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# Features of the Earth's Solar Climate Changes in the Present Epoch

**V. M. Fedorov***

*Moscow State University, Moscow, Russia*

**e-mail: fedorov.msu@mail.ru*

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**Abstract**—Calculated insolations of the Earth are analyzed. The main trends in the modern solar climate change are identified: increased latitudinal contrast and smoothed seasonal differences. The correlation of the meridional insolation gradient with the average annual energy transfer in the ocean–atmosphere system is revealed. The features of changes in the annual and semiannual meridional insolation gradients and the correlation of latitudinal regions of maximum changes with the spatial localization of circulation cells (Headley, Ferrel, and Polar cells) and the regions in which vortex formations are generated and developed (tropical and extratropical cyclones) are revealed. The possibility of a link of between the decrease in the inclination of the Earth's rotation axis and an increase in the meridional insolation gradient with an increase in climate turbulence is noted.

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## 1. INTRODUCTION

"It has long been known and is beyond doubt that solar radiation is the main source of heat for the globe" (Voeikov, 1903, p. 39). Incoming solar radiation to the Earth is the main source of energy for hydrometeorological processes (Kondrat'ev, 1980; Monin, 1982; Monin and Shishkov, 2000).

Variations in the incoming solar radiation to the Earth depend on two factors of different physical natures. The first is the change in solar the radiation activity. The second is governed by celestial and mechanical processes that change the Earth's orbit elements (the Earth–Sun distance, the duration of a tropical year, etc.) and the inclination of the axis of rotation (Milankovitch, 1939). The solar climate of the Earth is understood as the theoretically calculated (without atmospheric effects) inflow and distribution of solar radiation at the upper boundary of the atmosphere or on the Earth's surface (Milankovitch, 1939). Here, the solar constant (long-term average total solar irradiance) is assumed to be constant, and only the change in the orbital characteristics that affect the Earth's insolation is taken into account. This study presents new data on the solar climate of the Earth and its possible impact on modern global climate change.

## 2. TECHNIQUE FOR INSOLATION CALCULATIONS

The insolation was calculated at a high spatial and temporal resolution (Fedorov and Kostin, 2019). The calculations were performed with high-precision data on astronomical ephemerides (http://ssd.jpl.nasa.gov) for the Earth's entire surface (excluding the atmosphere) from 3000 B.C. to 2999 A.D. The initial astronomical data for insolation calculations were the declination and ecliptic longitude of the Sun, the Earth–Sun distance, and the difference between uniform (coordinate) and universal times. The Earth's surface was approximated by an ellipsoid (GRS80; Geodetic Reference System, 1980) with semiaxes of 6378137 m (major) and 6356752 m (minor) in length. The calculation algorithm can be generally represented by the expression

$$I_{nm}(\varphi_1, \varphi_2) = \int_{t_1}^{t_2} \left( \int_{\varphi_1}^{\varphi_2} \sigma(H, \varphi) \left( \int_{-\pi}^{\pi} \Lambda(H, t, \varphi, \alpha) d\alpha \right) d\varphi \right) dt, \tag{1}$$

where $I$ is the incoming solar radiation for the elementary $n$th fragment of the $m$th tropical year (J); $\sigma$ is the areal factor (m$^2$), which is used to calculate the area differential $\sigma(H,\varphi)d\alpha d\varphi$—the area of infinitesimal trapezoid (the cell of an ellipsoid); $\alpha$ is the hour angle (in radians); $\varphi$ is the geographical latitude (in radians); $H$ is the height of the ellipsoid surface relative to the Earth's surface (m); and $\Lambda(H, \varphi, t, \alpha)$ is the solar radiation intensity at a given point on the ellipsoid surface at a given time (W/m$^2$), and $t$ time (s). The spatial integration steps were 1° in longitude and 1° in latitude; the time step was 1/360 of the length of the tropical year. The solar constant (the long-term average total solar irradiance) was taken to be 1361 W/m$^2$. The change in solar activity was disregarded.

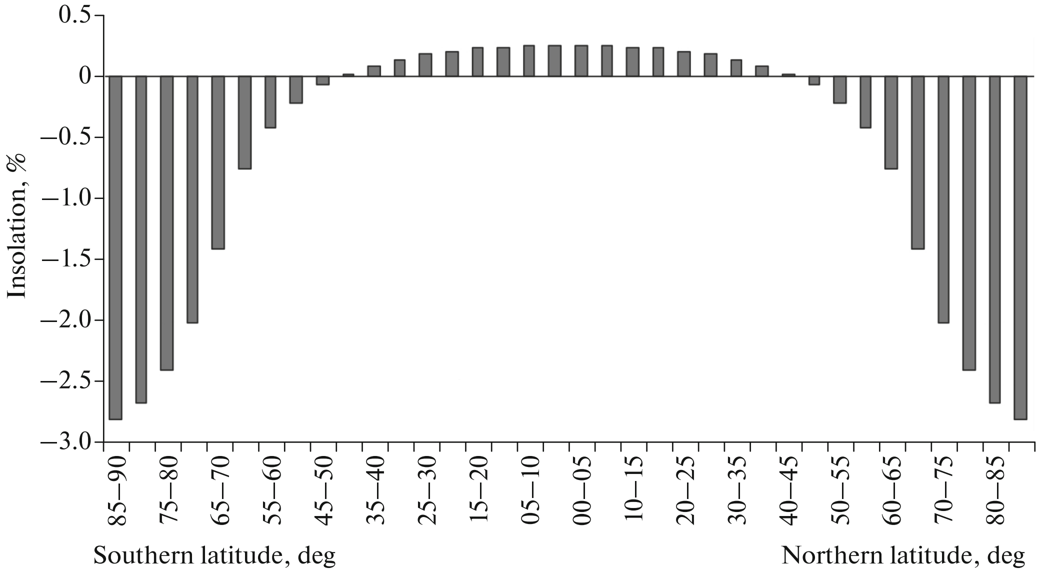

**Fig. 1.** Long-term changes in the distribution of the Earth's annual insolation by latitude from 3000 B.C. to 2999 A.D.

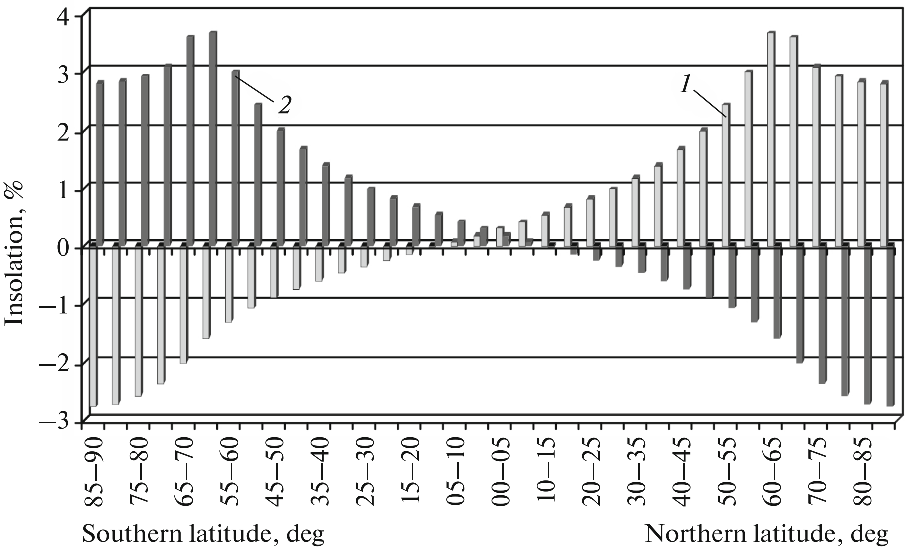

**Fig. 2.** Latitudinal change in the Earth's insolation (in %) from 3000 B.C. to 2999 A.D. in the winter (*1*) and summer (*2*) half-years (for the Northern Hemisphere).

## 3. RESULTS AND THEIR DISCUSSION

The results show (Fedorov, 2018, 2019) that the annual inflow of solar radiation to the Earth for 5999 years remains almost constant (reduced by only 0.005%). However, there is an insolation increase in the Earth's equatorial region (0.25%) and a decrease in polar regions (2.8%); i.e., the present epoch is characterized by an increased latitudinal contrast in the distribution of radiant incoming energy to the Earth (Fig. 1).

There is an insolation decrease in the summer half-year (2.9%) and an increase in the winter half-year (3.75%) for the hemispheres; i.e., the seasonal differences in the incoming solar energy incoming to the Earth tend to be smoothed (Fig. 2).

Against the background of these secular trends, there are small, high-frequency variations in insolation due to periodic disturbances in the Earth's orbital motion and the inclination of its rotational axis. The interannual and 2-, 3-, 8-, 11-, and 19-year variations in the incoming radiant energy are identified. The

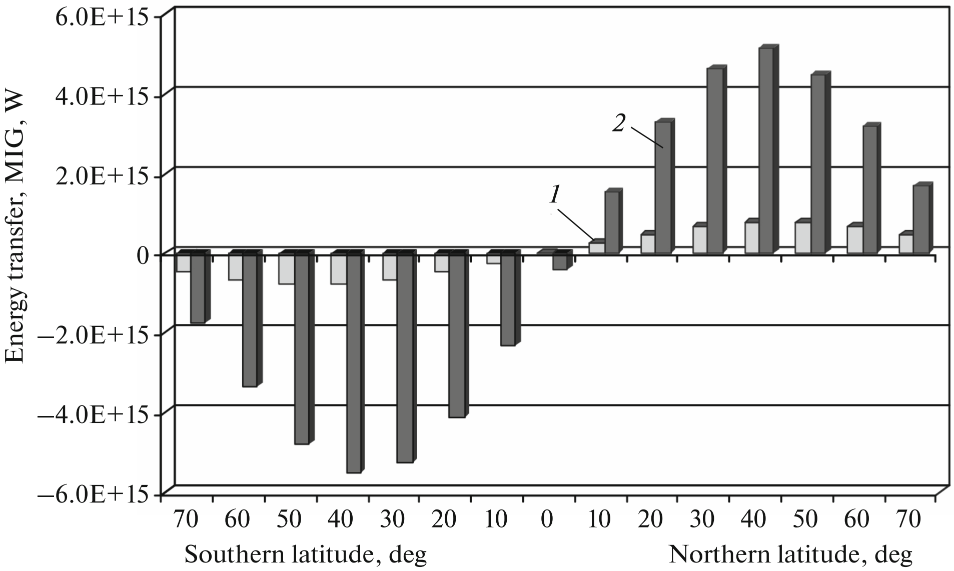

**Fig. 3.** Average long-term value of the annual MIG (*1*) and average annual energy transfer in the ocean–atmosphere system (*2*) [3].

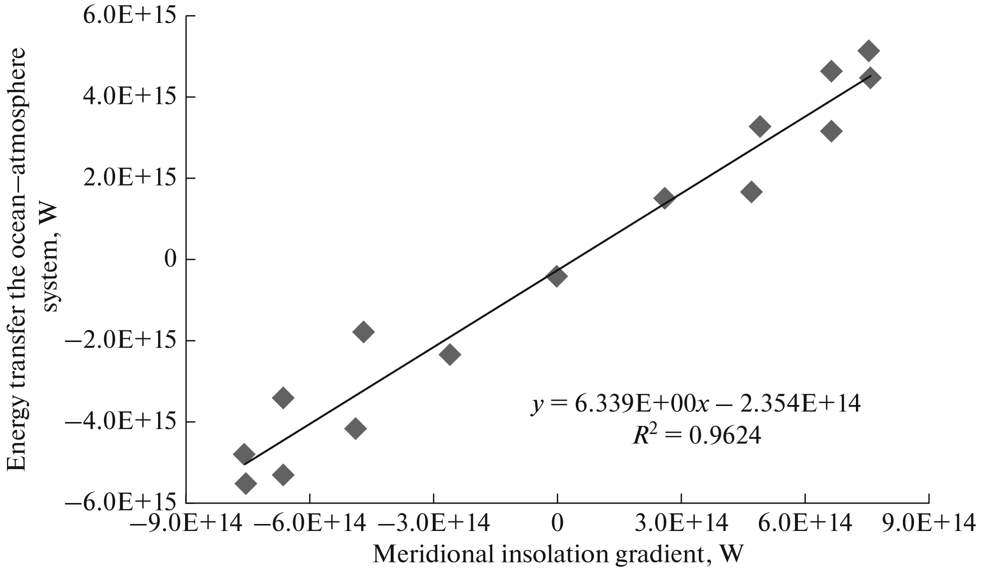

**Fig. 4.** Regression of MIG and energy (heat) transfer in the ocean–atmosphere system.

interannual variability of the energy incoming from the Sun is synchronized with 2- and 3-year periodicities, as well as 8- and 11-year phases of the 19-year cycle. Thus, the 2- and 3-year cycles form 8-year (2 + 3 + 3) and 11-year (2 + 3 + 3 + 3) summer series corresponding to the phases of the 19-year cycle. The 2- and 3-year periodicity is determined by the fact that the Earth is comparable with the nearest planets Venus and Mars in terms of average motion.

The uneven distribution (due to the spherical shape of the planet) of solar radiation on the Earth's surface (excluding the atmosphere and the ocean) leads to a meridional insolation gradient (MIG) (Fedorov, 2018). Traditionally, the northward energy transfer is calculated for the ocean and atmosphere (Lorenz, 1967; Palmen and Newton, 1969; Peixóto and Oort, 1984) (Fig. 3). The MIG and energy transfer in the ocean–atmosphere system are linearly connected (Fig. 4).

Subtracting the MIG values for latitudinal zones calculated for the first century (2900 B.C.–2999 B.C.) from the data array from the MIG values obtained for the last century (2900 A.D.–2999 A.D.), we obtain the change in the annual MIG in latitudinal zones for

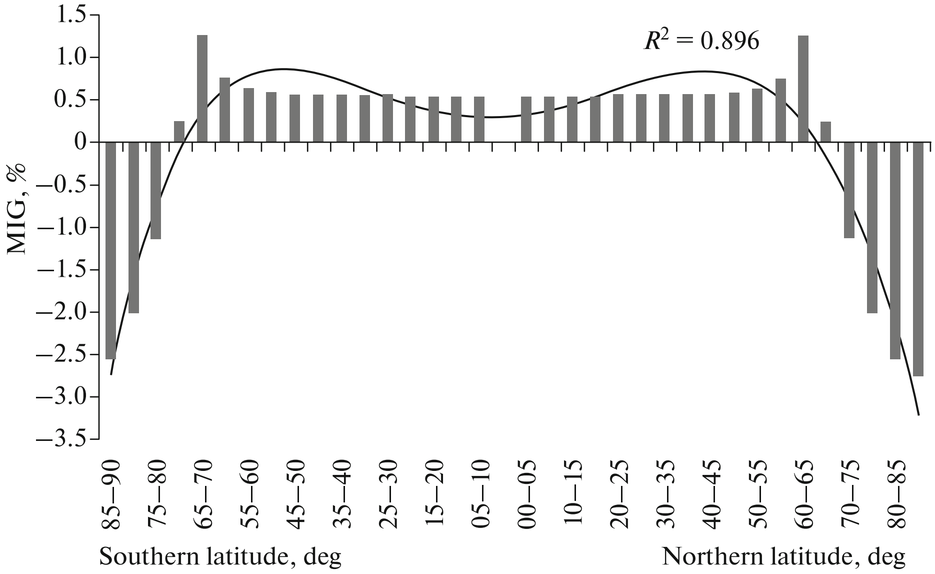

**Fig. 5.** Percentile change in annual MIG for 5998 years relative to the average value for the latitudinal zone.

5998. Dividing the resulting values (in J) by the average length of the tropical year (31556921.5 s), we obtain the change in the annual MIG (in W) and, then, as a percentage, its value relative to the meridional gradient averaged over the array (Fig. 5).

There is a gradual increase in the MIG on the Earth's surface (excluding the atmosphere and the ocean) from the equator to the polar circles in each hemisphere. The peaks in the increase are localized near the 65th parallel in each hemisphere (near the polar circles). The maximum is observed at latitudes of 60°–65° in the Northern Hemisphere and 65°–70° (annual "turbulence zones") in the Southern Hemisphere. Transpolar regions are characterized by a gradual MIG decrease from the polar circles to the poles. Thus, each hemisphere has regions of MIG increase (from the equator to the polar circle) and regions of MIG decrease (from the polar circle to the pole) (Fedorov, 2018). The regions of increase in the annual MIG are found in latitudinal ranges where Headley and Ferrel circulation cells are localized. The region of the decrease in the annual MIG is found in polar cells. The maximum increase (by 7.14E + 12 W or 1.25%) is observed near the polar circles (~65°) in each hemisphere (annual "turbulence zones"). The maximum decrease is observed near the geographic poles (by 8.98E + 12 W or by 2.56% in 85°–90° S and 80°–85° N). These "turbulence zones" coincide with the regions (60°–70° latitude) of the peak development of extratropical cyclones (cyclogenesis) in the hemispheres or low-pressure subpolar zones in the hemispheres (Lorenz, 1967; Palmen and Newton, 1969).

Similarly, the long-term changes in MIG for winter and summer (in the Northern Hemisphere) half-years were calculated (Fig. 6).

The MIG maximally increases in the winter (for the Northern Hemisphere) half-year at latitudes 20°–15° S (11.78%) and maximally reduces at 15°–10° S (–17.79%) relative to the values for the half-years averaged over the whole data array. In the summer (for the Northern Hemisphere) half-year, the maximum MIG increase (11.78%) is observed in the latitudinal zone 10°–15° N, and the maximum decrease (–17.79%) is observed in the latitudinal zone 5°–10° N. This identifies seasonal "turbulence zones" located near the latitudes 10°–20° in each hemisphere. Here, in the neighboring 5-degree latitudinal zones, the variation trends in summer MIGs differ maximally. In the polar regions (polar circulation cells), the MIG increases in the winter half-years and decreases in the summer half-years.

The vast majority of tropical cyclones are known to arise in the equatorial belt between 10° and 30° latitudes in both hemispheres. Approximately 87% of tropical cyclones arise in regions that are located at latitudes below 20°. Thus, the regions of tropical cyclone generation coincide with the seasonal "turbulence zones" in the long-term change in the MIG. The work of the "heat engine of the first kind"—the mechanism of interlatitudinal heat exchange in the atmosphere—is largely associated with vortex energy transfer. Vortices (cyclones) transfer energy in the atmosphere from the heat source (low latitudes) to its sink (high latitudes). However, the circulation intensity is likely to increase in Headley and Ferrel cells on an annual scale and in polar cells in the summer half-years.

The resulting average distribution of the annual MIG (Fig. 3) was compared with the distribution of the average annual energy transfer in the ocean–atmosphere system given by Palmen and Newton

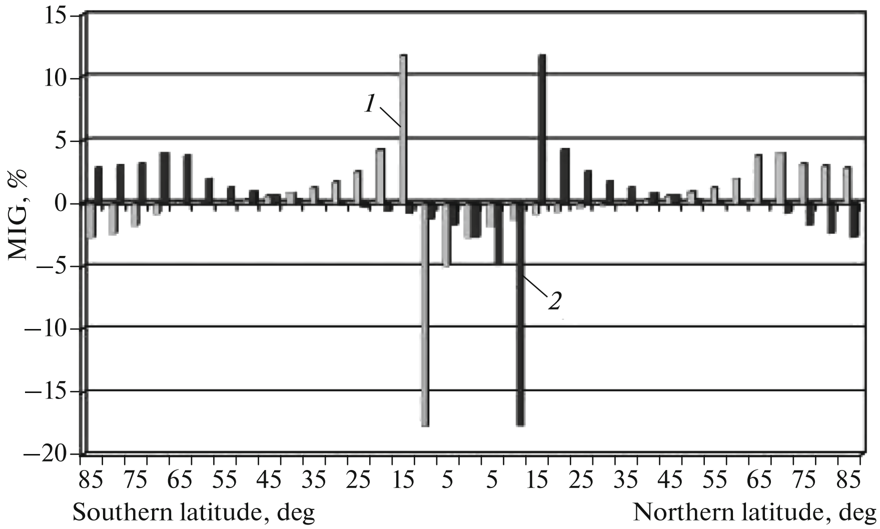

**Fig. 6.** Percentile change in MIG in winter (*1*) and summer (*2*) half-years for the Northern Hemisphere over 5998 years relative to the average value for the latitudinal zone.

(1969). The correlation between average values of the annual MIG and in the ocean–atmosphere system was 0.98 (Fig. 4) (linear relationship). The character of the average annual transfer in the atmosphere is similar for that obtained for the MIG (Lorentz, 1973). In this case, the numerical values of energy transfer in the ocean–atmosphere system given in the studies by Lorentz (1973) and Palmen and Newton (1969) are six to seven times higher than the long-term average values of MIG. The values of energy transfer obtained by Peixóto and Oort (1984) are on average three times higher than the MIG values. This may be caused by the fact that water and air masses are involved in energy transfer in the ocean–atmosphere system.

Since the average annual energy transfer in the ocean–atmosphere system is determined by the average annual MIG, the resulting changes for 5998 years (from 2999 B.C. to 2999 A.D.) can also occur in the ocean–atmosphere system. In other words, the difference of radiant energy "potentials" on the upper boundary of the atmosphere between the equator and poles controls the energy transfer to this boundary (the MIG is a reflection of the difference of equator/pole radiant energy "potentials").

It follows from these results that it follows that features of the MIG change are responsible for the increased intensity of vortex energy transfer in the atmosphere (tropical and extratropical cyclones). That is, there will be an increase in the work of the "heat engine of the first kind"—an increase in interlatitudinal heat exchange in the atmosphere. Here, the increase in annual heat transfer will be governed by extratropical cyclones and tropical cyclones (hurricanes and typhoons) in summer half-years for hemispheres. Thus, the meridional heat transfer by vortex formations can be governed by the MIG change at the upper boundary of the atmosphere (or on the Earth's surface excluding the atmosphere and the ocean). This may result in increased climate turbulence. Also, an increase in the circulation intensity in Headley and Ferrel cells is expected on an annual scale and in polar cells in winter half-years.

These features of the Earth's solar climate in the present epoch are associated with a decrease in the inclination of the Earth's rotation axis due to precession. The same is responsible for the nature of the MIG change, which regulates the energy transfer in the ocean–atmosphere system. The use of insolation variations of different physical nature (Fedorov, 2018; 2019) allows a more complete and objective assessment of the possible climate changes, because solar energy is the main source of energy for hydrometeorological processes.

## 4. CONCLUSIONS

(1) The annual insolation of the Earth is characterized by a slow decreasing trend.

(2) There is an increase in insolation in the Earth's equatorial region and a decrease in polar regions; i.e., the present epoch is characterized by a grown latitudinal contrast in the distribution of radiant energy incoming to the Earth.

(3) There is a decrease in insolation in the summer half-years and an increase in the winter half-years; i.e., the seasonal differences in the solar energy incoming to the Earth tend to be smoothed.

(4) Against the background of secular trends (low-frequency oscillations) in insolation changes, there are small, high-frequency variations due to periodic disturbances in the Earth's orbital motion and inclination of its rotational axis. The interannual and 2-, 3-,

8-, 11-, and 19-year variations in the incoming radiant energy are identified.

(5) The interannual variability of the energy incoming from the Sun is synchronized with 2- and 3-year periodicities, as well as 8- and 11-year phases of the 19-year cycle. Thus, the 2- and 3-year cycles form 8-year (2 + 3 + 3) and 11-year (2 + 3 + 3 + 3) summer series corresponding to the phases of the 19-year cycle.

(6) The change in the annual MIG is associated with a region of increase located between the polar circles with maxima (annual "turbulence zones") near the polar circles (near 65° in each hemisphere) and regions of decrease located beyond the polar circles. The peaks of the increase in annual MIG correspond to the regions of the peak development of extratropical cyclones (cyclones in both hemispheres).

(7) In the summer half-years, the region between 5° and 20° latitudes is characterized by the maximal divergence in the MIG change trends (seasonal "turbulence zones"). These zones are associated with the formation of tropical cyclones in the hemispheres. The seasonal MIG increases in polar regions in the winter half-years and decreases in the summer half-years.

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