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On present-day climatic changes

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ABSTRACT

The conclusion is made that present-day climate appears to have changed as a result of man's inadvertent impact and this change may be considerably increased in the nearest decades.

The article considers a possibility of using the numerical models of climatic theory to study future climatic changes under the conditions of increasing influence on climate of man's economic activity.

1. It is assumed that over the past few decades man's economic activity has begun to show itself in the influence on global climate and that the effect is rapidly increasing (Budyko, 1962). This raises the problem of developing a procedure of climatic change forecasting in order to reveal in time a possible danger of deterioration of environmental conditions. It is obvious that such a forecasting procedure can be developed only by using a physical theory of climatic changes.

Despite the recent great advances in the investigations on climatic theory, the problem of possible application of the available numerical models for a study of climatic changes remains as yet to be solved. The question was treated in the author's earlier papers (Budyko, 1968, 1969, 1971, 1972) and in a recently published monograph (Budyko, 1974), the materials of which are partly used in the present paper.

The numerous models in recent theories of climate differ greatly in two aspects: first, in how detailed is the treatment of atmospheric processes in time and space, and second, to what extent the external and internal factors of climate are taken into account.

Since even the most detailed and comprehensive models describing atmospheric processes cannot escape essential simplification, the authors of these models often doubt the possibility of their application for calculation of actual climatic changes.

It seems to us that in order to overcome these difficulties it is necessary to bring together theoretical and empirical studies in physical climatology.

The empirical data available on heat and water exchange in the atmosphere, as well as the data on annual changes of meteorological regime and those resulting from climatic fluctuations, make it possible to assess many hypotheses used in the development of climatic theories and to clarify the fitness of various models of climate to the actual atmospheric processes.

It should be noted that there is an essential difference between the prediction of climatic changes caused by man's activity and weather forecasting. While the latter problem may be restricted to the analysis of physical processes in the atmosphere and hydrosphere, the study of the former makes it necessary to take into account man's economic activity.

In this connection the problem of forecasting climatic changes includes two elements: the prediction of development of economics, and calculation of those climatic variations which are expected when corresponding aspects of man's activity are changed.

This brings about two specific features of forecasting anthropogenic changes of climate. Firstly, they inevitably have conditional character. If economic activity leads to deterioration of climatic conditions, it can be changed before such deterioration actually takes place. Therefore, the task is to determine climatic conditions corresponding to different ways of economic development rather than to predict the real climate of the future. Considering the results of such an estimation it is possible to optimize long-term planning of economy, taking measures to rule out unfavourable climatic changes.

The second peculiarity of forecasting the future climate is connected with its accuracy. Since quantitative prediction of economic development for decades in advance is rather difficult for a number of reasons, its accuracy cannot be high. Therefore the application of schematic models of the theory of climate would be justified if these models gave correct estimation of the sign and order of magnitude of possible climatic changes.

2. Obtaining the reliable estimations of anthropogenic changes of climate would necessitate elucidation of regularities in the present-day climatic changes.

The data shown in Fig. 1 give a general idea of these changes. The figure presents a secular course of air temperature at the earth's surface for the northern hemisphere (curve 1) and for latitudinal belt of 70–85° N (warm half of the year—2, cold half of the year—3).

The curves of a secular course of temperature based on data for 5-year periods show the temperature changes to increase with latitude. A similar conclusion is drawn from the data on a secular course of an average meridional temperature gradient in the latitudinal belt of 25–70° N (curve 4); these data show that the meridional temperature gradient increases with cooling and decreases with warming.

This figure also presents a secular course of precipitation over a cold period (November–March) in steppe and forest-steppe regions of the USSR (curve 5). In this case total precipitation is calculated for 5-year periods using records of 21 stations. Of note is the close agreement between curves of a secular course of the meridional temperature gradient and those of precipitation over central areas in Euro-Asia. The agreement may be explained by the effect of the pole–equator difference in temperature on the intensity of atmospheric circulation transferring water vapour from oceans to inland regions of the continents at temperature latitudes.

Fluctuations in precipitation falling over Eastern Europe result in a changed runoff of the Volga which regulates the Caspian sea level. In the 1930s a decrease in precipitation resulted in a considerable fall of the Caspian sea level. It was accompanied by certain deterioration of climatic conditions for agricultural production in a number of regions at temperate latitudes.

It would be of interest to compare changes in moistening conditions on the continents at temperate latitudes in the eastern and western hemispheres. For this purpose deviations of wheat yields in the USA for individual 5-year periods (1910–71) from smoothed mean values of a secular course have been used. These anomalies which in some 5-year periods amounted as much as 16% of the yield are mainly ascribed to the changes in moistening conditions.

In Fig. 2 anomalies of wheat yields in the USA expressed in per cent are compared with corresponding changes in the Caspian sea level, ΔH. There is a close correlation between the above values, the correlation coefficient being equal to 0.74. This correlation indicates that changes of precipitation in a secular course at temperate latitudes of the eastern and western hemispheres are largely analogous. The same conclusion may be inferred from Lamb's paper (Lamb, 1974) where world maps of precipitation anomalies for recent years are drawn as compared with the past years. The maps in this work reveal that in recent years precipitation over a considerable part of inland regions at temperate latitudes has appreciably increased.

The relation existing between the changes of the atmospheric thermal regime and precipitation variations essentially contributes to the practical importance of the present-day climatic changes. It is clear that the precipitation variations by tens of a per cent may greatly affect average crop yields.

Since in the last few years the problem of food supply of the rapidly increasing population of the globe has become more acute, the necessity to foresee possible changes in crop yields due to climatic fluctuations is easily apparent.

3. The data available indicate that the present climatic fluctuations are essentially influenced by the changes of the atmospheric transparency.

The author's earlier works (Budyko, 1967, 1969) noted a similarity between the curves of a secular temperature course in the northern hemisphere and a secular course of direct solar radiation for a cloudless sky constructed on the data observed at a number of actinometric stations. By assuming solar

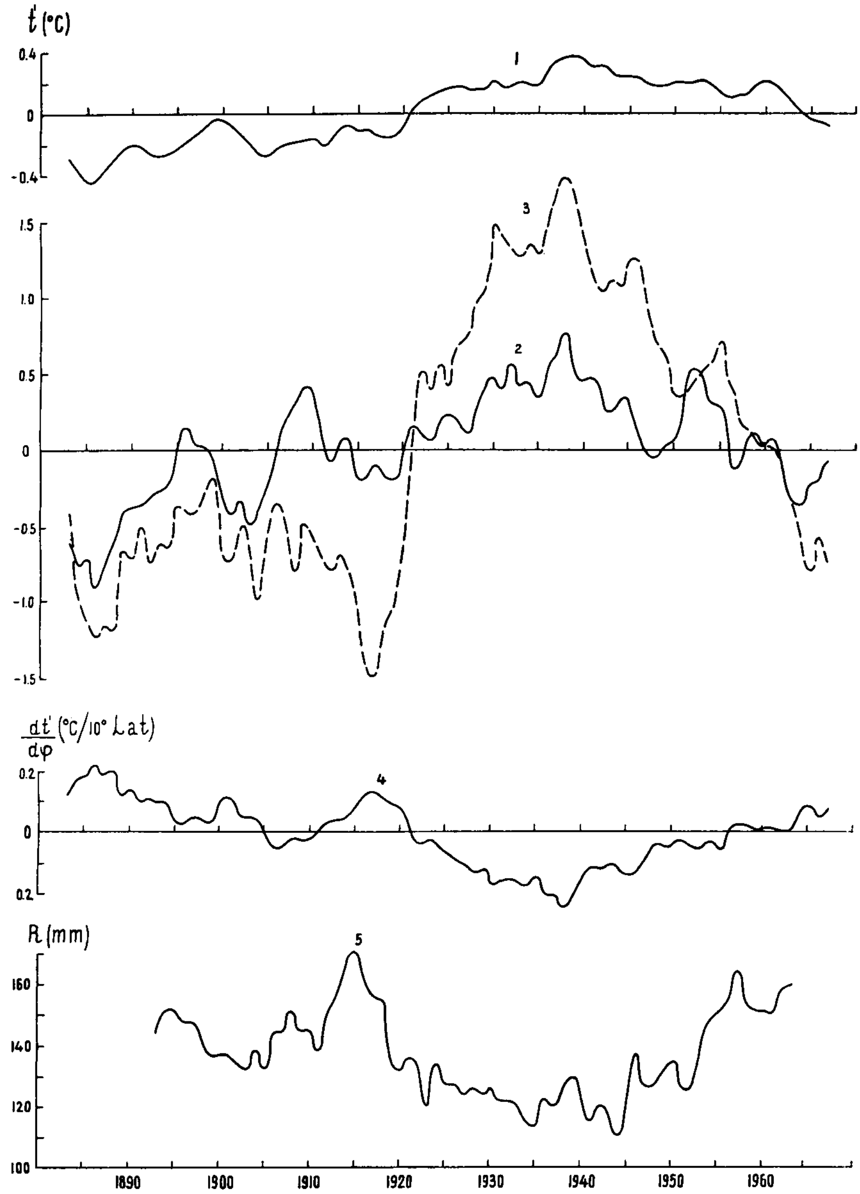

Fig. 1. Secular course of meteorological elements. 1—anomalies of the mean annual air temperature for the northern hemisphere; 2—anomalies of the temperature for the latitudinal belt of 70–85° N for warm seasons; 3—anomalies of the temperature for the latitudinal belt of 70–85° N for cold season; 4—mean meridional gradient of the air temperature; 5—precipitation amount over the steppe and forest-steppe zones of the USSR for the cold season.

radiation variations to depend upon fluctuations of aerosol concentration in the stratosphere, it was possible to calculate a secular course of global radiation incoming to the troposphere.

The above works compared the mean anomalies of air temperature at the earth's surface in the northern hemisphere and global radiation for the two periods: 1882–1917 and 1918–1947. During the second period the air temperature and global radiation were higher by 0.33° and 0.3% res-

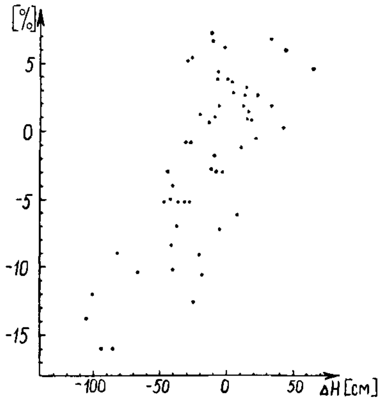

Fig. 2. Dependence between relative values of wheat yields anomalies in the USA (%) and the Caspian sea level fluctuations (ΔH).

pectively than in the first. From these data one can determine ΔT_1, the difference of average air temperature corresponding to a change of 1% in global radiation, its value being 1.1°.

Let us compare this value with analogous indices computed using different models of the climatic theory.

For the earth void of the atmosphere a temperature change of its surface corresponding to a 1% variation in solar constant is known to be 0.6°. This estimation can be derived from the equation of radiation equilibrium which for the planet void of the atmosphere characterizes the only feedback between radiation and temperature based on the dependence of outgoing long-wave radiation on the emitting surface temperature.

The dependence of the mean air temperature at the earth's surface on solar radiation for a real atmosphere is greatly affected by some other feedbacks revealed in recent investigations.

Möller (1963) noted in his work that water vapour amount in the atmosphere grows with temperature. This increases the "green house" effect, thus resulting in an additional rise in temperature. That feedback, unlike the above negative feedback between temperature and outgoing radiation, is positive and reinforces temperature changes with variations in radiation. Möller also points out the fact that temperature changes may depend significantly even on small changes of cloud amount.

When establishing the dependence of air humidity on temperature for average global conditions, the value of ΔT_1 was calculated by Manabe & Wetherald (1967) and found to be 1.2°. A similar value derived from the heat balance equation of the earth and from the empirical relation between long-wave radiation computed by a numerical model and air temperature equals 1.5° (Budyko, 1968). Both values refer to conditions of constant albedo of the earth–atmosphere system, which corresponds, in particular, to a constant cloud amount.

The above work (Budyko, 1968) noted that with lasting changes in the heat income the albedo of the earth–atmosphere system changed as a result of extension or reduction of areas covered with snow and polar ice. Being less significant for comparatively short changes of the thermal regime, the feedback between air temperature and snow-ice cover is not treated in the present paper.

A different situation is observed when albedo variations are due to changes in the cloud amount. These changes can develop over short periods of time and, consequently, the problem of the feedback between air temperature and cloudiness deserves a more thorough treatment.

If changes in the cloud amount for the earth as a whole depend on temperature, they must be taken into account for an accurate estimation of ΔT_1.

It should be noted that the study of the feedback between cloud amount and air temperature presents great difficulties.

Until recently even the sign of the influence of changes in cloudiness on the mean global air temperature at the earth's surface was not known. Lately, the prevailing view was that an increase in a cloud amount brought about a considerable fall in temperature. This view was based on the previous measurements of the cloud albedo which often gave high values close to the albedo of snow surfaces. Using these data and neglecting the cloud effect of reducing the outgoing radiation could lead one to the above conclusion.

In the past few years it was possible to determine an average cloud albedo using satellite observations. Its value proved to be much lower than the snow surface albedo. For example, the average albedo of clouds we found was 0.46, which differs little from the results obtained by other scientists who used meteorological satellite observations.

Taking into account the above value of the cloud albedo and using empirical dependence of long-wave radiation on air temperature, we concluded that under average global conditions an increase of

Table 1. *Annual course of air temperature and cloudiness*

		I	IV	VII	X
Northern hemisphere	T	9.1	15.2	22.3	17.1
	Δn	− 0.018	− 0.007	+ 0.022	+ 0.003
Southern hemisphere	T	17.1	15.1	11.6	13.6
	Δn	+ 0.022	− 0.007	− 0.027	+ 0.012

absorbed radiation with a decrease in the cloud amount is compensated almost completely by a decrease in the outgoing radiation (Budyko, 1971). It should be noted, however, that accuracy of such an estimation is not sufficient for the computation of the effect of cloudiness variations on air temperature fluctuations, which, however small, are significant for climatic conditions.

The cloud effect on air temperature was discussed by Schneider (1972), who constructed a numerical model of cloud effect on the radiation regime of the atmosphere. Schneider concluded (as earlier did Manabe and Wetherald) that the cloud effect on mean air temperature at the earth's surface depended upon the height of their upper limit.

He noted that due to the lack of data on the upper limit of clouds it was difficult to make a definite conclusion on the sign of cloud effect on the mean temperature near the earth's surface.

For the empirical estimation of the effect of cloudiness variability upon the dependence between the mean air temperature and radiation income one could use the data on annual course of temperature and cloudiness for the northern and southern hemispheres presented in Table 1.

Table 1 contains the data on air temperature T and cloudiness deviations from its mean annual value Δn (in fractions of a unit) for 4 months. The data on cloudiness shown in this table are obtained by generating numerous surface observations.

It is worthy of notice that the mean cloud amount variations for both hemispheres in the annual course are comparatively small. It means that there does not exist considerable feedback between variations in mean air temperature and cloudiness.

Recently several attempts have been made to include the feedback between air temperature and cloudiness in some numerical models of the thermal regime of the atmosphere (Paltridge, 1974; Weare & Snell, 1974). These papers contained the conclusions that the above correlation is negative and that it essentially reduces the solar radiation effect on air temperature. The assumptions used in these studies being largely conventional, the investigators left open the question of the applicability of the conclusions derived for the real atmosphere.

4. We shall use the opportunity for finding the dependence of air temperature near the earth's surface on the incoming radiation for the real atmosphere derived from empirical data, taking into account the equation of the global heat balance with solar constants S

$$\tfrac{1}{4} S(1-\alpha) = \mathscr{T} \tag{1}$$

and with the value of this constant being $S + \Delta S$

$$\tfrac{1}{4}(S+\Delta S)(1-\alpha-\Delta\alpha) = \mathscr{T} + \Delta\,\mathscr{T} \tag{2}$$

where $\Delta\alpha$ and $\Delta\,\mathscr{T}$ describe the corresponding changes of the albedo and outgoing radiation. From (1) and (2) we find that

$$\Delta S(1-\Delta\alpha-\alpha) - S\Delta\alpha = 4\,\mathscr{T} \tag{3}$$

It is assumed that within the range of air temperature variations ΔT

$$\Delta\alpha = A\Delta T \quad \text{and} \quad \Delta\mathscr{T} = B\Delta T,$$

as well as $\Delta\alpha \ll 1-\alpha$

Consequently we find

$$\frac{\Delta T}{\Delta S} = \frac{1-\alpha}{SA+4B} \tag{4}$$

The value of B can be determined from satellite observations of the outgoing long-wave radiation.

Fig. 3 presents the "Nimbus-3" observation data on outgoing radiation in the northern and southern hemispheres for different seasons (Raschke et al., 1973) as a function of the mean air temperature at

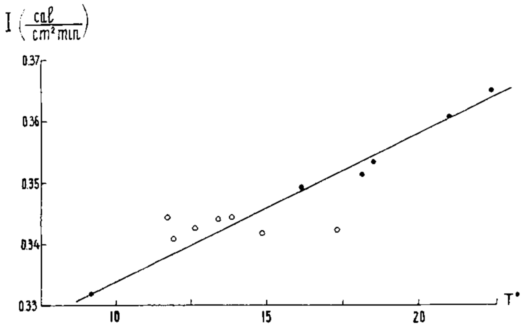

Fig. 3. Dependence of outgoing radiation on the air temperature.

the earth's surface for the corresponding periods. It is seen from Fig. 3 that there is a close correlation between these values; this justifies the above hypothesis that the outgoing radiation depends on temperature.

Using the data presented in the figure one can find that $B = 0.0024$ cal cm^{-2} min^{-1} deg^{-1}.

Similar data of satellite observations for 1962–66 (Vonder Harr & Suomi, 1971) give almost the same value of B.

If the albedo of the earth–atmosphere system is equal to 0.3 and does not depend on the air temperature ($A = O$), it follows from (4) that with B indicated above $\Delta T_1 = 1.4°$.

This value is in good agreement with the above estimates derived from the models of the atmospheric thermal regime for the constant cloud amount.

It is difficult to determine the value of A from the satellite observation data. The observation data for the period 1962–66 show that there is no correlation between the albedo and the mean air temperature for individual months in the northern and southern hemispheres.

The data of "Nimbus-3" observations (Raschke et al., 1973) reveal some correlation between the mean values of the albedo and temperature, but the points on the corresponding diagram are much too scattered to determine an exact value of the parameter describing the dependence.

At the same time the dependence of the albedo on air temperature in the northern and southern hemispheres revealed by satellite data may largely be determined by the annual radiation course in high latitudes rather than the temperature effect on cloud amount.

In summer the polar ice covers reflect an appreciable amount of radiation, and as a result the albedo increases throughout the hemisphere. This effect limits possible application of satellite data for a study of the dependence in question.

To estimate the influence of cloud amount variations on the mean albedo of the hemispheres the data of Table 1 may be used, assuming that

$$\Delta\alpha = (\alpha_n - \alpha_0)\Delta n \qquad (5)$$

where $\Delta\alpha$ is albedo deviation and Δn is cloud amount deviation from their mean values, α_n is the albedo of the earth–atmosphere system for cloudy conditions, α_0 is the albedo for cloudless conditions.

In calculation of the dependence between cloudiness and variations in temperature caused by changes in radiation, use could be made of the data from Table 1 for the northern and southern hemispheres. As is seen from this table, the feedback between variations in cloudiness and fluctuations in temperature is not intimate; that limits the accuracy of corresponding calculation. The value $A = \Delta\alpha/\Delta T$ obtained by this method is equal to about 0.00125 deg^{-1}, then from (4) we find $\Delta T_1 = 1.1°$.

It should be noted that the accuracy of the coefficient B determined with the help of the cited data is higher than that of the coefficient A. Since with A and B parameters accepted here the value of $4B$ is appreciably higher than SA, the computational accuracy of the ΔT_1 parameter is only slightly affected by errors in determining the coefficient A.

Of note is the good agreement between the estimation of ΔT_1 parameter thus derived and the above value obtained in the study of climatic changes, although the coincidence of the second sign in these estimations is probably accidental.

The values of this parameter derived from empirical data by two independent methods are also consistent with the estimations of this element which are obtained from the numerical model of Manabe and Wetherald, from our semiempirical model of thermal regime and some other theories of climate.

It is believed, therefore, that for the real atmosphere the value of ΔT_1 ranges between 1.0–1.5°. It is probable that the feedback between the air temperature and cloudiness affect this value to some extent, but the effect is rather slight and may be neglected in approximate analysis of climatic changes.

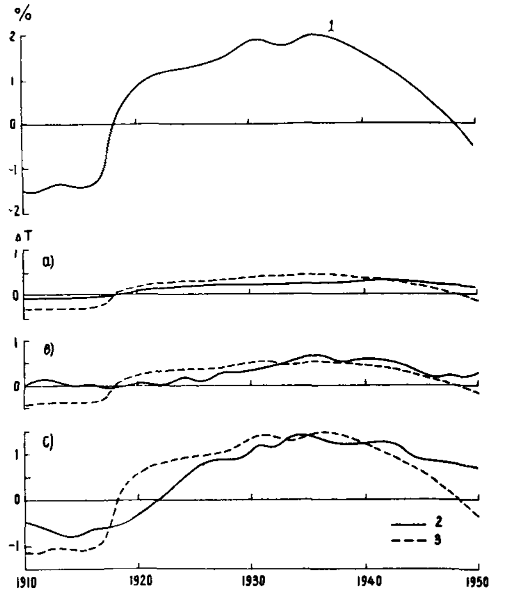

Fig. 4. Secular course of direct solar radiation (1) and the air temperature (2, 3).

The agreement between the values of ΔT_1, obtained from empirical data and from the thermal regime theory for the average global conditions indicates that the spatial averaging of the initial data changes little the value of ΔT_1.

It should be noted that the values of ΔT_1 derived here refer to time periods for which the feedback between temperature and polar ice position is of little importance.

It might be thought that for the present-day climatic changes this interval covers not less than several decades. Empirical data show (Budyko, 1971) that during the warming in the twentieth century the area of arctic ice decreased by about 10%. This may change the mean temperature near the surface in the northern hemisphere by some 0.1°, i.e. rather slightly. Over longer periods the value of ΔT_1 as influenced by the mentioned feedback would increase. At the same time for periods not exceeding a few years this value will be appreciably less in response to the thermal inertia of the earth–atmosphere system which is largely governed by the rate of warming or cooling of the upper layers of the ocean. A similar view was held in Reitan's work (1974).

5. When studying the physical regularities of the present-day climatic changes it would be necessary to find out the causes of different secular temperature courses at different latitudes. Some results of research in this field (Budyko, 1972) are cited below.

Fig. 4 presents a secular course of the anomalies (smoothed for 10-year periods) in direct radiation incoming to the earth's surface during 1910–50 (curve 1). The figure is plotted using the data of a number of radiation stations in Europe and North America in the belt of 40–60° N. Assuming that a secular course of direct radiation is mainly explained by changing the atmospheric aerosol mass, it is possible to calculate time changes of global radiation in different latitudinal belts from formulas of atmospheric optics.

In order to determine the air temperature changes corresponding to variations of radiation, one of the models of climate theory must be used. For this purpose a semiempirical model of the atmospheric thermal regime based on the equation of heat balance of the earth–atmosphere system (Budyko, 1968) is used.

The dependence of outgoing radiation on air temperature used in this model is derived from empirical data, which made it possible to take into account the effect of the feedback between the air temperature and humidity.

Estimations making use of this model have shown that although the changes in the sea ice boundaries which occurred during the warming in the first half of the twentieth century change but slightly the mean global temperature, they produce a marked influence on air temperature at high latitudes. Therefore, the model in question incorporated an empirical relationship between the changing boundaries of the polar ice and global radiation. The dependence turned out to be much weaker than the similar dependence for a steady state of the earth–atmosphere system.

Temperature variations at different latitudes were calculated for the period under consideration using the above relationship. The results of this estimation are presented in Fig. 4, the curves being fairly close to the observed temperature changes smoothed for 10-year periods (curves 2 and 3, respectively). It is of note that the temperature variations estimated are somewhat ahead of the observed changes.

The time lag in the observed changes may be attributed to the inertia effect of the ocean–polar ice–atmosphere system.

The estimation of temperature variations shows that a temperature increase in 1920–30s for most of the northern hemisphere was mainly caused by a higher global radiation incoming to the earth's surface.

Over the cold season temperature variations at low and temperate latitudes did not differ greatly from those over the warm period, while at high latitudes (mostly in the belt of 70–80° N) the changes in temperature sharply increased.

Estimations reveal that in this case temperature variations depended little on solar radiation fluctuations during the same season since over the cold season radiation at high latitudes is low and does not significantly affect the atmospheric thermal regime. These temperature variations were mainly caused by changes in sea polar ice area, bringing about an appreciable rise of air temperature.

The above semiempirical model of the atmospherical thermal regime was also used in the study of mechanism of the Quaternary glaciations. Taking into account the feedback between air temperature and ice cover boundary for a steady state of the earth–atmosphere system and using the above-mentioned model, it was possible to estimate the drift of the average ice cover boundary in the ice ages depending upon the astronomical factors determining the earth's surface position relative to the sun.

The changes of the ice cover boundaries thus obtained are in good agreement with paleogeographical data (Budyko & Vasishcheva, 1971).

Since the use of the model of climate theory made it possible to explain natural climatic changes, it is reasonable to believe that the model may be also applied to estimate the effect of the anthropogenic factors on climate.

6. The effect of economic activity on the global climate is determined by three factors: the growth of CO_2 concentration, the increase of the aerosol mass and the growth of heat production by sources of energy additional to solar radiation.

According to contemporary data the burning of different kinds of fuel results in the annual increase of CO_2 concentrations in the atmosphere by several tenths of a per cent, the rate of the increase appears to grow (*Inadvertent climate modification*, 1971; *Understanding climatic change*, 1975).

It is assumed that during the last century, CO_2 concentration in the atmosphere increased by 10–15% and by the end of the twentieth century this rise will reach 30–35%. Using the semiempirical model of the atmospheric thermal regime permits the revelation that a rise in CO_2 concentration by 10% raises the mean temperature near the earth's surface by 0.3° (Budyko, 1974).

It may be inferred from the above results that during the past hundred years the mean air temperature as influenced by an increasing CO_2 concentration rose by 0.3–0.4° and by the end of this century its general rise will be equal to 1.0°. One may suppose, therefore, that during the next quarter of a century increase in CO_2 amount will raise the temperature by 0.6–0.7°.

It is more difficult to estimate the influence of increasing aerosol concentration on climate. The amount of anthropogenic aerosol in the atmosphere has been determined with less accuracy compared with the mass of CO_2. One of the recent estimates gives this value to be about 10^7 tons, this figure corresponding to 25% of the total aerosol amount in the atmosphere (*Understanding climate change*, 1975).

The aerosol effect on the climate is mainly determined by the dependence of radiation fluxes in the atmosphere on the mass of aerosol particles. In this connection the observed radiation data are of importance both for estimating the aerosol amount changes and for revealing its influence on climate.

Many papers have been published which conclude on the basis of solar radiation observations that the aerosol mass has considerably increased in different regions of the globe in recent decades (McCormick & Ludwig, 1967; Bryson, 1968; Budyko, 1969; Flohn, 1973).

The validity of the conclusion was doubted by Dyer (1974) who supposed that radiation observations represented local air pollution in towns where the actinometric stations are situated rather than the global process of changes in the atmospheric transparency. His assumption was mainly based on the radiation data observed at Mauna Loa (Hawaii) which did not reveal a systematic decrease in the atmospheric transparency over the past 15 years.

It should be borne in mind that the series of radiation observations in Mauan Loa is comparatively short and part of the observations refer to the years of a sharply decreased transparency of the atmosphere after the Agung eruption. This makes it difficult to estimate a secular course of the atmospheric transparency from the data of this station.

Table 2. *Direct solar radiation variations observed in the USSR over the periods 1958–62 and 1968–72 (%) for April–September*

North-west of the European territory of USSR		Eastern Siberia	
Nikolaevskoe	−4.4	Oimyakon	1.5
Laryanskaya	−2.3	Yakutsk	1.0
Voeikovo	−1.5	Tulun	2.0
Leningrad	−2.1	Irkutsk	−1.3
South of the European territory of the USSR		Middle Asia	
Kamennaya Steppe	−6.0	Uilskaya	−2.0
Askania Nova	−4.5	Aralskoe More	−3.2
Belgorod	−2.7	Karakalpakskaya	−4.5
Karadag	−1.5	Fort Shevchenko	−5.0
Odessa	−6.0	Tashkent	−3.0

Since there exists a number of radiation stations where series of observations of direct radiation covering not less than few decades indicate a decrease in the atmospheric transparency both in the towns and far from them, it might be thought that the atmospheric transparency has decreased over vast areas.

For an additional study of this problem use was made of the data on the difference of direct radiation values for a cloudless sky obtained at a number of USSR radiation stations for the periods 1958–62 and 1968–72.

It should be emphasized that during the second period the effect of the Agung eruption on direct radiation has ceased.

The values of these differences expressed in per cent of direct radiation are given in Table 2.

Table 2 shows an appreciable decrease in direct radiation for the decade at most stations. It should be remembered that part of the stations is within towns and part is outside them. At the same time some stations do not show any attenuation in radiation.

It is believed that a 10-year period is too short to reveal anthrogenic decrease in the atmospheric transparency at all points of observations: In some instances natural fluctuations of transparency appear comparable with anthropogenic change.

It is possible that due to this circumstance the decrease in the atmospheric transparency at Mauna Loa is not observed. On the other hand, we cannot rule out a possibility that the data obtained at the station reflect the real fact of a small change in the atmospheric transparency in the central Pacific ocean most distant from the continents. It is clear, therefore, that further research is required into the problem of spatial regularities of the atmospheric transparency changes.

The data on a secular course of direct radiation for a cloudless sky to allow one to compute the anthropogenic aerosol mass in the atmosphere and estimate the effect of changes in its mass on the air temperature (Budyko & Vinnikov, 1973). The major results of this calculation are discussed below.

Fig. 5 presents the 5-year running means of the anomalies of direct radiation expressed in per cent of its normal calculated from the data observed at a number of stations (curve A). As mentioned above, it is widely thought that a gradual attenuation of direct solar radiation began in the forties due to the growth of anthropogenic aerosol mass. According to the data in Fig. 5 this attenuation is equal to about 6%.

It is possible to calculate the amount of anthropogenic aerosol which decreases direct radiation by about 6%.

Assuming that the attenuation of direct radiation is largely determined by its dispersion on aerosol particles and using the formulas of atmospheric optics, it is found that a decrease in direct radiation by 6% corresponds to a decrease of total radiation by 1% and occurs when the aerosol particle mass is 10^{-6} g cm^{-2}. This is the mass of optically active aerosol, the size of particles being tenths of a

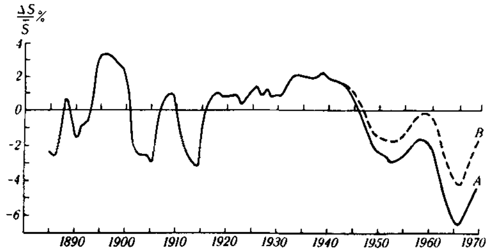

Fig. 5. Secular course of direct radiation.

micrometer. It is generally thought that about half the aerosol mass in the troposphere consists of the so-called "giant" particles, and their number is negligible as compared with the number of particles of the above-mentioned size: as a result, they do not appreciably affect the radiation attenuation. Taking this fact into account we find that the total mass of anthropogenic aerosol is 2.10^{-6} g cm^{-2}, i.e. about 10^7 tons (Budyko, 1974).

This value coincides with the above estimation obtained from other data. In order to determine the influence of anthropogenic aerosol on the air temperature it is assumed that variations in direct radiation over the last 30 years are caused by two processes: the growth of the anthropogenic aerosol mass which decreased radiation monotonically and the variations of the atmospheric transparency, independent of man's activity, which decreased direct radiation with the rise in aerosol concentration in the stratosphere or increased it up to the limit that corresponded to complete or almost complete aerosol absence in the stratosphere. It will be assumed that the change of direct radiation caused by the anthropogenic aerosol growth is characterized by a straight line passed through the points of the curve of the radiation secular course, corresponding to atmospheric transparency maximum in individual years. The mean global cloudiness is taken to be 0.5.

The anthropogenic aerosol effect on radiation for a cloudy sky is considered to be small as compared with that for a cloudless sky. It will then be found that in order to estimate the influence of radiation variations on the air temperature one should use the data on direct radiation values multiplied by half the change of direct radiation for a cloudless sky caused by the anthropogenic aerosol effect. The curve of a secular course of direct radiation constructed with proper adjustment is presented in Fig. 5 (line B).

Estimation of the effect of this change of radiation on temperature involves some difficulties caused, in particular, by imperfect knowledge of the mean values of the coefficients of radiation absorption by aerosol particles. Using the dependence of air temperature on aerosol concentration when considering the dispersion and absorption of radiation by aerosol particles calculated by Yamamoto & Tanaka (1972), it was established that under present-day conditions the anthropogenic aerosol reduces the mean air temperature by about 0.5°.

This value being higher than the above temperature rise caused by increase in CO_2 concentration, it is possible that the decrease in the mean global air temperature by some tenths of a degree which occurred in recent decades is fully or partly accounted for by the anthropogenic factors. Some authors entertained a similar viewpoint (Bryson, 1972; Flohn, 1973).

The problem of the anthropogenic aerosol effect on the climatic conditions of the future still remains to be solved, for it is difficult to give the valid estimation of the probable change in the aerosol mass.

In recent years many countries have taken measures to reduce industrial, transport and heating system aerosol particle exhaust in the atmosphere. At the same time measures are being taken in rural areas to fight soil erosion, also decreasing air pollution.

Thus, the current trend towards growth of the anthropogenic aerosol mass might be stopped and even reversed. This possibility is corroborated by data of observations carried out in recent years.

The third factor of man's influence on climate, i.e. the growth of heat from energy sources which are not connected with present transformation of solar energy, mainly affects the climate of towns and the most developed industrial regions. Though this factor may have a great effect on the climate of the next century if the contemporary rate of energy production is maintained, it will apparently remain less significant as compared with the two above factors until the end of the present century.

Thus, one should recognize the possibility of rising mean air temperature within the next quarter of the century. Then the calculations carried out using different models of climate theory show that in this case the boundary of polar ice will appreciably recess to the north. The available data show that this warming, possibly began in late or even mid-1960s.

The major consequences of this warming may be a decrease in total precipitation falling over some inland areas at temperate latitudes. It should be noted that an opportunity has recently been found for man's intentional impact on climate by changing aerosol particle concentration in the stratosphere (Budyko, 1974; Budyko, 1974a). This method, which is quite feasible with modern equipment, may reduce the mean air temperature near the earth's surface by some tenths of a degree or, perhaps, even by a few degrees. The use of this method may be important for preventing the warming of the climate.

7. The following conclusions can be made on the basis of the studies of the present-day climatic changes:

1) The present-day climate appears to have changed as a result of inadvertent impact of man's economic activity, and the rate of change may be considerably increased in the next decades.

2) When estimating the present anthropogenic changes of climate and forecasting similar changes in the future, the models of climatic theory should be used after verification with the data on the past climatic changes.

3) The results of this verification show that simple models of the semiempirical climatic theory are suitable for studying the climatic changes, if the major feedbacks between individual elements of climate are properly taken into account in these models.

4) Although simple models of climate theory are adequate to reveal the main regularities and general tendency of climatic change, they cannot supply much required information on possible features of the future climate, which makes it necessary to apply most comprehensive models of climate theory to calculate its changes.

5) Since the anthropogenic changes of climate have begun exerting their influence on man's activity, and this influence may increase essentially in the future, the study of climatic changes at the present moment becomes an urgent problem.

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О СОВРЕМЕНННХ ИЗМЕНЕНИЯХ КЛИМАТА. АННОТАПЛЯ

Получен вывод, что современный климат уже изменен в результате непреднамеренного воздействия хозяйственной деятельности человека, причем это изменение в ближайшие десятилетия может значительно усилиться. Рассматривается возможность применения численных моделей теории климата для изучения изменений климата и для предсказания климатических условий будущего в условиях усиливающегося влияния деятельности человека на климата.