mean annual precipitation. To convert °C to °F, multiply by 1.8 and add 32; to convert centimeters to inches, multiply by 0.394.

SOURCE: Adapted from A.L. Hammond, "Ecosystem Analysis: Biome Approach to Environmental Science," Science, vol. 175, 1972, pp. 46-48.

Figure 2-9-Long-Term Temperature and CO_2 Records from Antarctic Ice Cores and Recent Atmospheric Measurements



NOTE: Data show that CO_2 is increasing in the atmosphere much faster than it has at any time over the past 160,000 years. The observed increase in temperature is not yet outside the range of natural variability. To convert °C to °F, multiply by 1.8 and add 32.

SOURCE: C. Lorius, J. Jouzel, D, Raynaud, J. Hansen, and H. Le Trout, "The ice-Core Record: Climate Sensitivity and Future Greenhouse Warming," Nature vol. 347, 1990, pp. 139-145.

ity of individual organisms. One or several extreme events (such as a hurricane or drought) may shape ecosystem boundaries more than many years of "average" weather. Eventually, however, when the "average' has shifted well beyond "normal," ecosystems may have trouble persisting.[16]

The Role of Temperature

Temperature and its distribution are important determinant s of plant productivity and survival. Temperature range exerts three classes of effects on plants: 1) low temperatures can damage plant tissues, causing die-offs during unusual extreme events and controlling the northward or altitudinal migration of plants; 2) in intermediate ranges, temperature governs the rates of photosynthesis, respiration, the growth and development of seeds, and other processes; and 3) high temperatures may stress plants to the limits of their ability to withstand heat and moisture loss, thus controlling plant distribution and migration (19). Seasonal distribution, diurnal cycles (i.e., the variation from night to day),[17] and the occurrence and timing of extremes (e.g., late spring frosts, early winter storms, and peaksummer high and winter low temperatures) are all aspects of the effects of

16 A shift upward in the mean temperature (with an unchanged standard deviation) will make heat waves of today more "average" in the future.

17 A longer growing season based on temperature may actually prove beneficial for some plants because day length is a major factor in productivity.

Box 2-C—Climate Change and Coastal Fisheries

Background

The U.S. commercial, recreational, and sport fishing industries, worth an estimated $14 billion in 1988 (73), rely on the health of nearshore and coastal areas (such as tidal marshes, coral reefs, seagrass beds, mangrove forests, estuaries, and banks). Two-thirds of the world's fish catch, and many other marine spades, depend on coastal wetlands and estuaries for their survival (42). By far the greatest portion of U.S. commercial fisheries catches, with the exceptlon of those from Alaskan fisheries, are composed of estuarine-dependent spades. Ongoing alterations of critical habitat (such as geographic fragmentation and pollution) maybe exacerbated by climate **change.**

Much is yet to be learned about the marine environment and the long-term effects that humans have on it Understanding the breadth of environmental stresses that affect fish and coastal systems will be essential to forecasting how climate change may affect these valuable areas. During the 1970s and 1980s, populations of many commercially important estuarine-dependent fish plummeted. Human activities In the coastal zone are thought to have been responsible for many of the dramatic declines in fish populations. Overfishing has been implicated as a primary cause of the declines of some fish stocks, with some 42 percent of species in American waters considered to be overfished (52). The Atlantic cod fishery of the Grand Banks area has all but collapsed, triggering industry-related layoffs (primarily in Canada) of more than 30,000 people (75). Migratory species such as salmon, shad, herring, and striped bass have decreased due to a combination of habitat degradation and overfishing. The Chesapeake Bay's oyster harvest has declined 98 percent from the levels of 100 years ago due to disease, over-exploitation, predators, and habitat degradation (18). Neatly half of the Chesapeake's wetlands and seagrass meadows, which serve as primary nursery habitat for many migratory species, have been destroyed. Such destruction will adversely affect future fish populations.

The fishing industry from Southern California to Alaska is experiencing similar troubles as a result of overfishing, the damming of spawning rivers, water-quality degradation from logging, and other anthropogenic

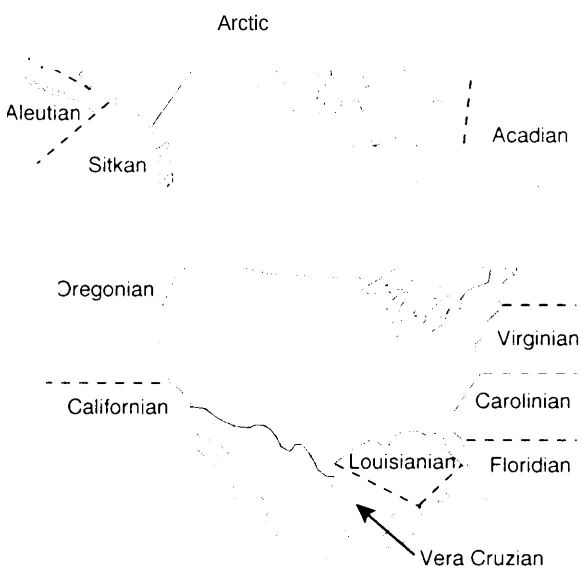
(Continued on next page)

temperature on plants. Length of the growing season is also very important, particularly for agricultural crops. Seed production generally requires a certain number of days with a temperature above freezing, often expressed in terms of degree-days. At northern latitudes, the growing season may not be long enough for some species to set seeds. Longer growing seasons in a warmer climate could boost productivity of trees and other plants, especially those that could tolerate erratic spring and fall weather (e.g., early or late hosts). Seeds of many tree species, including conifers, need to be chilled for particular periods before they will germinate (17,21), so a shortened Cool season could be detrimental to such species.

In addition to the numerous effects of temperature on vegetation, temperature exerts other direct and indirect influences on animals. Higher-than-usual temperatures can adversely affect the reproductive success of many birds, mammals, and insects (26). Increased water temperature limits the availability of oxygen in the water and, in turn, reduces the amount of oxygen available to fish and other aquatic organisms (87). For many fish species, ambient water temperature is critical for survival (see box 2-C). In addition, temperature increases can actually reduce the number of species in a given ecological community (87), though total biomass may increase.

Warmer temperatures could allow some insects, including various agricultural pests, to survive winters farther north than they now do. For example, the potato leafhopper, which is a pest on soybeans and other crops, now overwin-

Box 2-C-Climate Change and Coastal Fisheries-(Continued)



activities. In Alaska, where the seafood industry employs 23 percent of the State's work force, this could prove to be a major problem. More than half of the Nation's seafood harvest comes from Alaskan waters.

scientists have hypothesized that climate warming is likely to alter the distribution and reproductive success of coastal species (77). Many marine species are sensitive to narrow temperature variations. Water temperature controls the respiration and reproduction rates of fish. Changes in temperature can also affect the geographical distribution of species range because some species will thrive in warm waters, while others function effectively only in cooler waters. Changes in stream flows will also be important because they can alter the salinity of coastal bays and estuaries. The interactions of temperature and salinity determine the "tolerance zone" for most fish species. Anadromous fishes-which swim upstream to spawn, such as salmon—also depend heavily on stream flow and water quality (33). If these are altered by climate change, there maybe serious effects on reproductive success. In ail these cases, climate change would be expected to alter the dose associations between species distributions and reproductive success, and the success of the fishery as a whole. Although it is difficult to estimate the magnitude of these changes, impacts could upset the stability of the commercial fishing industry on which many coastal residents rely.

Coastal areas have also been affected by human activities that contribute toxic pollutants and polluted runoff to marine waters. Runoff from developed and agricultural areas and overflow from storm-water systems adversely impact these areas. Nutrients cause algal blooms, which deplete oxygen available for fish and other organisms. Stressed species may become more susceptible to disease and predators. Shoreline construction and dams have also contributed to fishery population declines. Destruction of estuarine and coastal zones limits nursery and breeding areas, and dams prohibit fish from reaching upriver spawning grounds {see vol. 1, ch. 4, and vol. 2, ch. 4).

Regulatory attention has generally not addressed coastal zone management in light of the potential impacts of climate change. Harvest regulations, which are either inadequate or insufficiently enforced, seem unable to keep pace with the decline in fish populations (52). In short, too many fishermen are taking too many fish from overburdened ecosystems. Traditional fishery management is concerned primarily with a few major resources and tends to pay far less attention to the other ecosystem elements that fish depend on (77). Increasing concerns about ecosystem management (see vol. 2, ch. 5) and the upcoming reauthorization of the Magnuson Fishery Conservation and Management Act (P.L 94-265, as amended) and the Clean Water Act (P.L 92-500, as amended) offer opportunities to work toward improving fisheries and their habitat. Below, we highlight the regional importance of marine fisheries and identify particular problems (77).

Regional Characteristics of the U.S. Coastal Marine Fisheries

Acadian-Boreal (Newfoundland and southern Greenland to Cape Cod, MA)

- ***Cultural:*** Indigenous coastal people-New England clam diggers.
- ***Fishing:***
  - —7 percent of the Nation's commercial fisheries
  - —estimated value, $250 million in 1990
  - —multispecies trawl fishery
  - -32 percent of species estuarine-dependent
  - -important species include hard dam, soft dam, American lobster, sea scallops, northern shrimp, Atlantic cod, butterfish, cusk, flounder, haddock, red and white hake (silver hake)
  - —Atlantic cod most commercially important fish in 1989 (valued at $45 million)
- ***Common problems:***
  - -only remaining self-supporting U.S. salmon runs are in Maine
  - -lobsters are overharvested
  - -northern shrimp are at maximum harvest and subject to environmental variability y, especially when waters are warmer

Virginian-Mid Atlantic (Cape Cod, MA, to Cape Hatteras, NC)

- ***Cultural:*** Indigenous coastal people--Chesapeake Bay watermen.
- ***Fishing:***
  - -estimated value, $500 million in 1990
  - —11 percent of the Nation's commercial fisheries
  - —most important species are blue crab and surf and ocean quahog
  - -Chesapeake Bay fish: 87 percent are estuarine-dependent
- ***Common** problems:*
  - -region is the most urbanized and densely populated in the United States
  - -disease, overharvesting, predation, and pollution are rampant-responsible for reductions in harvestable shellfish, forcing many watermen out of business
  - -second to the Gulf of Mexico in the number of point sources of pollution
  - -striped bass began a precipitous decline in 1973

Carolinian-South Atlantic (Cape Hatteras, NC, to Cape Canaveral, FL)

- ***Fishing:***
  - —3 percent of the Nation's commercial fisheries
  - -estimated valued, $189 million in 1990
  - —94 percent of species estuarine-dependent
  - -over half of this harvest fromestuarine-dependent species
  - -most important species indude Atlantic menhaden, bfue crabs, and penaeid shrimp
- *Common problems:*
  - -application of pesticides and fertilizers to extensive commercially harvested forested wetlands
  - -degradation of shellfish habitat due to agricultural runoff and septic system overflow

FloridIan-West Indian (Cape Canaveral to Key West, FL, and West Indies)

- ***Fishing:***
  - -values for individual species are not observed
  - -important species include the Queen conch, spiny lobster, Nassau grouper, and more than 100 reef fishes

(Continued on next page)

Box 2-C-Climate Change and Coastal Fisheries-(Continued)

- *Common problems:*
  - -growing human populations, greater demands, and technological improvements in catch
  - —virtually all assessed reef-fish stocks are overharvested
  - -major tropical storms, including hurricanes, generally affect the area

Louisiana-Gulf of Mexico (Northern Gulf of Mexico from Central West Florida to South Texas)

- *Fishing:*
  - —17 percent of the Nation's commercial fishery (with Vera Cruzian)
  - —estimated value, $648 million in 1989
  - -leading seafood producer among regions
- *Common problems:*
  - -subject to devastating floods, tornadoes, hurricanes and tropical storms, erosion, land subsidence, saltwater encroachment, and sedimentation
  - -second-fastest growing population rate of all regions
  - -more point sources of pollution than any other region
  - —application of pesticides to agricultural lands is the highest among all regions

Vera Cruzian-West Indian (South Texas to Yucatan Peninsula)

- *Fishing:*
  - —fourth leading U.S. port in fisheries value
  - -major commercial species are similar to those of the Gulf region
- *Common problems:*
  - -hurricanes and intense thunderstorms

California-Subtropical Eastern Pacific (Southern California (Los Angeles basin) southward to Mexico and Central America)

- *Fishing:*
  - --major commercial species include Pacific sardine, northern anchovies, and Jack mackerel
- *Common problems:*
  - -most wetlands already lost; restoration doubtful
  - -low-lying coastal areas subject to sea level rise

Oregonian-Temperate Eastern Pacific (California north of Los Angeles to British Columbia)

- *Fishing:*
  - -estimated value, $337 million in 1989
  - -one-fifth of catch estuarine-dependent species, especially Pacific salmon (Chinook, coho, sockeye, pink and chum)
  - -commercial landings of salmon valued at $140 million
  - --other important species include northern anchovies, Pacific sardine, Jack mackerel, and groundfish (flatfishes, rockfish, including Pacific whiting, sable fish, Dover sole, widow rockfish, and others)
- *Common problems:*
  - --conflicts among fishermen, the Fisheries Council, various States, Canada, and foreign fisheries regarding the allocation of resources
  - -worsening freshwater (spawning) habitat has been the main cause of the salmon decline, and wild coho stocks of the lower Columbia River were recently declared extinct

Sitkan-North Pacific (British Columbia to base of Alaska Peninsula)

- *Fishing:*
  - —*56* percent of the Nation's commercial landings of fish (with other Alaskan fisheries)

—estimated value, $1.5 billion in 1990
—5.4 billion pounds (2.5 billion kg) landed in 1990 (with other Alaskan fisheries)
—76 percent of species estuarine-dependent
-most important species include Pacific salmon, Pacific herring, Pacific halibut Gulf groundfish (Pacific cod, stablefish), king crab, and tanner crabs

■ Common problems:
-some rookeries threatened by fishery operations
—Exxon Valdez oil spill severely contaminated coastal areas

Arctic-Boreal/Arctic (Southeast Bering Sea to Chukchl and Beaufort Seas and Canadian archipelago)

■ Cultural: Coastal indigenous people-Eskimo, Aleute

■ *Fishing:*
-most important species include Pacific salmon, Alaska pollock, Pacific herring
—Pacific salmon fisheries rank as the State's largest nongovernmental employer
-provides an integral part of Alaska's native culture and heritage

■ *Common problems:*
-some stocks (chinook and coho) maybe harmed by foreign high-seas catches, and some salmon maybe regionally overfished
-destruction of spawning and rearing habitat
-human population in this area is expected to increase by 380 percent between 1960 and 2010

Aleutian-North Pacific (Alaska Peninsula base to Aleutian and Pribilof Islands and including southwest Bering Sea)

■ *Fishing:*
-estimated value of groundfish, $352 million in 1990
--dominant groundfish groups are walleye pollock, flatfishes (Yellow sole, rock sole, other), Pacific cod, Atka mackerel, and shrimp
—Alaska king crab value, $88 million in 1990

■ *Common problems:*
–*The* U.S. fishery for shrimp in Alaska is at a low level, and potential yields are not well-understood (91)

insular-lndo Pacific (Tropical Indian and Pacific Oceans; not shown in figure)

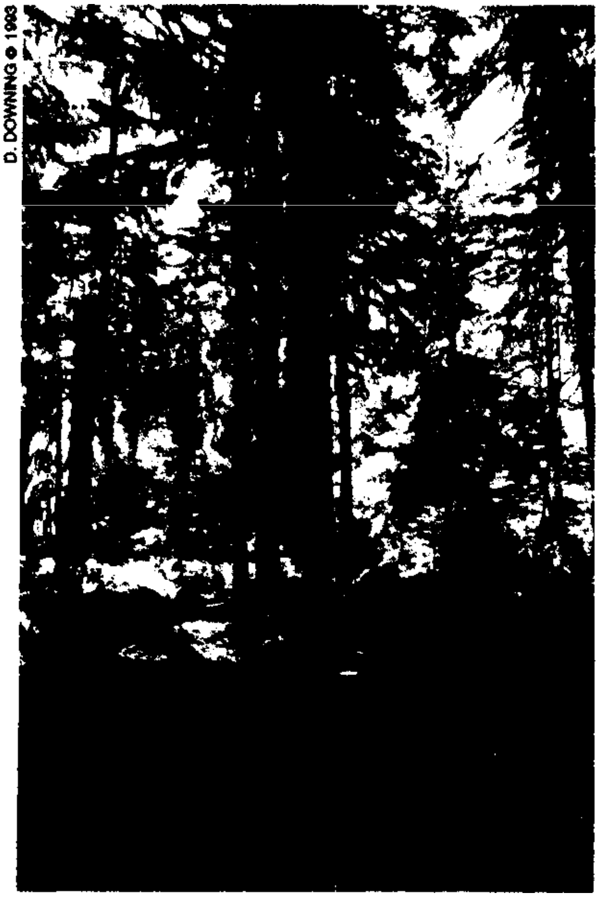
■ *Cultural:* Coastal indigenous people-Papuan, Micronesia, and Hawaiian

■ *Fishing:*
—7 percent of the Nation's commercial fisheries taken in the Pacific United States and Hawaii
-major species include invertebrates species (spiny and slipper lobsters; gold, bamboo and pink corals), bottom fish (snappers, jacks, groupers, Pacific armorhead), tropical tunas (yellowfin and skipjack), and albacore

■ *Common problems:*
-coastal pollution
destructive fishery technologies (explosives, poison, etc.)
-overfishing by foreign fleets
-ambiguous application of Federal environmental laws

SOURCES: M.R. Chambers, "U.S. Coastal Habitat Degradation and Fishery Declines," In: *Transactions of the North American Wildlife and Natural Resources Conference* (Washington, DC: The Wildlife Management Institute, in press); U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS), *Our Living Oceans, The First Annual Report on the Status of the U.S. Living Marine Resources*, NOAA Technical Memo, NMFS-F/SPO-1, 1991; C.G. Ray, G. McCormick-Ray, and F.M. Potter, *Global Climate Change and the Coastal Zone: Evaluation of Impacts on Marine Fisheries and Biodiversity of the U.S.*, contractor report prepared for the Office of Technology Assessment, 1993.

D. DOWNING © 1993



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ters in only a small area of the southern United States along the coast of the Gulf of Mexico. Warmer winter temperatures could greatly expand the overwintering range, allowing for much larger populations to develop in the spring, and potentially leading to increased plant damage (94).

The Role of *Precipitation and Soil Moisture*

Precipitation-or more precisely, soil moisture (the result of a combination of precipitation, infiltration, runoff, and evaporation--directly affects plant growth through its role in photosynthesis. Although average annual precipitation is often used to characterize climate zones, the seasonal distribution is more significant than the annual total. Adequate moisture during the growing season is critical. Seeds need moisture to germinate, and young plants-both annuals and perennial s-are often quite sensitive to drought. Vegetation may respond by defoliating, which reduces water and nutrient demand, helping plants survive dry periods. Precipitation during the growing season controls wood growth as well as the size and maturation time of seeds (21, 42). Decreases in soil moisture can slow growth, interfere with reproduction, and cause plants to die early. Increases in soil moisture are less likely to cause harm unless the soil in normally dry areas becomes saturated with water for extended periods. Standing water can drown the roots of plants not adapted to wetlands by interfering with normal respiration; extended saturation of roots may kill the entire plant.

Direct effects of moisture on many land animals may often be less important than the indirect effects-that is, moisture affects plant growth, which then affects the availability of food and habitat (86). However, moisture does play a critical, direct role in the natural history of invertebrate species (e.g., snails) and is essential to the survival and reproduction of amphibians (105). Fish and other aquatic organisms that inhabit rivers and streams can be threatened by either too little water during drought periods or too much runoff flowing into streams. During periods of high precipitation, water may become turbid, interfering with the health and functioning of the aquatic ecosystem. Moisture is also important to many microorganisms and fungi, including many that contribute to human disease or are considered forest or agricultural pests (described in more detail below and in vol. 1, ch. 6, and vol. 2, ch. 6).

sunlight

The amount of available sunlight, or *solar irradiance,* that strikes vegetation is an important variable in photosynthesis and productivity. Individual plants or species that make up the canopy, those near the edges, or those growing in clearings receive more light, whereas those in the understory are better adapted to lower light levels. Solar irradiance varies regularly from season to season and from latitude to latitude. Cloud cover also affects the quality and quantity of solar irradiance and its distribution over time, allowing less sunlight to reach the surface on cloudy days. If climate change is accompanied by increased cloudiness, as some models predict, overall plant productivity could decline. Water stress and high temperatures may also affect plant response; however, plant response to changes in solar irradiance is complex and difficult to predict (19).

In addition to the total amount of solar irradiance, the number of hours of sunlight per day (day length, or *photoperiod)* plays a role in plant fictions such as flowering and the setting of fruit, and influences the rising of sap in deciduous trees, such as sugar maple, in spring. Light quality may also affect productivity. For example, cotton depends on very regular day lengths, which only occur in southern latitudes. Plant species that might migrate northward as the climate warms may not be able to reproduce as effectively because day length is longer at northern latitudes during the summer and drastically reduced during the winter (41). On the other hand, adaptation to a shorter photoperiod may limit northward movement.

Increased CO_2

Rising concentrations of atmospheric CO_2 may affect the rates at which plants grow, respire, use water, and set seeds. This is known as the CO_2 *fertilization effect (see* box 2-D). Numerous laboratory experiments and intensively managed agricultural systems that have been studied suggest that CO_2 has the potential to boost plant growth and productivity by speeding the rate of photosynthesis, relieving nutrient stress (by improving efficiency of nutrient uptake and use), increasing water-use efficiency, decreasing respiration (which is a major source of water loss), slowing the rate at which leaves die, and speeding the development of seeds (27,42, 66,68,69, 93).

Theoretically, the fertilization effect could compensate for the water stress faced by plants in areas that become warmer and drier due to climate change, and might actually increase the total global biomass (41). On the other hand, various studies have suggested that in some settings, there may be limits to and even detrimental effects from increased CO_2. For example, changes in the amount of carbon in plant leaves affect nutritional quality (65), which could mean that foraging animals would have to eat more leaves to gain the same amount of nutrition. Increased CO_2 may also cause starch to accumulate in plant leaves to such high concentrations that it could actually harm the plant by interfering with photosynthesis (50), though there is no field data to support this.

Numerous complex factors interact to determine the extent to which fertilization actually occurs in natural ecosystems, and many uncertainties about the overall impacts remain. Plant responses to CO_2 vary according to species and stage of development, as well as to water and nutrient availability (42). Some plant species already use CO_2 efficiently and will not receive much of a boost, whereas other species are now limited by their inefficient use of CO_2 and could profit from higher atmospheric concentrations.

Plants may experience the greatest productivity boosts from increased CO_2 when other nutrients are plentiful (7). Thus, for example, field studies have demonstrated that higher CO_2 concentrations boost productivity in Chesapeake Bay salt marshes, where water entering the bay is rich in nutrients (2, 27, 28, 107), but CO_2 fertilization does not appear to be significant or permanent in nutrient-limited tundra and other arctic ecosystems (32, 68). Few other ecosystem types have yet been tested in the field. Intensively managed agricultural systems, in which nutrient deficien-

Box 2-D-Coping with Increased CO_2: Effects on Ecosystem Productivity

Climate, particularly the combination of temperature and moisture, largely determines where plants grow (14), and vegetation, in turn, is key to the distribution of animal species. Generally, climate belts vary within the United States from humid and damp in the Southeast and Northeast to moderately dry in the central regions, to arid in much of the West except for a humid belt along the Pacific Coast from northern California to Washington. Temperature and precipitation maps of the United States reveal bands across the Nation from north to south for temperature, and east to west for precipitation. Vegetation growth, in type and lushness, varies with temperature and altitude, but in all cases, solar irradiance is critical to the productivity of living things.

The sun provides the energy that fuels ecosystems; this energy is transformed through the processes of photosynthesis and photorespiration. During photosynthesis, plants use water and the energy from sunlight to convert carbon dioxide (CO_2) and other nutrients into organic matter and oxygen. This process is dependent on the concentration of $C0_2$ In the air (i.e., ambient CO_2, and, therefore, changes in normal CO_2 levels may affect photosynthesis and, likewise, plant growth. External environmental factors, such as temperature and the availability of nutrients, may modify photosynthesis as well. The output of organic matter by an ecosystem is characterized as its biological or *primary, productivity.* Linked to primary productivity is *nutrient cycling-the* absorption by plants of vital nutrients (e.g., carbon, nitrogen, and phosphorous) and their subsequent conversion into usable forms.[1] The combination of energy and nutrient cycling in vegetative systems determines the nature of the assemblage of plants and animals in a given area. Certain types of plants, growing in certain conditions, have higher primary productivities than others. Ecosystems that are highly productive often support both large numbers of other organisms and many diverse species—that is, they are characterized by high secondary *productivity* and high biodiversity.[2] Productivity is also key to *carrying capacity—the* number of organisms that a particular area can support. Carrying capacity can vary from year to year based on many factors, including climate,

1 Carbon is derived from CO_2 through photorespiration; nitrogen andphosphorousare taken up from the soil and converted to usable forms during the same process.

2 Although definitions vary, biodiversity generally refers to the "variety and variability among living organisms and the ecological complexes in which they occur" (89).

cies can be remedied by adding fertilizers, maybe more likely to receive a productivity boost from additional CO_2 than are natural ecosystems. Many complex interactions determine to what extent, if any, the CO_2 fertilization effect documented in laboratory studies will occur in natural ecosystems. The responses will likely vary so much fromn ecosystem to ecosystem and location to location that there cannot be a simple answer to the question of whether it will present a net benefit or a net harm.

■ Indirect Climate Impacts Through Stressors

Climate will also have numerous secondary impacts. Increases in herbivores, disease, and fires, which play an important and visible role in mediating the near-term effects of climate change on communities and ecosystems, could result. For example, although few trees in a forest may die outright due to heat or drought, it is likely that many trees will sicken and become more susceptible to insects and disease. At the same time, trees in decline will provide more fuel for fires (83). The extent to which an area is stressed by anthropogenic activities, such as land clearing and pollution, will also influence the effects of climate change.

Insects anti Disease

Climate may affect the proliferation of insects and disease in numerous ways. Higher temperaand refers to the indivdual species or mix of species in a particular ecosystem. overall, however, ecosystem health and productivity is dependent on the availability of sunlight water, nutrients, and $C0_2$.

Considerable experimental evidence has shown that an increase in the atmospheric concentration of CO_2 has the potential to increase plant growth and ecosystem productivity (28). This expected effect of Increased plant productivity in the presence of elevated CO_2 concentrations is known as the "CO_2 fertilization effect," and it **is** expected to be particularly pronounced in the presence of plentiful supplies of light, water, and nutrients. Over the long run, this effect may help alleviate the rate of global warming by drawing excess $C0_2$ from the atmosphere (8), although researchers are uncertain about the extent to which this will occur (vol. 2, see box 8-B).

Plants vary in their response to CO_2 in part because of differing photosynthetic mechanisms—most species follow the C_3 pathway and some, the C_4 pathway. C_3 species (e.g., wheat, rice, soybeans, and all woody plants) are not yet fully saturated with CO_2 and may greatly increase their productivity, whereas C_4 species (e.g., *corn,* sorghum, sugar cane, and tropical grasses) are almost saturated with $C0_2$ and their productivity may not be much affected. Added productivity of C_4 species from doubled $C0_2$ may be in the O to 20 percent range, and in the 20 to 80 percent range for C_3 species. The differential effects of $C0_2$ could alter the dynamics of competition among species, with C_3 plants potentially prospering at the expense of C_4 species. In agriculture, this competition among plants may prove important. Because 14 of the world's most troublesome weed species are C, plants that occur amidst C_3 crops, enhanced $C0_2$ concentrations may make such weeds less competitive (73). However, many of the major weeds of corn (a C, crop) in the United States are C_3 plants; climate change may favor the growth of these weeds. Similarly, natural grassland ecosystems where C_4 grasses now dominate maybe invaded by weedy plants. Competitive success, however, does not depend solely on response to CO_2. Competition among species in natural ecosystems will continue to depend on the ability of species to tolerate soil, light, temperature, and moisture conditions. Because of the complex effects of competition among species it is by no means clear how the overall productivity of natural ecosystems will increase under elevated $C0_2$ (8).

SOURCES: B.G. Drake, "The Impact of Rising CO_2 on Ecosystem Production," *Water, A/r, and Soil Pollution,* vol. 64, 1992, pp. 25-44; P.M. Kareiva, J.G. Kingsolver, and R.B. Huey (eds.), *Biotic Interactions* and G/06a/Change (Sunderland, MA: Sinauer Associates, Inc., 1993).

tures could accelerate the growth rate of insects. If the number of warm days per year increases, the number of insect generations per year may increase. Also, the range of many insects is determined by cold winter temperatures. As described in the section above on temperature impacts, milder winters could allow insects such as leafhoppers (agricultural pests) to spread north of their present range. Hot, dry conditions encourage the growth of numerous fungi in forests (such as *Armillaria mellea,* a fungus that causes root disease), which can cause widespread damage in many types of forests. Warm, humid conditions, which favor soil and leaf-litter organisms as well as decomposition, may encourage the growth of other fungi and insect pests, such as aphids, which can also be quite damaging.

Once stressed by heat or drought, vegetation may become more susceptible to pests (58). Changes in CO_2 concentration may affect the composition of leaves, potentially making them less nutritious, so insects might have to consume more to obtain the same amount of nutrients (8). Thus, damage from insects and disease might increase, and in some cases, the effects of climate change may become noticeable over the short term. Over the long term, damage from insects and disease may cause less-adaptable species to decline, potentially opening the way for exotic species to migrate into communities (21, 83).

Exfreme *Events*

Periodic but unpredictable events such as extended drought, storms, and fire are among the primary natural factors that shape ecosystems.

Severe storms accompanied by high winds and rain, hail, or ice may cause significant wind damage in forests, toppling older trees and leaving a trail of debris, but also clearing space for new vegetation to take root (see vol. 2, ch. 6). Storm damage may reduce habitat for birds and wildlife that prefer a dense forest canopy and little undergrowth, but could increase food and habitat for animals that thrive in mixed forests with cleared areas, such as deer. In coastal areas, tropical storms and their accompanying high winds and waves play an enormous role in coastal processes (see vol. 1, ch. 4).

The occurrence of fire is critical in determining vegetation types, successional history, and wildlife species in forests in more arid areas, such as prairie and chaparral, and in wetlands. Fire is important in maintaining prairie, but the control of fire has virtually eliminated most naturally occurring prairie areas. In some wetlands, including the Okefenokee Swamp and others along the Atlantic coastal plain, fire has played an important role in clearing shrubby growth and maintaining wetland vegetation. Under normal conditions, fire clears out forest undergrowth, damaging some trees but allowing new ones to take root, thus creating a more open stand of trees (see vol. 2, box 5-I).

Fire has been recognized for playing an important role in vegetation succession. In areas where fires have been suppressed and fuels have accumulated, however, fires may become so hot that they cause severe damage, and forests may regenerate slowly or not at all. For example, chaparral ecosystems in the foothills of California rely on fire to spur the growth of the shrubby plants that dominate the area; however, in areas where fire has been suppressed, a fire that does occur will be more damaging, and the regeneration of chaparral species maybe affected. Natural fire regimes are influenced by the frequency of lightning (which may or may not increase as the climate changes), the presence of hot, dry winds to carry a fire once ignited, and an abundance of dry fuel provided by the buildup of undergrowth or vegetation that has died from drought or disease, as well as by dry, living vegetation (22). Fires may increase under changed conditions, but the ability of species to regenerate in areas with less moisture, because of climate change, maybe reduced. Thus, recovery may not occur.

Anthropogenlc Forces

Climate change may serve to make species or ecosystems more susceptible to stresses from human disturbance. Human activities have become so widespread that they are now a pervasive influence on much of the environment. Agriculture, timber harvesting, road building, and urban development have fragmented the landscape, carving natural areas into ever smaller and less-connected patches (see vol. 2, box 5-E). This fragmented landscape may offer few opportunities for organisms to adapt to a changing climate. Fragmentation often isolates small populations of plants and animals, which may limit genetic diversity and make them less able to adapt to change over time. These small, isolated populations may also be prevented from moving to new and more favorable areas by barriers such as roads, buildings, or large cultivated fields. In addition, humans may respond to changes in climate by adopting land uses (such as more extensive cultivation) that further fragment the landscape, exacerbating the stresses on flora and fauna.

Human activities may also result in the introduction of weedy and nonindigenous species that flourish in the disturbed areas and that may eventually outcompete other species, leading to local extinctions and reducing the diversity of ecosystems. In areas where weedy or nonindigenous species already pose a threat to a particular species or ecosystem, the added stress of climate change may further tip the balance in favor of weedy species that thrive in disturbed conditions. Similarly, air pollution in urban areas, and in much of the Northeast, already threatens the health of many plant species. Climate change could further weaken individuals that are already stressed by pollution, and could make them more susceptible to insects or diseases.

Although climate change might not be the proximate cause of ecosystem harm, it could increase the potential for damage. In sum, climate change may exacerbate many other stresses, both natural and anthropogenic.

Direct Climate Impacts on Ecosystems

As temperature and moisture regimes change, climatic zones could shift several hundred miles toward the poles, requiring plants and animals either to migrate or adapt to a new climate regime. The rate of change will determine the degree of impacts: some species might be able to keep up with change, others could become extinct--either locally or globally (see box 2-E). The ability of a species to adapt will be critical to its survival. By the same token, the decline and disappearance of species that are unable to adapt will decrease the biodiversity of ecological communities. Such a reduction may leave the remaining species more vulnerable to catastrophic events. Ecosystems, the assemblages of plants and animals, are unlikely to move as units, but will instead develop new structures as species abundance and distribution are altered (42).

The general distribution of ecosystems is related to climatic conditions. The Holdridge life zones shown in figure 2-10 characterize regions of North America according to the general vegetative ecosystem suited to current climate conditions. Under climate change scenarios projected by four GCMS, this distribution of vegetation zones will shift significantly (34). There is general agreement among scenarios about the direction of change: the extent of tundra and cold-desert climate zones will decrease, and the area of potential forest and grasslands will increase. Despite this general agreement, there are qualitative differences, with dry forest types increasing under some climate scenarios, and moister forests increasing under others. Overall, as much 80 percent of the land in the United States may shift to a new vegetation zone (see fig. 2-11). Associated with such shifts in climatic zones could be large-scale disturbances to existing ecosystems.


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Alpine areas are awash in color when spring and surmmer flowers bloom.

Adjustment of Species

Natural adjustments to climate change could begin with the failure of some species to reproduce because flowering, fruiting, and seed germination-and in some animals, reproductive physiology or mating behavior-could be affected. All of those processes are particularly sensitive to climate. Reproductive failure might allow new species to invade, or give a competitive advantage to other species already present. Thus, a gradual adjustment could occur, although in

Box 2-E—Responses of Natural Systems to Climate Stress: Adaptation, Migration, and Decline

Responses of individuals and communities to climate stress fall into three basic categories: adaptation, migration, and decline and die-back. The extent to which individuals and communities respond may depend on the rate and magnitude of climate change.

Adaptation

It is difficult to predict which species, populations, communities, ecosystems, and landscapes will prove most able to cope with climate change because of the many variables and uncertainties that exist. However, biological diversity affords populations the ability to adapt to changes in the environment by serving as a natural protection against shocks and stress. "The rule that there is security in diversity is an axiom of ecology as well as finance. . . . Biological diversity is a natural protection against surprises and shocks, climatic and otherwise. Among diverse species will be some adapted to prosper in a new landscape in new circumstances" (21).

In species with diverse gene pools, the chances will be greater that some individuals will possess a combination of genes that is useful in new environments, such as genes that determine drought resistance and tolerance to extreme temperatures or salinity. These individuals will be the most likely to survive and pass along adaptive characteristics to their offspring. At the community level, diversity may also increase the chances for survival. For example, a forest stand composed of a single species or of trees that are all the same age may be less able to withstand climate change than a forest composed of several species within a range of ages. Biodiversity is generally considered an important trait at the ecosystem level, too, because it increases the charms that the overall structure and function of an ecosystem will persist or adapt to changing conditions, even if some species that were formerly part of the ecosystem no longer remain (21).

Some species may prosper under climate change conditions, others maybe able to adapt relatively quickly, and still others may prove unable to adapt at all and may face extinction. As a result, ecosystems may change as different plant species become dominant and different animal species become associated with altered habitats (21). Species in varied landscapes may be able to find microclimates within their current ranges that are suitable, and some species may even thrive and expand their ranges. Species already adapted to disturbed environments (e.g., weedy species) may be particularly resilient to changes in climate. On the other hand, species with extremely specific and/or narrow habitats may be more at risk to changes in climate. In addition, species on the fringe of habitats, in transitional zones, may also experience greater stress from the impacts of climate change because these species may not be well-established. On the whole, some species maybe restricted by a variety of biological and physical limitations, but others will be able to adapt to the conditions brought on by climate change.

Certain wildlife species may be able to alter their diet in favor of other, exotic but newly available plant species. White-tailed deer, mule deer, moose, elk and other species benefit from human activities that disturb ecosystems and alter habitat (22). if, for example, climate change contributes to the conversion of a dense, forested habitat to a more open area, species such as these would likely benefit. Similarly, some birds, such as robins, starlings, and gulls, may adapt easily to alterations in habitat caused by climate change (22). These species tend to feed on a variety of different organisms and are territorial and aggressive in nature. They are very good at vying for resources with less competitive and smaller birds.

Migration

Some communities and ecosystems might have to migrate to survive the environmental conditions that could result from climate change. Most species of vegetation and wildlife have the ability to migrate to some extent. However, adverse conditions, such as landscape fragmentation, may limit this ability (see vol. 2, ch. 5). In addition, the ability of a species to migrate depends not only on environmental conditions but on dispersal rate. Animals can generally disperse much more quickly than plants (22). However, because wildlife is dependent on vegetation for survival, many species are forced to migrate only as fast as vegetation does (94). Therefore, the health and survival of many species will be dependent on the response of vegetation to climate change.

Dispersal rates for vegetation are considerably slower than the projected rate of climate change, and, therefore, some species will not be able to migrate as fast as their corresponding climatic regimes. For example, most North American tree species can migrate at 12 to 25 miles (20 to 40 kilometers) per century, but climate regimes are expected to migrate at much faster rates, in some cases by at least an order of magnitude (106). In particular parts of the United States, climatic regimes may shift hundreds of miles by as early as the middle to the end of the next century (43, 74). Because some species will be unable to keep up with the pace of climate change, their range may be reduced, or they may become extinct.

Coastal and estuarine wetland vegetation will likely attempt to migrate inland as the sea level rises. Their success in migrating will depend on the steepness of the coast and obstructions to migration that might exist, such as rocky areas and human-built structures. Wetlands fringing the playa lakes of the Southwest may retreat along with the water levels if increased evaporation, in a hotter and drier climate, causes water levels to drop. Alpine tundra will likely migrate toward higher altitudes as lower areas become warmer and drier.

In all of these cases, wildlife and other organisms that are dependent on these ecosystems for survival may attempt to migrate as well. The least Bell's vireo, an endangered species completely dependent on riparian vegetation for survival, may lose a great deal of habitat if inland drying occurs (22). The jack-pine forest in northern Michigan, which provides critical habitat for the endangered Kirtland's warbler, could die off and be replaced by a sugar maple forest in as few as 30 years under climate change conditions (11).

In each case, the ability to migrate will be limited by adjacent land-use patterns and the availability of areas to which organisms can migrate. "Barriers," such as roads, cities, and agriculture, degrade habitat quality and limit the ability of vegetation and wildlife to move or spread. Roads may pose a formidable physical barrier to animal migration, and even plants may have difficulty "moving" across roads if their seeds are too heavy to be dispersed easily and over large distances by wind. Vast expanses of suburban developments now occupy sites that formerly could have offered either suitable destinations or pathways for migration of plants and animals from one locale to another. Many animals will not cross seemingly small obstructions, such as railroad clearings or roads, to get to nearby suitable habitat (22). Agricultural land and other highly managed areas prevent species from naturally establishing themselves. In general, the ability of plants and animals to migrate in response to climate change is largely affected by anthropocentric influences and factors. Nevertheless, many species will be sufficiently resourceful to migrate successfully, and some may even thrive and expand their ranges.

Decline and die-back

If climate change is rapid or severe, some species, ecosystems, and landscapes may not be able to adapt Changes in climate may cause severe loss of function or value in certain species, ecosystems, and landscapes, or may result in the disappearance of certain species or entire ecosystems. Just as human land-use patterns may limit migration, they may also ultimately limit the chances for some species or ecosystems to survive. Some species are well-suited to a very narrow set of environmental conditions, but lack characteristics that would allow them to move or adapt easily to new environments. When human activities reduce or eliminate their normal habitats, these species are likely to show signs of stress leading to decline or die-back.

In forest systems, decline and die-back occur when a large proportion of a tree population exhibits visible symptoms of stress, unusual and consistent growth decreases, or death over a large area. Such distinguishing characteristics can be irregular in distribution, and discontinuous but recurrent in time. In all cases, however, decline and die-back are the result of complex interactions of multiple stress factors (83). Some common abiotic factors include drought and low- and high-temperature stress. Biotic agents include defoliating insects, root-infecting fungi, and borers and bark beetles. Typicalty, declines are initiated by an abiotic stress, with mortality ultimately caused by a biotic stress agent.

(Continued on next page)

Box 2-E—Responses of Natural Systems to Climate Stress: Adaptation, Migration, and Decline-(Continued)

More often than not, the decline and die-back scenario is a direct or indirect response to a change in some climatic variable. Changes in precipitation and temperature patterns have been shown to have an interactive and sequential influence on the health of forest systems. Drought conditions tend to enhance the possibility of insect attack. For example, sugar maple in northern forests is extremely sensitive to extreme changes in temperature. Moist, warm weather is particularly conducive to the spread of Eutypella canker, a serious stem disease, whereas drought periods favor the spread of *Armillaria* root decay; wind damage and sudden temperature drops significantly favor certain cankerous fungi, and the Iack of snow cover can result in deep root freezing (83). Nevertheless, these phenomena have sufficient common characteristics in various forest tree species to allow for some generalization; changes in climate will almost certainly exacerbate existing stresses, further influencing forest decline and die-back.

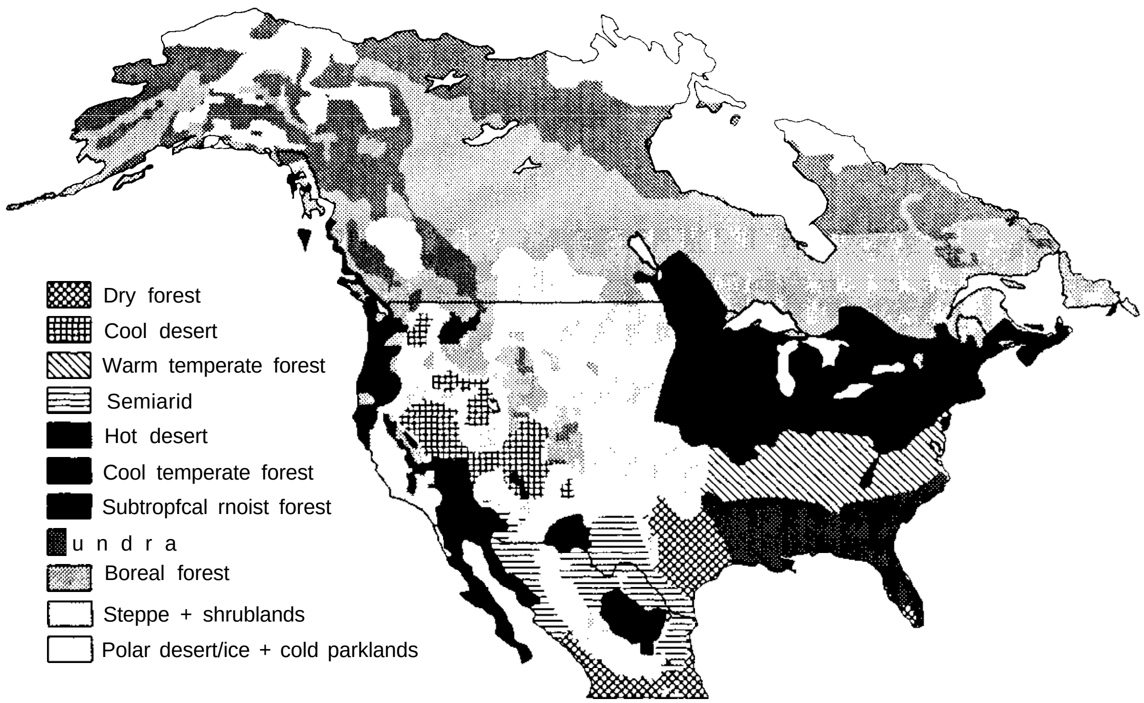
Some ecosystems will be influenced by changes in sea level rise. For example, coastal wetlands have been able to keep pace with a sea level rise of approximately 0.04 inches (1 mm) per year for the past 3,000 years, which is the rate at which many marshes are able to accumulate material. However, climate change is sure to increase the rate at which sea level rises, which may ultimately drown these wetlands (98). Likewise, alpine and arctic ecosystems may shrink and, in some sites, disappear if the amount and speed of climate change exceed the rate at which these systems can migrate upslope. On the whole, the rate at which climate change occurs will have a direct effect on the rate at which ecosystems experience declines in population and die-back responses.

SOURCES: P.M. Kareiva, J.G. Kingsolver, and R.B. Huey (eds.), *Biotic Interactions and Global Change* (Sunderland, MA: Sinauer Associates, Inc., 1993), 559 pages; R.L. Peters and J.D.S. Darling, "The Greenhouse Effect and Nature Reserves," *Bioscience,* December 19S5, pp. 707-17; C. Zabinski and M.B. Davis, "HardTimes Ahead for Great Lake Forests: A Climate Threshold Model Predicts Responses to $C0_2$-induced Climate Change," in: *The Potential Effects of Global Climate Change on The United States, Appendix O: Forests* EPA-230-95-89-054, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 19S9).

some areas, or for some species, slow processes of seed dispersal, soil development, and achievement of sexual maturity may curtail adaptation. Pollen records suggest that temperate forests can migrate at approximately 62 miles per century, but the correlated growing-season conditions may shift by 200 miles for every 4 OF (2 'C) of warming, so even in the lower range of climate change predictions, some tree species might not be able to keep up. Modeling results suggest that if a forest includes some species that are better adapted to a new climate, those species may become dominant, but if none of the species are better adapted, the whole forest might decline. However, climate change is unlikely to decimate vegetation and make land barren, except in limited areas that are now arid and that may become even drier. Rather, ecological communities are likely to change as rapidly moving and widely dispersing species (e.g., weeds) increase in number, while slower-moving species decline and disappear (21).

The adjustment process will not occur uniformly across species, communities, and ecosystems. Plants or animals attempting to migrate to new areas may face competition from those that still remain. Some migrators may be able to compete effectively, and others may not. For example, wetland vegetation may attempt to take root further inland as sea level rise inundates coastal marshes, but existing inland plants that survive may temporarily block the path. Migration may also be blocked by areas rendered unsuitable as a result of human use. Some wetland species may be more capable than others of establishing themselves among the inland vegetation. Thus, many species, as well as ecosystem processes and interactions, may be reshuffled,

Figure 2-10-The Distribution of Holdridge Life Zones Under Current Climate Conditions



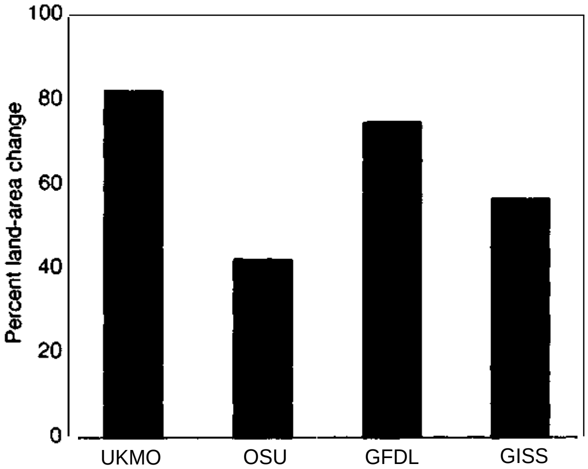
SOURCE: Office of Technogy Assessment, 1993, adapted from L.R. Holdridge, Life Zone Ecology(San Jose, Costa Rica: Tropical Science Center, 1987), and W.R. Emanuel, H.H. Shugart, and M.P. Stevenson, "Climatic Change and the Broad Scale Distribution of Terrestrial Ecosystem Complexes," Climatic Change, vol. 15,1985, pp. 75-82.

especially at the boundaries of current ecological zones, where ecosystems are the least mature and the most stressed (21). However, plants that are capable of migrating or adapting may not necessarily be the most desirable. Climate change could lead to an increase in less-valued species and a change in ecosystem composition.

Development of Asynchrony

The migration of vegetative species could put many organisms "out of sync' with their environments and disrupt many symbiotic relationships. As plants migrate inland and upland, pollinators and other vectors that assist in the reproductive process may not move at the same rate. If insects and birds are left behind, plants will face significant losses in populations, and some may become extinct. This may be especially true for organisms with very specific ranges, whether they be limited by topography, precipitation, or temperature. In addition, insects and birds may arrive at their migratory destinations prematurely, before feeding and nesting conditions are optimal, or too late, after resources have been exhausted. Organisms will be exposed to different and varying conditions, such as photoperiod, intensity of sunlight, and temperature, unlike what they are currently acclimated to, which may affect reproductive capabilities as well. In addition, some plant species may alter nutrient cycles and other processes in order to adapt to new soil and moisture conditions. This could not only adversely affect the health of plants, but could reduce their nutritional value, thereby affecting the health of the wildlife that depends on them for sustenance. Marine species will face similar

Figure 2-n-Percent of U.S. Land Area Shifting Holdridge Life Zones After CO_2 Doubling



NOTE: UKMO-United Kingdom Meteorological Office, OSU-Oregon State University, GFDL=Geophysical Fluid Dynamics Laboratory, and GISS=Goddard Institute for Space Studies.

SOURCE: P.N. Halpin, "Ecosystemsa at Risk to Potential Climate Change," contractor report prepared for the Office of Technology Assessment, June 1993.

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Many species of birds, like this Clark's nutcracker, are dependent on specific habitats that provide sustenance and cover. Fragmentation of these areas could have a dramatic impact on populations unable to locate mating, nesting, feeding, and over-wintering habitat.

difficulties because most fish require specific conditions for reproductive activities to occur at optimum rates. Anadromous fish (those that swim into freshwater streams from the sea to spawn) may be most affected as salinity in intertidal waterways is altered due to sea level rise. On the whole, the migration of vegetation in response to altered climate and the subsequent response of insects, birds, and other organisms could have significant impacts on ecosystem structure, function, and value.

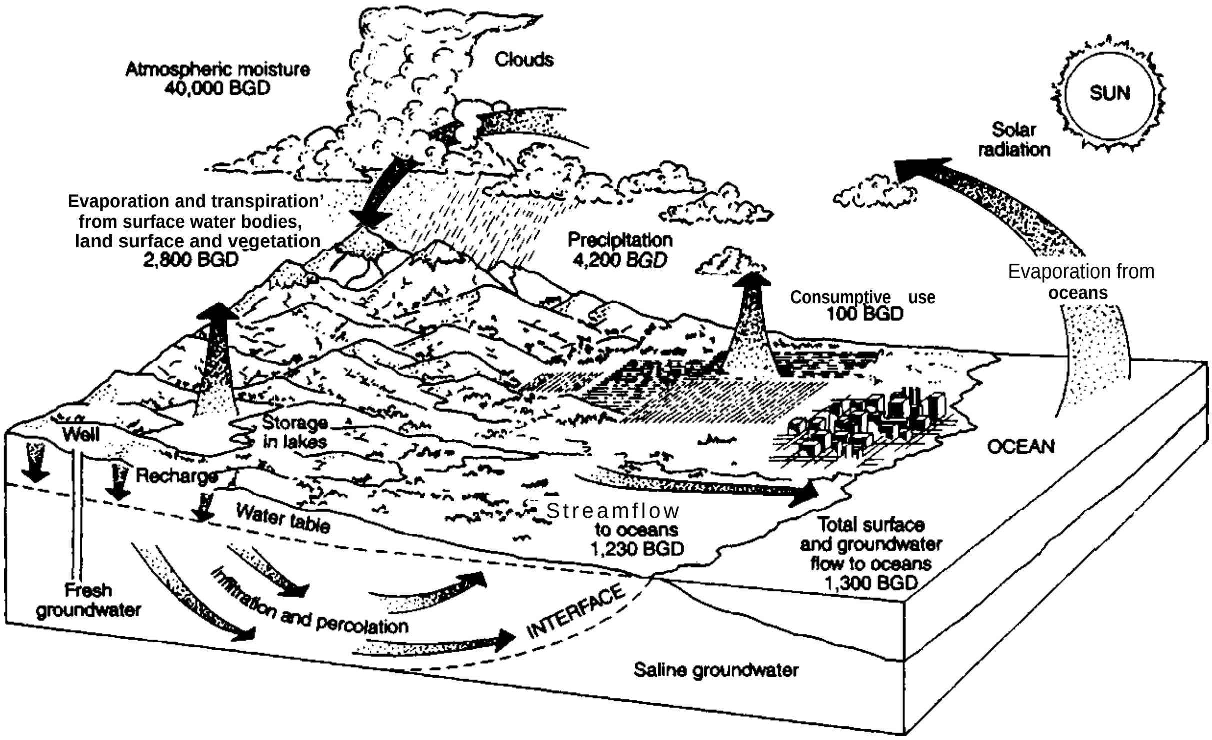
Interactions Among Climate, Ecosystems, and the Physical Environment

Climate change will affect living organisms both directly and indirectly, as described above, but it will also affect the processes of the physical environment in which they exist-soils and nutrient cycling, the hydrologic cycle, and photorespiration. Effects on the physical environment and living organisms will interact and cause further modifications to the environment and the organisms. Because the various biological and physical processes are intricately interconnected, with many feedbacks among them, it is difficult to predict what the overall effect of climate change will be. The following sections suggest the range of interactions between climate and the biological and physical processes it affects.

Interaction of Water Resources and Ecosystems

Water influences ecosystem function, but ecosystems, in turn, influence the flow of water through the hydrologic cycle (see fig. 2-12 and vol. 1, ch. 5). Water falls to the Earth's surface in the form of precipitation. Some water stays on the surface and evaporates relatively quickly. Some percolates into the soil and is taken up by vegetation, from which it is eventually transpired through the processes of photosynthesis and respiration. The remaining precipitation moves from upland to low-lying areas-on the surface, as shallow groundwater flow toward rivers or streams, or by infiltrating more deeply into and through aquifers, eventually emptying into rivers,

Figure 2-12—The Hydrologic Cycle Shows How Water Moves Through the Environment



NOTE: BGD = billions of gallons per day, To convert gallons to liters, multiply by 3.785.

SOURCE: Office of Technology Assessment, 1992.

lakes, and oceans, from which it eventually evaporates-and the cycle begins again.

The extent to which water evaporates, discharges to surface water, seeps into the ground, or remains on the surface depends on the amount and form of precipitation, the temperature, the topography, the nature of soils (whether sandy or clayey, and the content of organic matter), and the types of vegetation. Vegetation moderates the cycle in several important ways: it adds to the organic matter of soils, increasing their water retention; roots and stems may physically anchor soils and slow the passage of water and channel water below ground, further reducing runoff; and canopies of leaves reduce droplet impact on the soil and affect the rate of evapotranspiration. Because of these interactions, changes in vegetation may cause changes in the hydrologic cycle. For example, a semiarid grassland that is stripped of vegetation through overgrazing (by either wild or domestic herbivores) may lose some of its ability to retain water as plants no longer slow runoff or take up water to release it slowly later. The interaction of changes in the ecosystem and the hydrological system may eventually lead to desertification.

Climate interacts with the hydrologic cycle on different scales. Global average temperatures affect how much moisture can be carried in the air, how quickly clouds form, how readily clouds yield precipitation, and how much precipitation occurs and in what form (e.g., rain or snow), as well as the large-scale wind patterns that carry clouds from one region to the next. On a regional or local scale, temperature affects the rate at which water evaporates from the surface or transpires from plants. Temperature further affects the rate of evapotranspiration by influencing the form in which precipitation falls. Rain typically runs off soon tier it falls. Snow may remain on the surface for a considerable amount of time, with the delayed runoff supplying downstream and adjacent areas with water during the spring. Thus, global and regional changes in temperature and precipitation can affect the hydrologic cycle and the related ecosystem interactions in numerous ways.

The predicted changes in global climate will essentially increase the rate at which the hydrologic cycle occurs, although different hydrologic models yield rather different scenarios of what the regional results will be (79). As outlined above and in volume 1, chapter 5, total global precipitation is expected to increase 7 to 15 percent, but warmer temperatures will allow for greater and more rapid evapotranspiration, which could lead to drier conditions in some areas (particularly in midcontinent, midlatitude regions). Hydrologic studies suggest that river watersheds can be quite sensitive to even small climatic changes, particularly in arid and semiarid areas, where annual runoff tends to be highly variable. In river basins where snowmelt is important, both the annual total runoff and its seasonal distribution can be affected by changes in temperature and precipitation. Overall, climate change is expected to lead to significant changes in both high-flow and low-flow runoff extremes (42).

Soils, Nutrients, and Vegetation

Soil development and nutrient cycling rely on a dynamic interaction among rock, plants, fungi and microorganisms, and atmosphere. The development of soils depends in part on the rock that contributes sediments as it erodes and weathers, on the kinds of plants that grow on the soil, generating detritus of varying composition, and on the microorganisms associated with the plants that decompose the detritus into nutrients and organic matter. Nutrients, including carbon and nitrogen, are cycled in various forms through plants, soil, and the atmosphere. The type of soil that has developed may limit the kinds of plants that can easily take root and survive (which then provide habitat for particular animal species that affect nutrient turnover from plants). The presence of vegetation further affects the soil by anchoring it, thus preventing erosion.

Both temperature and moisture affect the type of vegetation that grows, the amount of detritus produced, and the rate at which litter decomposes and releases nutrients that can then be used by other plants, animals, and microorganisms. With intermediate levels of moisture, increased temperatures accelerate decomposition. This may free more nutrients in the short term, potentially boosting productivity. However, faster decomposition could also release more carbon (in the form of CO_2) from the soil, particularly in the northern United States, where soils store a large share of the global carbon, thus amplifying the greenhouse effect. Furthermore, as described in the earlier section on $C0_2$, increased concentrations of atmospheric $C0_2$ will likely lead to changes in the composition and structure of plant leaves. The ratio of carbon to nitrogen may increase, which may actually slow the rate at which these leaves decompose and release minerals (see box 2-D). Changes in precipitation and runoff will also affect whether nutrients are maintained or lost more quickly from soils. More-frequent or more-severe storms could cause more erosion and soil loss in areas where land use is intensive or where vegetation has declined because of altered climate conditions (19, 42, 64).

The overall effects of climate change on soils are difficult to calculate because of the many complex and interacting processes that contribute to soil development. Regardless of the long-term change in soils, in the shorter term, soils may play an important role in vegetation changes. As temperatures warm the suitable ranges or climate conditions for many plant species may expand northward. However, soils at the northern edge of the United States and into central Canada tend to be thinner and less fertile than those in the

Midwest, which may make adaptation difficult for some species. In agricultural systems, any lack of nutrients in the soils can be compensated for by adding fertilizers, although there may be environmental costs associated with this (see vol. 1, ch. 6).

Sea Level, *Oceans, and* Coastal Ecosystems

The many interconnected physical changes in oceans and coasts will affect marine ecosystems in numerous ways (see box 2-C). Wave patterns in certain areas could be altered as a result of changes in regional climate, which could affect the stability of coastal areas.

Coral-building organisms thrive at a rather narrow range of water temperatures and depths. Although these organisms build reefs at a rate of up to 0.6 inches (1.5 cm) per year, fast enough to keep up with predicted sea level rise, other factors such as storms and warmer water temperatures could interfere with their growth and, in some cases, could kill the organisms, Loss of coral reefs would change the wave and water patterns near the coast and could allow for increased coastal erosion. Likewise, mangrove trees along many tropical coasts play an important role in shore stabilization. Sea level rise could inundate some mangrove swamps. As these trees die, the coast would be left vulnerable to erosion. In addition, the potential elimination of salt marshes and seagrass beds could have serious effects on marine organisms. However, wetlands may migrate landward at a rate dictated by the landward slope and sea level rise. In any case, the physical and biological changes along oceans and coasts could interact to amplify the effects of climate change (see vol. 1, ch. 4).

WHICH NATURAL RESOURCES ARE MOST VULNERABLE TO CLIMATE CHANGE?

Although regional predictions of the natural resources most at risk from climate change cannot be made based on existing knowledge, certain characteristics may put some parts of a natural resource system at greater risk than others. For example, ecosystems with limited options for adaptability-such as alpine ecosystems, old-growth forests, fragmented habitats, and areas already under stress-may be particularly vulnerable to changes in climate (42) (see vol. 2, ch. 5). How ecosystems will fare under climate change also depends on other factors that influence soil and water chemistry, including land use, air pollution, and water use (21). A1though systems at the edges of their ranges and those already stressed may be at the greatest risk from climate change, some systems that now appear healthy could also suffer.

Natural ecosystems may be more vulnerable to climate change than managed ones. Furthermore, natural or less managed ecosystems may be affected not only by changes in climate, but by further stresses resulting from human responses to those changes, such as increased irrigation, diversion of water from streams, and expanded tillage or grazing (see vol. 2, chs. 4 and 5). On the other hand, poor management responses in forestry and agriculture, such as planting species that are not well-adapted or maintaining g stands at high densities, could make some managed areas vulnerable as well (see vol. 1, ch. 6, and vol. 2, ch. 6). Vulnerability to climate change will certainly vary widely, and predictions about how systems will respond to climate change are difficult to make.

Changes in soil moisture may be among the best indicators that a natural resource system is becoming stressed. Figures 2-6 and 2-7 illustrate areas of the United States that may face changes in soil moisture under the climate change scenarios projected by GCMS. The extent to which these changes in soil moisture will affect areas of significant natural cover (34) is presented in figure 2-13. The figure shows the percent of area in each land class that is becoming effectively wetter (measured above the zero axis) or drier (below the zero axis). The GFDL scenario produces dramatic effects, with the majority of all existing ecosystems except tundra and deserts

Natural disturbances, such as the Yellowstone fires, create openings in forested areas where grasses and wildflowers can flourish. This provides new food sources for elk and other wildlife, Fires also promote recycling of nutrients, which enriches the soil.

moving toward drier climatic regimes. Almost 80 percent of agricultural lands of the United States face drying under the GFDL, scenario. The GISS scenario produces a mix of wetting and drying in areas of natural cover, with the exception of some noticeable drying in the wetlands. Agricultural lands (the midwestern corn belt and California) are more effected, with over 40 percent of the agricultural lands showing some drying under the GISS scenario.

Natural resource systems could change in any number of ways in response to a changing climate, but not all changes damage things that humans value. For example, a gradual shift in the boundaries of a wetland would probably not be considered a damage unless this results in a reduction of the habitat, flood control, water filtering, or recreational services offered by that wetland. Similarly, an increase in tree mortality may be of no concern in a forest valued as wildlife habitat rather than as a source of timber supply.

The degree of human intervention may also influence the vulnerability of natural resource systems to climate change. Depending on how natural systems are valued, they may be managed along a spectrum from active to passive management regimes. Because intensively managed systems are considered valuable, and because people are already exerting effort and expense to keep them productive, use of additional measures to respond to a changing climate is likely. On the other hand, wilderness areas are essentially unmanaged--but highly valued precisely because of 'this lack of management. Active intervention to protect these areas seems unlikely (see vol. 2, ch. 5), but there may be little loss of value from any but the most extreme effects of climate change on these natural areas. Thus, climate impacts on natural resource systems and the need for taking precautionary actions in preparation for climate changes cannot be evaluated without also considering how people value and manage these resources. These are the issues considered in subsequent chapters that investigate the effects of and possible responses to climate change in individual natural resource sectors: coastal systems, water resources, agriculture, wetlands, preserves, and forests.

The Intergovernmental Panel on Climate Change, the National Academy of Sciences, and the U.S. Environmental Protection Agency have all conducted assessments of the potential impacts of climate change (see box 2-F). Their reviews describe numerous impacts of climate change on U.S. natural resource systems, which laid the foundation for this report. Subsequent chapters will summarize some of the predictions made by these reports for individual natural resources, then explore in greater detail the