# THE SOLAR CONSTANT AND CLIMATE

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(Received 22 March, 1982; in revised form 31 May, 1983)

**Abstract.** As has been shown by observations from the Nimbus-7 and SMM satellites, the non-periodic, comparatively rapid decreases of the solar constant (to 0.25%) are mainly determined by the size and location of groups of sunspots passing through the Sun's central meridian. Variations of a quarter per cent are a rare enough occasion (occurring approximately once every two years). In the majority of cases, drops to 0.1% are noted.

The question of long-period (11-, 22-, and 80–90-year) variations of the astronomical solar constant (ASC) is still open to speculation. The four-year series of observations on Nimbus-7 indicates very definitely the presence of a maximum in smoothed ASC values in January of 1979, and the following permanent decrease in 1980–82 with the varying rate up to 0.05% annual.

The compiled by the authors temporal series of the ASC variability for the 1925–1980 period has been confirmed, in our opinion, experimentally. Obviously, the long-period variations must be associated not with the development of active areas, but with temperature changes in the non-perturbed photosphere. It is supposed that the temperature gradient variation in the photosphere in the 11-year cycle leads to the redistribution of radiation from various photospheric levels. As a result, the ASC varies quasi-periodically both within the cycle, and from one cycle to another. Since the phase variation of the ASC has been noted in some cycles (e.g., cycle No. 16), the existence of a component of another periodicity can be supposed. Solar activity variations are relevant to different kinds of solar radiation: from cosmic and X-rays to radiofrequency radiation. The combined influence of these emissions on the atmosphere apparently leads to a several times enhancement of small ASC variations (drops), probably by a factor of ten. The 'enhancement' of the solar radiation variation can be detected in the so-called meteorological solar constant (MSC). Analysis of experimental data has shown that at tropospheric levels the cyclic MSC variations can reach 4% (cycle No. 19). It should be noted that in the mid-latitude belt of the northern hemisphere the MSC changes occur in phase with the variation of the intensity of galactic cosmic rays.

The 22-year component in the ASC is considerably weaker than the 11-year component.

## 1. Introduction

The results of investigations in the variability of the solar constant (SC) have not yet acquired the nature of definiteness necessary for understanding the causes of climate variations. However, the discrepancies in the estimation of the integral and spectral SC variations, revealed during recent years, indicate a narrow range of real SC variations which are apparently well within the limits of the accuracy of contemporary measurements. The absolute error of satellite and rocket measurements is within $\pm 0.3\%$ for the integral SC and within 2–20% for the spectral SC, depending on the solar spectral region.

Indirect estimates of the integral SC variations, for example, those obtained from remote measurements of the parameters of the absorption lines of ionized atoms of C

*Solar Physics* **89** (1983) 215–222. 0038–0938/83/0891–0215$01.20.

and Fe (located in the lower part of the photosphere, at an optical depth close to $\tau = 1$), from which photospheric temperature variations and, consequently, its brightnesses were to be determined, have an accuracy which is hardly better than $\pm 1\%$. Thus, Livingston (1978) reported on a photospheric temperature drop by 6 K, which must result in a 0.5% decrease of the SC during the 1975–1978 period. However, direct measurements from rockets and satellites (Willson *et al.*, 1980; Hickey *et al.*, 1980) yielded an opposite result – a small increase of the SC (0.4–0.6%) in 1976–78. A recent paper by Duncan *et al.* (1982) presents again the mean SC values from rocket and satellite measurements in 1976 (1367 W m$^{-2}$), 1978 (1374 W m$^{-2}$), and 1980 (1373 W m$^{-2}$). Although these data apparently indicate a change in the SC ($\sim$0.5%) in the current solar activity cycle (coinciding in phase with the sunspot number variation), the authors have evidently failed to overcome contradictions in discussing the results obtained and have found no convincing arguments in favor of such an interpretation. Later Livingston, on the basis of the analysis of absorption lines formed at great heights in the solar atmosphere, offered a more precise interpretation of his data. In a paper with Holweger (Livingston and Holweger, 1982) he has made a supposition that in 1976–80 a permanent, although small in value, temperature gradient decrease took place in the lower photosphere that must have been due to an increase in convection at a constant effective temperature of the photosphere and, consequently, at a constant luminosity ($L$). Nevertheless, in Livingston's opinion, variations in the solar luminosity and radius have their maximum at the minimum of solar activity.

A more logical interpretation of the variations of the temperature gradient in the photosphere is offered in the paper by Rosen *et al.* (1982) where, on the basis of calculations of the functions of darkening towards the edge, photospheric temperature profiles were obtained. Their analysis has revealed that a small temperature decrease in the lower photosphere is accompanied by a far stronger temperature increase in the abovelying photospheric layers.

Thus, at the decrease of darkening towards the edge, which is quite natural during the temperature gradient drop in the photosphere, the Sun's radiation from the entire disc rather increases. It can be supposed that this occurs due to a shift in the level of the Sun's effective temperature from greater photospheric depths to smaller ones which, in turn, may be considered as the Sun's radius growth.

## 2. On the SC Periodic Variations

As can be seen from a number of papers, the above-mentioned variations in the SC should not be directly connected with variations in sunspot numbers or their areas. On the basis of the analysis of the results obtained on 'Mariner-6 and -7' and the data available on the variation of sunspot and flare areas, Foukal *et al.* (1977) have shown that the variation of the areas of these parameters lead to short-term SC variations which do not exceed 0.03%. Analysis of SC measurements from the SMM satellite (Willson *et al.*, 1981) has revealed that the most significant SC dips (to 0.25%) are due to the effect of large sunspot groups and has shown a high-correlation dependence between

SC variations and the projections of sunspot areas on the plane which is perpendicular to the plane passing through the Sun's central meridian. SC variations subject to sunspot projection areas, on the average, do not exceed 0.1%. According to estimates made for various models, such SC variations can lead to changes in the near-surface temperature of 0.1–0.2 K. But, since the instrumentally-fixed temperature variations constitute 0.3–0.6 K, the examined external force function is responsible for 30% of the marked temperature changes at most.

Let us recall the results of a statistical analysis of the data of the Smithsonian Astrophysical Observatory (SAO) conducted at the University of Leningrad by Vasilyev *et al.* (1973). After eliminating the noise component with the help of Whitacker's operator and accomplishing the spectral analysis, all the main periodicities (5.5-, 11-, and 22-year ones) have been obtained, and the 80-year periodicity has also been noted. Analysis of phase relationships has shown that the 11- and 80-year periodicities are connected with sunspot variations, whereas the 22-year one is due to changes in the Sun's diameter. Figure 1 presents the results of the analysis of Smithsonian data together with the curve for the variation of annual mean Wolf numbers ($R_z$) for the 16th, 17th, and 18th solar activity cycles. The integral of the alternating series of sunspot numbers is presented here as the analogue of the relative variation of the solar radius change (Vasilyev and Rubashev, 1971, 1972). According to the periodicity of this curve, the maximum in the 22-year variation of the diameter ($D$) falls on 1974–1976. It follows from Figure 1 that the maximum values of $D$ correspond to the minimum in the solar luminosity variation. The doubled amplitude of this variation does not exceed 1 W m$^{-2}$.

Considering the present moment, it can be supposed that the $D$-bound luminosity variations in cycle No. 21 can hardly be very different from the given value. The mean rate of variation of $L$ between the maximum and minimum of solar activity constituted 0.006% annual. These estimates are in fair agreement with the results of Gilliland (1981), Labonte and Howard (1981). However, it should be noted that the results of this analysis of the Smithsonian data series do not claim to be absolutely true, since the series length is too short for accurate determining of the amplitude of the 22-year component (besides, the number of degrees of freedom does not exceed 3). The magnitude of the 22-year variation constituted 0.07% of the SC, and the phase was biased by 180° with respect to the variation of the solar radius. The presence of the 80-year component was assumed because of the existence of a weak trend in the SAO data. Therefore, SC variations may be presented as a sum of the 11- and 22-year components with the corresponding approximate regression coefficient. SC variations connected with the 11-year cycle were maximum during the 1944–1948 period and amounted to 0.33% of the SC.

Somewhat later Hoyt (1978) carried out another detailed analysis of the SAO data. One of his basic conclusions is that long-term (trend) variations of the SC never exceed 0.37%. For the period 1923–1954 the combination of data from all stations yielded an increase in the SC of $0.17 \pm 0.04\%$, but there are some uncertainties as to the permanence of scales at the stations. Another conclusion is that, according to the results of an auto-correlation analysis, no evidence has actually been obtained of the presence

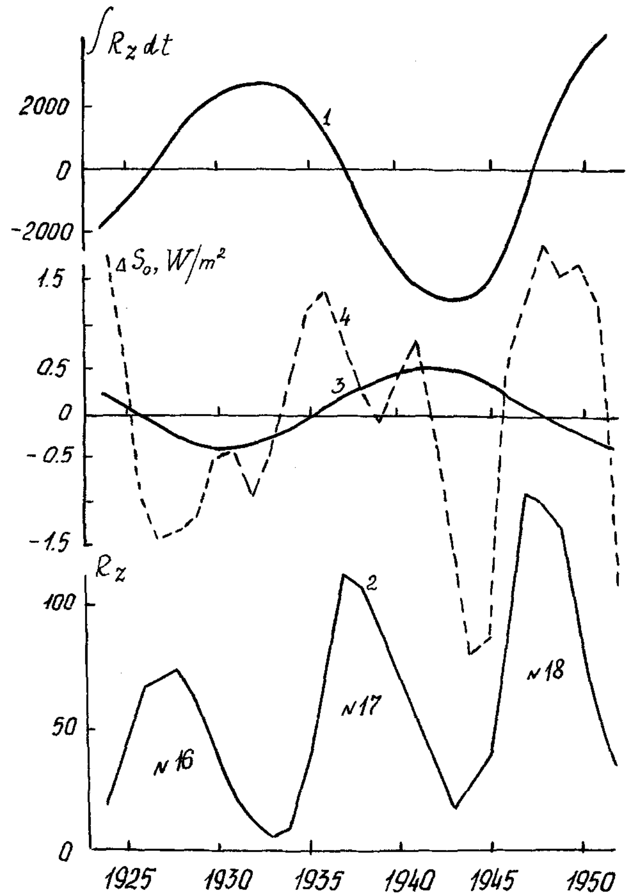


Fig. 1. Comparison of periodic solar constant variations, obtained from Smithsonian data by spectral-correlative analysis, with the solar radius variations and relative sunspot numbers (Wolf numbers): (1) the analog of the curve for the solar radius variations; (2) annual mean Wolf numbers; (3) the 22-year solar constant variation; (4) a curve characterizing the solar constant variation with other periods (the greatest contribution of the 11-year variation).

of the 11- and 22-year components in the SC. Nevertheless, it may be considered that periodic components found in our analysis exist in reality, since they were regular enough and were obtained after a kind of processing which practically excluded the possibility of their simulation. If one agrees with the above, Hoyt's conclusion on the absence of the dependence between the variations of the solar constant and solar activity ($\Delta S_0(R_z)$) can easily be accounted for. The temporal variation of $\Delta S_0(t)$ obtained by Vasilyev *et al.* (1973) shows the existence of a variable phase shift between $\Delta S_0$ $(t)$ and $R_z(t)$ which reaches 180° in the 16th cycle, approaches 0° in the middle of the 17th cycle and then increases again in the 18th cycle. It becomes obvious, therefore, that the dependence $S_0(R_z)$ will differ from cycle to cycle and that averaging over the three cycles will lead to its levelling. As is known, the 19th cycle was the most powerful, and it, therefore, would be logical to expect greater SC variations there than, e.g., in the 18th cycle, for which the SC variation of 0.33% has been obtained. It should be noted that it is only after the appearance of rocket and satellite data on the SC and publications on the variability of photospheric temperature that we have acquired evidence of the presence of the 11-year component both in the meteorological (see below), and the astronomical solar constant (ASC).

Figure 2 shows a hypothetical variation of SC changes as compiled from experimental data examined in this paper. The part of the curve designated by dotted lines gives a schematic idea only of potential limits of the SC variability.

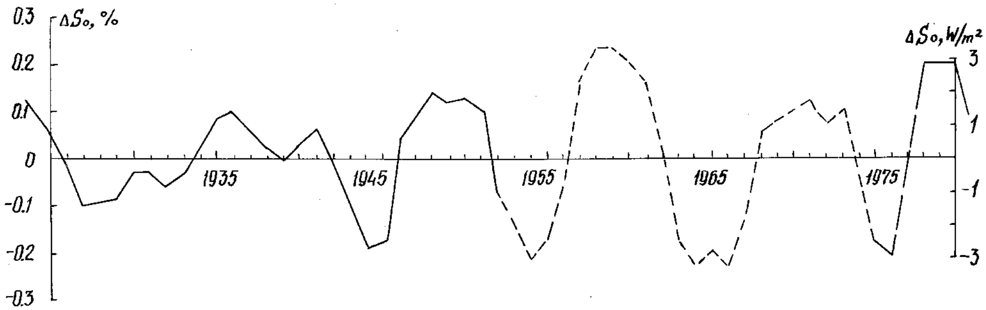


Fig. 2. Hypothetical (compiled from different data sources) temporal variation of the 11-year ASC component. The part relevant to 1924–1952 has been constructed from an extract from the Smithsonian data (see Figure 1, curve 4). The remaining part of the series has been compiled from $R_z$ variations and rocket data by Duncan *et al.* (1982).

If the suppositions on the ASC variations ($\sim$0.5%) are confirmed in the course of satellite experiments during the nearest several years, attention should be paid to the possible secular variability of the SC. Some indications of such a possibility can also be found in a paper by Heath (1980). Very attractive is his hypothesis of a relationship between the SC secular variability and changes in the ultraviolet range of the solar spectrum (the 200–300 nm region).

## 3. Meteorological SC Variations

Somewhat different is the problem of the effect of variability of the meteorological 'solar constant' (MSC). As has been shown by Nikolsky (1980) who has used the data of actinometric network observations for the 1954–1969 period, the variations of solar radiation incoming to the troposphere are closely connected with the variation of the intensity of galactic cosmic rays (GCR). Statistical analysis has revealed that the solar radiation decrease is maximum during the period when the GCR intensity passes through the maximum, i.e. somewhere near the minimum of solar activity. An essentially close relationship (but relevant to 30–33 km heights) has been discovered earlier by Kondratyev and Nikolsky (1979) on the basis of balloon soundings of solar radiation during the 1962–1970 period. It was characterized by a nonlinear variation of the MSC* dependence on solar activity represented by Wolf numbers. A maximum in the MSC values has been marked at $R_z = 50 - 70$ (Kondratyev and Nikolsky, 1979). The drop in the MSC (down to 1.2%) at $R_z > 70$ is evidently due to the effect of solar cosmic rays on the middle stratospheric composition. At the decrease of solar activity, the drop in solar radiation at the 30–33 km heigths was not large (~0.6%). This provides evidence that the main contribution of galactic cosmic rays to the composition variation takes place in the lower stratosphere.

In order to estimate the GCR contribution to the solar radiation attenuation in the lower stratosphere and troposphere, the data of the Voyeykovo actinometric station on the maximum values of direct solar radiation ($S_{\max}$) and the sums of direct solar radiation with real cloudiness ($\Sigma S$) (Pivovarova, 1977) have been compared with the intensity of the neutron component of cosmic rays (the Mt. Washington station). These stations are located at close geomagnetic latitudes. Observations of the secondary nucleon component at the network of neutron monitors make it possible to follow the variations of the primary low-energy component of GCR which comes to the level of the maximum number of cases of nuclear interactions (18–20 km at the middle latitudes) and forms the strongly ionizing meson and electron components which give away their energy in the lower stratosphere and upper troposphere.**

In order to determine the correlation coefficients ($K$), the trend components have been eliminated in the temporal series of $S_{\max}(t)$, $\Sigma S(t)$, and CRI($t$)† under investigation. For 15 years (1954–1969) the trend in $S_{\max}$ constituted $-3.73\%$, and $\Sigma S$ $+0.7\%$. The difference in the trends obviously needs an explanation. Essentially, the values of $S_{\max}$ (which are determined under the conditions of the greatest atmospheric transparency) characterize a state of the atmosphere which is close to the background one, and they may indicate, to some extent, changes in the solar radiation income to the troposphere. Apart from changes in atmospheric transparency, the trend in $\Sigma S$ is also connected with possible total cloudiness variation. Using Budyko's (1979) data on variations in atmos-

* In accordance with the proposals of a number of investigators, the influence of solar activity on the solar radiation absorption in the middle and lower stratosphere can be conveniently characterized through the variations of the meteorological 'solar constant' which is the astronomical solar constant (ASC) decreased due to attenuation by a certain optically active component whose concentration is excessive in layers located in the middle and/or lower stratosphere. Among these components, the first to be mentioned are ozone and nitrogen dioxide, since they have broad absorption bands in the visible spectral region and are subject to solar activity effects.

At the present moment, the variability of the balloon MSC (30–33 km) is discussed. Later the tropospheric MSC relevant to the heights 10–12 km will be discussed.

** Since we here touched upon the problem of interaction between GCR and the molecules of atmospheric gases, it should be noted that, for the historical past, the effect of solar activity on the climate of the middle latitudes can be determined rather unambiguously from the variation of the $^{14}C$ concentration in the atmosphere which is closely connected with the variation of the GCR intensity in solar activity cycles. The estimates obtained show that a 9‰ increase in the $^{14}C$ concentration corresponds to a 1% decrease of the meteorological 'solar constant' which characterizes the variation of solar radiation income to the troposphere ($S_{oM,\,tropo}$).

† The abbreviation 'CRI($t$)' denotes cosmic rays intensity against time.

pheric transmission for the period under consideration ( – 2.56%), we obtain that during this period $\Sigma S$ was subject to an effect (with real cloudiness) of + 3.26%. This effect should obviously be attributed to the decrease of total cloudiness in the middle latitudes of the northern hemisphere. Estimations from various empirical formulae yield the following values corresponding to the variation of $\Sigma S$ for 15 years: an approximately 2.2% decrease in cloudiness and about 2% decrease in the albedo of the 'surface-atmosphere' system.

Periodic components in the temporal variation of $S_{max}$ and $\Sigma S$ which correlate with the CRI variation have amplitudes of 4% ($S_{max}$) and 2% ($\Sigma S$). For the series of CRI($t$) and $\Sigma S(t)$ for 1954–1969, a high correlation coefficient ($K = -0.89$) has been obtained, a 1-year time lag having been introduced in the series $\Sigma S(t)$; without the time lag $K = -0.826$. For the series of $S_{max}(t)$ and CRI($t$), $K = -0.92$ (no time lag has been introduced). The level of significance for all cases exceeds 0.995.

It is known that the extreme values of CRI are retarded by a period of up to 1 year relative to the extremums of sunspots. For the 1958–1969 period, the retardation constitutes almost precisely 1 year. The dependence between $S_{max}(t)$ and the biased by 1 year series $R_z^{+1}(t)$ has been obtained for this period, and it appeared to be linear. As has been mentioned above, the 11-year component of the variability of $S_{max}$ constituted 4%. Such a great amplitude of $S_{max}$ is apparently characteristic for cycles with mostly high solar activity. Since the bias between CRI($t$) and $R_z(t)$ varies with time, and since the main conductor of the influence of solar activity on the lower stratosphere and troposphere is galactic cosmic rays (according to relationships found by Kondratyev and Nikolsky, 1979), the use of the index $R_z$ for determining solar-climatic relations is not justified. The presence of sunspots, as a characteristic feature of solar activity, is apparently more closely related to the radiative and thermal processes in the middle and upper stratosphere of high (solar cosmic rays – SCR) and low (UV radiation) latitudes. In the authors' opinion, for the time being the neutron component intensity is the most adequate characteristic of the influence of the 11-year component of solar activity on the radiative and, consequently, thermal regime of the lower stratosphere and troposphere of the middle latitudes. In this connection, it is clear that one can hardly count on the existence of a unique global dependence of the tropospheric meteorological constant ($S_{oM,\,tropo}$) on the galactic cosmic rays intensity (CRI). The dependence $S_{oM,\,tropo}$ (CRI) will be different in every latitudinal belt, every season and every solar cycle or a pair of them.

## 4. The Proposed Experiment

In order to obtain more precise relationships of this kind, it is proposed to establish a global network of neutron monitors (currently functioning) placed high in the mountains. In this way, part of the influence of the lower atmospheric layer on the income of cosmic rays (thermobaric effects) can be avoided, and the possibility can be provided for simultaneous accurate and precisioning measurements of the spectral and integral meteorological 'solar constant' with the help of a set of pyrheliometric and spectrophotometric instruments. In a certain sense, this might become the next step in the development of the program proposed by Abbot.

Our experience of this kind of observations shows that neutron monitors intended for the experiment should be located at heights 2300–2700 m above sea level.

Apart from the spectrophotometer with the range from 290 to 1100 nm provided with automatic scanning with the step 3–5 nm, the complex of spectral instruments for measuring solar radiation should also include an aureole photometer functioning at 3–5 wavelengths, and installation for monitoring the spectral darkening towards the disc's edge and an absolute radiometer of the PMO-6 type. More frequent registering of optical thicknesses should be started at a network of stations after an overall signal indicating the appearance on the Sun of flares of proper class and power.

## References

Budyko, M. I.: 1979, *The Problem of Carbon Dioxide*, Gidrometeoizdat, Leningrad.

Duncan, C. H., Willson, R. C., Kendall, J. M., Harrison, R. G., and Hickey, J. R.: 1982, *Solar Energy* **28**, 385.

Foukal, P. V., Mack, P. E., and Vernazza, J. E.: 1977, *Astrophys. J.* **215**, 925.

Gilliland, R. L.: 1981, *Astrophys. J.* **248**, 1144.

Heath, D. F.: 1980, in *Proc. Intern. Conf. Sun and Climate*, Toulouse, 1980, p. 447.

Hickey, J. R., Stowe, L. L., Jacobowitz, H., Pellegrino, P., Maschhoff, R. H., House, F., and Vonder Haar, T. H.: 1980, *Science* **208**, 281.

Hoyt, D.: 1978, in *Proc. 3rd Conf. on Atmospheric Radiation*, June 28–30, 1978, Davis, Calif.

Kondratyev, K. Ya. and Nikolsky, G. A.: 1979, in *Proc. Symp. on Solar-Terrestrial Influences on Weather and Climate*, D. Reidel Publ. Co., Dordrecht, Holland, p. 317.

Labonte, B. J. and Howard, R.: 1981, *Science* **214**, 967.

Livingston, W. C.: 1978, *Nature* **272**, 340.

Livingston, W. C. and Holweger, H.: 182, *Astrophys. J.* **252**, 375.

Nikolsky, G. A.: 1980, in *Abstracts of Papers of XI USSR Conf. on Actinometry*, Estonian SSR Acad. Sci. Publ., Tallin, p. 96.

Pivovarova, Z. I.: 1977, *Radiative Characteristics of the Climate of the USSR*, Gidrometeoizdat, Leningrad.

Rosen, W. A., Foukal, P. V., Kurucz, R. L., and Pierce, A. K.: 1982, *Astrophys. J.* **253**, L89.

Vasilyev, O. B. and Rubashev, B. M.: 1971, *Soln. Dann.* No.12, 93.

Vasilyev, O. B. and Rubashev, B. M.: 1972, *Soln. Dann.* No. 1, 95.

Vasilyev, O. B., Muragin, E. F., Nikolsky, G. A., and Rubashev, B. M.: 1973, *Soln. Dann.* No. 4, 99.

Willson, R. C., Duncan, C. H., and Geist, J.: 1980, *Science* **207**, 177.

Willson, R. C., Gulkis, S., Janssen, M., Hudson, H. S., and Chapman, G. A.: 1981, *Science* **211**, 700.