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Hourly to Decadal Time Scale Variations of the Spectral and Total "Solar Constant"

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With 5 Figures

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Summary

The most significant solar spectral radiation bursts that occurred during more than twelve-years observation period at an high altitude station are analyzed. It is shown that the number and amplitudes of solar spectral bursts increase when the solar activity (SA) maximum is approaching. A plausible mechanism of short-term variations of extra-atmospheric solar spectral irradiance (ETSSI) is discussed. It appears that a burst of ETSSI arises when the Earth is sporadically irradiated by a strong flux of induced violet-blue high coming out of magnetic flux tubes in the active region (AR) of the Sun. We confirm earlier conclusions that on the time-scale of decades there is a close relationship between variations in the areas of faculae, the solar constant, and surface air temperature. On the basis of these results we suggest that at the end of the 1930s, when the Sun was very active, its effective output was about 0.4%, and the surface temperature in the Northern hemisphere about 0.4 °C, higher than in the first decade of the 20th century.

1. Introduction

High mountain observations of spectral solar radiation were performed to estimate energy contributions of ultraviolet (UV), visible (VIS) and near infrared (NIR) regions of the spectrum to changes in climatic parameters in the presence of variations in solar activity of different periodicity (from minutes to 11-yr cycles). The observations of spectral fluxes and spectral transparency of the atmosphere were carried out over the period beginning at the maximum of the 21st cycle of the Sun's activity (1981), through the subsequent minimum and maximum phases of activity and ending at the middle of the decrease phase in the 22nd cycle (1994). In more than ten cases, occurrences of extremely anomalous high values of transparency of the atmosphere in the UV and violet-blue ranges of the spectrum were revealed. When analysing relevant circumstances we discovered that, as a rule, anomalies in transparency arise when an active region is passing through the central meridian and they are observed at noon, local time. One should keep in mind that when measuring through the thickness of the atmosphere the increase in ETSSI is revealed by the spectral transparency excess over the calculated (model) characteristic value of a clear dry atmosphere with air pressure and temperature profiles in the troposphere existing over the station at the moment of observations.

Further study shows that an apparent increase in transparency occurs when the Earth is illuminated by radiation coming from an AR and is characterized by an intensity maximum near 410 nm and by specific spectral variations. These kind of solar radiation bursts cannot be explained by the actual increase in transparency. This is because in such a case the transparency of the atmosphere (for wavelengths in the above mentioned spectral ranges) would have coincided with the values characteristic of the ideal atmosphere at the station level (2100 m) and in some cases (see Fig. 2) would have reached values corresponding to the ideal atmosphere at the 3400 m level.

Comparison of the energy contribution of the above mentioned "gleams" burst variations of solar spectral radiation (SSR) with the dispersion of the total solar constant (TSC) variations due to Nimbus-7 data (diurnal mean values) showed that the excessive radiation is generated by a very small part (1×10^{-7}) of the Sun's disc surface.

2. Instruments

An UV-spectrometer was the principal instrument used for our measurements – this consisted of a small-size double monochromator DH-10 UV (Jobin Ivon) supplied with an aperture tube with a milky diffuser and placed on a Sun-tracking device which provided continuous and controlled pointing at the Sun. When input and output slits are of identical width (equal to 0.05 mm) and dispersion is equal to 4 nm/mm (gratings with 1200 lines/mm) the resolution is 0.4 nm. A stepping motor provided scanning to 0.1 nm/step. A wavelength scale of the spectrometer was easily controlled by Fraunhofer lines. Recording time of the spectrum for the wavelength region 330–430 nm (1000 steps) was 1.5 min. Sensitivity stability was controlled 3–5 times a day by means of a lamp powered by stabilized current. In each case of optically stable weather recurring determinations were made of extra-atmospheric constants for typical maxima of radiation in the spectral region under study.

3. Observed SSR Anomalies

Before the analysis of the main results of the observations let us consider an example of an anomalous situation displayed by variability of optical parameters of the atmosphere in the period of high solar activity in October 1981. Figure 1 presents the daily variation (Oct. 12, 1981) of: (a) the total content of water vapor

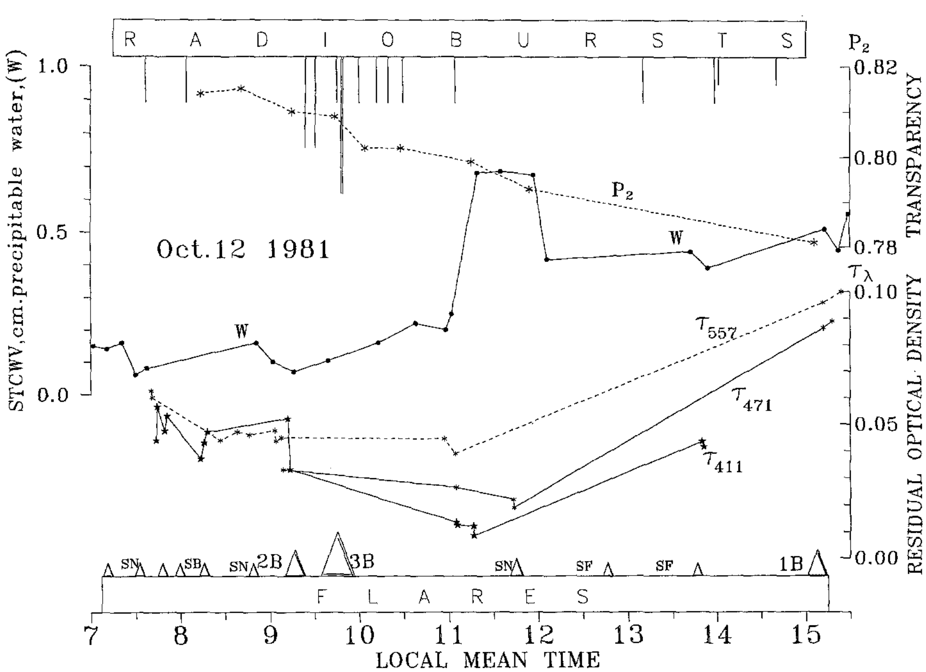

Fig. 1. Results of observations of optical and meteorological characteristics of the atmosphere (October 12, 1981) at the High Altitude Astronomical Station (N. Caucasus, 2100 m) of the Main Astronomical Observatory Russian Academy of Science. Anomalous change in the total (by spectroscopic data) content of water vapor (STCWV) and residual (aerosol) optical thicknesses of the atmosphere for the wavelengths 411, 471 and 557 nm were observed during 6 hours. Anomalous values of optical thickness and daily range of their variability should be assigned to high activity of the Sun, but not only to real atmospheric transmission changes

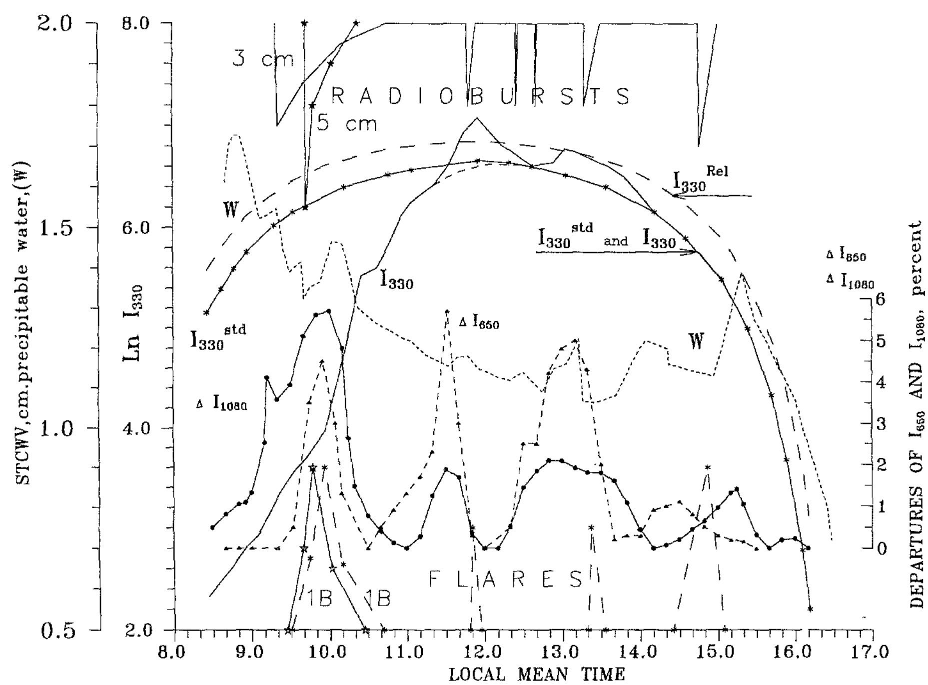

Fig. 2. Daily course of direct solar radiation at the wavelengths 330, 650 and 1080 nm and of the total content of water vapor under conditions of sharp changes in solar activity (flares and radiobursts) November 2, 1991.
I_{330} – measured relative values of the intensity of direct solar radiation at 330 nm (from the total of solar disc); I_{330}^{Rel} – the intensity of solar radiation in the ideal atmosphere at the height of 2100 m for $\lambda = 330$ nm; I_{330}^{std} – extrapolated values of the intensity based on I-values measured at that day after 15 LMT; ΔI_{650}, ΔI_{1080} – variations in irradiance at the effective wavelengths 650 and 1080 nm presented in percent of standard values for that day

W (according to IR-hygrometer data), (b) spectral optical thickness τ of the atmosphere for wavelengths 411, 471 and 557 nm, and (c) total solar radiation transmission through the atmosphere (P_2). The symbols of duration and power of flares (below) and those of radio emission bursts from ARs (above) are plotted on the abscissa. Data presented in Fig. 1 show the strongest transformation in optical characteristics of the atmosphere in the first half of the day which was the result of increasing power in the Sun's flares and radioburst intensity. Of note is the extremely low value of W (0.1–0.25 cm precipitable water) for the interval from 7 to 11 LMT, its unusually rapid increase to the normal mean level (0.6 cm) and consequent sharp decrease 40 min later. Possible causes of significant variations in the microphysical state of water vapor molecules accompanying solar emissions' bursts have been considered by Nikolsky (1994).

Of great importance is the situation never encountered before: an inverse (to normal) sequence of values of residual (aerosol) optical thickness (τ_{411}, τ_{471}, τ_{557}), as well as very low τ_{411} (~ 0.01) and τ_{471} values at noon. Such anomalously high transparency in the blue range of the spectrum should evidently be connected with 25% burst of ETSSI, the maximum of which is at 411 nm; at shorter wavelengths there is a long wing of increasing transparency.

We now need to focus our attention on the most impressive and well traced event on November 2, 1991. Figure 2 shows the development of specific changes in solar radiation following two flares (1B and 1B) with an 8-min interval between their peaks, and radiobursts at some frequencies (a peak amplitude – 3125 sfu at $\lambda = 5$ cm at 9 h 46 m LMT – local mean time). The beginning of the response of optical parameters to the flares was noted as early as 9 h 36 LMT. The increase in solar irradiance in the near IR-region (650 nm) reached 4.5% and at the wavelength 1080 nm – about 5.5%. It is interesting to note that the intensification of solar radiation at $\lambda = 1080$ nm – began 16 min before the first flare and 10 min before the beginning of the radioburst. The response of the total (according to spectroscopic data) content of water vapor (W), as it is plotted in Fig. 2, took place at 9 h 58 m LMT, that is 11 min after the maximum of the first flare. W-changes continued over about 30 min and reached 8.5%. For the flare 3 B on Oct. 12, 1981 W-change reached up to 45% and lasted for about 60 min.

As it is seen from Fig. 2, bursts of radiation were continuing till 14 LMT. At 650 nm a photometer displayed two more 5% bursts and a final 1%-burst. Three more bursts with 1.5–2.0% – amplitude were recorded by a photometer at 1080 nm.

4. Analysis of Events

On the basis of the evidence presented one can make some suggestions as to the nature of sources of spontaneous bursts of solar radiation on Nov. 2, 1991. A morning burst at wavelengths 650 and 1080 nm should be undoubtedly related to a pair of flares at 9 h 55 m LMT while subsequent bursts, as it follows from the work by Dyakonova and Chistyakov (1993), represent the manifestation of oscillating changes in the faculae rings' areas and in the Sun's diameter. Mid-day anomalies of UV-radiation and the increase in I_{330} anomalies are due to the occurrence of a powerful non-equilibrium source of radiation (see later section).

Now let us dwell on the main event of the day: the bursts of solar radiation in UV region (Fig. 2). From the data on I_{330}-variations near noon time it follows that 35 min before the upper culmination there appeared on the Sun an additional source of radiation characterized by essentially selective spectral variation. The main feature of this source was a strong increase of radiation in the blue spectral region. The observations show that a peak in I_{330}-increase took place at exactly noon local time. The burst lasted from 11 h 30 m to 12 h 30 m LMT. Figure 2 shows that rather than following the preceding tendency of an increase along a part of the dotted curve, coinciding with I_{330}^{Std}-curve which corresponds to a normal daily variation (the latter was constructed on the basis of data for the undisturbed atmosphere over the period 14 h 20 m–16 h 15 m LMT), the values of I_{330} lay outside of standard (normal) levels and reached levels corresponding to the ideal atmosphere (I_{330}^{Rel}) and even higher. The increase in I_{330} was about 50%. The second increase in I_{330} lasting from 13 h 00 m to 14 h 30 m LMT did not locate outside the "Rayleigh" level but nontheless was anomalous (+18%). After the second increase, I_{330}-values closely followed the I_{330}^{std}-course (in accordance with Bougher's law).

Figure 3 shows spectral variations in ETSSI which occurred at about noon on Nov. 2, 1991, Sept. 10, 1986 and Oct. 12, 1981, and the location of active regions on the Sun for the two first dates. We should notice that for the events on Nov. 2, 1991 $\Delta I_{0\lambda}$-variations in UV- and near IR-spectral regions do not coincide in time; the maxima of ΔI_{650} and ΔI_{1080}-variations are 25–30 min ahead of the I_{330}-maximum. This is the reason that ΔI_{650} and ΔI_{1080} were not taken into account when we made the calculation of a noon integral using ETSSI-curve for Nov. 2, 1991. One may suggest that a very close location of active regions to the central meridian of the Sun (CMS) was the most significant feature at the day and which provoked the repeated occurrence of radiation bursts in different parts of the spectrum.

The duration of the entire process – the burst of solar radiation at 330–430 nm and in the ranges 650 and 1080 nm – was about 4 hours. At noon, when the variation was at its maximum the integral in the range 330–430 nm was about $+100\ \mathrm{W/m^2}$ ($\sim 8\%$ of total solar constant I_0).

From the variation in spectral distribution for Sept. 10, 1986 towards 500 nm one may see that on that day there was also a probability of occurrence (a band limited by a small-dot line) of low values of $\Delta I_{0\lambda}$ for $\lambda > 500$ nm. The solar disc for that day is shown in the left map. The only AR at 30° N is located near the CMS; it is undoubtedly that object which contains a source of ETSSI-burst (its duration was about 7 min and it was observed at noon, local time).

The data for Oct. 12, 1981 suggest a longer period of ETSSI-increase (up to 6 hours) which is, however, now completely related to the previously mentioned effect of a noon illumination of the Earth. On Oct. 12, 1981 day we observed some power flares (2B, 3B) which were responsible for excess radiation occurrence (from 28% at 411 nm to 10% in 560–650 nm range and dropping to zero at 800 nm). The integral for the range 410–800 nm was about $80\ \mathrm{W/m^2}$. It should be taken into consideration that this integral does not include radiation with $\lambda < 410$ nm. This portion was estimated as approximately $\sim 10\ \mathrm{W/m^2}$.

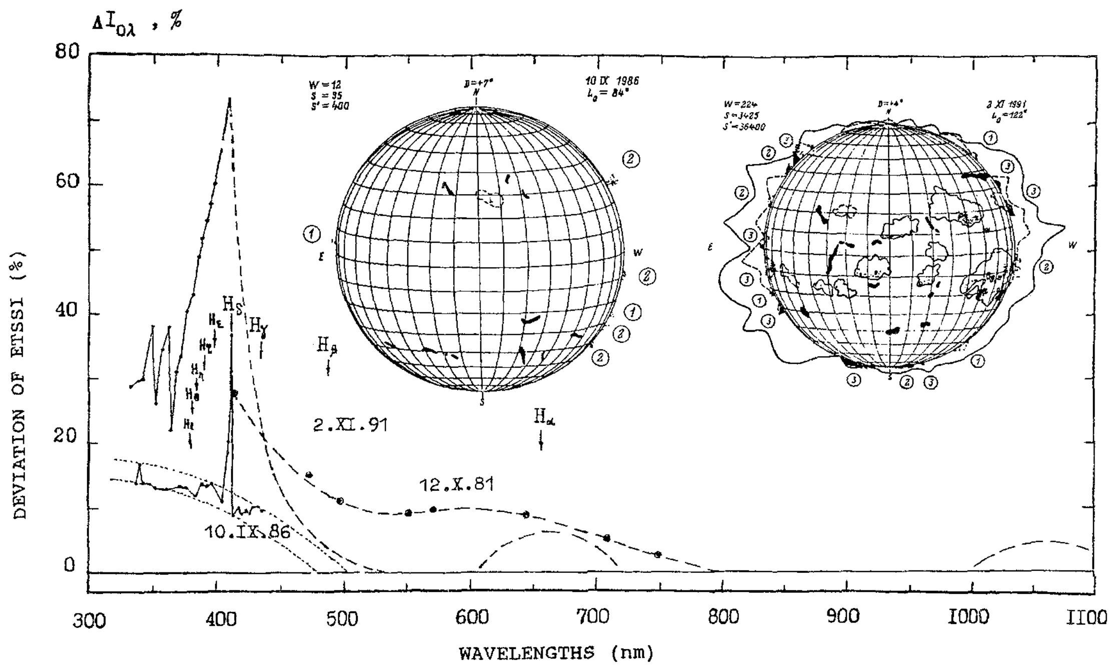

Fig. 3. Relative changes in extraatmospheric spectral solar irradiance (ETSSI) in three spectral regions: 330–400 nm with 0.1 nm/step; 650 nm (band halfwidth is 80 nm); and 1080 nm (half width is about 120 nm). The data are obtained on the basis of measurements of spectral transparency of the atmosphere on October 12, 1981, September 10, 1986 and November 2, 1991. The maps of the Sun are presented for two later dates. Spectral curves for these dates are obtained at local noon. In case of the event Nov. 2, 1991 the interpolation of a spectral curve is made in 400–520 nm-range

To make the statistical significance of the parameters characteristic of ETSSI-burst occurrences more reliable, the spectrometer was supplemented with a two-channel filter photometer for 405- and 630-nm wavelengths. This instrument also proved to be necessary for estimating the degree of spectral compensation of bursts in the total flux of solar radiation. On Nov. 10, 1992 at about 9 h 30 m UT a sharp rise in the intensity of solar radiation for 405 nm-channel was recorded, but the data for 630 nm-channel did not confirm the occurrence of this variation (as can seen in Fig. 4). Since measurements in each channel were made every 2 minutes and the increase in irradiance was very quick, it was not possible to precisely determine its beginning – it was therefore defined as 9 h 33 m $\pm$ 1 min UT. The intensity drop at 11 h 07 m $\pm$ 1 min UT was also very sharp.

5. Solar Beams and Faculae Fields

All the above mentioned observations indicate that the divergence of the "blue" ray is small; according to the duration of illumination and speed of solar beam movement along the Earth's orbit ($\sim$ 370 km/s) one may estimate the divergence as equal to 0.9°. Hence, it follows that in the solar atmosphere physical mechanisms of collimation of polychromatic radiation beams are sufficiently widespread. One conceivable reason for collimated beam occurrence is the generation of nonequilibrium (induced) super-emission in a column of hydrogen – helium plasma enclosed in a magnetic envelope – magnetic power flux tube (MPFT) about 250 km in effective diameter and some thousands kilometers in length.

MPFTs' of greater diameters (up to 1500 km) are less effective as sources of e.m. radiation but nevertheless, because of widerspread occurrence in the chromosphere (spicules), they throw out a great amount of e.m. energy to the upper chromosphere and the corona.

Approximate estimation of the contribution of super-emission from a great number of MPFT (for the whole Sun) leads to the change in luminosity value at the SA-maximum (for example in October 1981) equal to $\Delta L = 3{\cdot}10\,(-3)\%$.

If the observed time of additional illumination of the Earth is equal to 107 min (or 0.074 of a day)

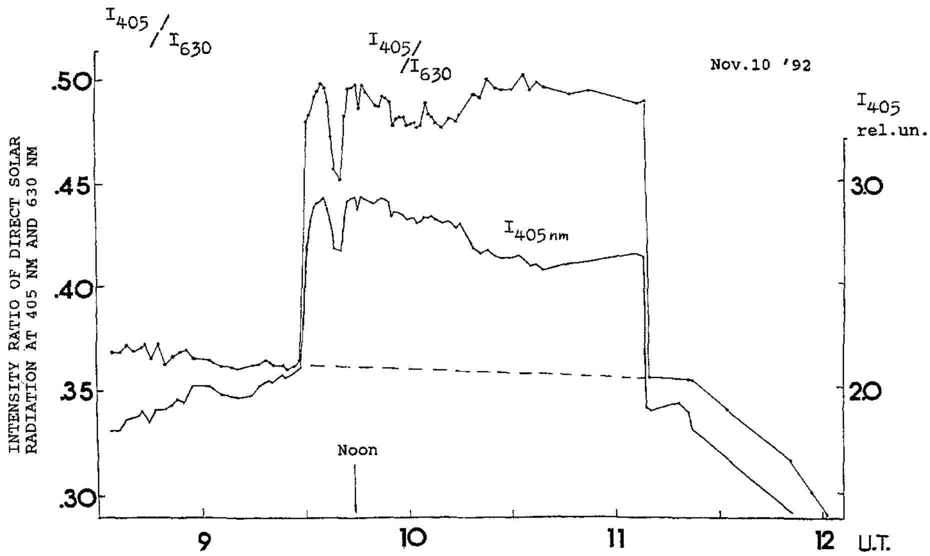

Fig. 4. The burst of solar irradiance in the spectral range near 405 nm observed on November 10, 1992 by means of a ground-based two-channel photometer with interference filters. The maxima of filter transmission are at 405 and 630 nm; a halfwidth of bands is about 8 nm

and if an excess "blue" beam is $\sim 8\%$ of I_0 ($100\,\mathrm{W/m^2}$) then the change in the solar constant would amount to $\Delta I_0 = 8 \cdot 0.074 = 0.6\%$. Hence, we have obtained a reason for further development of a hypotheses for the mechanism of nonequilibrium excess solar radiation and for consideration of temporal variations in spectral and total radiation. For this purpose let us turn to the work by Loginov and Sazonov (L & S) (1971) which treats causes of nonlinear dependence between the "solar constant" and solar activity and considers consequences of this non-linearity.

When analyzing the degree of correlation between the decrease in radiation through spots and its increase in faculae (two mutually compensating processes), L & S found out that for an 11-year cycle the correlation between spots and faculae differed greatly from cycle to cycle. To eliminate factors obscuring the links between these SA-parameters they averaged some hundreds of monthly mean values for areas of faculae (S_f) and of sunspot umbrae (S_u) taken from Greenwich catalogues of Solar activity between 1874 and 1963. As a result, they discovered a well-defined link between the magnitudes of S_f and S_u which appeared to be inherently nonlinear: when S_u-increase was more than 200 ppmvh (parts per million of visible hemisphere area of the Sun) the rate of S_f-increase was diminished by an order of magnitude, and when S_u-values were > 500 ppmvh there appeared a tendency for S_f to decrease. This implies that the cycle of variations in S_f does not coincide with the cycle of Wolf numbers R_z and that the link between the solar constant and solar activity is nonlinear: at $R_z \approx 80 \pm 20$ I_0-value reaches its peak. These data imply that the relation between R_z and mean surface air temperature (which would be particularly evident in summer in the subtropics) is non-linear as well.

6. Faculae Areas and Surface Air Temperature

Let us turn to the relationships between the parameters of interest when they are averaged over successive solar cycles, from the 12th to the 19th (see Fig. 5, for which most of the data are taken from L & S). Variations in ΔT_s are obtained from a weather network located in Northern latitudes from 30° to 40° N. Data for three summer months of each year within each SA-cycle over the period 1880–1963 were averaged and deviations from T_s-mean were calculated. S_f- and S_u-values also refer to the three summer months. Data for the ΔI_0-curve were obtained from the empirical relationship between variations in ΔI_0 and ΔT_s given by Reid (1991).

According to Fig. 5 the correlation between S_u and ΔT_s turns out to be less strong than between S_f and ΔT_s. Particular attention should be given to the essentially different tendencies of variations of S_u and in all the other parameters over the 19th cycle.

Since S_u-values increase while ΔT_s-values decrease one may conclude that it is due to a partial compensation effect by faculae S_u-increase which is responsible for ΔT_s-decrease.

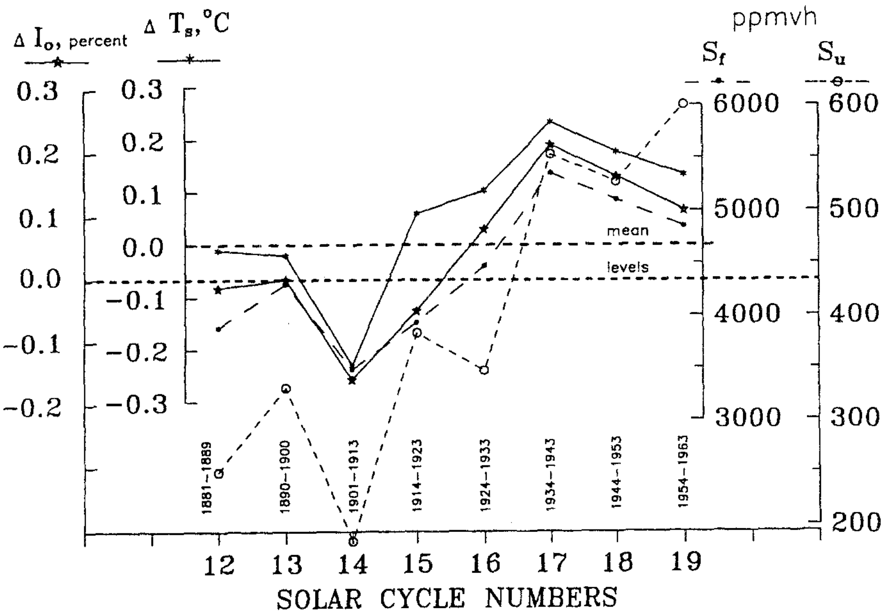

Fig. 5. Comparison of solar cycle mean values for deviations of surface air temperature (ΔT_s in the belt of 30°–40° N) with areas of faculae (S_f) and spot umbra (S_u) as well as with variations in the "the solar constant" (ΔI_0) over the period 1881–1963. S_f- and S_u-values are plotted in ppmvh (parts per million of a visible hemisphere area of the Sun). To mark the scale for ΔI_0-curve the relation between ΔI_0 and ΔT_s (according to Reid, 1991) was taken into account. An optimum of a link between ΔI_0 and ΔT_s was estimated near a lower limit by Reid, that is $\Delta T_s \approx 0.5\,°\mathrm{C}$ corresponds to $\Delta I_0 \sim 0.4\%$. ΔI_0-curve itself repeats in general S_f-variations. One should pay attention that there is fine correlation of the curves S_f and ΔT_s, while the area of spot umbra (S_u) and all other parameters correlate only partially. It indicates nonlinear character of connection between ΔT_s and solar activity; the latter is more often sumbitted to the areas of sunspots, spots umbra or Wolf numbers

7. Conclusion

In view of the importance of the problem discussed here we consider the data given in Figs. 1–3 and attempt to support them using evidence from other studies. We shall refer to the works by Dyakonova and Chistyakov (1993) in which the authors analyze prolonged observations of phenomena following solar flares, and by Chistyakova, K. G. and Chistyakov, V. F. (1975) in which an extremely important phenomenon – the increase in brightness (to 30%) and area (by 100–200%) of a faculae ring around the sunspot which took place ~30 minutes before the flare – was considered. Also of great importance is evidence concerning after-flare pulsations of faculae rings and the angular radius of the Sun (R_0). In connection with the problem of S_f-pulsations it is necessary to mention an event on Sept. 13, 1972 discussed by Dyakonova and Chistyakov (1993). In this event, the range of R_0-oscillations was 2.2″ after the flare 2F (03 h 09 m UT) and an amplitude of the first S_f-pulsation reached 98 ppmvh. Subsequent pulsations or R_0 and S_f were developing almost simultaneously in time with specific recurrences equal to 30 and 110 min. The observations were interrupted after the third (but evidently not the last) pulsation in their gradually decaying series. These data are very much similar to the series of oscillations of solar irradiance I_{650} and I_{1080}, given in Fig. 2 and having an amplitude equal to 6% of undisturbed values of spectral irradiances. Noon bursts at $\lambda = 300\,\mathrm{nm}$ are not distinctly related to flares and should rather be referred to as a gleam-like effect designated above as ETSSI-burst. The contribution of beam illumination (gleams), in spite of its short duration, adds some fraction of a percent to the incoming part of the Earth's radiation balance. Assimilation of the energy of gleams is most pronounced in tropical and subtropical areas of the ocean.

The impact of a sequence of powerful flares on spectral optical thickness of the atmosphere manifests itself in stepwise variations and, what is the most important, in spectral "convertibility" of optical thicknesses (see Fig. 1). Such an effect was never observed in many years of previous observations. It is also of interest that 90 min after the powerful flare 3B the value of spectroscopic total content of water vapor (STCWV or shorter W), increased strongly (up to 350% of a previous value of W). A spectral variation of ETSSI on Oct. 12, 1981 presented in Fig. 3 is characteristic of flare radiation for which an extended longwave wing is typical. Hence, we may say that our observations can confidently flux variable-scale events on the Sun, the analysis of which moves us closer to understanding the physical mechanisms driving the impacts of solar activity on weather and climate processes on the Earth.

The following conclusions emerge (1) that the mechanism of direct assimilation of e.m. solar energy is by the energy of beam polychromatic illumination from AR; the contribution of beam irradiance (the latter being very brief) adds some parts of a per cent to the "incoming" part of the Earth's radiation balance; (2) that impacts of solar radiation on the climate depend to a large extent on the variations in spectral composition (in 400–600 nm spectral range) of radiation from facula fields; (3) that the most significant indices of SA are the areas occupied by facula fields (S_f) and the location of AR about the central meridian of the Sun; (4) that the discovery and identification of beam irradiance proves to be a difficult problem because of specific features of its temporal and spectral variability; (5) that the phenomenon of gleams is more likely sporadic and short in duration and appears as a quasi-continuum in various spectral ranges, for example in 340–420, 440–490, 500–520 nm.

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