ISSN 0016-7932, Geomagnetism and Aeronomy, 2019, Vol. 59, No. 3, pp. 368–373.

Influence of Total Solar Irradiance on the Earth's Climate

L. Z. Biktash*
Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation (IZMIRAN), Troitsk, Moscow Region, Russia
**e-mail: lilia_biktash@mail.ru*

Received April 2, 2017; revised April 24, 2018; accepted January 24, 2019

Abstract—The results of analysis of variations in the total solar irradiance in the 17–24th solar activity cycles and their relation to the climate global warming are presented. The influence of galactic cosmic rays and volcanic activity on the climate is considered. It is shown that the Earth's temperature varied in the 17–20th cycles according to the behavior of solar activity without any observed trend: the temperature increased with an increase in solar activity and decreased in solar minima. Global warming began in 1976 in the 21st solar activity cycle. In light of the observed trend, the changes in the Earth's global temperature in the 21–24th solar activity cycles were related to the cyclical variation of the total solar irradiance in the same way as in the 17–20th cycles. By changing the atmospheric transparency on the background of reductions of the total solar irradiance, galactic cosmic rays also contributed to the increase in the temperature minima. Strong volcanic eruptions were accompanied by 1- to 2-year annual decreases in the temperature, which did not disturb the cyclical process of changes in the Earth's climate. In the absence of trends in the cosmophysical factors influencing the climate, the process of the gradual increase in the global mean temperature of the Earth in the 21–24th solar activity cycles is explained by the anthropogenic factor.

DOI: 10.1134/S0016793219030058

1. INTRODUCTION. GLOBAL WARMING OF THE EARTH'S CLIMATE

In recent years, numerous studies have been dedicated to the global warming of the climate, which is observed as a process of a gradual increase in the annual mean temperature of the Earth's surface and the World Ocean. Extensive experimental observations, climate change models, and many proposed theories have been used to explain the causes of global warming. Solar activity (SA) is considered the main cause of changes in the Earth's climate. The indirect influence of SA via the heliospheric current sheet, which modulates various processes occurring in the interplanetary environment, the atmosphere of the Earth, and its depths, is an important element of the complicated chain of solar influence on the climate. The simultaneous, often oppositely directed, action of many cosmophysical and geophysical factors, especially within the 11-year SA cycle, complicates the picture of atmospheric processes causing climatic changes. A detailed analysis of the experimental data and the mechanisms of SA's influence on the lower atmosphere state and meteorological parameters is presented in the review by Pudovkin and Raspopov (1992). It should be noted that this fundamental work promoted the development of the entire direction of climatic studies, not only in Russia but abroad as well. Nevertheless, the problem of physical mechanism of the SA influence on the climate remains unanswered due to the overly high rate of climatic changes observed during in recent decades.

The intensification of anthropogenic activity has substantially influenced the chemical composition of the atmosphere of our planet, leading to an increase in the greenhouse gas content and increased temperature. Volcanic activity, vice versa, reduces the temperature. Apparently, the current global warming is a result of many factors that require detailed study and control.

The main climatic changes occur on the Earth's surface and in the lower atmospheric layers, in the troposphere, where about 80% of the entire mass of the atmospheric air and approximately 90% of all water vapor available in the atmosphere are concentrated. Clouds and other meteorological phenomena that obtain energy directly from the Sun form in this thin layer. Eddy (1976) assumed that the flux of total solar radiation (total solar irradiance, TSI) is the main source of heat and climatic changes for the Earth's surface. The flux of total solar irradiance (TSI) is understood as the entire conglomerate of ray energy sent by the Sun. Most of the TSI, especially the most variable ultraviolet radiation of the Sun, is absorbed by the high layers of the Earth's atmosphere. The TSI is measured in W/m^2 on board satellites outside the Earth's atmosphere over a square of 1 m^2 located perpendicularly to the radiation flux at a distance of one astronomical unit from the Sun's center. Lean and

Fröhlich (1998) showed that the flux of TSI increases in the presence of sunspots and bright photospheric faculae. However, many scientists (Lean and Rind, 1998; Douglass and Clader, 2002) note that the TSI variations are not enough for a quantitative explanation of the observed global warming of the climate.

Global warming of the climate is already leading to destructive consequences in many regions of the Earth, such as the flooding of coastal territories as a result of rising of the World Ocean; fires; animal migration; and other cataclysms. Due to that, the study of changes in the TSI within SA cycles and the possible influence of this process on the Earth's climate is a goal of this work. Both the direct influence of TSI on the climate and the indirect influence of the Sun on the climate via the heliospheric current sheet and cosmic rays are considered in the paper. The results of the comparison of the TSI, volcanic activity, and annual variations in the Earth's global temperature in the 17–24th solar cycles are presented.

2. DATA AND METHOD OF DATA ANALYSIS

The annual mean values of the global air temperature (T) in centigrade from the site http://data.giss.nasa.gov/ and total solar irradiance (TSI) from the site //www.ngdc.noaa.gov/ were used in the paper. The annual mean sunspot numbers were taken from the site http://www.sidc.be/. The slope of the heliospheric current sheet was calculated based on the monthly mean data from the model of the Wilcox solar observatory of Stanford University (http://wso.stanford.edu/). The annual mean values of the galactic cosmic rays observed at IZMIRAN are taken from the site http://www.izmiran.ru/. The temperature trend from 1976 to 2016 was calculated by the least-squares method with the approximated linear function $y = bx + a$, where y is the annual mean global temperature of the air and x is years of observations.

3. LONG-TERM VARIATIONS IN THE EARTH'S GLOBAL TEMPERATURE IN THE 17–24TH SOLAR ACTIVITY CYCLES

Sunspots present the only direct method to study the evolution of the solar cycle over several centuries. From 1700 until now, the stability of the 11-year cycle of solar activity (SA) has been conserved. The interest in the influence of SA on the climate has not faded since the discovery of sunspots. The most known and weighty argument in favor of SA's influence on the weather and climate in early studies was the fact that the width of annual rings at cuts of perennial trees changes with the solar cycle. With the beginning of the satellite era and studies of the Arctic and Antarctic, new proofs appeared. Due to global warming, which is already leading to catastrophic events, the problem of the change in the Earth's temperature in relation to SA is of a special importance.

Since the TSI is closely related to solar magnetic activity (Lean and Fröhlich, 1998), TSI reconstruction models were developed based on this relation (Fligge and Solanki, 2000; Oster et al., 1982). That is why it is natural to assume that the TSI is a direct source—the main source—that determines and regulates many atmospheric processes, including the tropospheric temperature. Attempts to find the relation between the 11-year cycle of TSI and the global temperature were undertaken in a number of works. Camp and Tung (2007) used the data for 1959–2004 and detected for the first time the 11-year effect in the TSI with a change of 0.2 K from the solar maximum to the solar minimum. The authors used the Monte-Carlo method in their calculations, whereas the temperature trend was calculated according to NCEP data (http://www.ncep.noaa.gov/) beginning from 1959. The temperature trend was calculated in our works (Biktash, 2014, 2017) by the least-squares method for 1965–2014. The global temperature variations were on average ±0.1°C, reaching the highest values in SA maxima. The differences in temperatures between Camp and Tung (2007) and Biktash (2014, 2017) could be caused by both the methods of temperature trend calculations and the use of data from different sources. Moreover, we used the direct annual mean values of the global temperature in Centigrade, whereas Camp and Tung (2007) used the Kelvin scale.

Because of these disagreements, we first consider changes in the global temperature and SA expressed as the sunspot number and TSI in 17–20th SA cycles. The top part of Fig. 1 shows the annual mean values of the air global temperature (GT) for 1933–1976. The bottom part of Fig. 1 shows variations in the sunspot numbers manifesting SA and TSI. It is distinctly seen that the global temperature oscillates within the limits of +0.05°C and –0.25°C in the 17–20th SA cycles. The graph shows also the running 5-year mean values of the air global temperature. The temperature increases with an increase of the SA and decreases in the SA minima in the considered period, oscillating from –0.1°C to 0.05°C without any these to increase. Thus, the global temperature changed these in four SA cycles according to solar cycle phases.

A substantial temperature increase not related to SA is observed after the temperature and solar minima with the beginning of the new 21st cycle in 1976. Thus, the relation between the global temperature and SA in the 17–20th SA cycles makes it possible to assume that SA will also cyclically influence changes in the Earth's temperature in the next cycles, whereas the temperature trend observed since 1976 could be due to other causes.

For a clearer distinction of cyclic variations of the global temperature (GT) in the 21–24th SA cycles, it is necessary to subtract the well-pronounced temperature trend shown in Fig. 2a by a thick curve on the background of cyclic variations in TSI. Our calcula-

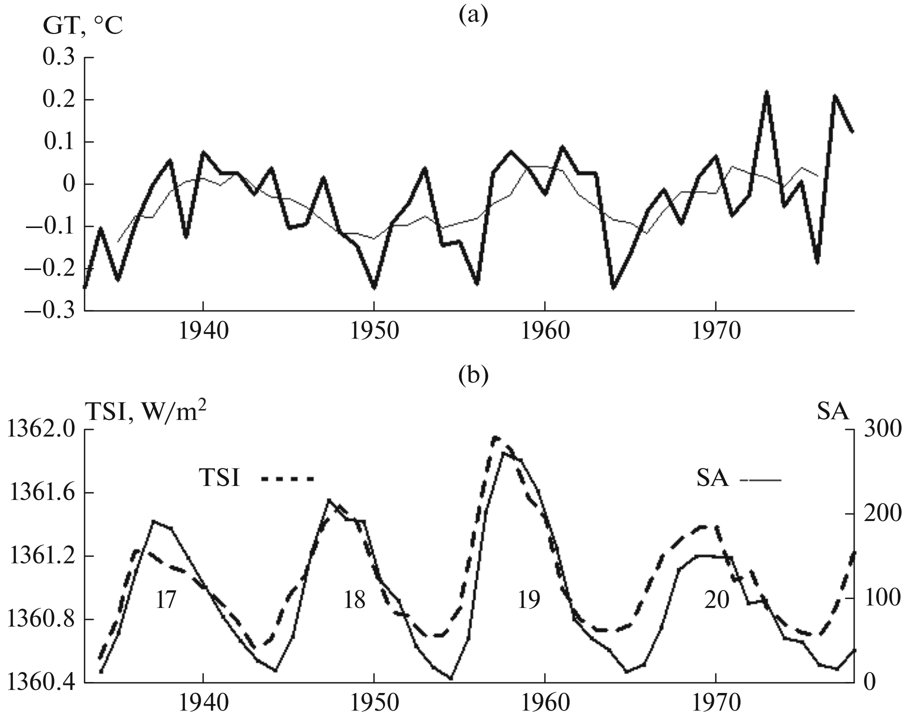

Fig. 1. SA, TSI flux, and changes in the Earth's global temperature in the 17–20th SA cycles: (a) the Earth's global temperature GT (solid thick curve) and 5-year running mean temperature GT (thin curve), (b) annual mean values of sunspots (SA) (solid curve) and TSI flux (dashed curve).

tions show that the temperature trend could be rejected with the regression equation, in which the global temperature (GT) is expressed as

$$Y = 0.018X + 0.053, \quad R = 0.84, \quad \delta = 0.09, \qquad (1)$$

where X are the year numbers beginning from 1976. Note that equation (1) differs from the equation obtained by Biktash (2017), with which the trend has been calculated since the beginning of the 20th SA cycle.

The solid curve in Fig. 2b shows the global temperature values from 1976 to 2017 with allowance for the trend according to formula (1) denoted as T°C, whereas the dashed curve in Fig. 2b shows the 7-year running mean values of T°C. The minimal T°C is −0.15°C in the presented cycles, and the T°C maximum is +0.15°C, whereas the average T°C oscillates around 0°C. Figure 2b shows that the 7-year running values of T°C did not exceed values of ±0.05°C.

Assuming that the TSI is the main source of the heat and climatic changes of the Earth's surface, we consider Figs. 2a–2c, where variations of GT, T, TSI, and SA as the number of sunspots are presented in the 21–24th SA cycles. An obvious correlation of T and TSI with SA is observed in the presented cycles. The temperature maxima in T correspond to the maximal values of the TSI, whereas periods of temperature variations coincide with the periods of TSI variation. The extended 23rd solar cycle causes also long temperature variations.

These results confirm the hypothesis proposed by Eddy (1976) and can be interpreted as a direct influence of TSI on the lower atmosphere and Earth's climate. Additional internal and external causes that may influence the increase in the global temperature will be considered in the following section.

4. COSMIC RAYS, HELIOSPHERIC CURRENT SHEET, AND VOLCANOES IN THE 21–24TH SA CYCLES

The influence of galactic cosmic rays (GCRs) and volcanoes on the Earth's climate remains one of the most controversial and discussed mechanisms of their influence on the atmosphere. The Wilson camera, which was invented in the beginning of the 20th century, was direct evidence of the influence of the cosmic rays on the formation of cloudiness. With the appearance in the camera of oversaturated vapor of some condensation centers (in particular, ions accompanying the trace of a rapid charged particle), small drops of liquid form on them. The discovery by Forbush in 1937 was the next important proof of cosmic ray influence on the atmosphere. He discovered that the count rate of GCRs decreases during magnetic storms and with increased SA. Based on these discoveries and in light of the deep penetrating ability of cos-

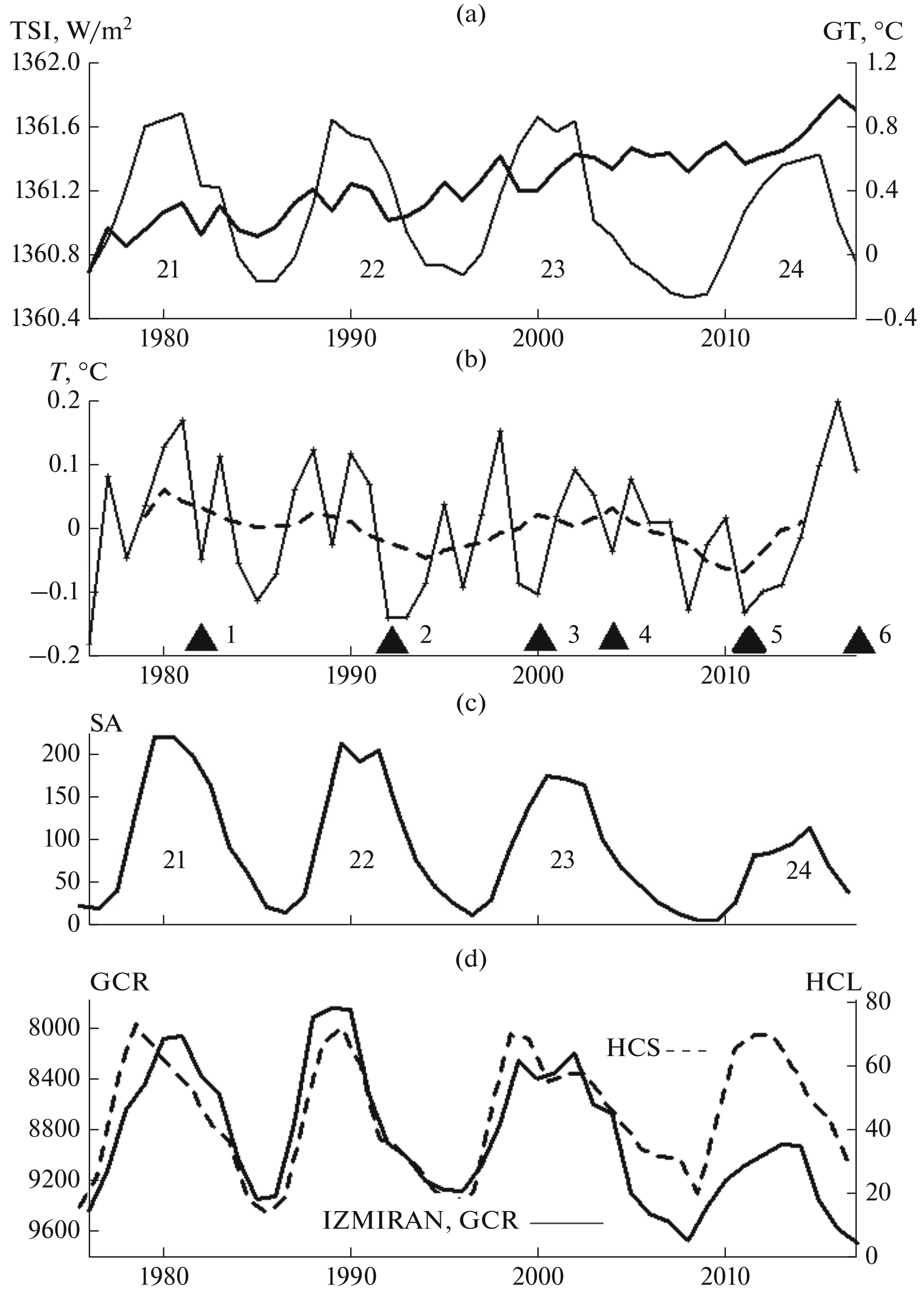

Fig. 2. (a) Variations in the TSI (thin curve) and GT (thick curve). (b) Variations in GT with allowance for the trend denoted as T°C variations from 1976 to 2017 (solid curve) and 7-year running mean values of the temperature T°C (dashed curve). (c) Annual mean variations of the sunspots (SA) from 1976 to 2017. (d) Annual mean variations in the GCR count rate observed at ISMIRAN (solid curve) and annual mean values of the inclination angle of the heliospheric current sheet in the 21–24th SA cycles (dashed curve).

mic rays, many scientists noted that climatic changes are related to GCR intensity much more closely than to other manifestations of SA. Pudovkin and Raspopov (1992) proposed a mechanism of cosmic ray influence on the atmosphere that explains the permanent changes in the meteorological parameters and climate. This mechanism is based on the known fact that cosmic rays are able to change the atmospheric transparency. The proposed mechanism has been widely discussed in numerous publications and is considered one of the main mechanisms responsible for changes in the climate. For example, Pudovkin and Veretenenko (1995), Tinsley (2000), and Swensmark (2000) showed that the Earth's cloud cover is exposed substantially to the cosmic ray effect, whereas the variability in SA and its magnetic field structure is the main cause of cosmic ray variation. Ferreira et al. (2003) showed that changes in the GCR fluxes are related to the structure of the heliospheric current sheet and the angle of its inclination relative the rotation axis of the Sun. Svensmark and Friis-Christensen (2007) explained the violation of the relation between cloudiness and cosmic rays observed since the beginning of 2000 by the effect of volcanic activity, whereas they gave a different explanation for the decreased water content in the lower clouds. Svensmark et al. (2009) related the decrease in the aerosol concentration to the Forbush decreases in GCR. Data on the decrease in the aerosol concentration at the moments of Forbush decreases were obtained in the scope of the MODIS, ISCCP, and AERONET projects. Veretenenko and Ogurtsov (2017) showed that this decrease is caused by a sharp weakening of circumpolar vortices.

Despite the fairly convincing evidence of the influence of cosmic ray on the climate, additional studies of this problem are needed. Figure 2d shows the annual mean variations of GCR count rate (the count rate decreases along the X axis) according to observations at IZMIRAN. The annual mean variations of the inclination angle of the heliospheric current sheet (HCS) calculated by the model of the Stanford University Solar Observatory are shown in the same figure by the dashed curve. Comparison of the graphs shown in Fig. 2 allow the following conclusions to be drawn. The minima of the temperature T°C (7-year running mean, dashed thick curve in panel (b)) and TSI minima (panel (a)) coincide with the maximal values of the cosmic ray count rate. This result does not deny the mechanism of cosmic ray effect on the climate: the maximal cosmic ray effect on the Earth's atmosphere is observed in the solar cycle minima, even if the TSI flux undergoes very small variations in the activity cycle (~1 W/m^2) or can be constant (the former name of the TSI is solar constant). In the long 23rd SA cycle, under approximately similar TSI values with the 21–23rd solar cycles, the cosmic ray fluxes were substantially higher than in 21st and 22nd SA cycles. This apparently reduced the mean temperature in this cycle. The mean temperature T oscillated around 0°C, whereas it reached values of 0.05°C in the maxima of the 21–22nd cycles. A substantial temperature decrease was observed in 2008 when the cosmic ray flux reached its maximum. Then, with the beginning of the 24th SA cycle, the temperature began to rise with the increase in the TSR and the decrease in cosmic ray fluxes. Thus, the cosmic rays influence the atmospheric transparency to a different degree due to the difference in their count rate in SA cycles.

In the SA maxima, cosmic rays are scattered and their flux is decreased due to the change in the inclination of the heliospheric current sheet. As a result, the atmosphere becomes more transparent for the penetration of the TSI due to the small flux of cosmic rays, leading to a temperature increase. In the SA minimum, when the narrow heliospheric current sheet near the eclipse plane does not substantially influence the GCR fluxes, a temperature decrease occurs as a result of intensification of the cosmic ray fluxes, which reduces the penetrating capacity of the atmosphere for the solar radiation. Thus, the GCR fluxes modulate the global temperature, additionally reducing and increasing it in the years of SA minima and maxima, respectively.

Volcanic activity is a source for the intake of aerosols of sulfuric acid and a large amount of carbon dioxide by the Earth's atmosphere. This could also influence the Earth's climate in a considerable way (Robock, 2000). Large eruptions are accompanied by cooling due to the intake of sulfuric acid aerosols and soot particles by the Earth's atmosphere, which could lead to a reduction of atmospheric transparency and, thus, to a decrease in the planetary temperature. Thus, the temperature decreases denoted by triangles in Fig. 2b can be explained by the activity of the following volcanoes: (1) El Chichon, (2) Pinatubo, (3) Ulvan, (4) Manam, (5) Eyjafjallajökull, and (6) Agung. A deep decrease of T°C in 1982 occurred during the TSI minimum; the effect of El Chichon volcano overlapped with it. Due to the eruption of the Pinatubo volcano in 1991, the temperature T°C decreased to –0.15°C. The Eyjafjallajökull volcano awakened in March 2010. A new eruption began on April 14, 2010, and ended on May 23, 2010. It was accompanied by the ejection into the atmosphere of a huge amount of soot. The prolonged temperature reduction until almost 2012 was a result of the action of this volcano. The studies of volcanic activity in solar cycles (Barlyaeva et al., 2009; Barlyaeva, 2013) show that the volcanic activity index rises upon the declines of SA cycles and that temperature also decreases with a decrease in the TSI.

Thus, powerful volcanic eruptions can change the Earth's climate, almost without changing the cyclical dependence of the global temperature on SA. The temperature decreases last for 1–2 years, but this happens very rarely, usually with one large eruption per solar cycle. Moreover, earthquakes and volcanos apparently are closely related to SA. This is manifested by the intensification of the volcanic activity index during solar cycle declines (Barlyaeva, 2013). The declining phases of solar cycles are accompanied by high-velocity fluxes of the solar wind, which cause long, recurrent geomagnetic storms and can cause seismic and volcanic activity. Thus, the anthropogenic factor remains the main cause of global warming in the absence of trends in cosmophysical events that affect the gradual increase in the annual mean temperature of the Earth in the 21–24th SA cycles.

5. CONCLUSIONS

The conducted studies of the global temperature behavior in 1933–1975 showed that the Earth's temperature underwent variations in the 17–20th cycles in agreement with the SA behavior without any observed trend: the temperature increased with increasing SA and decreased in solar minima. The break in the temperature trend observed in 1976–2017 proves that the cyclical process of changes in Earth's climate was also not broken in the 21–24th SA cycles. Thus, we are able to conclude that the cyclical variations in the global temperature are related to SA and are explained by the mechanism of the effect of TSI on the Earth's atmosphere modulated by GCRs, the fluxes of which are regulated by the heliospheric current sheet. Powerful volcanic eruptions are able to change the Earth's climate and reduce its temperature for 1–2 years, but they do not violate the cyclicity of changes in the global temperature. In the absence of trends in cosmophysical factors influencing the climate, the gradual increase in the annual mean temperature of the Earth in the 21–24th SA cycles is explained by the anthropogenic factor. Uncontrolled human activity was determined to be a powerful factor capable of influencing the thin atmospheric layer, in which the main climate changes occur. Due to this, there is a serious need for thorough research on the influence of anthropogenic factors on the climate in order to prevent catastrophic changes to the planet.

REFERENCES

Barlyaeva, T.V., External forcing on air-surface temperature: Geographical distribution of sensitive climate zones, *J. Atmos. Solar Terr. Phys.*, 2013, vol. 94, pp. 81–92.

Barlyaeva, T.V., Mironova, I.A., and Ponyavin, D.I., Nature of decadal variations in the climatic data of the second half of the 20th century, *Dokl. Earth Sci.*, 2009, vol. 425, no. 2, pp. 419–423.

Biktash, L.Z., Evolution of Dst index, cosmic rays and global temperature during solar cycles 20–23, *Adv. Space Res.*, 2014, vol. 54, pp. 2525–2531.

Biktash, L.Z., Sun and space weather influence on global temperature by the agency of cosmic rays during the solar cycles 19–23, in *Ground-Based Solar Observations in the Space Instrumentation Era*, Dorotovic, I., Fischer, C., and Temmer, M., Eds., Astronomical Society of the Pacific, 2016, vol. 504, pp. 265–268.

Camp, Ch.D. and Tung, K.K., Surface warming by the solar cycle as revealed by the composite mean difference projection, *Geophys. Res. Lett.*, 2007, vol. 34, L14703.

Douglass, D.H. and Clader, B.D., Climate sensitivity of the Earth to solar irradiance, *Geophys. Res. Lett.*, 2002, vol. 29, no. 16. https://doi.org/10.1029/2002GL015345

Eddy, J.A., The Maunder Minimum, *Science*, 1976, vol. 192, pp. 1189–1202.

Ferreira, S., Potgieter, M.S., Heber, B., and Fichtner, H., Charge-sign dependent modulation in the heliosphere over a 22-year cycle, *Ann. Geophys.*, 2003, vol. 21, pp. 1359–1366.

Fligge, M. and Solanki, S.K., The solar spectral irradiance since 1700, *Geophys. Res. Lett.*, 2000, vol. 27, no. 14, pp. 2157–2160.

Lean, J. and Fröhlich, C., Solar total irradiance variations, in *Synoptic Solar Physics, ASP Conf. Ser.*, Blasubramaniam, K., Harvey, J., and Rabin, D., Eds., 1998, vol. 140, pp. 281–292.

Lean, J. and Rind, D., Climate forcings by changing solar radiation, *J. Clim.*, 1998, vol. 11, pp. 3069–3094.

Oster, L., Sofia, S., and Schatten, K., Solar irradiance variations due to active regions, *Astrophys. J.*, 1982, vol. 256, pp. 768–773.

Pudovkin, M.I. and Raspopov, O.M., Mechanism of solar activity influence on the state of lower atmosphere and meteorological parameters, *Geomagn. Aeron.*, 1992, vol. 32, no. 5, pp. 1–20.

Robock, A., Volcanic eruptions and climate, *Rev. Geophys.*, 2000, vol. 38, pp. 191–219.

Swensmark, H., Cosmic rays and Earth's climate, *Space Sci. Rev.*, 2000, vol. 93, pp. 175–185.

Svensmark, H., Bondo, T., and Svensmark, J., Cosmic ray decreases affect atmospheric aerosols and clouds, *Geophys. Res. Lett.*, 2009, vol. 36, no. 15. https://doi.org/10.1029/2009GL038429

Tinsley, B.A., Influence of solar wind on the global electric circuit, and inferred effects on cloud microphysics, temperature, and dynamics in the troposphere, *Space Sci. Rev.*, 2000, vol. 94, pp. 231–258.

Veretenenko, S.V. and Ogurtsov, M.G., Low cloud anomalies at middle latitudes and their relationship to variations of galactic cosmic rays for the different states of the polar vortex, *Bull. Russ. Acad. Sci.: Phys.*, 2017, vol. 81, no. 2, pp. 245–248.

Translated by A. Danilov