ATMOSPHERE AND CLIMATE

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Contents

Summary

The basic aim of this contribution is to characterize the past geological changes of the climatic system, their causes and consequences and possible relations to future climates. The atmosphere has evolved as a result of the history of life, and there is good evidence that it is changing as a result of current human activities. The atmosphere controls climate and ultimately determines the environment in which we live. The climate is not

an isolated system. It is closely connected with the Sun and other parts of the Earth system such as the ocean, cryosphere, biosphere, and so on. The connection with other parts of Earth is a function of the spatial and temporal scale. For limited time scales—years and decades—the climate depends on the composition of the atmosphere and on solar activity, but for large time scales the other parts of Earth, such as the lithosphere and biosphere, must be taken into consideration. The climate cannot be considered only as the behavior of the atmosphere, but as the total response of the Earth and Solar systems to an ever-changing flow of influences. The biosphere activity buffers some of these changes and makes Earth more habitable.

The major goal of paleoclimate studies is to discover factors that cause climatic fluctuations. Vast amounts of information have recently been collected and it has been proven that *climates have varied more than previously considered*. The climate is never stable. It is always an oscillating curve moving up and down every few years or decades. Long-term cycles lasting 20, 40, 100, 400, and 1000 ky are also recorded in the Quaternary Period. The model of the orbital parameters predicts the next peak of natural cooling at around 5 ky, and another one at 22 ky from the present. The fossil record of the last few thousand years shows that prolonged periods of drought may represent the single most dangerous, in some regions even catastrophic, climate event. Climate change may be two things at once: a personal or regional disaster and another milestone of biological evolution.

1. Indicators of Past Climates

Direct methods of instrumental measurements span only a tiny fraction of Earth's climatic history, and so provide only an inadequate perspective on past climatic variations. A longer perspective can be obtained by the study of the climate-sensitive fossil record. It is represented by a set of dated rock strata, such as limestones, deep ocean sediments, or ice cores. The geological, and thus the climatic, past can be viewed only through the lens of time—the further back we go, the greater are the problems of dating, preservation, disturbance, and hence interpretation.

Any one type of sediment usually reflects few aspects of climate change or even a single one. For example, the isotopic composition of oxygen in carbonate sea sediments is dependent on the temperature of oceanic waters, but yields no information on continental precipitation. The grain size of eolian sand dunes reflects wind velocity during dust storms, but tells us nothing about the tranquil seasons. The fossil record contains climatic signals that often represent a mixture of local and global signals blurred by the random influences of extraneous "noise" arising from the nonclimatic effects. Paleoclimatologists thus seek long, continuous, well-dated, and unambiguous rock strata.

Evidence of cold climates abounds. Glaciers today cover approximately 10% of Earth's land surface and at the height of the Quaternary ice ages probably covered as much as 30%. A wide variety of sediment is deposited in glacial environments, including material transported in the ice and subjected to grinding at the glacier base. The inhomogeneous mixture of large boulders, pebbles, sand, and clay known as till is characteristic of glaciated regions. Valleys shaped like the letter "U," striated pavements, moraines, and other features represent morphological evidence of past ice ages.

Hot climates are also evident. The degree of weathering in warm areas depends on rainfall and its annual distribution. Reddish horizons (red beds) in soils and sediments are regarded as characteristic of warm climates, especially when aluminium oxides enrich them. Lithological and chemical characteristics of the sediment—such as kaolinite content, presence of free silica, and isotope composition—is indicative of the climatic development. The fossil content often represents the best guideline to the past history: coral reefs, plants and their pollen grains, and beetles are restricted to specific environments. Humid episodes can be deciphered from leached horizons in soils or by the presence of indicative minerals such as kaolinite.

The geological period we live in is the Quaternary. It is characterized by rapid climatic changes from the cold (glacial) mode to the warm (interglacial) mode. The methods of *Quaternary paleoclimate* reconstruction are more sophisticated and detailed, not only because the sediments are well preserved, but also because this era may provide the key to understanding our climatic future. The most useful sources of paleoclimate information in the Quaternary are the following:

- *Deep-sea sediments*. Several millimeters of fine-grained sediments are deposited in the marine abyssal plains every century, depending on the deep-sea currents and the prevailing climates. The oxygen isotopic composition and the floral and faunal abundance of the succession of layers reflect the seawater temperature. Planktonic (near-surface) and benthic (bottom-dwelling) species may help to determine the surface and the bottom conditions. Trace element contents, such as cadmium concentration, correspond to the nitrate and phosphate distribution, and thus to the velocity and nature of sea currents. The terrestrial dust in marine sediments indicates the activity of monsoon winds and, in temperate regions, the eolian activity during ice ages. Ice-rafted debris reflects episodes of iceberg discharge. The marine sediments are disturbed by sea worms and shell bioturbation, thus usually rendering their time sensitivity smaller than one thousand years. They provide, however, the longest known continuous climatic record and are used as the standard global timescales of climatic changes for the last three million years. The temperature curve is usually expressed as the distribution of the stable isotopes of oxygen.
- *Loess sequences*. Loess is an eolian sediment typical of ice ages, whereas in warm and more humid interglacial conditions black, red, and brown soils develop. The alternating sequence of loess and soil horizons corresponds to the glacial and interglacial climates and, even more importantly, enables marine and continental conditions to be correlated. The time sensitivity of the loess series is as low as that of the deep-sea sediments, but the series provides the basic continental climatic framework and furnishes the opportunity to reconstruct the coupled land–sea climate functions.
- *Laminated sediments and materials*. Some sediments and other materials, such as lacustrine muds, speleothems, tree rings, and corals, form parallel or concentric structures where each layer corresponds to annual, seasonal, or even diurnal climatic cycles. The width and the composition of the individual laminae often permit detailed climatic recognition, but such a detailed fossil record is seldom long, continuous, and well dated.

- *Ice cores*. The isotopic composition of water, presence of layers containing volcanic ash, and fossil atmosphere entrapped in the bubbles testify to the past precipitation, air temperature, and atmospheric composition. The ice cores provide a unique record of glacial–interglacial variations of the greenhouse gases in the atmosphere.

Figure 1. Climate is the condition of the atmosphere at a particular region over a long period of time. It is often evaluated in terms of mean temperature and humidity, but it consists of many other aspects such as seasonality, color of sky, wind pattern, prevailing type of clouds, etc. The notable climate change may take place even when the annual or decadal temperature and humidity remain stable, but the distribution of rainfall, for example, varies.

Almost any sediment can be used in many different ways as a paleoclimatic indicator. Several lines of evidence (e.g., fossil content, lithology, and geochemical and mineralogical composition) are regularly combined to obtain a reliable interpretation of past climates. *Historical data* and weather observations written, for example, in chronicles deal with short-term climatic fluctuations of the last thousand years. They are an invaluable tool for determining the high-frequency natural climatic phenomena with respect to the human-influenced changes of the last one or two centuries.

Figure 2. Fossil record is expressed as a sequence of individual layers. Each layer has its own characteristics, such as geochemical composition or fossil assemblage content. These characteristics are often dependent on various climatic factors (e.g., humidity, temperature, and the velocity of sea currents) and can be used for the reconstruction of fossil climates.

2. Milestones in Paleoclimatic Research

The state of the climate varies with time. This fact has been appreciated since classical times. Fragmentary climatic observations and hypotheses can be traced—as in most scientific disciplines—to antique times and thence to Renaissance and Baroque natural philosophy. Ever since Leonardo da Vinci, and before him Chinese Confucian sages, unearthed beds of fossil marine shells high up in the mountains, the record of the past has been challenging conventional theories of stable climate. Paleoclimatic reconstructions and descriptions have accompanied the earth sciences ever since geology was established by Charles Lyell (1797–1875; *Principles of Geology*, First Edition (1830)) as a coherent working method for studies of Earth's past. The threat of a greenhouse world has recently turned the "dusty" paleoclimatology into an applied science. In this paper, we do not follow the paleoclimatic lines leading to detailed descriptions of geological formations, but rather pursue that part of paleoclimatology that seeks to understand modern climate change and its potential consequences. Several milestones can mark this approach to the global change problem. They crystallized gradually over the past 200 years.

1815: Jean-Pierre Perraudin, Swiss mountaineer, became convinced that Alpine glaciers had once extended several kilometers beyond their present limit.

1837: Luis Agassis announced the hypothesis of a Great Ice Age.

1839: Timothy Conrad explained the morphology of North America using Agassis's glacial hypothesis.

1842: French astronomer Joseph Adhémar proposed the astronomical explanation of ice ages based on the precession of the equinoxes.

1864: Scottish philosopher James Croll published an astronomical theory of climate change based on orbital eccentricity. He speculated on the role of sea currents in global heat transfer. If a single person were to be chosen from the number of contributors, then James Croll (1821–1890; *Climate and Time* (1875)) can be proclaimed the founding father of global climate change study.

1894: James Geikie drew glacial maps of the Northern Hemisphere.

1909: Albrecht Penck and Eduard Brückner proposed four Pleistocene ice ages on the basis of four river terraces in the Alps.

1920: Serbian mathematician Milutin Milankovitch (1879–1958; *Mathematical Climatology and the Astronomical Theory of Climatic Change* (1930)) calculated the changing intensities of the incoming solar energy and argued that they could be sufficient to cause the ice ages.

1924: Wladimir Köppen and Alfred Wegener published a synthesis of the past climate study, the book *Climates of the Geological Past*.

1952: Gustav Arrhenius showed that the variations in the composition of the deep-sea sediments record climatic changes.

1966: Cesare Emiliani analyzed other deep-sea cores. The polyglacial concept (that is, the existence of many glacial periods and climate cyclicity) became accepted.

1970 and later: Up to the end of the 1960s, we observe a more or less academic interest in paleoclimatic changes. The widely published catastrophic expectations of the new ice age in the early 1970s and, later, the greenhouse global warming threat gave origin to global climatic and paleoclimatic studies asking if the geological past might hold the key to future climates. “Description-based” research changed into “cause-based” research and the originally regional scale was transformed into a global one. The major discoveries and attitude shifts are associated with works of G. J. Kukla, W. Broecker, J. Hays, W. Ruddiman, A. Berger, W. Dansgaard, H. Oeschger, and many others. The main paleoclimatic emphasis laid on Quaternary studies has recently shifted into the study of more ancient climates that may provide answers concerning past carbon storage, asteroid impacts, the connection between climate change and biological evolution, and even the existence of life on the other planets of the Solar System. The results of important paleoclimate projects can be found under CLIMAP, COHMAP, and PAGES bibliographic or Internet entries. Besides a number of established scientific journals such as *Science*, *The Holocene*, and *Quaternary Science Reviews,* supplementary information on the current paleoclimatic projects is disseminated via informative newsletters such as Change, PAGES Newsletter, Cogeoenvironment News, and others.See Quaternary History

Figure 3. The annually or seasonally banded natural objects, such as corals, tree rings, and lake or cave sediments, can help to reconstruct the past climates in detailed timescales—years, seasons, and sometimes days.

3. History of the Atmosphere

3.1. Early Evolution

We have little surviving evidence of how the primary atmosphere may have evolved during the early period when accretion was ongoing. Many of the impact bodies, especially carbonaceous chondrites, had a substantial content of frozen volatiles and occluded gases. The water vapor and other volatiles were degassed by the impacts and the thermal escape caused by Earth’s internal heat. The large impacts had the potential to blow off parts of the developing atmosphere. Any captured primary atmosphere must have been partly or completely lost, as evidenced by the pronounced depletion of rare gases in Earth's atmosphere compared to cosmic abundances. Escaping hydrogen can drag other gases into cosmic space, and the lighter isotopes are carried off more easily than the heavy ones. This hydrodynamic escape becomes more difficult in the postaccretionary period, because the solar ultraviolet flux diminishes and the escape rate is reduced by diffusion once the hydrogen becomes a minor component of the atmosphere.

The present secondary atmosphere was generated from volatile components contained within the solid planetesimals from which Earth formed. The models of planetary accretion suggest that Earth formed during less than 100 Ma and that its interior was initially hot as a consequence of gravitational forces generated by large impacts. The main accretionary phase can be characterized by the hydrogen (H_2O steam) atmosphere, but once this phase had ended and the surface had cooled, the remaining atmosphere would probably have been dominated by carbon and nitrogen compounds, as the steam would have rained out to form an ocean.

After water, carbon compounds (such as CO and CO_2) and nitrogen were the most abundant volatiles at Earth's surface. As much as 15% of carbon gases may have resided in the atmosphere before limestone rocks began to accumulate. The primitive atmosphere may have contained significant quantities of water vapor, together with CO_2 and CO, nitrogen, and rare gases. The mean surface temperature of the primitive atmosphere would have been some 85 °C. Despite this temperature, such an atmosphere would be stable. The heavy bombardment of Earth's surface ended ~3.8 Ga before the present (1 Ga, gigayear = 10^9 y). The ocean could have been vaporized several times and the planet almost sterilized, but the subsequent, more stable conditions enabled the evolution of life (**see** *Origin and Establishment of Life on Earth* **and** ***Early Earth***).

3.2 Secondary Atmosphere

A seldom-acknowledged fact is that the atmosphere developed as a by-product of biological evolution. Its composition is regulated and kept stable by biological processes, and the atmosphere can thus be viewed as a planetary-scale biological phenomenon. Without the intricate web of biological feedbacks, the composition of the atmosphere would deteriorate in a few months with respect to methane, carbon dioxide, and some other gases. The principal role of stable atmosphere "keepers" regarding oxygen levels can, during the last 350 Ma (1 Ma, megayear = 10^6 y), be attributed to the forests of the Northern Hemisphere and, to a lesser extent, to the tropical rain forest. The carbon dioxide levels seem to have been principally controlled over the last 500 Ma by marine plankton and carbonate precipitation. Organic carbon burial in the form of fossil fuels and disseminated graphite and kerogens represents the second most important mechanism of carbon removal after carbonate sedimentation. Microorganisms, in interactions with geological processes such as weathering or volcanic degassing, dominated the atmosphere formation between the origin of life at ~3.5 Ga and the Upper Paleozoic at ~350 Ma. In spite of the significant influence of the forests and continental flora, microorganisms are still in many ways involved in the global cycles of the atmosphere-forming elements. L. Margulis is justified in talking about microbial activities as the softening cradle for the evolution of multicellular organisms. The atmosphere has evolved as a result of the history of life and there is good evidence that it is changing as a result of current human activities. The atmosphere controls climate and ultimately determines the environment in which we live.

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Biographical Sketch

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Vaclav Cilek studied during 1970–1974 at the Mining Institute in Pribram, after which he joined the Department of Economic Geology of Charles University in Prague where he studied uranium deposits of Czech Republic. However, when coming in 1980 to Institute of Geology of the former Czechoslovak Academy of Science, he was asked to cooperate in Interkosmos Programme that was primarily involved in the study of lunar rocks brought by Russian satellites. He spent much of his free time in caving and karst research, and the study of karst infillings brought him finally in 1990 to Quaternary geology. He is principally interested in environmental changes and climatic oscillations in Holocene and in several last glacial cycles. V. Cilek teaches the courses on what he calls "cultural geology," he is the author of ~120 papers and has participated in approximately 12 books including two textbooks primarily concerning environmental topics such as atmosphere protection and landscape evolution.