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ON THE SIMILARITY OF CHANGES IN THE GENERAL ATMOSPHERIC CIRCULATION IN THE COURSE OF ANNUAL AND CLIMATIC FLUCTUATIONS

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RESUMEN

Partiendo de datos empíricos sobre la similitud aproximada en los cambios de los campos térmicos de las fluctuaciones anuales y las climáticas, se hace la hipótesis de que los cambios en la circulación general de la atmósfera son similares uno al otro también. Esta hipótesis es corroborada comparando los números de similitud que resultan de un sistema de ecuaciones de dinámica de fluidos y calor para una circulación zonalmente promediada. Se demuestra que las condiciones de similitud se mantienen.

La hipótesis mencionada, también se comprueba mediante reconstrucciones paleoclimáticas de los campos de elementos meteorológicos en el curso de las fluctuaciones climáticas.

ABSTRACT

Proceeding from empirical data on the rough similarity in the changes of thermal fields in the course of annual and climatic fluctuations, an assumption is made that the changes in the general atmospheric circulation are similar one to another as well. This assumption is backed up by comparing the similarity numbers resulting from a set of equations of fluid and heat dynamics for zonally averaged circulation. The similarity conditions are shown to be maintained. The above assumption is also proved by paleoclimatic reconstructions of the fields of meteorological elements in the course of climatic fluctuations.

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The increasingly strong impact of technology on the environment and possible resultant climatic consequences, stimulate the interest of researchers in the study of large-scale climatic changes that took place in the past. Available empirical evidence on past climatic changes is fragmentary, and accumulation of relevant data is proceeding at a very slow pace. Theoretical studies of large-scale climatic fluctuations involving the solution of a sufficiently complete system of equations are still pending. The difficulties in the way of building a strict and comprehensive system of equations representing climate dynamics are so considerable that quick results can hardly be expected. Hence, any novel suggestions that would allow to augment existing empirical foundations, obtain quantitative estimates of parameters, or improve the degree of understanding of the nature of climatic changes, would be welcome.

Let us consider large-scale climatic oscillations with typical times of about 10^4-10^5 years, termed glacial oscillations. The changes characteristic of these fluctuations in both hemispheres represent first a growth of the polar cap and a contraction and a shift of temporal subtropical and tropical zones toward the equator. These processes are accompanied by increased temperature differences between the pole and equator and decreasing mean temperatures followed by a reverse process (Markov and Velichko, 1967). Annual variations are represented by a similar picture. This indicates the existence of a rough similarity in the changes of thermal fields during glacial and annual oscillations. If we assume atmospheric circulation to be stationary for large characteristic times, the above-said similarity in the changes of thermal fields may result in similar changes between climatic and annual variations during general atmospheric circulation. The term "annual variations of general atmospheric circulation" implies changes wherein diurnal, synoptical and intraseasonal fluctuations are smoothed down. A study of the climatic course of the general atmospheric circulation presupposes smoothing of the annual fluctuations, i.e. only changes in mean annual characteristics are implied.

If one were to consider the atmosphere as a rotating liquid system heated nonuniformly at the equator and the pole, the most important criterion of similarity would be Kibel's thermal number (Monin, 1969):

$$\mathrm{Ki}_T = (gh/\alpha^2 \ell_0^2)\Gamma/\theta, \qquad (1)$$

where θ is the mean atmospheric temperature, Γ the difference of the averaged temperature between the equator and the pole, g the acceleration of gravity, α the Earth's radius, h the height of uniform atmosphere, and ℓ_0 the characteristic value of the Coriolis parameter. Estimates of Γ and θ for times of maximum and minimum glaciation, and also for January and July in recent times are shown in Table 1. Taking $g = 10$ m/sec^2 and $\ell_0 = 10^{-4}$ sec^{-1}, we obtain estimates for Ki_T, also shown in Table 1.

It is readily apparent that in the annual variations we can always select the time interval (month, season or any other part of the year) for which the Ki_T number is equal to the value characteristic of the climatic period that is of interest to us. Thus, January and maximum glaciation of the Northern Hemisphere are characterized by virtually the same Ki_T numbers. A warm half year, in respect to Ki_T, corresponds to minimum glaciation. Estimates for characteristic wind Velocity are readily found from the relation for the thermal wind (u_T). The calculated values of u_T are shown in Table 1. When estimating Γ, the averaged temperature at 10° N. was equated to that of Polar zone.

TABLE 1. ESTIMATES OFT, θ, Ki_T AND u_T FOR ANNUAL AND GLACIAL OSCILLATIONS*

Hemisphere		Recent Period		Glacial Oscillations	
		January	July	Maximum glaciation	Minimum glaciation
Northern	Γ, K	49	20	53	30
	θ, K	280	294	280	289
	Ki_T	0.018	0.007	0.019	0.01
	u_T, m/sec	18	7	19	10
Southern	Γ, K	34	50	49	39
	θ, K	289	283	282	286
	Ki_T	0.012	0.018	0.017	0.014
	u_T, m/sec	12	18	17	14

* Data on glacial fluctuations were taken from a paper by S. Ya. Sergin (1974) and those on annual fluctuations from R. F. Sokhrina *et al.* (1959).

The estimates refer to temperatures at the Earth's surface, though, strictly speaking, estimates of temperatures for the entire troposphere are required. On the other hand, it is common knowledge that the underlying surface temperature satisfactorily characterizes the temperature of the entire troposphere. The zonal profiles of temperatures at different altitudes (Khanevskaya, 1967) are shown in Fig. 1, wherefrom it is apparent that strong temperature changes depending on latitude correspond to weak changes in the vertical difference between temperatures in the troposphere. Hence, the vertical difference of temperatures in the troposphere, averaged over a lengthy period, is essentially a conservative characteristic**. Consequently, estimates of underlying surface temperatures characterize with sufficient accuracy the temperature of the entire thickness of the troposphere (see Table 1).

Estimates of Kibel's thermal numbers confirm the assumption concerning similarity of changes in the general atmospheric circulation during annual and glacial oscillations. This circumstance gives grounds for a detailed analysis of the problem of similarity that would be based on the study of the system of hydrodynamic and thermodynamic equations of the atmosphere.

1. ANALYSIS OF ZONAL ATMOSPHERIC CIRCULATION

The following equations were obtained by Kochin (1935) for non-stationary circulation:

$$\frac{\partial}{\partial r}\left(\mu\frac{\partial V_\vartheta}{\partial r}\right) + 2\omega\rho\cos\vartheta V_\psi = \frac{1}{r}\frac{\partial p}{\partial \vartheta} + \rho\frac{\partial V_\vartheta}{\partial t}, \qquad (2)$$

$$\frac{\partial}{\partial r}\left(\mu\frac{\partial V_\psi}{\partial r}\right) - 2\omega\rho\cos\vartheta V_\vartheta = \rho\frac{\partial V_\psi}{\partial t} \qquad (3)$$

** This fact forms the basis of the thermotropic model (Thompson and Gates, 1956), where the following equation is accepted $\partial T/\partial x = F(\xi)\partial T/\partial x$; $\partial T/\partial y = F(\xi)\partial \overline{T}/\partial y$. F (ξ) is a certain standard function determined empirically.

$$\partial p/\partial r + g\rho = 0, \tag{4}$$

$$\frac{\partial(\rho r^2 \sin\vartheta)}{\partial t} + \frac{\partial(\rho\omega r^2 \sin\vartheta)}{\partial r} + \frac{\partial(\rho V_\vartheta r \sin\vartheta)}{\partial\vartheta} = 0 \tag{5}$$

The heat influx equation is represented as follows:

$$c_p\rho\frac{\partial T}{\partial t} + c_p\rho\frac{V_\vartheta}{r}\frac{\partial T}{\partial\vartheta} = \frac{\partial}{\partial r}\lambda'\frac{\partial T}{\partial r} + \tag{6}$$

$$\frac{1}{r^2\sin\vartheta}\frac{\partial}{\partial\vartheta}\lambda''\sin\vartheta\frac{\partial T}{\partial\vartheta} + \frac{\partial R}{\partial r} + Lb$$

$$p = R\rho T, \tag{7}$$

where λ' and λ'' are coefficients of vertical and horizontal eddy thermal conduction; ϑ the latitude complement; R the net radiation flow per unit area; b the rate of moisture condensation for unit volume; and L the latent heat of vaporization. Other symbols are conventional. If we write (2)–(7) in dimensionless form, it turns out that all the similarity numbers in the system are contained in (2) and (6). Hence, let us confine ourselves to their analysis only.

$$\frac{1}{Re}\left(\frac{\alpha}{h}\right)^2\frac{\partial}{\partial r}\left(\mu\frac{\partial V_\vartheta}{\partial r}\right)\frac{1}{Ki}\rho\ell V_\psi = \frac{1}{Eu}\frac{1}{r}\frac{\partial p}{\partial\vartheta} + Sh\rho\frac{\partial V_\vartheta}{\partial t} \tag{2}$$

In the above equation, the primes representing dimensionless variables are omitted. The equation of heat influx is as follows:

$$\frac{\alpha}{u\tau}\rho\frac{\partial T}{\partial t} + \rho\frac{V_\vartheta}{r}\frac{\partial T}{\partial\vartheta} = \frac{\Lambda''_0}{u\alpha}\left(\frac{\lambda'_0}{\lambda''_0}\right)\left(\frac{\alpha}{h}\right)^2\frac{\partial}{\partial r}\lambda'\frac{\partial T}{\partial r} +$$

$$+\frac{\Lambda''_0}{u\alpha}\frac{1}{r^2\sin\vartheta}\frac{\partial}{\partial\vartheta}\lambda''\sin\vartheta\frac{\partial T}{\partial\vartheta} + \frac{R_0\alpha}{c_p\rho_0 T_0 u h}\frac{\partial R}{\partial r} + \frac{L b_0\alpha}{c_p\rho_0 T_0 u}b,$$

where Λ''_0 and u are characteristic values of the coefficient of horizontal eddy thermometric conductivity and horizontal velocity. Other characteristic values have a zero index. One can select the amplitude of annual and climatic temperature fluctuations as the characteristic temperature value T_0 . By using the known relationship $\alpha/u = h/\omega$ and noting that the characteristic value of vertical eddy heat flow $q = c_p\rho\omega'T'$ may be recorded as $Q_0 = c_p\rho_0\omega T_0$, we get $R_0\alpha/c_p\rho uhT_0 = R_0/Q_0$.

Similarly $Lb_0\alpha/c_p\rho_0T_0u = Lb_0h\alpha/c_p\rho_0T_0hu = B_0/Q_0$ where B_0 is the moisture condensation heat influx for unit area. Now the heat influx equation acquires the following form:

$$Sh\rho\frac{\partial T}{\partial t} + \rho\frac{V_\vartheta}{r}\frac{\partial T}{\partial\vartheta} = \frac{1}{Pe}\left(\frac{\lambda'}{\lambda''_0}\right)\left(\frac{\alpha}{h}\right)^2\frac{\partial}{\partial r}\lambda'\frac{\partial T}{\partial r} +$$

$$+ \frac{1}{Pe}\,\frac{1}{r^2\sin\vartheta}\,\frac{\partial}{\partial\vartheta}\lambda''\sin\vartheta\,\frac{\partial T}{\partial\vartheta} + \frac{R_0}{Q_0}\,\frac{\partial R}{\partial r} + \frac{B_0}{Q_0}\,b$$

The following similarity numbers follow from the equation of motion:

$Re = u\alpha/\mu$; $Ki = u/\alpha\ell_0$; $Eu = \rho u^2/\pi$; $Sh = \alpha/u\tau$,
where π is the characteristic pressure difference, and τ the characteristic time. The states of zonal atmospheric circulation similar with respect to the Ki_T number are also similar with respect to the Re, Ki and Eu numbers; this is apparent from the estimates of wind velocity and temperature difference (Table 1). The Sh number for $\tau \geqslant 1$ year is small (about 10^{-2} and less); hence the quasi-stationary circulation of the atmosphere.

In current investigations of general atmospheric circulation, the exchange coefficient is usually considered constant or dependent on the horizontal temperature gradient $\lambda''_0 \sim \Gamma$. Hence, the phenomena discussed may be considered similar with respect to $Pe = u\alpha/\lambda''_0$. A macroturbulent transfer in the atmosphere is achieved by cyclones and anticyclones, wherein the vertical and horizontal velocity components are interrelated in accord with the continuity equation. Consequently, the intensities of horizontal and vertical eddy transfers are also interrelated. Hence the constance of $\xi=\lambda'_0/\lambda''_0$ for general atmospheric circulation. In changes with large characteristic times, the moisture condensation rate for the whole atmosphere is unambiguously determined by evaporation rate. Turbulent flows of heat and moisture are interrelated by the known Bowen ratio. That is, turbulent heat flows and condensation rates are also interrelated and, hence, states of general atmospheric circulation are similar in respect to the ratio B_0/Q_0.

Annual fluctuations in general circulation are caused by the annual course of incoming solar radiation. Changes in solar radiation inputs during climatic fluctuations are unknown. In the worst case (for fulfilling conditions of similarity), radiation input should be considered constant. The amount of solar radiation absorbed directly in the atmosphere is from twenty to thirty per cent of the total solar radiation absorbed. This amount may serve as an estimate of the maximum error in fulfillling the similarity conditions for R_0/Q_0. On the other hand, the effect of that error may be insignificant. In her study, Rakipova (1966) calculated the vertical profile of the mean annual temperature for ice-free Arctica and the vertical profile of the temperature over the warm half year for the recent climatic epoch (Table 2). These calculations virtually coincide, despite the fact that in the warm half year of the recent period heat influxes are determined by changes in incoming solar radiation, while in the period when Arctica was ice-free they were caused by albedo variations, heat advections, and other causes.

In their numerical experiment, Manabe and Wetherald (1967) showed temperature distribution over the entire troposphere to be virtually the same, irrespectively of what had caused changes in heat influx, changes in incoming solar radiation, changes in the amount of cloudiness, or changes in the albedo of the underlying surface (Fig. 2).

TABLE 2. CALCULATED VALUES OF MEAN ANNUAL TEMPERATURES IN ICEFREE ARCTICA AND OF WARM HALF–YEAR TEMPERATURES IN THE RECENT EPOCH (RAKIPOVA, 1966).

	Ice-free Arctica, mean annual temperatures (calc.), T°C			Recent Epoch					
				Warm half year, calc.			Warm half year, found		
φ° c.w Z, km	70	80	90	70	80	90	70	80	90
0	2	0.5	−0.5	2	0	−2	3	−2	−5
1	−0.5	−1.5	−2.0	−1	−3	−4	−1	−6	−7
2	−4.5	−6.0	−7.0	−4	−7	−8	−5	−7	−10
4	−12.5	−13.0	−13.5	−14	−16	−17	−15	−17	−18
6	−31.5	−34	−34.5	−27	−30	−31	−28	−31	−32

The general impression is that the heat budget on the level of the underlying surface is chiefly important for the thermal regime of a stationary turbulent atmosphere. The effect of the nature of individual components of the budget is insignificant in its first approximation. The equality of temperatures over the underlying surface during annual and climatic variations indicates the equality of the heat budgets, wherein the solar radiation component absorbed directly by the atmosphere had already been accounted for. Thus, due to the specific properties of the atmosphere, insolation changes are accounted for under-conditions existing on the lower boundary, these conditions being decisive in determining thermal regime of the atmosphere.

An estimation of the similarity numbers resulting from the system of equations (2)–(7) allows one to consider the similarity of changes in the zonal atmospheric circulation in the course of annual and climatic fluctuations as established. At the same time, the states of the atmosphere, similar with respect to the Ki_T number, proved to be likewise similar with respect to all other numbers.

Changes in the temperature zonal field in the course of climatic variations with typical times of 10^2 or 10^3 years are of the same character as in the course of glacial and annual variations; the only difference is their small amplitude (Mitchell, 1966; Willet, 1958). The above-cited analysis of the similarity of changes in the zonal circulation of the atmosphere is fully justified for this case, too.

According to paleoclimatic reconstructions (Willet, 1958; Flohn, 1969), the beginning of a cold epoch is accompanied by a shift towards the equator of the main zonal system of winds and cyclone tracks. The wind velocity and the amount of precipitation increase in all the principal convergence zones. The warm epoch is characterized by a shift of zonal flows and cyclone tracks from middle to high latitudes and by increased precipitation in the area. The intensity of atmospheric circulation and the clarity of the zonal picture decrease. Annual variations, as is known, are characterized by similar events. Thus, the conclusion on the similarity of changes in zonal atmospheric circulation in the course of annual and climatic variations is confirmed by empirical facts.

2. PROBLEM OF SIMILARITY FOR NON–ZONAL CIRCULATION OF THE ATMOSPHERE

In our assessment, a smoothed annual course of general atmospheric circulation is essentially a physical model of the climatic course of mean annual fields of meteorological elements. It is common knowledge that two physical systems are similar if they are described by the same system of equations and are geometrically similar; if the same physical parameters of the equations are similar; if the processes are stationary or similar; if the initial conditions determining similarity numbers are equal (except for automodel cases); and if the boundary conditions are similar.

The first condition is fulfilled since variations of only smoothed values of variables are considered: annual course of meteorological element fields, averaged for a time period of about one or several decades, and climatic course of mean annual fields. The second and third conditions are fulfilled due to the physical identity of the systems. The processes are approximately stationary in both phenomena. As was established above for the case of zonal circulation, similarity numbers are approximately equal. It is readily apparent that in a more common case of non-zonal circulation no new questions arise regarding the equality of semilarity numbers.

It was stated above that insolation changes over the external boundary of the atmosphere are roughly expressed by lower boundary conditions, which themselves determine the thermal regime of the atmosphere. Precisely for that reason the equality of Kibel's thermal numbers proved sufficient to determine the similarity of the states of zonal atmospheric circulation. Consequently, in the more general case of non-zonal circulation, the determining condition of similarity is the similarity of thermal fields over the lower boundary of the atmosphere.

As is known, differences between the thermophysical properties of continents and oceans generate non-uniformities in the thermal fields along geographic latitudes. Due to the small coefficient of thermal conduction of ground, surface temperature on continents becomes steady within several hours or days. Hence, land surface reacts in about the same way to changes in heat flows with different times. The coefficient of eddy thermal conduction in the ocean is several times greater; hence, essentially different temperature changes on its surface should be expected with changes in heat flows with different characteristic times. This could be the reason for violations in the similarities of changes in the non-zonal component of the thermal field in the course of annual and climatic oscillations. Let us now attempt to find quantitative estimates for glacial climatic fluctuations.

The equality of the numbers $F_0 = K\tau / h^2$ essentially follows as a similarity condition from the heat conduction equation

$$\frac{\partial T(z, t)}{\partial t} = R \frac{\partial^2 T(z, t)}{\partial z^2} \quad (0 < z < h) \qquad (8).$$

Annual fluctuations involve the upper ocean layer $(1 \div 2).10^4$ cm thick. In taking $=10$ cm^2/sec for $\tau = 3.10^7$ sec, we find $F_0 \approx 0.8 \div 3$.

The entire ocean ($h \approx 4.10^5$ cm) is involved in climatic fluctuations ($\tau = 3.10^{11}$ sec). The thermal conduction coefficient for the entire thickness of the ocean is apparently one order of magnitude lower than that for the upper layer (Brien & Cox, 1967), for instance, recommend $R=1$ cm^2/sec for the entire ocean, even though for the upper layer it is 10 cm^2/sec, wherefrom $F_0 \approx 2$. The said estimates, despite all their approximation, reveal an interesting circumstance: the reaction of the ocean to fluctuations with characteristic periods of 1 and 10^4 years is similar in respect to Fourier's number. Along with what was stated previously concerning land reaction, this signifies that variations in temperature non-uniformities along latitudes in the course of annual and climatic fluctuations may be similar.

Now let us consider in greater detail the reaction of the ocean to annual and long-period changes in environmental conditions. In as much as horizontal transfers of heat and salts by currents are by one or two orders of magnitude higher than turbulent transfers (Koslov, 1969; Sarkisyan, 1966), we shall discard the latter. Geostrophical relationships for large-scale movements in the ocean are superior by 2–3 orders of magnitude to those in the atmosphere (Sarkisyan, 1966); hence, let us restrict ourselves to a geostrophic approximation. Then the equations in dimensionless form would be as follows:

$$\ell V_\psi = -\frac{\mathrm{Ki}}{\mathrm{Eu}}\frac{\partial p}{\partial \vartheta}, \quad \ell V_\vartheta = \frac{\mathrm{Ki}}{\mathrm{Eu}}\frac{\partial p}{\partial \psi}, \tag{9}$$

$$\frac{\partial p}{\partial r} = -\frac{\mathrm{Eu}}{\mathrm{Fr}}\rho, \tag{10}$$

$$\frac{1}{\sin\vartheta}\left[\frac{\partial V_\psi}{\partial \psi} + \frac{\partial}{\partial \vartheta}(V_\vartheta \sin\vartheta)\right] + \left(\frac{\alpha}{u}\;\frac{\omega}{h}\right)\frac{\partial \omega}{\partial r} = 0, \tag{11}$$

$$\frac{\partial T}{\partial t} + \frac{1}{\mathrm{Sh}}\left(\frac{V_\psi}{\sin\vartheta}\frac{\partial T}{\partial \psi} + V_\vartheta\frac{\partial T}{\partial \vartheta} + \omega\frac{\partial T}{\partial r}\right) = F_0\frac{\partial^2 T}{\partial r^2}, \tag{12}$$

$$\frac{\partial S}{\partial t} + \frac{1}{\mathrm{Sh}}\left(\frac{V_\psi}{\sin\vartheta}\frac{\partial S}{\partial \psi} + V_\vartheta\frac{\partial S}{\partial \vartheta} + \omega\frac{\partial S}{\partial r}\right) = F_0\frac{\partial^2 S}{\partial r^2} \tag{13}$$

$$\rho = \rho(T, S) \tag{14}$$

The primes designating dimensionless variables have been omitted. From (9) it follows that Ki/Eu=1, wherefrom $\pi = \rho_0 \ell_0 \alpha u$. This equality is well realized in the process of the annual reconstruction of current fields and cannot, apparently, be noticeably violated in the yet slower climatic evolution of currents. Eu/Fr=1, which follows from (10), is trivial and invariably realized for large-scale movements. As always, $\alpha\omega/uh=1$. Similarity of phenomena in respect to the F_0 number was established above. The numbers of $Sh=\alpha/u\tau$ for annual and climatic oscillations differ by at least one order of magnitude. This signifies that the adaptation processes of current fields in the course of annual and climatic variations do not possess temporal uniformity. Thus, as a result of the above analysis, it is possible to consider established only an approximate similarity, averaged for the area of the ocean's reaction to environmental changes, with characteristic times of 1 and 10^4 years.*

Yet, there is still another complicating factor. In the epoch of maximum glaciation, large continental ice covers additionally form non-zonal components of the thermal field. True, in winters of the recent epoch, snow fields on continents are also an important thermal factor. At such periods, areas with deepest snow covers prove to coincide approximately with areas where large covers were present in the past (Chizhov, 1972). And, hopefully, the glacial factor may not cause large deviations from the similarity of thermal fields.

The above analysis allows one to consider as established the similarity in the changes of zonal atmospheric circulation in the course of annual and climatic oscillations. Judging from our estimates, variations in general atmospheric circulation (without zonal averaging) are also roughly similar. Moreover, this similarity is realized better for warm half-periods, and worse, on account of the glacial factor, for cold periods.

The annual course of meteorological fields can be considered as a physical experiment. When information on changes in the annual course is available, it is possible to determine the mean annual characteristics

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** The values of Sh for annual and climatic oscillations are 10^{-1} and Sh $<<10^{-1}$, respectively. In the latter case, the processes are quasi-stationary, whence similarity conditions are fulfilled with higher accuracy.

of atmospheric circulation in differents climatic epochs. This can be readily achieved by selecting a certain time interval, not less than one month, characterized by the same Ki_T number as a given climatic epoch. The averaged integral characteristics of general atmospheric circulations, determined empirically for that interval, are characteristic of the mean annual circulation of the climatic epoch studied. The annual course of atmospheric circulation supplies experimental material that can be used to find numerical values for parameters in equations for different climate models and to construct all kinds of empirical relationships intended for climatological computations.

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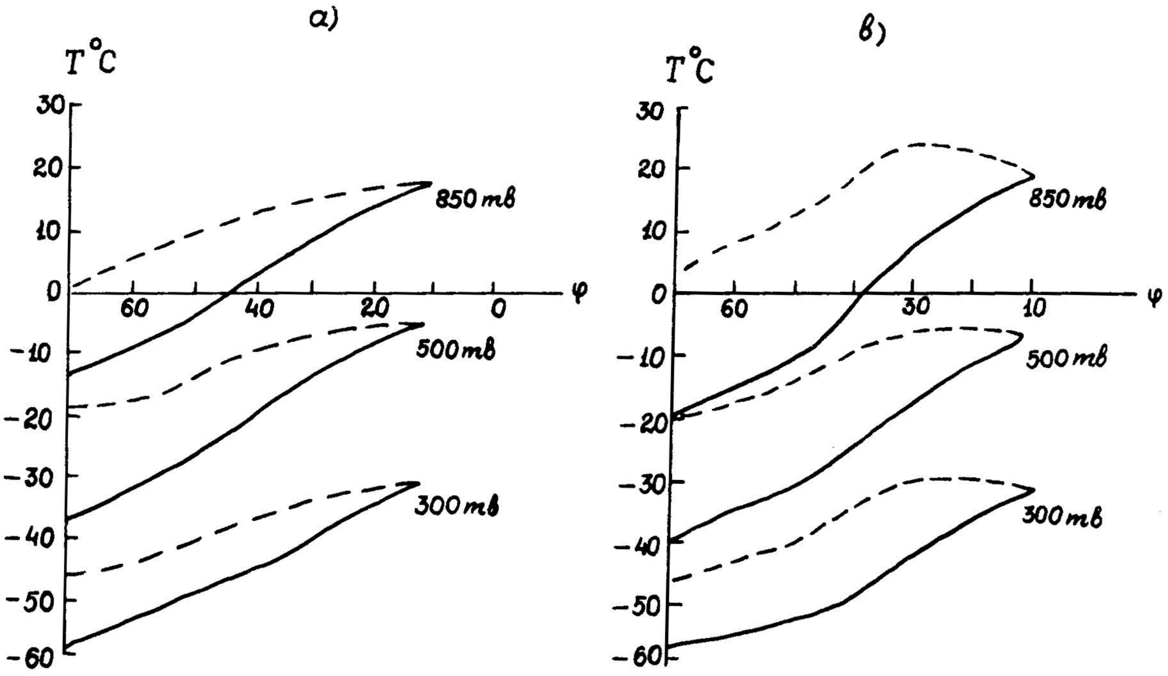

Fig. 1. Zonal temperature profiles over oceans (a) and continents (b) in Northern Hemisphere for January (———) and July (- - - - -) in accord with Khanevskaya (1967).

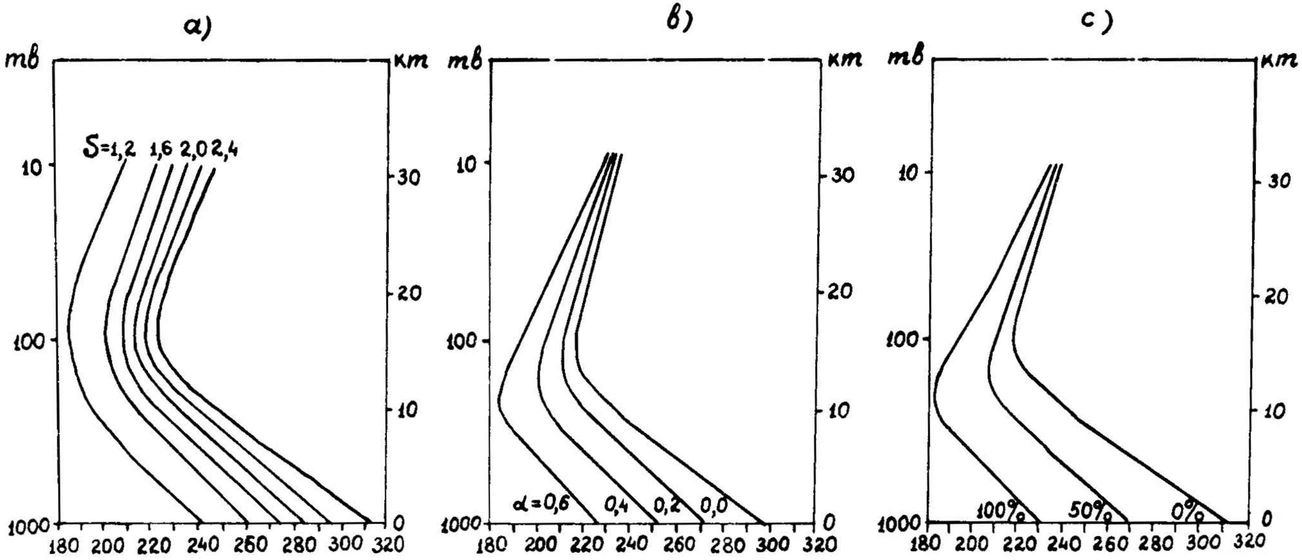

Fig. 2. Temperature variations in atmosphere with different a) solar constant S, b) Earth surface albedo α and c) amount of cloudiness, % (Manabe and Wetherald, 1967).

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