ISSN 0016-7932, Geomagnetism and Aeronomy, 2017, Vol. 57, No. 6, pp. 637–644. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © G.A. Zherebtsov, V.A. Kovalenko, K.E. Kirichenko, 2017, published in Geomagnetizm i Aeronomiya, 2017, Vol. 57, No. 6, pp. 687–695.

The Role of Solar Activity in Observed Climate Changes in the 20th Century

G. A. Zherebtsov, V. A. Kovalenko*, and K. E. Kirichenko**

Institute of Solar-Terrestrial Physics, Siberian Branch, Russian Academy of Sciences, Irkutsk, Russia

**e-mail: vak@iszf.irk.ru*

***e-mail: kirichenko@iszf.irk.ru*

Received March 24, 2017; in final form, May 22, 2017

Abstract—The possible contribution of solar and geomagnetic activity to changes in the characteristics of the main components of the climatic system—the ocean and the atmosphere—is considered and discussed. The mechanisms and models of the solar activity impact on thermobaric and climatic characteristics of the troposphere are presented. Based on a complex analysis of hydrometeorological data, it has been shown that changes in the temperature of the troposphere and the World Ocean reflect a response both to individual helio-geophysical perturbations and to long-term changes (1854–2015) of solar and geomagnetic activity. It is established that the climatic response to the influence of solar and geomagnetic activity is characterized by considerable spatio-temporal heterogeneity, is of a regional nature, and depends on the general circulation of the atmosphere. The largest contribution of solar activity to the global climate changes was observed in the period 1910–1943.

DOI: 10.1134/S0016793217060147

1. INTRODUCTION

The study of the influence of solar activity (SA) on weather and climate has a long history. Comparison of the characteristics of climate and SA on large time scales demonstrates a great similarity in their behavior. For the last 1000 years, the world climate experienced changes that quite closely corresponded to variations in SA: in the 11th–13th centuries, when SA was high, there was a warm period (the "medieval climatic optimum"), and two distinct temperature drops in the small ice age (16th–17th centuries) correspond to the Maunder and Spörer minima. A general rise in the level of SA occurred after the completion of the Maunder minimum, and the world climate became warmer during most of this period.

To date, there is a large number of published papers in which it has been reliably shown that the effect of SA on the state of the lower atmosphere is manifested at various time scales, from several days to hundreds of thousands of years (McCormack et al., 1982; Gray et al., 2010).

Long-term changes in SA from the work of Eddy (1976) are shown in Fig. 1 in comparison with the climatic characteristics of the planet. Eddy found that the maxima of SA were accompanied by a retreat of the Alpine glaciers, a decrease in the severity of winters, and general warming of the climate; he also found that the periods of SA minima corresponded to global cooling. Nevertheless, despite the numerous works in which reliable, statistically significant connections between different indices of helio-geophysical activity and the weather and climate characteristics are established, the question of whether SA makes a significant contribution to climate change is still debatable. In a series of works (Avdyushin and Danilov, 2000; Dergachev and Raspopov, 2010), the solar variable is considered an important cause of global warming.

What are the main reasons that make one doubt the reality and significance of the influence of SA on weather and climate?

1. First of all, changes in the energy flux reaching the troposphere due to changes in SA are negligible compared to the energy reserve in the stratosphere and troposphere, or even with the energy of one cyclone.

2. There is no physical mechanism capable of an exhaustive explanation of the numerous correlations between the various helio-geophysical indices and climatic characteristics of the troposphere, while manifestations of these connections on short-time intervals have a statistical nature.

3. When the effect of solar variability on weather and climate is studied, it is difficult to isolate the appearance of an external signal against the background of intrinsic perturbations in the atmosphere–ocean system.

One of the key parameters that determine the global climate change is the radiation balance at the upper boundary of the atmosphere for the entire

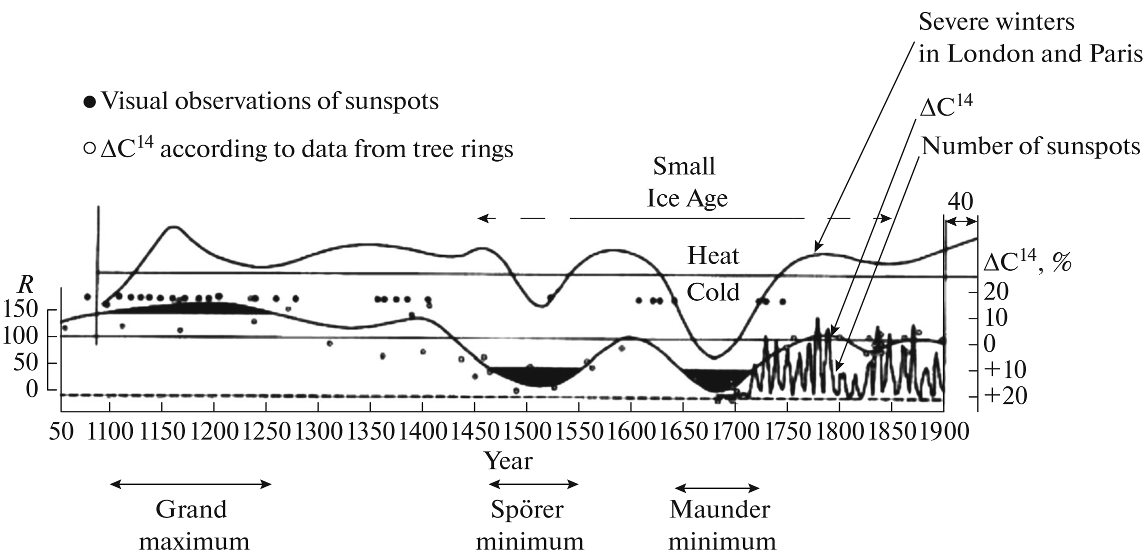

Fig. 1. Long-term changes in air temperature and solar activity from direct and indirect observational data (based on data from (Eddy, 1976)).

earth's surface, which characterizes the energy exchange between the terrestrial climate system and the outer space. The flux of shortwave radiation incident on the upper boundary of the atmosphere is fairly well known; this is the solar constant (SC). According to measurements on space vehicles during the last two cycles of SA (1980–2009), the SC does not change by more than 0.10%. Calculations carried out in the framework of global climate models (Mokhov and Smirnov, 2008) also show that changes in the SC cannot make a significant contribution to the observed variations in global temperature. In this regard, many climatologists strongly reject the very possibility of the impact of SA on the climate.

Thus, the changing proportion of energy flux falling on the upper boundary of the atmosphere to the Earth associated with SA cannot directly provide the change in the energy of the Earth's climate system.

It is quite obvious that, if the influence of SA on the climatic characteristics of the troposphere is significant and changes in the energy flux reaching the lower troposphere due to variations in SA are small compared to the energy reserve in the stratosphere and the troposphere, then the physical mechanism of this influence can be realized through changing parameters that control the balance of the energy flux entering the Earth's atmosphere and going into space. Thus, the question of changes in the energy flux radiated by the atmosphere into space is of no less, but, most likely primary, importance.

2. CLIMATE CHANGE AND SOLAR ACTIVITY

Climate change has a huge impact on human activities, agriculture, transport, the economy, and the environment as a whole. In this regard, it is extremely important to answer the question of its nature. The answer to this question has not only theoretical but also applied value. The question of the extent to which global warming in recent decades has anthropogenic origins, as opposed to natural origin, is of primary importance, both for an understanding of the nature of climate change on the Earth in the past and in the future and for the planning of those types of human activity that can affect climatic system of the Earth.

The International Panel of Experts on Climate Change has released its fifth report on the causes of changes in the mean temperature of the Earth and climate forecast for the next several decades (Stocker et al., 2013). Despite numerous reservations, the authors of the report assert that we are expected to further warm the planet. It is also recognized that climate science still contains uncertainties in assessing the effect of carbon dioxide (CD) emissions on near-Earth temperature increase and the growth rate of the world ocean level; it is also stresses that the Earth is probably less sensitive to CD emissions than previously thought, and justification for assessment of the impact of CD emissions on the increase in the Earth temperature raises serious questions. Nevertheless, the report states that "climate warming is unambiguous," and the likelihood of human impact on the growth of near-Earth temperature is very high. In the opinion of the authors (Stocker et al., 2013), it is necessary to sharply limit the emissions of CD into the atmosphere to reduce this impact.

In the last decade, the scientific community has again strongly increased its activity in determining the quantitative contribution of SA to the global climate change, since there are indications that global warming in the 21st century has noticeably weakened (practically ceased), while the concentration of greenhouse gases, mainly CO_2, continues to increase during this period. Therefore, it is extremely important to understand the nature of this phenomenon, given that the solar and, consequently, geomagnetic activity in the last decade have noticeably weakened.

Studies of long climatic series confirm the important role of helio-geophysical factors in formation of the climate regime of the planet (Valev, 2006; Roy and Haigh, 2010; Mufti and Shah, 2011). At the same time, despite ample evidence of the SA effect on the climate system, the mechanism of this influence has not been fully elucidated (Gray et al., 2010; Nigel and Svensmark, 2003).

The mechanisms of SA effect on weather and climate through galactic cosmic rays (GCRs) were discussed in a number of works (Svensmark and Friis-Christensen, 1997). Since the flux and spectrum of cosmic rays are modulated by the interplanetary magnetic field, which is controlled by SA, cosmic rays can represent one of the links between changes in the Sun and the global climate. Unfortunately, the experimental data on the relationship between cosmic rays and cloudiness are quite contradictory, and this hypothesis has not received any convincing confirmation from the point of view of real quantitative estimates (Kernthaler et al., 1999). Obviously, cosmic rays are not the only link in the solar-tropospheric connection. With the help of GCRs, it is impossible to explain the reaction of the troposphere to geomagnetic disturbances, as was reliably shown in numerous works (Mustel et al., 1990).

An essentially different physical mechanism of the SA impact on the climatic characteristics and the circulation of the atmosphere was proposed (Zherebtsov et al., 2004; Zherebtsov et al., 2005a, b). The block diagram of the model is shown in Fig. 2. The key concept of the model is the influence of helio-geophysical perturbations (fluxes of solar cosmic rays, perturbations of the solar wind and interplanetary field, geomagnetic storms and substorms) on the parameters of the Earth's climate system that control the flux of longwave radiation leaving the Earth into space in high-latitude regions. The amount of energy needed to regulate this flux can be quite small and has no fundamental significance.

According to the proposed model, an increase in helio-geophysical activity leads to an increase in the differential electric potential ionosphere-Earth and to a redistribution of charged condensation nuclei in the troposphere, which affect the phase state of water vapor (condensation of water vapor and cloud formation). This mechanism will have the greatest effect on the radiation balance and thermobaric field of the troposphere in high-latitude regions when there is no incoming radiation flux from the Sun (in a cold period) and in regions of enhanced meridional heat flux near the land–ocean boundaries. In this case, any

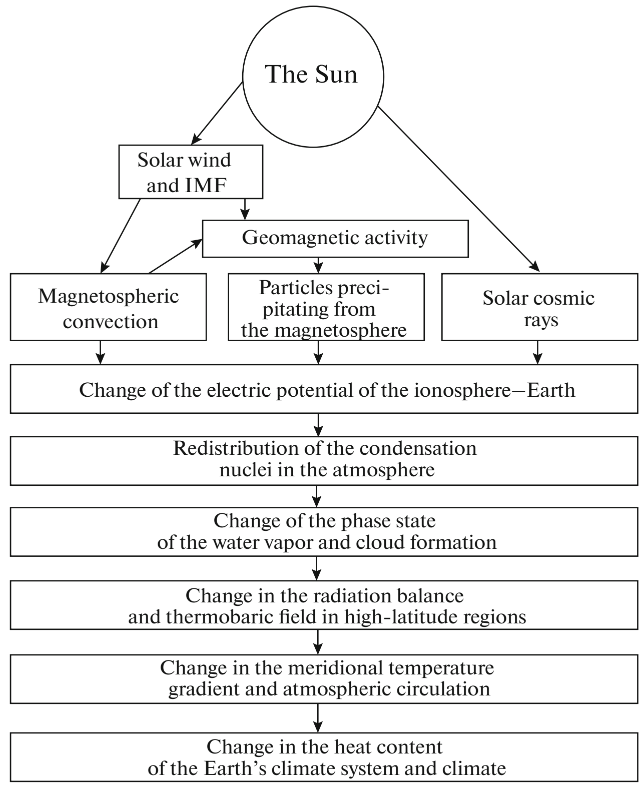

Fig. 2. Block diagram of the model of the solar activity impact on the Earth's climate system.

cloudiness will lead to warming due to a decrease in radiation cooling in high-latitude areas. The change in the radiation balance of high-latitude regions leads to a restructuring of the thermobaric field of the troposphere and changes in the meridional temperature gradient, which determines the meridional heat transfer. As a result, the heat content of the Earth's climate system and the global climate change.

The manifestation of helio-geophysical perturbations in the troposphere will depend on the time of the day, the season, and the state of the atmosphere in this region, namely:

(a) moisture and temperature altitudinal profile;

(b) initial distribution of condensation nuclei in altitude at the moment of perturbation;

(c) vertical turbulent mixing.

At the beginning of the 20th century, the global warming of the climate began, which, with the exception of the period from 1944 to 1976, continued until 2000. The average global temperature rose by 0.8°C over the past 100 years, and the temperature rise was not monotonous. Observation data show the presence of a very strong spatio-temporal inhomogeneity in changes of the mean annual surface air temperature (SAT). This was manifested, for example, in the fact that the climate warming in the 20th century occurred during two periods of time: 1910–1943 and 1977–

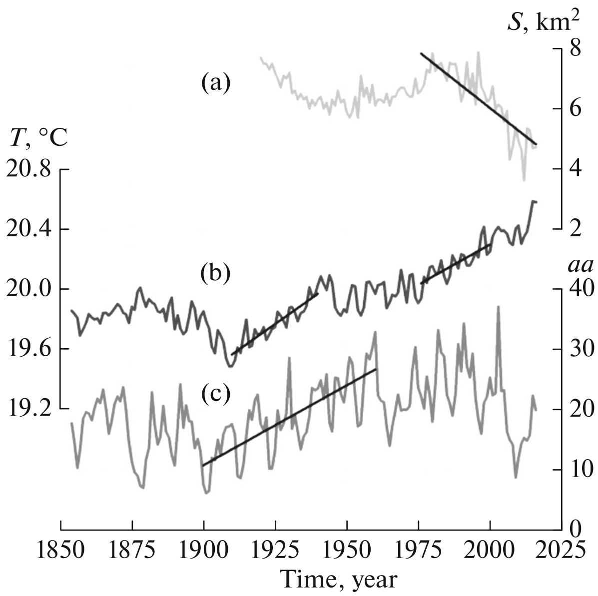

Fig. 3. Long-term changes in (a) the ice area in the Arctic basin for September; (b) the sea surface temperatures (60° N–60° S; 0°–360°); (c) *aa*-index of geomagnetic activity.

2000, and the warming practically ceased after 2000 (see Fig. 3).

It should be emphasized that the observed increase in solar and geomagnetic activity in the early 20th century coincided with the positive phase of the North Atlantic Oscillation (Hurrell, 1995). The latter contributed to the intensification of interlatitude heat transfer in the atmosphere and ocean due to intensive energy exchange associated with the wind stress at the ocean surface. The effective impact of geomagnetic activity on the radiative balance of the polar regions provided a reduction in radiative cooling and an increase in the SAT in high-latitude regions; as a result of which, effective melting of sea ice began in the Arctic basin with some delay (1920–1940) (see Fig. 3). Reduction of the area of sea ice enhances the effect of warming due to the positive feedback "warming—reducing ice cover—reducing albedo—increasing air temperature." It was during this period that the anomalous increase in SAT was observed, especially in the polar regions of the Northern Hemisphere, which was replaced by cooling in the period 1945–1976.

Along with the positive feedback (1920–1940) "warming—reducing ice cover—increasing air temperature," negative feedback also takes place (1940–1975): "warming—desalination of the upper layer—slowing of the thermohaline circulation of surface water in the ocean—reduction of heat flux from the ocean to the atmosphere—lowering of air temperature—increase in the extent of sea ice," which triggered the phenomenon of the Great Salinity anomaly observed in the late 1960s and early 1970s of the last century (Dickson et al., 1988).

3. ANALYSIS OF THE RESPONSE OF THERMOBARIC TROPOSPHERIC CHARACTERISTICS TO ISOLATED HELIO-GEOPHYSICAL PERTURBATIONS

Based on the NCEP/NCAR archive of data reanalysis (http://www.esrl.noaa.gov/psd/) (Kalnay et al., 1996), the response of the troposphere to the effect of individual helio-geophysical perturbations was analyzed (Rubtsova et al., 2008). On the basis of the obtained maps, changes in the pressure and temperature fields were studied for standard levels of the high-latitude troposphere during a period of anomalous helio-geophysical perturbation (HGP). It turned out that there is a change in the typical zonal transfer in the troposphere after HGP, which manifests itself in the appearance of some blocking moving structures (BMSs). These areas are the areas of the maximal response of the troposphere to HGP.

As an example, Fig. 4 shows the characteristics of one of the typical events. The reference date (0-day) is the day of the arrival of an anomalously large flux of solar cosmic rays, which was observed on January 31, 1982. A moderate geomagnetic storm was also observed during this period.

This case corresponds to the combined effect of two components of HGP that affect the electric field of the high-latitude troposphere: the flux of solar cosmic rays and magnetospheric convection. The difference in the response to these events lies only in the localization of the areas of maximum manifestation. For solar cosmic rays, the area of maximum manifestation is the region of the geomagnetic pole, while for geomagnetic storms it is the area of the auroral oval.

Successive changes in the altitudinal profile of air temperature deviations from the day preceding the day of HGP beginning (–1 day) at standard isobaric levels in the area of BMSs from January 31 to February 6, 1982, over land and ocean are shown in Fig. 5. It can be seen from the data shown in Fig. 5a on the first day after HGP that the air temperature increases from the surface of the Earth to a level of 300 hPa and reaches a maximum value on the third day (up to 15°), while the temperature decreases above the 300 hPa level. The maximum increase in air temperature in the BMSs area is observed on day 4 in the 500–700 hPa layer.

A significant difference in the heat capacity of the ocean and land leads to a slight change in the surface air temperature over the ocean (Fig. 5b), while the temperature of the troposphere increases by 10° at altitudes of 800–400 hPa. An increase in the temperature of the lower and middle troposphere leads to a restructuring of the thermobaric field and a decrease in the average meridional temperature gradient between the

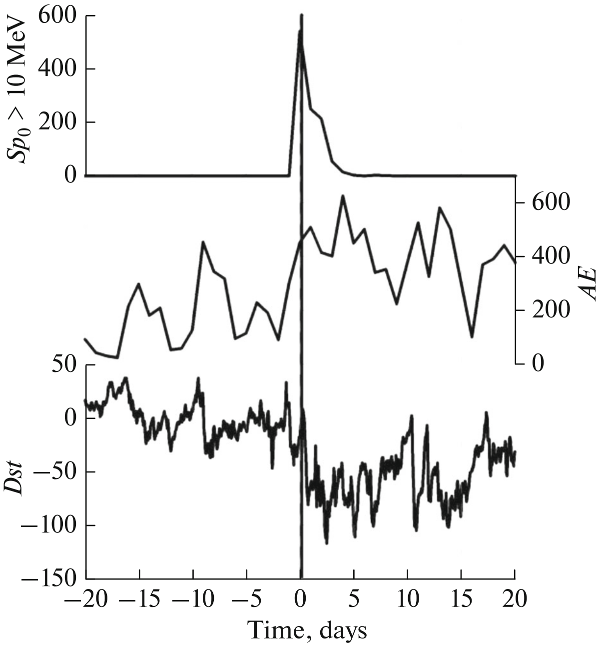

Fig. 4. Changes in the intensity of solar cosmic rays and geomagnetic activity in January–February 1982. The 0-day corresponds to January 31, 1982.

polar and equatorial regions, which determines the meridional heat transfer.

Thus, the observed regularities in changes of circulation in the polar latitudes fully correspond to the expected patterns within the considered model of the HGP effect on troposphere thermobaric field.

4. MANIFESTATION OF SOLAR ACTIVITY IN THE SEA SURFACE TEMPERATURE

The global climate change is closely related to the change in the heat content of the Earth's climatic system, the vast part of which is determined by the ocean. Oceans play an important role in the climate system, as they are a battery of solar radiation and actively participate in the global redistribution of heat between the tropical and polar regions. In this connection, the study of the manifestation of SA in the sea surface temperature (SST) is of particular interest.

Maps of the spatial distribution of the correlation coefficient between the SST and *aa*-index of geomagnetic activity (GA) for four periods with different types of atmospheric circulation were plotted for a more detailed identification of the spatial structure of the SST response to the impact of GA (Fig. 6). The maps show that the feature of these distributions is the presence of regions of both positive and negative correlation. The exception is the period 1911–1943 (Fig. 6b), in which the SST response to GA was positive practically in all regions, i.e. was of a global nature. This epoch corresponds to the longest period of the increase in the level of GA, at the end of which the average annual minimum values exceeded the maximum at the beginning of the epoch (Fig. 3).

Thus, the climatic response of the SST to the impact of GA is characterized by considerable spatio-temporal heterogeneity, is regional in character, and depends on the type of circulation. Similar results of the spatial structure of the response of tropospheric and stratospheric temperatures to SA, which were based on numerical simulation and data analysis, were obtained (Krivolutsky et al., 2015; Mitchel et al.,

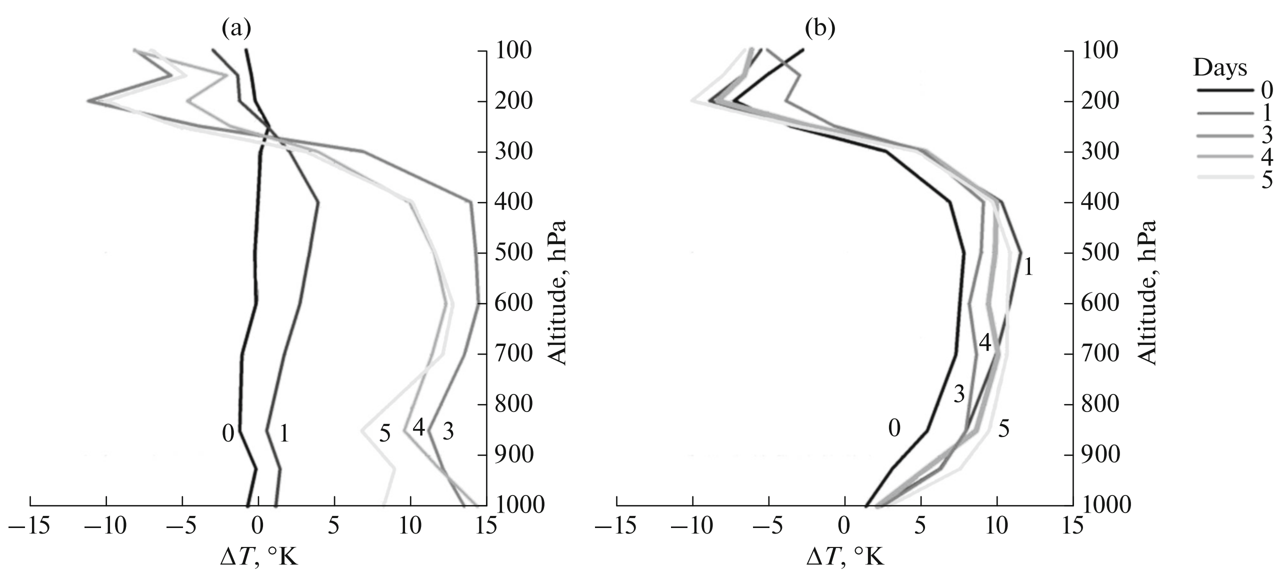

Fig. 5. Deviations of the vertical air temperature profile in the Northern Hemisphere: (a) above the land (60°–70° N, 160°–140° W); (b) over the ocean (45°–55° N, 160°–140° W) during the period from January 31 to February 5, 1982, from the day preceding the beginning of the HGP in the areas of BMSs.

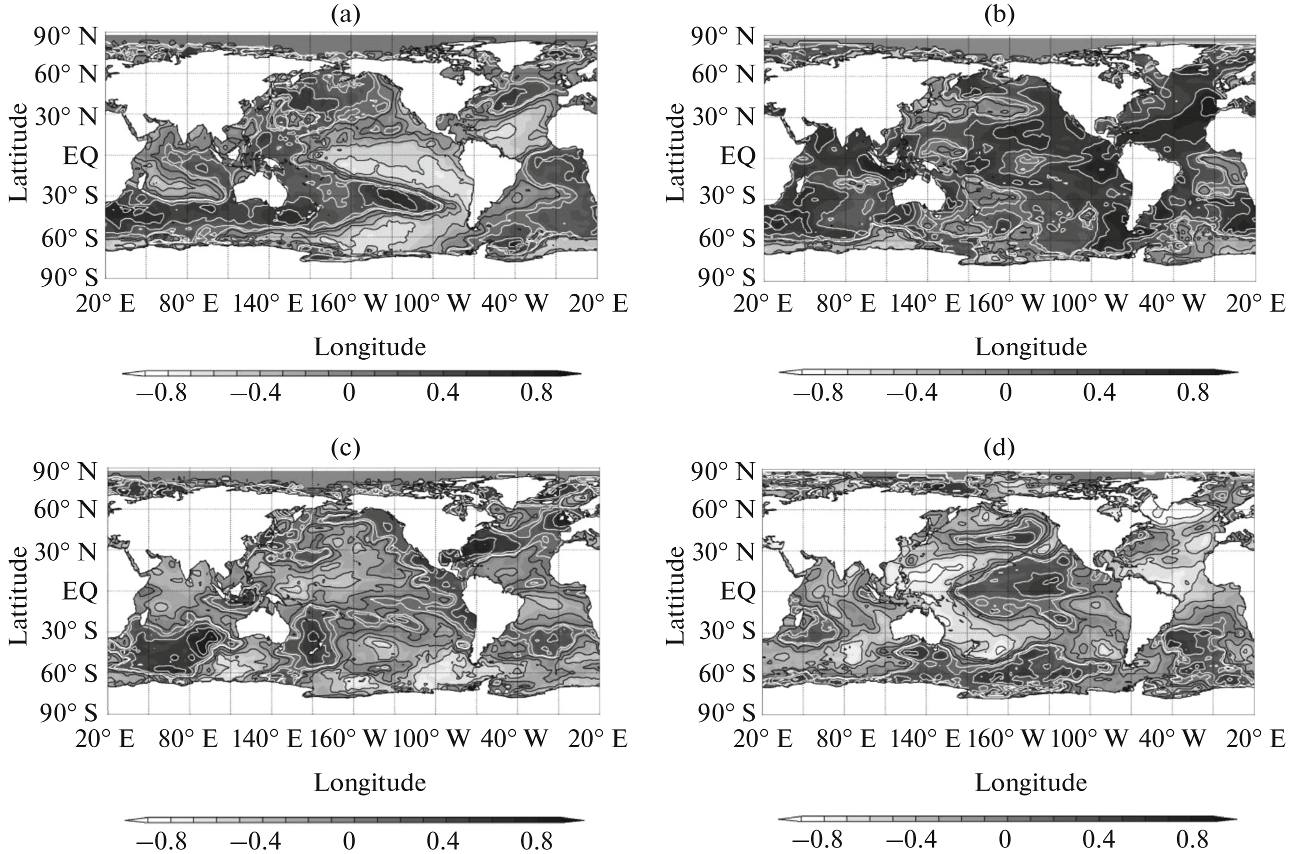

Fig. 6. Maps of correlations between smoothed SST values and *aa*-index of geomagnetic activity during 1868–2000 for different climatic epochs: (a) 1868–1910; (b) 1911–1943; (c) 1944–1976; (d) 1977–2000.

2015). In addition, it was shown that planetary waves play an important role in the formation of this response.

An analysis of correlation maps identified the regions of the World Ocean in which the changes in SST on long-term scales were mainly determined by variations in GA (Fig. 7). Of particular interest is the response of GA at a surface temperature of the Indian Ocean at latitudes of 30°–60° S and longitudes 15°–120° E (Fig. 6). In particular circulation epochs, this area of manifestation changes in latitude or shifts in longitude in an easterly direction. Figure 7a shows the region of the Indian Ocean for which the GA response in SST is stable throughout the considered period of time (1854–2014). This area is unique in sense of response to GA due to peculiarities of the physical-geographical location. It is characterized by maximal cyclogenesis in the Southern Hemisphere throughout the year (Sinclair, 1997) and adjoins the isolated structure of closed surface currents in the ocean, i.e. is least susceptible to global changes in the climate system, which contributes to the manifestation of the SA signal.

It can be noted that changes of the SST in the Southern Hemisphere show fluctuations with a characteristic time period of quasi-22 years, while these fluctuations began earlier in the Indian Ocean (from 1883 to 1925) than in the Atlantic Ocean (from 1911 to 1964).

When the change in the SST response for the North Atlantic area (Sargasso Sea) are considered, its physical and geographical location should be taken into account. Similar to the Indian Ocean, where there is a closed circulation of currents, the Sargasso Sea is characterized by the presence of a zone of convergence of surface currents, which apparently plays an important role in manifestation of GA.

The Sargasso Sea does not have clear geographical boundaries. Its area is delineated by streams forming a stable center of closed anticyclonic circulation in the central North Atlantic: the Gulf Stream in the west, the Canary Current in the east, the North Atlantic Current in the north, and the North Strait Current in the south. Due to these peculiarities, the long-term manifestation of GA in SST is observed in the North Atlantic region until 2007 (Fig. 7c). The "failure" of the relationship between SST and GA after 2007 is caused by abnormal change in the sea-ice area in the Arctic basin (Comiso et al., 2008), which led to a sharp jump in temperature over the Arctic Ocean, the most noticeable in the North Atlantic (Alekseev et al.,

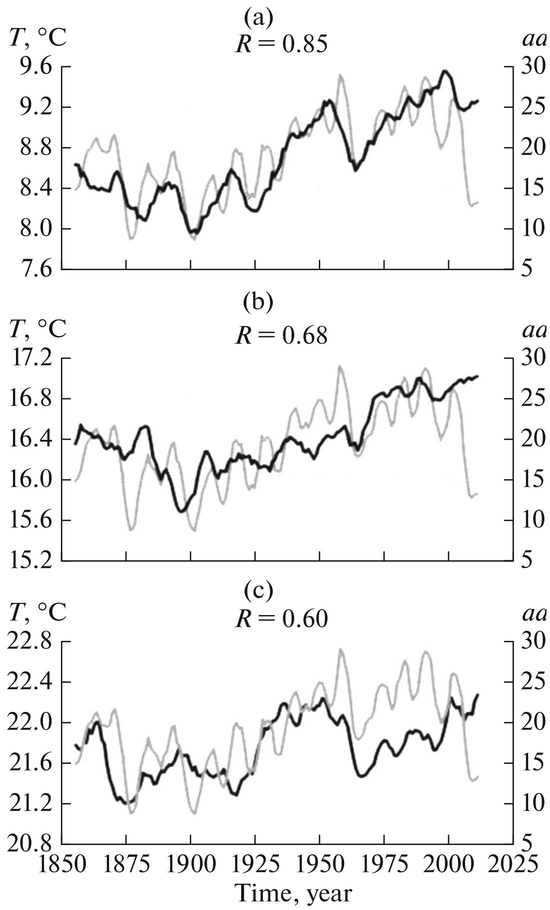

Fig. 7. Average annual values of SST (black line) smoothed for five years: (a) Indian Ocean (40°–50° S, 30°–60° E), (b) South Atlantic (20°–50° S; 0°–30° W); (c) North Atlantic (30°–40° N, 60°–70° W), *aa*-geomagnetic activity index (gray line) and correlation coefficients between SST and *aa*-index (R).

2011). This led to a decrease in the meridional gradients between the middle and high latitudes of the North Atlantic. As a result, we observe an increase in SST in the Sargasso Sea area, despite lowering of the level of GA.

5. CONCLUSIONS

Based on a comprehensive analysis of observational data and the model of the influence of solar activity on the climate system developed by the authors, a reliable response was revealed in the main climatic characteristics (surface air temperature, ocean surface temperature) to the effect of solar activity. It is established that the climatic response to the impact of solar and geomagnetic activities is characterized by considerable spatio-temporal heterogeneity, is of a regional nature, and depends on the general circulation of the atmosphere. Regions in the World Ocean for which long-term temperature changes are mainly determined by solar activity variation have been discovered.

It is shown that solar activity contributed significantly to the global climate change, mainly during the first warming in the 20th century (1910–1943). This period is characterized by a significant positive trend in the level of geomagnetic activity that was maximal over the entire considered time interval (1868–2015) and coincided with enhanced meridional heat transfer in the North Atlantic.

The results of this work allow us to look at the problem of the role of solar activity in climate change more justifiably and reliably.

ACKNOWLEGMENTS

The study was done under RF President Grant of Public Support for RF Leading Scientific Schools (NSh-6894.2016.5).

REFERENCES

Alekseev, G.V., Ivanov, N.E., Pnyushkov, A.V., and Kharlanenkova, N.E., Climate changes in the marine Arctic in early 21st century, in *Meteorologicheskie i geofizicheskie issledovaniya* (Meteorological and Geophysical Studies), Moscow: Evropeiskie izdaniya, 2011, pp. 3–25.

Avdyushin, S.I. and Danilov, A.D., The Sun, weather, and climate: A present-day view of the problem (review), *Geomagn. Aeron. (Engl. Transl.)*, 2000, vol. 40, no. 5, pp. 545–555.

Comiso, J.C., Parkinson, C.L., Gersten, R., and Stock, L., Accelerated decline in the arctic sea ice cover, *Geophys. Res. Lett.*, 2008, vol. 35, L01703. doi 10.1029/2007GL031972

Dergachev, V.A. and Raspopov, O.M., Reconstruction of the Earth's surface temperature based on data of deep boreholes, global warming in the last millennium, and long-term solar cyclicity. Part 1. Experimental data, *Geomagn. Aeron. (Engl. Transl.)*, 2010, vol. 50, no. 3, pp. 383–392.

Dickson, R.R., Meincke, J., Malmberg, S.A., and Lee, A.J., The "great salinity anomaly" in the Northern North Atlantic 1968–1982, *Prog. Oceanogr.*, 1988, vol. 20, no. 2, pp. 103–151.

Eddy, J.A., The maunder minimum, *Science*, 1976, vol. 192, no. 4245, pp. 1189–1202.

Gray, L.J., Beer, J., Geller, M., et al., Solar influences on climate, *Rev. Geophys.*, 2010, vol. 48, RG4001. doi 10.1029/2009RG000282

Hurrell, J.W., Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, 1995, vol. 269, no. 5224, pp. 676–679.

Kalnay, E., Kanamitsu, M., Kistler, R., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, 1996, vol. 77, no. 3, pp. 437–471.

Kernthaler, S.C., Toumi, R., and Haigh, J.D., Some doubts concerning a link between cosmic ray fluxes and global cloudiness, *Geophys. Res. Lett.*, 1999, vol. 26, no. 7, pp. 863–865.

Krivolutsky, A.A., Cherepanova, L.A., and Dement'eva, A.V., Solar cycle influence on troposphere and middle atmosphere via ozone layer in the presence of planetary waves: Simulation with ARM, *J. Geophys. Res.: Space Phys.*, 2015, vol. 120, no. 10, pp. 8298–8306.

Marsh, N. and Svensmark, H., Solar influence on Earth's climate, *Space Sci. Rev.*, 2003, vol. 107, no. 1, pp. 317–325.

McCormack, B., Seliga, T., and Roberts, W., *Solar–Terrestrial Influences on Weather and Climate*, Dordrecht: Springer, 1982; Moscow: Mir, 1982.

Mitchel, D.M., Misios, S., Gray, L.J., Tourpali, K., Matthes, K., Hood, L., Schmidt, H., Chiodo, G., Thieblemont, R., Rozanov, E., Shindel, D., and Krivolutsky, A., Solar signals in CMIM-5 simulations: The stratospheric pathway, *Q. J. R. Meteorol. Soc.*, 2015, vol. 141, no. 691, pp. 2390–2403.

Mokhov, I.I. and Smirnov, D.A., Diagnostics of a cause–effect relation between solar activity and the Earth's global surface temperature, *Izv.: Atmos. Ocean. Phys.*, 2008, vol. 44, no. 3, pp. 263–272.

Mufti, S. and Shah, G.N., Solar–geomagnetic activity influence on Earth's climate, *J. Atmos. Sol.-Terr. Phys.*, 2011, vol. 73, no. 13, pp. 1607–1615.

Mustel', E.R., Mulyukova, N.B., and Chertoprud, V.E., On the solar–tropospheric effect in the Earth's northern and southern hemispheres, *Nauchnye Inform.*, 1990, no. 68, pp. 99–117.

Roy, I. and Haigh, J.D., Solar cycle signals in sea level pressure and sea surface temperature, *Atmos. Chem. Phys.*, 2010, vol. 10, no. 6, pp. 3147–3153.

Rubtsova, O.A., Kovalenko, V.A., and Molodykh, S.I., Manifestation of isolated heliogeophysical perturbations in the high-latitude troposphere, *Opt. Atmos. Okeana*, 2008, vol. 21, no. 6, pp. 463–466.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M., *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press, 2013.

Svensmark, H. and Friis-Christensen, E., Variations of cosmic ray flux and global cloud coverage: A missing link in solar–climate relationship, *J. Atmos. Sol.-Terr. Phys.*, 1997, vol. 59, no. 11, pp. 1225–1232.

Valev, D., Statistical relationships between the surface air temperature anomalies and the solar and geomagnetic activity indices, *Phys. Chem. Earth*, 2006, vol. 31, nos. 1–3, pp. 109–112.

Zherebtsov, G.A., Kovalenko, V.A., and Molodykh, S.I., Radiation budget of the atmosphere and climatic manifestations of solar variations, *Opt. Atmos. Okeana*, 2004, vol. 17, no. 12, pp. 891–903.

Zherebtsov, G.A., Kovalenko, V.A., Molodykh, S.I., and Rubtsova, O.A., Model of solar activity action on the climatic characteristics of the Earth's troposphere, *Opt. Atmos. Okeana*, 2005a, vol. 18, no. 12, pp. 936–944.

Zherebtsov, G.A., Kovalenko, V.A., and Molodykh, S.I., The physical mechanism of the solar variability influence on electrical and climatic characteristics of the troposphere, *Adv. Space Res.*, 2005b, vol. 35, no. 8, pp. 1472–1479.

Translated by I. Ptashnik