The Winners of the Blue Planet Prize

1998

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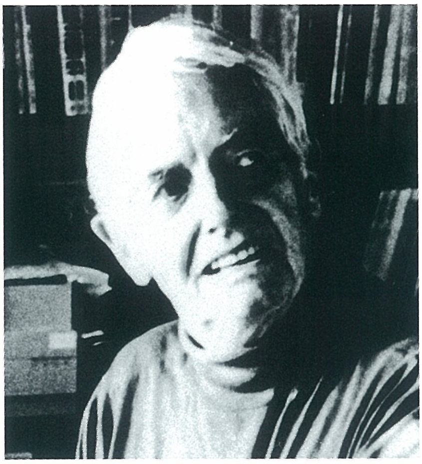
Blue Planet Prize

Professor Mikhail I. Budyko (Russia)

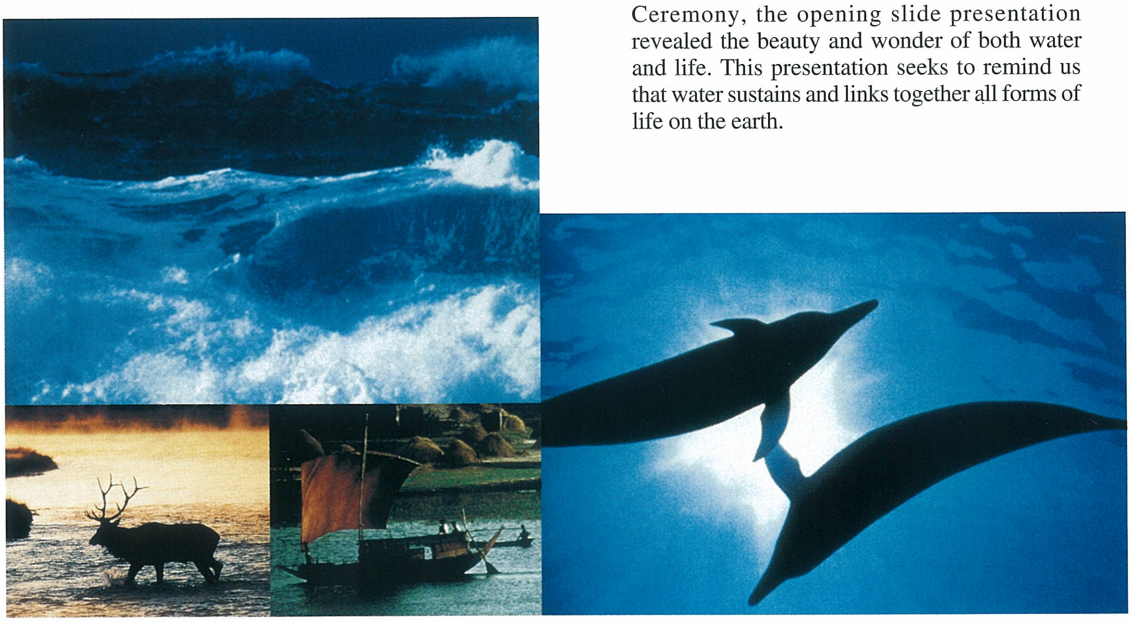
Head of the Division for Climate Change Research, State Hydrological Institute

Mr. David R. Brower (U.S.A.)

Chairman of the Earth Island Institute

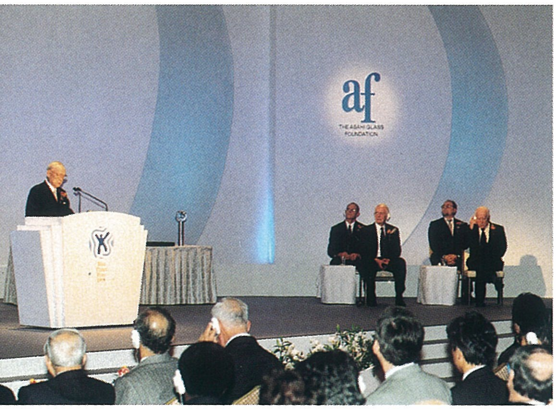


At the 1998 Blue Planet Prize Awards Ceremony, the opening slide presentation revealed the beauty and wonder of both water and life. This presentation seeks to remind us that water sustains and links together all forms of life on the earth.



Their Imperial Highnesses Prince and Princess Akishino at the Congratulatory Party.

His Imperial Highness Prince Akishino delivering a congratulatory speech.



Jiro Furumoto, chairman of the Foundation, delivers the opening address.

Prof. Mikhail I. Budyko and his research partner of 30 years, Gennady Menzhulin, in the Blue Planet Prize Commemorative Lectures.

Thomas S. Foley, Ambassador of the United States to Japan (left), and Vassili Dobrovolski, Minister-Counsellor of the Russian Embassy in Tokyo (right), congratulate the laureates.

Mr. David R. Brower and his son, environmental journalist Kenneth Brower, in the Blue Planet Prize Commemorative Lectures.

Profile

Professor Mikhail I. Budyko

Head of the Division for Climate Change Research, State Hydrological Institute

Education and Academic and Professional Activities

1920	Born in January in the former Soviet Union (now Belarus).
1942	M.Sc., Physics, Leningrad Polytechnic Institute.
	Researcher, Main Geophysical Observatory, Leningrad.
1951	D.Sc., Main Geophysical Observatory.
1951-1954	Deputy Director, Main Geophysical Observatory.
1954-1972	Director, Main Geophysical Observatory.
1958	Lenin National Prize.
1964	Corresponding Member, Academy of Sciences of the U.S.S.R.
1972	Prof. Lithke Gold Medal, Russian Geographical Society.
1972-1975	Head of Division, Physical Climatology, Main Geophysical Observatory.
1975-2001	Head of Division, Climate Change Research, State Hydrological Institute, St. Petersburg.
1987	Gold Medal, World Meteorological Organization.
1989	A. P. Vinogradov Prize, Academy of Sciences.
1991	Diploma, First Degree, Russian Knowledge Society.
1992	Academician, Russian Academy of Sciences.
1994	Prof. R. Horton Medal, American Geographical Union.
1995	A. A. Grigoryev Prize, Russian Academy of Sciences.
2001	Deceased, December 11.

In the 1950s, Prof. Budyko conducted quantitative studies of the global climate by calculating the heat balance of the Earth's surface, which involved energy from the sun. He announced his findings in 1956 with the publication of his book *Heat Balance of the Earth's Surface*. Until that time, climatology was essentially just a qualitative discipline used as part of the natural and geographical sciences. However, Prof. Budyko's book revolutionized climatology into a more quantitative discipline, sending a shock through the world's weather- and climate-related academic circles. In addition, under the direction of Prof. Budyko, an atlas of all components of the heat balance of the Earth was completed in 1963. The atlas has been important to efforts to research and solve global environmental problems.

Prof. Budyko studied not only the abiotical processes that shape our climate, but also the role of biological organisms and human activities. His efforts to analyze the interrelationships between climate and the Earth's inhabitants are a distinguishing feature of his work. In 1972, many scientists were predicting that the global climate was entering a cool-down phase. In contrast, Prof. Budyko issued a report warning that, based on his quantitative analysis, the consumption of fossil fuels was raising the concentration of carbon dioxide in the atmosphere and pushing up average temperatures.

Prof. Budyko also postulated that if a nuclear war were to occur and release large amounts of aerosol particles, the resulting climate change would be on such a scale as to threaten the extinction of humankind. His warnings of such a "nuclear winter" were made in the beginning of the 1980s and are believed to have helped bring about the signing of a treaty by the United States and the former Soviet Union to reduce mid-range nuclear missiles.

Essay

Global Biosphere Cataclysms

Professor Mikhail I. Budyko

October 2001

Abstract

Climate biosphere cataclysms, which occurred many times in the geological past, provoked climate changes that led to the extinction of populations of many fauna and flora species. The study of these cataclysms allows a conclusion that climate systems are very sensitive to relatively small changes in climate-forcing factors (atmospheric transparency, large glaciations, etcetera). It is important to take this conclusion into account while estimating the possible consequences of the presently occurring anthropogenic warming caused by the increase in greenhouse gas concentrations in the atmosphere.

Introduction

Climate catastrophes occur with large-scale environmental changes, which cause mass deaths of living organisms. In comparison with global climatic catastrophes, local ones induced by atmospheric factors occur much more frequently. These local catastrophes, because of their limited duration, are associated in many cases with weather changes and not with climate variations. However, in the absence of a universally adopted time scale distinguishing the synoptic processes determining weather and the climate-forming processes, it is not always easy to discriminate between weather and climate catastrophes. We will consider several examples of frequently occurring local ecological catastrophes caused by atmospheric factors.

The best-known example of this kind is large-scale droughts covering areas of thousands of square kilometers. During such droughts, a considerable part of the natural vegetation cover and crops perish. Most animals inhabiting the drought area also die, or if possible, move to other regions, which also results in the death of a part of forced emigrants.

The largest droughts in developing countries caused mass mortality in agricultural populations. Often epidemics spread far beyond the boundaries of the drought regions. The catastrophic droughts in Ethiopia's Sahelian region and in other countries are widely known recent examples.

Aftereffects of strong thermal variations disastrous for animate nature are also known and are frequently distributed over far greater areas than those affected by drought. These weather changes result less in mortality (although this always increases with excessive temperature variations), but inadvertently in mass deaths of animals and plants belonging to species sensitive to the thermal conditions of the environment.

Such an event is often observed in the mid-latitudes over vast areas. Long-term, strong reductions in temperature cause a considerable decrease in the number of many animal species—even full extinction. Particularly strong cooling reduces the area occupied by less frost-resistant plants.

One more example of comparatively frequent local climatic catastrophes is associated with the anomalous development of atmospheric processes when warm tropical waters move southward along the western coast of South America—the so-called *El Nino* phenomenon. In this case, the nutrient- and oxygen-rich cold waters of the Peruvian current are overlapped over long distances by warm waters, which destroys the nutrient links supporting the existence of large fish populations. The disappearance of fish results in the mass deaths of birds feeding on fish, and creates the threat of starvation for the populations of coastal regions whose existence depends on fishery. Without dwelling on further aspects of the *El Nino* effect on atmospheric and ecological processes, we mention that this same effect can be observed at great distances from the region where this current is located.

The general feature of all local climatic catastrophes is that, although in a number of cases these catastrophes result in disastrous consequences, they rarely cause complete extinction of various species of animals and plants. First, this can be explained by the fact that most living organisms can renew their population even after great reductions, and second, that these organisms can survive in areas with more favorable environmental conditions. The exception to this rule may be less numerous organisms occupying small areas, ones that were on the verge of extinction before the climatic catastrophe.

Passing to global climatic catastrophes, these are associated with the extinction of many species of organisms as a result of drastic changes in climate either over the entire globe or over a part that is so great that it covers areas where a number of representatives of animal and plant kingdoms live. It should be particularly emphasized that the time factor is of great importance in the occurrence of global climatic catastrophes.

Even comparatively great climatic changes developing for a period of many thousands or even millions of years have not led, as paleontological data show, to mass extinction of organisms. The most striking examples of these climatic changes pertain to cases of vast glacier advances, in particular to well-studied Pleistocene glaciations.

In glacial epochs of this time, the climatic conditions drastically changed in those regions of middle and high latitudes where glaciations advanced. At the same time, the climate changed at all latitudes, including the tropics, where, with some cooling, the moisture conditions varied noticeably.

These considerable climatic changes, greatly affecting living nature, did not result in the mass extinction of organisms. The cause of this is very simple: with slow climatic changes ecological systems had not been ruined. These systems were preserved in certain geographical zones, which shifted as the climate changed. In middle latitudes of the Northern Hemisphere these zones usually shifted southward.

At the same time, gradual changes developed both in the structure of geographical zones and ecological systems, which favored the evolution of the organisms involved in these systems. However, in these cases there was no mass extinction of organisms.

It is easy to imagine what would have happened to animals and plants if such climatic changes had developed not over thousands of years but in the course of one or two years, which sometimes can be a consequence of explosive volcanic eruption. Undoubtedly, in this case a massive ecological catastrophe associated with the extinction of a host of animal and plant species would have occurred.

Discussion

Benjamin Franklin was the first to pay attention to the possible climatic effects of volcanic gases and dust. He proposed that a large eruption of the Lacki volcano in Iceland in 1783 resulted in "dry fog," a haze that caused a cold summer and poor harvests in Europe. Later, Savinov (1913), Kimball (1918), Kalitin (1920) and other authors established that after an explosive volcanic eruption, solar radiation to the Earth's surface decreases drastically. In these cases, the value of direct radiation averaged over a large area can decrease by 10% to 12% over several months or years.

A far greater explosive eruption occurred in 1815 in Indonesia (Tambora). From the limited observations available at that time, it is difficult to estimate accurately the average air temperature reduction after the Tambora eruption. However, it is clear that this reduction was uneven and, in a number of regions, attained several degrees. In particular, in the summer of 1816 in Europe and North America, the temperature was so low that the year was called "a year without summer" (the cause of this was unknown at that time). The eruption of Tambora deserves attention, because it is the eruption nearest in time that induced a climatic change, which, in spite of its comparatively short duration, caused noticeable damage to living nature.

In particular, due to drastic decreases in crop yield in a number of regions far from the volcano, many thousands of people died of starvation (Stommel and Stommel, 1979, 1983).

It is possible that the climatic change after eruption of the volcano on the island of Santorin in the eastern part of the Mediterranean Sea, which took place approximately in 1500 B.C., was much more significant. Although the ecological aftereffects of this eruption are difficult to estimate, it is assumed that they were very considerable and led, in particular, to an abrupt decline of the highly developed Cretan civilization that had flourished up to that time. It is possible that this eruption is recorded in folk tales about the "outer darkness" recounted in the Bible (Rust, 1982).

There is no doubt that, for far longer time intervals comparable with geological epochs and periods, the effects of volcanic eruptions on climate and the biosphere were much greater than the effects of the eruptions that have occurred over the last several thousand years.

It was known long ago that possible deviations from the norm of intensity indices of many natural processes increase as the time interval under consideration increases. Thus, for example, a catastrophic earthquake, whose probability is very low for a short time interval, is quite probable over a longer time interval.

It is natural to assume that massive anomalies in natural processes—that could not be observed over the comparatively short period of mankind's existence and for the short time of environmental study—had occurred throughout the long geological history of the Earth.

On the basis of this concept, the theory was formulated of the occurrence of aerosol climatic catastrophes in the past. This theory is based on the following ideas.

If the influence of individual explosive eruptions on the Earth's temperature is comparatively small, due to the limited amount of aerosol that the stratosphere gains after every eruption, it is obvious that the Earth's temperature changes much more drastically when many explosive eruptions occur one after another within a short time interval. The possibility of such coincidences for long periods of time, as a consequence of general statistical rules, increases noticeably with variations in the mean level of volcanic activity. Similar to this, the greatest amount of aerosol entering the stratosphere during one volcanic eruption will rise as the studied time interval grows, due to the same causes that induce the greater frequency of eruptions.

By analyzing empirical data on the influx of aerosol to the stratosphere over the last 100 years (Lamb, 1969), a formula has been derived that relates the maximum aerosol amount entering the atmosphere within a certain time (t) depending on the total duration of the period (T), for which the corresponding analysis is carried out. It follows that the maximum influx of aerosol with T>t is proportional to the logarithm of ratio T/t.

Using this formula, it was deduced that for sufficiently long periods of time (thousands or millions of years), the amount of aerosol coming into the atmosphere during 10 years could exceed by 10- to 20-times the amount of aerosol contained in the stratosphere after the Krakatoa eruption (1883).

The analysis confirmed the conclusion as to the possibility of the formation of aerosol layers over sufficiently long time intervals, with the mass inducing the reduction of global mean surface-air temperature by 5 to 10 degrees centigrade or more. Since, in this case, air temperature on the continents decreased by far greater values than for the planet as a whole, such coolings could have led to the extinction of numerous species of animals and plants.

The hypothesis of the possibility of aerosol climatic catastrophes as a result of the collision of celestial bodies with the Earth was proposed at the end of the 1970s. Here we shall briefly explain this hypothesis. One of the results of the falling of large meteorites should be a considerable increase in aerosol layer optical density in the atmosphere. Preserved traces of meteor craters on the Earth's surface allow us to assume that during the long history of the Earth, meteorites, of a size up to several hundred meters or even more, collided with the Earth. If, as a result of the explosion caused by a meteorite falling on the Earth's surface, the stratosphere gained aerosol particles of even only a small portion of its mass, it would be sufficient to cause an abrupt decrease in the solar radiation reaching the Earth's surface.

By calculation it was concluded that after the falling of a sufficiently large meteorite, the temperature would be lowered by approximately 5 to 10 degrees centigrade for many months, and this would catastrophically affect various living organisms. The question of effects in the biosphere caused by the collision of celestial bodies with the Earth attracted great attention after the appearance of publications by Alvarez et al (1980).

A detailed calculation of climatic effects of the Earth's collision with a large asteroid was carried out by Toon and coauthors (Toon et al., 1982; Pollack et al., 1983). In these studies, it was concluded that, due to coagulation and sedimentation of the aerosol particles produced by the explosion of the asteroid, the concentration of these particles remains high only for several months after the asteroid falls. At this time, the solar radiation influx decreases to a level insufficient to support photosynthesis. This calculation shows that attenuating the solar radiation influx would reduce the mean surface-air temperature over the ocean surface by 2 or 3 degrees centigrade for two or more years, and over the continents by several tens of degrees for half a year. It was also determined in these calculations that for 10 months after the falling of an asteroid, the global mean temperature is reduced by 9 degrees centigrade and in 20 months, by 6 degrees centigrade, on average. These results are close to values obtained in the calculation by Budyko (1980).

The presented materials indicate that, in the geological past, large short-term climatic changes occurred, which could have affected living nature.

The possibility of these catastrophes occurring follows from the fact that a reduction of mean air temperature after the large explosive eruptions of the past centuries (Krakatoa and Tambora) was less in order of magnitude than would have resulted in a massive aerosol climatic catastrophe. Taking into account that volcanic activity changes considerably with time, and considering in terms of statistics the above possibility of the coincidence of a series of eruptions over short intervals, it is clear that throughout the Earth's history an increase in the density of the volcanic aerosol layer, by at least one order of magnitude, could have taken place many times.

It is also beyond doubt that a considerable increase in the density of the aerosol layer occurred after the fall of large celestial bodies on the Earth's surface, although it is much more difficult to estimate a decrease of atmospheric transparency after these events.

The recent investigations made it possible to assess the consequences of the falling of an asteroid that caused extinction of animals in the late Cretaceous. In particular, it was supposed that this collision resulted in aerosol emission into the stratosphere three orders of magnitude greater than that due to the largest volcanic eruption over the last 100 to 150 years (Krakatoa, 1883).

It was hypothesized that increased density of the stratospheric aerosol layer caused a drastic decrease in the influx of solar radiation to the Earth's surface. This resulted in a decrease in photosynthetic activity, which, in turn, caused the extinction of vegetation and then, of phytivorous animals. This hypothesis, as well as the assessments of some other consequences of the formation of an aerosol screen in the stratosphere, seems to be incorrect. The most probable cause of climatic catastrophes in the late Cretaceous was surface-air temperature decreases by several degrees due to the decrease in solar radiation influx resulting from the increased density of the aerosol layer after the collision of the asteroid with the Earth or increased volcanic activity due to the destruction of a part of the Earth's crust after that collision.

Discussing the possible causes of aerosol climatic catastrophes, the narrowness of the "climatic zone of life" (the range of physical and chemical conditions in the atmosphere and hydrosphere under which living organisms can exist) on our planet should be taken into account.

During the millions of years before the catastrophe of the late Cretaceous, climatic conditions at all latitudes of the planet differed comparatively insignificantly, being either warm or hot. Consequently, living organisms were stenothermal and a short-term, small temperature decrease (by several degrees) could cause mass extinction of many plants and animals.

Such changes in the biosphere did occur over the last 100-million years, such as in the late Cretaceous and Cenozoic periods. Information about the temperature regime over this period is presented in Table 1 (Budyko, Ronov and Yanshin, 1985), where Mc (%) is the bulk concentration of CO_2 in the atmosphere, DS/S is the ratio of the difference between solar radiation in the past and present to the modern solar constant, and DA is the difference between the Earth's albedos, expressed in the parts of unity.

Taking into account that present mean surface-air temperature equals 15 degrees centigrade, and assuming that a radiation increase of 1% with constant albedo causes a mean temperature increase of 1.4 degrees centigrade, while an albedo increase of 0.01 causes a temperature decrease of 2 degrees centigrade, the difference between the mean air temperature in the geological past and present can be determined from the data in Column DT in degrees of centigrade.

Table 1. Difference between mean air temperature in the geological past and present

Period	Duration (Million Years)	Mc (%)	dS/S	DA	DT
Late Cretaceous	101-67=34	0.178	0.004	0.016	10.4
Paleocene	67-58= 9	0.076	0.003	0.015	6.7
Eocene	58-37=21	0.120	0.003	0.015	8.5
Oligocene	37-25=12	0.032	0.002	0.014	2.8
Miocene	25-9=16	0.076	0.001	0.012	6.4
Pliocene	9-2= 7	0.045	0	0.008	3.4

Over the relatively short Quaternary period, CO_2 concentration in the atmosphere fluctuated considerably and the tendency for a CO_2 concentration decrease, which appeared long before the beginning of the Cenozoic, continued to intensify. In the coldest Pleistocene epochs, when glaciation developed, the mean surface-air temperature was about 5 degrees centigrade lower than the modern one.

Calculations using climate theoretical models show that in the warm epochs of the Phanerozoic the climate changed comparatively little in the tropical latitudes, while in the middle and especially in the high latitudes, air temperature was much higher than at present (Manabe and Bryan, 1985). As a result, the climate in the polar regions was comparatively warm. Paleogeographic investigations show that in the Mesozoic and early Cenozoic, forests consisting of evergreen species existed in the high latitudes.

The comparison of empirical data on mean air-temperature fluctuations with the changes in CO_2 concentration and albedo confirm the conclusion that those were climate-forming factors for the intervals mentioned in Table 1.

The idea of the influence of atmospheric chemical composition on nature was put forward in the early 19th century by Geoffroy St.-Hilaire, who wrote: "Let us suppose that with time gradual changes occurred in the ratio between different elements of the atmosphere and it was an unavoidable consequence that these changes affected the fauna" (E. Geoffroy St.-Hilaire, 1833). For a long time the idea of Geoffroy St.-Hilaire did not attract any attention due to the absence of reliable information about the changes in atmospheric chemical composition in the geological past. In recent years, after new data on atmospheric chemical composition changes in the geological past had been received, these data were compared with the history of natural evolution.

It is probable that, of the different components of the external environment, the amount of oxygen in the air is one of the most essential factors of life activities for terrestrial animals (or for aquatic animals, the amount of oxygen in the water, which depends on the atmospheric oxygen concentration). The level of metabolism of aerobic animals is directly dependent on the amount of oxygen in the environment, increasing, other things being equal, with an increase in oxygen content.

Additional energy received by an animal in the environment with increased oxygen content may be used for different purposes, including the development of a more complex structure of the organism, or its individual organs and tissues, in the course of evolution. Especially important, in this case, might be the improvement of organs maintaining metabolism, such as circulatory and respiratory systems in vertebrates.

Of considerable interest is the question about general principles of animal evolution throughout a long period from the end of the Carboniferous to the end of the Triassic, when the atmospheric oxygen level decreased for the longest time in the Phanerozoic. As a result, at the end of the Permian and throughout a part of the Triassic, oxygen was only 20% to 25% of its present level, which is close to the average Late Proterozoic amount of oxygen. The lower (exothermal) vertebrates that used relatively little oxygen could more easily adapt to such conditions. It is very doubtful whether the higher (endothermal) vertebrates could exist at such low oxygen concentrations.

It is evident that with a decrease in atmospheric oxygen content, the life activities of animals and their mutual relations with other components of ecological systems must have been changing. A gradual deterioration of the conditions for the existence of animals must have been reflected in the specific features of the evolutionary process in the period in question.

These features were long noted by paleontologists, although their causes were unknown. In particular, Simpson (1961) wrote: "It is interesting that no phylum has expanded steadily from the time of its appearance to the present day. The most nearly general feature is that most of the phyla contracted in the Permian, Triassic or both."

The principle indicated by Simpson was also confirmed by many other investigators. For instance, Raup and Stanley (1971) present a scheme of temporal variations in the number of taxons of fossil animals in the Phanerozoic, which shows that against a gradual increase in the number of taxons, their number abruptly declined in only one single period, in the Triassic. The authors indicate that, in fact, this contraction began in the middle of the Permian. Robinson (1971) states that from the Permian to the Late Triassic the number of genera of therapsids became ten times less and the number of genera of sauropsids increased considerably. This shows that conditions were unfavorable for the existence of mammal-like reptiles for the greatest part of the Triassic. Worth noting is also a tendency that appeared in the Triassic toward a decrease in size of the therapsids, which belonged to the most progressive groups. This tendency may be due to a growing shortage of oxygen, since the maintenance of the metabolism of large animals requires more oxygen than for small animals, other things being equal.

It might be supposed that a decrease in oxygen content during the Late Permian and the Triassic greatly retarded the process of the formation of mammals, which extended over an enormous interval of time, about one-hundred-million years. This class of vertebrate spread only with a new rise in atmospheric oxygen, which began in the second half of the Triassic.

Another considerable decrease in oxygen concentration occurred during the second half of the Cretaceous. At this time, the oxygen content decreased by more than 1.5 times and approached a level somewhat lower than the modern one. Although this level was rather high compared to the average conditions of the Phanerozoic, it is probable, however, that the oxygen decrease in the Cretaceous was of importance for the fauna of that time, and, in particular, caused the extinction of some groups of animals at the end of the Mesozoic.

Following these considerations, it might be concluded that the formation of modern classes of vertebrates was determined to a great extent by global changes in the environment, one of the causes of which was variations in the degassing of the Earth's mantle.

As mentioned earlier, with increases in the amount of oxygen in the atmosphere in the range of its variations throughout the Phanerozoic, possibilities emerged for the new groups of animals, which use more energy in the course of their vital activity, to evolve. Therefore, it is natural to suppose that in the epochs of increased oxygen concentrations, the diversity of fauna grew larger, while in epochs of decreased oxygen content their diversity diminished.

Turning to the problem of the influence of carbon dioxide changes in the atmosphere on animate nature, let us note that in some cases this influence was combined with that of atmospheric oxygen changes. Thus, in particular, in the example of the dissemination of aerobic organisms with the formation of oxygen atmosphere, the oxygen concentration in the atmosphere started to grow after a decrease in atmospheric carbon dioxide content below a certain limit, which resulted from a relevant decrease in the influx rate of carbon monoxide and other not fully oxidized gases in the atmosphere.

During the Phanerozoic, carbon dioxide fluctuations considerably influenced photosynthetic productivity and climatic conditions. These fluctuations undoubtedly influenced the life of plants and, to a lesser extent, that of animals.

The comparison of variations in carbon dioxide with principal events in the development of vegetation is impeded by the lack of a generally accepted chronology of the considerable changes in the nature of vegetation. Krasilov (1977) identified four major epochs in the formation of the higher taxonomic groups of plants: the second half of the Devonian, the Permian to the beginning of the Triassic, the Cretaceous and the Miocene. The first of these epochs is associated with the formation of progymnospermous forests, the second with the expansion of coniferous forests, the third with the emergence of archaic flowering plants and the fourth with the appearance of steppe plant communities.

It may be noted that these epochs correspond to four out of the five maxima in carbon dioxide concentration that were enumerated. This testifies that an increased productivity of photosynthesis considerably affected the progressive development of plants.

Since the existence of all living organisms depends on the atmospheric chemical composition, the question naturally arises: why did the atmospheric chemical composition vary for about four-billion years within a range permitting not only continuous preservation of life on the Earth (the continuous existence of the biosphere), but also the progressive development of organisms, among which many achieved a high level of complexity in the course of a long evolution?

Although this question has rarely been discussed in scientific studies, it could be answered in two different ways. One of them is the so-called "Hypothesis of Gaia," which suggests that living organisms have the ability to control the environment, and to maintain a state favorable for their life activity (Margulis and Lovelock, 1974; Lovelock, 1979). The authors of this hypothesis have not adduced any definite proofs in favor of their idea, and it is mainly based on the apparent impossibility of otherwise accounting for the long existence of the biosphere.

The presented conclusions about the mechanism of the evolution of the atmosphere have indicated that variations in the physical state and chemical composition of the atmosphere depend mostly on two external factors, namely, the evolution of the Sun, which leads to a gradual increase in solar radiation, and the evolution of the Earth, in the course of which the process of degassing of the upper mantle gradually attenuates. The first of these processes is entirely independent of the activity of terrestrial organisms and the second almost so.

The causes of the antiquity of the Earth's biosphere can therefore be explained otherwise. In might be thought that this antiquity is a result of random coincidence (independent of the existence of organisms) of the direction and rate of the processes of the Sun and the Earth's evolution, which are not connected to each other. Since the probability of such a coincidence is extremely low, it means that life (and particularly its higher forms) in the Universe is an exceptionally rare phenomenon.

This point of view has been developed in a number of works (Budyko, 1977, 1980, 1984; Hart, 1978, 1979). As has been noted in these works, the atmosphere in which life on any planet can exist must have a specific physical state and chemical composition.

Let us conclude that life could originate on Earth and be preserved for billions of years because of the coincidences of several factors. It might well be considered that the probability of each of these coincidences was very low.

Conclusion

In the early 1970s, an estimate of the increase in the carbon dioxide concentration and mean surface-air temperature expected to occur in the next century was presented (Budyko, 1972). In recent years, many forecasts of changes in mean air temperature in the next century have been published. It should be noted that these forecasts, as a rule, are in good agreement. The investigations show that in the nearest decades, due to the effect of man's economic activity on the atmospheric chemical composition, considerable climate changes are to occur. In the past, it took thousands of years for climate changes of such scale to develop. As these climate changes would influence different economical objects, which are now being projected or built, it is clear that information about the forthcoming climate changes is of great practical importance.

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Lecture

Global Climate Warming and its Consequences

Professor Mikhail I. Budyko

Modern Climate Change

It has been recognised in the second half of the present century that the chemical composition and physical state of the atmosphere started to change under the impact of man-made activity, contributing to overall biospheric change. Uncontrolled anthropogenic impact on large-scale processes in the biosphere might result in a global ecological crisis, hence the necessity to better understand all possible anthropogenic climate-related changes in the biosphere in order to be able to predict these changes, whatever the scenario for economic development. To resolve this question in a similar way to many other environmental issues, we have to meet a certain challenge that is different from those of most other scientific disciplines. The study of the relationship between living organisms (including human beings) and the environment requires the mobilisation of data and methods inherent in other areas of study, particularly those of biology, geography, geophysics, geochemistry, geology, economics, engineering and others. Each of the science sectors mentioned includes a wide spectrum of more specific disciplines.

Today, when the information volume in each science field is such that they must be further sub-divided into more specialities, the ability to combine all the data of all these fields to resolve our problems becomes more limited. However, without such a synthesis of currently available information, no progress in the study of global ecology would be possible.

During the past few decades, a number of scientific works have been published dealing with models of global ecological system development. One of the themes of these works addresses the study of modern climate change. This study has revealed that, due to the burning of ever increasing amounts of coal, oil and other types of fossil fuel, the chemical composition of the atmosphere will undergo certain changes, mainly caused by the growth in the amount of carbon dioxide in the atmosphere. This change has resulted in a significant enhancement of the greenhouse effect in the atmosphere, which is believed to be a major cause of global warming. This warming has already induced changes in many biospheric components, including the hydrosphere, cryosphere, soil, vegetation and animal life. Some of these changes affect the lives and activities of man. This illustrates the need to develop forecasts of possible future effects of anthropogenic factors on the biosphere. If these forecasts are to be used in the long-term planning of economic development, they should be highly trustworthy. Necessary forecast reliability can only be ensured by further developments in the study of global ecology.

To make a correct assessment of future changes in the biosphere, we should have a better knowledge of the evolution of the biosphere in past geological epochs with emphasis on the epochs when the biosphere underwent most rapid changes.

The considerable effort invested in these studies has provided a global reconstruction of summer and winter surface-air temperatures as well as annual precipitation levels during three warm epochs of the past (Optimums of Holocene, Riss-Wurm Interglacial and Pliocene), when mean surface-air temperatures were, respectively, 1°C, 2°C, and 3°C to 4°C higher than those of the preindustrial period. Figures 1, 2, and 3 show surface-air temperature changes during (a) warm and (b) cold seasons of the year, and (c) the same for annual precipitation amounts. These maps can be used as paleoanalogue scenarios of regional climatic changes under current global warming, by the end of the first decade, and the first quarter and the middle of the next century, respectively.

During the last 15 years, a group of Russian scientists has been carrying out a study into the changes in the chemical composition of the atmosphere in the geological past. The main attention was directed toward studying the history of two atmospheric components, carbon dioxide and oxygen, during the Phanerozoic period, that is 570– to 590– million years ago. Data on the evolution of the chemical composition of air was compared with data on the development of animate life. A close correlation has been established between major organism evolutionary stages and changes in the chemical composition of atmospheric air. Evidence regarding carbon dioxide variations in the geological past obtained during the study has been used to obtain a better insight into modern anthropogenic climate changes, which are caused by an increase in carbon dioxide in the atmosphere as a result of fossil fuel burning. A trend of atmospheric carbon dioxide decrease during the cenozoic era (the last 70 million years) has been revealed. It has been shown that this decreasing trend alternated with epochs with higher carbon dioxide concentrations. The general pattern of the variations in mean surface-air temperature in the cenozoic era was found to be in step with that of carbon dioxide in the atmosphere.

A close correlation between the variation in carbon dioxide content and changes in mean surface-air temperatures is particularly important. The correlation for the mean air temperature for geological series during the Tertiary period has a correlation coefficient higher than 0.9 (Fig. 4). This correlation can be used to assess the carbon dioxide greenhouse effect on air temperatures. This effect manifests itself in an increase in mean surface-air temperature of 3°C with a doubling in the level of carbon dioxide. This value is close to a similar coefficient obtained to estimate the impact of carbon dioxide on the thermal regime of the atmosphere employing climate theory methods. Assuming that the relationship between surface-air temperatures and the chemical composition of the atmosphere is fairly well known, we can use paleoclimatic data to ascertain a similar relationship for various regions of the globe. A similar goal was set up for the study of other modern climate element changes, particularly atmospheric precipitation. The correlation of future climate predictions obtained by certain independent methods of climate theory and by empirical methods used to estimate expected changes in major climate elements can be proposed as a criterion for the skill score in forecasting regional climate changes. These methods can include paleoanalogues of modern climate changes, data on climate conditions during recent warm geological epochs and various models of the theory of climate.

It was only after 1970 that the mechanisms of modern climate change were included in the scope of research efforts. It was recognised in 1970 that during several recent decades a slow surface-air temperature decrease occurred, but what caused the cooling was not yet clear.

One school of climatologists believed the cooling would continue in the coming years, while most of the experts were sure that it would be impossible to predict the climate of the future reliably and with sound scientific substantiation. I, however, firmly believed that in the near future we would witness a global warming that would reach a few degrees Celsius in the next century. I expressed the belief at an international conference in Leningrad in 1971. At the same time, I published this viewpoint, though in the 1970s nobody supported my suggestion. In the middle of the 1970s, observational data was published that suggested a possibility of warming in the high latitudes. Similar evidence was found for certain regions of the middle latitudes. Finally, in the 1980s and 1990s mean surface-air temperatures were observed to reach record high values. Recently, global warming has been recognised as fact by international research organisations and has also been confirmed by numerous climatological scientific publications.

Empirical analysis of climate regularities during the past 15 years has shown that in a number of regions on our planet anomalies in precipitation and surface-air temperatures in summer and winter over this time period seemed to be similar to those predicted for the early 21st century. The predictions have been made based on data on regional climatic features of climate change in the Holocene Optimum.

Our publications, starting with the first ones concerned with a forthcoming global warming, discussed its impact on the environment, in particular on the cryosphere. At the end of our century, this prediction has proved to be correct: the extent of sea ice in the Arctic Ocean has decreased; the sea ice itself has become thinner; many mountain glaciers have broken off; permafrost in the high latitudes of the Northern Hemisphere has retreated northward; and the precipitation regime in arid and semiarid areas has changed.

The increase in mean surface-air temperatures over the past 30 years, predicted by us as early as the 1970s, should exceed 0.5°C. This estimate is in agreement with the results of weather observations for the same time interval (Fig. 5). It is a remarkable and quite unusual event in the history of climatology that a forecast of global climate change has been confirmed by direct observations, since repeated attempts to predict future climate changes as a rule used to fail. One could think that the use of physical climatology methods would allow us to make a successful forecast of climate change in the first half of the 21st century. Unfortunately, the accuracy of such a forecast and the period for which it could be made would be limited. This limitation can be attributed to two factors, the major one being insufficiently reliable estimates of the chemical composition of atmospheric air in the future, which will be dependent on international treaties controlling gas emissions into the atmosphere. The second reason is insufficient predictions of climate change for periods several decades long, though this accuracy has much improved of late. It is possible that by using several empirical and theoretical methods to estimate anthropogenic impacts on climate simultaneously, it will be possible to increase this accuracy.

In general, we can conclude that today it is possible to make quite a reliable forecast of regional mean surface-air temperature changes in the cold season, particularly for high latitudes. If this problem seems to be resolved, the temperature changes in the warm season cannot be predicted with the same accuracy. This might, to a certain degree, be explained by the fact that the values of these predicted changes in the warm season are relatively small. With respect to precipitation, we can conclude that both modelling and analogue estimations are not capable today of providing forecasts of potential future precipitation changes with required accuracy. For relatively short periods (the next two decades), we can suggest that the forecasts made on the basis of empirical evidence (analogue method) are capable of ensuring a certain degree of reliability.

We might express our hope that to improve predictions of future climate changes a certain international body be set up to ensure cooperation among leading specialists in the field of physical climatology.

Consequences of Modern Climate Warming

Climate Changes and the Global Food Problem

We can assume that among the numerous consequences of expected global warming the ones that relate to the impact on agriculture are the most significant from the point of view of the economy. The accuracy of predicting the impact of these changes is closely related to the perception of the economic importance of modern climate changes. It also predetermines the answer to the issue of global warming adaptation strategy.

The problems of the future of agriculture should be resolved with a due account of predictions of the earth's population growth, which indicate that by the middle of the next century the earth's population will reach about 10-billion people. It is a well-known fact that, excluding developed countries, the availability of food for the earth's population is insufficient. This results in periodic food supply crisis and famine in a number of African and Asian countries. In this regard,one would like to hope that in the next decade food production per capita would, if not increase, at least would not decrease. Simple estimates indicate that to achieve this, it is necessary to double total world food production. This begs the question, "What will be the impact of expected global warming on this important problem for mankind?"

To answer this question we should consider a number of factors. Analysing the prospect of a significant expansion of arable land over the next decades, we can assume that this is unlikely due to the high level of investment needed to effect agricultural development over large new land areas with low soil fertility.

The second important question for assessing prospects for future agricultural development and the role of global warming relates to possible levels of crop yield growth resulting from the introduction of new intensive agricultural technologies. An analysis of this possibility has shown that for a number of crops and regions, where the present yields are low, we might expect certain tangible improvements. However, our calculations show that we cannot expect world agriculture to double its production by the middle of the next century only as a result of the introduction of intensive agricultural technologies. However, as already stated, it is this production doubling that is needed to maintain the present world level of per capita food consumption.

In the context of the present discussion, we can pose another question. What would be the effects of important expected global changes like the growth in concentration of atmospheric carbon dioxide and changes in temperatures and precipitation?

As stipulated by fundamental concepts of plant physiology, the concentration of carbon dioxide in the atmosphere is one of the major factors in crop productivity. Together with solar radiation, atmospheric carbon dioxide is the photosynthesis substratum and, in accordance with the laws of biological kinetics, contributes to higher crop productivity. Various problems regarding the direct physiological impact of atmospheric carbon dioxide increases on plant productivity have been discussed in detail in special publications. In fact, we can conclude, on the basis of the experimental results reported in a large number of publications, that the increase in atmospheric carbon dioxide is a factor that favourably affects the main crops.

Specific estimates of the effects of atmospheric temperature and precipitation changes on potential productivity in various regions of the earth depend on the climate-change scenarios that are used in the calculations. As an example, I can demonstrate the potential productivity changes in the three most important crops in the world (wheat, rice and maize) in a number of countries corresponding to different levels of global warming and atmospheric carbon dioxide (Table 1).

Assessing the importance of expected climate change by its impacts on world agriculture, we can conclude that growing anthropogenic global warming and, in particular, the increase in carbon dioxide concentration in the atmosphere can have a favourable effect on crop productivity in many regions of the earth. However, we should not forget that these estimates for different regions could be significantly different.

Climate Change Effects on Natural Zonality

Climate changes predicted for the next few decades should have a considerable impact on natural terrestrial vegetation and its geographical distribution.

As demonstrated by the analogue scenarios, during the first stages of a global warming of 1°C to 2°C, the Arctic continental tundra in northern Europe would completely disappear, while its southern boundary in Siberia might significantly shift northward. If global temperatures increase 2°C, the southern boundary of taiga forests might move northward, reaching 65°N, where the taiga would replace mixed forest. At the same time, the coniferous forest areas would shift northward by almost 10 degrees latitude. The boundary of the forest/steppe would also move northward, eastward and westward. The steppe in Russia would cover the area currently occupied by coniferous forests.

According to the paleoanalogue scenarios, the areas occupied by tundra and forest/tundra in Eurasia would be greatly affected and their areas would significantly decrease. Today, these two zones taken together cover almost 20% of Russia. Under the impact of a global warming of 2°C, it would shrink to merely 4%. The coniferous forest might suffer a reduction by a factor of three or even more. On the contrary, the broad-leaf forest geographicrange would cover 15% instead of the current 1%. According to various estimates, the area of forest/steppe within the former Soviet Union would double and the steppe geographic range would increase by 80%.

When summarising the results obtained by different methods, we should state that, despite some differences in quantitative estimates, the principal conclusions on major trends in the variations of natural phytoceonoses under the impact of global warming are similar.

There is broad agreement among many investigators regarding the important inferences to be drawn from the predicted climate changes, such as the shrinking of the tundra zone and boreal forest, the expansion of the steppe area and a possible decrease in deserts and semidesert areas. This allows us to express our hope that these methods can be used in practice, particularly when making environmentally sound decisions of socio-economicsignificance with respect to the protection of natural vegetation under the impact of expected global warming.

Global Warming and Permafrost

The permafrost areas in Eurasia and North America are quite extensive. During the past decades, they have been subject to considerable anthropogenic impact. This poses a problem of substantiating and forecasting their future optimal development. An important aspect that should be taken into account when developing forecasts concerning the state of the permafrost area in the near future and the long-term is the evolving changes in the thermal regime of the earth's surface under the impact of global warming.

The possible evolution of permafrost within Russia has been analysed in great detail, drawing extensively on paleoanalogue scenarios of climate change. Figure 6 illustrates the area of cryolithozone in Eurasia where a "separation" of the permafrost from the upper layer of seasonally freezing soil could be expected under a 2°C warming. The computations have shown that given such climate change, a significant variation in the upper layer of the permafrost would be observed over an area covering 15% to 20% of the territory currently characterised by the permafrost. Computations made at sites located in various latitudinal zones of the permafrost allow us to make an assessment of the "velocity" with which this area of permafrost degradation would move northward under the impact of such warming. Estimates indicate this velocity to be 10–15 km per year in western Siberia and 20–25 km per year in eastern Siberia and the Far East. With regard to the rate of vertical shift of the upper boundary of the permafrost due to downward thermal disturbance penetration caused by global warming, calculations have shown that over the next 50 years the separation of the permafrost from the upper soil layer might be about seven metres.

Changes in Energy Consumption for Heating

A reduction in the consumption of energy resources due to shorter and less severe cold seasons might be one of the important implications of global warming in the northern regions of the Northern Hemisphere. As estimations show, a global warming of 1°C would make the heating period (when heating is required to maintain room temperature) one to two months shorter in the north of Russia and 10 to 15 days shorter in its central regions and in the southern republics of the former Soviet Union. Under a more significant warming (3°C to 4°C), the duration of the heating period in these regions might decrease even more, i.e. two to four months in the north and one to two months over the rest of the former Soviet Union.

Calculations made with respect to the middle latitudes of Asia (Mongolia, the People's Republic of China and the Korean Peninsula) show that with a global warming of 1°C, the heating period might decrease by 10 to 15 days. By the middle of the next century, with a more substantial warming, the duration of the heating period in these countries might become a month shorter. For most of Canada and Alaska during the first stage of global warming, the period should be 20 to 30 days shorter and 10 to 15 days shorter in the United States, where, by the middle of the 21st century; this reduction might reach a month or a month and a half. For northern Canada this reduction might amount to three months, and a month and a half to two months for its southern regions.

Today in Russia, the consumption of energy required for heating during the cold season amounts to 300–350 degree-months (the total of daily difference between room temperature and outside temperature of each month) in the north of the country and 50–100 degree-months in its southern regions. Calculations indicate that, at the beginning of the next century, heat consumption should decrease 15% to 20% compared to the present rate in the far northern regions of European Russia and in west Siberia. Should the warming continue and reach 3°C to 4°C, energy consumption costs would decrease by a factor of two in the north of East Siberia and the Far East.

In western and central Europe, energy consumption during a heating period at the beginning of the 21st century might fall by 10% to 20%, and by 20% to 40% by the middle of the next century. For Mongolia, the PRC and the Korean Peninsula, estimates for the reduction in energy costs are predicted to decrease by 10% to 15% and 30% to 40%, respectively. In Canada and the U.S.A., these would be 10% to 15% and 30% to 50% lower, respectively.

Unlike the northern regions, for which a reduction in energy costs is expected under the potential climate change, a number of southern countries might need to spend more on energy to provide quality air conditioning in buildings. This is one of the negative consequences of global warming. Remembering that it is in the southern countries that most of the world's population lives, higher costs of energy for air conditioning inside buildings might exceed the savings gained by lower energy consumption in the northern regions. Detailed study of this problem would provide an answer regarding future energy export/import requirements.

Hydrological Response to Climate Change

Without doubt, among the main consequences of anthropogenic climate change, variations in water resources in many territories and the hydrologic regime of many rivers, lakes, water reservoirs and the ground water could be very serious. Possible changes in hydrologic parameters will impact directly on many sectors of industry, agriculture, hydroenergetics and certainly on the environment. As an example, we could examine some data obtained using similar methods concerning three large Eurasian river basins—those of the Volga, Dnieper and Yenisey rivers.

The analysis of the data obtained for these rivers shows that, under changes in climate parameters according to all available models and paleoanalogue scenarios of global warming to the middle of the next century, we can expect an increase in water resources in their basins. The estimates according to the model scenario developed in the Geophysical Fluid Dynamic Laboratory (Princeton University, U.S.A.) and the Pliocene Optimum paleoanalogue scenario indicate that the annual runoffs for the Volga and Dnieper rivers could increase by approximately 35%. According to these scenarios, the Yenisey river runoff will increase by 20%. When using the climate change scenario developed by British specialists, which is characterised by the largest estimates in precipitation growth, the runoffs of these rivers will increase considerably more. In this regard, we can conclude that the increase in runoff due to climatic change will provide future growth in water withdrawals from the Volga and Dnieper rivers. As for the Yenisey river, we can only hope that its future as the great Siberian river is not at risk.

Whilst it is interesting to predict changes in annual river runoff, we should have a better understanding of how it changes season-by-season. Calculations have shown that the seasonal distribution of the runoff of rivers such as those mentioned above would respond strongly to the temporal dynamics of precipitation and air temperature. Estimates indicate that the current temporal dynamics of the runoffs of the Volga and Dnieper have a well-pronounced Spring maximum caused by snow melting, when most of the runoff occurs. A minimum is observed in autumn, winter and late summer. This pattern might change under global warming. As the predictions show, the maximum runoff of the Volga and Dnieper might increase considerably from November to April, while from May to October, based on predicted changes in the regional climate, the runoff of these rivers would decrease with a minimum reached in July. As for the Yenisey, the changes in climate regime would have a less profound effect on the seasonal runoff distribution. Predictions for the middle of the next century show a similar situation to the present day in that the largest runoff will occur in spring, though in time the spring flood should last longer and start a little earlier.

Conclusion

In addition to the probable effects of global warming discussed above, the most important and adverse effects of projected changes in climate on other related sectors would be caused by higher air temperature, higher evapotranspiration, dryer soils and a rise in the sea level. As indicated in many crop response studies, higher air temperature would lead to increased high-temperature injury to crops (rice, maize, sorghum) and domestic animals, and to increased incidence of heat-stroke in the aged and young population in summer seasons. It is also expected that the projected global warming would cause a northward shift of weeds, pests and diseases that are now mainly found in subtropical and tropical regions. The rise in sea level, resulting from the thermal expansion of the oceans and partial melting of glaciers, should affect agriculture and other sectors, mainly through the inundation of low-lying lands. Therefore, in the mid- and lower latitudes, where higher summer temperatures and drying soil may be expected to occur frequently due to global warming, the potential yield of many crops could be reduced by 10% to 30%.

On the other hand, our simulation results obtained using paleoclimatological data and semi-empirical weather-crop models indicated clearly that the potential productivity of crops in the northern regions of Russia and the Canadian prairies, where such productivity is largely limited due to lower summer temperatures at present, may be enhanced by projected global warming. However, much of the increased potential in these regions may not be exploited for future food production because of inappropriate soils and difficult terrain. Therefore, it seems that the productive advantages of global warming at higher latitudes, such as the northern regions of Russia and the Canadian prairies, would not compensate for the projected reduction in potential yield in current major crop producing regions, such as the U.S. Great Plains and southern Europe. On balance, it is very difficult to conclude with higher accuracy whether the projected global warming would be globally beneficial to human society or not.

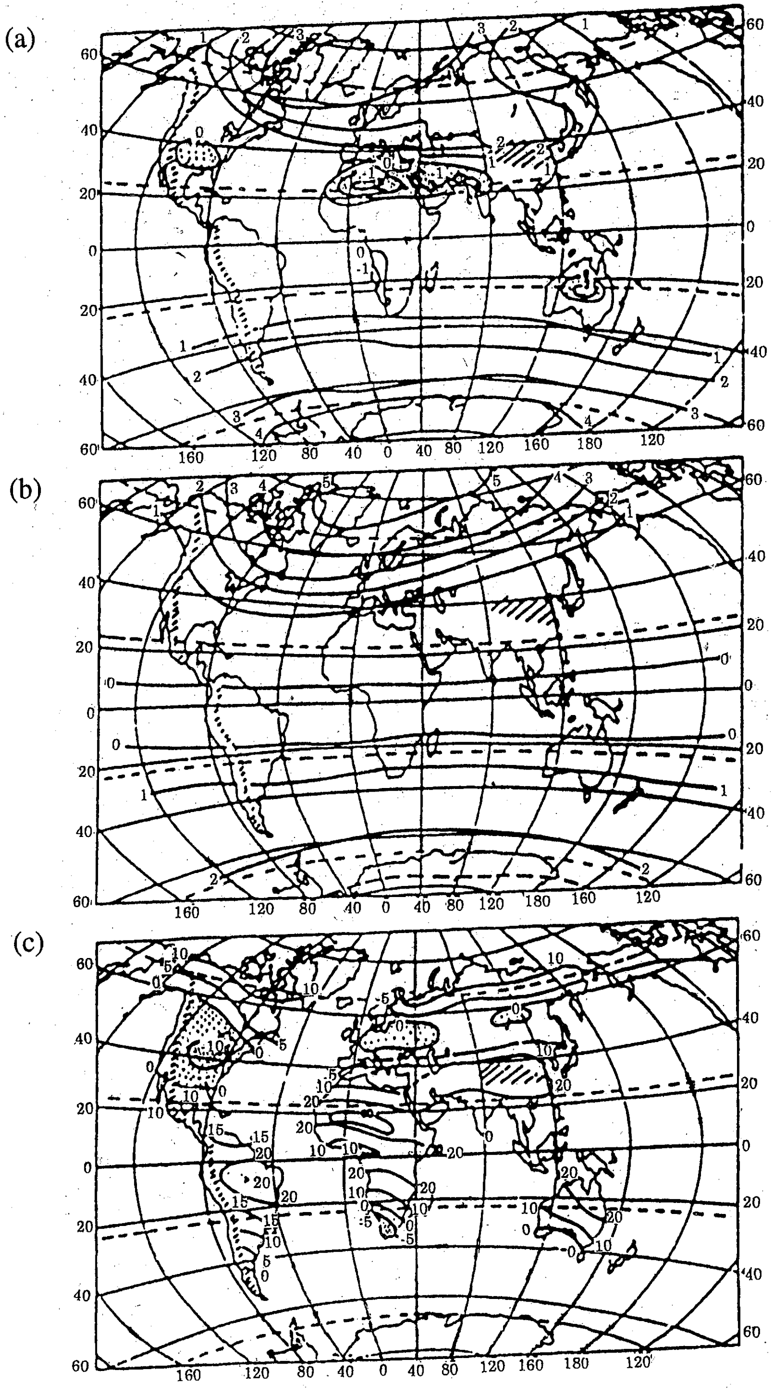

Figure 1. Climate changes for the years 2005-2010 according to the Holocene Optimum analog scenario. From top to bottom: surface-air temperature in July/August(°C); surface-air temperature in January/February; and annual precipitation(cm).

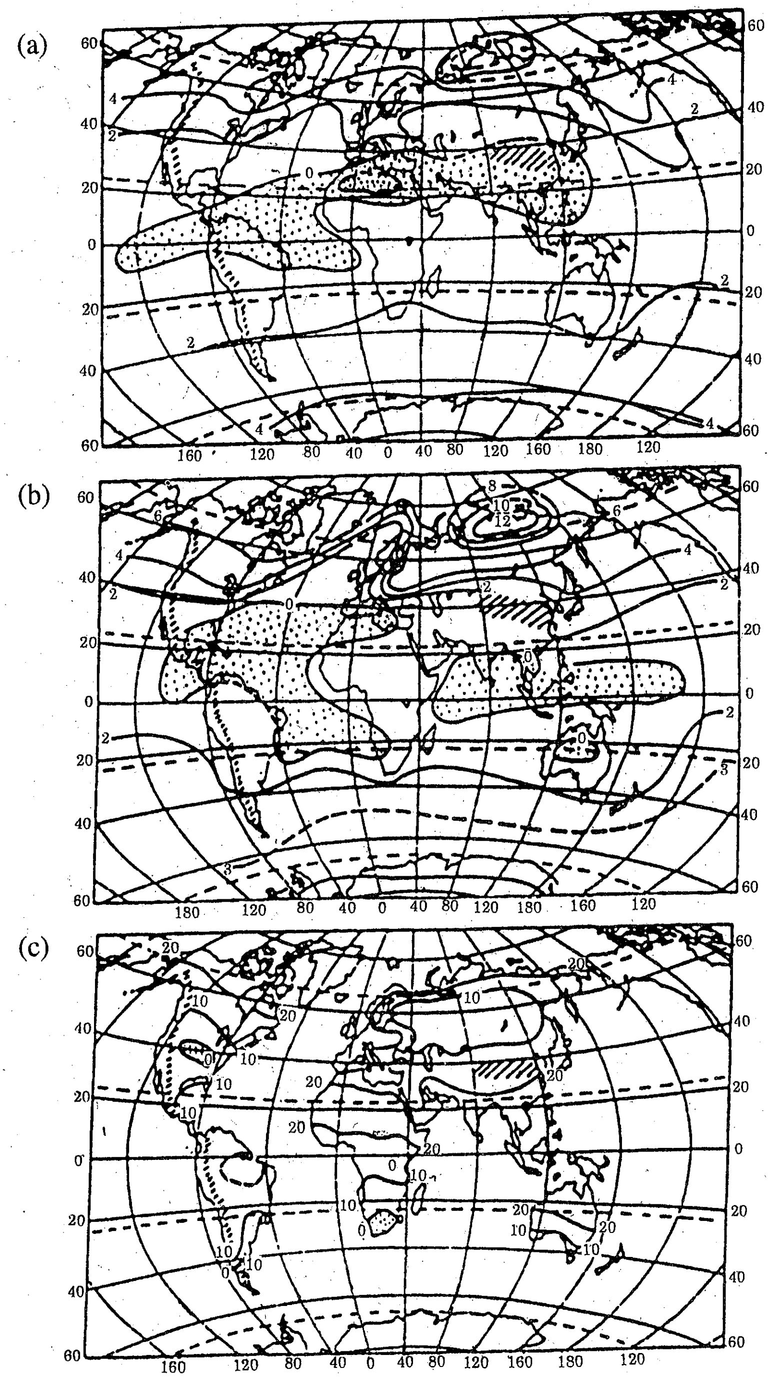

Figure 2. Climate changes for the years 2025-2030 according to the Riss-Wurm Interglacial Optimum analog scenario. From top to bottom: surface-air temperature in July/August(°C); surface-air temperature in January/February; and annual precipitation(cm).

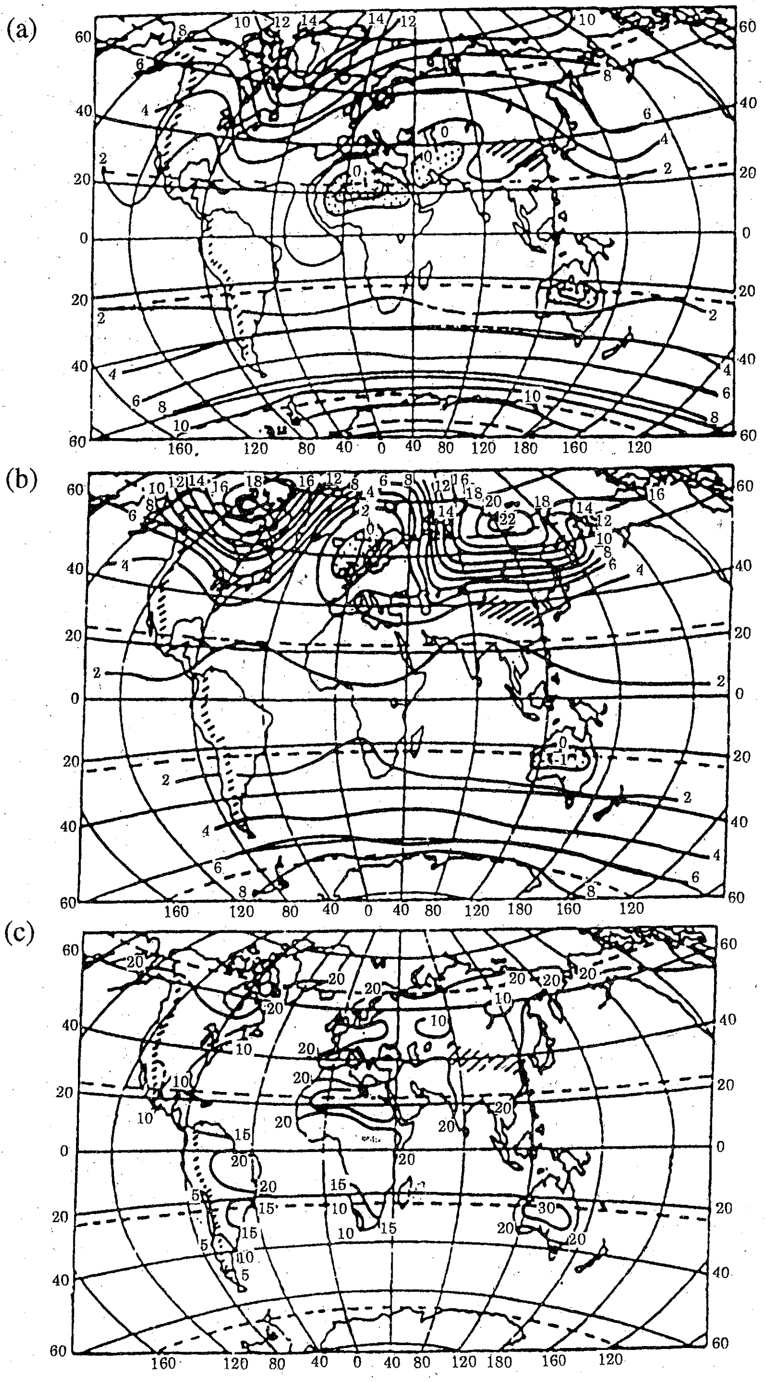

Figure 3. Climate changes for the years 2045-2050 according to the Pliocene Optimum analog scenario. From top to bottom: surface-air temperature in July/August(°C); surface-air temperature in January/February; and annual precipitation(cm).

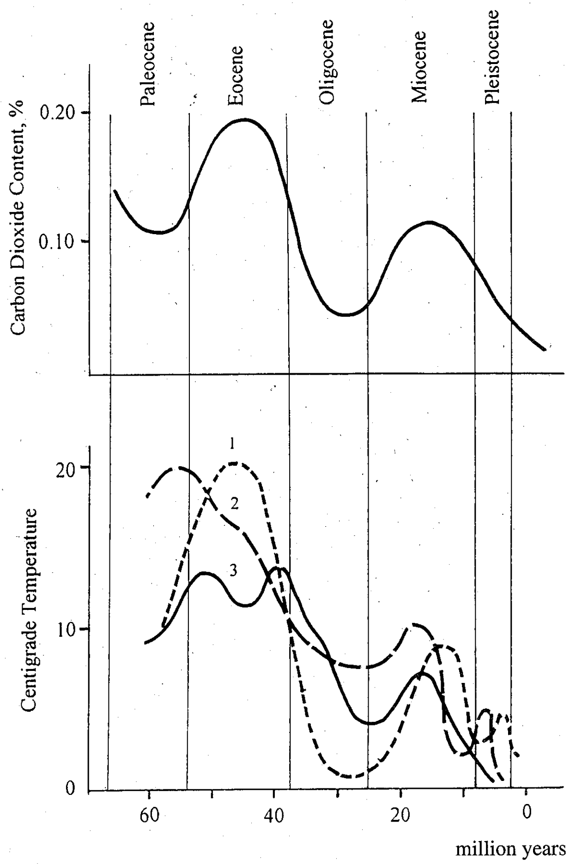

Figure 4. The changes in carbon dioxide content in the earth's atmosphere (upper curve) and the surface-air temperature (three lower curves) during the last 70 million years.

Curves 1, 2 and 3 correspond to the data for the west of Northern America, for the Northern Hemisphere as a whole and for the northern part of the North Sea, respecitively.

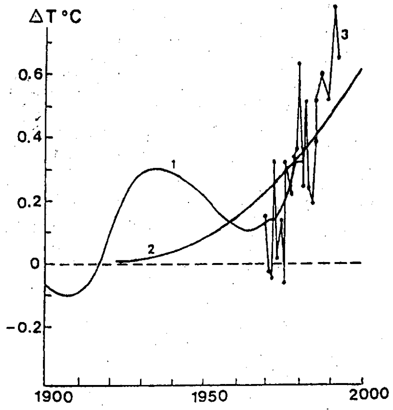

Figure 5. The changes in the surface-air temperature during the 20th century:

Curve 1. The changes in 11-year smooth values of mean surface-air temperature in the Northern Hemisphere.

Curve 2. The forecast of the changes in globally averaged mean surface-air temperature offered in 1972.

Polygonal line 3. Annual values of mean surface-air temperature anomalies observed after 1970.

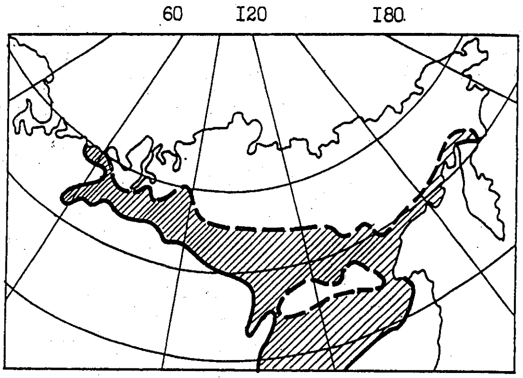

Figure 6. The areas of permafrost degradation (shaded) in Eurasia under a global warming of 2°C.

Table 1. Changes in climatic potential of productivity (%) for three principal crops (wheat-W, rice-R, maize-M) according to three paleoanalog scenarios of future climate change

1: 1°C global warming, 400 ppm carbon dioxide content
2: 2°C global warming, 460 ppm carbon dioxide content
3: 3°C global warming, 550 ppm carbon dioxide content

Countries	1			2			3		
	W	R	M	W	R	M	W	R	M
Austria	9	-	-	14	-	-	31	-	-
Denmark	10	-	-	15	-	-	32	-	-
France	9	-	26	13	-	38	28	-	51
Germany	7	-	21	12	-	24	23	-	47
Hungary	3	-	8	7	-	10	16	-	13
Italy	4	10	6	7	15	8	16	23	12
Netherlands	5	-	-	11	-	-	21	-	-
Russia	6	-	-	10	-	-	22	-	-
Ukraine	5	-	9	9	-	17	20	-	30
Spain	6	15	12	9	26	15	22	43	29
Canada	5	-	-	9	-	-	22	-	-
Mexico	34	-	-	55	-	-	69	-	-
USA	2	-	2	8	-	17	21	-	31
Argentina	5	-	9	11	-	21	21	-	30
Brazil	4	7	6	7	11	11	16	22	17
Bangladesh	3	4	2	7	5	4	14	15	10
China	8	19	14	8	20	15	17	32	24
India	9	8	29	11	12	42	24	19	67
Indonesia	-	1	0	-	4	1	-	9	2
Iran	32	-	-	56	-	-	73	-	-
Japan	7	11	7	9	18	11	15	30	19
Kazakhstan	8	-	-	14	-	-	27	-	-
Korea	7	10	8	8	14	15	19	21	29
Laos	-	5	3	-	7	4	-	14	8
Pakistan	7	-	10	12	-	16	23	-	29
Philippines	-	2	1	-	5	1	-	9	4
Thailand	3	4	2	7	6	2	12	11	5
Turkey	6	-	11	9	-	20	21	-	27
Vietnam	-	4	3	-	6	4	-	11	9
Algeria	22	-	-	30	-	-	41	-	-
Angola	-	-	49	-	-	61	-	-	72
Ethiopia	6	-	9	10	-	13	21	-	25
Ghana	-	7	3	-	8	4	-	16	6
Guinea	-	2	1	-	5	1	-	11	3
Kenya	3	4	2	4	5	3	12	10	4
Mali	-	12	5	-	14	6	-	19	8
Nigeria	3	3	2	6	5	2	20	13	3
Senegal	5	-	8	10	-	10	16	-	13
S.Africa	3	-1	2	8	18	22	14	22	36
Sudan	27	-	-	45	-	-	64	-	-
Zaire	-	3	2	-	5	4	-	12	6
Australia	6	-	-	11	-	-	26	-	-
N.Zealand	7	-	-	14	-	-	28	-	-

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Professor Mikhail I. Budyko

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