The effect of solar radiation variations on the climate of the Earth

By M. I. BUDYKO, *Main Geophysical Observatory, Leningrad, M. Spasskaja 7*

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ABSTRACT

It follows from the analysis of observation data that the secular variation of the mean temperature of the Earth can be explained by the variation of short-wave radiation, arriving at the surface of the Earth. In connection with this, the influence of long-term changes of radiation, caused by variations of atmospheric transparency on the thermal regime is being studied. Taking into account the influence of changes of planetary albedo of the Earth under the development of glaciations on the thermal regime, it is found that comparatively small variations of atmospheric transparency could be sufficient for the development of quaternary glaciations.

As paleogeographical research including materials on paleotemperature analyses has shown (Bowen, 1966, *et al*), the Earth's climate has long differed from the present one. During the last two hundred million years the temperature difference between the poles and equator has been comparatively small and there were no zones of cold climate on the Earth. By the end of the Tertiary period the temperature at temperate and high latitudes had decreased appreciably, and in the Quaternary time subsequent increase in the thermal contrast between the poles and equator took place, that was followed by the development of ice cover on the land and oceans at temperate and high latitudes.

The size of Quaternary glaciations changed several times, the present epoch corresponding to the moment of a decrease in the area of glaciations that still occupy a considerable part of the Earth's surface.

To answer the question of in what way the climate will change in future, it is necessary to establish the causes of Quaternary glaciations initiation and to determine the direction of their development. Numerous studies on this problem contain various and often contradictory hypotheses on the causes of glaciations. The absence of the generally accepted viewpoint as regards this seems to be explained by the fact that the existing hypotheses were based mainly on qualitative considerations allowing different interpretation.

Taking into account this consideration, we shall examine in the present paper the possibility of using quantitative methods of physical climatology to study the problem in question.

Firstly we shall dwell upon the problem of climate change regularities during the last century. Fig. 1 represents the secular variation of annual temperature in the northern hemisphere that was calculated from the maps of temperature anomalies for each month for the period of 1881 to 1960 which were compiled at the Main Geophysical Observatory. Line 1 in this figure characterizes the values of anomalies that are not smoothed, line 2 the anomalies averaged by ten-year periods.

As is seen from this figure, a rise in temperature that began at the end of last century stopped in about 1940, and a fall in temperature started. The temperature in the northern hemisphere that increased in the warming period by 0.6°C then decreased by the middle of the fifties by 0.2°C. A comparatively short-period rise in temperature with smaller amplitude was also observed in the last years of the XIXth century.

The curve of secular temperature variation can be compared with the curve of secular variation of direct solar radiation with cloudless sky that was drawn by the data from a group of stations in Europe and America with the longest-period series of observations. This curve presenting the values of solar radiation smoothed

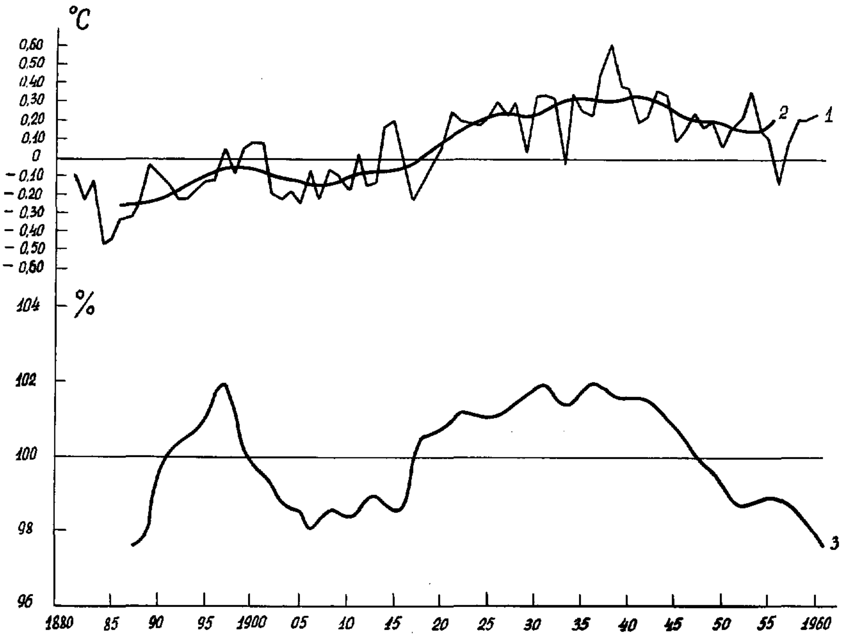

Fig. 1. Secular variation of temperature and direct radiation.

for ten-year periods corresponds to line 3 in Fig. 1. As is seen from the above figure, the direct radiation had two maxima—a short-period one at the end of the XIXth century and a longer-period one with the maximum values of radiation in the thirties.

The problem of the causes of secular variation of direct radiation was already discussed by Humphreys (1929, and others) who considered that it was determined by the change in the atmospheric transparency due to the propagation of volcanic eruption dust in it. Having agreed to this point of view that is confirmed by many new data, it should be suggested that a decrease in radiation after 1940 could also depend on the increase of dust in the atmosphere due to man's activity.

As can be seen from Fig. 1, the curves of secular variations of temperature and radiation are more or less similar.

To find out the dependence between the radiation change and that of temperature, let us compare the radiation and thermal regimes of the northern hemisphere for two thirty-year periods: 1888–1917 and 1918–1947. It follows from the data given in Fig. 1 that the temperature in the latter of these periods was by 0.33°C higher than that in the former, and the direct radiation by 2.0% higher.

To estimate the corresponding change in total radiation, it should be taken into account that the atmospheric transparency changes after volcanic eruptions as a result of propagation of dust with particles of the order of 1 μ in the lower stratosphere. This dust considerably increases the short-wave radiation diffusion, as a result of which the planetary albedo of the Earth becomes higher. Because of the radiation diffusion by dust mainly in the direction of an incident ray (Mie effect) the direct radiation decreases with diffusion to a greater extent than the total radiation does. Using the calculation method developed by K. S. Shifrin and his collaborators (K. S. Shifrin, I. N. Minin, 1957; K. S. Shifrin, N. P. Pyatovskaya, 1959), one can estimate the ratio of decrease in total radiation to that in direct radiation.

Such a calculation shows that this ratio computed for the average annual conditions changes slightly with the change of latitude, and on an average for the Earth equals 0.15.

Thus, the difference in total radiation for the periods under consideration amounts to 0.30%. In this case the ratio of temperature change to the change of radiation turns out to be equal to 1.1°C per 1% of radiation change.

This value should be compared with the values of similar ratio obtained as a result of calculating the radiation influence on the thermal regime of the Earth.

To determine the dependence of temperature on solar radiation with the average relationship between temperature, air humidity and other factors influencing the long-wave radiation, we used the results of calculations of monthly mean values of radiation at the outer boundary of the atmosphere that were made when preparing *Atlas of the heat balance of the Earth* (1963).

On the basis of these data relating to each month for 260 stations an empirical formula was derived

$$I = a + BT - (a_1 + B_1 T)n \qquad (1)$$

where I = outgoing radiation in kcal/cm² month,

T = temperature at the level of Earth's surface in °C,

n = cloudiness in fractions of unit,

the values of dimensional coefficients of which equal: $a = 14.0$; $B = 0.14$; $a_1 = 3.0$; $B_1 = 0.10$.

The root-mean-square deviation of the results of calculation by this formula from the initial data accounts for less than 5% of the radiation values.

Comparing formula (1) with similar dependence that can be obtained from the work by Manabe and Wetherald (1967), it is possible to conclude that they practically coincide for the conditions of cloudless sky and differ in considering the cloudiness effect on radiation.

For mean annual conditions, the equation of the heat balance of the Earth-atmosphere system has the following form:

$$Q(1 - \alpha) - I = A \qquad (2)$$

where Q = solar radiation coming to the outer boundary of the atmosphere;

α = albedo;

A = gain or loss of heat as a result of the atmosphere and hydrosphere circulation, including heat redistribution of phase water transformations.

Taking into account that for the Earth as a whole $A = 0$, we shall find from formulae (1) and (2) the dependence of the Earth's mean temperature on the value of solar radiation. In this case it turns out that the change of solar radiation by 1%, with the average for the Earth value of cloudiness equal to 0.50 and constant albedo equal to 0.33, causes the temperature change by 1.5°.

This result can be compared with similar estimate obtained from the work by Manabe and Wetherald from which it follows that with constant relative air humidity the mean temperature at the Earth's surface changes by 1.2° solar radiation changes by 1%.

It is clear that both of these values agree satisfactorily with the relation between changes in temperature and radiation that was obtained from observational data. One can believe that some excess of the computed temperature changes as compared to observational data reflects the thermal inertia effect of oceans the heating or cooling of which smoothes the Earth's temperature variations in comparison with the computed values for stationary conditions.

Thus, it seems probable that present changes of the Earth's temperature are determined mainly by the atmosphere transparency variations that depend on the level of volcanic activity.

If the present changes in volcanic activity cause radiation variations by several tenths of per cent and the planetary temperature variations by several tenths of a degree, one can believe that in the past respective variations of radiation and temperature reached appreciably larger values.

It is evident that the number of volcanic eruptions for the given interval of time is different with constant mean level of volcanic activity for statistic reasons, these differences being the greater, the longer general period of time being considered. The standard of volcanic activity in different geological epochs is also known to change noticeably in connection with the change of tectonic processes intensity.

Since the volcanic activity variations caused by tectonic factors are characterized by long periods of time to calculate the influence of radiation variations associated with them on the thermal regime, changes in the Earth's albedo should be taken into account that are due to expansion or reduction of the area covered with ice on the land and oceans.

As observations from meteorological satellites

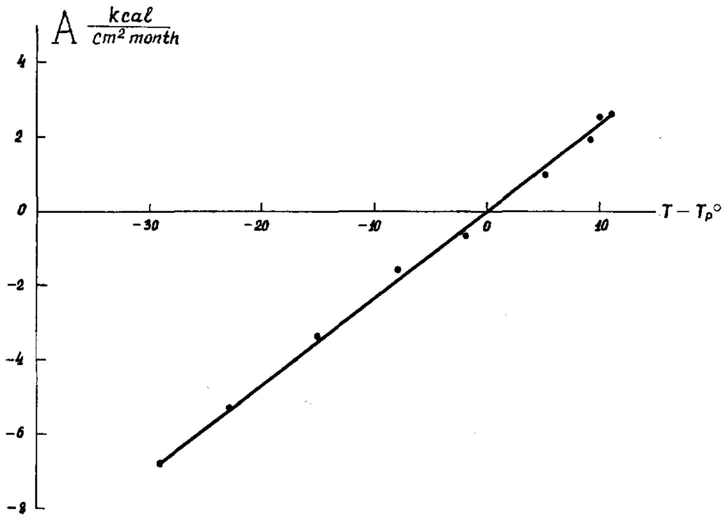

Fig. 2. The dependence of horizontal heat transfer upon temperature difference.

have shown (see Raschke, Möller, Bandeen, 1968), the albedo of the Earth-atmosphere system over areas with ice cover is greater than that over ice-free areas, due to which fact the change in area covered with ice increases the radiation variation effect on thermal regime.

To estimate the radiation variation influence on the temperature of latitudinal zones, taking into account the indicated effect, one of numerical models of the average latitudinal temperature distribution should be used. Since in this case we are only interested in temperature distribution near the Earth's surface it is possible to use, instead of existing comparatively complicated models, a simple scheme based on the solution of equations (1) and (2) to which the relation should be added that characterizes the relationship between temperature distribution and horizontal heat transfer in the atmosphere and hydrosphere.

Such a relation can be obtained by comparing the mean latitudinal values of term A calculated from formula (1) with quantities $T - T_p$, where T is annual mean temperaure at a given latitude, T_p is the planetary mean temperature.

The result of the above comparison is shown in Fig. 2 from which it follows that the corresponding dependence can be expressed in the form of equation

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

where $\beta = 0.235$ kcal/cm² month degree

From formulae (1), (2) and (3), taking into consideration that for the Earth as a whole $A = 0$, we obtain equations

$$T = \frac{Q(1-\alpha) - a + a_1 n + \beta T_p}{\beta + B - B_1 n} \tag{4}$$

$$T_p = \frac{Q_p(1-\alpha_p) - a + a_1 n}{B - B_1 n} \tag{5}$$

(where Q_p and α_p are planetary values of radiation and albedo) by which the average latitudinal annual mean temperatures were computed for present climatic conditions of the northern hemisphere. The values of Q, Q_p accepted in this calculation correspond to the value of solar constant 1.92 cal/cm² min, the albedo, according to observational data available, at the latitudes of 0° to 60° is considered to be equal to 0.32, at the latitude of 70° to 0.50, at the latitude of 80° to 0.62. In the calculation, the influence of deviations of cloudiness values from its mean planetary value equal to 0.50 on temperature is neglected.

The possibility of such an assumption results from the conclusion established in the calculations made using the above formulae concerning a comparatively weak effect of cloudiness on the mean indices of thermal regimewithin a rather wide range of conditions. Such a conclusion drawn, taking into account the dependence of albedo on cloudiness, implies that the effect of cloudiness on the change in absorbed radiation in a number of cases is compensated for by its influence on the outgoing long-wave radiation. The results of calculating the contemporary average latitudinal distribution of temperature are presented in Fig. 3 where they correspond to line T_0. As is seen, these results are in good agreement with the observed temperature at different latitudes that is represented in Fig. 3 by line T. Such an agreement allows us to use the scheme described for evaluation of the radiation variation effect on the Earth's thermal regime and glaciations.

The southern boundary of the existing ice cover on the seas and land in the Arctic corresponds to the mean latitude of 72° N. Let us consider that with a decrease in solar radiation the surface of ice cover expands in accordance with the extension of the surface area with temperature equal to or lower than the temperature observed now at 72° N. In this case let us assume that albedo on the ice-covered area is equal to 0.62 and at the southern boundary of this ice cover to 0.50.

It follows from the above values of albedo that with the change of ice cover area the mean albedo of the Earth changes by value $0.30\,S$ where coefficient 0.30 corresponds to the difference of albedo values with the presence and absence of ice cover, and quantity $S = lq$, (l = the ratio of ice area change to the whole area of the Earth, q = the ratio of mean radiation in the same zone of ice area change to the mean value of radiation for the Earth as a whole).

To take into account the influence of the glaciation area change on the annual mean temperature of the Earth, we shall use formula

$$\Delta T_p = \frac{Q_p}{B - B_1 n}\left[\frac{\Delta Q_p}{Q_p}(1 - \alpha_p - 0.30\,S) - 0.30\,S\right] \tag{6}$$

which is obtained from formulae (1) and (2), where ΔT_p is the Earth's temperature change with the change of mean radiation Q_p by value ΔQ_p.

From (1), (2), (3), (6) we shall deduce a formula for temperature at some latitude

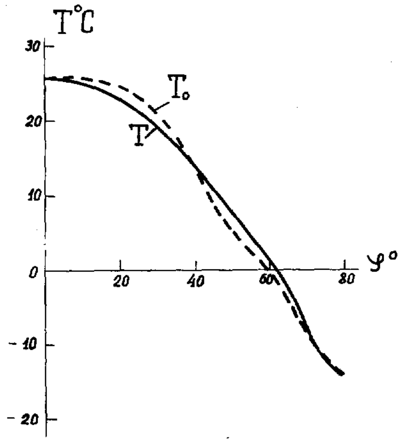

Fig. 3. The average latitudinal temperature distribution.

where T'_p is the existing mean temperature of the Earth.

Using this formula and considering the dependence of values Q and S on latitude, one can compute the position of glaciation boundary for different values of $\Delta Q_p/Q_p$. By this formula it is also possible to calculate the distributions of temperature at different latitudes that correspond to these values. The results of such a calculation are shown in Fig. 4, where lines $T_{1.0}$ and $T_{1.5}$ correspond to temperature distributions with the decrease in radiation income by 1.0% and 1.5% respectively. In the above-mentioned calculation the interrelationship between the thermal regimes of the northern and southern hemispheres is neglected (which assumption is reasonable with the similar change of thermal regime in both hemispheres). It is assumed in calculation that the relative decrease in radiation at different latitudes is the same.

Fig. 5 represents the values obtained from this calculation for the mean planetary temperature T_p and mean latitude to which glaciation extends φ_0 depending on relative radiation changes. As is seen from this figure, the radiation variation effect on thermal regime considerably increases as a result of glaciation development, the corresponding dependence becoming nonlinear.

$$T = \frac{Q(1-\alpha)\left(1 + \dfrac{\Delta Q_p}{Q_p}\right) - a + a_1 n + \beta T'_p + \dfrac{\beta Q_p}{B - B_1 n}\left[\dfrac{\Delta Q_p}{Q_p}(1 - \alpha_p - 0.30\,S) - 0.30\,S\right]}{\beta + B - B_1 n} \tag{7}$$

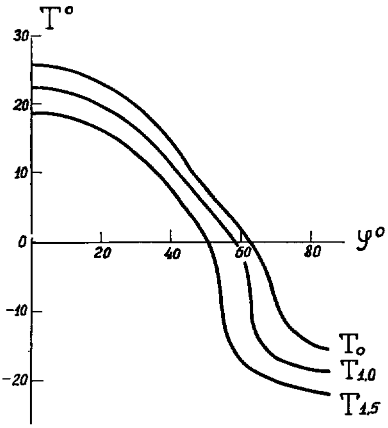

Fig. 4. The dependence of temperature distribution on radiation amount.

If with the decrease in radiation by 1% the mean temperature of the Earth drops by 5°, then with the decrease in radiation by 1.5% such a drop reaches 9°. Simultaneously with the above temperature drop the glaciation displacement 10–18° to the south takes place, i.e. the distances approximately corresponding to the expansion of quaternary glaciations. When radiation decreases by 1.6% the ice cover reaches the mean latitude of about 50°, after that it starts shifting towards lower latitudes up to the equator as a result of self-development. At the same time the planetary temperature drops sharply and reaches the value of several tens of degrees below zero.

A conclusion on the possibility of complete glaciation of the Earth after ice cover reaches some critical latitude follows from the calculation, using the above formulae, of the values of decrease in radiation necessary for further movement of ice to the equator. Such a calculation shows that to the south of critical latitude ice will move to the equator with the decrease in radiation by less than 1.6%, and at lower latitudes ice will move in the indicated direction with the existing values of radiation and even with its values exceeding those in the present epoch.

It should be noted that similar conclusion from other considerations was drawn previously by Öpik (1953, *et al.*) who considered, however, that for glaciating the Earth a considerable decrease in solar constant is necessary. The possibility of existence of complete glaciation of the Earth with the present value of solar constant was mentioned in the author's works (Budyko, 1961, 1966).

Thus, the present thermal regime and glaciations of the Earth prove to be characterized by high instability. Comparatively small changes of radiation—only by 1.0–1.5%—are sufficient for the development of ice cover on the land and oceans that reaches temperate latitudes.

It should be noted that such changes in radiation are only several times as great as its variations observed due to the changeability of volcanic activity in the last century.

Taking into consideration that according to the data of geological investigations the level of volcanic activity for long periods of time in the past changed by a factor of several times (see Ronov, 1959), one can believe that the influence of long-period variations of volcanic activity is a probable factor of glaciation development.

This conclusion is confirmed by the fact, established by Fuchs and Patterson, of correspondence between the main epochs of quaternary glaciations and the periods of considerable increase in volcanic activity in a number of regions of low latitudes (1947).

Though in this paper the author has no possibility to discuss numerous other hypotheses as to be causes of quaternary glaciations, nevertheless it is necessary to dwell upon popular idea concerning the influence of changes of the Earth's orbit elements on glaciations.

Such a conception substantiated by Milankovich (1930 and others) and other authors is shared by many specialists studying quaternary glaciations.

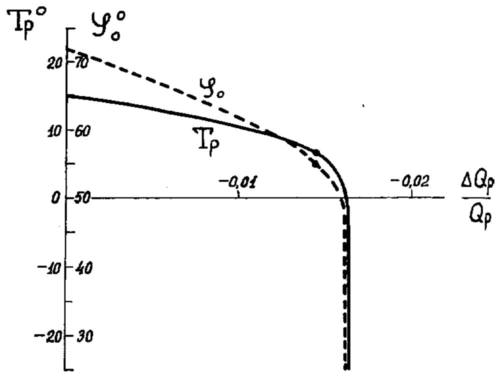

Fig. 5. The dependence of the Earth's temperature and ice cover boundary on radiation variations.

As is known, the effect of changes in the Earth's orbit elements leads to appreciable redistribution of radiation amount coming to different latitudes. Considering these changes and using the model of latitudinal temperature distribution suggested by him, Milankovich concluded that with the changes of orbit elements at temperate and high latitudes considerable changes in temperature occur that can result in glaciation.

It should be mentioned that the model of temperature distribution suggested by Milankovich did not take into account horizontal heat transfer in the atmosphere and hydrosphere due to which it had to overestimate considerably the influence of changes in radiation in a given latitudinal zone on the thermal regime of the same zone.

To verify the hypothesis of Milankovich, there were calculated, using the above-mentioned scheme, changes in thermal regime and glaciations for the case of considerable change of the Earth's orbit elements 22 thousand years ago which is usually associated with the last glaciation. The calculations made have shown that though the variations of orbit elements influence in a definite way the thermal regime and glaciation, this influence is comparatively small and corresponds to possible displacement of the glaciation boundary by a little less than 1° of latitude. It should be borne in mind that such a calculation allows for the change in annual radiation totals. According to Milankovich, the main influence on the glaciation is exerted by the variations of the summer radiation values that at latitudes 65–75° are 2 to 3 times as large as the variations of annual values. Emphasizing the necessity of further study of the problem on the effect of annual radiation variation on the glaciation, it should be noted that the above-obtained result casts some doubt on the hypothesis that the effect of the Earth's orbit changes is sufficient for the explanation of the quaternary glaciations.

Now we shall proceed to the question of why the volcanic activity variations, that occured during the whole history of the Earth, did not result in the development of glaciations during hundreds of millions of years previous to the quaternary period.

It has been established in geological investigations that in the pre-quaternary time the gradual rise of continents level took place. This caused weakening of water circulation in the oceans between low and high latitudes.

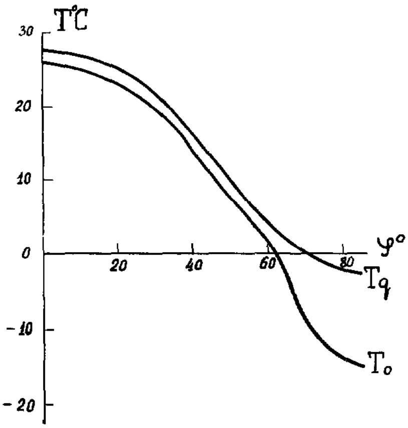

Fig. 6. Ice cover effect on temperature distribution.

It was ascertained long ago (Budyko, 1948, *et al.*) that the heat transfer between the equator and the poles in the hydrosphere is a considerable portion of the corresponding transfer in the atmosphere, in connection with which the changes in water circulation in the oceans should influence essentially the thermal regime at high and temperature latitudes.

To clear up this question, temperature distribution was calculated using the above-mentioned scheme for the case of absence of ice at high latitudes.

The results of such calculations are shown in Fig. 6 where line T_0 represents the present-day temperature distribution, and line T_q temperature distribution with the absence of polar glaciations. In these calculations the albedo at high latitudes is accepted to be equal to the albedo of ice-free areas and, the coefficient β is considered to be equal to its value accepted above.

As is seen from Fig. 6, the polar ice changing little the temperature at low latitudes considerably decreases the temperature at high latitudes. As a result, the mean difference in temperature between the pole and the equator decreases and the annual mean temperature in polar zone turns out to be equal to several degrees below zero.

One can believe that with ice-free regime the meridional heat transfer in the polar ocean will increase as compared to present conditions since this ocean, that is now isolated from the atmosphere by ice, will give off a considerable amount of heat to the atmosphere through turbulent heat exchange.

If to consider that with the absence of ice the Arctic Ocean receives additionally an amount of heat equal to the mean value coming now to the ice-free areas of the oceans at high latitudes, the mean air temperature in the Arctic must be somewhat higher than the above value, i.e. close to zero.

This result is in agreement with the conclusions drawn using other methods in previous works by the author (Budyko, 1961, 1962, 1966), L. R. Rakipova (1962, 1966), Donn & Shaw (1966), and others. It confirms once more the possibility of existence of ice-free regime in the polar basin in the present epoch and at the same time indicates high instability of such a regime.

It is evident that with the annual mean temperature in the Central Arctic close to water freezing point comparatively small anomalies of radiation income may lead to ice restoration.

Thus, with the present distribution of continents and oceans the existence of two climatic regimes is possible one of which is characterized by the presence of polar ice and large thermal contrast between the pole and the equator, and the other by the absence of glaciation and small meridional mean gradient of temperature.

Both of these regimes are unstable since even small variations of solar radiation income could be sufficient either for freezing of the ice-free polar ocean or melting of the existing ice. Such a peculiarity of climatic regime seems to determine the main features of climate variations in the Quaternary period.

In the periods of decreased volcanic activity the temperature distribution corresponded to ice-free regime which characterizes the climate of comparatively warm inter-ice epochs. When volcanic activity increased, ice formed firstly in the arctic seas, and then greater or smaller glaciations were developed on the land.

As it was mentioned in the author's work (Budyko, 1968), in the mesozoic era and in the paleogene the northern polar basin was connected with the oceans of low latitudes with much wider straits as compared to the Quaternary period. In this case the heat income to the polar basin as a result of activity of sea currents seemed to exceed those values that are observed at high latitudes under present conditions. If this income was 1.5 to 2 times as great as its present mean value for the ice-free areas, then according to the calculations by the above formulae, the annual mean temperature in the Arctic reached 10°, which fact excluded the possibility of glaciation even with appreciable anomalies of radiation.

During the Tertiary period the isolation of polar basin from the tropic regions of ocean gradually developed, which caused the temperature decrease near the pole and approaching of temperature distribution to the values characteristic of inter-ice epochs.

It follows from the above considerations that the present epoch is a part of glacial period since any noticeable increase in volcanic activity should lead to new glaciation development.

Moreover, it seems probable that one of the following glaciers expansion could reach the critical latitude after which the complete glaciation of the Earth would set in. Such a possibility was on the point of being realized in the period of maximum quaternary glaciation when the temperature of the Earth and the position of ice cover corresponded to dots plotted on lines T_p and φ_0 in Fig. 5.

As is seen from this figure, the ice cover under these conditions has moved about 0.8 of the way from the present ice boundary to the critical latitude.

From such a viewpoint the Quaternary History of the Earth seems to be the period of coming climatic catastrophe due to which the existence of higher forms of organic life on our planet may be exterminated.

When estimating the probability of such a catastrophe being realized in future, the character of man's activity should be taken into account which influences to some extent the climate at present. Without touching upon the possibility of implementing in future some projects of active influence on the climate which could affect the glaciation development, ever increasing influence of man's activity on the energy budget of the Earth should be mentioned.

All the energy used by man is transformed into heat, the main portion of this energy being an additional source of heat as compared to the present radiation gain. Simple calculations show (Budyko, 1961) that with the present rate of growth of using energy the heat produced by man in less than two hundred years will be comparable with the energy coming from the sun. Since glaciations are greatly influenced by the changes in energy budget which are a small part of solar radiation income then it is probable that in the comparatively near future the possibility of glaciation expansion will be excluded and there will appear the reverse one of polar ice melting on the land and oceans with all the changes in the Earth's climate that are associated with it.

It should be mentioned that the conclusions stated in this paper on the effect of changes in solar radiation on climate have been drawn as a result of using a strongly schematized model of the Earth's thermal regime. It is considered desirable to make similar calculations with the use of more general models.

REFERENCES

Atlas of the heat balance of the Earth. Ed. M.I. Budyko, (In Russian), 1963, Moscow.

Bowen, R. 1966. *Paleotemperature analysis.* Amsterdam.

Budyko, M. I. 1948. The heat balance af the northern hemisphere. (In Russian), *Proceedings of the Main Geophysical Observatory, 18.*

Budyko, M. I. 1961. On the thermal zones of the Earth. (In Russian), *Meteorology and Hydrology,* No. 11.

Budyko, M. I. 1962. Polar ice and climate. (In Russian), *Proceedings Ac. Sci. USSR,* ser. geograph., No. 6.

Budyko, M. I. 1962*a*. Some ways of climate modification. (In Russian), *Meteorology and Hydrology,* No. 2.

Budyko, M. I. 1966. Polar ice and climate. Proceedings of the Symposium on the Arctic heat budget and atmospheric circulation.

Budyko, M. I. 1968. On the causes of climate variations. *Sveriges Meteorologiska och Hydrologiska Institut Meddelanden,* ser. B, No. 28.

Donn, W. L. & Shaw, M. 1966. The heat budgets of ice-free and ice-covered Arctic Ocean. *Journ. of Geoph. Res., 71,* No. 4.

Fuchs, V. S. & Patterson, T. T. 1947. The relation of volcanicity and orogeny to climate change. *Geological Magazine,* v. LXXXIV, No. 6.

Humphreys, N. J. 1929. Physics of the air. Second edition. N.Y.

Manabe, S. & Wetherald, R. 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *Journ. of Atmosph. Sciences, 24,* No. 3.

Milankovich, M. 1930. Matematische Klimalehre und Astronomische Theorie der Klimaschwanungen.

Rakipova, L. R. 1962. Climate change when influencing the Arctic basin ice. (In Russian), *Meteorology and Hydrology,* No. 9.

Rakipova, L. R. 1966. The influence of the Arctic ice cover on the zonal distribution of atmospheric temperature. *Proceedings of the Symposium on the Arctic heat budget and atmospheric circulation.*

Raschke, E., Möller, F. & Bandeen, W. R. 1968. The radiation balance of Earth-atmosphere system .... *Sveriges Meteorologiska och Hydrologiska Institut Meddelanden,* ser. B, No. 28.

Ronov, A. B. 1959. To the post-Cambrian geochemical history of the atmosphere and hydrosphere. (In Russian), *Geochemistry,* No. 5.

Shifrin, K. S. & Minin, I. N. 1957. To the theory of non-horizontal visibility. (In Russian), *Proceedings of the Main Geophysical Observatory, 68.*

Shifrin, K. S. & Pyatovskaya, N. V. 1959. Tables of slant visibility range and day sky brightness. (In Russian), Leningrad.

Öpik, E. Y. 1953. On the causes of paleoclimatic variations and of ice ages in particular. *Journ. of Glaciology, 2,* No. 13.

ВЛИЯНИЕ ИЗМЕНЕНИЙ СОЛНЕЧНОЙ РАДИАЦИИ НА КЛИМАТ

Физические закономерности, связывающие приход солнечной радиации с термическим режимом Земли, используются для изучения физического механизма современных изменений климата и изменений климата в геологическом прошлом. Выполненные расчеты показывают, что колебания климата, имевшие место в двадцатом веке, в основном объясняются изменениями поступающей в тропосферу солнечной радиации, обусловленными изменениями запыленности нижних слоев стратосферы. Учет (влияния колебаний площади ледового покрова на планетарное альбедо позволяет заметно уточнить оценки изменений термического режима при изменениях солнечной радиации в геологическом прошлом. При этом выясняется, что относительно малые изменения приходящей солнечной радиации, обусловленные нестабильностью прозрачности атмосферы из-за переменной вулканической активности были достаточны для развития крупных континентальных оледенений.