HISTORY OF THE EARTH'S CLIMATIC CHANGES

Irena I. Borzenkova
Department of Climatology, State Hydrological Institute, Russia

Keywords: abrupt climatic change, ancient supercontinents (Gondwana, Pangaea), biostratigraphy, catastrophism, continental drift, Earth's ancient climates, feedback mechanism, forcing factors, glacial or ice ages, greenhouse effect, interglacial, Little climatic optimum, Little Ice Age, Medieval warming, Mesozoic climate, Messinian salinity crisis, Milankovitch theory, orbital variations, palaeothermometry, Pre-Cenozoic climate, Pre-Pleistocene climate, sea-floor spreading, the Holocene climatic optimum, uniformitarianism.

Contents

Summary

Based on different proxy data (e.g. lithological, palaeobotanical, isotopic etc.) the main stages of the Earth's climate during the last 4.5 billion years are presented in this chapter. The climatic history is given in more detail for the last 65 million years (the Cenozoic time) reflecting an increased quantity and quality of available empirical data. Changes in the atmospheric CO_2 and other "greenhouse" gases are shown to be one of the main factors causing the climate of the Mesozoic and the Cenozoic time. The Eocene-Oligocene boundary (about 36-37 Ma) marks the beginning of the transition

between non-glacial and glacial climatic regimes. This transition proceeded in several stages (31-29, 15-12, 10-9, 7-6, 2-0 Ma) relating to the appearance of continental ice sheets and sea ice, first in the southern and then in the northern hemisphere. A rapid decrease in carbon dioxide concentration in the atmosphere at the Neogene time appeared to be the main cause of a drastic decrease in global temperature and may have led to increase climate sensitivity to relatively small changes in insolation pattern due to orbital factors. Like the modern time, the signs of global temperature trends was determined by the temperature in high latitudes, whereas in low latitudes temperature trends could be of an opposite sign The reconstruction of air temperature and annual precipitation is given for the last cooling of the Pleistocene time (about 18 ka BP) and for the warmer time of the Holocene (about 6-5 ka BP).

1. Introduction

Palaeoclimatology is the science of studying climates of the past. It has developed into an independent discipline only recently. Earlier it was considered a part of historical geology and palaeogeography. The amount of information on past climates has recently increased considerably. The development of some powerful concepts (first, the idea of continental drift) and new methods (foremost the methods of palaeothermometry and absolute age dating) led to a revolution in the Earth sciences and stimulated progress in palaeoclimatology as an independent discipline.

In the late 1940s, climate history studies were mainly based on geological evidence from the sedimentary records of land rocks. These included calcareous rocks (limestone, marble, marls), carbonaceous rocks (coal, oil-gas-bearing layers), red beds (sandstone, clay, pebble, etc.), evaporites (salt, potash, gypsum), and glacial deposits (tillites and moraine materials). In practice, nothing was known of the past climates of the World Ocean that occupies about two-thirds of Earth's surface. Past ocean temperatures were first reconstructed in the beginning of the 1950s, when Harold Urey (1893-1981) and his colleagues discovered the "geological thermometer". This method of isotope palaeothermometry is based on the relationship between the contents of heavy (^{18}O) and light (^{16}O) oxygen isotopes in the carbonate skeletons of marine organisms. In the early 1950s, the oxygen-isotope analysis was widely applied to study belemnites, a large group of marine organisms that inhabited earlier shallow-water intercontinental and marginal seas (from 120 to 130 million years ago).

Deep-sea drilling techniques allowed the application of the oxygen-isotope method to study fossil sediments containing biogenic remains of plankton and benthic marine microfauna. The development of deep-sea drilling technology produced unique empirical data on the World ocean climate throughout the Late Mesozoic and Cenozoic. More than 1000 sites have been drilled and thousands of ocean sediment cores have been obtained. The results were quantitative data on surface and bottom ocean water temperatures in different latitudinal zones during the last 130 million years.

The oxygen-isotope data on fresh-water lake carbonates, cave sediments (speleothems), travertines, continental ice sheets in high latitudinal and mountain ice cores proved to be very promising. Ice cores from Greenland and the Antarctic and mountain ice cores were the richest sources of new independent palaeoclimatic information about temperature changes, greenhouse gas concentrations in ancient atmospheres and the intensity of explosive volcanic eruptions (See *Glaciers, Ice Cores from the Land Sheets and the Mountains).*

The extensive empirical information collected recently has expanded considerably and changed in some respects our views about past climate variations. These new views can be generalized as follows:

- Climatic changes even in the warmest epochs of the Mesozoic and the Cenozoic appear to be more complicated issues than had been anticipated;
- The intervals with relatively similar climates were interrupted by abrupt (in terms of geology) changes that were disastrous in individual cases;
- These abrupt climatic changes considerably affected the biosphere as a whole, which in some cases precluded the use of the principle of uniformitarianism in the reconstruction of past climates;
- The idea of past global climatic catastrophes occurring from time to time was developed at the beginning of the nineteenth century by the French palaeontologist Georges Cuvier (1769-1832) in his book "Discours sur les revolutions de la surface du globe", 1812, Paris. Cuvier's concept was probably based on the views of Pierre Simon Laplace (1749-1827), who assumed that natural catastrophes were caused by the collision of comets with the Earth. In the middle of the nineteenth century the idea of catastrophism was rejected mainly due to the views of James Hutton (1726-1797) and Charles Lyell (1797-1875) proposing the original approach to the development of Earth's processes (See *Global Climatic Catastrophes*).

At present a new concept about the development of organic and inorganic nature is being formed replacing the concept of uniformitarianism. 'New uniformitarianism' accepts the fact that the development of the Earth as a planet and the evolution of living nature included the cataclysms and catastrophes of various scales and magnitudes. It supposes that the present might sometimes, but not always, be the key to the understanding of the past. It might be summed up by the phrase: "The past can become the key to the present and future".

According to the new mode of thinking and new concepts, climate and environment varied in the past more and faster than it had been ever supposed. It is clear that if the causes of past climate and environmental variations are understood well, it will be possible to understand the mechanisms of present climate fluctuations and to look to the future climatic changes. If the mechanisms of past climatic changes can be understood on the basis of palaeoclimatic data, the long-term climate and environment forecasts are expected to be possible.

Until quite recently the past climatic changes, could only be explained by using changes in incoming solar radiation due to changing the luminosity of the Sun as a star or due to changes in orbital parameters (Milankovitch's theory), or changes in the Earth's surface structure. In spite of intensive studies on physical climatology and climate modeling, the true causes of climatic changes of the past remained uncertain until the late 1970s and early 1980s. At that time, the first quantitative estimates of atmosphere gas composition in the past were obtained by using different quantitative models describing atmospheric gas cycles, or the data on the rate of ocean floor spreading, or by measuring the rock volume by the maps of the World Lithological Association for all geological systems since the Early Riphean time (about 1.6 billion years ago). These data showed that the atmospheric carbon dioxide varied greatly during the Phanerozoic time (the last 570 million years) ranging from 0.4% to 0.03%.

The analysis of geological data showed a correlation between climate and atmospheric gas composition with higher concentrations of carbon dioxide associated with global warming and lower concentrations associated with cooler conditions. In the beginning of the 1980s, the first empirical data on the atmospheric gas composition in the past were obtained from the analysis of air bubbles preserved in ancient ice sheets from the Antarctic and Greenland. These data showed that during the glacial maximum of the Pleistocene the atmospheric CO_2 dropped to 0.018-0.020% by volume and then rose during the late glacial time and of the Holocene to 0.028% by volume. This result confirmed the hypothesis proposed by Owen Chamberlain and Svante Arrhenius (1859-1927) in the beginning of the twentieth century. They had proposed that the cause of past climate change (in particular, during the Pleistocene) could be changes in atmospheric carbon dioxide.

Now it appears that by burning fossil fuel man is restoring the atmospheric gas composition to a level characteristic of the Cenozoic warm epochs. Atmospheric CO_2 of 0.036% by volume was reached by the end of the 1990s compared to 0.028% in the middle of the nineteenth century. Climatic conditions of the geological time intervals with warmer climates are believed to serve as possible analogues of future climatic conditions. For this reason, the geological data producing the idea of environmental and climatic conditions for past warm epochs are of great scientific and practical importance. They yielded independent quantitative information on climate variations in the past.

2. Methods of palaeoclimatic reconstructions

The methods of palaeoclimatic reconstructions can be classified into four groups:

- Lithological-genetic,
- Ecological-palaeontological,
- Isotopic,
- Geochemical.

The basic characteristics of these methods and the main sources of palaeoclimatic information are presented in Table 1.

Data sources	Methods of investigation	Period open to study	Climate-related inferences
Ocean sediments	1. Isotope composition of microphone. 2. Morphological	The last 100-130 million years.	Global ice volume, surface and bottom water temperature,

	analyzes of sediments. 3. Mineralogical composition.		prevailing wind direction and strength.
Ice cores from continental ice sheets, mountain glaciers, underground (polygonal ice wedges)	1. Isotope composition. 2. Geochemical analyses. 3. Trace chemistry and electrolytic conductivity.	The Late Pleistocene (Last 200,000-300,000 years).	Temperature, gas composition (CO_2, CH_4 and other gases), transparence of the atmosphere, volcanic eruptions.
Bog or lake sediments	1. Pollen analyzes. 2. Fossil analyzes. 3. Geochemical and sedimentological composition.	The Late Pleistocene and the Holocene.	Temperature, precipitation, soil moisture.
Closed basin lakes (especially in arid and semi-arid regions).	1. Lake level.	The last 40-50,000 years.	1. Lake levels status. 2. Moisture conditions and precipitation.
Tree rings	1. Dendrological analyze. 2. Isotope analyze.	The last 5000-6000 years.	Temperature and precipitation.
Written records and archeological data.	1. Artifacts. 2. Ceramics. 3. Written records.	The Late Pleistocene and the Holocene.	Moisture conditions, temperature and precipitation.

From: Borzenkova I.I. (1992). *The changing climate in the Cenozoic*, 246 pp. Gidrometeoizdat, S. Petersburg.

Table 1: The main sources of palaeoclimatic information

2.1 Lithological-genetic methods

These methods include two principally different subgroups. The first describes the lithogenetic processes reflecting types of global climatic conditions existing over a long period of time (within quite a wide range of changes in temperature and precipitation). This subgroup is the basis for isolation of long-term variations in climate from two to three millions to hundreds of millions of years in the past.

The second subgroup, on the contrary, makes possible the detection of relatively short-term climatic variations related to changes of structural deposits. For example, the alteration of loess with fossil soils or lacustrine layers with salt layers can serve as excellent indicators of the deposits in the regions of moisture deficit covered with scarce information of different kinds. Deposits of bauxite show that climate in the past was close to the present “Mediterranean type” of climate. Bauxite formed in a dry season of one to three months in duration with high summer temperatures, and good moisture conditions during the rest of the year.

Cryogenic textures related to phase transitions of water into ice, and vice versa, provide data on permafrost and also data for assessing the amplitude of seasonal temperature variations. These data are important, in particular, because they indicate climatic conditions of cold epochs, for which there is considerably less information than for warm ones.

2.2 Ecological-palaeontological methods

These methods are the most widely accepted ones to estimate the thermal and moisture conditions in the past. For example, species like fan palm spread northward up to a January 5° C isotherm and laurel up to a 3 °C isotherm. As for the sea surface temperature, the northern boundaries of large foraminifera and corals correspond to an 18 °C isotherm.
The most detailed information, including that for determining temperature and precipitation, can be derived from the palaeobotanic data (spore-pollen and macrofossils) processed by the arealographic and information-statistical methods. It seems that the arealographic method of reconstructing temperature and precipitation by combining climatic characteristics for the majority of definite plant species is the most universal for the entire Quaternary time. The results of the experimental use of this method for even earlier periods of the Cenozoic are encouraging. The method of arealograms has recently been successfully applied to small mammals (for example, rodents) as well as to fossil insects.

The information-statistical method has recently been used extensively to process palaeobotanic and marine microfauna data. For this purpose different types of transfer function between species of plant fossils or marine microfauna species and environment data have been used. This method was widely applied to reconstruct the water surface temperatures within such international projects as DSDP, CLIMAP and COHMAP.

2.3 Isotopic and geochemical methods

Isotopic palaeothermometry is based on the assumption that there is an equilibrium exchange between oxygen isotopes (^{16}O and ^{18}O) of water and calcium carbonate precipitating from it.

When isotope composition of seawater is constant, the data on oxygen-isotope composition of carbonate fossils of marine fauna (plankton and benthos) provide reliable data on the surface and bottom water temperatures. A 1 ‰ (per mil) change in the isotope composition is equal to a 4 °C temperature change. Interpreting isotopic data pertaining to the time of continental ice sheet formation, when the natural process of oxygen isotopic fractionation occurred, is the most difficult. When the volumes of continental ice changed, the oxygen-isotopic data obtained for plankton and benthic foraminifera is believed to reflect changes in isotopic composition of seawater to a larger extent (about by 2/3) than the temperature changes of surface or bottom water.

Isotopic methods can be applied to analyze both ocean sediment and ice cores, as well as fresh-water carbonates, tree trunks, speleothems (stalactites and stalagmites from caves), travertines and any other remains. Similar isotope techniques are applied to hydrogen and carbon.

Of the geochemical methods, the method of magnesium palaeothermometry is of particular interest. This method is based on the relationship between Ca/Mg ratios in fossil shells of marine organisms and their environmental temperature. This method was developed in the 1970s by Russian geologists and is widely used to reconstruct water temperatures in shallow seas at the beginning of the Late Mesozoic to the Quaternary period.

2.4 Dating techniques

One of the most important problems in analyzing various types of palaeoclimatic information is dating of evidence. The scales based on palaeomagnetic and absolute methods of dating are widely used in addition to biostratigraphical (biochronological) temporal scales (plankton, nanoplankton, mammal fauna, etc.) and the scales based on the analysis of visual annual bands, such as tree rings, varve deposits (annual layers formed by glacial meltwater), and ice layers resulting from seasonal freezing and thawing of glaciers.

Very reliable dating is ensured by some physical methods that are based on radioactive isotopic decay. One is through carbon-14 or other radioisotope analysis. The most popular is the carbon isotopic method, although its range is limited to the last 30 000 to 40 000 years. Another method, potassium-argon (K/Ar), allows dating in a broader temporal interval (from a thousand to a billion years, but its application is restricted because there must be volcanic materials (lava or tuffs) in the geological sections. The fission-track and the so-called non-equilibrium uranium method have been widely used in recent years. The latter yields the most reliable results only for information from shells and corals. Basic characteristic of dating methods is presented in Table 2.

Method	**Object of dating**	**Period of dating**
Dendrochronological	Wood	0-7000 yr.
Radiological methods:		
-carbon isotope (^{14}C)	Organic remnants (wood, bones, shells).	0-30,000 yrs
- potassium-argon	Volcanic lava.	1000 yr.$^{-1}$ billion yr.
- tracks of spontaneous fission of uranium nucleus	Glass, tektite, mica, apatite, zircon, meteorite	From 20 to $1.4 \cdot 10^6$ yr.
- non-equilibrium uranium (U^{234}, Io (Th^{230}), Pa^{231}	Fossil bones, stalactites and stalagmites, natural waters, travertine, soils, peat, shells of fresh-water mollusks, corals, marine oozes	100 thousand yr. for Pa^{231}, 300 thousand yr. for Io, 1 million yr. for U^{234}
Physiochemical methods	Ceramics, stalagmites, loess (quartz)	From 0 to several thousand yrs
Thermoluminescence - amino-acid*	sands, granite, bones	

*At the development stage.

From: Borzenkova I.I. (1992). *The changing climate in the Cenozoic,* 246 pp. Gidrometeoizdat,

S. Petersburg.

Table 2: Basic methods of absolute dating

-
-
-

Bibliography

Alvarez L.W., Alvarez W., Asaro F., Michel H.V. (1980). Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science*, vol. 208, 1095-1108. [This paper presents the data on the extraterrestrial causes of climatic changes at the Maestrichtian-Danian boundary].

Borzenkova I.I. (1992). *Climatic changes in the Cenozoic,* 246 pp. Gidrometeoizdat, St. Petersburg, Russia (in Russian). [Based on various empirical (proxy) data on the main stages of climatic changes over the Late Cretaceous and Cenozoic on the global scale].

Bradley R.S. (1985). *Quaternary palaeoclimatology*. *Methods of palaeoclimatic reconstructions*. Boston, London, Sydney. [This book presents different methods for reconstruction of climatic changes over the Pleistocene by using different proxy data and the reliability of this reconstruction].

Budyko M.I. (1982). *The Earth's Climate: Past and Future,* 308 pp. New York, London etc. Academic Press. [This book presents the analysis of causes of climatic changes in the past and the assessment of the future climate change].

CLIMAP Project Members (1984). The last interglacial ocean. *Quaternary Research*, vol.21, 123-224. [This paper presents the maps' reconstruction of seasonal sea-surface temperatures for the last interglacial (125-130 ka) by using palaeontological information obtained from deep-sea drilling].

CLIMAP Project Members (1976). The surface of the Ice-Age Earth. *Science*, vol.191, 1131-1138. [This paper presents the maps' reconstruction of summer and winter sea-surface temperatures for the last glacial maximum (18 ka) obtained from palaeontology and isotopic data].

Climate since A.D. 1500 (1985), 706 pp. / Eds. R.S. Bradley and Ph.D. Jones. [This book provides the documentary evidence, dendroclimatic and ice core data for the reconstruction of climate change for the historical period when the instrumental data were absent].

COHMAP Members (1988). Climatic changes of the last 18,000 years: Observations and model simulations. *Science*, v.241, .1043-1052. [This presents the maps' reconstruction of the climate change on the continents for the last glacial maximum, 18 ka and its comparison with model simulation].

Emiliani C. (1961). The temperature decreases of surface seawater in high latitudes and of abyssal water in open ocean basins during the past 75 million years. *Deep Sea Research*, vol.8, 144-147. [In this paper the author has made the conclusion about sea bottom and surface temperature decreases in the high latitudes over the past 75 million years].

Frakes L.A. (1979). *Climate throughout geologic time,* 310 pp. Amsterdam, Elsevier. [This fundamental book is about climatic changes over the Earth's history since the Precambrian time].

Lamb H.H. (1977). *Climate: Present, Past and Future,* vol. 2, 835 pp. Methuen, London. [This fundamental book is about the present and past (historical time) climate change and the causes of climatic variations at present and in the future].

Monin A.S., Shishkov Yu.A. (1972). *Climate history,* 407 pp. Gidrometeoizdat, Leningrad (in Russian). [This book provides the extensive information about proxy data and their use for palaeoclimatic reconstruction].

Sinitsyn V.M. (1980). *Environment and history climate in the USSR territory in the Early and Middle Cenozoic,* 103 pp. Leningrad University Press, Russia (in Russian). [This presents a series of palaeoclimatic reconstructions obtained by using different proxy data].

The methods of the palaeoclimatic reconstructions (1985), 198 pp. / Eds. Velichko A.A. et al. "Nauka", Moscow, Russia (in Russian). [This book deals with different methods of palaeoclimatic reconstruction, and a more detailed description of palaeoecological methods].

Zubakov V.A., Borzenkova I.I. (1990). *Global palaeoclimate of the Late Cenozoic. Ser. Development in Palaeontology,* 12, 456 pp. Elsevier, Amsterdam, New York, London etc. [This book presents an extensive review of the Cenozoic climate and a more detailed information about Pleistocene and Holocene climates].

Biographical Sketch

Irena I. Borzenkova is Leader of the Scientist Research Department of Climatology, State Hydrological Institute, Russia.

Degrees: M.S. Meteologiya and Climatologiya. Gidrometeorological Institute, 1960, Leningrad, Russia.

Ph.D. Geographical Sciences (Physical Climatology). 1966. Thesis: "*The heat balance of the mountain regions"*. Advisor: Prof. M. Budyko.

Doctor of Sci., Geographical Sciences, 1991. Thesis: *"The climatic change during the Cretaceous-Cenozoic time"*.

About 40 speeches at National and International meetings and conferences.

Research areas: The global climate change in present and geological past, secular changes in global and regional temperature and precipitation, reconstructions of the past climate, moisture conditions in past and present.

About 80 scientific papers and seven monographs among them:

"*Global paleoclimate of the Late Cenozoic*". Ser. Developments in Paleontology. 12. Elsevier, Amst. etc. 1990. 456 pp. (Co-author V. Zubakov).

"Anthropogenic climate changes "1987, Gidrometeoizdat, Leningrad (Co-authors M. Budyko et al.,) (in Russian). (Translated into English, Arizona Press, 1992, 485pp).

"Cambios anthropogenicos del clima en America del Sur". (Co-authors M. Budyko, G. Menzhulin, I. Shiklomanov). Boenos Aires, 1994.

"Climate change in the Cenozoic". 1992. St. Petersburg. 246 pp. (in Russian). English translation was made under auspice of the Working Group VIII USA/Russia, 1995.