ISSN 0038-0946, Solar System Research, 2019, Vol. 53, No. 5, pp. 376–382. © Pleiades Publishing, Inc., 2019.
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Analysis of the Components of a Different Physical Nature in the Interannual Variability of the Total Solar Irradiance Flux

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Received July 2, 2018; revised September 19, 2018; accepted January 22, 2019

Abstract—By its physical nature, the interannual variability of the solar radiation arriving at the Earth is a duplex with varying ratios of the amplitudes of the components depending on the time resolution. The analysis shows that the amplitude of the long-term variability of the radiation intensity is approximately 95% determined by the variations related to changes in the solar activity. At an annual resolution, the component determined by the solar activity is predominant in amplitude (approximately 80%). At a monthly resolution, the leading component of the duplex is the variation caused by the celestial-mechanical processes (approximately 55%). Thus, the interannual variations determined by the celestial-mechanical processes dominate in the interannual variability of incoming solar radiation within seasonal changes. The results point toward the necessity for a differentiated approach to the use of the values of the interannual solar radiation variability of different physical nature in the climatic models since their weight ratios depend on the time resolution.

Keywords: solar radiation flux, solar radiation intensity, solar activity, celestial-mechanical processes, interannual variations

DOI: 10.1134/S0038094619040026

The most important characteristic of the solar radiation arriving at the Earth is total solar irradiance (TSI) over the whole spectrum passing through the unit area normal to the solar rays at an average distance of the Earth from the Sun outside the Earth's atmosphere per unit time. The average perennial TSI value is taken as the solar constant (Kopp and Lean, 2011; Fröhlich, 2012; Kopp et al., 2012).

Since the intensity of solar radiation (ISR) changes in inverse proportion to the distance squared, it varies throughout a year and follows a regular annual cycle with the minimum at the aphelion and maximum at the perihelion (Fig. 1). The annual cycle of the ISR is determined by a celestial-mechanical process: the motion of the Earth in an elliptical orbit.

However, the mean annual and mean monthly TSI values also change from year to year. The variability of the solar radiation arriving at the Earth has two main causes of a different physical nature. One is determined by the variation in the physical solar activity associated with the processes occurring on the Sun: sunspot formation, solar faculae, etc. (http://www.pmodwrc.ch/). Another cause is associated with the variation in the Sun–Earth distance due to the perturbing influence of the nearest celestial bodies on the orbital motion of the Earth (Borisenkov et al., 1985; Fedorov, 2012, 2013, 2015, 2016). Further, we will use the following notations for the components of interannual TSI variability. The variations related to the celestial-mechanical processes are denoted as ISR_{CMP}. The variations related to the changes in the solar activity are denoted as ISR_{SA}. The studies of the solar-activity-related variations in TSI have been widely developed (http://www.pmodwrc.ch/; Frohlich and Lean, 1998; Lean et al., 2005, Foukal et al., 2006; Fröhlich, 2000, 2012; Kopp et al., 2012). At the same time, perennial and interannual TSI variations related to changes in the Sun–Earth distance are still little studied.

CALCULATION PROCEDURE

To determine the variations in the distance between the Earth and the Sun, the average Earth–Sun distances were determined per calendar day in the interval from the year 1740 to 2050 using the astronomical ephemerides DE-406 (http://www.ssd.jpl.nasa.gov). The accuracy of the ephemerides in distance is 10^{-9} AU or 0.1496 km. The solar constant at 1 AU between the Earth and the Sun was taken as I_0 = 1361.0 W/m^2 (Kopp and Lean, 2011). It is known that if a is the average distance between the Earth and the Sun equal

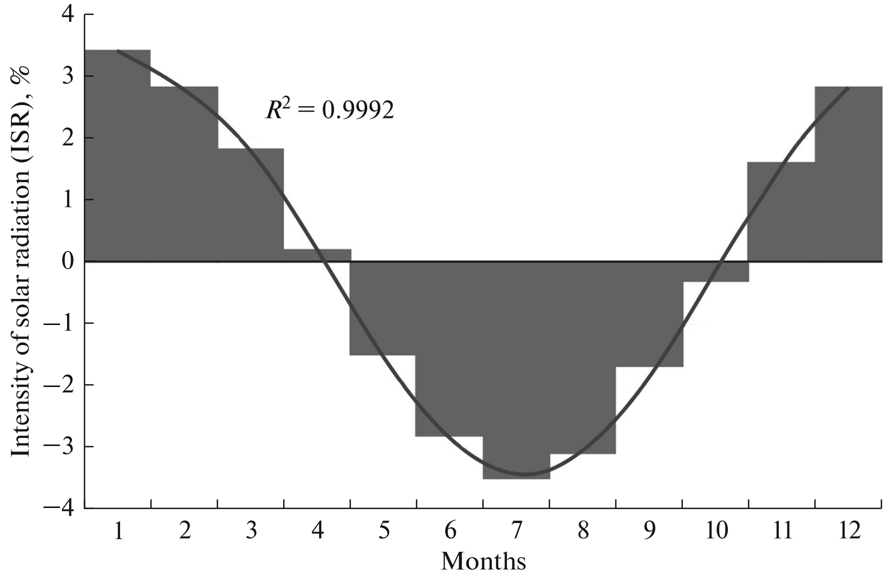

Fig. 1. The annual cycle of ISR in percent, relative to the TSI value at an average distance of the Earth from the Sun (approximation with a 6th degree polynomial).

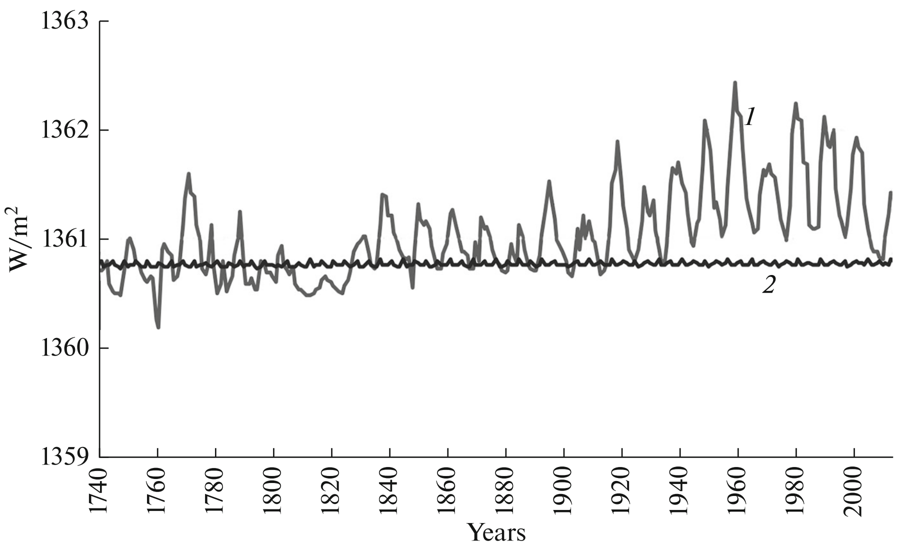

Fig. 2. Perennial variability of (*1*) the annual TSI values ("Climate Change", 2013) and (*2*) ISR_{CMP} values.

to the semimajor axis of the ellipse of the Earth's orbit (1 AU), then at a distance l,

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

From the calculated daily values (Eq. (1)), we obtained the monthly and annual (Fig. 2) ISR values, nonnormalized relative to the average Sun–Earth distance. These nonnormalized ISR values are denoted as ISR_{CMP}.

By sequentially subtracting the values of each consecutive year from the values of the preceding year, the series of the interannual TSI and ISR_{CMP} variability were obtained. The series of the interannual variability of the TSI and ISR_{CMP} monthly values (for each month of the year) were found in the same manner. These values reflect the sequential year-to-year variation in TSI (with an annual and monthly resolution) in connection with the variation in the Sun–Earth distance. As a result of the analysis of the calculated series, we obtained the amplitude characteristics of the

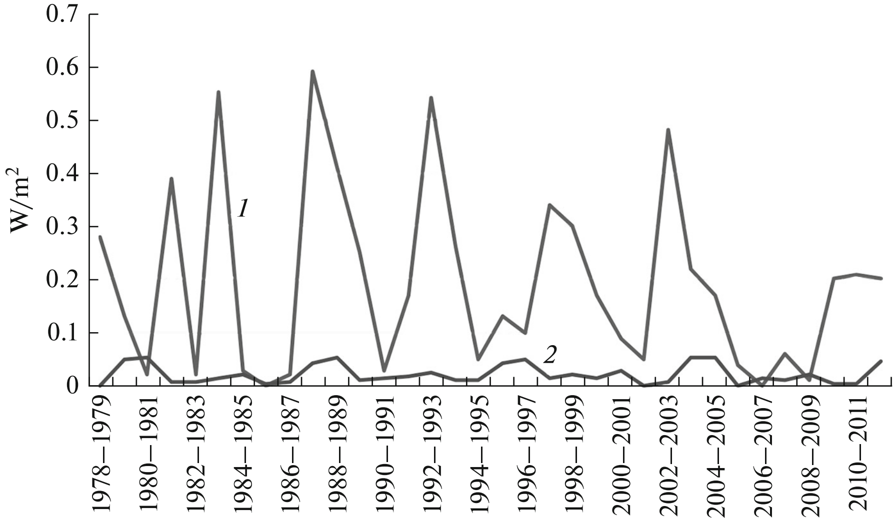

Fig. 3. Amplitude of the interannual (*1*) TSI and (*2*) ISR_{CMP} variations in the analysis at an annual resolution.

interannual TSI and ISR_{CMP} variability associated with the perturbed orbital motion of the Earth. The amplitude is understood as the average modulus of the interannual variations in TSI, ISR_{CMP}, and ISR_{SA}. The variations associated with the changes in solar activity were not taken into account in these calculations.

The satellite radiometry measurements of TSI have been carried out since 1978. There are known reconstructions of TSI based on the processed radiometric data (by the sunspot number and solar faculae). The data with an annual resolution are available from 1610, and with a monthly resolution, from 1882 (Lean et al., 1995; Kopp and Lean, 2011). As the initial data in the analysis of the interannual solar radiation variability with an annual resolution, we used the TSI values from 1740 to 2012 (Fig. 2), which are recommended for the use in physical-mathematical climate models (Kopp and Lean, 2011; “Climate Change”, 2013; http://solarisheppa.geomar.de/cmip5). In the analysis of the data with a monthly resolution, we used the series published at (http://solarisheppa.geomar.de/cmip5) (TSI 11-year cycle).

RESULTS AND DISCUSSION

The perennial TSI variability is mainly determined by the variations related to the solar activity (ISR_{SA}). In this case, the annual ISR_{CMP} values (calculated by Eq. (1)) were subtracted from the initial annual TSI values. The average TSI amplitude in the initial series (Kopp and Lean, 2011) (Fig. 2) is 0.3242 W/m^2. The average ISR_{CMP} amplitude is 0.0158 W/m^2. Thus, the ISR_{CMP} variations are 4.67% of the amplitude of the perennial TSI variability. The ISR_{SA} variations are 95.33%.

The ratio between ISR_{CMP} and ISR_{SA} in the interannual TSI variability with an annual resolution in the interval from 1740 to 2012 was analyzed in detail (“Climate Change”, 2013). The average perennial TSI value (solar constant) for this dataset is 1361.0 W/m^2 (Kopp and Lean, 2011). In the calculations of ISR_{CMP} by Eq. (1), this value was taken as I_0. In the annual variation, the ISR amplitude is approximately 3.5% (Fig. 1); in the interannual variability with an annual resolution (of the annual values), the amplitude of the TSI variations is significantly smaller: 0.014% from the value of I_0, which equals 1361 W/m^2. However, these minor variations are important due to the fact that the top of the atmosphere (TOA) is the surface that characterizes the initial conditions for the calculation of the radiation balance of the Earth, its surface and atmosphere. The capabilities of model calculations depend on the accuracy of determining the initial conditions.

The calculated amplitudes of the interannual ISR_{CMP} variability (Fig. 3) are 0.02 W/m^2 or 10.5% from the average amplitude of the interannual TSI variability (0.19 W/m^2) in the interval from 1978 to 2012. The maximum value of the ISR_{CMP} amplitude in this interval is 0.05 W/m^2 or 26.3% from the average amplitude of TSI. In the interval from 1740 to 2012, the average amplitude of the interannual ISR_{CMP} variability is also 0.02 W/m^2 or 13.3% (from 0.15 W/m^2, i.e., the average amplitude of the interannual TSI variability on this interval).

The ratio between the ISR_{CMP} and ISR_{SA} variations in the interannual TSI variability was found in the following way. The interannual ISR_{SA} variations were obtained by subtracting the calculated values of the interannual ISR_{CMP} variability from the interannual

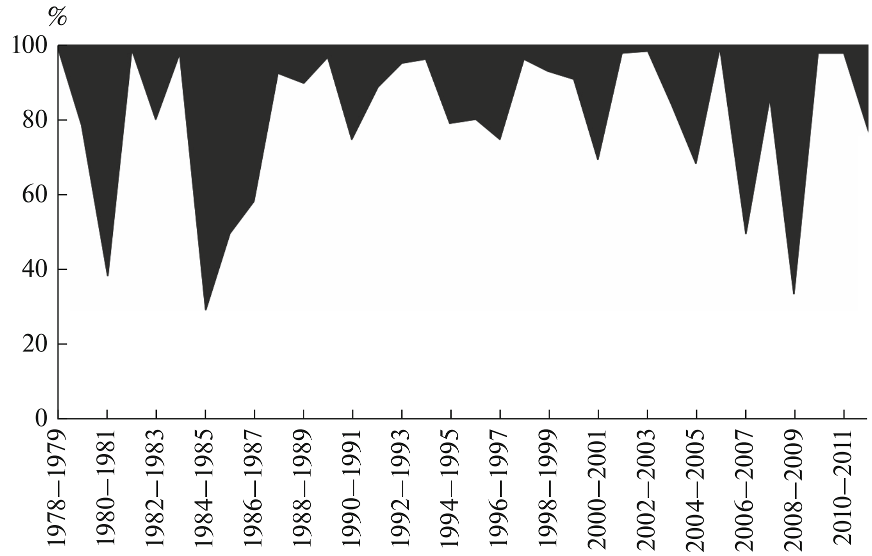

Fig. 4. Ratio between the ISR_{SA} and ISR_{CMP} variations (shown by the dark background) in the interannual TSI variability in the interval from 1978 to 2012 at an annual resolution.

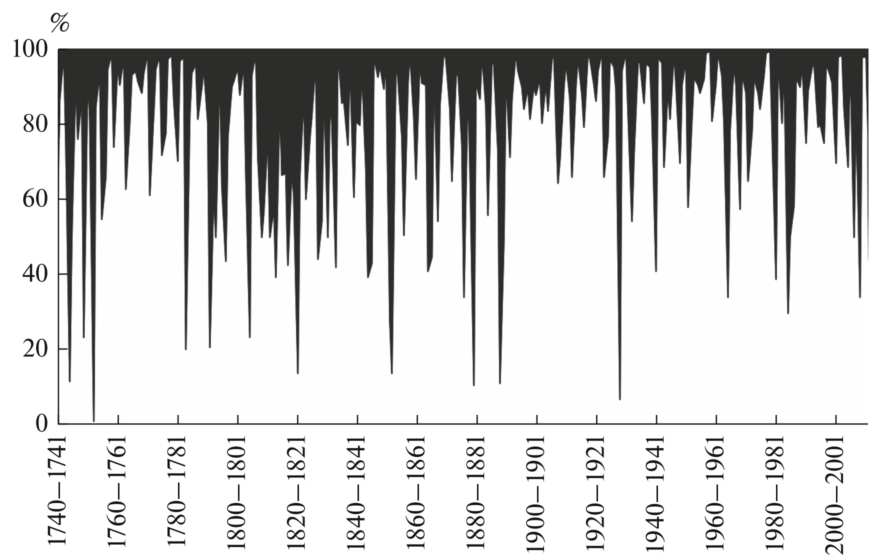

Fig. 5. Ratio between the ISR_{SA} and ISR_{CMP} variations (shown by the dark background) in the interannual TSI variability in the interval from 1740 to 2012 at an annual resolution.

TSI variability. Further, the moduli of the ISR_{SA} and ISR_{CMP} values were determined. The sum of the ISR_{SA} and ISR_{CMP} moduli for each year was taken equal to one. From the resulting proportion, the ratios between the ISR_{SA} and ISR_{CMP} variations in the interannual TSI variability were calculated. By multiplying by 100, these ratios were converted to percent. As a result, it was found that in the interval from 1978 to 2012 (Fig. 4), the ratio of the interannual variations is, on average, 80.6% (ISR_{SA}) and 19.6% (ISR_{CMP}). In the interval from 1740 to 2012 (Fig. 5), this ratio is characterized by the values 78.7% (ISR_{SA}) and 21.3% (ISR_{CMP}). Thus, at an annual resolution, the ISR_{CMP} variations amount to approximately 1/5 part of the interannual TSI variability.

The ratio between the ISR_{SA} and ISR_{CMP} variations in the interannual TSI variability was also analyzed at a monthly resolution (in the year-to-year variability of the monthly values). In this case, the dataset from 1882 to 2008 (http://solarisheppa.geomar.de/cmip5) was used for the analysis. The average TSI value for these data is 1365.9 W/m^2. For this reason, I_0 in the calculations by formula (1) was taken equal to 1366 W/m^2.

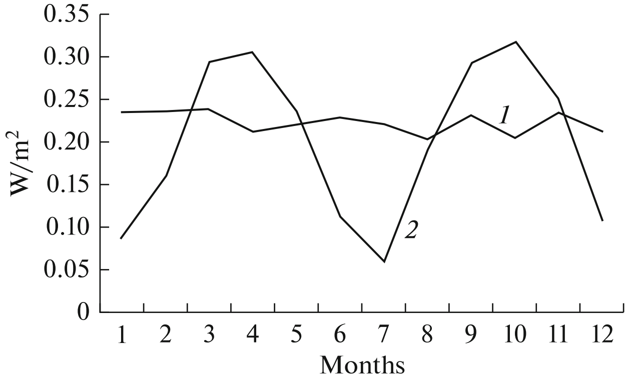

Fig. 6. Amplitude of the interannual (*1*) TSI and (*2*) ISR_{CMP} variations in the interval from 1882 to 2008 at a monthly resolution.

In the interval from 1882 to 2008, on average per month, the ISR_{CMP} amplitude is 0.20 W/m^2, while the TSI amplitude is 0.22 W/m^2. Thus, the ISR_{CMP} amplitude is 90.9% of the amplitude of the interannual TSI variability. In the interval from 1978 to 2008, the average ISR_{CMP} amplitude is 0.21 W/m^2, and the TSI amplitude is 0.27 W/m^2. In this interval, the amplitude of the interannual ISR_{CMP} variability is 77.8% from the TSI amplitude. In some months (March–May and September–November), the amplitude of the interannual ISR_{CMP} variability exceeds the TSI amplitude, while in other months, it falls below (Fig. 6).

The ratio between the ISR_{SA} and ISR_{CMP} variations in the interannual TSI variability for each month was found in the same manner as in the analysis at an annual resolution. The average ratios between the ISR_{SA} and ISR_{CMP} variations in the interannual TSI variability (from 1882 to 2008) turned out to be 45.19 and 54.81%, respectively. The annual course of the ISR_{SA} and ISR_{CMP} ratio in the interannual TSI variability is illustrated in Fig. 7.

The difference of the interannual ISR_{SA} and ISR_{CMP} variability follows a distinct annual cycle (Fig. 8).

It can be seen from the distribution that at a monthly resolution, the interannual variations (of the monthly values) in ISR_{SA} exceed the ISR_{CMP} variations by amplitude on four months (1/3 year): June, July, December, and January. The time intervals when the ISR_{SA} variations are predominant are chronologically localized around the points of summer and winter solstices. During the other eight months (2/3 year), the ISR_{CMP} variation is predominant in the interannual TSI variability. The maximum values of the ISR_{CMP} variations lie in the intervals close to the equinox points. Since the vernal equinox points are currently located near the semiminor axes of the Earth's elliptical orbit, this is consistent with the Laplace theorem of stability regarding the small variability of semimajor axes (their intersections with the ellipse are presently located close to the solstices) and, therefore, the Earth–Sun distance during these periods. For the period of the satellite radiometric observations from 1978 to 2008, the average ratio is characterized by the values of 45.71% (ISR_{SA}) and 54.29% (ISR_{CMP}). Thus, the ratio of the ISR_{SA} and ISR_{CMP} variations in the interannual TSI variability changes in connection with the time resolution. At an annual resolution, the interannual ISR_{CMP} variations are approximately 1/5 of the interannual TSI variability, while at a monthly resolu-

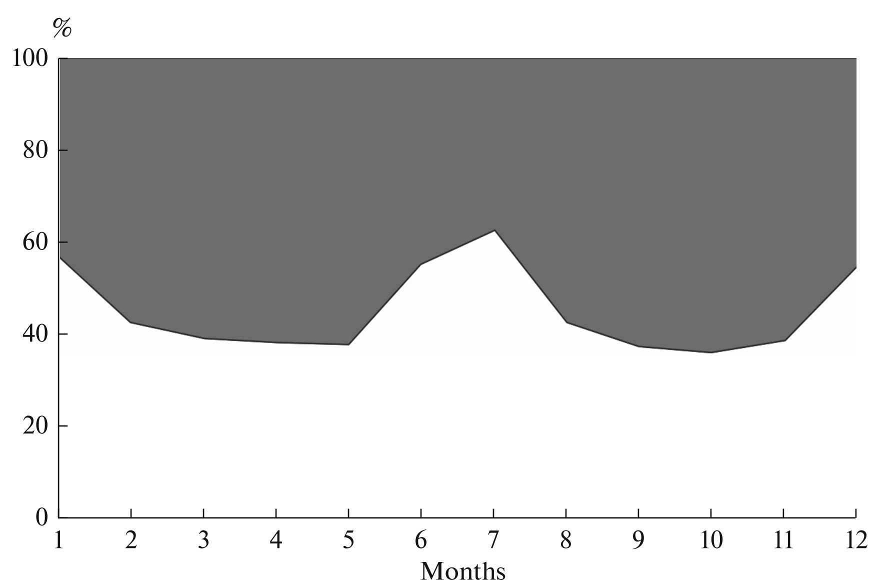

Fig. 7. Ratio between the ISR_{SA} and ISR_{CMP} variations (shown by the dark background) in the interannual TSI variability in the interval from 1882 to 2008 at a monthly resolution.

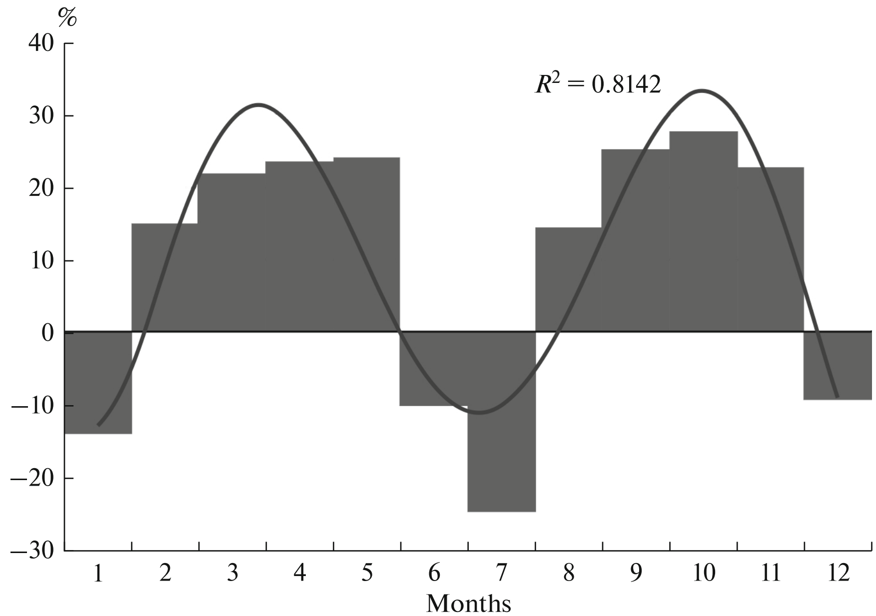

Fig. 8. Annual cycle of the difference of the interannual ISR_{CMP} and ISR_{SA} variability values in the interval of 1882–2008 (approximation with a 6th degree polynomial).

tion, more than 1/2. The seasonal change of the interannual TSI variations is thus significantly determined by the ISR_{CMP} variations associated with the changes in the Sun–Earth distance due to the perturbing influence of the Moon and the planets.

CONCLUSIONS

The perennial TSI variability is approximately 95% determined by the variations associated with the changes in solar activity. By its physical nature, the interannual TSI variability is a duplex of the ISR_{SA} and ISR_{CMP} variations. The ratio between the ISR_{SA} and ISR_{CMP} variations in amplitude changes depending on the time resolution. At an annual resolution, the ISR_{SA} component is predominant (approximately 80%). At a monthly resolution, the leading component of the duplex is the ISR_{CMP} variation (approximately 55%).

The interannual ISR_{CMP} variability is calculated (formula (1)) based on the Sun–Earth distance (the values of which are taken from the astronomical ephemerides) both to the past and to the future. For this reason, the ISR_{CMP} variations can be used in physical-mathematical models to search for the response of the climatic system to the interannual ISR_{CMP} variability (at a monthly resolution) in connection with the change in the Sun–Earth distance. The results can also possibly facilitate the improvement of separate estimates of the influence of the interannual ISR_{SA} and ISR_{CMP} variations on climatic processes at various time resolutions both for the Earth and for other planets of the Solar System.

Recommendations for CMIP5 solar forcing data. http://solarisheppa.geomar.de/cmip5.

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Translated by M. Chubarova