Role of the solar and geomagnetic activities in change of the Earth's climate

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The problem of global climate change in the 20th century and its nature is under discussion. The issue of anthropogenic nature of global warming in last decades, as well as contribution of natural factors and solar activity, is of special importance. IPCC experts (Climate Change 2007) concluded that the Earth's climate in the 20th century changes due to the increasing CO_2 content caused by anthropogenic activity. A new concept of the effect of solar activity on parameters of the Earth climate system managing the energy flux outgoing from the Earth into the space in high-latitude regions is described. A physical mechanism and a model of the effect of solar activity on climate parameters and heat content of the atmosphere are presented and discussed. Long-term variations of the temperature and heat content in the troposphere are analyzed. The probable contribution of solar activity to variations of the tropospheric heat content and the Earth's climate system in the 20th century is estimated.

Climate change strongly affects the human activity, agriculture, transport, economy, and environment in general. The answer to the question what is the cause for global warming (GW) in the last decades is of primary significance. The most important aspect of the problem is that although the fact of warming in the 20th century is doubtless (especially, in the last quarter of the century), the causes of the phenomenon and, especially, quantitative estimates of contributions from different factors to the global climate change remain unclear. This is especially true for prognoses of climate taking into account the anthropogenic impact. One of the main unsolved problems is the lack of convincing *quantitative* estimates of the contribution of anthropogenic factors to formation of global climate. There are many uncertainties in the modern understanding of the global climate and causes for its change. The main uncertainty is associated with inadequate consideration of interactive processes in the "aerosol – clouds – radiation" and "atmosphere – hydrosphere – cryosphere" systems. Intensification of the atmospheric greenhouse effect due to assumed doubling of the CO_2 concentration in the atmosphere may amount about $4\ W/m^2$, while uncertainties associated with consideration of the climate-forming role of atmospheric aerosol and clouds in numerical simulation of climate can achieve $10–15\ W/m^2$ [Ref. 1].

The scientific opinion now tends to accept that GW in the last decades is caused by anthropogenic impacts. It is known, however, that it is not the only factor affecting climate. Observed correlations between long-term fluctuations of GW and the CO_2 content do not mean that CO_2 causes GW, since the actually observed increase of the ocean temperature also causes the increase of atmospheric CO_2, that is, CO_2 fluctuations may be a consequence, rather than cause of GW.[2]

Solar activity and climate

In a series of papers,[3–6] solar variability is considered as one of possible causes for global warming. Comparison of variations of climate characteristics and solar activity at large time scales shows a similarity in their behavior. For the last 1000 years, climate underwent variations corresponding to variations of the solar activity: in the 17th–18th centuries, when the solar activity was high, the warm period was observed (Medieval climate optimum), and two clear temperature decreases in the Little Ice Age (16th–17th centuries) correspond to long periods of the low solar activity (Maunder and Sporer minima). The termination of the Maunder Minimum was followed by general increase of the solar activity. This increase is especially pronounced from 1900 up to now, and the most part of this period is characterized by warming the global climate. The main reason casting some doubt upon the actual and significant effect of the solar activity on the weather and climate is the absence of quantitative estimates on the solar variability possible contribution to the heat content of the Earth's climatic system and, consequently, to the climate change.

One of the key parameters determining variations of the global climate is radiative balance at the top boundary of the atmosphere, which characterizes the energy exchange between the Earth's climatic system and the space. The shortwave radiation flux incident on the top atmospheric boundary is known rather well: it is the solar constant (SC). According to measurements for two last cycles of solar activity, SC changes no more than by 0.15%. The energy flux of the solar wind and the interplanetary magnetic field, solar and cosmic rays, whose variations are more significant within the sunspot cycle, makes up 10^{-6} of

SC variations. Thus, the varying part of the external action cannot directly provide for variation in energy of the Earth's climatic system.

It is quite obvious that if the solar activity influence on climatic characteristics of the troposphere is significant, while variation of the energy flux incident on the lower troposphere due to variation of the solar activity is negligibly small as compared to the energy stored in the stratosphere and troposphere, then the connecting physical mechanism can be realized through variation of parameters controlling balance between the incoming and outgoing energy fluxes. In this connection, of primary importance is the problem of variations of the energy flux outgoing from the Earth and atmosphere to the space. The key role in regulation of this flux belongs to cloudiness and minor atmospheric constituents, in particular, H_2O, CO_2, O_3, methane, and others.

Mechanism of the solar activity influence on weather and climate

The mechanisms of the solar activity influence on weather and climate through galactic cosmic rays (GCRs) are under active discussion now. Since the flux and spectrum of cosmic rays are modulated by the interplanetary magnetic field, which is controlled by the solar activity, cosmic rays may serve as a link between solar variations and the global climate. The possibility of albedo modulation due to cloudiness variations caused by changes in the GCR flux was mentioned in Ref. 4. Unfortunately, experimental data on the correlation of cosmic rays with cloudiness for midlatitudes are contradictory, and this hypothesis still did not get a somewhat convincing confirmation from the viewpoint of actual quantitative estimates. It is obvious that cosmic rays are not the only link of the sun–troposphere correlation. With only GCR, we cannot explain the reaction of the troposphere to geomagnetic perturbations, as was shown in numerous papers, for example in Ref. 3.

Principally different physical mechanism of the solar activity influence on climatic characteristics and atmospheric circulation through atmospheric electricity was proposed, theoretically justified, and tested against observations in our papers.[7–9]

According to this mechanism, atmospheric electricity is a link between solar activity and climatic characteristics of the troposphere. According to measurements of atmospheric electricity during geomagnetic disturbances, as well as in the periods of invasion of large fluxes of solar cosmic rays (SCRs) in the region of polar latitudes, a considerable increase of the electric field is observed near the Earth's surface and the ionosphere – Earth current.

Variations of the electric field affect charged particles in the troposphere and, consequently, result in vertical redistribution of aerosols, which may serve as condensation nuclei in the atmosphere and thus influence on the conditions of cloudiness formation. The appearance of cloudiness alternates the radiative balance, decreases radiative cooling, and changes the thermobaric field of the troposphere.

Model of the solar activity impact on the troposphere

Based on the considered mechanism, we have developed a physical model of action of the solar activity on climatic characteristics of the Earth's troposphere.[7–9] The key concept of this model is the influence of heliogeophysical disturbances on parameters of the Earth's climatic system governing the energy flux outgoing from the Earth to the space.

This influence is most pronounced in high-latitude regions (in the auroral oval zone in the period of magnetospheric disturbances and near the polar cap with a maximum at the geomagnetic pole during SCR invasion), resulting in additional formation of cloudiness (the regions with a sufficient concentration of water vapor) over oceans in coastal areas.

As the level of solar activity increases, the following effects are observed: the radiative cooling in high-latitude regions decreases, the temperature of the lower troposphere increases, the thermobaric field changes, and the mean meridional temperature gradient between polar and equatorial regions, which determines the meridional heat transfer, decreases. These effects are accompanied by the decrease of heat outflow from low-latitude regions, which results in the increase of the surface air temperature (SAT) in the middle and low latitudes and the heat content of the ocean and the climatic system in general.

Long-term changes of temperature in the troposphere

Let us consider the scenario of possible contribution of solar activity to observed climate changes in the 20th century in accordance with the considered model. It should be emphasized that almost all climatic models include the effect of solar activity through the direct impact (change in solar irradiation by roughly 0.1%) on the troposphere, which, in our opinion, cannot contribute significantly to the change in the Earth's climate.

The change of global climate is, first of all, the change in the heat content of the Earth's climatic system, whose overwhelming part is determined by the ocean. The Earth's radiative balance is characterized by the fact that at low latitudes the solar radiation, absorbed by the Earth, exceeds losses due to emission. In high latitudes, the opposite pattern takes place: heat losses here exceed the absorbed solar radiation. The observed climatic temperature distribution on the Earth is sustained due to the latitudinal energy transfer. This climatic function is executed by circulation systems in the atmosphere and the World Ocean. In this connection, the system appears to be sensitive to changes in the heat losses in high latitudes and to the corresponding changes in the meridional temperature gradient and the heat outflow from low-latitude regions. Consequently, changes in the losses in high-latitude regions can affect significantly the heat content of the Earth's climatic system and climate.

In the model proposed by us, the main agents of solar activity, which affect the weather-climate characteristics of the troposphere, are parameters of the solar wind and the interplanetary magnetic field, which determines the *geomagnetic activity* and affect the change of the electric field in the high-latitude atmosphere. It should be noted that long-term variations of geomagnetic disturbance smoothed over 11-year cycles correlate rather well with the sunspot number. However, within individual 11-year solar cycles the correlation is unstable. In addition, to be emphasized is a very important, in our opinion, feature in long-term variations of the geomagnetic activity: starting from 1900 and until 1960 the minimal values of geomagnetic activity increased, while the minimal values of the solar activity level estimated by Wolf numbers practically did not change during the whole period of observations. This is illustrated by the data shown in Fig. 1.

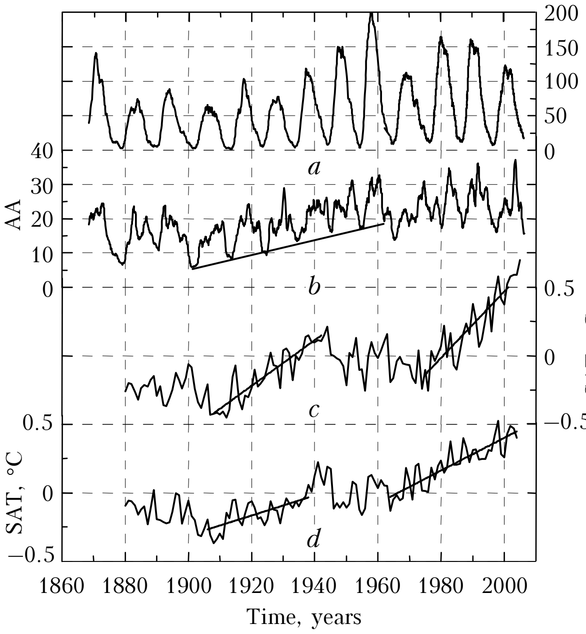

Fig. 1. Long-term changes of the Wolf number (*a*), geomagnetic index AA (*b*), anomalies of the surface air temperature in the Northern (*c*) and Southern (*d*) hemispheres.

Starting from the beginning of the 20th century, the geomagnetic activity increases permanently until now, and this increase is characterized by modulation by the 11-year cycle and some gap in the period of 1965–1975 with the following increase until 2004. If the proposed model is realistic and correctly describes the main physical processes in the Earth's climatic system, then some regularities should be expected in variation of climatic characteristics due to variations of the geomagnetic activity. According to this model, the increase of the geomagnetic activity since the beginning of the 20th century should lead to the decrease of radiative cooling and the corresponding temperature increase in high-latitude regions with some delay due to thermal inertia.

Late in the 19th century, the warming has started and continues until now except for the period of 1940–1970. For the last 100 years, the mean global temperature increased by 0.7°C. This increase was not monotonic. Observations demonstrate the presence of the pronounced spatiotemporal inhomogeneity in variations of the annual-average SAT. This inhomogeneity manifests itself, in particular, in the fact that the climate warming in the 20th century occurred in two periods: 1919–1945 and since 1976 until now. The period of 1940–1970 was characterized by the cooling in the Northern Hemisphere. To be emphasized is a very important and principal feature: both the first and the second warmings in high- and middle-latitude regions were observed mostly in the cold period. The highest SAT increases took place for night (minimal) temperatures of the local winter. These features correspond to predictions of the model.[9]

The increase of the solar and geomagnetic activity in the early twentieth century coincided with the positive phase of the North Atlantic Oscillation, which favored the intensification of the latitudinal heat transfer in the atmosphere and the ocean due to intense energy exchange, connected with the wind stress near the ocean surface, especially, in the North Atlantic. This was accompanied by intensification of the meridional circulation in the atmosphere and in surface ocean waters, corresponding to the intense meridional heat transfer to the Arctic in 1900–1940. The increase of the tropospheric temperature (in 1910–1940) started earlier in polar regions with almost 10-year delay relative to the increase of the geomagnetic activity. This delay is connected with the high heat capacity of the Arctic basin. The amplitude of warming decreased significantly from high to low latitudes.[10] The efficient triggering of the influence of geomagnetic activity on the radiative balance of polar regions provided for the decrease of radiative cooling and increase of SAT in high latitudes. With some delay (1920–1940), the efficient thawing of sea ice and the decrease of ice area in the warm season started in the Arctic basin (Fig. 2).

The decrease of the sea ice area intensifies the action of the warming due to the positive feedback "warming – decrease of ice coverage – decrease of albedo – increase of air temperature." Just in this period, the SAT increase is observed, especially, in polar regions of the Northern Hemisphere. This increase alternated with cooling in 1940–1976. In the Southern Hemisphere, the warming continued in this period.

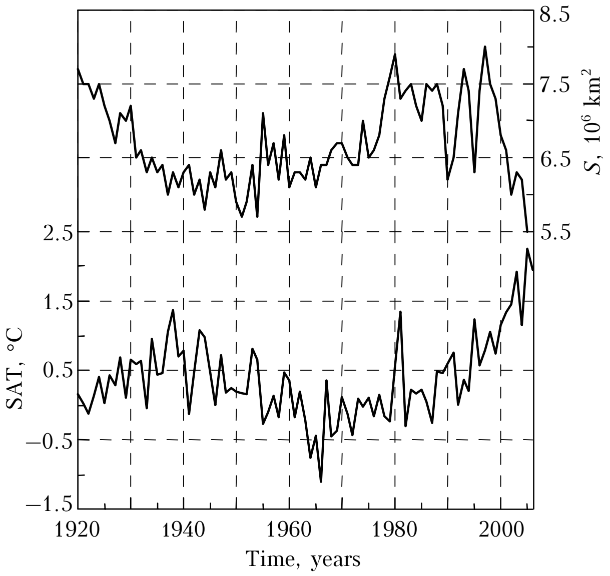

Fig. 2. Long-term changes in the ice area and anomalies of the surface air temperature in high latitudes of the Northern Hemisphere (57.5–87.5°N).

Causes for decrease of SAT in the Northern Hemisphere in 1940–1976

The main physical components of the climatic system are ocean, atmosphere, land, and cryosphere. These components determine the heat content of the Earth's climatic system (ocean is the basic component). The distribution of these components over hemispheres is characterized by significant asymmetry. Therefore, reactions to external actions and to changes in thermal conditions are significantly different in the Northern and Southern hemispheres both for SAT and for the heat content of different components of the climatic system. Because of different surface areas, occupied by land and ocean in the Northern and Southern hemispheres, the heat capacity and heat content of oceans in the Southern Hemisphere are much higher than in the Northern Hemisphere, and since the annual-average SAT over continents (16°C) is higher than the surface temperature of the World Ocean (8.6°C), the heat content in the Northern Hemisphere *atmosphere* is higher than that in the Southern Hemisphere. That is why the increase of SAT in the period of 1910–1940 in the Northern Hemisphere was much larger than in the Southern Hemisphere (smoothing role of the ocean). This resulted in the increase of asymmetry in temperature and heat content of the atmosphere in the Northern and Southern hemispheres. Since the SAT increase in high latitudes was much larger than in equatorial regions, the meridional temperature gradients in the Northern Hemisphere decreased in all latitudes, whereas in the Southern Hemisphere they decreased only in latitudes higher than 60°.

Thus, in the early 1940 the thermobaric field of the troposphere changed significantly, mostly, in the Northern Hemisphere and in equatorial areas, which resulted in the stepwise internal reconstruction of the global circulation of the climatic system from one state to another equilibrium state.

The analysis of circulation conditions by the Vangengeim–Girs classification[10] for 1900–1997 has shown that, actually, in the later 1930s–early 1940s the abnormally fast alternation of the meridional and zonal circulation forms was observed in the Northern Hemisphere. The decrease of meridional temperature gradients resulted in the weaker meridional circulation in the atmosphere and surface layers of the Atlantic Ocean in the Northern hemisphere and in the corresponding decrease of the meridional heat transfer from equatorial regions to high latitudes in the Northern Hemisphere and gradual decrease of temperature in latitudes higher than 30°. In equatorial latitudes and in the Southern Hemisphere to 60°, the temperature rise was observed in 1945–1978 (Fig. 3).

In this period, the heat content of the atmosphere in the Northern Hemisphere decreased, while in the Southern Hemisphere it increased. The global SAT virtually did not change, while the total heat content of the Earth's climatic system increased significantly due to increase in the heat content of the ocean.[11–13] Thus, in this period, the asymmetry in temperature and heat content in the atmosphere of the Northern and Southern hemispheres smoothed up to the late 1970s. According to observations, during a short period (1976–1979) the structure of global circulation alternated again. This alternation was accompanied by a significant intensification of meridional circulation in the Northern Hemisphere and weakening of the zonal circulation. Simultaneously, the heat content of the atmosphere in the Northern and Southern hemispheres increased considerably. The interaction and circulation in the system "atmosphere–ocean–cryosphere" affected significantly long-term variations of atmospheric temperature in the Northern Hemisphere in the period of 1940–1980.

Abnormal increase of heat content of the North Atlantic Ocean in 1970–1980

The ocean along with the atmosphere takes part in the latitudinal heat transfer and contributes significantly to observed climate changes. The particularly important role belongs to the Atlantic Ocean. In the North Atlantic, the Gulf Stream, enveloping the east coast of the North America, transports warm tropic waters to northern regions of the ocean. In the Labrador Sea and near Greenland and Norway coasts, these waters cool, become denser, and descend to the depth. This process is important for formation of climate, because the depth water is formed in these regions and just this water is the driving force of the thermohaline circulation and, consequently, heat transfer in the ocean (Fig. 4*a*) [Ref. 14].

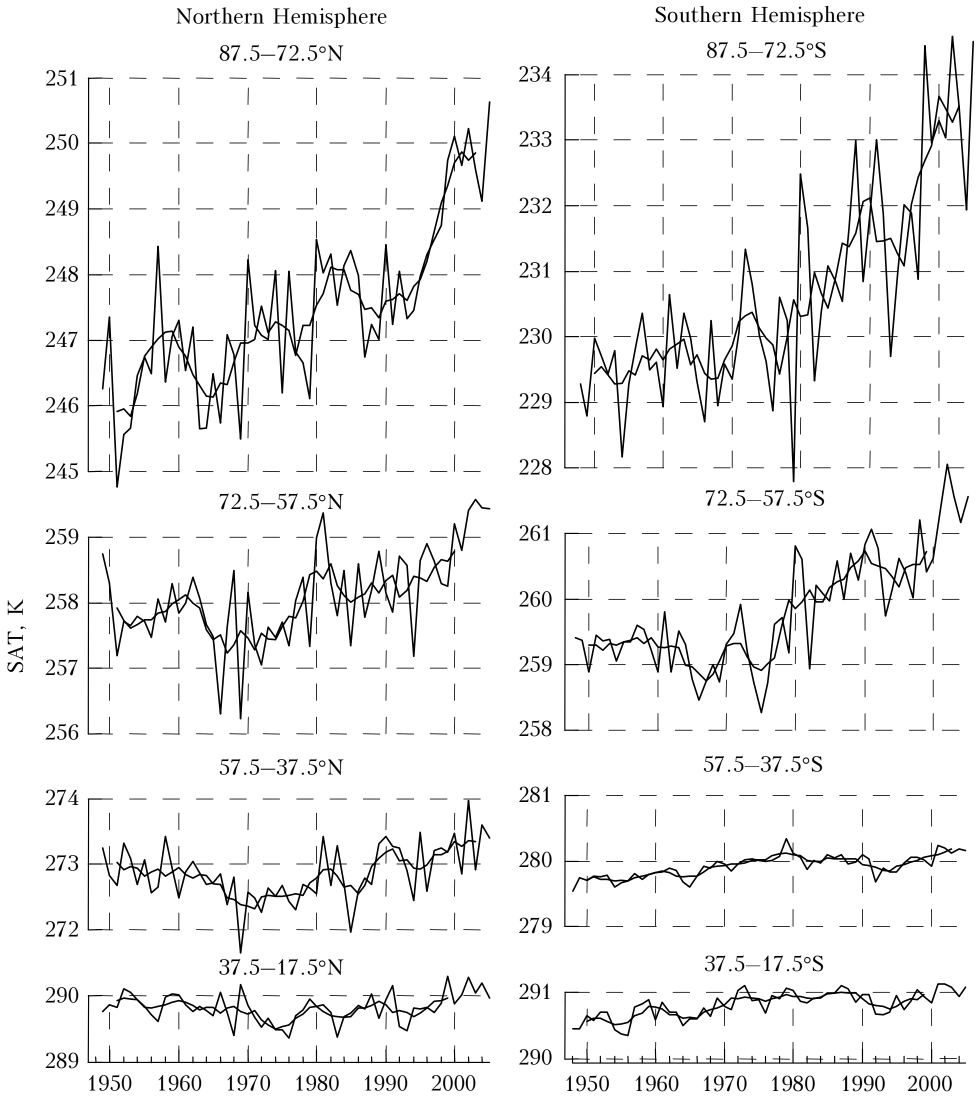

Fig. 3. Long-term variations of the surface air temperature in different latitudinal zones of the Northern and Southern hemispheres in winter season.

The Arctic warming in the early 20th century was characterized by a significant spatiotemporal and seasonal inhomogeneity.[15] Maximal annual-average SATs in the Arctic were observed in the late 1930s. However, in the period since the late 1950s up to the middle 1960s, an unusually high air temperature was observed in summer near the coast of the Arctic Ocean and especially high temperature was noticed in the region of the Western Greenland, the Baffin Bay, and the adjacent part of the Canadian Arctic Archipelago. This was accompanied by intensification of snow and ice thawing, increase of run-off from the continents, and changes in the atmospheric circulation over the Arctic Ocean. The annual average temperature of air in this region of Arctic in summer is the lowest, and the largest amount of snow and ice is accumulated here in the winter period. The pronounced positive anomalies of air temperature here favored the intense summer thawing and run-off of fresh water into the Arctic basin, Canadian straits, Baffin Bay, and Hudson Bay. As a result, in the late 1960s due to the escape of the anomalously large amount of ice from the Arctic basin to the east from Greenland and its following thawing in the upper 200-m layer, the salinity decreased. This phenomenon was called a Great Salinity Anomaly.

The presence of a layer of freshed and, consequently, lighter water on the surface in the regions of the depth water formation has led to gradual weakening and then termination of the deep winter vertical convection in the Labrador Sea. In this period, significant changes occurred in the water circulation in the North Atlantic. These changes are shown schematically in Fig. 4*b*. The region of formation of the depth water shifted to the south up to a latitude of about 50°.

The surface heat transfer in the ocean became much slower, since the deep convection in the Greenland, Island, and Norway seas became weaker.

Warm waters accumulated at an intermediate depth (300–800 m) at latitudes to the south from 50°. The observations shown in Fig. 5 confirm this scenario of climatic changes in the atmosphere and the ocean.

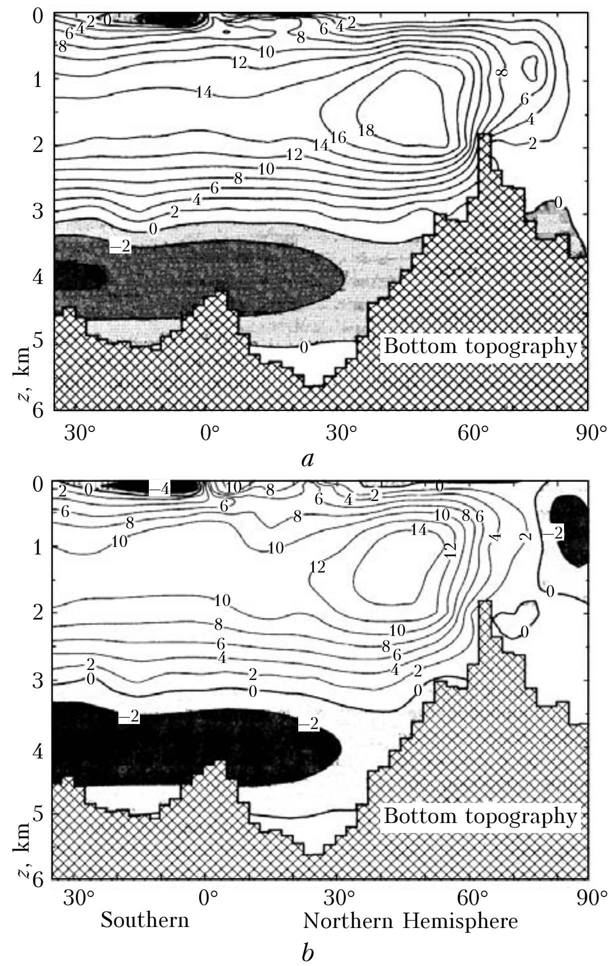

Fig. 4. Current lines of meridional circulation of water in the Atlantic Ocean: period of 1900–1950 and current conditions (1990–2000) (*a*); period of 1970–1980 (*b*).

In this period, the heat content in the Atlantic Ocean increased anomalously just at depths of 500–700 m due to the significant change in the circulation of not only surface, but also depth water in the North Atlantic.

The Great Salinity Anomaly had other consequences as well. Since the meridional surface water exchange through the subpolar front in the North Atlantic became weaker, the heat inflow and its outflow into the atmosphere in high latitudes decreased. In this period, anomalously low temperatures were observed both on the ocean surface in the North Atlantic[16] and in air in the Arctic; the sea ice area in the Arctic basin in the warm period increased.

Thus, along with the positive feedback (1920–1940) "warming – decrease of ice coverage – increase of air temperature," the negative feedback (1940–1975) "warming – freshening of the upper layer – slowing down of the thermohaline circulation of surface water in the ocean – decrease of heat flux from the ocean to the atmosphere – increase of sea ice coverage – decrease of air temperature" takes place. The negative feedback is responsible for the anomalously high increase of the heat content in the Atlantic and World oceans (see Fig. 5).

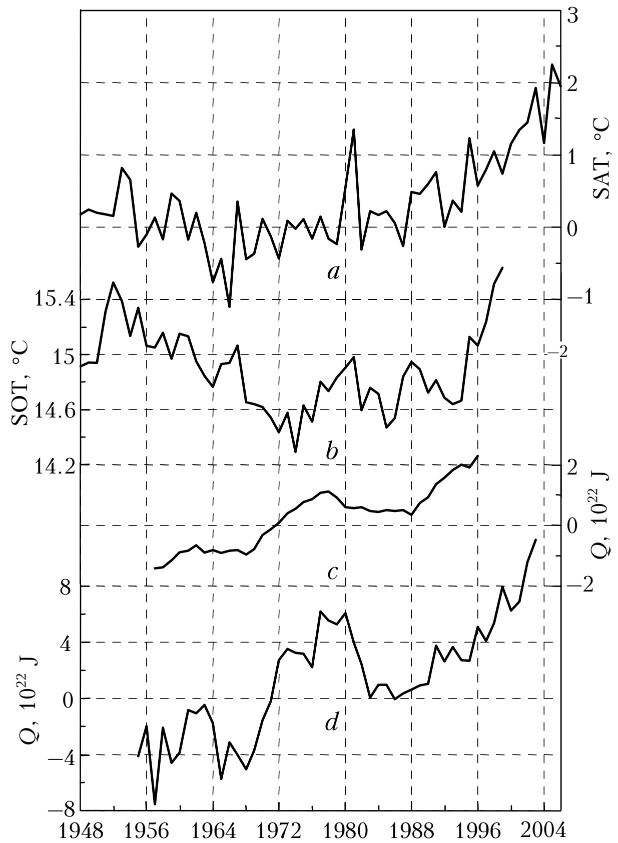

Fig. 5. Long-term changes of anomalies of the surface air temperature in high latitudes of the Northern Hemisphere (57.5–87.5°N) (*a*), surface ocean temperature (SOT) in the North Atlantic (*b*), heat content in the Atlantic Ocean in the 0–1000 m layer (*c*), and heat content of the World Ocean in the 0–700 m layer (*d*).

In conclusion, we would like to note some important and principal features of functioning of the Earth's climatic system in the 20th century. The analysis of regularities in changes of the geomagnetic activity and thermobaric characteristics of the troposphere within the considered model, as well as consideration of fast radical changes in the global circulation of the atmosphere and the ocean, suggests that a significant part of the observed warming in the 20th century can be caused by changes in the level of the solar activity. The SAT anomalies in 1940–1945 and 1976–1979 periods, as well as the anomalies of the heat content of the World Ocean, are consequences of natural many-year fluctuations of the thermal and dynamic conditions of the World Ocean and the atmosphere, as well as changes in the processes in the atmosphere, ocean, and cryosphere, the start of which is connected with the warming in polar regions early in the 20th century. Very important role in these processes belongs to changes of the ice cover in high latitudes, which regulate the salinity of water in the North Atlantic, characteristics of the thermohaline circulation, and energy exchange between the atmosphere and the ocean.

Acknowledgements

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