CLIMATE VARIATION AND ITS EFFECTS ON OUR LAND AND WATER

Part A. Earth Science in Climate Research

GEOLOGICAL SURVEY CIRCULAR 776-A

WORKSHOP ON EARTH SCIENTISTS' PERSPECTIVES OF CLIMATE CHANGE

Convened near Denver, Colorado, December 7-9, 1976

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Climate Variation and Its Effects on Our Land and Water

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By George I. Smith, Editor

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A product of the Workshop on Earth Scientists' Perspectives of Climate Change, convened near Denver, Colorado, December 7-9, 1976.

United States Department of the Interior

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PREFACE

The enormous impact on society of climatic variation is being recognized increasingly by both the public and government. Numerous recent publications as diverse as the public press, governmental documents, scientific journals, and special volumes of learned societies have dealt with the subject. Despite this heightened awareness of human vulnerability to shifts of climate, solutions to the political and scientific problems involved continue to be elusive.

Climate changes constantly. The reasons for climatic variability are not well understood, however, despite the formulation of many attractive and reasonable hypotheses. Perhaps of even greater concern is the growing realization that we do not yet fully understand the numerous subtle ways in which changing climate affects us. These are problems that merit more concentrated scientific attention.

Climate is generally considered primarily of interest to atmospheric scientists. Yet all scientists who have dealt with the earth, and even with other planetary bodies, have had to consider climatic problems. That past changes of climate on Earth have exceeded those measured by meteorologists is well recorded in rocks and surface features studied by earth scientists. The detailed histories of parts of the Earth's crust developed in studies of resource and environmental problems document beyond doubt that many of the differences in rocks and fossils found in local stratigraphic sequences were caused by changes in climate and their geological consequences. The rates at which geologic processes modify the landscape and impact man's use of the land are affected by climatic changes. And water supplies are obviously affected by changing climatic patterns.

In the course of their studies of the Earth and its geologic history, scientists of the Geological Survey have thus also contributed to a better understanding of past climatic changes. They are also fully aware of their obligation to help apply that knowledge of climatic history to the recognition of present and future climatic trends and to their probable future impact on human activities.

For these reasons, a workshop was convened near Denver on December 7-9, 1976, by scientists of the Geological Survey to explore the role of earth science in addressing national needs regarding information on climate. This three-part report is an outgrowth of the discussions by members of the workshop. Part A explores the roles and methods of the earth sciences in climatic research. Part B summarizes the types of climate-oriented work now being carried out by earth scientists of the Geological Survey. Part C proposes a research strategy designed to increase our understanding of the earth-science aspects of climatic variation.

V. E. McKelvey

Director
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SUMMARY

Climate is considered by many to be an atmospheric phenomenon. Those who study it, however, realize the extent of interaction between the atmosphere and other surface components of our globe--the oceans, ice sheets, and land--and past changes in climate are therefore imprinted on the geologic record. For nearly a century, earth scientists of the U.S. Geological Survey have been among those studying the record of past climate change and the geological consequences of our present climate.

To better coordinate information being generated by the Geological Survey, a workshop was convened near Denver on December 7-9, 1976, to exchange ideas about research that is oriented toward climate, climate variation, and the effects of climate on the Nation's land and water resources. This is the first of a three-part report resulting from that workshop.

The broad goals of climatic research are to improve our understanding of how the climate system works, what it may do in the future, and what may be the consequences. Earth science has three major roles to play toward the achievement of these goals:
(1) Defining the long-term record of climate variability.
(2) Determining geologic, geochemical, and geophysical factors that contribute to climate change.
(3) Estimating the physical and biological consequences of possible future climates.

The responsibilities of the Geological Survey lead to a heavy concentration of its efforts on research that contributes toward these goals in the continental environment. Climate leaves its imprint on and around the continents in an extraordinarily large number of ways that are preserved in the earth science record. The reconstruction of past climates, necessary to establish the constraints and causes of climate variability and change, involves translating these records into separable climate <u>elements</u>-- temperature, precipitation, wind, storm frequency, humidity, cloudiness, and storm trajectories. However, many of these imprints are direct records of the very phenomena that would be of importance to man in the event of future climatic variation--floods, erosion, avalanches, landslides, mudflows, hurricanes, dust storms, droughts, and many others. These earth science records can be used directly for estimating climate-related risks and hazards, and in many instances they provide a better basis for resource <u>management</u> decisions than would information on the climate itself.

INTRODUCTION

The winter of 1976-77 brought the coldest weather ever recorded to the north-central, central, and southeastern part of the United States, cold and nearly unprecedented amounts of snow to the northeastern part of the country, and the driest recorded winter to California, Nevada, and much of the West. Europe suffered from similarly severe weather. In contrast, Alaska, Greenland, and Iceland experienced warmer winters than normal. Should modifications be made in the geographic distributions of our agricultural belts? Should we reassess what constitutes adequate supplies of gas and fuel oil? Should the reservoir capacities of western water districts be drastically enlarged? The answers depend on whether this is a climatic pattern that will persist or occur more often in the future. No one knows. They also depend in part on the effects that the persistence of such climate would have on our Nation's land and water resources. Here, part of the answer can be provided--but only part.

The importance of climate, and the need for more information about it, is well expressed in the Introduction of the 1975 report by the National Academy of Sciences "Understanding Climatic Change, A Program for Action":

> "Climatic change has been a subject of intellectual interest for many years. However, there are now more compelling reasons for its study: the growing awareness that our economic and social stability is profoundly influenced by climate and that man's activities themselves may be capable of influencing the climate in possibly undesirable ways. The climates of the earth have always been changing, and they will doubtless continue to do so in the future. How large these future changes will be, and where and how rapidly they will occur, we do not know.
>
> "A major climatic change would force economic and social adjustments on a worldwide scale, because the global patterns of food production and population that have evolved are implicitly dependent on the climate of the present century ...
>
> "...Reducing this climatic dependency will require coordinated management of the nation's resources on the one hand and a thorough knowledge of the climate's behavior on the other. It is therefore essential that we acquire a far greater understanding of climate and and climatic change than we now possess..."

The widespread recognition of the importance of climate, as well as of the pressing need for more research, is further documented by:

- "Symposium on Long-term Climatic Fluctuations," published by the World Meteorological Organization under United Nations auspices, 1975.
- "The National Climate Program Act," hearings before the House Subcommittee on the Environment and the Atmosphere, Committee on Science and Technology, U.S. House of Representatives, 1976.
- "Climate and Food," published in 1976, and "Energy and Climate" and "Climate, Climate Change, and Water Supply," both published in 1977, by the National Academy of Sciences.
- "A United States Climate Program Plan," published at the direction of the President's Science Advisor in 1977 by the Interdepartmental Committee for Atmospheric Sciences of the Federal Coordinating Council for Science, Engineering, and Technology.
- Several reports by the Global Atmospheric Research Program, sponsored and developed jointly by the World Meteorological

Organization and the International Council of Scientific Unions.

- Two reports by the Central Intelligence Agency that directed attention to the geopolitical consequences of climate change.
- A wave of recent magazine and newspaper articles, television programs, and books.

All these sources document beyond a doubt that climate greatly affects our water, food, energy, and land resources--and that long-term variations and future change in climate would markedly affect our lives.

Although climate is considered by many to be an atmospheric phenomenon, those who study it realize the extent of interaction between the atmosphere and the other surficial components of our globe--the oceans, ice sheets, and land. Changes in any one component produce changes in all of the others. Past changes in climate are therefore also imprinted on the geologic record, and it is the evidence of those former climate changes in the oceans, ice sheets, and continents that is the object of study for a large number of earth scientists.

For nearly a century, earth scientists of the U.S. Geological Survey have been among those studying the record of past climate change as well as the geological consequences of our present climate. These studies, carried on within the same research organization for this length of time, have resulted in (1) advances in our understanding of past climates, (2) constantly improved bases for estimating the impact of future climate change on our land and water resources, and (3) maintenance of a nucleus of scientists that have developed high levels of expertise in these fields. Although most of the information generated by these studies is available to scientific journals, books, and maps, it is widely scattered as a result of the diversity of subject matter, and no center for coordination of such data currently exists because of the full-time commitment of Survey scientists to other programs and projects that also have high priorities.

As a start in coordinating information being generated by the Geological Survey, a workshop was convened near Denver on December 7-9, 1976, to exchange ideas about research that is oriented toward climate, climate variation[1], and the effects of climate on the Nation's land and water resources. During workshop discussions, a consensus arose that: (1) the roles of earth scientists and the research methods available to them are not well known to many non-scientific groups and agencies, and that a brief and relatively non-technical summary would be helpful, (2) a very large amount of information related to present and past climates is being generated by current Survey projects, and that scientists, both in and outside the Survey, would benefit from a review of the scope and findings of these projects, and (3) a program of research by Survey scientists should be developed, emphasizing certain lines that are especially needed. This is the first of a three-part report that responds to these needs.

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[1] "Climate" is commonly defined as the synthesis of "weather," with the "normal climate" being defined as the average of the last 30 years. "Climate variation" is a general term that includes both "climate fluctuation" and "climate change". The first of these terms is most frequently used for weather that significantly differs from the norm for periods lasting many years to decades; the second term is restricted by many to longer term climatic shifts that have durations measured in decades to centuries.

ROLES AND METHODS OF EARTH SCIENCE IN CLIMATE RESEARCH

The goals of climatic research are to improve our understanding of how the climate system works, what it may do in the future, and what may be the consequences. Earth science has three major roles to play toward the achievement of these goals:

(1) Defining the long-term records of climate variability.

(2) Determining geological, geochemical, and geophysical factors that influence climate change.

(3) Estimating the physical and biological consequences of possible future climates.

The first responsibility stems from the principle that an understanding of the causes and the probability of future climatic variation requires knowledge of the timing, nature, and limits of past variations over long periods of time. This perspective comes from viewing past climates as recorded by the geologic record. The second role follows from the geologic evidence that changes in factors that strongly influence the climate system have occurred with time; these influences include the distribution and thermal properties of the oceans, ice sheets, and continents and the occurrence of events such as large volcanic eruptions. The third responsibility follows from the fact that it is the physical consequences of a new climate that would become most important to man in the event of future climatic change. Measuring the relations between climate and earth-surface processes can lead to estimates of the physical and biological consequences of future climatic variation. Quantitative interpretations of the relations between both present and past climates and their effects on the earth's surface become keys to assessing the human consequences of possible future climatic variations.

The relation between the earth sciences and meteorological, oceanographic, and other sciences involved in a climate program is complex because their scientific domains overlap extensively. Investigations of both present and past climates are inherently interdisciplinary; many branches of the theoretical, observational, and laboratory sciences are involved, and almost all of them draw on data, constraints, and techniques derived from others.

The methods used by the earth sciences to fulfill their roles are many and varied. One way of dividing them is on the basis of the area from which the record is collected--from the ocean floors, the ice sheets, or the continents. Records from the ocean floors have yielded exciting and rather complete evidence of climatically induced changes in the fauna and in the temperature, salinity, and isotopic composition of sea water during the ice ages. Work on existing ice caps has also produced important information about the history of global climate in the polar regions. The continents account for only 30 percent of the Earth's surface, and they influence climates the least, but they respond to climate change most rapidly. As they also provide the main source of food and shelter for most of the Earth's population, relatively direct benefits stem from investigations of the ways in which climate interacts with natural processes in the continental environment. One major goal of a climate program, therefore, must be to understand more about how that environment could be affected by inadvertent or naturally caused climatic variation. Most of the climate research now in progress in the Geological Survey, described in Part B of this Circular, is concerned with this aspect of the climate problem.

Long cores from the deep sea floor have been available in large numbers only during the past decade or two. The methods used by earth scientists in studying them, therefore, have mostly been developed or improved during that period. Sea-floor sedimentation tends to be slow but continuous, and the records from these cores are valuable for their completeness. Climate data from the cores are chiefly derived from fossil, mineralogical, chemical, and isotopic variations that indicate past changes in the composition and temperature of the ocean water and the volume of water locked in the polar ice sheets. Other records include volcanic ash layers, which record major eruptions that possibly altered the atmospheric transparency, and debris dropped by melting icebergs, which record the existence of sea-level glaciers. The ages of events in sea-floor cores are commonly based on a combination of biostratigraphic, radiometric, paleomagnetic, and sedimentation rate methods. Dated cycles of ocean-wide isotopic variations provide a secondary correlation and dating method; these cycles were caused by the changing proportions of the isotopes oxygen-18 and oxygen-16 in the oceans and the polar ice sheets (which concentrate oxygen-16 more than does sea water) as the ice sheets expanded and contracted. Continuous records of the past several million years are recorded in many cores. Reports by the CLIMAP research group[2] exemplify paleoclimatic data obtained from the sea floor, and those papers plus the references in them to the work of others encompass a part of the known techniques and sources of data.

Earth scientists studying ice sheets in the Antarctic and Greenland, and glaciers in mountainous regions, derive data on climate from the hydrogen and oxygen isotopes of successive layers of snow and ice, or the chemical, biological, or clastic variations in the stratigraphy provided by the annual accumulation layers. Isotopic variations in the oxygen-18 and deuterium (hydrogen-2) of the ice reflect changes in atmospheric temperatures where the snow crystallized. Variations in the other ingredients reflect atmospheric transport phenomena and conditions in ice-free areas of those latitudes. The climates that were responsible for large expansions and contractions of ice sheets and glaciers in the past are also estimated on the basis of variations in the present glacier sizes that occur in response to observed variations in climate. Records based on the stratigraphy of glacier ice extend back several tens of thousands of years; ages are assigned by counting annual layers in the younger deposits and calculating theoretical rates of compaction and flow in the older deposits.

Climate leaves its imprint on the continents in an extraordinarily large number of ways, and the earth science record of continental climate consists of the numerous kinds of imprints that leave a permanent record. Almost all of them are indirect measurements of the climate itself, and much of the science concerned with the reconstruction of past climates thus involves translating these records of climatic response back into separable climate elements--temperature, precipitation, wind, storm frequency, humidity, cloudiness, and storm trajectories. However, a very large number of these imprints are direct records of the very phenomena that would be of importance to man in the event of future climatic variation--floods, erosion, avalanches, landslides, mudflows, hurricanes, dust storms, droughts, and many others. Earth science records of these types, therefore, can commonly be used directly for estimating climate-related

[2]The CLIMAP program is funded by the National Science Foundation; two of its major products are cited in Part C of this Circular.

risks and hazards, and in many instances, they provide a better basis for resource management decisions than would information on the climate itself.

Reconstructions by earth scientists of past climate-related events, climates, and climate change on the continents normally use several criteria. These criteria are commonly based on a blend of theory, laboratory sciences, and empirical observations of natural processes. Examples of climate parameters based primarily on theory and laboratory sciences are:

-Runoff velocity, based on the known relations between water velocities and the maximum sizes of transported fragments as determined by laboratory experiments.

-Lake floor temperatures, based on the ratio of stable isotopes in certain salts which laboratory synthesis has shown is a function of crystallization temperatures.

-Mean annual temperatures for each of the past 100 years or more, based on heat conduction theory and measurements of the distribution and downward velocity of variations in the near-surface geothermal profile.

Examples of parameters based chiefly on empirical or statistical criteria are:

-Relation between rainfall and runoff, based on the observed statistical relation between simultaneous measurements of both variables.

-Relation between temperature, humidity, wind, solar radiation, and lake evaporation, based on observations of the climatic variables and empirically determined evaporation from exposed pans.

-Relation between climate and fossil communities, based on the presently observed preferences of those plants and animals for certain climatic environments.

-Relation between climate and soil type, based on the present geographic and climatic distribution of developing soils.

Planning and making use of studies by earth scientists of the physical consequences of our present climate and past climate variation require an understanding of the strengths and constraints inherent to these disciplines. What follows are brief discussions of three of the many factors that influence studies in the continental environment: (1) the types of physical evidence that may be available, (2) the durations of geologic time that may be involved, and (3) the areas that were probably most affected by climate variation.

TYPES OF EVIDENCE AVAILABLE

Hydrologic records provide information to the earth scientist about the responses of ground water, surface water, and glaciers to climatic change; geologic sequences provide evidence of earth-surface responses to climatic change; biological records yield information about the effects of climatic change on the Earth's biota; archeological records tell us where and how man was able to live under changing climatic conditions; and historical records allow the specific effects of short-term changes in climate to be accurately documented. The interrelation between present and past geologic environments, various methods of study, and the span of time over which the results can be applied are shown in the adjacent table.

Two main components of climate are <u>temperature</u> and <u>precipitation</u>. The fossilized remnants of the climatically sensitive plant and animal communities that once occupied the terrestrial or aquatic deposit under study are commonly used indicators of these components; comparison of these communities with the present life zones of these organisms and the accompanying

Studies that yield climate information

Indices of present and past climates	Geologic environment: Coastal, nearshore continental shelf features	Streams, alluvial fans, estuaries	Lakes, playas, reservoirs	Ground water (including karst features)	Snow and ice (including sea ice, shelf ice, glaciers)	Permafrost, ground ice	Eolian features (wind deposition and erosion)	Slopes (including mass wasting features)	Soil development and stability	Bogs, swamps, and related wetlands	Useful time scale (years): 1, 10, 100, 1,000, 10,000, 100,000, 1,000,000, 10,000,000
I. Modern and historical processes[1]											
A. Water and ice											
1. Quality, areal extent	X	X	X	X	X	X		X	X	X	
2. Flow or diffusion (velocity, discharge, currents)	X	X	X	X	X			X	X		
3. Chemistry, water quality	X	X	X	X	X	X			X	X	
B. Sediment (weathering, erosion transportation, deposition)	X	X	X	X	X		X	X	X	X	
C. Landscape change and vegetation change	X	X	X	X	X	X	X	X	X	X	
D. Natural hazards (landslides, subsidence, floods, thermokarst)	X	X		X	X	X		X	X		
II. Geologic evidence of past processes and climates[2]											
A. Stratigraphic indices (stratigraphic sequence and discontinuties)	X	X	X	X	X	X	X	X	X	X	
B. Sedimentologic indices	X	X	X	X	X	X	X	X	X	X	
C. Pedologic (soil) indices, weathering indices	X	X	X	X	X	X	X	X	X	X	
D. Geomorphic indices (landforms)	X	X	X	X	X	X	X	X	X	X	
E. Paleontologic, paleoecologic, and biogeographic indices (pollen, plant megafossils, marine and terrestrial microfossils and megafossils)	X	X	X	X	X	X	X	X	X	X	
F. Stable isotopic indices (oxygen, hydrogen, carbon, sulfur, lead)	X	X	X	X	X				X	X	
G. Geochemical indices	X	X	X	X	X		X	X	X	X	
H. Dendroclimatologic indices (tree rings)	X	X	X	X	X	X	X	X	X	X	
I. Physical indices (temperature)			X		X	X					

[1]Climatic information derived primarily from direct measurement and (or) statistical analysis.
[2]Climatic information derived primarily from interpretation of rocks, sediments, stratigraphic relations, and fossil assemblages.

climatic conditions allows actual values of past temperatures and precipitation to be estimated. Lakes in closed basins that enlarged during periods of wetter climates indicate, by their sizes and areas, a definite ratio of inflow (related to precipitation) to evaporation (related to temperature). Similar and comparably accurate estimates of these climatic elements can be made on the basis of the former increased extent of glaciers. The mineralogy and ratios of stable isotopes in some sediments and cave deposits provide approximations of the mean annual temperatures of the surrounding areas. The geometry of a stream channel that is underfit or no longer occupied indicates the size of the largest stream that occupied it, and this allows estimates of peak runoff volumes in the past that may suggest the seasonal distribution of maximum rainfall. Evidence indicating variations in the past elevations of perennial snow and permafrost at high latitudes and altitudes quantitatively documents past variations in the mean annual temperatures of the regions. The distribution and annual variation in the vertical positions of near-surface thermal profiles record the mean annual temperatures of an area during the past century or more.

Maximum wind velocities and directions during storms are indicated by the shape and internal structures of stable or buried sand dunes, by wind-eroded landforms, and by the location and size of erosional shorelines and sand or gravel bars formed in extinct lakes. The sizes of fragments transported by winds or waves allow estimates of maximum wind velocities. High-altitude wind directions are indicated by the downwind distribution of volcanic ash from major eruptions.

Brief periods of unusual climate--droughts, drenching rains, floods, hot spells, cold snaps, dust storms, and hurricanes--also are recorded in the record available to the earth scientist. Long droughts, for example, are indicated by soils or interlayered thin beds of salts in lake beds, by strata that contain unusual amounts of windblown sand, by the development of badland topography, and by concentrations of certain fossils--the remains of terrestrial animals that died for lack of water, of aquatic animals that succumbed to increased salinities, or of dry land plants that moved into areas formerly occupied by lakes or swamps. Times of drenching rain and major floods are suggested by deposits indicative of widespread landslides and mudflows and by layers of abnormally coarse sediments in stream deposits or nearshore lake and marine records. Brief periods of atypical warming or cooling are suggested by temporary changes in fossil assemblages. Periods of exceptional wind or reduced vegetation cover are documented by wind-eroded landforms and by isolated layers of windblown silt or sand in both continental and marine deposits.

The characteristic storm paths and the synoptic meteorological patterns that prevailed during successive periods also can be inferred. The directions of the strongest winds, deduced from the criteria noted above, indicate the synoptic regimes that produced the strongest barometric gradients. The isotopic composition of samples of "fossil" water in glaciers, permafrost, ground water, and certain saline minerals provide information on the storm tracks and condensation-level temperatures that produced rain and snow during past intervals of time. Plant communities are sensitive to the seasonal distribution of precipitation as well as the amount, and changes in the composition of a fossil fauna and flora can indicate changes in the synoptic nature of the seasonal climates.

LENGTHS OF TIME INVOLVED

Dated chronologies of climatic change are established by a variety of radiometric and other laboratory age-dating techniques, by field methods that produce both absolute and relative ages, and by correlation of undated strata with strata in other areas where they are dated. Ages are usually expressed in terms of years (before the present, B.P.) or geologic periods (see back cover).

Climate records may be viewed in terms of the time span and time resolution they provide. Time resolution and accuracy of climatic reconstruction are progressively better for younger events. This point can be illustrated by describing the climatic histories and the nature of their record for six progressively longer blocks of time; successive blocks contained comparably greater climatic changes, but the quality and resolution

Group	Method	Approximate age range, in years[1] (percent resolution)	Minimum expectable uncertainty, in percent, for age given	Use in dating common Quaternary deposits: --, Seldom (if ever) used; x, Occasionally used; xx, Often used; xxx, Very often used; ( ), Potential rather than actual use — Glacial	Marine	Pluvial lake	Alluvial	Eolian	Volcanic
Numerical methods	Historical records	0 to 6,000 (±0) (±2)	0 (500 yr)	x	x	x	xx	x	x
	Carbon-14	100 to >40,000 (±100) (±2)	1 (15,000 yr)	xxx	xx	xxx	xxx	xx	x
	Uranium series	5,000 to >300,000 (±50) (±10)	5 (100,000 yr)	--	xx	xx	x	--	--
	Potassium-argon	50,000 to [2]2,000,000 (±20) (±2)	2 (1-2 m.y.)	x	x	(x)	x	--	xxx
	Fission track	50,000 to [2]2,000,000 (±40) (±5)	5 (1-2 m.y.)	x	x	x	x	x	xxx
	Dendrochronology[4]	0 to 9,000 (±0) (±2)	0-1 (<5,000 yr)	x	--	--	xx	x	x
	Varve chronology[4]	0 to 12,000 (±0) (±10)	0-1 (<8,000 yr)	x	--	x	--	--	--
Relative-age methods	Lichenometry	50 to 8,000 (±10) (±25)	10 (<1,000 yr)	x	--	--	--	--	x
	Obsidian hydration	100 to [2]2,000,000 (±20) (±30)	10 (100,000 yr)	(x)	--	(x)	(x)	--	x
	Tephra hydration	1,000 to [2]2,000,000 (±100) (±70)	50 (100,000 yr)	(x)	(x)	(x)	(x)	(x)	(x)
	Thermoluminescence	<2,000 to 250,000 (±50) (±10)	5 (100,000 yr)	--	(x)	(x)	(x)	--	x
	Amino acid racemization[4]	100 to 1,000,000 (±50) (±50)	20 (100,000 yr)	--	xx	(x)	(x)	--	--
	Rate of deposition	0 to [2]2,000,000 [3](5-50)	[3]5	--	xxx	xx	x	x	x
	Soil development	100 to 2,000,000 (±100) (±90)	25 (100,000 yr)	xxx	xx	xx	xxx	xx	x
	Rock and mineral weathering	100 to 2,000,000 (±50) (±50)	15 (100,000 yr)	xx	--	x	xx	x	x
	Progressive landform modification	100 to [2]2,000,000 (±100) (±100)	50 (100,000 yr)	xxx	x	x	xx	x	xx
	Geomorphic position	0 to 2,000,000 (±100) (±100)	70 (100,000 yr)	xxx	xx	xx	xxx	xx	xx
Correlation methods	Paleomagnetism	0 to [2]2,000,000 [3](5-20)	[3]5	(x)	(xx)	(xx)	(xx)	(xx)	xxx
	Volcanic tephra layers	0 to [2]2,000,000 [3](2-10)	[3]2	xx	xx	x	x	x	xx
	Fossils and artifacts	0 to [2]2,000,000 [3](10-50)	[3]10	x	xx	xx	xx	xx	--
	Stable isotopes	0 to [2]2,000,000 [3](5-20)	[3]5	--	xxx	(xx)	--	(x)	--
	Stratigraphic sequence and other physical properties	0 to [2]2,000,000 [3](5-50)	[3]5	xxx	xxx	xxx	xxx	xxx	xxx

[1]Limits are those between which a technique is normally applied. Approximate resolutions at each limit is given in parentheses.

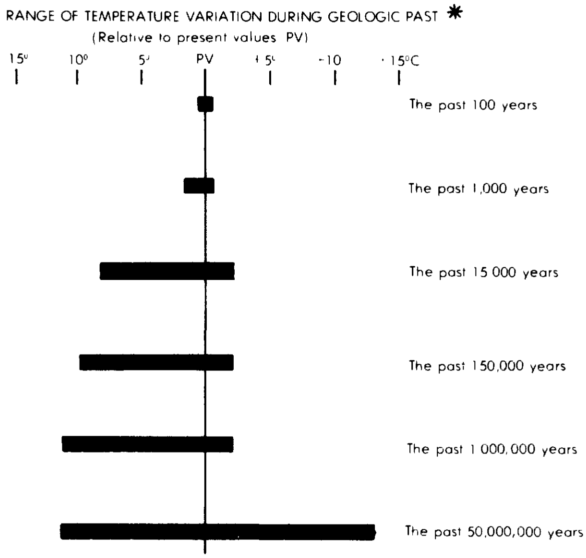
[2]These methods may be applicable to pre-Quaternary (2 m y. old) materials.

[3]Where resolution is mostly dependent on factors other than age, a single range of resolution is given, and the minimum uncertainty does not apply to a specific age.

[4]Also used as a correlation method.

of their records become progressively less: (1) the past 100 years, (2) the past 1,000 years, (3) the past 15,000 years, (4) the past 150,000 years, (5) the past 1,000,000 years, and (6) the past 50,000,000 years.

Climatic variation during the past 100 years is reconstructed from instrumental, written, photographic, and geologic records from much of the globe. The waning stage of a centuries-long cold period produced temperatures during the first part of this period that were still 0.2 to 0.4 degrees (C) below present normal values. A gradual warming trend that lasted until the 1940's reversed this pattern, with comparably above-normal temperatures being recorded over much of the globe. Since that time, temperatures have lowered to values nearer the averages of this millenium. Weather events in this period can generally be reconstructed to the nearest hour or day.



* Data generalized from information in National Academy of Sciences report Understanding climatic change and unpublished data from the U S Geological Survey

Substantial climatic fluctuations during the past 1,000 years are recorded by historical as well as some archeological, geological, and biological records, although sea-floor sediments generally do not record the relatively brief climatic changes of this period. Written documents in Europe reveal a relatively warm climate at the beginning of this millenium, followed by a cold period that extended from the mid-15th to mid-19th century. Several forms of evidence in North America show that a century-long drought, which started in the southwestern U.S. about 1300 A.D., caused widespread incision of gullies in the alluvial flood plains and extensive displacement of the native population. A cold period followed, like that recorded in Europe, and it was terminated by a period of rapid warming that began about 1880. Many climatic events within this block of time can be dated to the nearest day or year.

The past 15,000 years includes the time of transition from the last major continental glaciation (the Wisconsin Glaciation of the Pleistocene Epoch) into the current (Holocene) interglacial condition. The last transition from the climate associated with large continental ice sheets in Europe and North America to a climate much like that of the present, occurred about 10,000 years ago--quite possibly over a period of a few centuries or less. Over the next few thousand years, North America was warmer than now. The record of climate during the past 15,000 years is contained in sediments deposited in marine, lake, stream, colluvial, and windblown environments, and by the very young deposits of continental and alpine glaciers. More than 50 percent of the United States is covered by deposits formed during this interval, hence the geologic record for this block of time is geographically extensive and relatively complete. In favorable localities, tree ring records reflect annual climate variations during the past several thousand years. The absolute chronology of deposits less than 15,000 years old has been established primarily by carbon-14 dating, which has a resolution of a few centuries in this time range.

The past 150,000 years includes all of the last glacial stage and the preceding interglacial stage when the climate at times may have been much like that of the present. Multiple advances and retreats of the continental ice sheet margins occurred during this period, and these correlate with other indices of climatic change. The most continuous records of climate variations come from marine sediments and lake beds in areas not covered by Pleistocene ice. Discontinuous records are provided by glacial deposits in the north-central, northeast, and mountainous parts of the United States, river and deltaic deposits in the south and southeast, alluvial deposits in the west and southwest, and deposits of windblown silt in the midcontinent regions. Age control, provided by carbon-14, uranium series, potassium-argon, and other methods allows climatic events that lasted less than a century to be identified in the younger deposits and events that lasted several thousand years to be identified in older deposits.

The past 1,000,000 years saw repeated cycles of glacial and interglacial climates. Continuous records representing all of this block of time are rarely exposed, but drill cores from the sea floor and in selected lakes and valleys provide nearly complete documentation. Dating by potassium-argon, uranium-series, fission-track, and other methods allows ages to be assigned to climatic events of this period, but the accuracies of dates in older deposits generally are limited to several tens of thousands of years. Thus, climatic events that lasted shorter periods cannot be accurately correlated with similar events in other areas. Furthermore, many parts of these records are not accurately dated, and the relative ages of the recorded climatic changes are more certain than their absolute ages.

The past 50,000,000 years included the most dramatic change found in any of these intervals of time. A warm global climate underwent several fluctuations that lasted about 10,000,000 years each, but it cooled markedly about 30,000,000 years ago and then warmed again. This trend continued until about 10,000,000 years ago when an even more marked cooling trend began and polar ice caps and glaciers developed at higher elevations. By 3 million years ago, the glaciers had spread to low elevations where they calved into the sea, forming icebergs. Multiple fluctuations of glacial and interglacial--or less glacial--climates followed, with climates as warm as the present climate being representative of only a small part of that block of time. Dating of deposits in the early part of this time period by potassium-argon, fission-track, and other methods generally allows ages to be assigned to within a few million years in the older deposits and a few hundred thousand years in the intermediate age deposits. Many records, however, consist of sequences that have only widely spaced dates or points of correlation. Climatic variations that lasted less than a few hundred thousand years are not generally recognized and dated.

AREAS MOST AFFECTED BY CLIMATIC CHANGE

All parts of the Earth's surface are affected by climate. Most of the physical, chemical, and biological balances that characterize a region are climate dependent, and a change in climate forces the rebalancing of all dependent systems. The terrestrial environment responds rapidly to climate change, commonly within a period of less than a year. Biological communities and runoff of surface waters are thus criteria of short-term or rapid climate change. Other environments, such as lakes and glaciers, provide some averaging of climate and react significantly only after several years or decades of persistent change. Continental ice sheets and the oceans respond much more slowly, because of their enormous thermal inertia, and they require long, persistent climate changes to create measurable variation.

Some parts of the Earth's surface are particularly sensitive to climatic change. Many of these are the vegetational transition zones where existing forms of plant life can barely survive under the present climatic regime. Existing balances between them and animal and human life are therefore also in jeopardy, and even small changes in climate, or small changes in the annual variability of climate, produce major consequences to all forms of life. Examples of these fragile environments are the transition zones between the arctic tundra and the subarctic forest, the upper and lower treeline zones of the western mountain forests, and the grasslands and deserts. Deltas, estuaries, and coasts are also highly sensitive to climate change because they represent delicate physical and biological balances between runoff volume and velocity, and they are markedly affected by the frequency and character of coastal storms.

- Past climate variations in the transition zones between the arctic tundra and subarctic forest can be reconstructed on the basis of well-preserved plant and animal remains, permafrost thickness, cryogenic soil structure distribution, vertical temperature profiles in permafrost and in boreholes, lake and swamp stratigraphies, glaciers and glacial deposits, and tree ring variations and chronologies. The arctic and subarctic regions are especially affected by climate change because the inherent nature of the atmospheric circulation system tends to magnify the change in those areas relative to that felt in temperate latitudes.

- Past changes in the elevations of the upper and lower treeline zones of the western mountain forests, as determined from the fossil remains of the plants and animals associated with them, are themselves sensitive criteria of climate although the relative importance of changes in precipitation, temperature, and wind is not always clear. Evidence of past migrations in elevation of vegetational zones on steep slopes are most informative because the accompanying temperature changes can be estimated on the basis of normal atmospheric lapse rates.

- Minor climate fluctuations, especially in precipitation, result in major changes in the boundaries between the grasslands and deserts. These are recorded in the geologic record by fossil remains, the type of soil development, and by the intensity of erosion.

- Changes in climate affect the coasts by altering the frequency and intensity of storms and the wave directions associated with them, and these changes affect the rate and location of erosion and deposition. Estuaries and deltas are markedly sensitive to even short-term changes in the volume of runoff and in water level; sediment and vegetation changes sensitively record such fluctuations. The much longer term variations in climate, which caused changes in sea level and the locations of shorelines as a result of major glaciations and deglaciations, produced downcutting or filling of channels, burial of marshes and forests, emergence of reefs, migration of beaches and bars, and the erosion of terraces.

AGENCIES AND INSTITUTIONS CONCERNED WITH CLIMATE

An understanding of climatic change and its effects is necessary to fulfill the responsibilities of many national and international groups and agencies. Careful coordination of efforts is required because of the number and diversity of international organizations and U.S. Government agencies that produce or require information on climate (see boxes). To assure coordination between agencies in the United States, recommendations were made in 1974 by the Domestic Council and in 1975 by the National Academy of Sciences. These were combined by an interdepartmental committee under the auspices of the Federal Coordinating Council for Science, Engineering, and Technology into a document published in 1977 entitled "A United States Climate Program Plan." That plan spells out the major objectives of a coordinated interagency Federal Program and identifies involved agencies. It also identifies priority research and service in five categories:

- Impact assessments of climatic variability on crop yields, livestock production, energy demand , land and water resources, transportation, national security, and other activities.
- Diagnosis and projection of observed climatic variations, particular seasonal and interannual anomalies and fluctuations.
- Research to gain basic understanding of natural climate variability and of man's potential impact on climate, such as the long-term increase in the amount of carbon dioxide in the atmosphere. dioxide.
- Observations by satellite and other means to help determine the earth's radiation budget, air composition, sea-air interactions, and other processes that cause climate to vary.
- Management of the vast array of measurements needed for climate research and services--oceanic, atmospheric, hydrologic, solar, and other types of data.

The National Research Council of the National Academy of Sciences has, in turn, established a Climate Research Board that is expected to provide overview and advice to the Government on research carried out as part of the Climate Program Plan.

The elements of the Climate Program Plan underlined here are the ones that are most directly related to the effects of climate on our land and water resources or that require major components of the earth science data. The two Government agencies most concerned with the earth science record of climate are the Geological Survey (USGS) and the National Science Foundation (NSF), so that the research activities of these two agencies require careful coordination. The activities of the NSF consist mostly of support for work carried out in universities and university-sponsored research institutions.

The Geological Survey performs a wide variety of climate-related earth science investigations. Most of the research is done by USGS scientists, but some is done by universities, state surveys, and other institutions on a grant or contract basis. These investigations are coordinated with and used by many U.S. Government agencies as well as several international programs. Data on water quantity and quality collected by the Survey, for example, are used by and coordinated with various agencies in the Departments of Interior; Health, Education, and Welfare; Defense; Commerce; Energy; and Agriculture. Many State and local governmental agencies use these data and also perform earth-science investigations related to climate.

Much of the research sponsored by NSF dealing with-science aspects of climate is being conducted by research institutes and centers linked to educational institutions: Center for Climatic Research (University of Wisconsin), Coastal Studies Institute (Louisiana State University), Desert Research Institute (University of Nevada), Great Lakes Research Center (University of Michigan), Institute of Arctic and Alpine Research (University of Colorado), Institute of Arctic Biology (University of Alaska), Institute of Marine Sciences (University of Miami), Institute of Polar Studies (Ohio State University), Institute of Quaternary Studies (University of Maine), Laboratory of Tree-Ring Research (University of Arizona), Lamont-Doherty Geological Observatory (Columbia University), Limnological Research Center (University of Minnesota), Museum of Applied Science Center for Archeology (University of Pennsylvania), and Quaternary Research Center (University of Washington).

Earth science researchers in these institutes, the USGS, and scores of colleges, universities, and private research organizations have combined to produce an impressive array of climate-related studies that have been applied to every geologic time period as well as the present. The notable breadth of the Geological Survey's current efforts is the subject of Part B in this Circular.

INTERNATIONAL ORGANIZATIONS INVOLVED IN CLIMATIC STUDIES

(Organizations most actively involved in studying the effects of climate on land and water resources are underlined)

- United Nations
  - <u>World Meteorological Organization (WMO)</u>
  - <u>Food and Agricultural Organization (FAO)</u>
  - UN Environmental Program (UNEP)
  - <u>Conference on Desertification</u>
  - <u>International Hydrological Program</u>
  - International Biological Program
  - <u>World Climate Program</u>
- International Council of Scientific Unions (ICSU)
  - International Union of Geodesy and Geophysics (IUGG)
    - International Association of Hydrologic Sciences (IAHS)
    - International Association of Meteorology and Atmospheric Physics (IAMAP)
    - International Association of Physical Sciences of the Ocean (IAPSO)
  - <u>International Geographical Union (IGU)</u>
  - International Union of Geological Sciences (IUGS)
    - Commission on Stratigraphy (CS)
    - International Geologic Correlation Program (IGCP)(with UNESCO)
  - International Union of Biological Sciences (IUBS)
  - Scientific Committee on Oceanic Research (SCOR)
  - Scientific Committee on Water Research (COWAR)
  - Scientific Committee on Antarctic Research (SCAR)
    - <u>International Antarctic Glaciologic Program (IAGP)</u>
  - Special Committee on Problems of the Environment (SCOPE)
  - Federation of Astronomical and Geophysical Services (FAGS)
    - <u>Permanent Service on the Fluctuations of Glaciers (PSFG)</u>
  - World Data Centres
  - Inter-Union Committees on Geodynamics
  - Pacific Science Association
- Global Atmospheric Research Program (GARP) (ICSU/WMO)
  - <u>First Global Garp Experiment (FGGE)</u>
  - GATE, NORPAX, JASIN, and others
- Other scientific organizations
  - <u>International Quaternary Association (INQUA)</u>
  - International Glaciological Society (IGS)
  - International Association of Hydro-Geologists (IAH)

U. S. GOVERNMENT AGENCIES INVOLVED IN CLIMATE STUDIES

Coordination

Office of Science and Technology Policy (OSTP).
Federal Coordinating Council for Science, Engineering, and Technology (FCCSET).

Basic Data Collection and Analysis in Support of Agency Objectives

Department of Commerce (DOC)

The National Oceanic and Atmospheric Administration (NOAA) is the lead agency for weather monitoring and prediction and has responsibilities for atmospheric and oceanic aspects of climate, including the National Weather Service, National Environmental Data Service, Geophysical Fluids Dynamics Laboratory, Center for Climate and Environmental Assessment, Center for Experimental Design and Analysis, National Climate Center; Large Area Crop Inventory Experiment (with DOA and NASA); and monitoring of sea ice, oceanic water column, global albedo, and the surface of oceans (with DOD and NASA).

National Aeronautics and Space Administration (NASA)

NASA provides satellite technology appropriate for modern weather and ocean observations. It performs research on solar radiation, on the climate of other planets, and on climate factors monitored by satellite.

National Science Foundation (NSF)

NSF has major responsibilities for basic research. The Climate Dynamics Research Program and other programs support research on climate history, on predictive models of climate, and on the impacts of climate change on man. NSF functions include operating the National Center for Atmospheric Research, the International Decade of Oceanographic Exploration (which includes CLIMAP, NORPAX, GEOSEC, ISOS, and Coastal Upwelling Experiment), and research programs on meteorology/climatology, oceans and sea floor, earth science, polar studies, and ecology.

Department of Interior (DOI)

The Geological Survey (USGS) collects data and performs geologic and hydrologic research on climatic history and its effects on land and water, to support appraisals of land and water resources and of environmental impacts. The Bureau of Reclamation (USBR) has responsibilities in management of water resources and performs experiments in precipitation augmentation. Other bureaus need climate data for resource management.

Department of Defense (DOD)

Performs supporting services and study of air-sea interaction, solar radiation, behavior of sea ice, influence of weather and climate on communications, and other factors in pursuit of its missions.

Department of Transportation (DOT)

DOT is involved in weather-related activities and recently completed the Climate Impact Assessment Program which studied environmental impacts of aircraft effluents. The Federal Aviation Administration makes meteorological observations. The Federal Highway Administration studies environmental and land stability factors related to highways.

Department of Energy (DOE)

DOE is involved with the effects of energy production on climate, particularly the effects of carbon dioxide production from the burning of fossil fuel, and also needs climate and weather prediction to make policies concerning supplies of heating fuel.

Environmental Protection Agency (EPA)

EPA is concerned with pollutants in the atmosphere.

Department of Agriculture (DOA)

DOA is concerned with relations between climate and crop yield. It studies soil development and conservation and makes snow surveys.

Governmental policy making that requires data on climate

Department of State (DOS)
Department of Health, Education, and Welfare (HEW)

CLIMATE VARIATION AND ITS EFFECTS ON OUR LAND AND WATER

Circular 776-B -- Current Research by the Geological Survey

CONTENTS

Circular 776-C -- Geological Survey Climate Plan

CONTENTS

Names and bounding ages of geologic eras, periods, and epochs, and frequently used names of Quaternary stages.

Geologic time scale, complete

Era or Erathem	System or Period		Estimated ages of time boundaries, in millions of years ago
Cenozoic	Quaternary		
			2 - 3
	Tertiary		
			65
Mesozoic	Cretaceous		
			130
	Jurassic		
			180
	Triassic		
			225
Paleozoic	Permian		
			?280
	Carboniferous Systems	Pennsylvanian	
			310
		Mississippian	
			350
	Devonian		
			410
	Silurian		
			435
	Ordovician		
			480
	Cambrian		
			600
Proterozoic & Archeozoic	Precambrian		
			4500±

Cenozoic time scale

	Series or Epoch	Estimated ages of time boundaries, in millions of years ago
Quaternary	Holocene	
		0.01
	Pleistocene	
		2 - 3
Tertiary	Pliocene	
		5.5
	Miocene	
		26
	Oligocene	
		38
	Eocene	
		54
	Paleocene	
		65

Quaternary stage names

Holocene	(interglacial)
Pleistocene	Wisconsin (glacial)
	Sangamon (interglacial)
	Illinoian (glacial)
	Yarmouth (interglacial)
	Kansan (glacial)
	Aftonian (interglacial)
	Nebraskan (glacial)