THE INFLUENCE OF MAN ON THE CLIMATE

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Abstract

In the author's previous works (Climate and Life, 1971, Leningrad, Gidrometeoizdat, etc.), the results of applying the methods of physical climatology to study climate changes caused by both natural causes and human activity were set forth.

This paper publishes materials from new research on this issue, during which some information was obtained about possible future climatic conditions.

Since the mechanism of modern climate change is in many ways analogous to the mechanism of climatic changes that occurred in the past, in order to clarify the climatic conditions of the future it is necessary to study the causes of climate fluctuations that took place earlier. In accordance with this, after discussing the general patterns of climate genesis, this paper examines issues of its changes during the Quaternary period and over the last century. Analysis of past climate changes made it possible to test a numerical model of the thermal regime of the atmosphere, which was then used to assess future climatic conditions.

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INTRODUCTION

Back in the last century, A.I. Voeikov established that by changing the state of the earth's surface, humans in many cases have a noticeable impact on the climate of the lower air layer (Voeikov, 1894, etc.). Subsequently, climate changes caused by human activities were studied by many researchers who showed that the influence of changes in the state of the earth's surface on the climate is mainly local in nature and does not extend to the planet as a whole.

And in recent years the view has been expressed that the process of climate change under the influence of human economic activity has now accelerated, that its further development under certain conditions can lead to abrupt climate changes over large areas, and that in the not too distant future it will become possible to regulate the climate across the entire planet (Budyko, 1962).

In 1970-1971, several scientific meetings were held to discuss the impact of human activities on the climate[1]. These meetings confirmed that climate specialists face the responsible task of assessing how the climate can change over vast territories under the influence of human activities.

Let us look at the extent to which modern climate science is prepared to solve this problem.

It is obvious that traditional climatology methods that aim to describe the meteorological regime based on observations from a network of stations are insufficient to elucidate the impact of human activities on the climate. These methods can be used to assess local climate changes that result from economic activities already implemented. But even in this case, to understand the mechanism of ongoing climate changes, it is necessary to use physical research methods.

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[1] Two meetings on this issue were held abroad (July 1970, Williamstown; July 1971, Stockholm). The first was attended by US scientists, the second by meteorologists and climatologists from 14 countries. Based on the materials of these meetings, monographs (Man's Impact on the Global Environment, 1970; Inadvertent Climate Modification, 1971) were prepared on this issue. Great attention was paid to the issue of human impact on climate at the International Symposium on Physical and Dynamic Climatology in Leningrad (August 1971).

Physical methods become even more important in studying global climate changes that may occur in the future and whose trends either do not manifest at all in modern meteorological observations or manifest in a relatively weak form.

It seems that assessing the upcoming climate changes across vast territories is only possible using methods based on accounting for the physical patterns of large-scale processes in the atmosphere, hydrosphere and on the earth's surface.

Although the foundations of physical climatology were laid back in the 19th century in the works of A.I. Voeikov and some of his contemporaries, the development of this branch of climatology accelerated mainly over the past few decades, when theoretical methods began to be widely used to study the patterns of meteorological regimes.

The main objective of physical climatology is to develop a theory of climate that aims to elucidate the patterns of meteorological regimes by the method of physical deduction, i.e. based on general physical laws. According to a recently published review (Inadvertent Climate Modification, 1971), existing climate theories can be divided into four groups.

1. Theories relating to the planet as a whole, i.e. not considering changes in the meteorological regime by latitude and longitude.
2. Semi-empirical theories that include, along with exact physical relationships, some empirical dependencies.
3. Dynamical-statistical theories in which methods of physical analysis are applied to numerically simulate the average fields of meteorological elements.
4. Numerical models that allow, along with the average fields of meteorological elements, the study of their variability over periods of time on the order of several days.

Different climate theories differ from each other in the degree of completeness in accounting for factors influencing the climate. In a number of models, for simplification of the problems being solved, individual climate-forming processes are not taken into account. In other cases, the values of some meteorological elements that can be found in the general theory of climate are set according to observational data.

Without exception, all modern climate theories use, along with the theoretical methods of physical meteorology, empirical data obtained from observations. The values of these materials vary significantly for different theories. The authors of more general numerical models tend to limit themselves to using empirical values for such parameters that can be considered constant for certain intervals of conditions, such as albedo, radiation ability of various surfaces, and others. In addition to these parameters, semi-empirical models include relationships between individual climate elements that are justified by observational data.

Of great importance for semi-empirical climate theories are the materials obtained from studies of the heat and water balances of the earth's surface and atmosphere. To study the processes of heat exchange and water circulation, these works used materials from actinometric, aerological and hydrological observations, data from observations at the network of surface meteorological stations, and results of various expeditionary studies.

In works of recent decades, extensive materials were obtained on the components of the heat and water balances, including two world atlases of the heat balance (Heat Balance Atlas, 1955; Atlas of the Heat Balance of the Globe, 1963). It should be noted that along with semi-empirical models, materials on heat and water balances are widely used in many modern studies in the general theory of climate. These materials are used in a number of works on climate theory to substantiate the simplifications adopted, formulate the boundary conditions of the problems being solved, and verify the results obtained.

The progress achieved in recent years in work on climate theory opens up opportunities for explaining the patterns of climate formation, including the patterns of climate change under both natural causes and human activities.

The first steps in applying the methods of physical climatology to study climate change were taken by Milankovic (Milankovic, 1930, etc.) and Humphreys (Humphreys, 1940, etc.). In their work, they used numerical models to study climate change, which resulted in conclusions that have partially retained their significance to the present.

Subsequently, significant contributions to this area of research were made by Bernard (Bernard, 1963); Flohn (Flohn, 1964, etc.), Lamb (Lamb, 1970, etc.), Manabe (Manabe, 1970, etc.), Mitchell (Mitchell, 1965, etc.) and others.

When studying the physical mechanism of climate change, it is necessary to identify the main factors that determine the genesis of the Earth's climates. As is known, the climatic conditions on our planet depend on the solar radiation coming to the outer boundary of the atmosphere, the structure of the earth's surface, the physical and chemical properties of atmospheric air and waters of the hydrosphere.

From a general point of view, the parameters characterizing the physical state of ocean waters and the continental ice sheet are not external to the climate factors. However, these parameters can be associated not only with the climatic conditions of the current era, but also with the meteorological regime of the past due to the great thermal inertia of ocean waters and continental glaciations.

For understanding the patterns of climate formation, an important question is whether the modern climate is the only one possible for our era, or whether there may be other climate variants that differ significantly from the observed one.

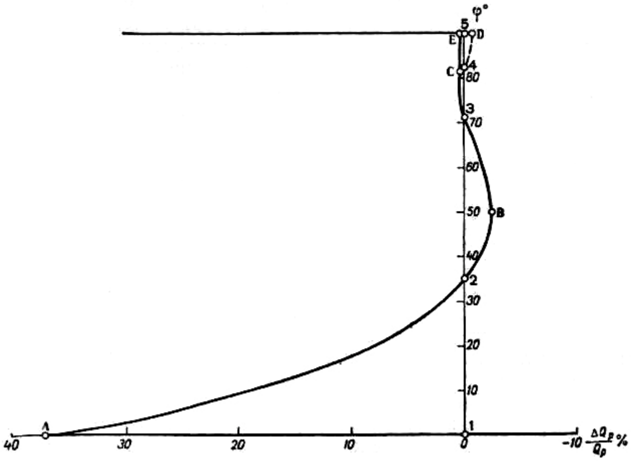

Figure 1: Dependence of the average latitudinal boundary of the ice sheet on the value of solar radiation.

Consideration of this issue shows that under current conditions, several sharply differing climate types can exist.

The diagram illustrating possible climate variants is shown in Fig. 1. The horizontal axis shows changes in the energy influx to the outer boundary of the atmosphere (as a percentage of the solar constant), and the vertical axis shows the average latitude of the polar ice sheet boundary in the Northern Hemisphere.

Point 3 on this graph corresponds to the currently observed climate type with an average ice sheet boundary close to 72° N.

As established in a number of works, with the current value of heat influx to the outer boundary of the atmosphere, the stable existence of a complete glaciation of the planet with very low temperatures at all latitudes ("white Earth") is possible. The stability of such a regime is explained by the very high albedo of the surface covered with snow and ice. As observational data show, for large glaciations the albedo of the earth's surface increases to 0.7–0.9, and the albedo of the Earth-atmosphere system to 0.6–0.8.

It is obvious that when the planetary albedo of the Earth changes from the current value, close to 0.3, to the values given above, the radiation absorbed by the Earth decreases 2–3 times, which sharply reduces the temperature of the earth's surface. In this case, the climatic conditions now characteristic of Antarctica can exist over the entire surface of the Earth.

The conclusion about the possibility of a stable existence of a "white Earth" can probably be obtained from any realistic climate theory that allows calculating the temperature of the earth's surface with an error of no more than a few tens of degrees.

Consequently, for the existing solar radiation influx, the regime of complete glaciation of the Earth, denoted in Fig. 1 by point 1, is possible. Such a regime is also possible with incoming radiation less than the modern value (which is depicted in the figure by a line going to the right of point 1 along the horizontal axis of coordinates), and with an increase in incoming radiation up to a value greater than the modern one, up to the value which corresponds to reaching the melting point of ice in the warmest areas of the earth's surface. After reaching this temperature, part of the earth's surface can be freed from the ice cover, which will lead to a decrease in albedo and an increase in absorbed radiation. The point corresponding to the boundary of the complete glaciation regime with an increase in solar radiation is shown in Fig. 1 by the letter A.

It is natural to assume that between the conditions depicted by points A and 3, there exist regimes of partial glaciation of the Earth, which can be depicted on the graph under consideration as a line connecting these points. The shape of such a line can be determined as follows.

Observational data, as well as general physical considerations, show that under modern climatic conditions, an increase in heat influx to the earth's surface leads to an increase in the average air temperature near the earth's surface and a retreat of polar ice. With a decrease in heat influx, a decrease in the average temperature and an ice advance is observed.

In accordance with this pattern, the line going from point A to point 3 should approach the vertical axis on the right, which is possible if this line intersects the vertical axis at least at one more point (point 2).

Thus, we come to the conclusion that under present conditions, a third climatic regime is possible, which is the second variant of partial glaciation of the Earth, with a larger ice sheet area compared to the climatic regime currently observed.

After intersecting the vertical axis at point 3, the line characterizing the partial glaciation regimes should, at some value of incoming radiation exceeding its modern value, reach the horizontal line corresponding to the ice-free regime (point E).

From point E, the line corresponding to a further increase in radiation becomes a horizontal straight line going to the left.

A number of studies (Budyko, 1961, 1962, etc.; Rakipova, 1962, 1966; Donn and Shaw, 1966, etc.) carried out calculations showing that an ice-free regime is possible in the Arctic with the modern radiation influx. If we accept this conclusion, then in the graph under consideration, this regime should be represented as a point at the end of the vertical axis of the graph (point 5), and in this case, the line characterizing the partial glaciation regimes should reach the horizontal line corresponding to the ice-free regime not to the left of the end of the vertical axis, but to the right. Such a position of the point connecting these lines is explained by the fact that if an ice-free regime is possible with the existing radiation influx, then it is also possible with a very small decrease in radiation.

Thus, in the case under consideration, the line characterizing possible glaciation regimes passes through point 5 as a horizontal straight line, which requires this line to intersect the vertical axis at least at one more point (point 4). Consequently, under the conditions of the possibility of an ice-free Arctic with the modern level of incoming solar radiation, there should be another partial glaciation regime with a smaller ice area compared to modern climatic conditions.

The dependence of the glaciation regime on incoming solar radiation for this case is shown in Fig. 1 by a dotted line.

The above considerations, from which the conclusion follows about the possibility of the existence in the modern era of several climate variants, are not strict and give only a qualitative idea of the factors determining the climatic conditions on our planet.

In order to find the dependence shown in Fig. 1 in quantitative form, a numerical model of the thermal regime of the atmosphere should be used, including accounting for the direct and feedback of the air temperature field and polar glaciations. Such models have so far been developed only within the framework of semi-empirical climate theories, which we now turn to.

1 SEMI-EMPIRICAL THEORY OF THERMAL REGIME

As noted above, the construction of semi-empirical climate theories became possible as a result of research on the heat and water balances of the Earth. In the course of this research, the spatial distributions of the main components of the heat and water balances of the earth's surface and atmosphere were found and the connections between the balance members and various meteorological elements were established.

Let us consider a simple numerical model of the thermal regime of the atmosphere (Budyko, 1968) based on using the heat balance equation for the Earth-atmosphere system in the form:

$$Q(1-\alpha) - I = C, \tag{1}$$

where Q is solar radiation at the outer boundary of the atmosphere; a is the albedo of the Earth-atmosphere system; I is the longwave outgoing radiation at the outer boundary of the atmosphere; C is the total heat influx due to horizontal movements in the atmosphere and hydrosphere.

To determine I, the following relationship is used:

$$I = a + bT - (a_1 + b_1 T)n, \tag{2}$$

where T is the temperature at the earth's surface in degrees Celsius; n is cloud cover in fractions of unity; a, b, a_1, b_1 are dimensional coefficients.

The value C for average latitudinal conditions is determined by the empirical formula

$$C = \beta(T - T_p), \tag{3}$$

where T_p is the average planetary surface temperature; β is a dimensional coefficient.

Formulas (2) and (3) were obtained by generalizing a large empirical material. The first of them was obtained from the data of calculations of average monthly values of radiation at the outer boundary of the atmosphere, performed during the preparation of the Atlas of the Heat Balance of the Globe (1963). These data related to each month of the year for 260 points uniformly located on the surface of the globe.

Thus, formula (2) is constructed from data characterizing all the variety of climatic conditions on our planet. The root mean square deviation of the calculation results using this formula from the source data is less than 5% of the outgoing radiation value.

It should be noted that formula (2) for cloudless conditions coincides with a similar relationship theoretically found by Manabe and Wetherald (Manabe and Wetherald, 1967).

Formula (3) was obtained by comparing the values of meridional heat redistribution in the atmosphere and hydrosphere, found from heat balance data, with deviations of average latitudinal air temperatures at the earth's surface from their average global value. These values turned out to be closely related (correlation coefficient 0.99). It is noteworthy that, as the analysis showed, such a relationship exists not only for average annual conditions, but also for the conditions of individual months or seasons.

Given that for the planet as a whole $C = 0$, we find from formulas (1)–(3)

$$T_p = \frac{1}{b - b_{1n}} \big[Q_p(1-\alpha_p) - a + a_1 n\big] \tag{4}$$

(where Q_p and α_p relate to the planet as a whole) and

$$T = \frac{1}{\beta + b - b_{1n}} \big[Q(1-\alpha) - a + a_1 n + \beta T_p\big]. \tag{5}$$

Using formulas (4) and (5), the distribution of average latitudinal air temperatures at the earth's surface can be calculated both for the modern value of the solar constant and for its modified values.

Such a calculation for modern conditions was performed in two versions. In one case, the albedo values of latitudinal zones were set according to satellite observation data, in the other, only two average albedo values were used, corresponding to the ice-free regime and the presence of an ice sheet. In both cases, the calculation results turned out to be close to the observational data (Budyko, 1971).

Since the position of polar ice changes when the thermal regime changes, to take into account their influence on air temperature, it can be assumed that the ice boundary corresponds to a certain temperature at the earth's surface. Taking into account empirical data on the position of the snow line in the mountains at different latitudes, it can be found that such an average annual temperature in extratropical latitudes is approximately equal to −9°, and in the tropics it gradually increases, reaching −1° at the equator.

In the zone where the temperature is below this value, the albedo of the Earth-atmosphere system should correspond to the value characteristic of the area with permanent snow cover. In a number of calculations performed according to observational data, this value was taken to be 0.62.

Using formulas (4) and (5) and taking into account the dependence of albedo changes on latitude for ice-free areas according to satellite observation data, the position of the average glaciation boundary can be calculated by the method of successive approximations for various values of $\frac{\Delta Q_p}{Q_p}$ (ΔQp is the difference between the value of the changing solar constant and its modern value), expressed as percentages.

The result of the corresponding calculation for the Northern Hemisphere is shown in Fig. 1 as a bold line, which intersects the vertical axis at points 1, 2 and 3. As can be seen, the shape of this line corresponds well with the general considerations stated above.

Note that in calculating the position of the polar glaciation boundary, we neglected the interaction between the thermal conditions of the Northern and Southern hemispheres. For average annual conditions, this assumption means the assumption of a similar change in the boundaries of glaciation in both hemispheres.

The calculations showed that if, when applying the thermal regime model outlined above, heat exchange between the Northern and Southern Hemispheres is taken into account and it is assumed that when the ice boundary changes in the Northern Hemisphere, this boundary remains constant in the Southern Hemisphere, the position of the line in Fig. 1 will change slightly, but all its main features will remain.

In earlier works (Budyko, 1968, etc.), the part of the dependence between the influx of solar energy and the ice sheet boundary corresponding to the case of a decrease in solar radiation influx with the displacement of the ice boundary to the equator from its modern position to the critical latitude, after which the spread of the ice sheet to the equator becomes possible, was calculated and presented graphically.

The corresponding part of the line (segment $3B$) in the previously constructed graph (Budyko, 1968) differs slightly from the same segment in Fig. 1, since in the previous calculation, changes in the average albedo values with latitude in the zone free of ice sheet were not taken into account. Taking these changes into account, which are mainly associated with latitudinal cloudiness changes, slightly alters the shape of the dependence under consideration.

This conclusion once again confirms the earlier conclusion that in many cases, cloudiness changes have little effect on the thermal regime at the earth's surface, since an increase in albedo with increasing cloudiness is compensated by a decrease in outgoing longwave radiation (Budyko, 1971).

When considering the dependence shown in Fig. 1, it should be borne in mind that it refers to a stationary state, i.e. a state in which there is correspondence between the position of the ice sheet in both hemispheres and the thermal regime of the atmosphere and hydrosphere. For non-stationary conditions, when there is no such correspondence, the line depicting glaciation regimes in this figure will be replaced by a family of lines that depend not only on current climatic conditions, but also on the meteorological regime of the past.

The dependence shown in Fig. 1 is of great importance for understanding the patterns of climatic conditions that should be taken into account when studying climate changes due to both natural causes and human activities. Analyzing the curve shown in this figure, one can conclude that not all climatic regimes corresponding to this curve are stable.

Obviously, the regimes of complete glaciation of the planet and the complete absence of ice, depicted in Fig. 1 by horizontal lines, are stable.

The question of the stability of the partial glaciation regimes depicted by the line AE is more complex.

It can be assumed that only those regimes are stable, for which the shape of the dependence shown in Fig. 1 corresponds to the condition: a small increase in radiation influx decreases the area of glaciation, and a small decrease in radiation influx increases this area. In the case when the extent of glaciation changes regardless of incoming radiation, the regime cannot be considered stable. If, however, the relationship between these values for a section of the AE curve is inverse, it should be considered that a small increase in radiation will lead to a transition from this state to a regime with significantly less glaciation (or its absence), characterized by another part of the line of possible regimes. A small decrease in radiation in this case will also lead to a transition from a given regime to a significantly different regime, with greater glaciation.

Thus, partial glaciation regimes with a latitude less than the critical one (denoted by point B) are unstable.

The question of the stability of regimes with a small area of glaciation, where the corresponding part of the AE curve approaches a vertical straight line, is not entirely clear. Perhaps the accuracy of calculations using the model utilized is insufficient to elucidate this issue for these conditions.

If we accept the hypothesis about the possibility of an ice-free regime in the Arctic with the modern heat influx, then the partial glaciation conditions corresponding to the CD curve segment will be unstable, while the DE line will characterize stable states (it should be borne in mind that the dotted CE line does not follow from the model used and is constructed based on qualitative considerations).

Note that the dependence shown in Fig. 1 shows that a radical climate change does not require (as was often thought before) changes in the energy influx to the earth's surface comparable in magnitude to the solar constant. A decrease in energy influx by about 2% from the current value can cause complete glaciation of the Earth, an increase in this influx by a few tenths of a percent will lead to melting of polar ice, i.e. also to a significant change in climate at high and temperate latitudes.

Thus, the modern climate turns out to be highly sensitive to small changes in climate-forming factors.

To study the thermal regime of the atmosphere in different seasons, the model outlined above should be modified by taking into account several additional factors.

Such a more general model was proposed in the work (Budyko, Vashishcheva, 1971), in which the heat balance equation for the Earth-atmosphere system was used in the form:

$$Q_h(1-\alpha_h) = C_h + B, \tag{6}$$

$$Q_c(1-\alpha_c) = C_c - B, \tag{7}$$

where B is the heat influx or outflow due to cooling or heating of the Earth-atmosphere system, which is determined mainly by the process of ocean cooling or heating. Here and below, the values relating to the warm and cold half-years are denoted by the indices h and c, respectively.

To determine the I and C members, we use formulas (2) and (3). We will find the value B using the relationship:

$$B = s\gamma(T_{wh} - T_{wc}), \tag{8}$$

where T_w is the average latitudinal temperature of the ocean surface for cold and warm half-years; s is the ratio of the area of the oceans in a given latitudinal zone to the total area of the latitudinal zone; γ is a dimensional coefficient.

To calculate the ocean surface temperature, we use the heat balance equation for the ocean surface in the form:

$$R_{wh} = LE_h + P_h + \frac{B}{s}, \tag{9}$$

$$R_{wc} = LE_c + P_c + \frac{B}{s} + B_1, \tag{10}$$

where R_w is the radiation balance of the ocean surface; LE is the heat expenditure for evaporation; P is the turbulent heat flux between the ocean surface and the atmosphere; B_1 is the heat transfer by ocean currents.

To determine the values of LE, P and B_1, we apply the approximate relationships:

$$LE = fT_w, \tag{11}$$

$$P = c(T_w - T), \tag{12}$$

$$B_1 = \beta'(T_c - T_p), \tag{13}$$

where T_w is the ocean surface water temperature in degrees Celsius.

The approximate formulas (8), (11) and (12) were obtained by simplifying the equations describing the processes of heat exchange in the upper ocean layers and at its surface. Formula (13) was found by a method similar to that used in obtaining formula (3).

When deriving equality (11), the following schematization was used. The known formula for evaporation from the ocean surface

$$E = A(V)(q_w - q)$$

(q_w is the humidity at the ocean-atmosphere interface, equal to its saturation value at the ocean surface temperature, q is the air humidity, $A(V)$ is the wind speed dependent coefficient characterizing water vapor diffusion in the air layer near the water) for approximate calculations was slightly simplified. If we neglect the dependence of the A coefficient on wind speed V and the deviations of q/q_w from the average value, then, using the relationship between the saturation humidity value and temperature, the approximate relationship (11) can be obtained.

The schematization of the listed formulas is justified by the fact that the calculation uses only the average latitudinal and seasonal average values of the corresponding members of the heat balance, as well as by the fact that the results of calculating the temperature distribution depend relatively little on errors in determining these heat balance components.

This makes it possible, when determining, for example, the heat expenditure for evaporation from the ocean surface, to neglect the influence on evaporation of changes in air relative humidity over the oceans and changes in wind speed in different latitudinal zones. Such neglect simplifies the method of calculating air temperature and has relatively little effect on the accuracy of the results obtained.

The numerical coefficients in the formulas given above, when determining the values of heat fluxes in kcal/(month·cm^2), have the following values: $\alpha = 14.0$; $b = 0.14$; $a_1 = 3.0$; $b_1 = 0.10$; $\gamma = 3.0$; $f = 0.4$; $\beta_h = 0.22$; $\beta_c = 0.27$ for the Northern Hemisphere south of the average boundary of the Arctic ices, $\beta_c = 0.40$ for the Southern Hemisphere north of the average boundary of the Antarctic ices, $\beta_c = 0.22$ for zones with an ice sheet, $\beta' = 0.14$ for the Northern Hemisphere and 0.20 for the Southern Hemisphere; $c = 0.84$.

From the given relationships, the following formulas can be obtained for determining the average latitudinal temperatures for the Northern Hemisphere:

$$
\begin{aligned}
T_h = {} & \frac{Q_h(1-\alpha_h) - a + a_1 n_h + \beta_h T_{p1} - \dfrac{\gamma s}{f+c+2\gamma}(R_{wh} - R_{wc} - \beta' T_{p2})}{b - b_1 n_h + \beta_h + \dfrac{\gamma s c}{f+c+2\gamma} - \dfrac{\gamma s(\beta' - c)(b - b_1 n_h + \beta_h)}{(f+c+2\gamma)(b - b_1 n_c + \beta_c)}} - \\
& - \frac{\dfrac{\gamma s(\beta' - c)}{f+c+2\gamma}\left[\dfrac{Q_h(1-\alpha_h) + Q_c(1-\alpha_c) - 2a + a_1 n_h + a_1 n_c + \beta_h T_{p1} + \beta_c T_{p2}}{b - b_1 n_c + \beta_c}\right]}{b - b_1 n_h + \beta_h + \dfrac{\gamma s c}{f+c+2\gamma} - \dfrac{\gamma s(\beta' - c)(b - b_1 n_h + \beta_h)}{(f+c+2\gamma)(b - b_1 n_c + \beta_c)}}
\end{aligned}
\tag{14}
$$

$$
\begin{aligned}
T_c = {} & \frac{Q_c(1-\alpha_c) - a + a_1 n_c + \beta_c T_{p2} + \dfrac{\gamma s}{f+c+2\gamma}(R_{wh} - R_{wc} - \beta' T_{p2})}{b - b_1 n_c + \beta_c + \dfrac{\gamma s(c - \beta')}{f+c+2\gamma} - \dfrac{\gamma s c(b - b_1 n_c + \beta_c)}{(f+c+2\gamma)(b - b_1 n_h + \beta_h)}} - \\
& - \frac{\dfrac{\gamma s c}{f+c+2\gamma}\left[\dfrac{Q_h(1-\alpha_h) + Q_c(1-\alpha_c) - 2a + a_1 n_h + a_1 n_c + \beta_h T_{p1} + \beta_c T_{p2}}{b - b_1 n_h + \beta_h}\right]}{b - b_1 n_c + \beta_c + \dfrac{\gamma s(c - \beta')}{f+c+2\gamma} + \dfrac{\gamma s c(b - b_1 n_c + \beta_c)}{(f+c+2\gamma)(b - b_1 n_h + \beta_h)}}
\end{aligned}
\tag{15}
$$

In these and subsequent formulas, the index “p” for the values T, Q, n, α, R, s means that the values refer to the planet as a whole, the index “1” refers to the warm half-year of the Northern Hemisphere and the cold half-year of the Southern Hemisphere, the index “2” refers to the cold half-year of the Northern Hemisphere and the warm half-year of the Southern Hemisphere.

Formulas (14) and (15) can also be used to calculate average latitudinal temperatures in the Southern Hemisphere, considering in this case that T_{p1} refers to the cold half-year of the Southern Hemisphere, and T_{p2} refers to the warm half-year of the same hemisphere.

For the zone with an ice sheet, formulas (14) and (15) are somewhat simplified. Taking into account that in this zone the annual variation of heat content in the Earth-atmosphere system is insignificant and the meridional heat transfer by currents is small or equal to zero, we find that for this zone we can use the formulas

$$T_h = \frac{Q_h(1 - \alpha_h - a + a_1 n_h + \beta_h T_{p1} - lh}{b - b_1 n_h + \beta_h} \tag{16}$$

$$T_c = \frac{Q_c(1 - \alpha_c - a + a_1 n_c + \beta_c T_{p2} + lh}{b - b_1 n_c + \beta_c} \tag{17}$$

where lh is the heat influx (or outflow) as a result of cooling (or heating) of the ice sheet and freezing (or melting) of ice.

Since the lh value is relatively small, we will limit ourselves to taking into account its average value for all latitudinal zones, equal to 0.8 kcal/(month·cm^2).

To determine the average planetary temperatures, we use formulas that can be obtained from (14) and (15) by taking into account that for the planet as a whole, the meridional heat exchange is equal to zero:

$$\begin{aligned} T_{p1} = {} & \frac{Q_{p1}(1 - \alpha_{p1}) - a + a_1 n_{p1} - \dfrac{\gamma s_p}{f + c + 2\gamma}(R_{wp1} - R_{wp2})}{b - b_1 n_{p1} + \dfrac{\gamma s_p c}{f + c + 2\gamma} + \dfrac{\gamma s_p c(b - b_1 n_{p1})}{(f + c + 2\gamma)(b - b_1 n_{p2})}} + \\ & + \frac{\dfrac{\gamma s_p c}{f + c + 2\gamma}\left[\dfrac{Q_{p1}(1 - \alpha_{p1}) + Q_{p2}(1 - \alpha_{p2}) - 2a + a_1 n_{p1} + a_2 n_{p2}}{b - b_1 n_{p2}}\right]}{b - b_1 n_{p1} + \dfrac{\gamma s_p c}{f + c + 2\gamma} + \dfrac{\gamma s_p c(b - b_1 n_{p1})}{(f + c + 2\gamma)(b - b_1 n_{p2})}} + \end{aligned} \tag{18}$$

$$\begin{aligned} T_{p2} = {} & \frac{Q_{p2}(1 - \alpha_{p2}) - a + a_1 n_{p2} - \dfrac{\gamma s_p}{f + c + 2\gamma}(R_{wp1} - R_{wp2})}{b - b_1 n_{p2} + \dfrac{\gamma s_p c}{f + c + 2\gamma} + \dfrac{\gamma s_p c(b - b_1 n_{p2})}{(f + c + 2\gamma)(b - b_1 n_{p1})}} + \\ & + \frac{\dfrac{\gamma s_p c}{f + c + 2\gamma}\left[\dfrac{Q_{p1}(1 - \alpha_{p1}) + Q_{p2}(1 - \alpha_{p2}) - 2a + a_1 n_{p1} + a_2 n_{p2}}{b - b_1 n_{p2}}\right]}{b - b_1 n_{p2} + \dfrac{\gamma s_p c}{f + c + 2\gamma} + \dfrac{\gamma s_p c(b - b_1 n_{p2})}{(f + c + 2\gamma)(b - b_1 n_{p1})}} + \end{aligned} \tag{19}$$

By applying formulas (14)–(17), the distribution of average latitudinal temperatures for each half-year can be calculated.

In such a calculation, it was assumed that the polar ice boundary corresponds to an average latitudinal temperature of the warm half-year equal to $-1°$. For the polar ice zone, the albedo of the Earth-atmosphere system was taken to be 0.62 for the Northern Hemisphere and 0.72 for the Southern Hemisphere. The albedo of latitudinal zones where permanent snow and ice covers are absent was determined from the data in Table 1. The albedo values given in the table were obtained from satellite observation data (Raschke, Moller, Bandeen, 1968, etc.).

When determining the amount of radiation coming to the outer boundary of the atmosphere, the radiation flux incident on a surface element perpendicular to the solar ray was taken to be 1.92 cal/(cm^2·min) (the "meteorological solar constant"). The average latitudinal values of the radiation balance of the ocean surface were taken from the Atlas of the Heat Balance of the Globe (1963).

The results of the calculation are shown in Fig. 2. For comparison, this figure shows the distribution of average latitudinal temperatures obtained from observational data. As can be seen, the discrepancy between the measured and calculated temperatures at different latitudes in most cases does not exceed $1 - 2°$ C.

The model of the distribution of average latitudinal temperature for different seasons outlined here, just like the model for average annual conditions, can be used to study the genesis of climate. The dependence calculated using this model between the average latitude of polar glaciation and incoming radiation turned

Table 1: **Albedo of Latitudinal Zones**

Half-year	Northern Latitude, deg.						
	65	55	45	35	25	15	5
First	0.49	0.40	0.35	0.29	0.27	0.27	0.29
Second	0.54	0.48	0.45	0.40	0.30	0.25	0.26

Half-year	Southern Latitude, deg.					
	5	15	25	35	45	55
First	0.25	0.25	0.29	0.40	0.46	0.53
Second	0.27	0.26	0.28	0.32	0.41	0.49

out to be similar to the dependence obtained by applying the model for average annual conditions, which is shown in Fig. 1.

The application of this model, just like the model for average annual conditions, leads to the conclusion that a very small increase in radiation, not exceeding a few tenths of a percent, is sufficient to destroy the polar ice. Since these models refer to stationary conditions, it should be assumed that such an increase in radiation must be very longon the order of hundreds or thousands of years.

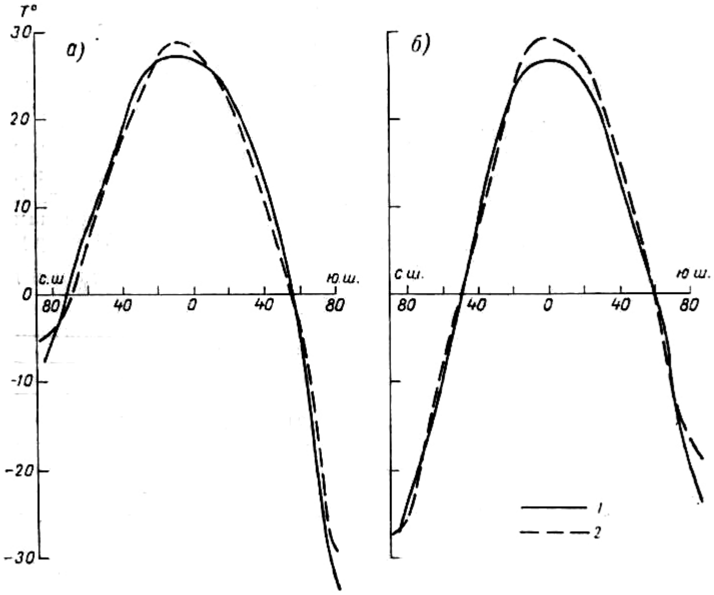

Figure 2: Distribution of average latitudinal air temperatures.
a - first half-year, b - second half-year;
1 - observational data, 2 - calculation results.

It should be noted that the accuracy of calculations using these models (especially the model for different seasons) for small areas of polar ice, when their position depends on very small variations in climate-forming factors, is apparently insufficient. In this regard, it is difficult to obtain an unambiguous conclusion about the possibility of an ice-free regime in the Arctic in the modern era from such calculations (a more detailed discussion of the ice-free Arctic regime is given in other works of the author - Budyko, 1971, etc.).

2 CLIMATE CHANGE IN THE QUATERNARY PERIOD

Since all existing numerical climate models are approximate in nature, before using them to calculate the impact of human activities on the climate, it is advisable to test these models against empirical data.

Of great importance for testing these models are the materials on natural climate changes that occurred both in the geological past and in the modern era. It should be assumed that a model that can quantitatively explain natural climate changes will provide reliable results when assessing the impact of economic activities on climatic conditions.

As is known, a characteristic feature of the last (Quaternary) geological period was a large variability of climatic conditions at temperate and high latitudes. Paleogeographic data show that the air temperature in these latitudes at times decreased significantly, which was accompanied by the development of ice sheets that occupied large spaces on land and oceans. During periods of warming, the ice sheets retreated to high latitudes and may have completely disappeared.

The question of the causes of Quaternary glaciations has been discussed in numerous studies, which have proposed various hypotheses to explain this phenomenon.

The difficulty in elucidating the causes of glaciation development was that there were apparently no major changes in external climate-forming factors during the Quaternary period. The assumptions of some authors that the solar constant or other factors significantly affecting the climate changed significantly during this time are not sufficiently substantiated. The influence on climate change in the Quaternary of only two factors can be considered beyond doubt.

The first is the change in the amount of radiation received by different latitudinal zones of the Earth in different seasons, due to changes in the position of the earth's surface relative to the Sun, which depends on the eccentricity of the Earth's orbit, the inclination of the Earth's axis of rotation to the orbital plane, the time of the equinoxes. All these astronomical elements periodically change, which leads to some change in the amount of radiation received at different latitudes in different seasons. These changes can be calculated with fairly high accuracy for the last tens of thousands of years and with less accuracy for more distant time intervals.

The second factor is fluctuations in the transparency of the atmosphere due to changes in the amount of dust in it, caused mainly by volcanic activity. Such fluctuations slightly change the amount of radiation reaching the earth's surface. Based on modern actinometric observations, the order of their magnitude can be estimated; some idea of changes in atmospheric transparency in the past can be obtained from geological data on volcanic activity in different eras.

It should be noted that until recently, the question of the influence of these two factors on the glaciation regime remained unclear. Taking into account that these factors can change the Earth's radiation regime only to a limited extent, many authors expressed doubts about the possibility of their influence on the development of glaciations.

To clarify this issue, it is necessary to use a numerical model that allows calculating the position of ice sheets depending on external climate-forming conditions.

Let us first consider the question of the influence of changes in astronomical factors on the climate.

The assumption that such changes could lead to the development of glaciations was made in the first half of the last century by Adhemar. Subsequently, this issue was studied in a number of studies, of which the works of Milankovic (Milankovic, 1930, etc.) deserve special attention. Milankovic noted the good agreement between the times of glaciation development and the periods of decrease in radiation in the warm season in the temperate and high latitudes.

The numerical model of the thermal regime of the atmosphere proposed by Milankovic made it possible to estimate temperature changes at different latitudes under changes in radiation. However, this model did not take into account the influence on the temperature distribution of many processes, including circulation in the atmosphere and hydrosphere, in connection with which the temperature changes found by Milankovic were not sufficiently reliable. For this reason, until recently, a number of researchers denied the possibility of the influence of astronomical factors on the Quaternary glaciations.

In the author's work (Budyko, 1968), to clarify this issue, the above numerical model of the thermal regime for average annual conditions was used. The application of this model showed that the change in the radiation regime during the last Würm glaciation could lead to the displacement of the ice sheet in the Northern Hemisphere to the south by about 1° latitude, which is much less than the displacement of ice that actually took place. Discussing this result, we noted that determining average annual temperatures is not enough to assess the impact of changes in orbital elements on glaciations, since the glaciation regime is mainly influenced by the thermal conditions of the warm season.

In a subsequent study (Budyko, Vashishcheva, 1971), a model describing the distribution of average latitudinal temperature for different seasons, outlined in the previous section, was used to study the climatic conditions of glacial epochs.

It should be noted that, as can be seen from the structure of the corresponding equations, the accuracy of temperature change calculations using this model, as well as using the model for average annual conditions, is significantly higher than the accuracy of calculating average air temperatures. This makes it possible to effectively use this model to study climate change.

When applying this model, a calculation was made based on the method of successive approximations of the position of the average boundary of polar ice for periods of time when, under the influence of astronomical factors, the influx of radiation for the warm half-year significantly decreased at high latitudes. Data on the radiation regime for these periods were taken from the work of Milankovic (Milankovic, 1941).

In the calculation performed, the dependence of the planetary albedo on the polar ice boundary was taken into account:

$$\Delta\alpha_p = \frac{Q_{\mathrm{LN}}\Delta L_{\mathrm{LN}}}{Q_p L_0}(\alpha_{p\mathrm{N}} - \alpha_{\mathrm{LN}}) + \frac{Q_{\mathrm{LS}}\Delta L_{\mathrm{LS}}}{Q_p L_0}(\alpha_{p\mathrm{S}} - \alpha_{\mathrm{LS}}), \tag{20}$$

where α_p is the change in the planetary albedo compared to its modern value; ΔL_{L} is the change in the area of the latitudinal zone occupied by ice in one hemisphere compared to the modern regime; L_0 is the area of the globe; α_{P} is the albedo of the zone occupied by polar ice; α_{L} is the albedo of the zone to which glaciation extends as a result of radiation changes in the absence of ice there; Q_{L} is radiation in the zone to which glaciation extends and the area of which is equal to L_{L}; Q_p is the average planetary radiation value. The indices N and S refer to values relating to the Northern and Southern hemispheres.

In this calculation, the influence of changes in the radiation balance of the ocean surface and changes in cloudiness compared to the existing regime was neglected.

Some results of the calculations are given in Table 2.

Table 2: Note. $\Delta\phi^{\circ}_{\mathrm{S}}$ is the decrease in the average latitude of the polar ice boundary in the Northern hemisphere compared to its modern position, $\delta\phi^{\circ}_{\mathrm{U}}$ is the decrease in the average latitude of the polar ice boundary in the Southern hemisphere compared to its modern position, ΔT is the change in the average temperature of the warm half-year at 65° N. Lat.

Climate changes in glacial epochs

Time, thousand years before 1800 AD	$\Delta\phi^{\circ}_{\mathrm{N}}$	$\Delta\phi^{\circ}_{\mathrm{S}}$	ΔT°
22.1 (Würm III)	8	5	-5.2
71.9 (Würm II)	10	3	-5.9
116.1 (Würm I)	11	2	-6.5
187.5 Riss II	11	0	-6.4
232.4 (Riss I)	12	-4	-7.1

As follows from the data in this table, fluctuations in the radiation regime caused by changes in the position of the earth's surface relative to the Sun can lead to significant climate changes. The calculations show that while the average planetary temperature fluctuates relatively little, decreasing by no more than 1°C compared to the modern temperature, such a small change is accompanied by a noticeable displacement of the boundaries of ice sheets.

The calculations show that with the modern position of the average latitudinal boundary of ice in the Northern Hemisphere, close to 72° N, and in the Southern Hemisphere to 63° S, the maximum displacement of the ice boundary in the Northern Hemisphere over the period under consideration is 12°, and in the Southern Hemisphere 5°.

In the zone where the ice sheet penetrates, there is a significant decrease in temperature. Thus, at 65° N latitude, with the advance of ice, the average temperature of the warm half-year decreases by 5–7°C. It should be noted that this value characterizes the decrease in temperature at sea level. Obviously, in the presence of continental glaciations of considerable thickness, the decrease in temperature at the ice surface will be greater than the specified value.

It is of interest to compare the results included in Table 2 with paleogeographic data on the natural conditions of glacial epochs. Such a comparison involves a number of difficulties. Some of them are a consequence of the schematic nature of the calculation performed, while others depend on the incompleteness of the available empirical data on the natural conditions of the past.

Of the various assumptions adopted in the specified calculation, we note the assumption that the position of ice and the thermal regime are stationary for those moments in time to which the calculations refer. It is easy to understand that in reality the development of ice sheets occurred rather slowly and apparently lagged behind the moments of maximum weakening of radiation at high latitudes. Neglecting the influence of the non-stationarity of glaciations can lead to some error in calculating the area occupied by the ice sheet.

One of the difficulties in comparing the obtained results with empirical data is associated with the lack of accurate dating of Quaternary glaciations. The correspondence indicated in the table of certain moments of change in the radiation regime with the main epochs of the last two glaciations coincides with the point of view adopted by Milankovic, which is not shared by all researchers of the Quaternary glaciations.

Another difficulty with such a comparison is the lack of sufficiently accurate data on the average latitudinal boundaries of ice sheets for the epochs of different glaciations. Therefore, only a schematic comparison of the main results of the calculation obtained with empirical data on the natural conditions of glacial epochs can be made. Of the greatest interest in such a comparison is the comparison of the calculated ice sheet boundaries with data on these boundaries during glaciations.

It can be noted that the largest value obtained in the calculation of the average latitude reached by the ice sheet in the Northern Hemisphere is consistent with empirical data. Thus, for example, in Lamb's work (Lamb, 1964) it is noted that at the greatest glaciation the average ice boundary in the Northern Hemisphere reached 57° N, which corresponds to a displacement of this boundary by 15° compared to modern conditions. The similar value found in our calculation is 12°, which is quite close to the value given by Lamb.

It is difficult to make such a comparison for each glacial epoch due to the lack of data on the average latitudinal boundaries of ice sheets. However, the available materials on the boundaries of ice sheets in individual regions of the globe can be used for this purpose. For example, Zeuner's monograph (Zeuner, 1959) provides data on the distances to which glaciers spread in different eras in Central and Northern Europe. These distances, expressed by Zeuner as percentages of the distance to which the ice spread during the Mindel II epoch, are compared in Fig. 3 with the calculated changes in the latitude of the northern polar ice boundary for the Riss I, Riss II, Würm I, Würm II and Würm III epochs. Since Zeuner gives a certain range of values for the boundaries of ice spread for each of these epochs, the results of comparing these values are depicted in the graph by line segments. As can be seen from the data in Fig. 3, there is a definite relationship between the values under consideration, which indicates the possibility of correctly estimating the comparative characteristics of different glaciations by calculation.

The conclusion that changes in astronomical factors could cause the development of Quaternary glaciations does not exclude the possibility of the influence on glaciations of fluctuations in volcanic activity. According to modern observational data, fluctuations in atmospheric transparency due to changes in the amount of volcanic dust in it change the average values of total radiation by values on the order of a few tenths of a percent (Budyko, 1969). Calculations using the scheme described above show that if such radiation changes lasted for thousands of years, they were sufficient to move the boundaries of the ice sheet by hundreds of kilometers. Although geological studies have shown that volcanic activity in the past fluctuated widely, it is currently difficult to quantify the long-period changes in the volcanic dust content in the atmosphere associated with these fluctuations. This limits the possibilities for a more detailed study of the impact of volcanism on Quaternary glaciations.

It should be noted that the above agreement between the results of calculating the position of polar ice and paleogeographic data could only be achieved by taking into account the feedback between the position of polar ice and the thermal regime of the atmosphere.

An interesting example of the results of studying the causes of polar glaciations, when the indicated feedback was not taken into account, is contained in the work of Saltzman and Vernekar (Saltzman, Vernekar,

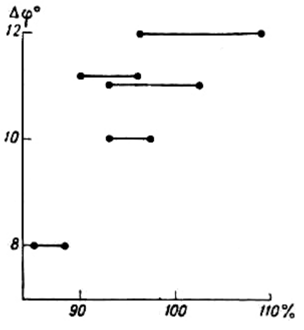

Figure 3: Glacier boundaries in glacial epochs.

1971). It used a numerical model of the average latitudinal distribution of temperature, wind, evaporation and precipitation based on integrating the equations of atmospheric dynamics. Using this model, changes in the distribution of surface temperature in the Northern Hemisphere that took place 10 and 25 thousand years ago compared to modern conditions were calculated. In the calculation performed, all factors influencing the climate were considered constant, except for radiation at the outer boundary of the atmosphere, the distribution of which under the influence of astronomical factors differed slightly from the modern one.

Saltzman and Vernekar found that for these periods of time, the greatest temperature differences for the warm half-year at individual latitudes did not exceed 1.5°. They suggested that such relatively small temperature changes are insufficient for the development of glaciations.

It can be assumed that by not taking into account the feedback between the ice sheet and the temperature field, Saltzman and Vernekar had to obtain underestimated temperature changes with changes in radiation at the outer boundary of the atmosphere. It seems interesting to compare the results of their calculation with the results of a similar calculation made using the model outlined in our work without taking into account the feedback in it, i.e. assuming that with changes in radiation the albedo of the Earth-atmosphere system remains constant. The results of such a calculation are shown in Fig. 4, which depicts the distribution of differences between the average latitudinal temperature of the warm half-year calculated for modern conditions and the temperature for the periods 10 and 25 thousand years ago.

As can be seen from Fig. 4, the results of calculations using different schemes in the absence of feedback between the ice sheet and the thermal regime are close. The agreement obtained in this case deserves attention, since the Saltzman–Vernekar model is significantly different from the much more schematic model used in our calculation. The agreement of the results of paleoclimatic calculations performed using different climate theory models indicates the reliability achieved by these models and confirms the possibility of significant simplifications in constructing semi-empirical models of the thermal regime.

Calculations using the above semi-empirical model taking into account the feedback between the ice sheet and the thermal regime show that the feedback amplifies the influence of changes in radiation factors on air temperature at high latitudes by several times. This makes it possible to spread glaciations over large spaces.

It should be assumed that a similar conclusion can also be obtained when considering the Saltzman–Vernekar model taking into account this feedback.

3 MODERN CLIMATE CHANGE

Studying climate fluctuations that occurred in the first half of our century is of great importance for understanding the mechanism of climate change. These fluctuations were the only noticeable change in the global climate that occurred after the establishment of a global system of meteorological observations in the second half of the last century.

In numerous studies on this climate change, observational data established that there was a noticeable warming in the first half of the 20th century, which occurred in both the Northern and Southern Hemispheres.

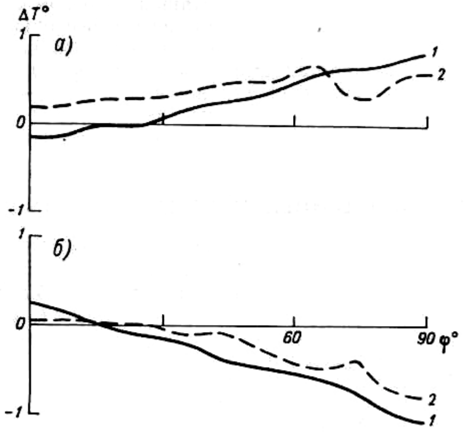

Figure 4: Changes in average latitudinal air temperatures
in the warm half-year under the influence of changes in
incoming radiation caused by astronomical climate factors.
a - 10 thousand years ago; b - 25 thousand years ago;
1 - calculation results using the model outlined in this paper;
2 - calculation results by Saltzman and Vernekar.

The main features of this warming can be seen from the data obtained by L.P. Spirina by averaging maps of air temperature anomalies. These data are shown in Fig. 5 by curves 1. Fig. 5a shows the secular variation of anomalies of the average air temperature at the earth's surface in the Northern Hemisphere (without equatorial latitudes), and Figs. 5b and 5c show it for the zone 70-80° N. The temperature anomaly values are smoothed over sliding ten-year periods. The data in Fig. 5a refer to average annual conditions, since the anomalies of the temperature of the warm and cold half-years for the hemisphere as a whole do not differ very strongly. The data for the zone 70-80° N (Figs. 5b and 5c), however, are presented separately for each half-year.

It can be seen from Fig. 5 that there was a warming in the first half of our century, which reached its maximum in the 1930s, after which a gradual cooling began.

For the hemisphere as a whole and for the warm half-year at high latitudes, the average temperature anomalies were equal to several tenths of a degree, while at high latitudes for the cold half-year they reached 1.5°. This well-known feature of the climate change in the 1920s-1930s is reflected in the common name of this change - the "Arctic warming".

The question of the causes of this climate change has until recently been considered unresolved.

Leaving aside the numerous hypotheses about the probable causes of this phenomenon, which are qualitative in nature, let us consider the possibility of a quantitative explanation of the main patterns of climate change in the first half of our century. This task was set in one of our previous works (Budyko, 1967), where data on the secular variation of direct radiation coming to the earth's surface were used for this purpose.

In that work, it was established that the warming period of the 1920s-1930s coincided with a period of elevated values of direct radiation reaching the earth's surface. Based on this, according to the data on changes in direct radiation, we calculated the change in the average air temperature at the earth's surface for the Northern Hemisphere. The calculated value of the anomaly of the average temperature for the warming period turned out to be quite close to the value obtained from observational data, which confirmed the assumption about the dependence of temperature changes on radiation changes.

To study the patterns of climate change in the first half of the 20th century in more detail, we use the above model of the thermal regime of the atmosphere. Let us first consider the patterns of the radiation regime for the period under consideration.

Fig. 6 shows the secular variation of anomalies of direct radiation reaching the earth's surface under cloudless skies for 19101950 (Budyko, 1969). This graph is constructed from data from a group of actinometric stations in Europe and North America located in the zone 4060 N. In the above-mentioned work, it was

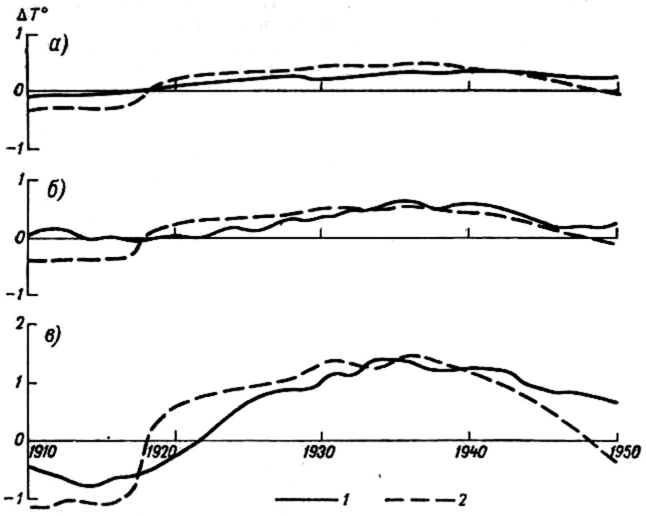

Figure 5: Secular variation of air temperature anomalies at the earth's surface.
a - Northern Hemisphere;
b - zone 70–80° N, warm half-year; c - zone 70–80° N, cold half-year;
1 - observational data; 2 - calculation results.

suggested that in accordance with Humphreys' hypothesis, changes in direct radiation are explained mainly by fluctuations in the transparency of the lower stratosphere layers caused by changes in the concentration of volcanic dust in these layers.

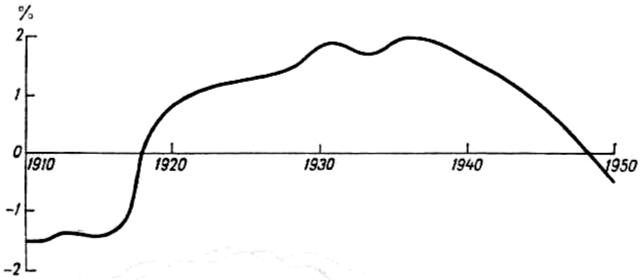

Figure 6: Secular variation of direct radiation anomalies.

Using the data presented in Fig. 6, taking into account the relative optical thickness of the dust layer and assuming that the dust content in the stratosphere has little difference at different latitudes of the Northern Hemisphere, one can calculate the secular variation of direct radiation at different latitudes for both average annual conditions and individual seasons.

To determine the secular variation of total radiation, it should be borne in mind that changes in total radiation under the influence of fluctuations in the concentration of volcanic dust constitute a small part of the changes in direct radiation (see Budyko, 1969). Taking into account the dependence of the ratio of changes in total radiation to changes in direct radiation on the solar elevation angle, presented in the mentioned work, one can calculate changes in total radiation over time in different latitudinal zones based on the above data.

Fig. 7 shows the dependence used in this calculation of the ratio of changes in total radiation at different latitudes of the Northern Hemisphere to changes in direct radiation at 50 N for the warm and cold half-years.

To calculate temperature changes corresponding to the above data on radiation changes, the relationship between the thermal regime and the ice sheet should be taken into account.

Obviously, in such a calculation, we cannot use the assumption of a stationary state of the ocean – polar ice – atmosphere system adopted in the previous section. Due to the great thermal inertia of the oceans and the continental ice sheet, this system can be considered stationary only for long periods of time - probably at least thousands of years.

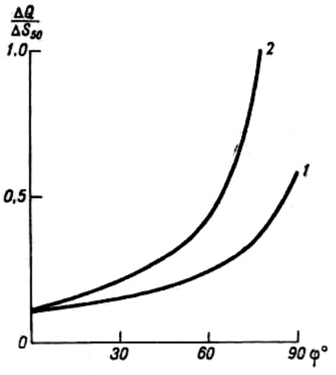

Figure 7: The ratio of changes in total radiation at different latitudes of the Northern Hemisphere to changes in direct radiation at 50° N. 1 - warm half-year, 2 - cold half-year.

In this regard, the assumption of stationarity of the system, justified in the study of Quaternary glaciations, is clearly unsuitable for the study of modern climate changes, which lasted only a few decades.

At the same time, when studying modern climate changes, one cannot ignore the associated changes in the polar ice regime. Observational data show, in particular, that the Arctic warming led to a reduction in the area of sea ice by about 10% (Ahlman, 1953, Chizhov and Tareeva, 1969, etc.).

An accurate calculation of non-stationary processes in the ocean – polar ice – atmosphere system involves great difficulties, especially due to insufficient study of the mechanism of heat exchange between the surface and deeper layers of ocean waters. Therefore, it seems expedient to simplify the problem of numerical modeling of the modern climate change process by approximately considering this process over periods of time on the order of decades as quasi-stationary, assuming that for these periods of time there is a definite relationship between the area of polar ice and the values of external climate-forming factors. By determining the parameters of this relationship according to empirical data, this dependence can be used as an additional equation that will replace the condition in the thermal regime model outlined above that connects the ice area with the elements of the thermal regime for a stationary state.

From the relationships of the semi-empirical theory of the thermal regime it follows that with an increase in incoming radiation, the relative change in the area of marine polar ice is approximately proportional to the change in radiation. Such a dependence takes place with relatively small changes in the area of polar ice.

This connection can be represented in the form:

$$-\frac{\Delta p}{p} = \mu \frac{\Delta Q_p}{Q_p}, \tag{21}$$

where $\frac{\Delta p}{p}$ is the relative change in the area of marine polar ice, $\frac{\Delta Q_p}{Q_p}$ is the relative change in the planetary value of total radiation, μ is a dimensionless coefficient.

The value of the coefficient μ for modern climate changes can be determined from empirical data on changes in total radiation and ice cover during the Arctic warming epoch. From Fig. 6 it follows that during the Arctic warming epoch, direct radiation at 50° N increased by about 2% compared to the previous period. Assuming that radiation changes occurred mainly in the Northern Hemisphere, where fluctuations in dust concentration at different latitudes differed little, we find the value of the corresponding change in the global value of total radiation, which turns out to be about 0.25%.

Taking this value into account and assuming that during the Arctic warming epoch the area of polar ice decreased by 10%, we find $\mu = 40$. This value is much smaller than the similar coefficient that can be obtained from the semi-empirical theory of the thermal regime for a stationary state.

Using the data in Fig. 6 and the above numerical model of the thermal regime, which includes relationship (21) instead of the assumption adopted in it about the relationship between the ice boundary and air temperature, one can calculate temperature changes at different latitudes for the time period of interest.

The results of such a calculation are shown in Fig. 5 by curves 2, which turn out to be quite close to the observed temperature changes. It is noteworthy that the calculated temperature changes are slightly ahead of the changes found from observational data. The lag of the observed temperature changes behind the calculated ones is obviously explained by the inertia of the ocean – polar ice – atmosphere system, which, however, is relatively small in this case. It should be noted that good agreement of the calculated secular variation of temperature with observational data is achieved by applying a numerical model of the thermal regime, the empirical parameters of which are determined without using data on temperature changes and which, therefore, gives results independent of the experimental data used for comparison.

The agreement between the calculation results and observational data suggests that the main cause of climate change in the first half of our century was a noticeable decrease in dust concentration in the lower stratosphere of the Northern Hemisphere due to the absence of explosive volcanic eruptions for several decades. Judging by Lamb's data (Lamb, 1970), such a weakening of volcanic activity is a noticeable anomaly in the regime of volcanic activity over the past centuries. This gives the climate change under consideration the character of a relatively rare phenomenon for the modern era.

An analysis of the calculation materials on temperature changes at different latitudes shows that over most of the Northern Hemisphere, the main cause of rising temperatures in the 1920s-1930s was an increase in total radiation reaching the earth's surface.

At the same time, temperature increases during the warm half-year at different latitudes differed little. As can be seen from the calculations, the screening effect of dust at high latitudes increases due to the growth of its optical mass and an increase in the ratio of the change in total radiation to the change in direct radiation with a decrease in the average solar elevation. In the warm hemisphere, the influence of radiation changes on the thermal regime at high latitudes decreases due to the decrease in solar radiation with increasing latitude. These factors act in opposite directions, as a result of which the temperature change at high latitudes increases only slightly compared to low latitudes.

During the cold half-year, temperature fluctuations at low and moderate latitudes differed little from the corresponding fluctuations during the warm half-year, but at high latitudes (mainly in the belt 70-80° N) temperature changes increased sharply.

As the calculation materials show, in this case, temperature changes were weakly related to fluctuations in solar radiation in the same season, since in the cold half-year at high latitudes the radiation is very small and does not have a large impact on the thermal regime of the atmosphere. The main cause of temperature change in this case was the change in the area of marine polar ice, which significantly increased the air temperature in the cold season.

The influence of this change on the temperature of the warm half-year is relatively small, it also decays rather quickly with distance from the latitudinal belt 70-80 for the cold half-year period.

The conclusion obtained here is in good agreement with the previously developed concept of the influence of polar ice on air temperature, according to which ice sharply reduces the temperature at high latitudes in winter, reduces it much less in this zone in summer, and has relatively little effect on air temperature at temperate and low latitudes (Budyko, 1971).

4 CLIMATE OF THE NEXT CENTURY

The studies have shown that of the various ways in which modern human activities affect atmospheric processes, only a few can lead to climate change on a global scale. One such way is associated with the growth of energy production used by humans.

In the author's work on this issue (Budyko, 1962), it was noted that in the territory of the most industrially developed countries, as a result of human economic activities, additional heat is currently being created, the amount of which is already not small compared to the value of the radiation balance of the earth's surface.

An increase in energy production from 4 to 10% per year will lead to the fact that no later than in 100-200 years, the amount of heat created by humans will be comparable to the value of the radiation balance of the entire land surface. Obviously, in this case, there will be huge climate changes across the entire planet.

Some idea of the possible impact of energy production growth on the climate of the future is provided by the materials presented in Fig. 8. This figure shows curve 1 depicting the secular variation of the deviation from the norm of the average air temperature for the Northern Hemisphere constructed from observational data. Curve 2 represents the results of calculating changes in the average planetary temperature with an increase in energy production by 6% per year. This calculation is based on using the model outlined above, assuming that the temperature change occurs as a result of a change in heat influx, with all other factors affecting the climate, including the albedo of the Earth-atmosphere system, remaining constant.

As shown above, this assumption means that the possibility of melting polar ice is not taken into account, which leads to an underestimation of the value of the upcoming temperature increase.

Fig. 8 shows that the increase in temperature in the first half of the 21st century due to the growth of energy production will become greater than the temperature changes that occurred in the first half of the 20th century due to natural causes. In the future, the temperature rise will increase rapidly, leading to major changes in the global climate. Thus, the growth of energy production consumed by humans can have a significant impact on the climate of the future.

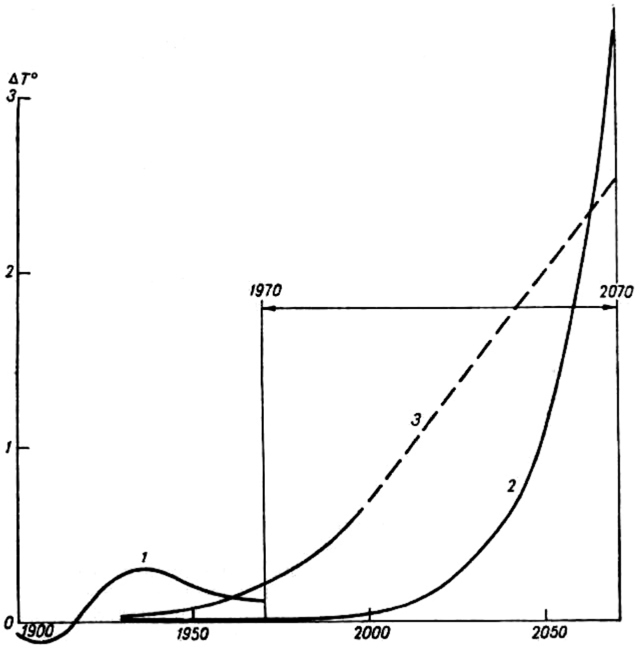

Figure 8: Secular variation of air temperature anomalies at the earths surface.
1 - observational data; 2 - changes due to increased energy production;
3 - changes due to increased carbon dioxide concentration.

The second factor that can significantly change the climate is the increase in carbon dioxide concentration in the air. Observational data show that in recent decades, as a result of burning an increasing amount of fuel, the concentration of carbon dioxide in the air has been growing at a rate of about 0.2% (of its total amount) per year. It is possible that in recent years this rate has increased slightly. Based on these data, Machta and other authors concluded that by 2000 the concentration of carbon dioxide in the atmosphere will increase by approximately 15-20% (see Inadvertent Climate Modification, 1971).

Since atmospheric carbon dioxide, absorbing longwave radiation, is one of the factors creating a greenhouse effect in the atmosphere, it is obvious that the growth of its concentration should lead to a temperature rise at the earth's surface.

The effect of carbon dioxide concentration on the thermal regime has been discussed in numerous studies, the conclusions of which differ in some cases. In the above-mentioned monographs on the problem of human impact on the climate, to assess the possible temperature change with increasing carbon dioxide concentration, the results of Manabe's research (Manabe, 1970, etc.) were used. He found that under the influence of this factor, the average planetary temperature by 2000 compared to 1970 may increase by about 0.5. The change in global temperature based on the result of such a calculation is shown in Fig. 8 by curve 3.

It is noteworthy that after 1950 the effect of changes in carbon dioxide concentration on the average planetary temperature is becoming noticeable. In 1970, this effect is comparable to the anomaly of the average planetary temperature observed in that year.

As can be seen from Fig. 8, the temperature change resulting from the increase in carbon dioxide concentration by 2000 may exceed the anomalies of natural fluctuations in global temperature observed during the first half of the 20th century. It can be assumed that the continued growth of carbon dioxide concentration in the 21st century will lead to even more significant climate changes.

Of the other factors associated with human economic activities that can lead to climate change, the change in dust concentration in the atmosphere should be mentioned.

Taking into account the available observational data, it can be concluded that in recent decades, human activity has led to a noticeable increase in dust concentration, especially in industrial areas, as well as in arid climate regions where virgin land development has expanded. There is some data suggesting that the increase in dust concentration due to human activities is spreading over large areas and may be acquiring a global nature.

In particular, actinometric observational data show that after 1950 most stations recorded a noticeable decrease in the value of direct radiation under a cloudless sky. This change in direct radiation apparently depends significantly on local fluctuations in atmospheric transparency in the areas of cities where actinometric stations are located.

In this regard, to assess global changes in atmospheric transparency over the past two decades, observational data obtained away from settlements should be used. Unfortunately, there is very little such data.

The findings of F.F. Davidy (1965), who assessed changes in dust concentration in the atmosphere from data on dust content in various layers of mountain glaciers, deserve attention. He found that the concentration of atmospheric dust began to increase rapidly after the 1940s of this century.

A study of the impact of human-generated dust on the thermal regime has shown that this impact is much more complex than the relatively simple mechanism of action of fine volcanic dust in the lower stratosphere on air temperature mentioned above.

Studies have shown that dust generated during human activities is characterized by particles of various sizes that penetrate into different atmospheric layers. Such dust can have a significant effect not only on shortwave radiation fluxes, but also on longwave radiation.

Although the effect of human-generated dust on air temperature is still largely unclear, it can be assumed that in some cases an increase in dust concentration leads to a temperature rise, while in others it leads to a decrease (Mitchell, 1970; Landsberg, 1970; Inadvertent Climate Modification, 1971).

It is difficult to make any assumption about the possible impact of dust on the global climate of the future, since it is unknown what changes in the concentration of human-generated dust may occur in the coming decades. In connection with the existing tendency for dust concentration to increase with the acceleration of industrial development in many countries, measures are now being taken to reduce air pollution, which may lead to a halt in the increase in dust concentration. In this regard, it is now more expedient to refrain from assessing the impact of dust on the global climate of the future, although the possibility of such an impact cannot be ruled out.

Thus, for the next century, climate change is most likely under the influence of two factors - the growth of energy production and the increase in carbon dioxide concentration. Both of these factors influence the climate in the same direction, causing an increase in air temperature.

The practical significance of the issue of future climatic conditions is determined by the scale of possible climate changes and the time of their onset. If these changes are large enough and occur in the not too distant future, then clearly in this case the problem of predicting impending climate changes should be considered as one of the most important tasks of modern meteorology.

The importance of this problem is determined, in particular, by the fact that the national economy of all countries essentially depends on modern climatic conditions, and even a noticeable change in climate in the most favorable direction will require huge capital investments to ensure adaptation of economic activities to new conditions.

The time period for which information on climate change is needed is apparently comparable to the probable service life of industrial and agricultural structures and systems currently being designed, the operation of which depends on the climate. For the most durable structures, this period will be at least one hundred years. If the climate can change significantly in the future, then obviously this possibility should be taken into account to one degree or another when designing these structures.

Another criterion for assessing the duration of the period for which it is desirable to have information about possible climate changes is the time required to prepare and implement measures to regulate climate change and adapt the national economy to these changes. Given that the implementation of such measures will require the solution of many complex scientific and technical problems, this time cannot be less than several decades.

Thus, it should be considered desirable to have information about possible climate changes for a period of up to one hundred years.

The problem of predicting climate change as a result of human activities is fundamentally different from the problem of weather forecasting. While the development of the second problem can be limited to analyzing physical processes in the atmosphere and hydrosphere, to study the first problem, in addition to this, it is necessary to take into account the change over time in indicators of human economic activity.

In this regard, the task of predicting climate change contains two main elements - the forecast of the development of a number of aspects of economic activity (growth in fuel consumption, which increases the concentration of carbon dioxide in the atmosphere, growth in energy production, etc.) and the calculation of those climate changes corresponding to the change in relevant indicators of human activity.

This leads to two important features of these predictions. First, they will inevitably be conditional in nature. Human economic activity is not an independent process of its impact on climatic conditions. So, in particular, if this activity can lead to significantly adverse climate changes, then probably the nature of economic activity will be changed before these changes occur. Therefore, the climatologist's task is not to predict the real climate of the future, but to calculate the parameters of such a climate for a number of possible options for economic development. Taking into account the results of such a calculation, it will be possible to optimize the long-term planning of economic development, while taking measures against adverse climate changes. Thus, the forecast of possible climate changes is the rationale for climate control measures.

The second feature of forecasts of the future climate is related to their possible accuracy. Since it is difficult to quantitatively predict the rates of economic development tens of years in advance for a number of reasons, the accuracy of such a prediction cannot be high. In this regard, in calculations of the future climate, it seems justified to use schematic models of climate theory, which, however, should give the correct estimate of the order of magnitude of possible climate changes.

The practical significance of such assessments is determined by the fact that they make it possible to single out those options for economic development that can lead to major (i.e. most significant for the national economy) climate changes exceeding the errors of the corresponding calculations.

Turning to the consideration of possible climate changes in the next century, one should first of all discuss the consequences of the further growth of energy production, which was mentioned in the previous section.

As can be seen from Fig. 8, even without taking into account the feedback between the polar ice regime and air temperature, we come to the conclusion that with an annual growth in energy production by 6%, a rapid increase in planetary temperature will begin in the middle of the 20th century. This increase will be accompanied by tremendous climate changes that could have catastrophic consequences for the economies of many countries. Thus, uncontrolled growth in heat production will lead to the emergence of a kind of "heat barrier" to the development of energy.

It should be noted that the assumptions made in constructing curve 3 in Fig. 8 cannot be considered unrealistic. A 6% per year increase in energy production roughly corresponds to the rate of increase in this production that has taken place in recent years (Inadvertent Climate Modification, 1971). The value of the additional heat influx per unit area obtained in this calculation, reached by 2070, corresponds to the amount of heat currently released in some areas of the most industrially developed countries.

In this regard, the possibility of reaching a thermal barrier within a period of about a hundred years should be considered as one of the major problems that energy and technology will face in the not too distant future.

The issue of solving this problem requires special discussion beyond the scope of this work. Here one can only recall N.N. Semenov's considerations about the advisability of widespread use of solar radiation energy for economic purposes in the future, which will make it possible to limit the overheating of the earth's atmosphere.

The conclusion that a thermal barrier can be reached in the next century is of great importance as evidence of the real possibility of climate control in the not too distant future. This conclusion can be illustrated by comparing curves 1 and 2 in Fig. 8. When possible global temperature changes due to human activities become much larger than temperature fluctuations under the influence of volcanic activity and other natural factors, the prospect of regulating the global climate will open up, which will make it possible, in particular, to prevent undesirable climate fluctuations caused by natural causes.

When studying climate changes caused by rising global temperatures, the state of the ice sheet at high latitudes is of great importance. In previous works by the author (Budyko, 1962, 1971, etc.), several methods have been proposed to assess the impact of changes in meteorological factors on marine polar ice. One of these methods, based on calculating the heat balance of the ice sheet, makes it possible to calculate the change in ice thickness with an increase in air temperature by a given value. This calculation showed that with an increase in air temperature during the warm season by 4°C, marine polar ice will completely melt in a few years.

Since such a calculation does not take into account the feedback between the area of the ice sheet and air temperature, it is obvious that it should overestimate the temperature anomaly value sufficient for complete ice melting. Nevertheless, this calculation suggests that the temperature rise, which according to Fig. 8 data will be achieved in about a hundred years, will lead to the complete melting of marine polar ice.

Obviously, sea ice can partially melt before the thermal barrier is reached, i.e. before the average global air temperature rises by several degrees.

To estimate the change in the area of polar ice, we use formula (21), assuming that the value of the relative change in global radiation in this formula can be expressed through the corresponding change in global temperature determined from the relationship of the semi-empirical theory of the thermal regime at a constant albedo. In this case, according to the ratio (21), the area of polar ice can be calculated for different values of the average global temperature increasing as a result of the increase in carbon dioxide concentration and energy production growth in accordance with the data presented in Fig. 8. The results of this calculation are shown in Fig. 9, where the average latitude of the boundary of marine ice in the Northern Hemisphere is plotted along the vertical axis.

When discussing the materials presented here, which characterize the possible climate changes in the next century, it is necessary to take into account that they are conditional in many respects.

First of all, it is necessary to repeat the above consideration that the extrapolation of the existing growth rates of energy production and carbon dioxide concentration in the atmosphere used in the calculations is a possible but not mandatory hypothesis regarding the economic activities of the future.

Moreover, it can be assumed that if further research confirms the conclusion about the possibility of abrupt climate changes during the next century, then measures will be taken to limit the impact of industrial development on climatic conditions. For example, it is apparently possible to limit the temperature rise at the earth's surface by dispersing fine dust in the lower stratosphere, which will increase the planetary albedo of the Earth. Such a climate impact project may be available to the technology of the near future.

It should then be emphasized that the data presented here on possible future climate conditions were obtained as a result of a very approximate calculation. This calculation is based on a highly schematic model of the thermal regime of the atmosphere, the use of which in analyzing future climatic conditions involves the use of additional approximate assumptions.

For this reason, the data presented in Figs. 9 and 10 are characterized by significant errors. Although it is quite difficult to estimate the values of these errors, some considerations can be made about the reliability of the results of calculating future climate conditions presented here.

The model used in this study includes accounting for all the main components of the heat balance affecting the horizontal temperature distribution. This model takes into account two most important feedbacks between air temperature and other meteorological factors: the dependence of air temperature on its absolute humidity (due to the influence of absolute humidity on outgoing radiation, which is taken into account in formula (2)) and the dependence of air temperature on the position polar ice. Both of these feedbacks

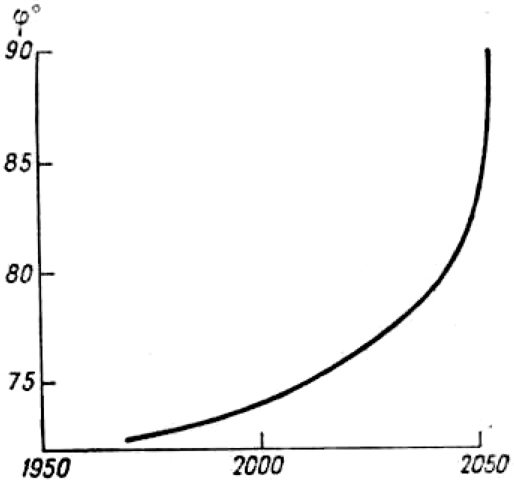

Figure 9: Change in the boundary of marine polar ice in the Northern Hemisphere.

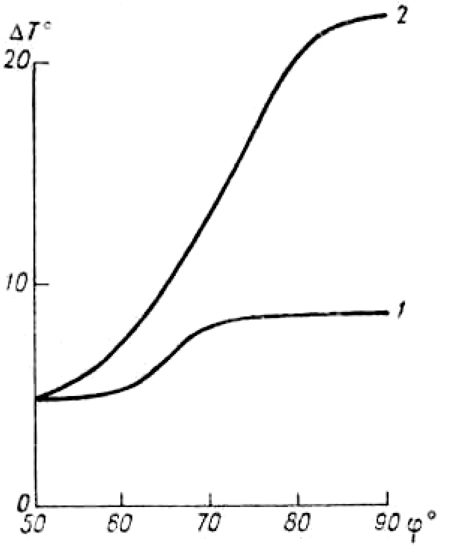

Figure 10: Change in the average latitudinal air temperature during the melting of polar ice.
1 - warm half-year,
2 - cold half-year.

enhance the effect of changes in climate-forming factors on the thermal regime and reduce the stability of the modern climate.

Of the various simplifications adopted in substantiating the model under consideration, the strong schematization of the meridional heat redistribution in the atmosphere and hydrosphere and the lack of accounting for the possible effect of cloudiness changes on the climate should be mentioned.

As noted above, in our previous works (Budyko, 1970, etc.) it was found that globally, the effect of cloudiness changes on absorbed radiation and outgoing radiation is compensated in many cases. In this regard, deviations of zonal cloudiness values from its average planetary value do not have a large impact on average latitudinal air temperature values.

However, the conclusion about the small influence of cloudiness changes on temperature is not universal, in connection with which the lack of direct accounting for the influence of cloudiness changes on the thermal regime can lead to certain errors in the calculations performed.

Undoubtedly, the schematization of the meridional heat exchange process in the model used also creates errors that reduce the accuracy of the calculations performed.

The errors arising from the inaccuracy of relation (21) and additional hypotheses adopted in its use to assess future climatic conditions should be considered separately. Some of these errors are indicated above.

In addition, temperature changes at high latitudes affecting the position of the ice sheet may differ even with the same changes in global temperature caused by different reasons (fluctuations in solar radiation, changes in carbon dioxide concentration, growth in energy production).

These differences may not be very large, since all three mentioned mechanisms of global temperature change lead to a more significant fluctuation in temperature at high latitudes compared to the average temperature for the entire hemisphere. However, these differences are also a source of additional calculation errors made when constructing the graph presented in Fig. 9.

Certain errors also arise from the limited accuracy of empirical data used to determine the proportionality coefficient in formula (21).

Taking all this into account, it can still be assumed that the errors in the calculations performed are not large enough to significantly affect the main patterns of climate change in the future established in this study. This assumption is based on the fact that the model used made it possible to obtain satisfactory results in quantitatively explaining the patterns of climate change in the Quaternary and modern eras.

It should also be noted that when assessing the reliability of the main results of this work, it is necessary to take into account their special nature. Thus, in particular, it follows from Fig. 9 that after the start of polar ice melting, the rate of reduction of their dimensions will increase rapidly. This pattern allows us to obtain a relatively accurate estimate of the time required for complete ice melting, even with very large errors in calculating the curve shown in Fig. 9. Changing the ordinates of this curve twofold towards their increase or decrease changes the time period required for complete ice melting by about 10%, which is insignificant from a practical point of view.

In other words, due to the rapid change in climatic conditions as the "thermal barrier" is approached, it is difficult to make a big mistake in calculating the polar ice melting time even when using very schematic climate models.

Various hypotheses about changes in carbon dioxide concentration in the atmosphere in the 21st century (the assumption that after 2000 the carbon dioxide concentration remains constant increases the ice melting time by a relatively small amount) also have little effect on the calculation result.

Assuming that the results presented here provide a general idea of possible future climate conditions, it must be recognized as necessary to obtain new independent data on this issue that could be compared with the results presented here.

The need for such data is primarily determined by the very great practical importance of the problem of climate change in the future - information about the climate of the future can change the development prospects of the most important sectors of the national economy of many countries. It is easy to understand that reliable initial data on possible climate changes are necessary to solve issues that are of such great economic importance.

In addition, the results presented here provide only a general and very schematic idea of possible climate changes. Obviously, these results should be supplemented by much more detailed developments, including, in particular, assessments of changes in moisture circulation conditions in various territories.

The only way to obtain such detailed data is to apply more general climate theory models that have been successfully developed in recent years in studies by Smagorinsky, Manabe and their colleagues (Smagorinsky, Manabe and Holloway, 1965; Holloway and Manabe, 1971, etc.), Mintz (Mintz, 1965, etc.), M.E. Shvets (Shvets et al., 1970) and others.

It seems to us that despite the need to overcome great difficulties in applying general climate theory models to study its changes, this problem will be solved in the relatively near future.

It is to be hoped that further research in this direction will make wide use of the cooperation of scientists from different countries. The need for such cooperation follows from the special nature of the problem of human impact on the climate, which was indicated by E.K. Fedorov (1958, etc.). E.K. Fedorov's works noted that climate changes over large areas occurring as a result of human activities will raise a number of complex international issues, the solution of which will only be possible with a significant increase in the level of international cooperation.

It can be assumed that in accordance with E.K. Fedorov's considerations, the issue of possible changes in the global climate will require in the future the development of special international agreements similar to those currently in place regarding the use of nuclear energy and the study of outer space.

Worthy of mention is the first experience in organizing research on climate change on an international basis, conducted under the leadership of Professor Carl Wilson of the Massachusetts Institute of Technology. As a result of this work, the monograph "Inadvertent Climate Modification" was prepared and published in 1971. It can be assumed that this work will be the beginning of broader international research in this field.

In conclusion, we present the main conclusions that follow from the materials of this work.

The calculations performed show that with the existing rates of economic development, human activities may soon lead to changes in the global climate. In 20-30 years, these changes will begin to have a noticeable impact on economic conditions, in 50-80 years they will radically change these conditions on the territory of many countries.

Given the great practical importance of clarifying future climatic conditions, it should be considered necessary to study these conditions in detail on the basis of applying the most effective methods of physical climatology.

Although it would be premature to apply the preliminary results obtained here for planning economic activities, these results can be used to estimate the time during which accurate information about future climatic conditions must be obtained. Taking into account the above data on possible rates of climate change, it should be assumed that this time does not exceed ten years. A later solution to the problem of the climate of the future may make it impossible to take the necessary measures in time to prevent the harmful effects of climate change on the national economy.

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