INFORMATION ON SELECTED CLIMATE AND CLIMATE-CHANGE ISSUES

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U.S. GEOLOGICAL SURVEY

Open-File Report 88-718

Reston, Virginia

1988

DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
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PREFACE

During the spring and summer of 1988, large parts of the Nation were severely affected by intense heat and drought. In many areas agricultural productivity was significantly reduced. These events stimulated widespread concern not only for the immediate effects of severe drought, but also for the consequences of potential climatic change during the coming decades. Congress held hearings regarding these issues, and various agencies within the Executive Branch of government began preparing plans for dealing with the drought and potential climatic change. As part of the fact-finding process, the Assistant Secretary of the Interior for Water and Science asked the Geological Survey to prepare a briefing that would include basic information on climate, weather patterns, and drought; the greenhouse effect and global warming; and climatic change. The briefing was later updated and presented to the Secretary of the Interior. The Secretary then requested the Geological Survey to organize the briefing material in text form. The material contained in this report represents the Geological Survey response to the Secretary's request. The report is divided into three distinct sections, conforming to the three elements that composed the original briefings.

CONTENTS

THE WEATHER AND CLIMATE SYSTEM

by *Harry F. Lins*

The General Circulation of the Atmosphere

The global wind system, more specifically referred to as the general circulation of the atmosphere, functions to transport warm air from equatorial regions toward the poles, and to maintain a return flow of cold air from polar to tropical latitudes. It results from four primary conditions: solar radiation, the rotation of the Earth, the distribution of land masses and seas across the Earth's surface, and tidal forces. Solar radiation and the Earth's rotation combine to form the "brute force" driver of the system. They are, by far, the dominant factors. Topographic and thermodynamic differences arising from the spatial distribution of land and sea are major modulators of the brute force component. Tidal forces are minor modulators of brute force.

The general circulation has both vertical and horizontal structure (fig. 1). The vertical structure, composed of the tropical Hadley, mid-latitude Ferrel, and a very weak and intermittent polar cell, mixes heat and moisture through the depth of the atmosphere. The horizontal structure, manifest as the tropical trade winds, mid-latitude westerlies, and polar easterlies, performs the same function across the Earth's surface. These large-scale features primarily determine the broad pattern of global climate. Embedded within this large-scale system are smaller circulations which tend to perturb the global flow. These smaller-scale cyclonic (low pressure) and anticyclonic (high pressure) circulations are responsible for the transitory, short-term variations in atmospheric conditions, which we refer to as the weather.

Manuscript approved for publication
December 5, 1988

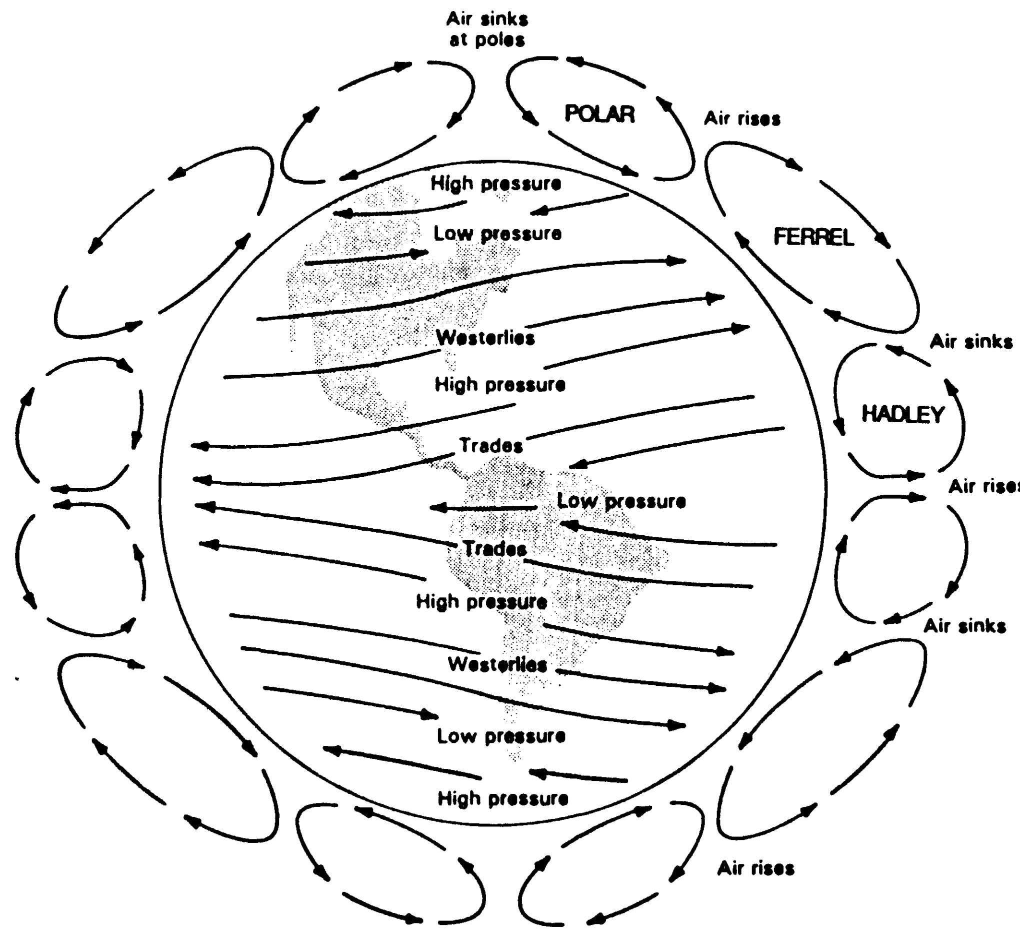


Figure 1. Schematic depiction of the general circulation of the Earth's atmosphere. (Source: Washington and Parkinson, 1986).

Zonal and Meridional Circulation

Large-scale movements of warm air poleward and cold air equatorward provide a balance between energy surpluses at low latitudes and energy deficits at high latitudes. When the temperature difference between high and low latitudes is relatively small, as is typical in summer, the circulation of the atmosphere is weaker and more zonal, or more nearly west to east (fig. 2). When the temperature contrast is high, as in winter, the circulation may become stronger and more meridional, or north-south. Thus, seasonal variations in weather patterns can typically be characterized by the persistence of one or the other of these two circulation regimes.

Changes in the amplitude of these planetary-scale circulation "waves" reflect the positions and intensities of high and low pressure systems around the globe. The region beneath a wave crest is characterized by high pressure. It is typically referred to as a high pressure "ridge." Such ridges serve to move relatively warm air poleward and are generally associated with fair weather conditions. The wave depressions are regions of low pressure, and are referred to as low pressure "troughs." Troughs of low pressure within the general circulation move relatively cold air equatorward and are generally associated with stormy conditions. Occasionally the amplitude of a low pressure trough becomes so great that the circulation folds back onto itself, thereby cutting the low pressure system off from the general circulation. Without the momentum provided by the general circulation such "cut-off" lows tend to persist over an area, sometimes bringing storminess for a week or more. In contrast, protracted periods of fair weather can accompany a high pressure ridge cut-off from the general circulation. Such ridges are frequently referred to as "blocking" highs, because they tend to block the movement of storm systems into an area.

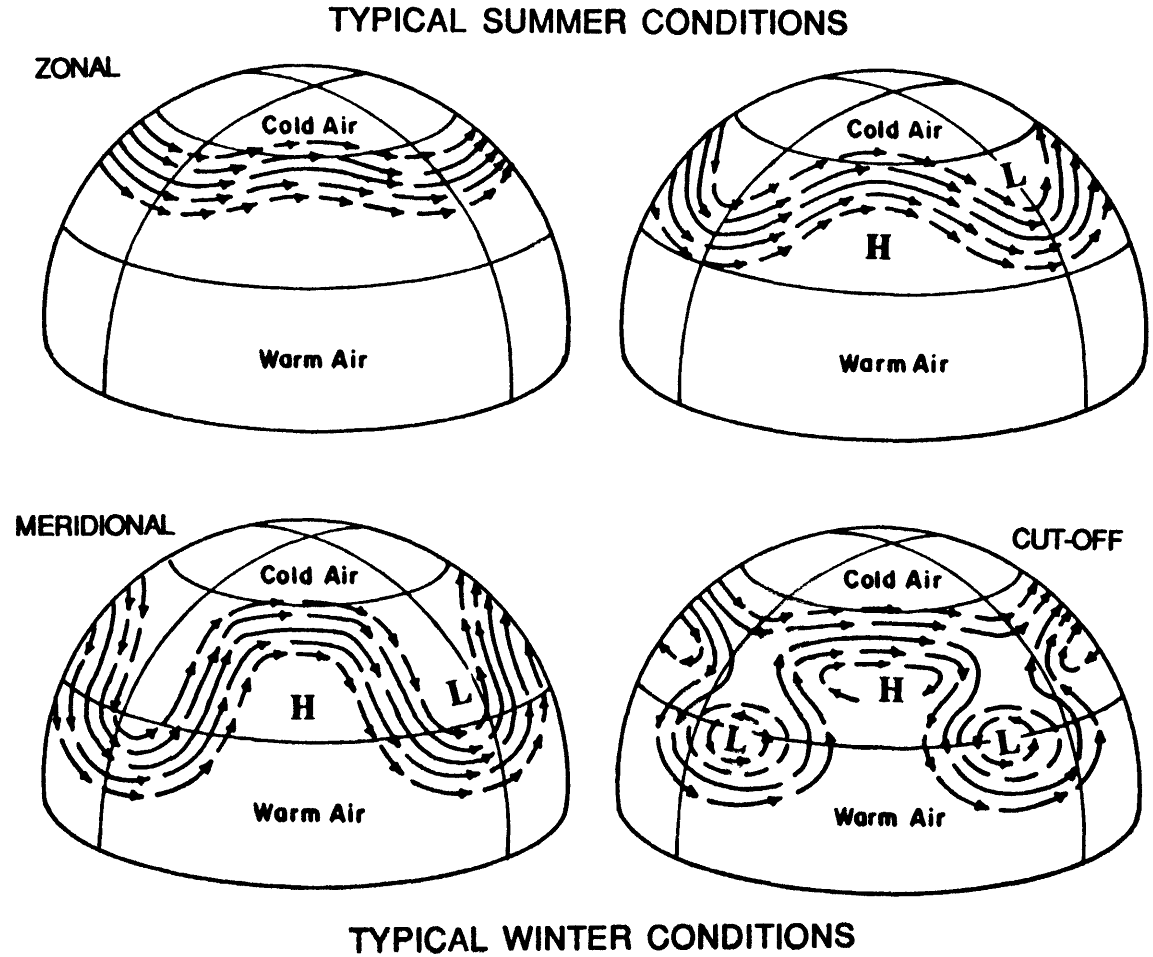
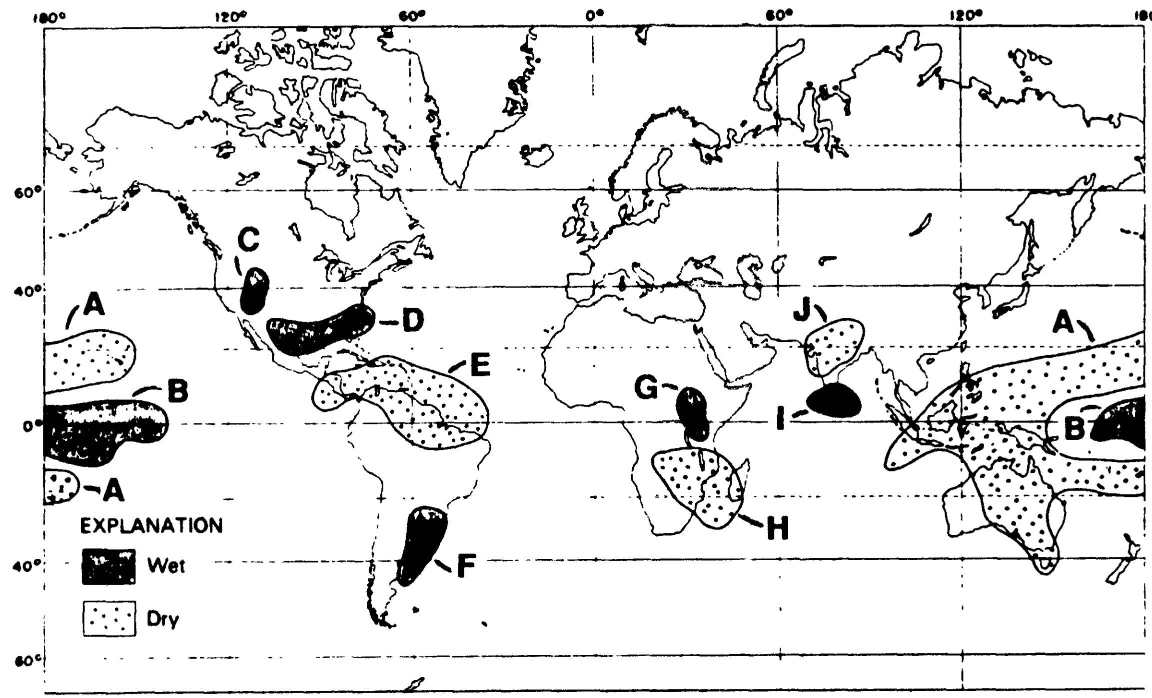


Figure 2. Zonal and meridional components of the horizontal circulation of the atmosphere. The letter L refers to low pressure and H to high pressure.

Global Associations (Teleconnections)

Recent research indicates that weather patterns in specific regions of the globe tend to exhibit consistent responses to certain large-scale atmospheric and oceanic circulations. These associations, frequently referred to as teleconnections, provide a basis for improving weekly weather prediction and seasonal climate forecasting. The concept of teleconnections actually refers to the statistical cross-correlation between atmospheric anomaly patterns (usually atmospheric pressure) separated by synoptic (1,000-2,500 km) to hemispheric distances.

The synoptic, or more proximal teleconnections are associated with variations in the location and intensity of the persistent subtropical high pressure regions (such as the Bermuda High) and subpolar low pressure regions (such as the Aleutian Low). The global, or more remote teleconnections stem from events such as El Nino-Southern Oscillation (ENSO). Research to date (1988) indicates that ENSO events generally coincide with distinct seasonal precipitation anomaly patterns, such as above normal precipitation along the Gulf and Southeast Atlantic coasts of the United States in winter and in the Great Basin in summer (fig. 3). High precipitation amounts also are found in southeastern South America in summer, the central Equatorial Pacific throughout the year, southern India in autumn, and east central Africa during the winter. Drought tends to accompany ENSO episodes in southeastern Africa in summer, most of India during the summer, northeastern South America and adjacent Caribbean basin in summer, and in a broad region of the western Pacific including Indonesia and Australia in various seasons.



LOCATION KEY

A - Indonesia, Australia, and western Pacific Ocean
B - Central Equatorial Pacific Ocean
C - Great Basin
D - Gulf and Southeast Atlantic Coasts of U.S.
E - Northeastern South America and Caribbean
F - Southeastern South America
G - East Central Africa
H - Southeastern Africa
I - Southern India
J - Northern and Central India

Figure 3. Regions exhibiting a consistent precipitation response signal to El Nino-Southern Oscillation episodes. (Source: Ropelewski and Halpert, 1987).

Precipitation Variability and Trends

Precipitation is a highly variable quantity both in space and time. Analysis of precipitation data for the Northern Hemisphere from the mid-19th century to the present (Bradley and others, 1987), and of much longer proxy series reconstructed from tree rings, indicate that significant regional variations have occurred over decadal and longer time scales. Hemispherically, decadal and longer fluctuations in precipitation are also evident, although there does not appear to be any systematic trend over the past century (fig. 4*A*).

Patterns in specific regions have been variable (fig. 4*B*). Europe, for example, has undergone a small but steady increase in precipitation since the 1860's. In the United States, precipitation declined between the 1880's and the 1930's. Since the 1930's, however, there has been a general increase with the most marked rise occurring since the mid-1950's. Precipitation over the Soviet Union has increased significantly since the 1880's, with most of the change occurring before 1900 and after 1940. In Northern Africa and the Middle East, precipitation exhibited little trend between 1900 and the late-1940's. Since then, however, precipitation has declined dramatically. In Southeastern Asia, a relatively wet period in the 1920's and early 1930's separated two protracted periods of relative dryness. The first was centered around 1900 and the second extended from the mid-1960's until the present.

During the past 30 to 40 years there have been some significant differences in the temporal distribution of precipitation on a latitudinal basis. In the middle latitudes (35° to 70° N), for example, a significant precipitation increase has occurred since 1940. In the subtropical latitudes (5° to 35° N), however, a significant decrease is evident since the mid-1950's. In the north equatorial region (0° to 5° N), little or no trend is evident in the record during the past century.

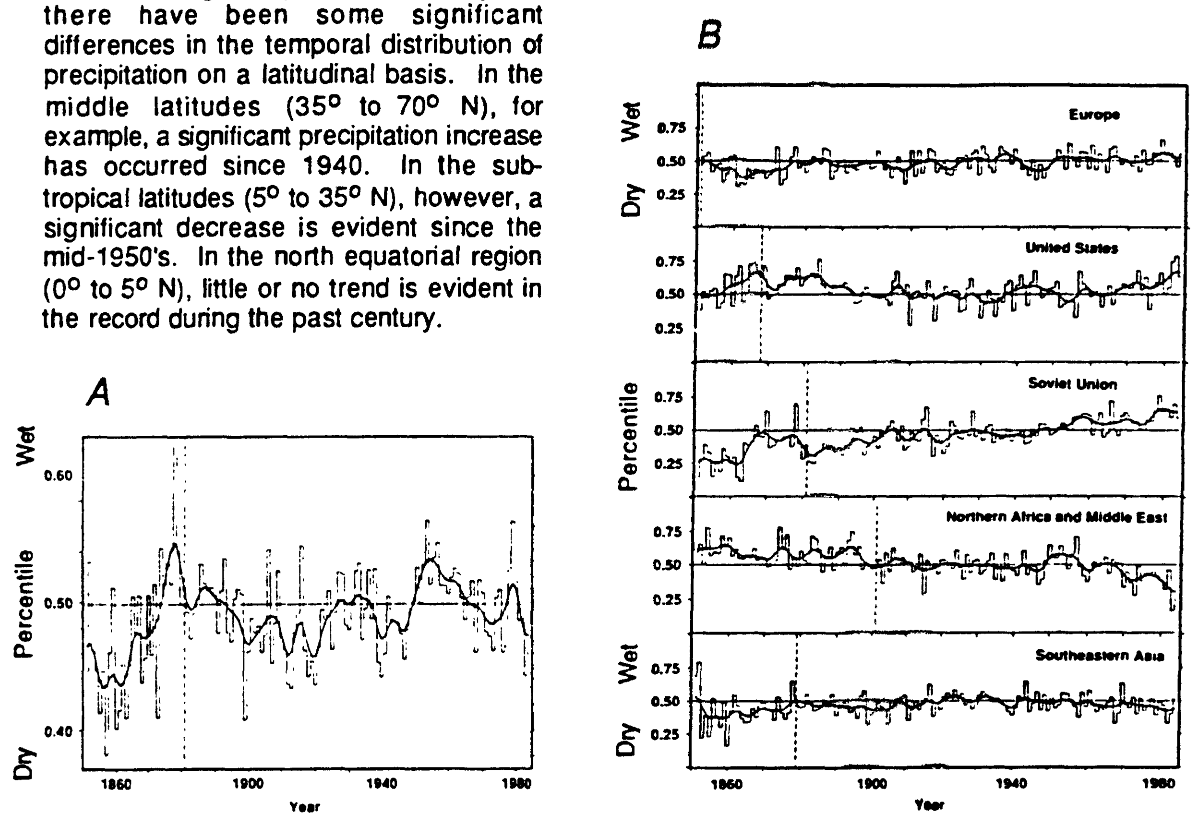


Figure 4. Annual precipitation index (mean of percentiles of the gamma distribution for Northern Hemisphere continental (*A*) and constituent regions (*B*). Vertical dashed line shows year in which 50 percent of the grid points became available for analysis. Curved line shows the smooth trend line fitted through individual values. (Source: Bradley and others, 1987; Copyright 1987 by the AAAS).

In 1975 the World Meteorological Organization issued a Special Environmental Report on Drought. In that report, Helmut Landsberg, the father of American climatology, noted that after 50 years of climatological and statistical analyses it was clear that "drought is a recurrent phenomenon. There is no need to invoke climatic change as a cause each time drought occurs. Quite the contrary is evident: drought is an integral, if irregular, component of climate as it exists now" (Landsberg, 1975).

Part of the problem associated with understanding drought results from the fact that there are at least three different kinds of drought: meteorological, agricultural, and hydrological. Meteorological drought is generally defined in terms of lower than average precipitation for some time period. Agricultural drought refers to a shortage of water in the root zone of crops such that the yield of plants is reduced considerably (a lack of soil moisture). Hydrologic drought is defined in terms of low levels of streamflow, reservoir storage, ground water, or some combination of these. A drought episode may contain all three elements, two of them, or only one. Winter droughts, for example, are often only meteorological events since it is a time of little or no agricultural demand for water and generally lower water supply needs.

Drought is also highly variable both in space and time. In figure 5, standardized scores of the Palmer Drought Severity Index are plotted for nine regions around the United States. Several points are apparent from these plots. First, the occurrence of dry years varies considerably from region to region. Second, there is a relatively high year-to-year variability in nearly all regions. There does appear, however, to be some tendency for severe drought to persist over several years in the West North Central, Southwest, and South regions. Third, although some regions appear to exhibit decadal-scale trends toward both wetness and dryness, no region exhibits any systematic trend over secular time scales or over the 85-year period of record. In other words, the frequency of drought across the United States does not appear to have changed during the past century.

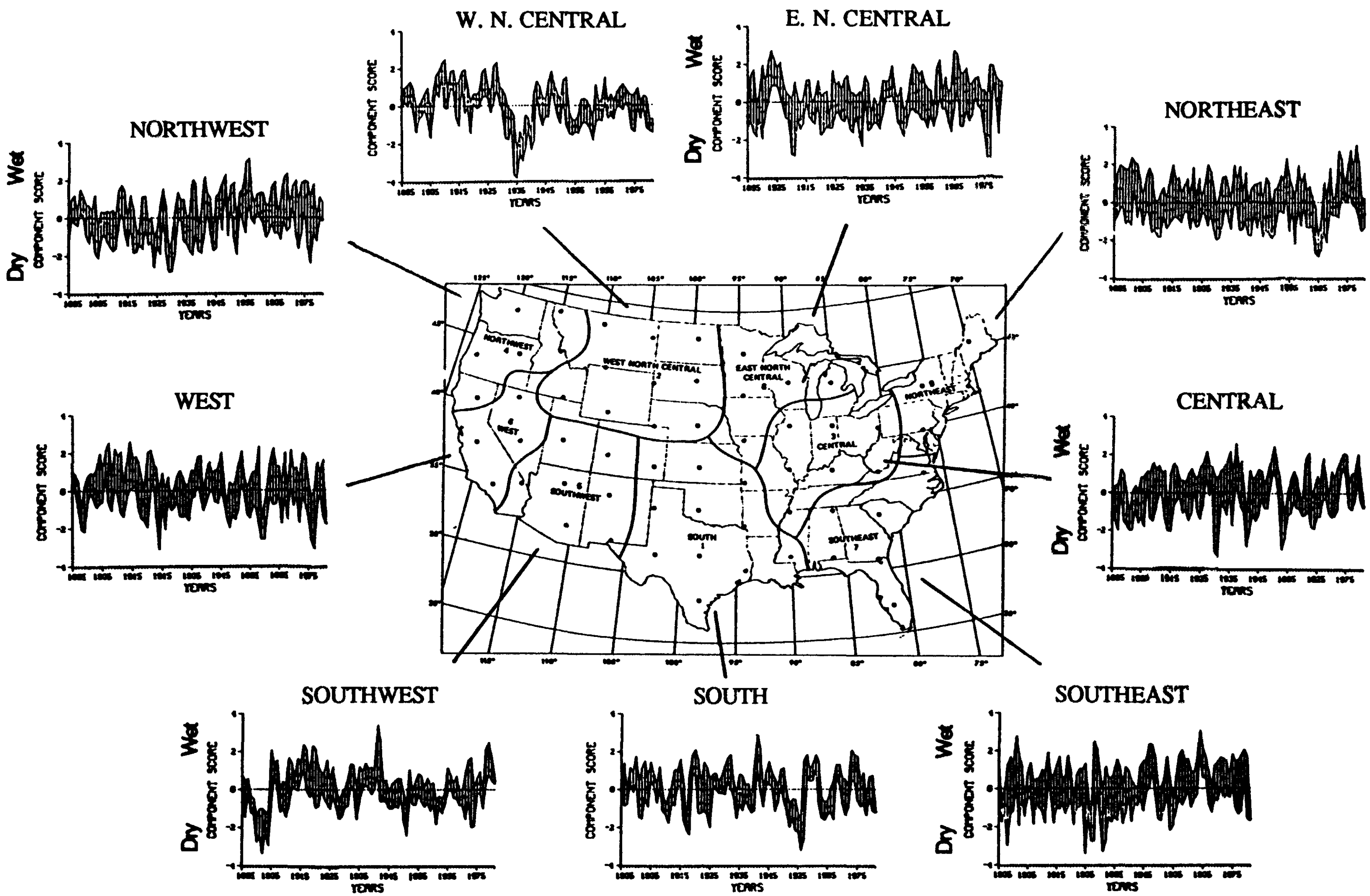


Figure 5. Annual maximum, minimum, and median principal component scores of the Palmer Drought Severity Index, 1895-1980. The plotted scores contrast years of relative wetness (above the zero line) with those of relative dryness (below the zero line). (Source: Karl and Koscielny, 1982).

The Drought of 1988

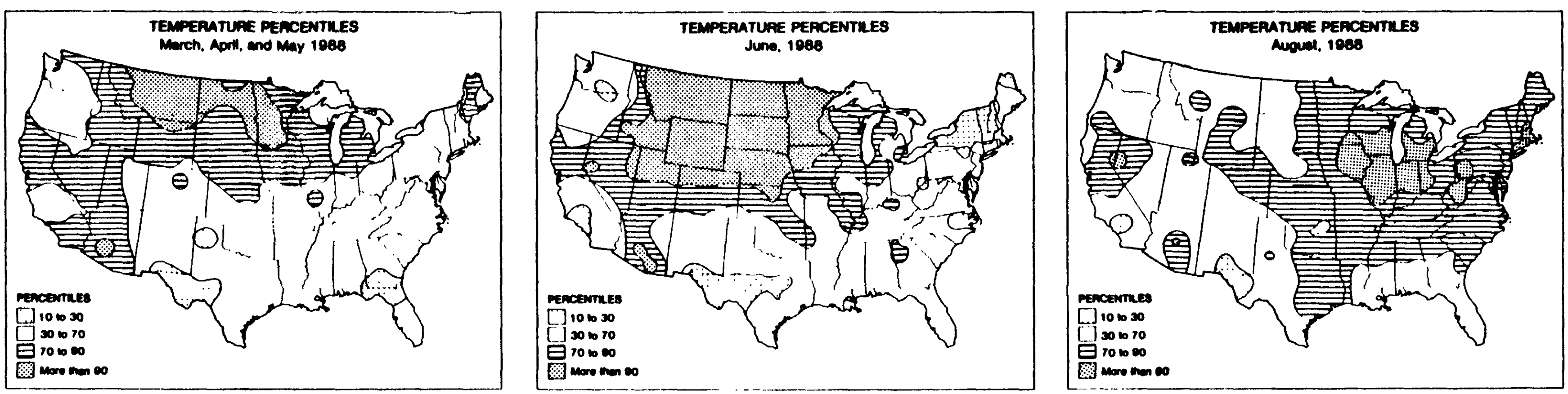
During the spring of 1988 a severe, though relatively short-term drought developed over the Northern Plains and Midwest regions of the United States. The conditions in these areas arose amidst longer-term drought that had been plaguing parts of the West since 1987 and parts of the Southeast since 1984. Although little was reported about these ongoing episodes, the event in the Nation's heartland quickly became a national news item.

The Northern Plains-Midwest drought had its beginnings in February when precipitation from the western Great Lakes to the Southern Plains was below to much-below normal. By March, the low precipitation coupled with above normal temperatures to begin widespread drying of soils in the northern half of the Great Plains. During April the situtation worsened as both below-normal precipitation and above-normal temperatures covered much of the Northern Plains and Midwest. Thus, at the critical time of plant germination, when soil moisture needs are relatively high, elevated temperatures and low precipitation severely depleted soil moisture reserves and reduced crop development (fig. 6*A* and *B*). Conditions continued deteriorating through June, with temperatures averaging 6 to 12 degrees F above normal over most of the Northern Plains and Midwest, with precipitation less than 40 percent of normal over much of the region (fig. 6 *A*, *B*, and *C*).

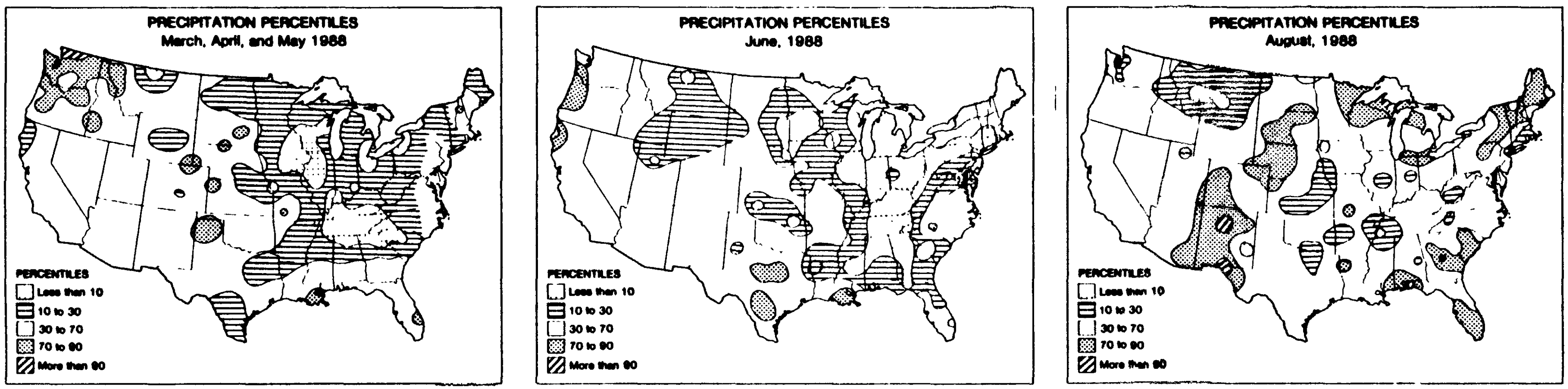
In July and August conditions began changing. Although temperatures remained above normal across much of the Nation throughout the summer, precipitation in the Northern Plains and Midwest returned to near normal conditions. Streamflow lagged behind precipitation in recovering as much of the rain went toward recharge and, because of the high temperatures, to increased evapotranspiration. Still, by summer's end the drought

Figure 6. Sequences of meteorological and hydrological conditions across the United States during the spring season and the months of June and August. *A*, temperature. *B*, precipitation. *C*, streamflow. *D*, atmospheric circulation at the 10,000-foot level. (Sources: meteorological data - National Oceanic and Atmospheric Administration, National Weather Service and Climate Analysis Center; streamflow data - U.S. Geological Survey.)

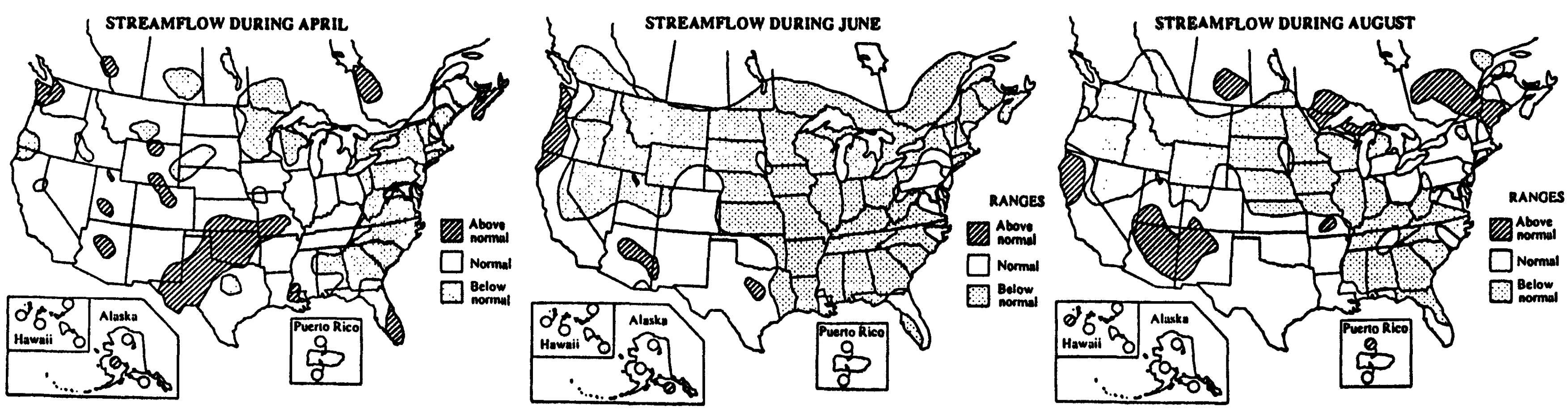
A



B


PRECIPITATION PERCENTILES
March, April, and May 1988
PERCENTILES
Less than 10
10 to 30
30 to 70
70 to 90
More than 90
PRECIPITATION PERCENTILES
June, 1988
PERCENTILES
Less than 10
10 to 30
30 to 70
70 to 90
More than 90
PRECIPITATION PERCENTILES
August, 1988
PERCENTILES
Less than 10
10 to 30
30 to 70
70 to 90
More than 90

C


STREAMFLOW DURING APRIL
Above normal
Normal
Below normal
Alaska
Hawaii
Puerto Rico
STREAMFLOW DURING JUNE
RANGES
Above normal
Normal
Below normal
Alaska
Hawaii
Puerto Rico
STREAMFLOW DURING AUGUST
RANGES
Above normal
Normal
Below normal
Alaska
Hawaii
Puerto Rico

of 1988 was essentially over in most parts of the Northern Plains and Midwest. Although this event was quite severe in a short-term sense, when considered in the context of drought over an entire year, 1988 may or may not be remembered as a great drought year. Conditions during October, November, and December will contribute significantly to how 1988 is recorded in the drought record books.

Perhaps of greater significance is the cause of this drought. Why did it occur? To answer this first question we need only look to the atmospheric circulation during the spring and summer months (fig. 6 *D*). During April, the circulation over the North American sector at 10,000 feet was characterized by abnormally deep troughs (stippled areas) of low pressure over the Aleutian Islands and Newfoundland with an abnormally strong ridge (cross-hatched area) of high pressure extending northward from the U.S. central Rockies to the Northwest Territories of Canada. This ridge was responsible for the warm, dry conditions that occurred at that time over the Northern Rockies and northern Great Plains. By June, the ridge of high pressure expanded drammatically to encompass more than half the U.S. and Canada. The abnormal intensity of this ridge lead to the unusally high temperatures and reduced precipitation across the central part of the country at that time. In July, however, and persisting in August, the circulation pattern changed as both the mid-continent high and the lows on both coasts broke down. In fact, the atmospheric circulation for both July and August was normal. This, in itself, didn't bring an end to the hot and dry condtions, since recovering from such conditions takes time. It did, however, signal an end to the abnormal circulation conditions which were directly responsible for the drought. Of course, the real question of what caused the drought is the question of what caused the circulation anomalies.

ATMOSPHERIC CIRCULATION IN APRIL | ATMOSPHERIC CIRCULATION IN JUNE | ATMOSPHERIC CIRCULATION IN AUGUST

D

L - Low pressure   H - High pressure

The Drought in a Global Perspective

In recent years, a growing amount of evidence has been acquired indicating that atmospheric and oceanic conditions in one part of the globe affect the weather and climate in another part of the globe. The El Nino/Southern Oscillation is one of the most frequently cited examples. However, during the drought of 1988 there was no El Nino occurring in the tropical Pacific. So what can we say about the relation of this drought to regions of anomalous conditions elsewhere around the world? In short, nothing definitively at present. Although several scientists have hypothesized that the drought was linked to anomalously warm sea surface temperatures in the tropical Pacific (north of the El Nino region), this explanation has not yet gained general acceptance. In addition, despite the "teleconnections" or correlations between pressure patterns in one part of the world with those in another, most such correlations are weak to moderate and tend to be strongest during the winter season when pressure gradients are strongest. West central Canada, the area where the anomalous high pressure ridge was centered, is not a region where anomaly patterns correlate well with patterns elsewhere around the world in spring and summer (fig. 7). Moreover, the global meteorological anomalies during June, 1988 do not appear to reflect a global climate change. One can look at charts such as those in figure 7 for any month of the year, in any year, and see temperature and precipitation anomalies of similar or even greater spatial extent widely distributed around the world. There do not appear to be any trends evident in these anomalies that are in any way indicative of a condition differentiable from the natural variability of the climate system.

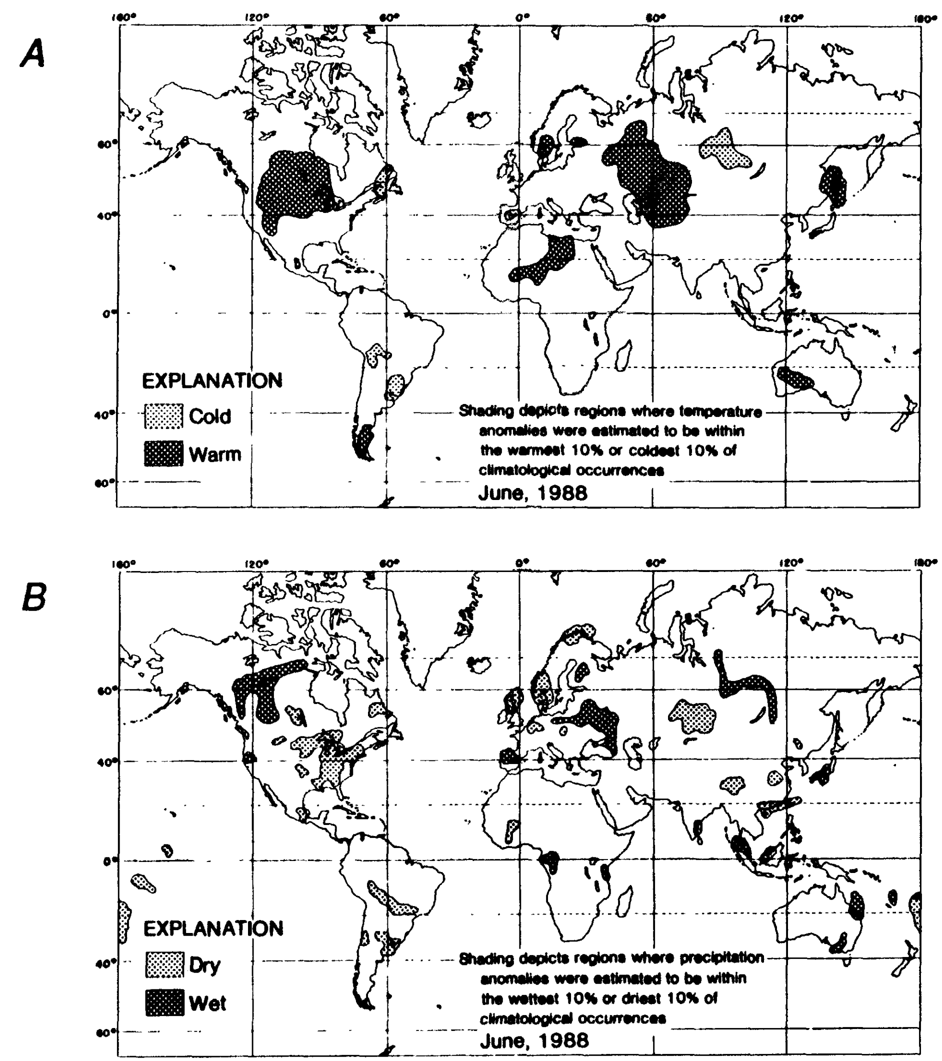


Figure 7. Global temperature (*A*) and precipitation (*B*) anomalies for June, 1988. (Source: National Oceanic and Atmospheric Administration, Climate Analysis Center).

THE GREENHOUSE EFFECT AND GLOBAL WARMING *by Eric T. Sundquist*

Critical Questions and Essential Facts

Questions

Throughout the summer of 1988, the greenhouse effect received wide attention in the press and in a variety of public discussions throughout the world. This attention focused on several questions that are critical to our understanding of current climate and climate change, including:

- **What is the greenhouse effect?**
- **Does the current global warming confirm the greenhouse effect?**
- **Was the 1988 U.S. drought a result of the greenhouse effect?**
- **How well can the greenhouse effect be predicted?**

This section presents background information that is useful in the discussion of these questions.

Facts

The greenhouse effect is the absorption of long-wave radiation by certain gases in the Earth's atmosphere. This phenomenon has been documented and studied for more than a century. Although scientists continue to discover new and sometimes unexpected aspects of the greenhouse effect, the following points are now firmly established:

The greenhouse effect is a fact, not a theory. Its basic physical principles are well understood. The specific wavelengths of radiation absorbed by atmospheric trace gases are precisely known. The absorption of radiation by a gas causes its temperature to increase. The scientific challenge associated with the greenhouse effect is not to establish whether it exists, but rather to understand the manifestation of its basic physics throughout the Earth's immensely complex climate system.

The greenhouse effect is a natural phenomenon. The atmospheric gases which absorb the most long-wave radiation are water vapor and carbon dioxide, which have been present in the Earth's atmosphere for billions of years. Without the greenhouse effect of these two gases (and without the effect of clouds formed by the condensation of water vapor), the earth's average surface temperature would probably be near -18 degrees Celsius (0 degrees Fahrenheit).

The greenhouse effect was variable before human influence. There is good evidence for significant changes in the atmospheric concentrations of carbon dioxide and methane (another greenhouse gas) during the last 160,000 years.

The greenhouse effect is presently changing as a result of human activities. During the last 200 years, anthropogenic production of carbon dioxide has caused atmospheric concentrations to increase by 25 percent. Atmospheric methane concentrations have doubled. Other "greenhouse" gases -- nitrous oxide, halocarbons, and tropospheric ozone -- are also known to be increasing in the atmosphere at significant rates due to human activities. The combined influence of these changes in atmospheric composition is the principal reason for concern about present and future changes in the greenhouse effect.

Energy Balance of the Earth's Surface and Atmosphere

The complexity of the global climate system, of which the greenhouse effect is a part, is illustrated in figure 8. Pathways of incoming solar (short-wave) radiation appear in the dark-shaded areas on the left side of the illustration; pathways of long-wave radiation are depicted on the right. The units shown are relative to the total incoming solar radiation value of 100.

At the outer edge of the Earth's atmosphere, incoming solar short-wave radiation is balanced by predominantly long-wave outgoing radiation. The energy balance at the Earth's surface is dominated by long-wave radiation exchange with the atmosphere. The long-wave energy exchanged at the Earth's surface is much larger in magnitude than the amount of short-wave solar energy that reaches the Earth's surface. This amplication of the Earth-surface energy balance is caused by clouds and the greenhouse effect.

An idealized equilibrium energy balance is depicted in the figure. The units of incoming solar energy are exactly balanced by an equal number of units of outgoing radiation. In reality, the energy balance is currently shifting as a result of changing concentrations of greenhouse gases. The exact nature of this shift is very difficult to understand and predict because it involves all of the intricate feedbacks that comprise the Earth's climate system.

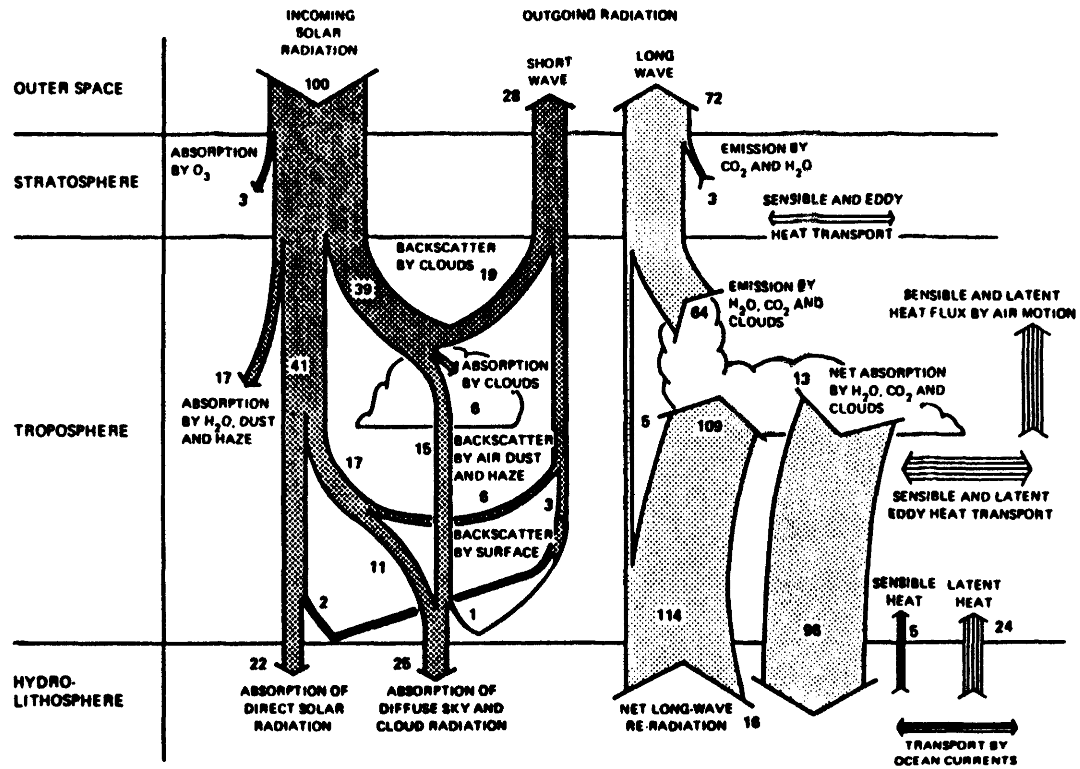


Figure 8. Energy balance of the earth's surface and atmosphere, in percent. (Source: Schneider and Mesirow, 1976).

Long-Term Changes in Atmospheric Carbon Dioxide

Evidence for changes in the greenhouse effect before human influence appears in figure 9. The plotted data are derived from analyses of a 2,000-meter ice core from Vostok, Antarctica, by a team of French and Soviet scientists (Barnola and others, 1987). The core contains ice deposited as snow over the last 160,000 years. Measurements of deuterium (an isotope of hydrogen) in the ice provide a record of the temperatures at which the ice was formed. Analyses of air bubbles trapped in the ice provide a corresponding record of past atmospheric compositions.

The lower curve in the graph shows deuterium values corresponding to the ages indicated on the lower axis. The record clearly shows relatively high deuterium values (corresponding to higher temperatures) during the last 10,000 years, lower values representing the last ice age, and high values for the preceding interglacial period from about 120,000 to 140,000 years ago. The upper curve shows carbon dioxide concentrations corresponding to the same time. The data show that atmospheric carbon dioxide and climate changes were closely related throughout the last 160,000 years. Ice core analyses for methane indicate a similar correlation with climate.

Unfortunately, it is not possible to separate past changes in climate and atmospheric composition into cause versus effect. Atmospheric carbon dioxide concentrations are very sensitive to changes in other components of the global carbon cycle, particularly the carbon contained in the oceans, plants, and soils. Although it is tempting to attribute past climate changes to the changing greenhouse effect, many hypothesized explanations for past carbon dioxide changes invoke climate change as a cause of carbon-cycle change. Like the climate system, the global carbon cycle contains many complex feedbacks which are all affected by a perturbation anywhere in the system.

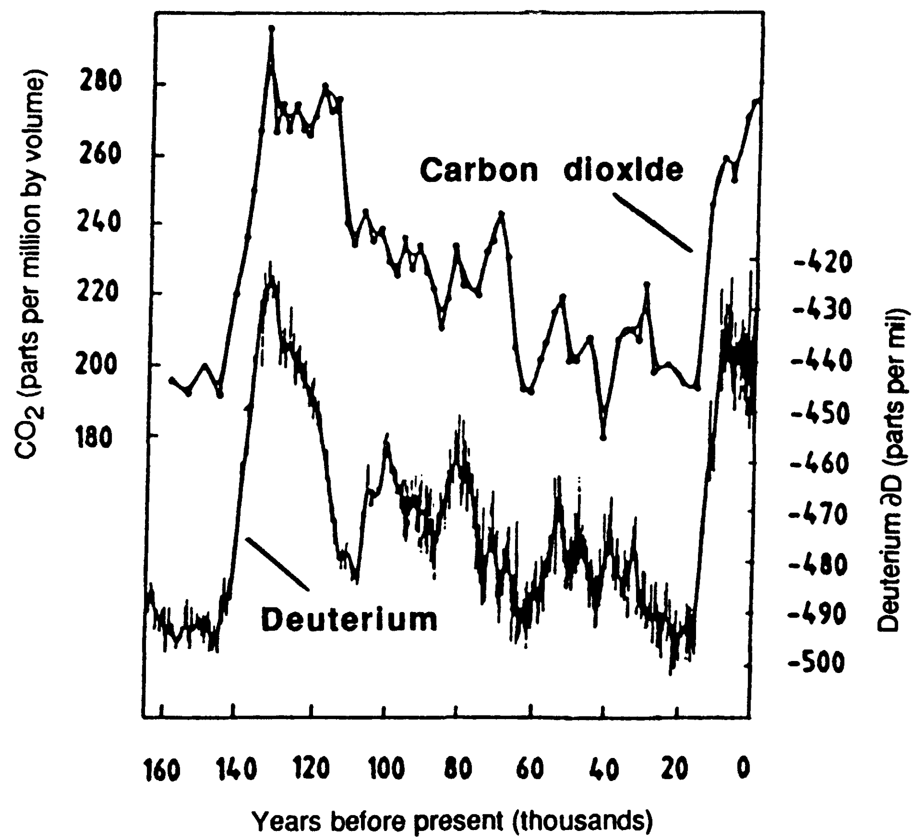


Figure 9. Long-term variations in carbon dioxide and deuterium as determined from the Vostok ice core. (Source: Barnola and others, 1987).

Historical Changes in Atmospheric Carbon Dioxide

Analyses of ice cores from Greenland and Antarctica show that the atmospheric CO_2 concentration remained near 280 parts per million for nearly all of the 10,000 years since the end of the last ice age. Then, in the late eighteenth century, atmospheric CO_2 began to increase. The increase, determined by measuring ice core air bubbles and, beginning in the early 1950's, by continuous direct atmospheric measurements, appears in figure 10. The historic rate of increase has been exponential, rising to a present-day atmospheric CO_2 concentration of about 350 parts per million.

The source of this carbon dioxide increase is predominantly the burning of fossil fuels, with smaller contributions from changes in land use (for example, deforestation) and the production of cement from limestone. In fact, the total amount of CO_2 released by these activities during the last 200 years is about twice the amount of carbon dioxide that has remained as added atmospheric CO_2. The remainder of the anthropogenic carbon dioxide has been removed from the atmosphere by carbon-cycle exchange, primarily with the oceans. There is no doubt that the atmospheric CO_2 increase shown here is the result of human activities, but there is significant uncertainty about the response of the global carbon cycle to this perturbation in one of its key components.

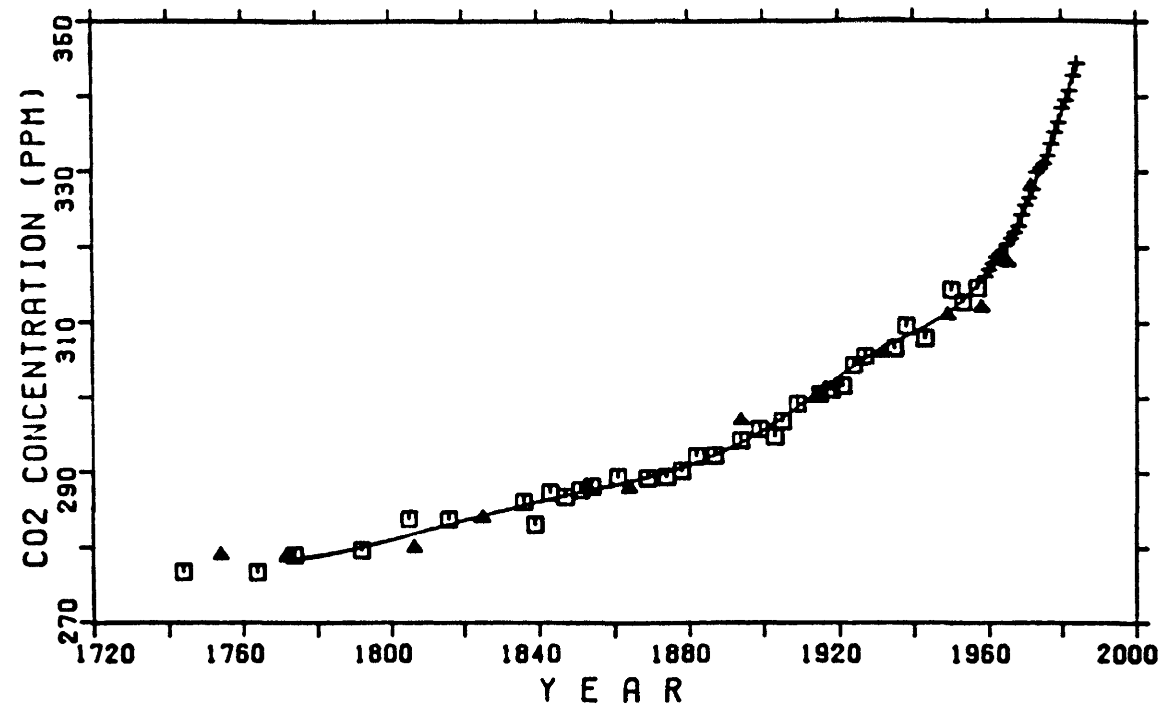


Figure 10. Variations in the concentration of atmospheric CO_2 as determined from ice cores in Greenland and Antarctica. (Source: Siegenthaler and Oeschger, 1987).

Historical Changes in Atmospheric Methane

The historical increase in atmospheric methane, derived from analyses of ice core air bubbles and, for the last decade, from direct atmospheric measurements, appears in figure 11. Although the relative increase in methane (from 800 to 1600 parts per billion) has been greater than that for CO_2, the sources of the methane increase are much less understood. The timing and magnitude of the change strongly indicate human influence. The most likely sources seem to be rice cultivation, enteric fermentation in animals, biomass burning, and fossil fuels. Unlike carbon dioxide, methane is actively consumed by chemical reactions in the atmosphere. However, because methane is not as readily absorbed by plants and the oceans, its average lifetime in the atmosphere may be greater than that of carbon dioxide. Predicting future concentrations of methane is very difficult because there are so many uncertainties about both its sources and sinks.

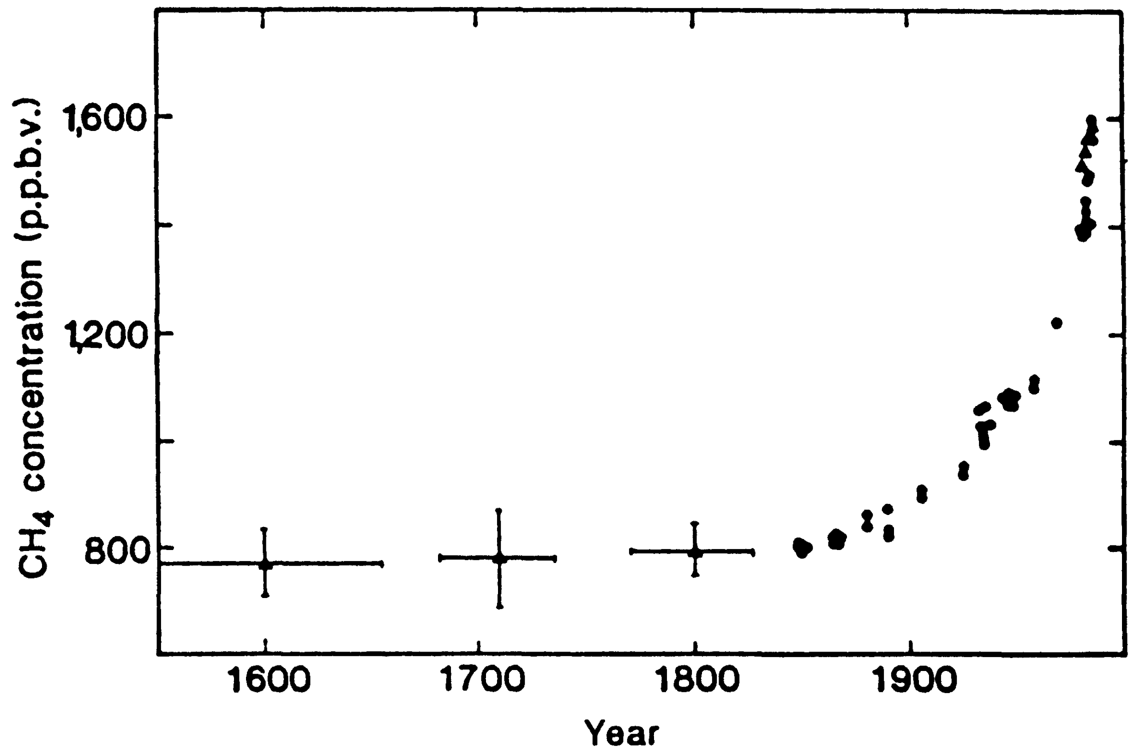


Figure 11. Atmospheric methane variations over the past few centuries. (Source: Pearman and Fraser, 1988).

Historical mean global temperatures can be estimated using data from meteorological stations throughout the world. These stations are not uniformly distributed, however, and spatial averaging assumptions must, therefore, be applied to the stations that are available. Other corrections must be used for stations where measurement techniques or locations have changed during the period of record. Nevertheless, the data show a statistically significant global warming trend.

A graph of normalized mean global temperatures from 1880 through 1987, compiled by Hansen and Lebedeff (1988), appears as figure 12. The overall warming apparent in this record is close to 0.8 degrees Celsius (1.4 degrees Fahrenheit). Hansen and Lebedeff estimate that 0.1 to 0.2 degrees of this trend can be attributed to the heat released locally in urban areas, where many meteorological stations are located. Their estimate of the overall warming during the last century, including uncertainties, is 0.4 to 0.8 degrees Celsius (0.7 to 1.4 degrees Fahrenheit). This estimate is supported independently by other compilations (Jones and others, 1986), including analyses of sea surface temperature data. The average global warming over the last century is roughly consistent with the magnitude of warming expected from the increase in greenhouse gases during the same period.

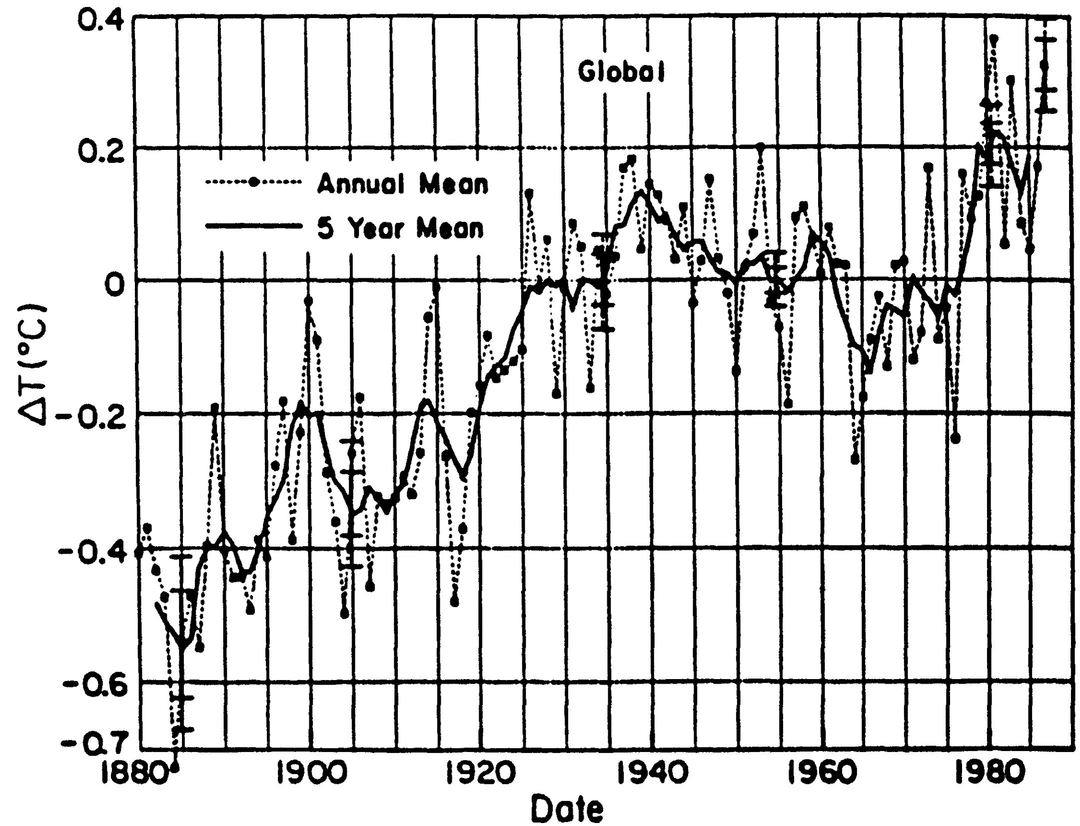


Figure 12. Normalized mean global temperatures, 1880-1987. (Source: Hansen and Lebedeff, 1988).

Global Warming in the 1980's

Global mean temperatures for the years 1980, 1981, 1983, and 1987 were the highest in the historical record. The high global mean temperatures in 1980, 1983, and 1987 were associated with pronounced warming at low latitudes. In particular, the temperature peaks of 1983 and 1987 were contemporaneous with "El Nino" conditions at low latitudes (figure 13). Historically, such events have often been followed within a few years by low latitude cooling ("La Nina" conditions) and a corresponding drop in mean global temperatures. In contrast to the observation that global warming in the 1980's has been associated primarily with low-latitude warming, climate model simulations of the effects of a greenhouse warming indicate that the warming should be most pronounced at high latitudes.

The global temperature data for early 1988 show continued warming. It is clear that the 1980's are the warmest period for which global mean temperatures can be reliably estimated from meteorological measurements (see figure 12). Does this confirm the presence of the anticipated CO_2-induced greenhouse warming? Although a few scientists have argued yes, most believe that it is too early to attribute the global warming to the greenhouse effect. Most scientists are reluctant to emphasize the warming of the 1980's more than the overall century-long warming trend. For example, the warming of the late 1930's was the warmest period in the record to that time, yet it was followed by three decades of cooler temperatures. Most scientists agree that, although the historical global warming is cause for serious concern, we cannot yet detect a climatic change caused by the greenhouse effect because it may be obscured by other causes of global temperature variation.

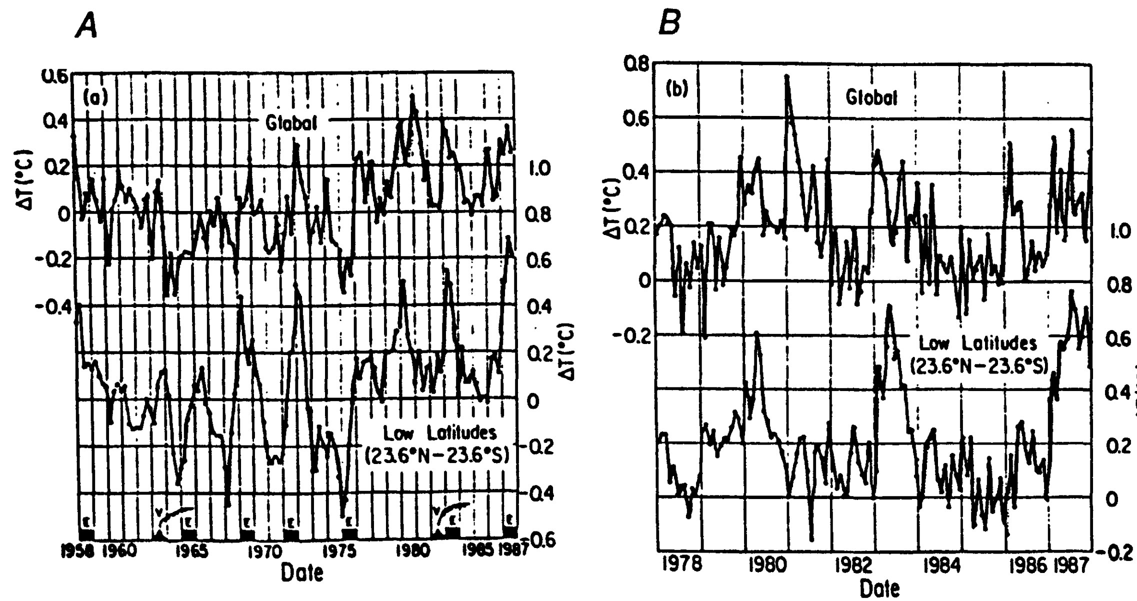


Figure 13. Global mean surface air temperature. *A*, Annual variations, 1958-1987. *B*, Monthly variations, 1978-1987. The letters **E** and **V** mark the years of major El Nino and volcanic eruptions, respectively. (Source: Hansen and Lebedeff, 1988)

Predicting the Greenhouse Effect

Predicting future climates is one of the most challenging and important scientific problems of our time. Predicting the climatic effects of trace gases requires the most sophisticated climate models and the most powerful supercomputers. Changes in mean global temperature and precipitation, as computed by five of the most widely cited atmospheric general circulation models (GCM's), are given in Table 1. These changes were computed for equilibrium climate conditions after a doubling of atmospheric CO_2, which is expected to occur sometime during the next century. Mean global temperatures are expected to increase by about 2 to 5 degrees Celsius, while mean global precipitation is predicted to rise by about 7 to 15 percent. The global precipitation increase is accompanied by a corresponding increase in the modeled global evaporation. The effects of increasing concentrations of trace gases other than CO_2 are expected to accelerate and add to the effects modeled here.

The significance of these predicted climate effects can be gaged by comparison to the estimated 5-degree Celsius mean global temperature change associated with the end of the last ice age. Unfortunately, there is no consistency among greenhouse predictions beyond the global equilibrium mean effects represented by the results shown in the table. There are still too many uncertainties in climate models to realistically predict regional effects, or to project changes that will occur during the time of transition to a new equilibrium climate.

Model/Study	Change in Temperature (°C)	Change in Precipitation (Percent)
Geophysical Fluid Dynamics Laboratory / Wetherald and Manabe (1988)	4.0	8.7
Goddard Institute for Space Studies / Hansen and others (1984)	4.2	11.0
National Center for Atmospheric Research / Washington and Meehl (1984)	3.5	7.1
Oregon State University / Schlesinger and Zhao (1988)	2.8	7.8
United Kingdom Meteorological Office / Wilson and Mitchell (1987)	5.2	15.0

Table 1. Changes in the global mean surface air temperature (T_s) and precipitation rate (P) simulated by various atmospheric general circulation/mixed-layer ocean models for a CO_2 doubling. (Source: Schlesinger, 1988).

Major Uncertainties in Global Climate Model Projections

Many fundamental uncertainties are widely acknowledged throughout the climate and trace gas research communities. These include the following problems:

- Predicting **future greenhouse gas and aerosol emissions** requires a vast array of assumptions about future tech-nologies, economic and social developments, international relationships, and resource needs and availabilities.

- A thorough knowledge of the sources and sinks of atmospheric trace gases requires understanding the **global biogeochemical cycles** of carbon, nitrogen, sulfur, and related elements.

- Climate warming will be delayed by **ocean heat exchange**, which will absorb some of the heat retained in the atmosphere. Understanding this process will require coupling non-equilibrium models of atmospheric and oceanic circulation.

- Many climate model uncertainties are attributed to the **effects of clouds**, which can both enhance and attenuate warming at the earth surface, depending on their interactions with other feedbacks in the climate system.

- The **hydrologic cycle** is the most important and poorly understood component of energy and water exchange at the land surface.

- Climate modelers are increasingly emphatic that their work cannot yet be used to predict **anything on a regional scale**.

Major Uncertainties in Regional Climate Predictions

The following statement is representative of the consensus among climate modelers concerning predictions of regional effects such as droughts: "Although the results of the general circulation models often agree well with each other and with historical surface air temperature data over large scales (global/hemispheric/zonal), ... [they are] simply not yet ready to be used for quantitative prediction at anything approaching even a multi-state region, let alone a single surrogate gridpoint representing a particular state, county or city. Over such small scales, a wide range of responses is currently predicted" (Grotch, 1988).

The model results shown in figure 14 exemplify the differences among climate model simulations of regional effects. These plots show soil moisture simulated for three regions by two different general circulation models developed by the National Center for Atmospheric Research (NCAR) and the Geophysical Fluid Dynamics Laboratory (GFDL). Although these model simulations are not strictly comparable, they illustrate the inconsistencies among regional climate predictions. These differences in soil moisture projections reflect the models' disagreement on regional land surface water balances under greenhouse conditions. The solid curves approximate seasonal soil moisture trends for present atmospheric CO_2 levels, whereas the dashed curves represent equilibrium seasonal trends for increased CO_2 levels (doubled in the NCAR model; quadrupled in the GFDL model).

For the regions shown, there are obvious differences between the models in their simulations of both present-day and increased-CO_2 conditions. For the Great Plains, the GFDL model predicts decreased soil moisture with increasing CO_2. The NCAR model, however, predicts increased or nearly unchanged soil moisture for increased CO_2 in central North America. Clearly, it is premature to attempt to link regional drought to the greenhouse effect.

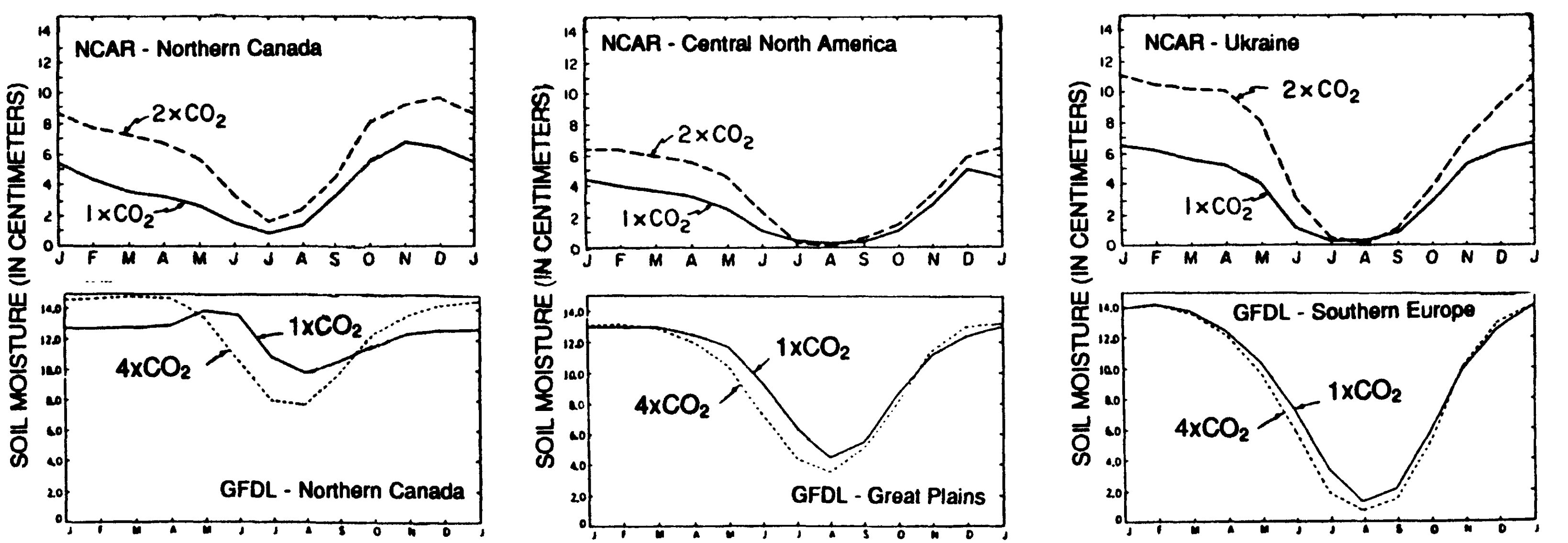


Figure 14. Annual cycle of soil moisture amounts (cm) averaged over several regions, as calculated by the National Center for Atmospheric Research (NCAR) and Geophysical Fluid Dynamics Laboratory (GFDL) general circulation models. (Source: Meehl and Washington, 1988).

The Greenhouse Effect in a Geological Context

Geologists have long hypothesized that changes in the greenhouse effect may have contributed to climate change in the geologic past. This possibility is strongly supported by the record of atmospheric climate and carbon dioxide and methane changes from ice cores. Thus, the geologic record offers the possibility of testing climate predictions using data from real past changes in the greenhouse effect and other climate parameters.

On the basis of the geological record of climate and atmospheric change, it appears that the present-day atmospheric CO_2 concentration is higher, as a result of human activities, than at any time during the last several hundred-thousand years. Hypothetical past and future atmospheric CO_2 levels are compared in figure 15. The diagram's time scale discontinuity (logarithmic for the left-hand section and linear for the right-hand side) emphasizes the extremely rapid rate at which future CO_2 concentrations may rise.

Most geologists believe that, to find geologic analogs of possible future atmospheric CO_2 levels, it is necessary to go back at least several million years in the geologic record. The evidence for higher atmospheric CO_2 concentrations in the distant geologic past is indirect, requiring inferences from sediment data and geochemical models. To relate this evidence to present and future changes in the greenhouse effect, we will need to acquire a much broader understanding of both the long-term processes that affected geologic carbon-cycle and climate change, and the short-term processes that will dominate trends during the coming decades and centuries.

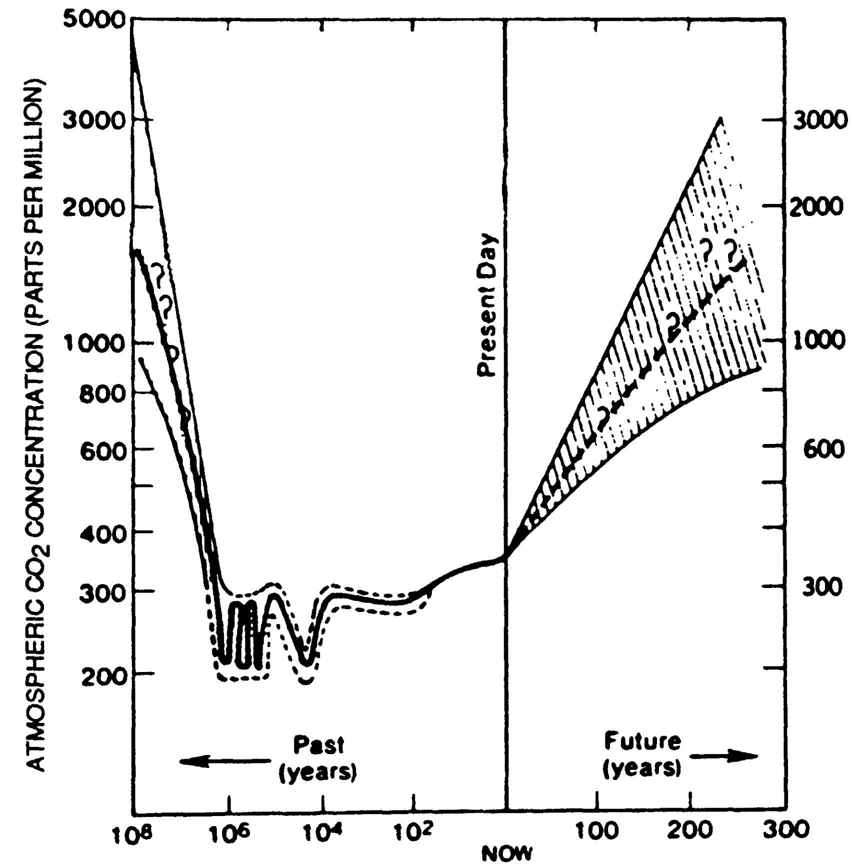


Figure 15. Overview of the history of atmospheric CO_2 from 10^8 years ago to the present day on a log-log scale. For comparison, the possible future CO_2 levels projected for the next few centuries are shown on a linear time scale. (Source: Gammon and others, 1985).

CLIMATE CHANGE IN THE GEOLOGIC PAST

by Thomas A. Ager

Perspectives on Long-Term Changes in Climate

Much of our understanding of the workings of the global climate system is based upon the instrumental meteorological observations that have been recorded systematically around the world during the past century. Our concept of what constitutes "normal" climate, therefore, is heavily influenced by average global climatic conditions covering only a short span of time. By examining the geologic record we can begin to see global climates from a much longer time perspective. We can look back far beyond the past century to see how variable climate has been during the past 1,000, 10,000, 100,000, or even millions of years.

Evidence of past climatic conditions is preserved in the geologic record in marine and lake sediments, in glacier ice, in peat and coal deposits, in cave deposits, coral reefs, and other stratified deposits. Innovative methods have been developed to extract information about past climates from geologic evidence and to date these past events by application of several isotopic techniques and other dating methods. It is, therefore, possible to reconstruct the broad outline of global climate history spanning many millions of years. More detailed climate reconstructions over time scales of centuries to tens of thousands of years are now available from many parts of the world. By examining changes in assemblages of climate-sensitive organisms represented by fossil remains over time, it is possible to reconstruct the consequences of past climate changes upon ecosystems in both marine and terrestrial environments. Studies of air bubbles and dust preserved in glacier ice provide insights into the changing composition of the atmosphere through time during the past 150,000 years. Ice core studies also allow us to document periods of time when volcanic eruptions were more frequent, when winds carried greater amounts of dust from the continents to distant ice sheets and ice caps.

The geologic record of past climate change provides insights into the causes and mechanisms of climate change, the rates at which some past climate changes occurred, and preserves important information about the effects of those changes on ecosystems, landscapes, and the oceans. The geologic record tells us that there is no single cause of climate change. Many factors influence global climate. The geologic record indicates that climate varies on all time scales due to natural causes. Those causes are not all well understood, or perhaps not all influences on climate are yet recognized. The causes and predictability of climate variation on time scales of greatest relevance to human populations (decades to centuries) are not well understood. To illustrate how much climate has varied in the past, global climate trends on several time scales will be briefly examined.

Climate Change During the Past 130 Million Years

A reconstructed temperature curve, spanning the past 130 million years, appears in figure 16. The curve reconstructs changes in the temperature of deep ocean waters at low latitudes over time. It is, therefore, colder than mean global air temperatures. Nevertheless, it is useful for illustrating the probable global temperature trends over that very long time interval. The curve shows that the dominant trend over the past 130 million years has been toward cooler climatic conditions. Superimposed upon this long-term trend are significant temperature oscillations that lasted up to several million years. These periodic warming and cooling events had significant impacts upon global ecosystems both in the marine and terrestrial realms. Causes of these long-term and intermediate-term climate trends are not well understood. On time scales of tens of millions of years, however, plate tectonics influenced global climate by shifting the positions of continents, causing intervals of mountain building and volcanic activity, and influencing the distribution and depths of oceans and seas. All of these factors influence global climate. The gradual shift of continental land masses into polar latitudes, and the opening of the Atlantic Ocean were important factors contributing to long-term cooling trends during the past 100 million years. Intense volcanism can cause short-term cooling of climate by injecting ash particles into the stratosphere, where the ash reflects incoming radiation into space. Prolonged volcanism may cause longer-term climate change by altering the atmosphere's carbon dioxide content. High mountain ranges influence atmospheric circulation patterns and serve as accumulation centers for ice and snow.

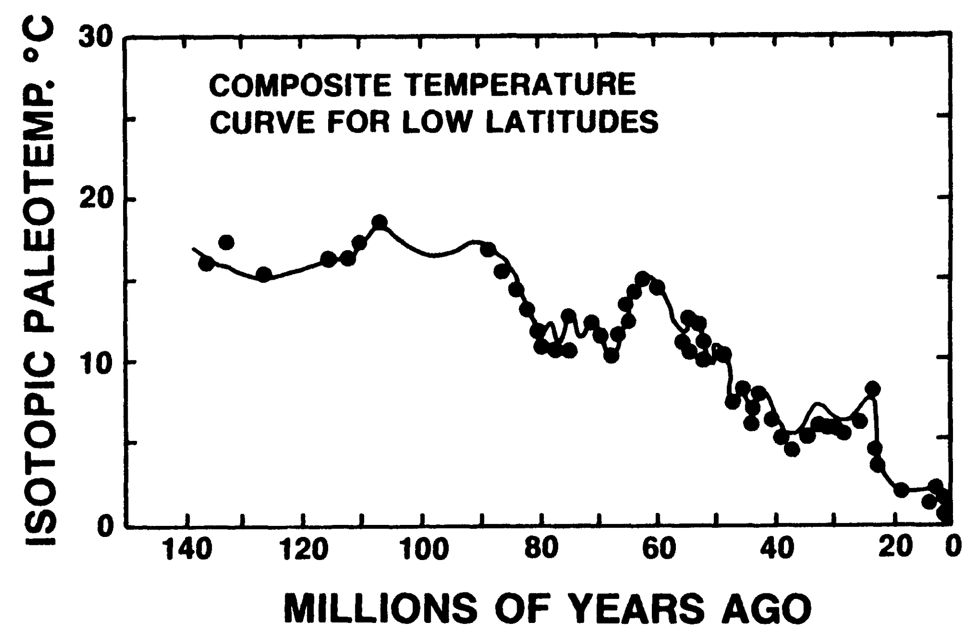


Figure 16. Deep sea water temperature history for the past 130 million years. (Source: Douglas and Woodruff, 1981).

Milankovitch Forcing of Climate Change

About 2.5 million years ago the climate regime of the Earth changed into an unusual mode of high amplitude oscillations between long intervals of cool or cold climate interrupted by generally shorter intervals of warmer climate. The reasons for this shift are not completely clear. The emergence of the Isthmus of Panama and the opening of the Bering Strait about 3 million years ago altered oceanic circulation patterns, and these events may have contributed to the change in global climate pattens.

One of the causes of the major climatic oscillations during the past million years, however, has been identified. During the 1920's and 1930's a theory was developed by a Yugoslavian engineer and mathematician, Milutin Milankovitch. According to his theory, the sequence of ice ages periodically interrupted by warmer interglacials and interstadials of the past million years could be largely explained by celestial mechanics. By calculating the changes in the Earth's orbital parameters through time -- axial precession, axial tilt, and orbital eccentricity -- Milankovitch showed that different latitudes would receive differing amounts of solar energy over time scales of tens of thousands to hundreds of thousands of years. The theory could not be tested adequately until the past two decades or so, when detailed studies of marine sediment cores from all around the world showed strong agreement between the frequencies of past environmental changes and Milankovitch's calculated sequence of solar insolation changes. The chronology of past ice ages and warm interglacials fit the predictions of the theory quite well. The Milankovitch theory does not explain all the observed variation in global climates of the past million years, but it does show that orbital geometry has been the dominant influence on time scales of tens of thousands of years or more. Projecting the orbital parameters into the future indicates that if human influence on the greenhouse effect were not of immediate concern, we might instead be concerned about the gradual onset of a new glacial interval. It would probably require 10,000 years to attain full-glacial conditions, however. Even the early stages of a global cooling could have serious consequences for human populations.

Oxygen isotope variations measured from fossil foraminifera preserved in low latitude marine sediment cores during the past 750,000 years are plotted in figure 17. The isotopic variations were initially believed to reflect sea surface temperature changes through time. Later work indicated that changes in global ice volume also contribute to variations in isotopic composition of foraminifera. A temperature scale added to the curve (figure 17) shows that the global mean annual temperature (MAT) has varied about 1°C (1.8 degrees F) above current MAT and as much as 5°C (9 degrees F) below current MAT during the past 750,000 years. The peaks in the curve that intersect the dashed line indicate past intervals of warm interglacial climates. The current interglacial has lasted for about 10,000 years, and the record indicates that past interglacials lasted about 8,000 to 12,000 years. Such warm intervals have been relatively rare during the past 2.5 million years and intervals warmer than today are even rarer over that time. Only a few percent of that time has been characterized by global temperatures comparable to that of the present time. Some climate models predict that global mean annual temperatures may rise 2 to 5 degrees Celsius (3.6 to 9.0 degrees F) above the present mean temperature as a result of human influence on the greenhouse effect. If that prediction proves to be correct, such a global warming would have no precedent in the Earth's climatic history during the past 2.5 million years or more. Many of the organisms now living on earth evolved during the past several million years of generally cooler climates. It may be difficult, therefore, to predict how these species, and the ecosystems that they are a part of, would react to a rapid global warming of such magnitude.

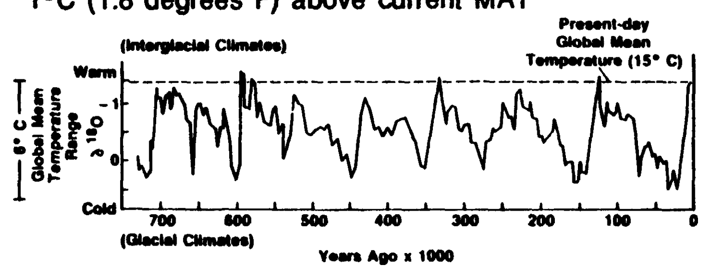


Figure 17. Composite oxygen isotope curve for the past 750,000 years of Earth history. (Source: Emiliani, 1978).

The Last 1,000 Years

Even during the past 10,000 years of a warm interglacial climate (the Holocene), the time span during which human civilization developed, there have been oscillations of global climate of sufficient magnitude to significantly influence human history. Global mean temperatures oscillated about 1.0 degree Celsius or more above and below the present mean value during the Holocene. Climate change of that magnitude is sufficient to cause glacier advances and retreats in alpine and polar regions, and to significantly impact human populations in many parts of the world. Changes in crop yields, the types of crops that could be raised, and the frequency of crop failures were some of the manifestations of Holocene climate fluctuations. The Norse colonization of Greenland occurred during a warm interval that permitted settlers to grow oats, rye, and barley. Declining temperatures between about 1250 A.D. and 1450 A.D. led to the disappearance of the Greenland colonies as agriculture became precarious and sea ice drifted farther and farther south., inhibiting contact with Europe. Cold temperatures persisted in Europe between about 1430 A.D. and 1850 A.D. This cold interval is called the "Little Ice Age." The hardships caused by this long interval of severe winters and more frequent crop failures is preserved in the art, literature, and commercial records of the time. Glaciers advanced in the mountains of Europe and Alaska during the Little Ice Age. Yet the magnitude of the global temperature change (about 1 degree C) was small in comparison with the temperature decline during the coldest part of the major glacial intervals during the past 1 million years (about 5 degrees C colder than the present global mean).

There is currently a controversy about the significance of an apparent increase of about 0.6 degree C in the global mean annual temperature during the past century. One part of the controversy relates to whether the meteorological data are sufficiently reliable to detect a change of that magnitude averaged globally. The other part of the controversy is whether or not the temperature increase, if it is real, represents natural variation in climate or whether it is an early manifestation of the changing greenhouse effect from increases in carbon dioxide and other trace gases in the atmosphere during the past century of intense industrial development and population growth. From the geologic perspective, the apparent temperature rise of the past century may simply represent a natural warming trend that is part of the oscillation toward warmer conditions following the end of the Little Ice Age (figure 18).

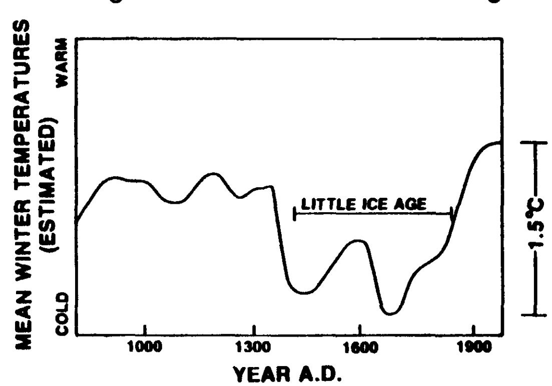


Figure 18. Winter temperature estimates for Eastern Europe during the past 1,000 years, based largely on historic non-instrumental records. (Source: Lamb, 1977).

The potential for human influence on climate appears to be a valid concern for the world's human populations. The global climate system is complex and poorly understood and, therefore, it is very difficult to predict its future response to human influences such as changes in the composition of the atmosphere. It is important to keep in mind, however, that there is a large amount of natural variability in the climate system. It is, therefore, premature to attribute individual "unusual" climate events such as the drought of 1988 in the United States or the succession of "warmer-than-normal" years during the 1980's to the anthropogenic enhancement of the greenhouse effect at this time. Historical data provide a brief glimpse of this natural variability, and the geologic record documents significant natural variability over a broad spectrum of time scales. Anticipating future climate change will require understanding not only the future greenhouse effect, but also the naturally variable climate system.

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