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**PHYSICS OF EARTH, ATMOSPHERE,  
AND HYDROSPHERE**

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## **Geophysical Thermodynamics: Features of Atmospheric Temperature Stratification in the Annual Cycle**

**I. I. Mokhov<sup>1,2\*</sup>**

<sup>1</sup>*Department of Physics, Lomonosov Moscow State University, Moscow, 119991 Russia*

<sup>2</sup>*Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow, 119017 Russia*

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**Abstract**—The results of data analysis and model calculations are presented, indicating the significant role of the temporal periodicity of boundary conditions with periodic spatial scanning in the formation of atmospheric temperature features of the planetary system, as an object of geophysical thermodynamics, along with key physical processes, including radiative and convective heat transfer. Specifically, the results of model calculations with a changed length of the annual cycle confirm that the tropopause height corresponds to the height characteristic of the temperature skin layer for the annual cycle of insolation.

**Keywords:** atmospheric temperature stratification, tropopause, annual cycle of insolation, data analysis, modeling, general circulation models, scanner-model

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### INTRODUCTION

The terrestrial system, including the Earth's climate system (ECS) with the atmosphere, oceans, lithosphere, cryosphere, and biosphere as its components, is considered as an object of geophysical thermodynamics ([1], see also [2–9]). In geophysical hydrodynamics, rotation and stratification are fundamental; while, in geophysical thermodynamics, the temporal periodicity (cyclicity) of boundary conditions, including those with periodic spatial scanning by a heat source (solar radiation flux), is of key importance [1]. In this case, the applicability of thermodynamic models with temperature as the key variable is characterized by the condition (for example, see [10])

$$\tau_D/\tau_T \ll 1, \quad (1)$$

and the applicability of zonal thermodynamic models is characterized by the condition

$$\omega \tau_T \gg 1, \quad (2)$$

where  $\omega$  is the angular frequency of the Earth's rotation,  $\tau_D$  and  $\tau_T$  are the characteristic times of dynamic and thermodynamic (radiative) processes in the climate system, respectively.

In thermodynamically nonequilibrium planetary systems, including the ECS, the cyclicity of external conditions and internal processes is essential. The

energetics of the ECS as an open system is determined by the influx of solar radiation with periodic changes in insolation in both diurnal and annual cycles and in the millennial features of changes in the parameters of the Earth's orbit around the Sun. The cyclicity of the boundary conditions for the ECS is associated with the structural features of climatic variables, such as the temperature field, and their evolution, which leads to the formation of forced structural features in different components of the Earth's system (atmosphere, hydrosphere, lithosphere, cryosphere, and biosphere). Against the background of forced structural features (due to external periodic forcings) in the terrestrial dynamical system with a large number of variables, structural features are also formed as a result of intrasystem self-organization processes. Depending on negative and positive feedbacks, there can be not only regimes with the adaptation of the Earth system to certain, not necessarily stationary, states as a function of external (time-dependent) conditions, but also unstable regimes with the increase of fluctuations with possible transitions to new regimes. The manifestation of resonant phenomena is also possible under the corresponding external periodic forcings and the natural oscillatory features of the system [1]. The periodicity of the solar radiation influx, including strong variations in the annual and diurnal cycles, is associated with the features of the atmospheric and oceanic stratification; the features of the active layer

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\*E-mail: mokhov\_ii@physics.msu.ru

of the land, the cryosphere, and biosphere manifest themselves.

For the Earth's atmosphere, the distribution of temperature in the atmosphere with height has characteristic layers (the troposphere, stratosphere, mesosphere, and thermosphere) as well as an outermost region (the exosphere). Within the near-surface troposphere, surface and planetary boundary layers appear. Different ionospheric layers are also identified. In the oceanic temperature field, the near-surface layer, the upper mixed layer, the seasonal thermocline, and the main thermocline are identified. There are also layers in the density and salinity fields (pycnocline and halocline). The manifestation of layered structure features of climatic fields, including the tropopause, can be associated with different processes. For example, the main features of the vertical distribution of temperature in the troposphere and stratosphere can be described using the heat influx equation, incorporating radiative influxes and vertical heat transfer in a turbulent atmosphere [11–14].

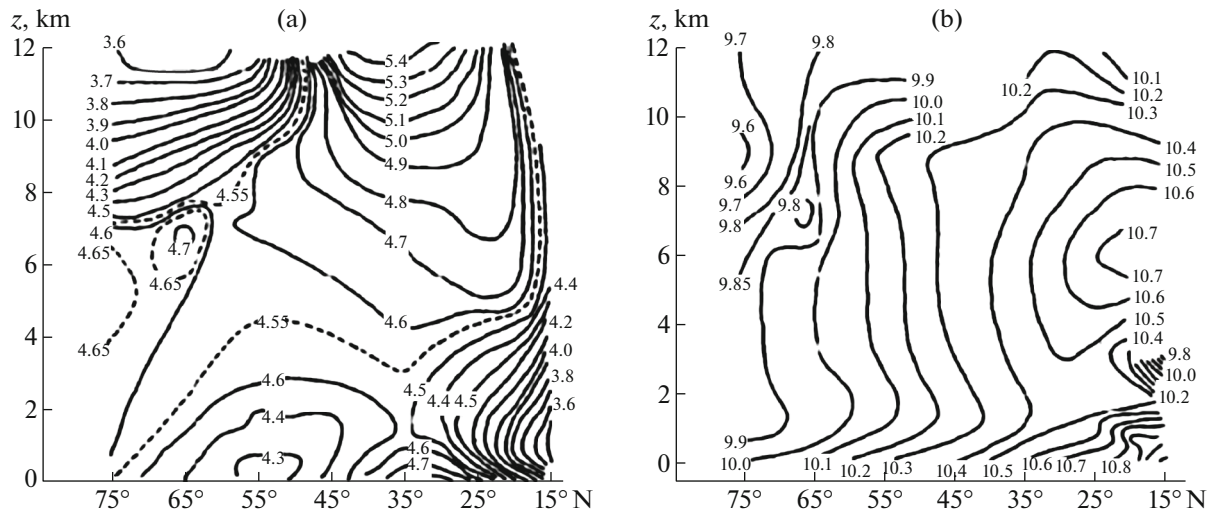
This paper considers the features of the temperature stratification of the Earth's atmosphere and its changes due to the annual cycle of insolation. Specifically, the features of temperature changes in the troposphere with the formation of the tropopause are analyzed. One problem of atmospheric physics that has important implications for climate and climate change is to identify the mechanisms of the tropopause height formation. The troposphere is the near-surface layer with three-quarters of the total mass of the Earth's atmosphere and almost the entire mass of water vapor. The troposphere, that is, the layer of the Earth's atmosphere from the surface to a height of 8–9 km in polar and up to 15–17 km in equatorial latitudes, also includes boundary and surface layers [1, 13, 15, 16]. The troposphere is characterized by a nearly linear decrease in temperature with height at about 6 K/km on average [17–19].

Processes in the annual cycle are analyzed largely through harmonic Fourier analysis [20] as well as other methods with decomposition into different modes. However, cyclic changes with significant asymmetry with respect to the average (annual mean) value lead to problems in the physical interpretation of the results of harmonic analysis of the processes. In view of this, [2, 3] proposed a special method of amplitude–phase characteristics (MAPC) without decomposition into modes to analyze climatic variations in the annual cycle, such as temperature variations at different atmospheric levels and in different latitudinal zones of the Northern (NH) and Southern (SH) hemispheres. The MAPC allows one to reveal the fundamental differences in the temperature dynamics in the troposphere in the

annual cycle in the warming (in spring) and cooling (in fall) seasons, which is difficult to diagnose using the Fourier expansion into annual, semiannual, and other harmonics. Among others results, the MAPC for the NH generally revealed that the annual-mean temperature regime within the troposphere up to the mean-hemispheric height of the tropopause (about 12 km) is achieved during spring warming with a delay relative to the surface. This indicates that the tropospheric heating up to the tropopause in the annual cycle occurs generally from the surface. Above the tropopause, the annual-mean regime is reached in spring earlier than at the surface and the stratospheric source of heating must be different associated with heating due to the ozone layer. The use of the MAPC is also characterized by specific features of the surface layer (due to the diurnal variation of insolation) associated with a local maximum of heating delay relative to the surface as well as the planetary boundary layer associated with a local minimum of heating delay relative to the surface.

An analysis of atmospheric heating in the annual cycle depending on latitude and altitude suggested that the “spring” (0-phase: the time when local annual-mean temperature regime is reached) in the NH propagates from the equator to the tropospheric subtropics and simultaneously shifts from the subpolar stratosphere due to heating for the ozone layer in the stratosphere. In subpolar latitudes, the maximum ozone content in the stratosphere is lower than in middle and low latitudes, and the identified feature of subpolar stratospheric heating in spring is in good agreement with its position [2, 13]. Then, the atmosphere begins to warm from the surface at midlatitudes, followed by the formation of a common isochron from isochrones of the spring 0-phase from the equatorial side and from the surface of midlatitudes. In this case, the subtropical high-pressure region within the boundary layer has the feature that the local “spring” comes later. The convergence of the 0-phase isochrones shifting from the surface and from the stratosphere results in the formation of “secondary” isochrones, with the extension of the spring phase into the polar troposphere and the upper troposphere of middle and subtropical latitudes [2]. In this case, a delay in the heating phase is revealed both in the region of the subtropical jet stream and in the region of the polar jet stream.

The dynamics of isochrones of the  $\pi$ -phase characterizing the time when the local annual-mean temperature regime is reached during fall cooling, differs significantly from the dynamics of the 0-phase isochrones (see Fig. 1) [2]. For the spring phase, the atmospheric heating from the surface is generally convective, and the stratospheric heating is associated with the ozone layer. The fall thermodynamics



**Fig. 1.** Successive isochrones of (a) 0-phase and (b)  $\pi$ -phase of the annual cycle of atmospheric temperature depending on altitude and latitude in the Northern Hemisphere.

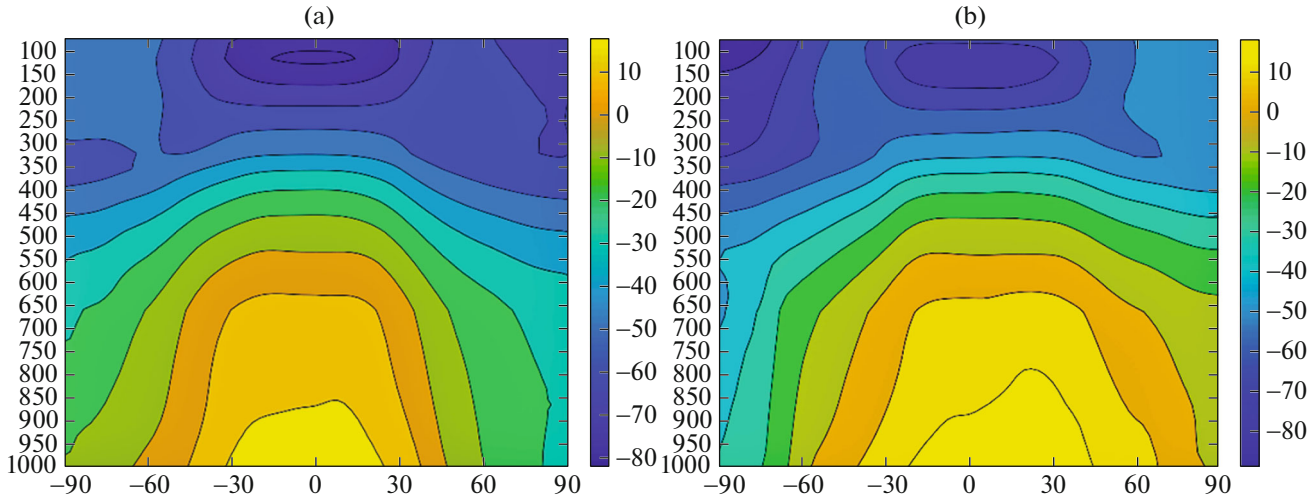
is characterized by atmospheric cooling of the advective type. The fall-phase isochrones are vertical and shift from polar to low latitudes. At the same time, the  $\pi$ -phase isochrones shift from the equator in the opposite direction above the boundary layer. As a result, the “front” of the  $\pi$ -phase moving from polar latitudes is divided into two “secondary” parts continuing to move towards the equator: one over the atmospheric boundary layer and the other inside it. The characteristic rates of displacement of the 0- and  $\pi$  phases for the atmospheric temperature regime in the annual cycle are estimated at about 10 m/h for the vertical velocity and about 10 km/h for the horizontal velocity. The results of the analysis of temperature variations in the atmosphere in the annual cycle led to the conclusion that the height of the tropopause corresponds to the height characteristic of the temperature skin layer for the annual cycle [2, 3].

The annual cycle of insolation is also associated with fundamental differences in intra-annual temperature dynamics in the stratosphere and mesosphere [1, 7]. Along with the features of the vertical temperature stratification of the atmosphere in connection with the annual cycle of insolation, structural features of the dynamics of the latitude–longitude fields of climatic variables are manifested. In the annual cycle of solar radiation influx to the ECS (with significant effects of its scanning by the Sun as a heating source), regional features appear not only in the temperature field, but also in other climatic variables [1]. For example, the cloudiness field is characterized by a counterclockwise circular rotation of isochrones of the annual mode for general cloudiness over Eurasia and adjacent water areas around Central Asia. When identifying the 0- and

$\pi$ -phases against the background of circular rotation over Eurasia and adjacent water areas, one can reveal that their successive isochrones (in spring and fall) have different shift directions in the Indian monsoon region [1, 21, 22]. These features of the dynamics of cloudiness and related precipitation make it possible to explain the well-known correlation [23] of snow cover in Eurasia (depending on cloudiness and precipitation in cold months) and subsequent monsoonal precipitation over India (see [1]).

The key features of the annual cycle of the atmospheric temperature regime in latitude–altitude resolution, revealed in [1–3], can be qualitatively described using the model of a two-dimensional system with vertical thermal conductivity and horizontally moving (scanning) heat source (scanner-model), which was proposed in [8] (see also [1]). According to [1, 2], the average rate of the interlatitudinal displacement of the boundaries of the 0- and  $\pi$ -phases of the annual cycle of the temperature regime (modes of reaching the local annual-mean regime in spring and fall) in the troposphere is close to the rate of displacement (approximately 10 km/h) of corresponding phase boundaries for insolation with a delay of about a month. This rate corresponds to a fast (within a month) horizontal displacement of the phase boundary of the mean annual regime from the pole to tropical latitudes (70° latitude/month).

When describing the spring warming of the atmosphere quickly scanned by a heating source (by variable insolation with an annual period  $T = 2\pi/\omega$ ) with noninteracting vertical atmospheric columns (without horizontal exchange), even the simplest version of the proposed scanner model reproduces the main features of the annual cycle of the temperature



**Fig. 2.** The seasonal distributions of temperature (right-hand scale in °C) in the troposphere and lower stratosphere depending on latitude (from 90° N to –90° S) and altitude (in hPa) in (a) December–February and (b) June–August according to model calculations with the current length of the annual cycle.

field reported in [1–3]. In this case, the vertical heat transfer in each atmospheric column is described by the nonstationary equation

$$c\rho(z)\frac{\partial T}{\partial t} = \frac{\partial(\lambda(z,t)\partial T/\partial z)}{\partial z} + F(z,t) \quad (3)$$

with a variable coefficient of thermal conductivity. Here,  $\rho(z)$  is the air density at level  $z$ ,  $c$  is the heat capacity,  $\lambda$  is the coefficient of thermal conductivity,  $T$  is temperature, and  $F$  is a nonstationary heat source. The atmospheric columns in the scanner-model are characterized by the corresponding latitude  $\varphi$ . The study [8] considered the simplest version of the scanner-model (with a constant coefficient of thermal conductivity and an exponential vertical density profile with the boundary condition  $T(z=0, \varphi, t) = T_0 \cos[\omega(t - t_0(\varphi))]$  at the lower boundary), for which the solution of the heat equation for the atmospheric column at latitude  $\varphi$  has the form

$$T(z, \varphi, t) = T(z=0, \varphi) - \gamma z + A_0 e^{-az} \cos[\omega(t - t_0) - az]. \quad (4)$$

Here,  $t_0(\varphi) = R_E(\varphi - \varphi_0)/V$ ,  $R_E$  is the Earth's radius,  $V(\varphi)$  is the characteristic rate of interlatitudinal displacement of a certain phase of the temperature wave at the lower boundary in the annual cycle of insolation,  $\gamma$  is the vertical temperature gradient in the troposphere,  $a = (\omega/2k)^{1/2}$  is the annual cycle frequency, and  $k$  is the effective coefficient of thermal conductivity. The characteristic equation for (4) in the plane of vertical ( $z$ ) and horizontal ( $x = R_E\varphi$ ) coordinates has the form

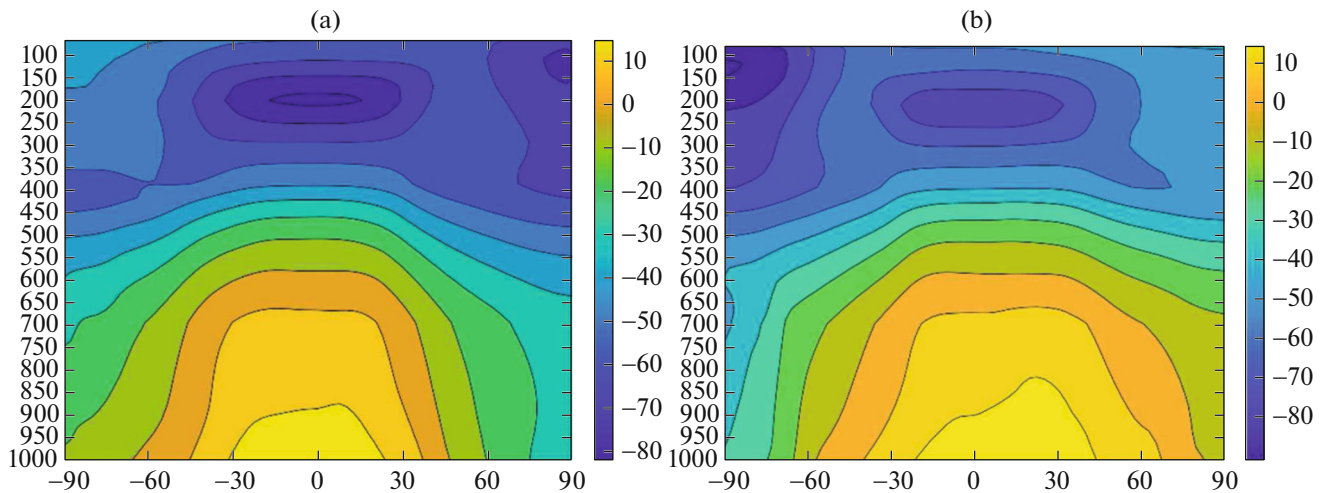
$$az + \omega(x - x_0)/V = \text{const.} \quad (5)$$

Here, the isochrones of the constant phase of the annual cycle of the atmospheric temperature regime in the scanner-model [8] are determined by the equation

$$[\omega/2k(x)]^{1/2}z + \omega V^{-1}(x)x = \text{const.} \quad (6)$$

If we assume that  $V(\varphi) > 0$  [21, 22] (the boundary of the 0-phase of the near-surface temperature shifts from the equator to the pole) in spring for the NH as a whole, the 0-phase isochrones in the atmosphere have an equatorward slope. In fall, when  $V(\varphi) < 0$ , successive  $\pi$ -phase isochrones shift equatorward from the pole and are inclined towards the pole. The scanner-model describes the key features of temperature changes (noted from real data) in different latitudinal zones in the annual cycle, taking into account the inhomogeneity of the underlying surface and differences in the thermodynamic properties of the ocean and land. The model also takes into account the ozone-related heating at higher layers of the atmosphere (in the stratosphere). The scanner-model proposed in [8] has the limitation that it cannot identify the features of the boundary layer, over which the horizontal heating and cooling of the atmosphere propagate faster than inside it. To describe these effects in the ECS as a thermodynamic-type system, low-parameter models should take into account the horizontal transfer [1].

A more detailed analysis of results of simulations with the model of atmospheric general circulation in [24] revealed that simulations of the annual cycle allow the key general features of the change in the atmospheric temperature regime in the annual cycle, revealed in [2, 3] from observational data, to be rather adequately reproduced. In this case, there are some



**Fig. 3.** The seasonal distributions of temperature (right-hand scale in °C) in the troposphere and lower stratosphere depending on latitude (from 90° N to –90° S) and altitude (in hPa) in (a) December–February and (b) June–August according to model calculations with half the value of the current annual cycle.

differences arising from modeling the interaction between the troposphere and the stratosphere.

To assess the role of the annual cycle of insolation (periodic forcing) in the tropopause formation, we conducted special numerical calculations using a climate model of general circulation for different annual cycle lengths (see [25]). Figure 2 shows the seasonal latitude–altitude distributions of temperature in the troposphere and lower stratosphere in (a) December–February and (b) June–August according to model simulations for the current length of the annual cycle (365 days). In this case, the height of the tropical tropopause is at a level of about 100 hPa (approximately 16 km), and the height of the tropopause in polar latitudes is about 300 hPa (approximately 8–9 km).

Figure 3 shows the seasonal latitude–altitude distributions of temperature in the troposphere and lower stratosphere in (a) December–February and (b) June–August according to model simulations with a half value of the current annual cycle length. In this case, the tropical tropopause height is at a level of about 200 hPa (approximately 11–12 km). The model results confirm the conclusion made earlier from the analysis of climate data using the MAPC that the troposphere thickness (tropopause height) corresponds to the height of the temperature skin layer for the atmosphere under cyclic heating from the surface due to the annual cycle of insolation. In model simulations, the tropopause height obtained with half the annual cycle length was  $\sqrt{2}$  less than the value obtained with the current length of the annual cycle.

The influence of cyclic boundary conditions with different periodicity (from diurnal cycle to periods of hundreds of thousands of years, including different

Milankovitch cycles for changes in the Earth’s orbital parameters) manifests itself in the layered structure of the ocean, in active layers of land, in the cryosphere, and in the biosphere [1]. For example, in the annual cycle of oceanic temperature fields, boundary layers of the influence of continents appear at a distance of hundreds of kilometers within the upper mixed layer of the ocean due to the annual cycle of insolation [6]. At different time scales, the Earth’s crust layers associated with the formation and degradation of permafrost soils (with hysteresis effects) manifest themselves [26]. The estimates obtained here give evidence of the significant role of the temporal periodicity of boundary conditions with periodic spatial scanning in the formation of atmospheric (and climatic) structural features of the planetary system as an object of geophysical thermodynamics, along with key physical processes such as radiative and convective heat transfer. Similar effects should manifest themselves for the atmospheres of other planets as well. Specifically, the substantial difference in characteristic heights of the tropopause for planets of the Solar System is associated not only with the composition and thermodynamic features of planetary atmospheres, but also with the parameters of their orbits around the Sun and rotation around their axis and their variations.

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