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GEOPHYSICS

Periodic Perturbations and Small Variations of the Solar Climate of the Earth

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The problem of global changes in the Earth's climatic system is quite topical for modern natural science. The most important question regarding the studies and prediction of climate changes is the problem of what causes these changes [2, 6, 8].

Solar radiation that supplies light and heat to the Earth is the most important factor in the genesis of Earth's climate and origination of life [2, 4, 12]. Variations in solar radiation reaching the Earth are determined by two main causes of different physical natures. Investigations of variations in solar radiation related to the changes of solar activity have been being carried out for a very long time; nevertheless, the relationship between variations in solar activity and climate change is still under discussion [6, 8]. The variations in solar radiation related to celestial mechanics have studied for a very long time. These studies imply comparison between variations in solar radiation and astronomical elements suffering long-term perturbations such as perihelion longitude, eccentricity, and inclination of the Earth's revolution axis [7, 8, 13, 14]. The detailed comparison between variations in solar energy supplied to the upper atmosphere and celestial mechanical processes in the range of periodic (in terms of Laplasian stability theory) perturbations of elements of the Earth's orbit has not been implemented until present. The availability of abundant information about the climate at present provides a high topicality to the study of variations in the solar climate and the search for relationships between them and climate changes comparable in size to those observable for humanity.

With the change in the geocentric distance of the Sun and with the period of the Earth's revolution around the Sun (tropical year) taken into account, the values of solar radiation reaching the upper atmosphere boundary in the interval from 1900 until 2050 were calculated [10, 11]. The value of the solar constant, at the distance between Earth and Sun of 1 a.u., is $I_0 = 1367$ W/m^2. It is known that if a is the average distance between the Earth and the Sun, whose length is the major half-axis of the Earth's orbit ellipse (1 a.u.), then, at distance l,

$$I_l = I_0\left(\frac{a}{l}\right)^2. \tag{1}$$

The energy reaching Earth per time unit is

$$I_0\left(\frac{a}{l}\right)^2 \pi r^2, \tag{2}$$

where r is the Earth's radius. For a tropical year, the Earth receives

$$\sum_Y = I_0 \pi r^2 \int_0^T \left(\frac{a}{l}\right)^2 dt, \tag{3}$$

where T is the duration of the tropical year [8]. To simplify the calculations, the Earth was assumed to be a flat circular disc (the radius is assumed as the average radius of the Earth, 6 371 302 m), and the line connecting the centers of the Sun and the Earth is perpendicular to it.

The values of the duration of the tropical year, calculated from astronomical ephemeredes DE-406 [15], were divided into 365 parts of equal time (i.e., the discreteness of this rendering corresponded to about one day period, or 1° of geocentric solar longitude). For the beginning of every time interval of $\frac{T}{365}$, the distance l between the Earth and the Sun was calculated. In accordance with formula (1), we calculated the solar constant value for every $\frac{T}{365}$ interval. Using formula (2), we determined the energy reaching the Earth for each of $\frac{T}{365}$ intervals of the tropical year. Then these values were summed for the entire tropical year (formula (3)), and thus, the solar energy reaching the Earth's disc for a tropical year was calculated (Fig. 1).

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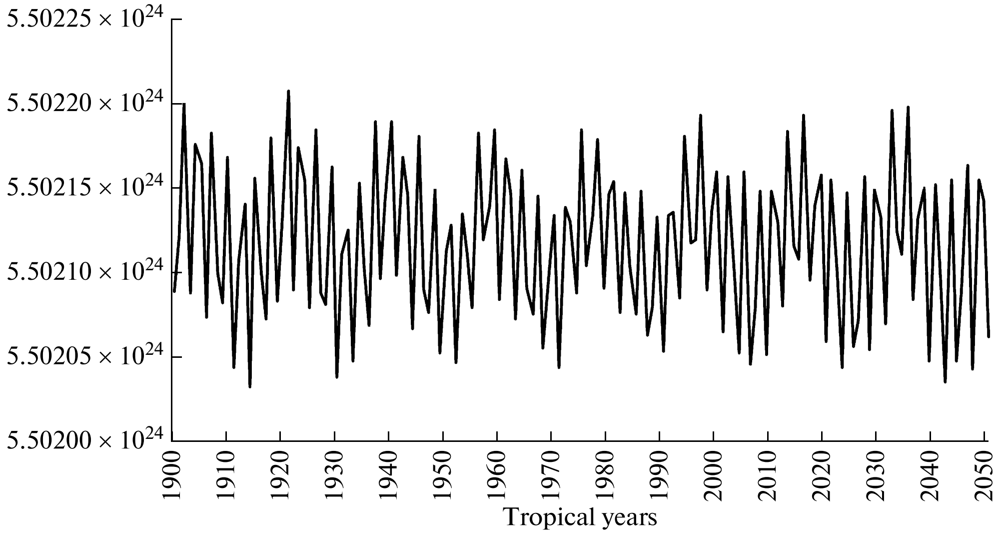

Fig. 1. The multiannual variations in solar radiation (J) reaching the upper atmosphere boundary during tropical years in the period from 1900 until 2050.

The resulting distribution shows the periodic character of variations in solar energy, against the background of a weak reduction tendency; this periodicity is represented by alternation of two- and three-year cycles incorporated into the longer cycles of nearly 19 years long. The interannual variations related to the period of the Earth's revolution around the Sun are also expressed.

The found variations in solar radiation are related to periodic perturbation of the Earth's orbital motion and its elements (distance between the Earth and the Sun and the duration of the Earth's revolution around the Sun) by the Moon and the nearest planets—Venus and Mars. For example, two- and three-year periodicities are determined by resonant perturbation of the Earth's orbital motion by Venus and Mars; note that the averaged relative ratios of planets' revolution are $\frac{2}{1}$ for Mars and Earth and $\frac{3}{5}$ for Venus and Earth [3, 11]. Alternation of two- and three-year cycles form 8- and 11-year combinations (2 + 3 + 3 and 2 + 3 + 3 + 3, respectively) that form a 19-year cycle after summation; this 19-year cycle corresponds to the period of the lunar orbit (lunar nodes) revolution, 18.61 year, or to the Metonic cycle of 19 years long. This cycle reflects an approximate equity of 19 tropical years and 235 synodal months, so that every 19 years the lunar cycle goes in the same day with the solar one (i.e., repetition of similar configurations in motions of the Earth, Sun, and Moon occurs) [5, 9].

At an average annual anomaly for the multiannual series of solar radiation (3.9289×10^{19} J), the average amplitude of two- and three-year variations is 4.64858×10^{19} J or 0.00085% of the average solar radiation for the tropical year (5.50212×10^{24} J). The average amplitude of 19-year cycles is 7.7574×10^{19} J or 0.00141% of the average annual solar energy received by a disc in the absence of an atmosphere; i.e., the average amplitude of 19-year cycles is 1.67 times more than that of two- and three-year cycles of solar radiation.

The calculations made show that, in the second half of the 20th century and in the first half of the 21st century, the Earth's disc has received a lesser amount of solar radiation than in the first half of the 20th century. For the second half of the 20th century, this decrease was as small as 9.5705×10^{17} J per year, or approximately 0.00002%. For the first half of the 21st century, reduction of the solar energy reaching the Earth is more noticeable: 8.75869×10^{18} [18] J per year, or approximately 0.00016% (the percentage is relative to the average annual value in the first half of the 20th century).

Interannual variations in solar radiation were calculated by the sequential subtraction of annual values. The average amplitude of interannual variations is 6.78124×10^{19} J per year, or approximately 0.00123% of the average value of solar radiation supplied per tropical year (5.50212×10^{24} J). In the case of the maximal amplitude value, this is 0.0023%. The interannual difference in the solar energy supply is 0.00247%, on average, and 0.00153% at maximal (the percentage is relative to the average annual solar energy per tropical year). The average amplitude of the two- and three-year variations in solar radiation is 8.41435×10^{19} J per year, or approximately 0.00153% of the average annual radiation. The 19-year variations are manifested poorly in the interannual series, and only upon smoothing of values in the series (Fig. 2).

Interannual variations in the solar energy reaching the Earth's disc are characterized by a close correla-

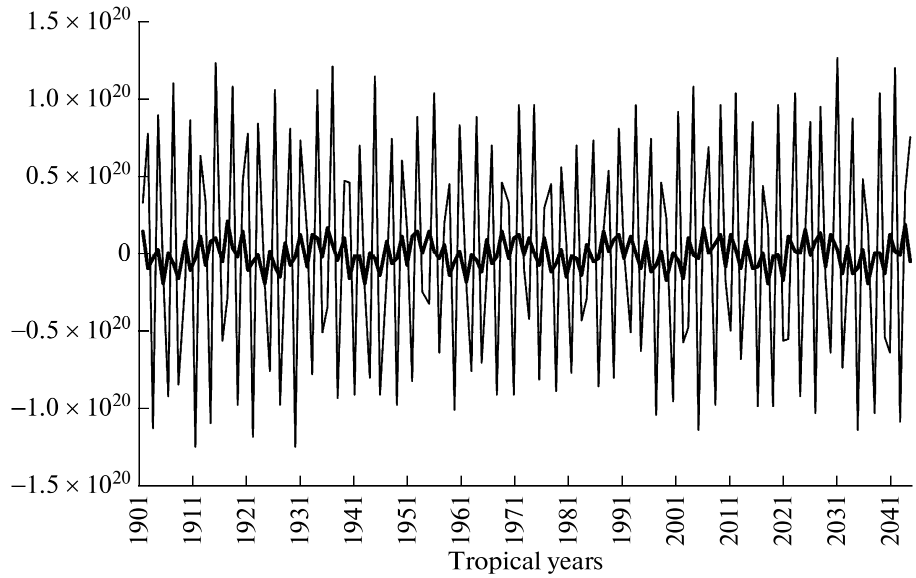

Fig. 2. The multiannual variations in total solar radiation and its smoothed values (J).

tion with the interannual variations in the duration of the tropical year (the correlation factor is 0.794 at 0.99 probability).

The spectral analysis of the calculated series of the total solar energy reaching the upper atmosphere boundary for tropical years within the interval of 1900–2050 shows two periods of increase in spectral density: 2.7 and 18.75 years long. In the spectrum of interannual variations in solar energy, only the peak with 2.7 years in the period is presented; it reflects the contribution of the two- and three-year variations. The 2.7-year period is determined by the ratio of two- and three-year variations within the series, where two-year variations made up about 1/3 and three-year variations comprises about 2/3 [11].

The amplitude of interannual variations exceeds the average one for the 150-year series in the first halves of the 20th and 21st centuries, while it is below average in the second half of the 20th century (Fig. 3). The decrease in amplitude of interannual variations for the second half of the 20th century can reflect weakening of the resonant perturbation of the Earth's orbital motion by Mars and Venus.

Thus, the mechanisms generating small-scale variations in solar energy and controlling the values of solar radiation reaching the upper atmosphere boundary are related to the perturbation effect of the closest celestial bodies—the Moon, Venus, and Mars—on the Earth's orbital motion. The solar energy supply to the Earth, against the background of its reduction, demonstrates the periodicities of 19, 2, and 3 years; the last two form 8- and 11-year-long cycles, which, in turn, make up the 19-year cycle. In addition, interannual variations are found in the series, but only two- and three-year variations are identified in them.

Bearing in mind that two- and three-year variations are multiple of and close to the period of the Earth's revolution around the Sun, we can expect the intensification of small-scale variations in solar energy by the classical resonance mechanism and the manifestation of these variations in the atmosphere dynamics. Another possible cause of the intensification of small-scale variations in solar energy is the stochastic resonance, which is a response of the bistable or metastable nonlinear system to a periodic signal at a noise effect of a certain power [1].

In general, the results obtained can serve as a basis to search for a relationship between the global and regional climate changes on the Earth, on the one hand, and the periodic variations of the Earth's solar climate, on the other hand.

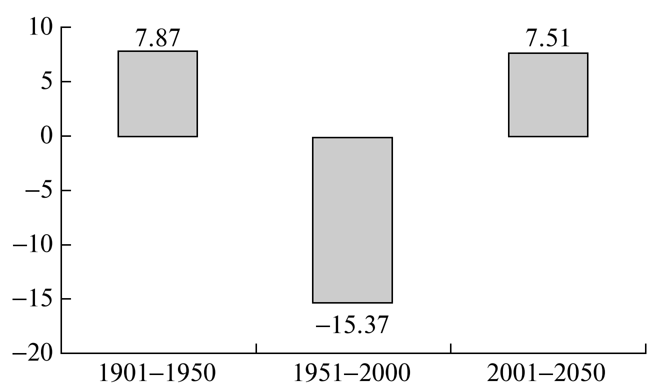

Fig. 3. Differences of average amplitudes of interannual variations in solar radiation for the half-century intervals relative to the average amplitude values of the entire series, with the indicated percentage of the values relative to this average.

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