HISTORY OF PLANETARY AND GEOLOGICAL FACTORS

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Summary

Radiation incoming from the Sun to the Earth is the only form of radiant energy, which determines the thermal regime of the globe. Due to spherical shape of the Earth, a unit area at the top of the atmosphere receives, on the average, one-fourth of the total flux—about 350 W/m^2. At the present time, only half of this flux reaches the Earth's surface thus supporting the average global temperature of about 15 °C. However, throughout the Earth's history, the average global temperature, being a certain measure of the climate system condition, has significantly changed. Three major planetary factors—solar radiation change, atmospheric gas composition, and surface albedo—determined the diversity of climatic variations in the past. The total output of solar energy, or the "solar constant," has changed over the geological time due to variations in the luminosity or *brightness* of the Sun, as a star. During the time interval of 4 to 1 billion years ago solar luminosity was 5 to 20% lower than at present. The largest variations in solar radiation incoming at the upper atmosphere occurred due to periodic changes in the Earth's orbit elements. These changes are determined by three parameters of the Earth's orbit: the eccentricity, obliquity, and precession or *wobble*.

Along with the long-term variations in the incoming solar radiation, there are comparatively short-term ones associated with changes in the transparency of the upper layers of the atmosphere due to volcanic eruptions and impact events caused by the collision of celestial bodies with the Earth. Changes in the Earth's atmospheric composition (primarily, in the concentration of greenhouse gases CO_2, H_2O, CH_4, etc. and in surface albedo) were the important factors influencing climate change in the past. This paper discusses certain geological factors that might have had a pronounced effect on climate variations in the past. Continental shift, sea-level variations, openings or closings of ocean gateways and mountain building exerted a pronounced effect on the global climate. These factors have been operating throughout geological time (many hundreds or millions of years) to complete their effect.

1. Introduction

The climatic conditions are known to be closely connected to an average altitude of the Sun, i.e., the latitude of different regions. Different amounts of radiation incoming to the Earth's surface due to the spherical form of the Earth provide an uneven heating of the atmosphere in different regions of the globe. The equator-pole surface temperature difference is particularly great, and this is the major factor of atmospheric circulation.

The global temperature is one of the indicators of the state of the climate system. It can be obtained by averaging the mean surface air temperature over latitudinal zones for the entire Earth or more frequently for the Northern Hemisphere. The three major planetary factors—solar radiation variations, atmospheric gas composition and surface albedo—determined the diversity of climatic changes in the past. There are some other less important forcing factors such as changes in the velocity of Earth's rotation, the position of magnetic and geographical poles, the location of continents in Polar Regions, mountain uplift, and others.

2. Planetary factors of climatic variations

According to their nature, planetary factors can be classified as follows:

a) Solar factors associated with the evolution of the Sun, as a star, acting through variations in "Solar constant" or *solar luminosity*;
b) Astronomical factors arising due to variations of the Earth's orbit parameters;
c) Incoming solar radiation variation due to changes in the transparency at the top of the atmosphere after explosive volcanic eruptions and the falling of celestial bodies (comets, asteroids, meteorites, etc.) on the Earth's surface;
d) Changes in the atmospheric gas composition related to the evolution of the Earth, as a planet;
e) The Earth's surface and Earth–atmosphere system albedo can vary due to changes in ice and snow cover, shifts of vegetation zones, and variations in the continent/sea area ratio.

2.1. Changes in solar radiation over the geological past

2.1.1. Changes in solar luminosity *or brightness* throughout the Earth's history

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Throughout geological time the total output of solar energy or *luminosity* of the Sun is a significant forcing factor. Analyzing data on structure and evolution of stars M. Schwarzschield (1958) was the first to propose that luminosity or *brightness* of the Sun had increased over the Earth's history. In the earliest history of the Earth (about 4.5 Ga), the Sun's luminosity was 25% less compared to the present value. In the beginning of the Phanerozoic (about 600 Ma), the Sun's luminosity was assumed to be almost 3% less than its modern value.
The "solar constant" is called the flux of solar energy per minute falling on an area of 1cm^2 perpendicular to Sun's rays beyond the atmosphere in the middle of the distance of 149.5 million kilometers between the Earth and the Sun. At present the solar constant is about 1395 W/m^2. Throughout the Cenozoic (the last 60 millions years), changes in the solar constant were not above 0.03-0.01% compared to its modern value. With constant surface albedo a 1% increase in incoming solar radiation at the top of the stratosphere raises the global temperature by 1.4 °C. Due to these small variations in the solar constant the global temperature could change by as much as hundredths of a Celsius degree. Increased luminosity of the Sun could have exerted a pronounced effect on temperature conditions noticeable only for long-term intervals of geological history.

At the present time, the annual global mean incoming solar radiation at the top of the atmosphere is about 350 W/m^2. Of this, about 35% is lost by reflection from clouds, 16% is absorbed by the atmosphere (mostly by its water vapor, carbon dioxide, ozone, and oxygen), and only 51% reaches the Earth's surface. The present average air temperature near the Earth's surface is about 15 °C.

Periods of relatively warm climate in the past seem to be attributed to higher CO_2 concentrations in the atmosphere relative to the modern value. In the Precambrian, carbon dioxide content is believed to have been 10 to 100 times above the modern. This factor compensated for the effect of lower solar luminosity (solar constant) on the temperature of the atmosphere. As a result, the Earth's biosphere has been able to exist for almost 4 billion years.

Between 4 and 1 billion years ago solar radiation was 5% to 20% lower than at present, and, other things being equal, this should have decreased the mean air temperature by 7 to 28 °C, compared with the present epoch.

2.1.2. Changes in the incoming solar radiation due to orbital factors

The largest variations in solar radiation incoming at the upper atmosphere occurred due to periodic changes in the Earth's orbit elements. The history of the astronomical theory of climatic changes runs to more than 100 years. J. Adhèmar, a French mathematician, was the first to present this theory in 1842 in his book *Les rèvolutions de la Mer. Déluges Pêriodiques* (Paris). Later, in the 1860s, J. Croll further developed this theory. In 1930, the Yugoslav geophysicist Milutin Milankovitch (1879—1958) converted it into a new astronomical climate theory. The latter includes variations in the angle of Earth's axis, and the geometry of the Earth's orbit around the Sun.

In the upper atmosphere, variations in solar radiation depend on changes in the Earth's orbit elements determined by the following three parameters:

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a) The Earth's orbit eccentricity varying with periodicities of about 100 000, 415 000–420 000, and 1 200 000 years;
b) The Earth's orbit obliquity or *tilt* away from a vertical drawn to the plate, varying, on the average, within a 41 000 year period;
c) The precession or *wobble* of perihelion is the point where the Earth's orbit intersects the Sun's path, varying with the frequencies of about 19 000 and 23 000 years. The Earth's orbit eccentricity, characterizing its deviation from a circle, varies within the range of 0.0007 to 0.0658 (at present it is 0.017). The obliquity of the Earth's axis changes from 21°39' to 24°36' (the present value is 23°27'), and the precession characterizes the position of the Earth's rotation axis in space and depends on the action of the solar system planet's and the Moon's gravity.

These periodic changes have caused comparatively small changes in the seasonal redistribution of solar radiation incoming at different latitudes, which in turn exerted effects on seasonal variations in surface air temperature.

In the middle of the last century, J. Croll proposed the hypothesis about astronomical causes of the origin of Pleistocene ice ages. Milankovitch's calculations confirmed quite a good agreement between the geological age of Pleistocene glaciation (glacial epochs) and the minima of incoming (summer) solar radiation. The spectral analysis of oxygen-isotopic records reflecting fluctuations in surface water temperatures and volumes of the continental glaciation over the last 700 000 years shows that the periods of 20 000; 40 000; and 100 000 years, close to those of changes in Earth's orbit elements, are most clearly defined. This appeared to be a convincing evidence of the astronomical theory of Ice Ages.

However, until the present time the physical mechanism of ice age initiation has remained unclear. How these small changes in seasonal solar radiation sums could lead to so drastic lowering of surface air temperature is not clear. In the early 1980s, scientists answered this question, when they obtained the first data on the composition of air bubbles trapped in continental ice cores. These data showed that during Pleistocene Ice Ages carbon dioxide concentration in the atmosphere reduced down to 180-200 ppmv, whereas over the interglacial time, it increased up to 280-300 ppmv. These variations in the glacial-interglacial cycle appeared to be a considerable positive feedback intensifying small changes in air temperature due to orbital factors (see Radiative Forcing of Climate System).

2.1.3 Variations in solar radiation due to changes in atmosphere's transparency

Along with long-term variations in incoming solar radiation, there are the comparatively short-term ones related to changes in upper atmosphere's transparency due to explosive volcanic eruptions or due to impact events caused by collision of celestial bodies with the Earth**.** There are two types of volcanic eruptions: effusive and explosive. With effusive eruptions a mass of liquid easy-fusion lava is outpoured with insignificant release of gases into the lower troposphere only. With explosive eruptions and release of enormous amounts of gaseous products, lava is almost non-existent. All kinds of explosive eruptions are accompanied with release into the atmosphere of volcanic aerosol and different gases, primarily, CO_2, H_2O, CO, and sulfur-containing gases. As for the shorter time intervals of

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tens and the first hundreds of years, of most importance for climate change is release of sulfur-containing gases (H_2S, SO_2, etc.) reaching the stratosphere from a small-disperse layer consisting of sulfur acid droplets. Most of stratospheric aerosol particles are localized in a layer of several kilometers thickness, with the center being at altitudes between 18 and 20 km**.**

The stratospheric aerosol layer forms after powerful volcanic eruptions of the explosive type. Due to this layer the total background aerosol in the stratosphere can increase by 1-2 orders of magnitude. This causes a considerable decrease in solar radiation reaching the Earth's surface. Solar radiation passing through the stratospheric aerosol layer dissipates partly due to absorption, however mainly due to its scattering by aerosol particles. Decrease in short-wave radiation incoming to the troposphere noticeably affects Earth's climate. As a result, the surface air temperature can drop by tenths of a Celsius degree during 1 to 3 years after volcanic eruptions **(**see Upper Atmosphere Chemistry and Circulation). The influence of a single explosive eruption on Earth's climate is comparatively small because of limited aerosol amounts ejected into the stratosphere. By contrast, significant changes in the Earth's temperature take place when several powerful explosive eruptions occurring in quick succession within a short time interval. Therefore, a series of ten or more explosive eruptions can induce a global climatic catastrophe. Some researchers believed that such global catastrophic climatic changes occurred at the Cretaceous-Cenozoic boundary due to drastically increased explosive volcanic activity**.**

In Earth's history, there could be another possibility of aerosol climatic catastrophe, when different celestial bodies collided with the Earth. L. and W. Alvarez and their colleagues proposed this hypothesis at the end of the 1970s. O. Toon and J. Pollack carried out the detailed calculation of climatic effects of Earth's collision with a large celestial body (for example, a large asteroid). These estimates showed that the ejection of 10^{11} t of dust (the amount to be expected from the collision with a body of 2 kilometers in diameter) would lower the level of solar radiation flux to an extent insufficient for supporting photosynthesis**.** Impact craters in different regions of the Earth serve evidence of its collision with different types of celestial bodies. This evidence indicates that in the geological past, large short-term (in geological terms) climatic changes occurred and probably affected living nature. Evidence of large dust storm on Mars is important for better understanding physical mechanisms of aerosol climatic catastrophe in the geological history of the Earth's planet.

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