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Impact of Helio- and Geophysical Disturbances on Thermobaric and Climatic Characteristics of the Earth's Troposphere

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Abstract—We present the mechanism and the concept of a model of the solar activity impact on thermobaric and climatic characteristics of the troposphere. Both are based on the idea of parametric action. The results of analysis are presented concerning specific features and regularities of changes in temperature regime of the troposphere in the period of variable helio- and geophysical activity, as well as long-term variations of temperature and heat content of the troposphere. The influence of changes in circulation in the atmosphere and ocean on processes in the system atmosphere–ocean–cryosphere is considered: thermohaline circulation of the oceans and energy exchange between the atmosphere and ocean. The revealed regularities find their complete explanation within the context of a model and mechanism of solar activity impact on climatic characteristics of the troposphere that were suggested previously by the authors.

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INTRODUCTION

Changing climate exerts a great impact on men's activity, agriculture, transport, economy, and environment as a whole. Of utmost importance is an answer to the question: what are the causes of global warming (GW) in recent decades? In many respects these causes remain unclear, as well as quantitative estimations of contributions of various factors to variation of the global climate. Even to a greater extent this is true about forecasts of climate taking into account anthropogenic impacts. One of the main among unsolved problems is the absence of convincing *quantitative* estimates of the contribution of anthropogenic factors to formation of the global climate (we emphasize that the very fact of anthropogenic impact on climate is without doubt). There are many uncertainties in modern knowledge about the global climate and causes of its variation. The biggest uncertainty is associated with inadequate consideration of interactive processes in the system "aerosol–clouds–radiation" and also interactions in the system "atmosphere–hydrosphere–cryosphere." Intensification of the greenhouse effect caused by presumed doubling of the CO_2 concentration in the atmosphere can be equal to about 4 W/m^2, while uncertainties in numerical simulation of climate associated with due regard of climate-forming role of the atmosphere aerosol and clouds can reach 10 to 15 W/m^2 [1].

At the moment most scientists are inclined to believe that the GW in recent decades is caused by the anthropogenic factor. However, this factor is known to be not alone, and there are other factors influencing the climate. Observed correlations of long-term variations of the global temperature (GT) and CO_2 content do not mean that CO_2 is the cause of increasing GT, since the increasing temperature of the ocean (which is really observed) also leads to an increase of CO_2 content in the atmosphere, i.e., the variation of CO_2 content can be a consequence rather than a cause of the GW [2].

SOLAR ACTIVITY AND CLIMATE

In papers [3–8] the solar variability is considered as one of possible causes of the global warming. In recent years the mechanisms of solar activity influence on weather and climate through galactic cosmic rays are widely discussed. Since both flux and spectrum of cosmic rays are modulated by the interplanetary magnetic field which is controlled by solar activity, the cosmic rays can represent one of connecting links between variations on the Sun and the global climate. The possibility of albedo modulation due to changes in cloudiness caused by variations of the flux of galactic cosmic rays (GCR) was indicated in paper [4]. Unfortunately, experimental data on the relation between cosmic rays and cloud coverage at middle latitudes are rather contradictory, and this hypothesis has so far no anywhere convincing confirmation from the standpoint of real quantitative estimations [9]. It is obvious that cosmic rays are not a single link in the solar-troposphere connection. Reaction of the troposphere to geomagnetic disturbances cannot be explained with the help of GCR, as was demonstrated in many papers [3].

A fundamentally different physical mechanism of solar activity impact on climate characteristics and the atmosphere circulation through atmospheric electricity was suggested by the authors in papers [10–12]. According to the data of measurements of atmospheric electricity, during geomagnetic disturbances, as in the periods of intrusion of large fluxes of solar cosmic rays into the polar latitude regions, considerable increases of the electric field in the troposphere and of the current from the ionosphere to the ground are observed. Variations of the electric field can have an effect on charged particles in the troposphere and, hence, they lead to redistribution in height of charged aerosols which can serve as nuclei of condensation in the atmosphere, thus impacting the conditions of cloud formation. The appearance of cloudiness results in changed radiation balance, diminished radiation cooling, and changed thermobaric field of the troposphere.

MODEL OF SOLAR ACTIVITY IMPACT ON THE TROPOSPHERE

Based on the mechanism considered, a physical model of impact of solar activity on climatic characteristics of the Earth's troposphere is developed [11]. The key concept of this model is an influence of helio- and geophysical disturbances (HGD) on those parameters of the terrestrial climatic system that control the energy flow going away from the Earth into space through the high-latitude regions. The main agent of solar activity making an impact on weather and climate characteristics of the troposphere is the parameters of the solar wind and interplanetary magnetic field which determine geomagnetic activity and influence variations of the electric field of the high-latitude atmosphere. In addition, a certain contribution to the electric field variations in the high-latitude troposhere is made by the fluxes of solar cosmic rays (SCR) generated during solar flares.

The most efficient manifestation of this should be observed in high-latitude regions (in the zone of the auroral oval during magnetospheric disturbances and in the polar cap region, with a maximum at the geomagnetic pole, during SCR intrusions), leading to additional cloud formation (in the regions where there is sufficient concentration of water vapors) over oceans in coastal areas.

With increasing level of solar activity, a decrease of the level of radiation cooling of high-latitude regions will take place, as well as an increase of temperature of the lower troposphere, reconstruction of the thermobaric field, and reduction of the average meridional gradient of temperature between polar and equatorial regions, which determines the meridional heat transfer. This will be accompanied by a decrease of heat outflow from the low-latitude regions, which should result in increased surface air temperature (SAT) in middle and low latitudes, and an increase of heat content in ocean and the climatic system as a whole.

MANIFESTATIONS OF ISOLATED HELIO- AND GEOPHYSICAL DISTURBANCES IN TEMPERATURE OF HIGH-LATITUDE TROPOSPHERE

Based on the data of NCEP/NCAR Reanalysis, we have performed our analysis of the response of thermobaric characteristics of the troposphere to intrusion of anomalously large fluxes of solar cosmic rays (SCR) in the period 1968–2005. It should be noted that, as a rule, substantial geomagnetic disturbances are observed in 1–2 days after SCR intrusion. Daily maps of anomalies in pressure and temperature at standard levels were constructed for every event in the Northern hemisphere. Based on these maps, an analysis of changes in the field of pressure and temperature of the high-latitude troposphere was performed for the period of anomalous helio- and geophysical disturbances (HGD). In [11] it was shown that after HGD a change in the typical zonal transfer was observed, consisting in the fact that some moving structures became stationary. Moreover, it turned out that precisely the regions where this occurred were the regions of maximum response of the troposphere to HGD.

As an example, Fig. 1 presents helio- and geophysical characteristics for one typical event. The anomalously large flux of SCR was observed on November 7, 2004. An extreme magnetic storm followed on the second day after the arrival of the SCR stream. One can see this in the data on the indexes of geomagnetic activity K_p and D_{st} presented in Fig. 1. The day of arrival of SCR stream is chosen as a reference date (day 0).

Successive changes of the altitude profile of deviations of air temperature from the day preceding the HGD onset (day –1) in the 'stationary' region (55–65°N, 205–215°E) are presented in Fig. 2 for the period 7–12 November, 2004. It is obvious that after HGD an increase of air temperature is observed from the ground surface to the level of 300 hPa. Above this level a decrease of temperature takes place. The maximum increase of air temperature in the stationary region is observed on the 4th day in the layer 500–700 hPa.

This event corresponds to the resultant action of two components of helio- and geophysical disturbance which exert influence upon the electric field of the high-latitude troposphere. These components are the flux of solar cosmic rays and magnetospheric convection.

SPECIFIC FEATURES OF CHANGES IN HEAT CONTENT OF HIGH-LATITUDE TROPOSPHERE AFTER INDIVIDUAL HGD

The analysis of changes in heat content of the troposphere (925–500 hPa) in the regions of individual HGD manifestations and in the entire latitude zone 50°–90° north has shown that an increase of the heat content of the lower and middle troposphere is observed, and it can reach a few percent of the seasonal trend amplitude.

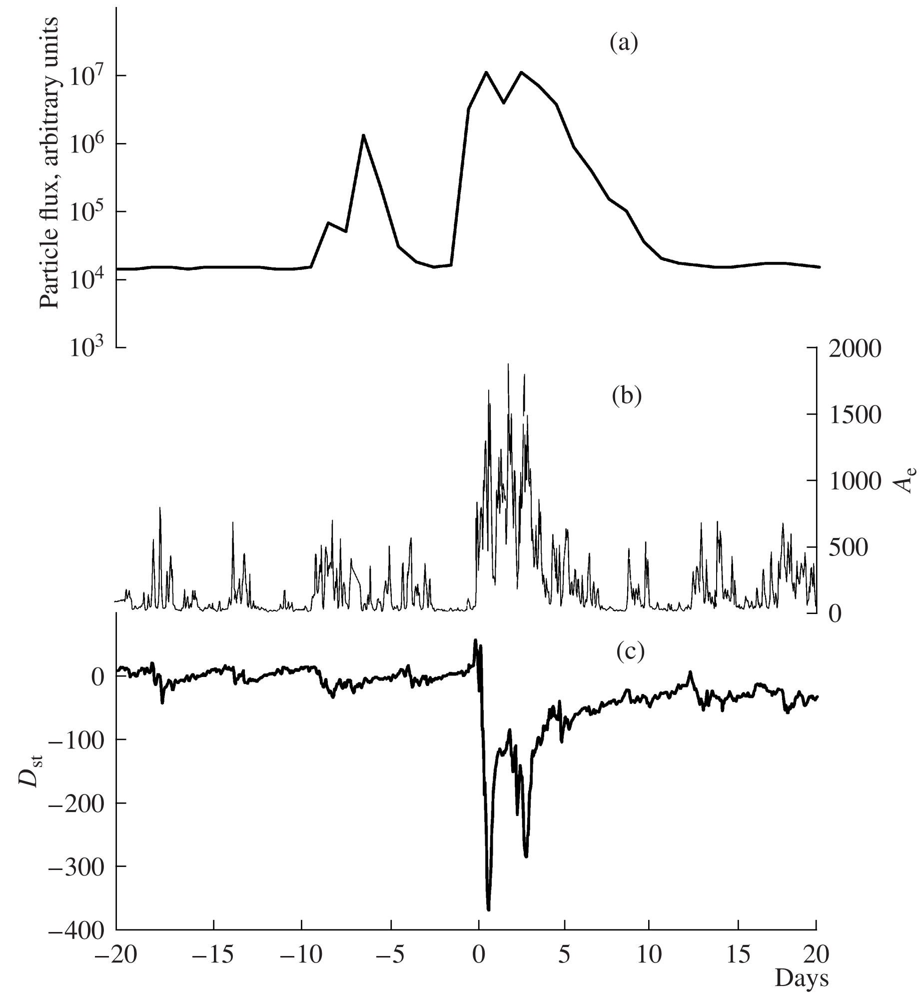

Fig. 1. Characteristics of a helio- and geophysical disturbance: solar cosmic ray flux (a), A_e index (b), and D_{st} index (c). Days from the onset of HGD are laid off on the abscissa axis.

Figure 3 presents the plot of variation of the anomalies of the mean zonal heat content in the zone 50°–90°, obtained by the epoch superposition method for 13 events. It is clear that a substantial increase of the heat content of the lower and middle troposphere is observed after HGD.

It should be noted that the real increase of the heat content of the climatic system is much larger, since heat fluxes to the underlying surface (especially to the ocean) are not taken here into account, as well as latent heat.

LATITUDE DEPENDENCE OF TEMPERATURE VARIATION IN THE TROPOSPHERE

In accordance with the climatic models that include both natural and anthropogenic factors the manifestation of warming substantially differs with latitude. In particular, from global climatic models it follows that with increasing concentration of greenhouse gases in the atmosphere at the initial stage of warming, when a significant part of heat is expended in the polar regions for melting the ice sheets, one should expect the strongest warming at the middle and low latitudes. According to the model suggested by us the regularity is quite opposite, i.e., warming should be first observed in high latitudes with subsequent expansion to low latitudes. In addition, the maximal increase of air temperature should be observed in the cold season of the year, when arriving flux of shortwave solar radiation is small or absent in the polar region, and the appearance of any cloudiness should result in diminished radiation cooling below the level of cloud formation, i.e., to warming.

Figure 4 presents variations of the near-ground air temperature in different latitude zones of the Northern and Southern hemispheres in the period 1948–2006. It is obvious that warming in the second half of the 20th century started earlier at high latitudes (namely, in the beginning of 1960s), and at low latitudes it began in the middle of 1970s, i.e., the wave of warming propagates from high to low latitudes. In this case, the increase of the near-ground air temperature (NGAT) at polar lati-

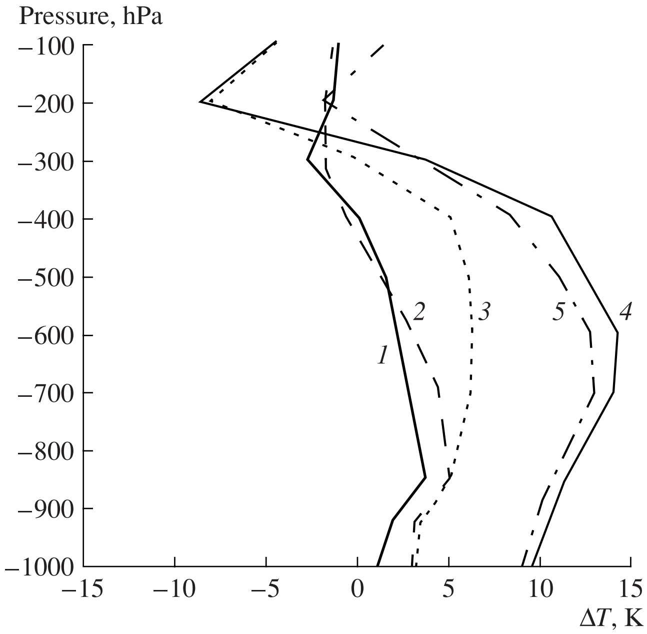

Fig. 2. Altitude profile of deviations of air temperature from that on the day preceding the HGD onset in the stationary region (55°–65°N, 210°–220°E) in the period from 7 to 12, November, 2004. *1* is zero day (day of HGD), and *2–5* are the numbers of says after HGD beginning.

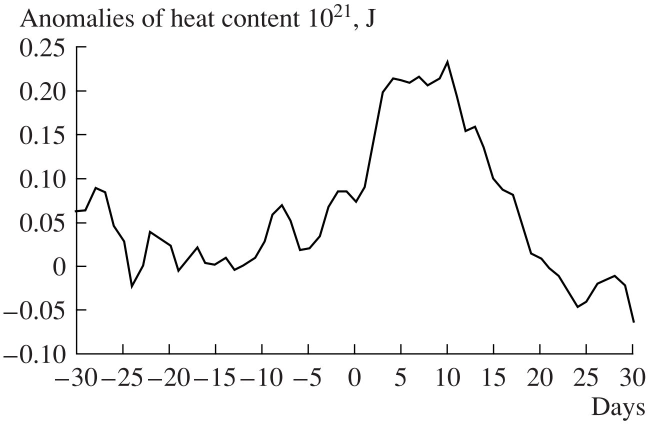

Fig. 3. Deviations of the mean heat content in the interval 50°–90° north latitude for 13 HGD (method of superposed epochs). Days from the onset of HGD are laid off on the abscissa axis.

tudes was ~4–5° (for the cold period). The amplitude of NGAT variation is maximal at high-latitude regions, both in the Northern and Southern hemispheres, and it decreases with approach to the equator. It should be also noted that in the period of cooling of the Northern hemisphere troposphere in 1950–1976 observed at middle and low latitudes, an increase of temperature took place at low and middle latitudes of the Southern hemisphere.

Of special interest is to analyze, in connection with the suggested model, the NGAT variations in different seasons. From the data presented in Fig. 5 it follows that the increase of mean annual NGAT for high-latitude regions is caused mainly by an increase in the cold period. In the period under consideration virtually no increase of NGAT is observed in the warm season at latitudes above 40° both in the Northern and Southern hemispheres.

LONG-TERM VARIATIONS OF TEMPERATURE IN THE TROPOSPHERE

Let us consider a scenario of possible contribution of solar activity to the observed climatic changes in the 20th century according to the model under discussion. We emphasize that almost in all climatic models the effect of solar activity is included via direct influence (variation of the solar radiation approximately by 0.1%) on the troposphere, which, in our opinion, cannot make a significant contribution to changes of the Earth's climate.

Changes in the global climate are associated with changing heat content of the Earth's climatic system, whose major part is determined by the ocean. The radiation balance of the Earth is characterized by the fact that at low latitudes the solar radiation absorbed by the terrestrial system exceeds losses due to emission. The situation is opposite at high latitudes: here the heat losses exceed the amount of absorbed solar radiation. The observed climatic temperature distribution over the Earth is maintained due to inter-latitude transport of energy. This climatic function is executed by the systems of circulation in the atmosphere and the World Ocean. In this connection the system turns out to be sensitive to changes in heat losses in high-latitude regions and to corresponding changes in the meridional gradient of temperature and in the heat outflow from low-latitude regions. Consequently, the changes of losses in high-latitude regions can substantially influence the heat content of the terrestrial climatic system and the climate.

In the model suggested by us the main factor exerting the decisive impact of the solar activity on the weather-climate characteristics of the troposphere is parameters of the solar wind and interplanetary magnetic field which determine the geomagnetic activity. It is worthy of noting that long-term variations of the geomagnetic disturbance smoothed over 11-year cycles correlate sufficiently well with the sunspot number. However, within separate 11-year solar cycles this correlation is unstable. In addition, one should pay special attention to the following (very important from our point of view) peculiarity in long-term variations of the geomagnetic activity: starting from 1900 and until 1960 the minimum values of geomagnetic activity increased, while minimum values of the solar activity level estimated by the Wolf numbers were virtually invariable

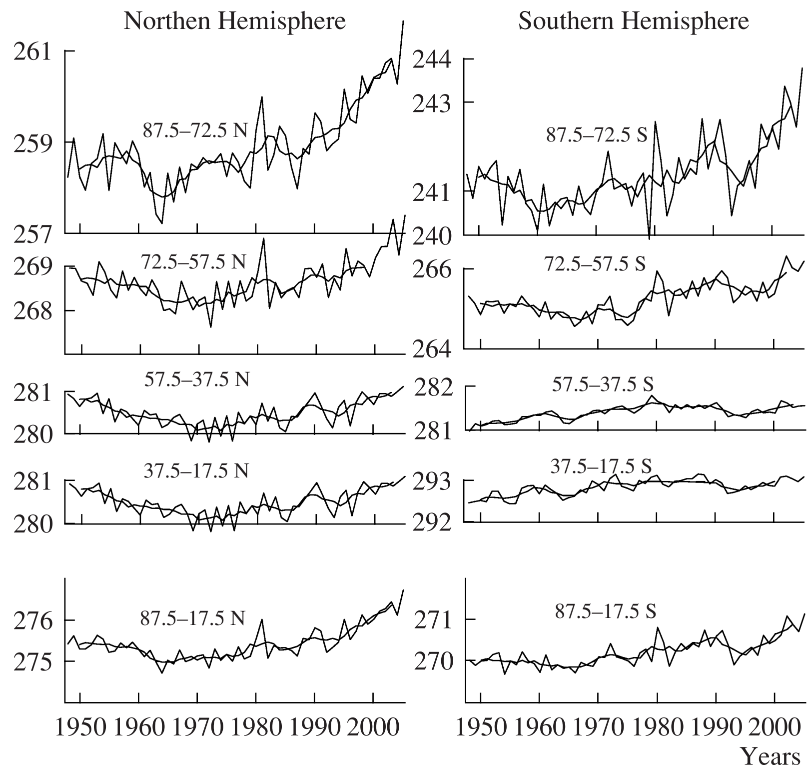

Fig. 4. Long-term variations of near-ground temperature of air in different latitude zones of the Northern and Southern Hemispheres.

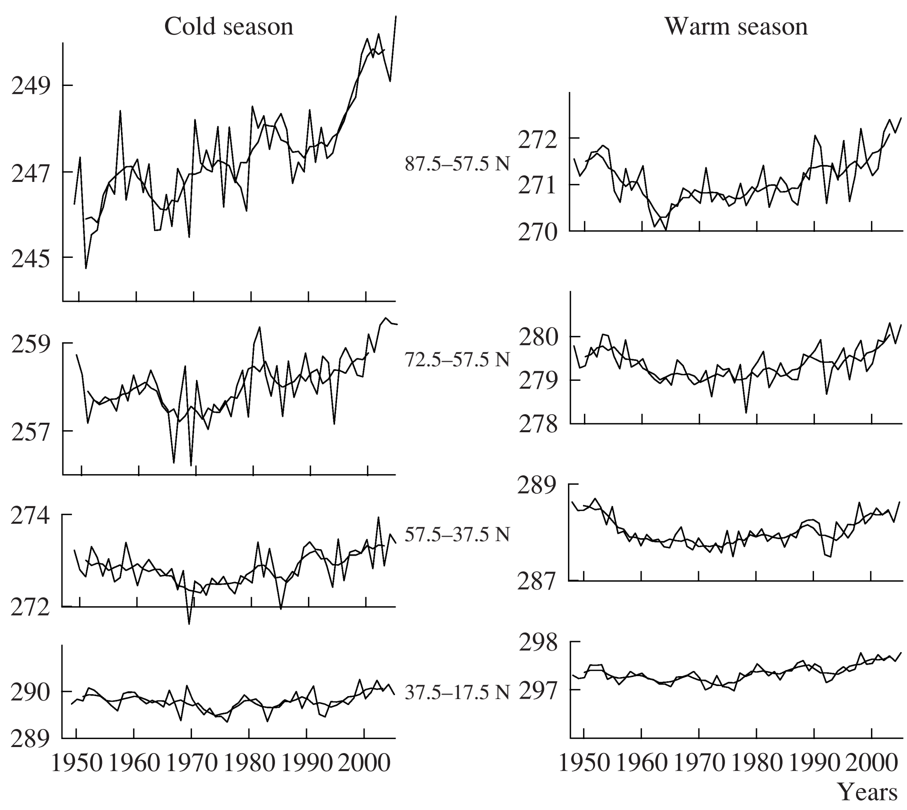

Fig. 5. Variations of NGAT of latitude zones of the Northern Hemisphere in different seasons.

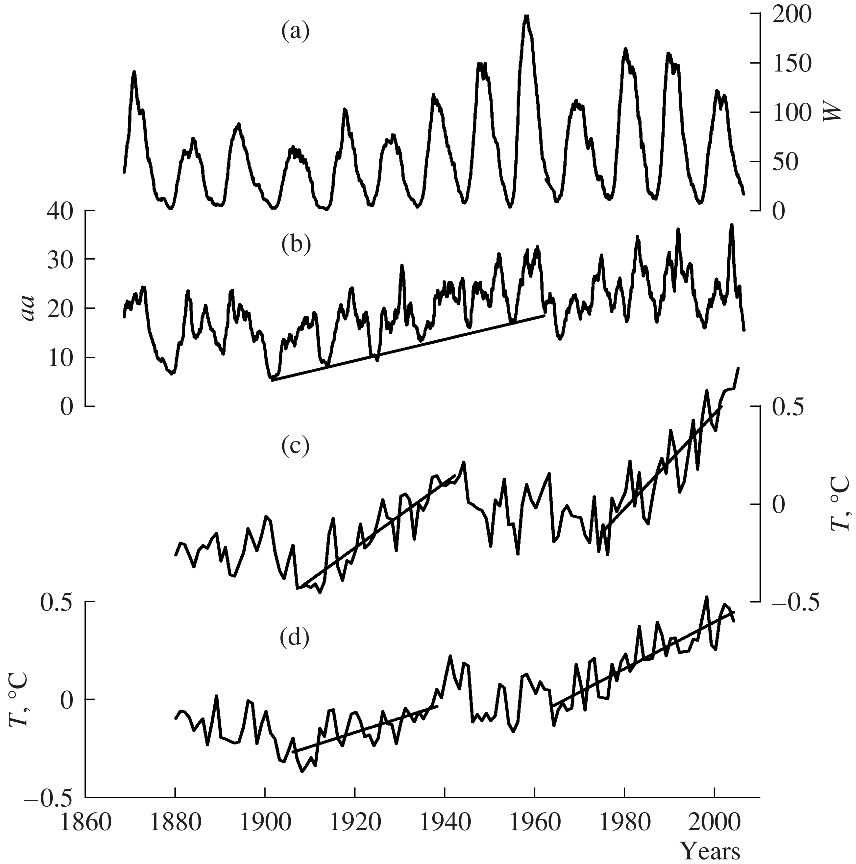

Fig. 6. Long-term variations of Wolf numbers (a), geomagnetic index aa (b), and anomalies of near-ground air temperature in the Northern (c) and Southern (d) Hemispheres.

over the entire period of observation. This can be clearly seen from the data presented in Fig. 6.

Since the beginning of the 20th century a persistent increase of geomagnetic activity is observed, still continuing at the present time. It is characterized by modulation according to 11-year cycle and a certain depression in the period 1965–1975 with a subsequent increase up to 2004. If the proposed model is realistic and correctly describes the basic physical processes in the terrestrial climate system, one should expect certain regularities in changes of climate characteristics due to variations of the geomagnetic activity. In accordance with this model, the increase of geomagnetic activity since the beginning of the 20th century should result in a decrease of radiation cooling and a corresponding increase of temperature in high-latitude regions, with a certain delay due to thermal inertia.

At the end of the 19th century the global warming started to be continued, with an exclusion of the interval 1940–1970, until the present time. The average global temperature has increased by 0.7°C for the last 100 years. This increase of the mean global air temperature during the last century was not monotonic. The data of observations show the existence of a very strong space-time irregularity of changes in the mean annual NGAT. This became apparent, for example, in the fact that climate warming in the 20th century proceeded in two periods: 1919–1945 and from 1976 until present time. Cooling was observed in the Northern hemisphere in the period 1940–1970. One should emphasize a very important and fundamental feature peculiarity: both the first and the second warming were observed mainly in the cold period. The largest increases of NGAT were recorded for night-time (minimum) temperatures in the local winter. These peculiarities correspond to expectations of the model [12].

The increased solar and geomagnetic activities at the beginning of the 20th century coincided with the positive phase of the North Atlantic Oscillation, which facilitated intensification of the inter-latitude heat transport in the atmosphere and ocean due to intense energy exchange associated with the wind stress near the ocean surface, especially in the North Atlantic region. This was accompanied by increased meridional circulation in the atmosphere and the ocean surface waters, which corresponded to the intense meridional heat transfer to the Arctic Zone in 1900–1940. The increase of troposphere temperature (in the period 1910–1940) started earlier in the polar regions with a delay (approximately by 10 years) with respect to the geomagnetic activity increase, which is associated with large heat capacity of the Arctic Basin. The amplitude

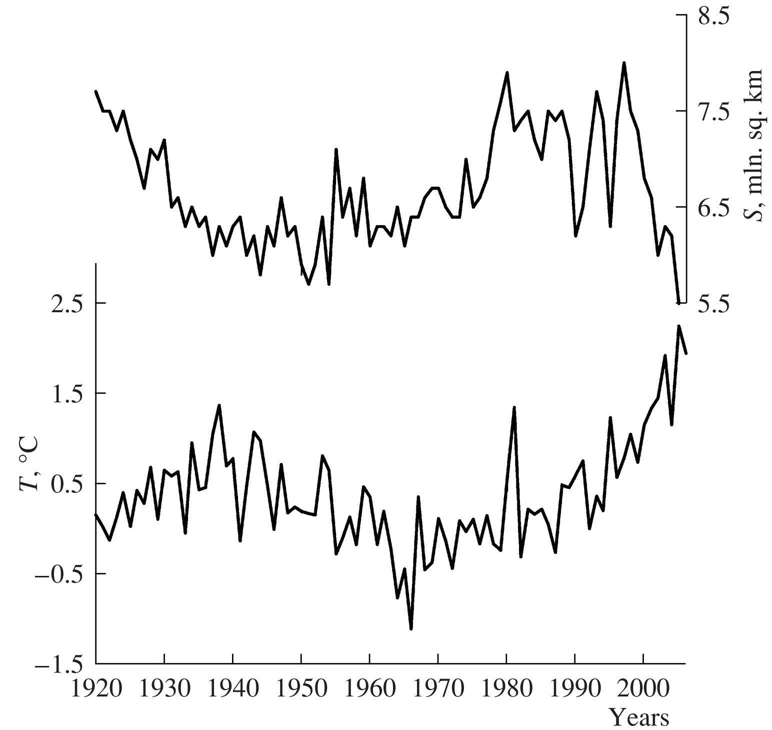

Fig. 7. Long-term variations of the area of ice in the Arctic Zone and anomalies of the near-ground air temperature in high latitudes of the Northern Hemisphere (57.5°–87.5°).

of warming substantially decreases from high to low latitudes. The effective impact of geomagnetic activity on the radiation balance of the polar regions provided for reduced radiation cooling and increased NGAT in high-latitude regions. With a certain delay (1920–1940) effective melting of sea ice in the Arctic Basin (57.5°–87.5°N) began, together with reduction of its area in the warm season (Fig. 7).

The reduced area of sea ice intensifies the action of warming due to positive feedback "warming–decreased icing–decreased albedo–increased air temperature." It is in this period that anomalous increase of NGAT was observed. Being especially significant in the polar regions of the Northern hemisphere, it was changed by cooling in the period 1940–1976. Taking into account that solar and geomagnetic activity continued increasing in this period, until recently the causes of cooling were unclear. A very important feature should be noted: warming continued in this period in low-latitude regions and in the Southern hemisphere. In this connection, let us consider the changes in climatic characteristics occurred in this period more carefully.

CAUSES OF REDUCED NGAT IN THE NORTHERN HEMISPHERE IN 1940–1976

The ocean, atmosphere, dry land, and cryosphere are the main physical components of the climatic system. These components determine the heat content of the terrestrial climate system (ocean giving the capital contribution). There is a considerable asymmetry in distribution of these components over the hemispheres. Accordingly, the reaction to an external action and changes in the thermal regime will be substantially different in the Northern and Southern Hemispheres, both in NGAT and in changes of the heat content of separate components of the climate system. Because of different areas of underlying surface occupied by mainland and ocean in the Northern and Southern Hemispheres, heat capacity and heat content of the Southern Hemisphere is substantially larger. However, since the mean annual air temperature (NGAT) above the continents (16°C) is larger than the surface temperature of the World Ocean (8.6°C), the heat content of the atmosphere in the Northern Hemisphere is larger in comparison with that of the Southern Hemisphere. Precisely due to this fact the NGAR increase in the period 1910–1940 in the Northern Hemisphere was considerably larger than in the Southern Hemisphere (smoothing role of the ocean), which resulted in increased asymmetry of temperature and heat content of the atmosphere in the Northern and Southern Hemispheres. In addition, since the NGAT increase at high latitudes was larger than in low-latitude regions, meridional gradients of temperature in the Northern Hemisphere decreased considerably at all latitudes, while in the Southern Hemisphere this took place only for latitudes higher than 60°.

Thus, in the beginning of 1940s the troposphere's thermobaric field changed significantly, mainly in the

Northern Hemisphere and in equatorial regions. This resulted in a jump-like reconstruction in the beginning of 1940s of the global circulation of the climate system from one state into another equilibrium state. The analysis of circulation conditions in the period 1900–1997 according to the Vangenheim–Girs classification [13] shows that, indeed, anomalously rapid change of the circulation pattern was observed in the Northern Hemisphere at the end of 1930s–beginning of 1940s. A decrease of meridional temperature gradients led to weakening of the meridional circulation in the atmosphere and surface layers of the Atlantic Ocean in the Northern Hemisphere. Accordingly, the meridional heat transfer from equatorial regions to high latitudes reduced in the Northern Hemisphere, and temperature gradually decreased at latitudes higher than 30°. In equatorial latitudes and in the Southern Hemisphere up to 60° a temperature increase was observed in the period 1945–1978 (Fig. 4).

In this period the heat content of the atmosphere decreased in the Northern Hemisphere, while it increased in the Southern Hemisphere. The global NGAT in this case was virtually invariable, and the total heat content of the terrestrial climate system increased considerably due to increasing heat content of the ocean in this period [15–16]. Thus, equalization of the temperature asymmetry and heat content of the atmosphere in the Northern and Southern Hemispheres proceeds in this period until the end of 1970s. According to observational data, during a short period of 1976–1979 the structure of global circulation has changed again, and this was accompanied by a considerable intensification of meridional circulation in the Northern Hemisphere, while zonal circulation became weaker. At the same time, the heat content of the atmosphere of the Northern and Southern Hemispheres has increased substantially. Interaction and circulation in the system atmosphere–ocean–cryosphere had a profound effect on long-term temperature variations in the atmosphere of the Northern Hemisphere in the period 1940–1980.

ANOMALOUS INCREASE OF HEAT CONTENT IN NORTH REGION OF THE ATLANTIC OCEAN IN 1970–1980

Together with the atmosphere, ocean participates in inter-latitude and global heat transfer, thus making substantial contribution to observed climate changes. The Atlantic Ocean play especially important role. The Gulf Stream turning round the west coast of North America carries warm tropical waters in the northern regions of the Atlantic Ocean. These waters are cooled in the Labrador sea and near the coasts of Greenland and Norway, becoming denser they go down to deep sea. This process is of utmost importance for climate formation, since deep waters are formed in these regions, and precisely they represent a driving force of thermohaline circulation that provides for heat transfer in ocean [17].

Warming in the Arctic Zone in the beginning of the 20th century was characterized by considerable space-time and seasonal heterogeneity [18]. The maximum mean annual NGATs were observed in Arctic at the end of 1930s. However, in the period from the end of 1950s to the middle of 1960s unusually high temperatures of air were observed in summer in the region of West Greenland, Baffin Bay, and the adjacent part of the Canadian Arctic Islands. This was accompanied by intensified melting of snow and ice, increased water flow from the surrounding continents, and changes in circulation over the ocean. The mean summer air temperature over many years is the lowest in this region for the entire Arctic Zone, and the largest amount of snow and ice is concentrated here in the winter season [18]. Here, great positive anomalies of air temperature in the period from the end of 1950s to the middle of 1960s facilitated intense summer melting and flow of fresh water into the Artic Basin, Canadian straits, Baffin Bay, and Hudson Strait. The result was that at the end of 1960s water salinity decreased in the upper 200-meter layer because of carrying-out of an anomalously large amount of ice from the Arctic Basin to the east of Greenland and its subsequent melting. This phenomenon was referred to as the Great Salinity Anomaly (GSA). The existence of fresher and, therefore, lighter water on the surface in the regions of forming deep waters led to gradual weakening and then stopping of the deep winter vertical convection in the Labrador sea. Radical changes in water circulation in the North Atlantic occurred in this period. The region of formation of deep waters was displaced to the south to a latitude of about 50°. The surface heat transfer in the ocean became significantly slower, since deep convection became weaker in Greenland, Iceland, and Norwegian seas. Warm waters were accumulated at an intermediate depth (300–800 m) in the regions to the south of 50° north latitude. The anomalous increase of heat content occurs in this period in the Atlantic Ocean precisely at depths of 500–700 m [16]. It was caused by a considerable change of circulation of not only surface, but also deep waters in the North Atlantic. The GSA had other consequences too. Since the meridional surface water exchange through the subpolar front in the North Atlantic became weaker, the ingress of heat into high latitude regions and its release to the atmosphere decreased. The anomalously low temperatures were observed in this period both for the ocean surface in the North Atlantic [19] and for air in Arctic, as well as increased area of sea ice in the Arctic Basin during warm seasons.

Thus, together with the positive feedback (1920–1940) "warming–reduction of icing–increased temperature of air", the following negative feedback operates (1940–1975): "warming–desalination in the upper layer–slower (weakened) thermohaline circulation of water in ocean–decreased heat flux from ocean into the atmosphere–decreased air temperature–increased extension of the sea ice." This process is responsible for anomalously strong increase of heat content of the Atlantic and World Oceans in 1970–1980.

CONCLUSIONS

In conclusion, let us emphasize some important and fundamental features of functioning the terrestrial climate system in the 20th century. The results of performed analysis of regularities in changes of geomagnetic activity and thermobaristic characteristics of the troposphere, as well as allowance made for rapid radical changes of the global circulation in the atmosphere and ocean, allow us to draw the conclusion that the major part of warming observed in the 20th century can be caused by variation of the solar activity level. The anomalies of NGAT in the periods 1940–1975 and 1976–1979, and changing heat content of the World Ocean are a consequence of special features of the response of the thermal and dynamic regimes of the World Ocean and the atmosphere to changes in the processes in the atmosphere, ocean, and cryosphere, whose beginning is associated with warming in the polar regions in the early 20th century. Of extreme importance in this case are the changes in ice mass in the Arctic Basin and in runoff of northern rivers (both regulate water salinity in the North Atlantic, characteristics of thermohaline circulation, and energy exchange between the atmosphere and the ocean).

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