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USE OF SPACE INFORMATION ABOUT THE EARTH  
STUDYING ATMOSPHERIC PROCESSES  
AND CLIMATE CHANGE FROM SPACE

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## The Tendencies of Change of the Incoming Solar Radiation to the Upper Atmosphere Boundary and Their Spatial Localization

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**Abstract**—Satellite-based measurements of the total flow of incoming solar radiation arriving at the Earth (total solar irradiance (TSI)) have been carried out since 1977. By now, a continuous series of variations of the TSI is obtained. The 11-year cycle and its amplitude in multiyear variations of solar radiation are revealed. However, two mechanisms having different physical nature are defined in regulation of the incoming solar radiation to the Earth (with the atmosphere not accounted for), and in its distribution over the Earth surface (solar climate of the Earth). One mechanism is related to the variation in solar activity. Another mechanism is defined by celestial-mechanical processes, which alter the orbit elements of the Earth (Earth–Sun distance, duration of the tropical year, etc.), the Earth rotation axis tilt, and the relevant variations in the Earth’s insolation. The performed calculations of the insolation related to the celestial-mechanical processes were used as a basis for differentiating the satellite observational data on the changes of the TSI with respect to the mechanisms of different physical nature. It was made possible to estimate the contributions of the variation in solar activity and of the celestial-mechanical processes to the total incoming solar radiation.

**Keywords:** satellite measurements, total flow of solar irradiance, Earth’s insolation, alteration trends, tilt of rotation axis, astronomical seasons, latitudinal localization

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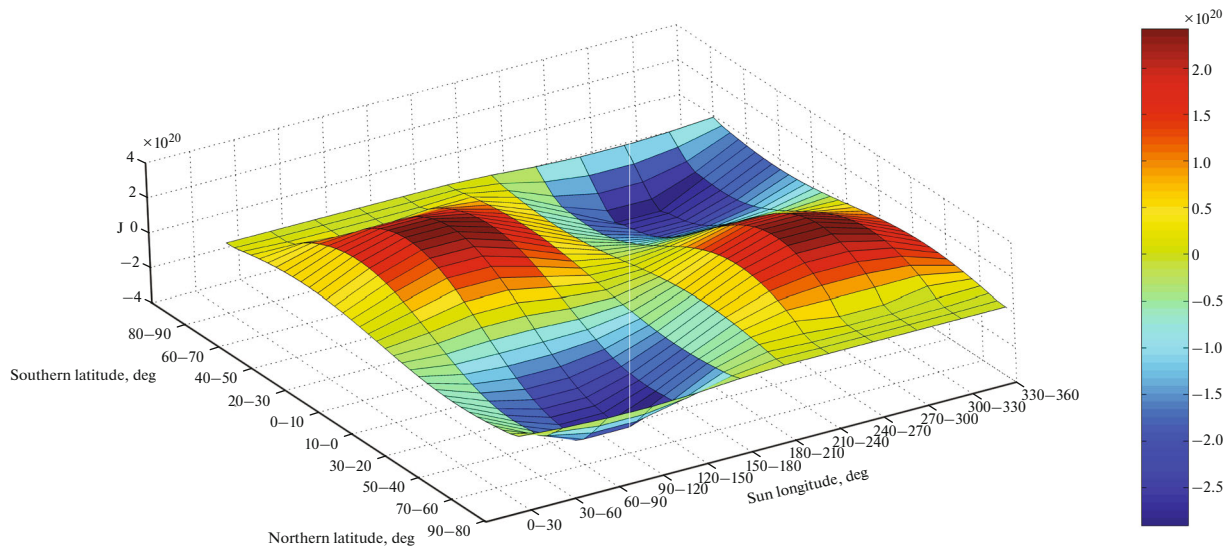
### INTRODUCTION

Solar radiation is the main energy source determining the radiative thermal balance of the Earth. The annual amount of solar radiation incoming on the upper atmosphere boundary (UAB) of the Earth is  $5.49E24$  J on average (Budyko, 1974; Drozdov et al., 1989; Fedorov, 2018; Khromov and Petrosyants, 2006), or  $1.0777E10$  J/m<sup>2</sup>. This amount is not constant in time, it changes both in time and in space. Variations in the incoming radiant energy are determined mainly by two things with different physical natures. One of the causes is the variation in the solar radiation activity. Another cause determining a change in the incoming energy is the celestial-mechanical processes inducing variations in the Earth’s orbit elements (Milankovich, 1939; Monin, 1982; Monin and Shishkov, 2000) and in the rotation axis tilt. In this work the spatial and temporal variations associated with celestial-mechanical processes are considered. The alteration of solar activity is neglected.

Satellite-based measurements of the total solar irradiance (TSI) have been carried out since 1977. By now, a continuous series of direct TSI measurements has been obtained, which were performed by several special spacecrafts (Nimbus-7, launched in November 1978, and the Solar Maximum Mission (SMM)

launched in February 1980). These measurements are performed for three complete cycles of solar activity (21–23) and are in progress within current cycle 24. The TSI variation data received from satellites is read with respect to the unchanged distance between the Earth and the Sun, which is equal to 1 AU (annual average). While calculating variations in the insolation, which are related to the celestial-mechanical processes, the calculations are performed from the accepted and unchanged value of the solar constant (multiyear average TSI) and are not normalized to the distance. The analysis of our calculated data on insolation from the satellite information on TSI allows a ratio of different-nature variations (associated with solar activity and with celestial-mechanical processes) to be determined in the TSI (Fedorov, 2019a).

The solar radiation variations related to celestial-mechanical processes are determined by computational methods. The solar climate of the Earth is understood as the theoretically calculated arrival of solar radiation and its distribution along the upper atmosphere boundary (UAB) or over the surface of the Earth without consideration for the atmosphere (Drozdov et al., 1989; Milankovich, 1939; Monin and Shishkov, 2000; Fedorov, 2018). The TSI data from remote sensing of the Earth, taking into account the insolation values derived with the performed theoretic-



**Fig. 1.** Spatiotemporal variation in the Earth’s insolation for the period from 3000 BC to AD 2999 (J).

cal calculations, may be differentiated with respect to the involvement of variations of different physical natures in TSI alteration.

### TECHNIQUE OF CALCULATIONS

Calculations of the incoming solar radiation were performed using the data on astronomical ephemerides (Giorgini et al., 1996; Jet Propulsion Laboratory), which are composed from satellite data for the entire surface of the Earth without consideration for atmosphere within an interval from 3000 BC to AD 2999. Initial astronomical data for the insolation calculations were as follows: the declination and ecliptic longitude of the Sun, the distance from the Earth to the Sun, and the traveltime difference between the equally passing time (coordinated time) CT and universal corrected time UT. The Earth’s surface was approximated by the GRS80 ellipsoid (Geodetic Reference System, 1980) with semiaxis lengths of 6378137 m (major) and 6356752 m (minor). In the general form, the algorithm of calculations can be presented by the expression

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

where  $I$  is the incoming solar radiation during the elementary  $n$ th fragment of the  $m$ th tropical year (J);  $\sigma$  is the areal multiplier ( $m^2$ ), using which the areal differential  $\sigma(H, \varphi)d\alpha d\varphi$  (an area of infinitely small trapezium—ellipsoid cell) is calculated;  $\alpha$  is the hour angle;  $\varphi$  is the geographic latitude, expressed in radians;  $H$  is the height of the ellipsoid surface with respect to the Earth’s surface (m);  $\Lambda(H, \varphi, t, \alpha)$  is the insolation at the given moment at the specified place of the ellipsoid surface ( $W/m^2$ ); and  $t$  is the time (s). The steps of

integration were as follows:  $1^\circ$  in longitude,  $1^\circ$  in latitude,  $1/360$  part of the tropical year in time (Fedorov, 2012, 2013, 2014, 2015a, 2015b, 2016). The solar constant value (the multiyear average of TSI) was assumed to be  $1361 W/m^2$  (Fedorov, 2018; Kopp and Lean, 2011). The solar activity alteration was neglected.

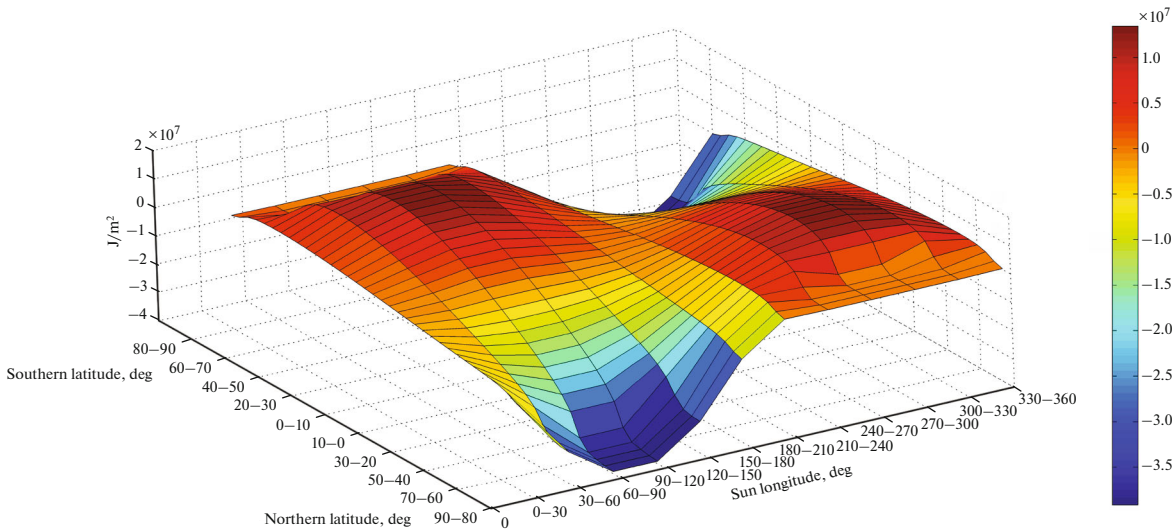
### RESULTS

As a result of the Earth’s insolation calculation (Fedorov, 2019b; Bertrand et al., 2002; Fedorov, 2013), the insolation distribution in J and in  $J/m^2$  is obtained. The spatiotemporal variation in the solar radiation arriving at the UAB for the period from 3000 BC to AD 2999 is presented in Figs. 1 and 2. The insolation variation was determined as a difference of averages for the last 100 years and the relevant values of the first 100 years in the array of the calculated insolation values.

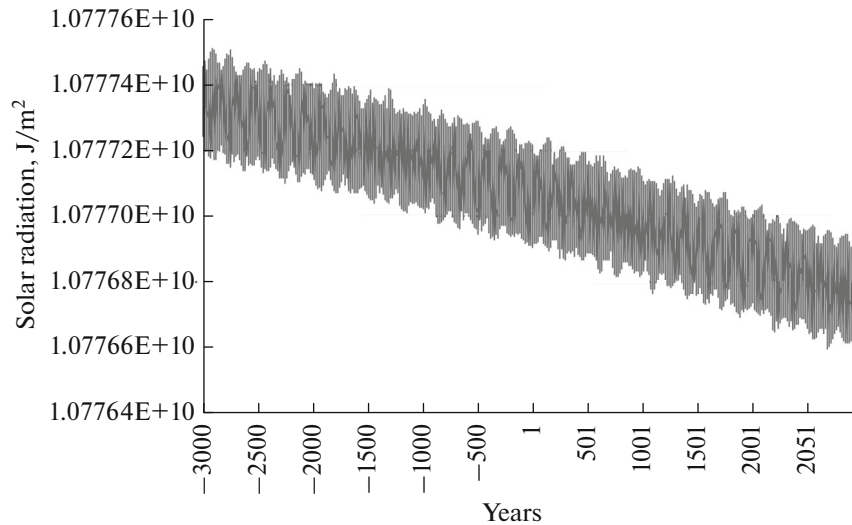
The results show that the annual average amount of solar energy arriving at the UAB of the Earth in the last century (on the interval from 3000 BC to AD 2999) relative to the first century for this period reduced insignificantly (by  $5.78E + 05 J/m^2$ , or by 0.005%). This slow trend of insolation reduction (Fig. 3) is determined by the secular variations in the eccentricity of the Earth’s orbit (Milankovich, 1939; Frolov, 2018, 2019).

With the total small reduction in the solar radiation arriving at the UAB for a tropical year in the regions below  $45^\circ$  latitude in each hemisphere, an appreciable trend to the insolation increase is manifested, while above  $45^\circ$  there is an appreciable trend to the insolation reduction (Fig. 4).

The reduction of the solar energy arriving at polar regions ( $85^\circ-90^\circ$  of geographic latitude) for the entire period is  $1.53E + 08 J/m^2$ , or 2.73% of the initial value.



**Fig. 2.** Spatiotemporal variation in the Earth's insolation for the period from 3000 BC to AD 2999 ( $\text{J}/\text{m}^2$ ).



**Fig. 3.** Variations in the Earth's insolation within an interval from 3000 BC to AD 2999.

The increase in the equatorial region (in latitudinal zones of  $0^\circ\text{--}5^\circ$  N and  $0^\circ\text{--}5^\circ$  S) is  $3.23\text{E} + 07 \text{ J}/\text{m}^2$ , which is 0.25% of the initial value of insolation. Thus, an increase by 2.98% is noted in the meridional gradient of insolation between the equatorial area and polar regions. The intensity alteration of the incoming radiation occurs in a similar way. A reduction in the intensity of the incoming solar radiation in polar regions is about  $5 \text{ W}/\text{m}^2$ ; its increase in the equatorial area is  $1 \text{ W}/\text{m}^2$ . An increase in the meridional gradient of solar radiation intensity is  $6 \text{ W}/\text{m}^2$ . Consequently, one of trends in the alteration of the incoming solar energy in the modern epoch is the enhancement of the latitudinal contrast (increase in the meridional gradient) of insolation (Fedorov, 2014, 2015a, 2015b, 2018, 2019). This effect

manifests itself both in the total solar radiation arriving at unit area of the earth ellipsoid and in the intensity of its arrival.

The insolation values calculated for seasons (the winter and summer astronomical half-years) were also analyzed (Fig. 5). Secular variations (trends) were estimated by a difference of values of the incoming solar radiation ( $\text{J}/\text{m}^2$ ) in the last (AD 2900–2999) and the first (3000–2901 BC) centuries for the corresponding latitudinal zones in the relevant half-years. In the summer half-year for the Northern Hemisphere, an increase in absolute values of the solar radiation arriving at the earth ellipsoid is observed in the zone of  $5^\circ\text{--}10^\circ$  N and in the latitudinal area located southerly. The maximum increase in the incoming radiation is noted

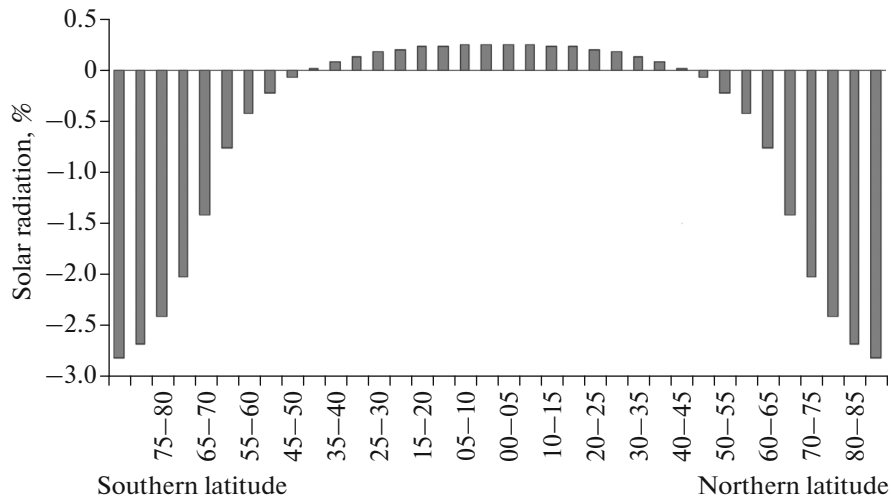


Fig. 4. Latitudinal variation in the Earth's insolation within an interval from 3000 BC to AD 2999.

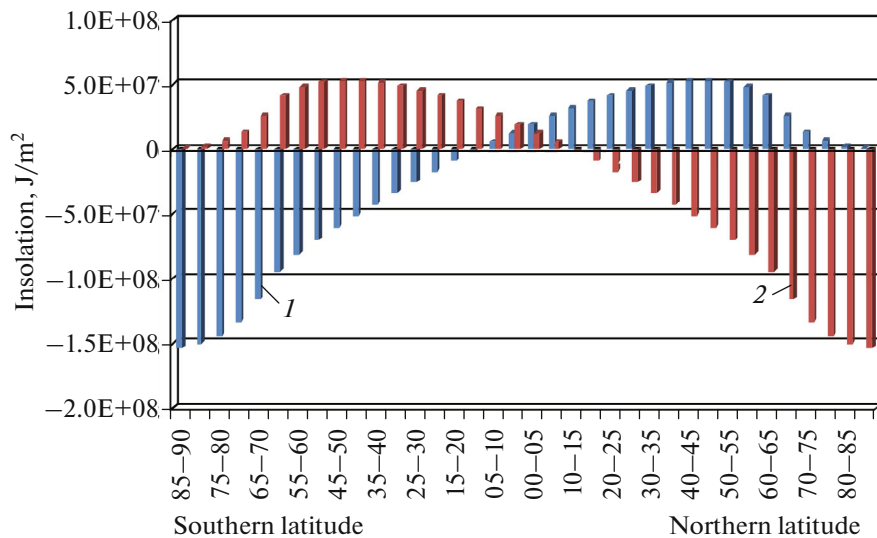
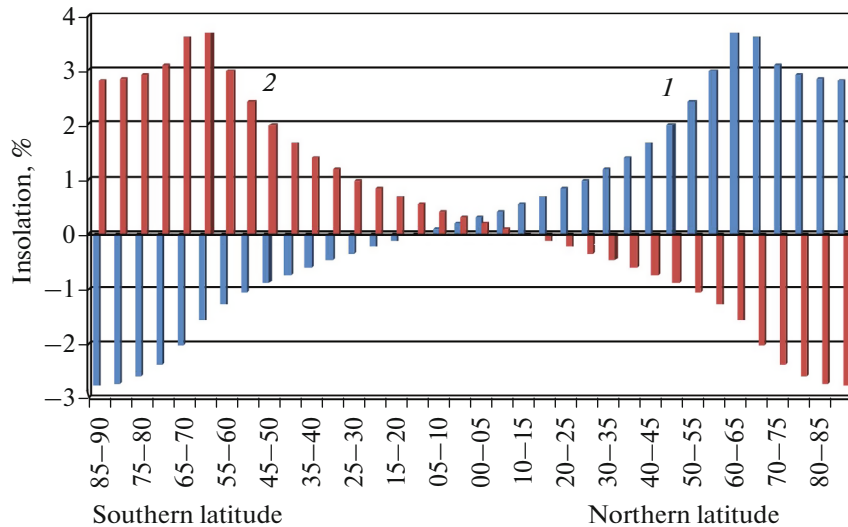


Fig. 5. Latitudinal variation in the Earth's insolation within an interval from 3000 BC to AD 2999 during the winter (1) and summer (2) half-years (for the Northern Hemisphere).

within a latitudinal zone of  $45^{\circ}$ – $50^{\circ}$  S, where it amounts to  $5.41E + 07 \text{ J/m}^2$ , or 2.038% of the annual average value of solar radiation arriving at this zone during the summer half-year for the Northern Hemisphere. The increase, which is average for the five-degree latitudinal zone in this area, is  $3.14E + 07 \text{ J/m}^2$ . The insolation reduction at this time is observed in the zone of  $10^{\circ}$ – $15^{\circ}$  N and in the area located northward of this zone. The maximum reduction is localized in the zone of  $85^{\circ}$ – $90^{\circ}$  N and amounts to  $1.56E + 08 \text{ J/m}^2$ , or 2.83% of the annual average value of the solar radiation, arriving at this zone. The average reduction for the five-degree zone is  $7.55E + 07 \text{ J/m}^2$ . The annual average insolation reduction in the century, which is the last for the interval, with respect to the first century

during the summer half-year for the Northern Hemisphere amounts to  $2.98E + 05 \text{ J/m}^2$  (0.006%). The reduction by  $4.8 \text{ J/m}^2$  in the radiation, arriving at the latitudinal zone of  $65^{\circ}$ – $70^{\circ}$  N (on UAB), during the preceding 1000 years for mid-July (the point with the geocentric latitude of  $120^{\circ}$ ) is reported also in the work by Belgian researchers (Bertrand et al., 2002).

In the winter half-year for the Northern Hemisphere (Fig. 5), the reduction in the solar energy arriving at the earth ellipsoid within the latitudinal area from  $10^{\circ}$  to  $90^{\circ}$  S is observed. The reduction reaches maximum in the southern polar region:  $1.56E + 08 \text{ J/m}^2$ , or 2.83% of the annual average value of solar energy arriving at this latitudinal zone of the earth ellipsoid



**Fig. 6.** Latitudinal variation in the Earth's insolation in % (3000 BC to AD 2999) during the winter (1) and summer (2) half-years (for the Northern Hemisphere).

during the winter half-year. The insolation reduction average for the five-degree latitudinal zone within this interval (3000 BC–AD 2999) is  $7.55E + 07 \text{ J/m}^2$ . Positive values during this half-year are typical for the area of  $5^\circ$ – $10^\circ$  of southern latitude and for all latitudinal zones located northward of this zone. The maximum insolation value of  $5.42E + 07 \text{ J/m}^2$ , or 2.04% of the annual average value of the energy, arriving at this zone during the winter (for the Northern Hemisphere) half-year, is observed in the latitudinal zone of  $45^\circ$ – $50^\circ$  N. The insolation increase (average over five-degree zone) is characterized by a value of  $3.14E + 07 \text{ J/m}^2$ . The annual average increase in the insolation during the last century of the interval (from 3000 BC to AD 2999) relative to the first century of the summer half-year for the Northern Hemisphere is  $2.80E + 05 \text{ J/m}^2$  (0.005%). Thus, in winter half-years for the hemispheres, an increase in the incoming solar energy is noted, while in summer half-years its reduction is observed. Seasonal difference in the solar energy coming at the earth ellipsoid, consequently, are smoothed (Fedorov, 2015b, 2018, 2019).

The observed low-frequency variations—trends (enhancement of latitudinal contrast and smoothing of seasonal difference)—in the Earth's insolation are associated with the secular trend of a decrease in the tilt angle of the Earth's rotation axis (with respect to a normal to the plane of ecliptic) as a result of precession. It is known that, with an increase in the angle of the rotation axis tilt, the amount of solar radiation arriving at polar regions increases; i.e., the smoothing of the latitudinal contrast in hemispheres and the enhancement of seasonal difference occur. When the tilt angle decreases, there is an increase in radiation arriving at the near-equatorial areas and a decrease in radiation coming to polar regions and the latitudinal

contrasts grow, while the seasonal difference is smoothed (Milankovich, 1939; Monin and Shishkov, 2000).

In relative units (Fig. 6), the maximum variations of the incoming solar radiation are localized in the summer half-year for the Northern Hemisphere within the latitudinal zone of  $60^\circ$ – $65^\circ$  S (3.75%). In the winter half-year for the Northern Hemisphere, the maximum of the semiannual variation of the incoming radiation falls on the latitudinal zone of  $60^\circ$ – $65^\circ$  N (3.75%).

Based on the analysis of the insolation calculation results, the following specific features in the secular trend of alteration of the incoming solar radiation are highlighted (Figs. 1, 2).

(1) In winter half-years for the hemispheres, the amount of incoming solar radiation increases, while in the summer half-years, it decreases (the seasonal difference is smoothed). The analysis of the alteration of incoming radiation in the considered interval for hemispheres and half-years shows that, in the summer half-years for the hemispheres, the reduction (by average values of the first and last centuries in the array) for hemispheres is  $3.89E + 07 \text{ J/m}^2$  (0.57%), while in winter half-year, the increase (by average values of the first and last centuries in the array) amounts to  $3.83E + 07 \text{ J/m}^2$  (0.96%).

(2) In winter half-years for hemispheres, the most significant increase is noted in the 3rd month (more exactly, 1/3 of the astronomical season) of the autumn season and the 1st month of the winter astronomical season in each hemisphere. The maximum increase in the incoming radiation is observed within the latitudinal range, which is located between  $35^\circ$  and  $50^\circ$  of latitude in both hemispheres.

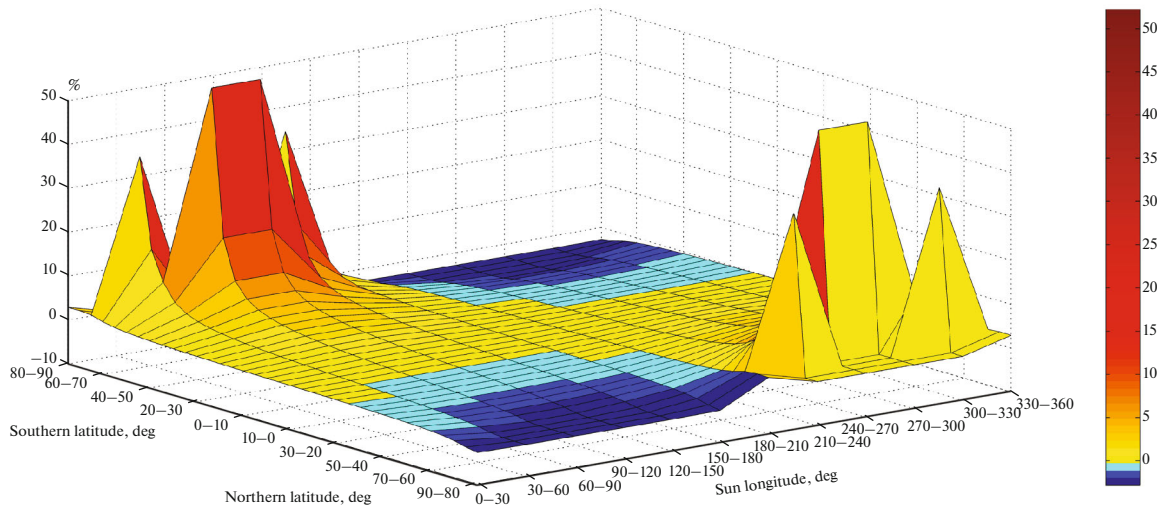


Fig. 7. Spatiotemporal variation in the Earth's insolation in J for the period from 3000 BC to AD 2999 (%).

(3) In the summer half-year for hemispheres, the most significant reduction is typical for the 2nd and 3rd astronomical months (more exactly, 1/3 parts of astronomical season) of the spring season and the 1st and 2nd months of the summer astronomical season in each hemisphere. The reduction in the mentioned seasons successively grows with an increase in latitude.

(4) The “dead” zones are separated, which are polar regions not receiving the solar radiation in individual seasons of the year in the course of the whole interval (5999 years). During the 2nd and 3rd astronomical months of autumn and two first winter (for the hemisphere) astronomical months (the two first thirds of the season), the latitudinal zones from 80° to 90° of latitude in each hemisphere do not receive solar radiation at all. In the last third of the astronomical autumn and the first third of the astronomical winter in the hemisphere, the amount of the incoming solar radiation is also zero in the zones from 70° to 80° of latitude in each hemisphere.

(5) The near-equatorial zone from 5° S to 5° N is separated for which, on the entire interval under study, the increase in the incoming radiation is typical during the whole tropical year. This area expands to 10° of latitude in the second and third months of astronomical spring and the first two thirds of astronomical summer of each hemisphere, as well as to the latitude of 15° in the last third of astronomical spring season and the first third of astronomical summer season in each hemisphere (Fedorov, 2015b, 2018).

Thus, in the interval from 3000 BC to AD 2999, a weak reduction of incoming radiation is observed in the Earth's insolation. The increase in the radiation arriving at the equatorial area (heat source) and the reduction in the polar regions (areas of heat sink) are noted. In summer half-years, the reduction of incoming radiation is observed, while in winter half-years,

the increase is noted. In the annual incoming amount, the smoothing of seasonal difference and an increase of latitudinal contrast are noted.

In relative units, the pattern of alteration of the solar radiation arriving at the UAB for a period from 3000 BC to AD 2999 changes appreciably (Fig. 7).

In the Northern Hemisphere during the summer half-year, the gradual reduction of the incoming solar radiation from the equatorial area to the pole is observed. In the first and sixth astronomical months (the first astronomical month corresponds to the calendar April), the incoming radiation reduces from  $-0.07$  and  $-0.06\%$  in the latitudinal zone of 10°–15° N to  $-2.74$  and  $-2.72\%$  in the latitudinal zone of 85°–90° N. In the second and fifth astronomical months, the incoming solar radiation reduces from  $-0.05\%$  in the latitudinal zone of 10°–15° N to  $-2.85\%$  in the latitudinal zone of 85°–90° N. In the third and fourth astronomical months, the incoming solar radiation reduces from  $-0.12\%$  in the latitudinal zone of 15°–20° N to  $-2.85\%$  in the latitudinal zone of 85°–90° N.

In the Northern Hemisphere during the winter half-year, the increase in the incoming solar radiation is noted on the entire territory. An exception is dead zones. In the 7th and 12th astronomical months, an incoming amount increases from 0.06% in the latitudinal zone of 0°–5° N to 2.87% and 2.89% in the latitudinal zone of 85°–90° N. In the 8th and 11th astronomical months, the increase is noted from 0.31% in the latitudinal zone of 0°–5° N to 9.83% in the latitudinal zone of 65°–70° N. In the ninth and tenth astronomical months, an increase from 0.59% in the latitudinal zone of 0°–5° N to 2.76% in the latitudinal zone of 55°–60° N is noted. The maximum values are characteristic of the 8th and 11th astronomical months and are localized in the latitudinal zones of 70°–75° N (16.5%) and 75°–80° N (36.83 and 36.85%, respec-

tively). In the ninth and tenth astronomical months, the significant increase is observed in the latitudinal zone of  $60^{\circ}$ – $65^{\circ}$  N (18.3%). The absolute maximum falls on the ninth and tenth astronomical months (calendar January and February) and is localized in the latitudinal zone of  $65^{\circ}$ – $70^{\circ}$  N: 52.24 and 52.22%, respectively. It is known that the latitudinal zone of  $60^{\circ}$ – $70^{\circ}$  N is a zone of the extratropical cyclogenesis (Fedorov, 2018; Khromov and Petrosyants, 2006).

In the Southern Hemisphere during the winter half-year, an increase in the incoming solar radiation is noted for the entire territory except for the area of dead zones. In the first and sixth astronomical months, the increase is from 0.06% in the latitudinal zone of  $0^{\circ}$ – $5^{\circ}$  S to 2.85 and 2.88%, respectively, in the latitudinal zone of  $85^{\circ}$ – $90^{\circ}$  S. In the second and fifth astronomical months, the increase is from 0.31% in the latitudinal zone of  $0^{\circ}$ – $5^{\circ}$  S to 9.83% in the latitudinal zone of  $65^{\circ}$ – $70^{\circ}$  S. In the 3rd and 4th astronomical months, the increase is noted from 0.59% in the latitudinal zone of  $0^{\circ}$ – $5^{\circ}$  S to 9.76% in the latitudinal zone of  $55^{\circ}$ – $60^{\circ}$  S. Maxima of the increase in the incoming radiation are characteristic of the second and fifth astronomical months. They are localized in the zone of  $70^{\circ}$ – $75^{\circ}$  S (1.51 and 16.49%, respectively). In the latitudinal zone of  $75^{\circ}$ – $80^{\circ}$  S in these months, the increase in the incoming solar radiation is 38.83 and 36.86%, respectively. In the third and fourth astronomical months in the latitudinal zone of  $60^{\circ}$ – $65^{\circ}$  S, the increase is 18.83 and 18.82%, respectively. The absolute maxima chronologically fall on the third and fourth astronomical months (calendar June and July) and are localized in the latitudinal zone of  $60^{\circ}$ – $65^{\circ}$  S (52.24 and 52.22%, respectively).

In the Southern Hemisphere during the summer half-year, a small increase in the incoming solar radiation is observed only in the equatorial area. In the latitudinal zone of  $0^{\circ}$ – $5^{\circ}$  S, it is noted from 0.02 in the 7th and 12th astronomical months to 0.40 and 0.39% in the 9th and 10th astronomical months, respectively. In these months an increase of 0.22% is also noted in the latitudinal zone of  $5^{\circ}$ – $10^{\circ}$  S. On the remaining area of the hemisphere, a reduction in the incoming radiation is observed. In the 7th and 12th astronomical months, the arrival of radiation is reduced from  $-0.06\%$  in the latitudinal zone of  $10^{\circ}$ – $15^{\circ}$  S to  $-2.73\%$  in the latitudinal zone of  $85^{\circ}$ – $90^{\circ}$  S. In the 8th and 11th astronomical months, the amount of incoming radiation reduces from  $-0.17\%$  in the latitudinal zone of  $15^{\circ}$ – $20^{\circ}$  S to  $-2.85\%$  in the latitudinal zone of  $85^{\circ}$ – $90^{\circ}$  S. In the ninth and tenth astronomical months, the reduction is observed from  $-0.12\%$  in the latitudinal zone of  $15^{\circ}$ – $20^{\circ}$  S to  $-2.85\%$  in the latitudinal zone of  $85^{\circ}$ – $90^{\circ}$  N.

In relative values, the increase in the incoming radiation during the winter half-years for the hemispheres exceeds the reduction in the solar radiation incoming during summer half-years.

## CONCLUSIONS

For the annual insolation of the Earth, the slow trend to the reduction is typical. An increase in the insolation in the equatorial area of the Earth and a reduction in polar regions is observed; i.e., for the modern epoch, the enhancement of latitudinal contrast in the distribution of radiative energy arriving at the Earth is typical. An increase in the incoming solar radiation is observed during winter half-years for the hemispheres and the reductions during the summer half-years. These trends are associated with a decrease in the tilt angle of the Earth's rotation axis in the modern epoch. Maxima of the relative increase in the incoming solar radiation are observed in January and December in the Northern Hemisphere and in June and July in the Southern Hemisphere. These maxima are localized in the latitudinal zone of  $60^{\circ}$ – $70^{\circ}$ , which is the zone of the extratropical cyclogenesis and may manifest themselves in circular processes in the atmosphere. The maxima in the incoming amount of radiation observed near polar circles are determined by the decrease in the tilt of the rotation axis of the Earth are associated with the relatively large increase in the incoming radiation with its relatively small total amount arriving at these zones.

These results may be taken into account in radiation blocks of physical–mathematical models of climate and create a basis for finding contributions from factors of different physical natures to the TSI variations which are determined as a result of remote sensing of the Earth.

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