GENERAL TRENDS IN THE CHANGES OF INDICES OF SOLAR ACTIVITY IN THE LATE XX - EARLY XXI CENTURY

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Abstract. The analysis of the observations of solar activity indexes SSN (NOAA Sunspot Numbers), the radio flux at a wavelength of 10.7 cm ($F_{10.7}$) and the solar constant (TSI) during the cycles 22 - 24 is presented. We found a decrease of the observed values of the SSN$_{obs}$ which was calculated with SSN$_{syn}$ (using regression relationships between SSN and $F_{10.7}$) after 1990 year on 20 - 25% instead of 35%, as was previously assumed. The changes in characteristics of the most popular index, SSN, such as decrease in the number of sunspots, the reduction of the magnetic field in small and medium-sized spots are not in full compliance with the proposed scenario of solar activity predicted by radio flux $F_{10.7}$ in the cycles 23 and 24, and cannot be fully explained by the influence on the SSN values of additional minimum of 50 - 70 year cycle. We have also showed that the observed changes of SSN lead to a slight increase of the solar constant TSI during the cycles 23 - 24 compared to the cycle 22.

Key words. solar cycle, observations, solar activity indices.

1 Introduction

Indices of solar activity studied in this paper are very important not only for analysis of solar radiation which comes from different altitudes of solar atmosphere. The most important for solar-terrestrial physics is the study of solar radiation influence on the different layers of terrestrial atmosphere (mainly the solar constant TSI and radiation in EUV/UV spectral range which effectively heats the thermosphere of the Earth and so affects to our climate).
Solar irradiance is the total amount of solar energy at a given wavelength received at the top of the earth’s atmosphere per unit time. When integrated over all wavelengths, this quantity is called the total solar irradiance (TSI) previously known as the solar constant. Regular monitoring of TSI has been carried out since 1978. From 1985 the total solar irradiance was observed by Earth Radiation Budget Satellite (ERBS).

All the indices of solar activity are in most cases closely related, as the main source of all their variations is an variable magnetic field. We have studied monthly averaged values of three global solar activity indices (SSN, TSI and $F_{10.7}$) during activity cycles 21, 22 and 23. Most of these observed data we used in our paper were published in Solar-Geophysical Data Bulletin (2009) and in Reports of National Geophysical Data Center Solar and Terrestrial Physics (2014).

Monthly averages allowed us to take into consideration the fact that the major modulation of solar indexes are the consequence of 27 - 28 days variations of radiative fluxes (these variations correspond to the mean solar rotation period). After monthly averaging we reduced the influence of the rotational modulation on the observational data, see Bruevich et al. (2014a) The various activity indices which characterized the different aspects of the solar magnetic activity correlate quite well with the most popular solar index such as the sunspot numbers and with others indices over long time scales.

When various reconstructions of the past (and the predictions of the future) there means that the relationship between the indices of the activity remains unchanged over time. This is true for indices that are closely related, as, for example, fluxes in radio and UV ranges.

Floyd et al. (2005) showed that the mutual relation between sunspot numbers and also between three solar UV/EUV indices, the $F_{10.7}$ flux and the Mg II core-to-wing ratio (which is the well known chromospheric UV index, see (Viereck et al. (2001), Viereck et al. (2004)), remained stable for 25 years until 2000. At the end of 2001 these mutual relations dramatically changed due to a large enhancement which took place after actual sunspot maximum of the cycle 23. On the other hand the connection between the radiation fluxes and indirect indices, such as the SSN is not so obvious: processes of formation and evolution of spots are different and are poorly studied.

Indeed, while a time there was a confidence in the close connection between the radio flux $F_{10.7}$ and the SSN that we can always possible to calculate the value of one from another, see Bruevich and Yakunina (2011), now
we see that this relationship has being not so stable. Observers believe that low values of global activity indices in 23-rd and 24-th solar cycles can be explained in recent years with help of the overlap of the current 11-year cycle with the minimum of 50 - 70 year cycle. The ratio of SSN to the radio flux $F_{10.7}$ (which is considered the most reliable solar index) from 1950 to 1990 was almost constant, and from 1990 to 2012 began to decrease parabolically 30 - 35% (Livingston et al. (2012); Svalgaard (2013)).

Simultaneously, the magnetic field strength of sunspots, averaged over all spots, was gradually decreases from 1998 to 2011 by about 25%, see Livingston et al. (2012). If these two trends would develop in the same direction, the spots on the Sun would be disappeared, as in the era of the Maunder minimum.

Other indices of activity associated with surface magnetic fields also are acting by unusual way in recent time. The analysis of the total area of sunspots as well as the total space of the flare regions has made on the basis of observational data from Observatory of San Fernando (Spain), see Chapman et al. (2014).

It was shown that the relative amplitude of the total areas of the sunspots were reduced from 1.0 in the maximum of the cycle 22 to 0.74, and 0.37 in the maximums of cycles 23 and 24 respectively.

Also at the Observatory of San Fernando the rations of total area of faculae to the total area of chromospheric network (the ratio of faculae/network images in the $CaII$ K line) has been measured for the cycles 22, 23 and 24. In Chapman et al. (2014) was also found that the total area of faculae which were observed in the line of $CaII$ K is reduced from the cycle 22 to the cycle 24. But in the cycle 24 the ratio of the total areas of faculae to the total areas of spots increases.

We use the TSI data set from NGDC web site [http://www.ngdc.noaa.gov](http://www.ngdc.noaa.gov) and combined observational data from National Geophysical Data Center Solar and Terrestrial Physics (2014). A significant contribution to TSI variations (Active Sun/Quie Sun) has a UV/EUV flux that was pointed in Krivova and Solanki (2008). Up to 63,3 % of TSI variability is produced at wavelengths below 400 nm. It is important that this UV/EUV flux determines the heating of the upper thermosphere of the earth and correspondingly affects the earth’s climate. Towards activity maxima the number of sunspots grows dramatically. But on average the TSI is increased by about 0,1% from minimum to maximum of activity cycle. This is due to the increase amounts of bright features, faculae and network elements on the solar
surface. The total area of the solar surface covered by such features rises more strongly as the cycle progresses than the total area of dark sunspots. Some physics-based models have been developed with using the combined proxies describing sunspot darkening (sunspot number or areas) and faculae brightening (faculae areas, \( \text{CaII} \) or \( \text{MgII} \) indices), see Fontenla et al. (2004), Krivova et al. (2003).

The aim of this work is the analysis of recent general trends in the behavior of monthly averages of global indices of solar activity, such as relative spot numbers SSN, radio flux \( F_{10.7} \) and the solar constant TSI in the cycles 22 - 24.

2 Analysis of recent general trends in solar activity

The SSN - relative sunspot numbers index has decreased by a quarter over the past 30 years according to the observations of Penn and Livingston (2006).

Analysis of the data of Penn and Livingston (2006), Penn and Livingston (2011) held in Nagovitsyn et al. (2012) showed that along with the detected trend towards decreasing magnetic field spot, averaged over all spots, for the largest spots such reduction of the magnetic field is not observable but the normal variations typical of the 11-year cycle.

In the period 1998 - 2011 the number of large spots decreased in accordance with the predictions of cyclical activity, whereas the number of small and medium-sized spots increased. So, a negative correlation between the number of small and big spots was found, and an explanation for this contradiction was given. It turned out that only in the separation of the spots on small and large we have the opportunity to explain the contradictions between the forecast and observations in the trends in changes of magnetic fields in spots in the cycles 22, 23 and 24.

The ratio of the SSN to the magnitude of the radiation flux on the wave of 10.7 cm remained almost constant from 1950 to 1990, after which this ratio has steadily decreased, see Livingston et al. (2012).

For an objective assessment of this trend for observations 1950 - 1990 with using the coefficients of the polynomial regression between SSN and the radiation flux \( F_{10.7} \), the \( SSN_{syn} \) values were calculated, see Fig. 1.
Figure 1: Dependences: a) - SSN from $F_{10.7}$; b) - SSN from $(F_{10.7} - F_{10.7}^{\text{min}})$. Observations from 1950 to 1990.

According to our calculations of the coefficients of the polynomial regression from Fig. 1a the dependence of SSN from $F_{10.7}$ is described by the following formula:

$$SSN_{\text{syn}} = -83.63 + 1.41 \cdot F_{10.7} - 0.0011 \cdot F_{10.7}^2 \quad (1)$$

Fig. 1b shows the dependence of SSN from 10.7 cm radio flux where, instead of a full flux $F_{10.7}$, we use only its variable part which is equal to $F_{10.7} - F_{10.7}^{\text{min}}$.

It is known that the lowest value of the 10.7 cm radio flux in the minimums of 22 - 24 cycles is $F_{10.7}^{\text{min}} = 68 \, \text{sfu}$ ($1 \, \text{sfu} = 10^{-22} \, \text{Watt} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$), which roughly corresponds to the radiation flux of the Sun in the complete absence of spots.

The dependence of the SSN from $(F_{10.7} - F_{10.7}^{\text{min}})$ according to the polynomial regression from Fig. 1b is described by the following formula:
\[
SSN_{syn} = 6.70 + 1.26 \cdot (F_{10.7} - 68) - 0.0012 \cdot (F_{10.7} - 68)^2 \quad (2)
\]

For each month of the observation based on the \(F_{10.7}\) data with using the formulas (1) and (2) the \(SSN_{syn}\) values are computed.

Then we have computed the relationship \(SSN_{obs}\) (observed) to \(SSN_{syn}\) (calculated). Time series of these relations are shown in Fig. 2 in accordance with the method of constructing of annual averages \(SSN_{obs}/SSN_{syn}\) according to Svalgaard (2013).

Figure 2: a) - the time dependence of the average ratio of the observed numbers of sunspots \(SSN_{obs}\) to values \(SSN_{syn}\), calculated (crosses) using the coefficients of the polynomial regression between SSN and the radiation flux \(F_{10.7}\). Annual average \(SSN_{obs}/SSN_{syn}\) from Svalgaard (2013) are marked with asterisks; b) - the time dependence of the ratio of the observed average monthly number of sunspots \(SSN_{obs}\) to values \(SSN_{syn}\) calculated using the coefficients of the polynomial regression between SSN and the flux of radiation \((F_{10.7} - F_{10.7}^{min})\). The months with SSN>10 are included in consideration.
In Fig. 2a we show a time series of monthly averages of \( \frac{SSN_{\text{obs}}}{SSN_{\text{syn}}} \) (crosses) from 1950, extended by us until the beginning of 2015.

We can see that in 2013 - 2014, the number of sunspots increased markedly, and ultimately a reduction in the amount \( \frac{SSN_{\text{obs}}}{SSN_{\text{syn}}} \) was not so great as in Livingston et al. (2012); Svalgaard (2013) and is of about 20%.

In the case where \( SSN_{\text{syn}} \) is calculated depending on the variable part of the radiation flux by the formula (2) the decrease in the \( \frac{SSN_{\text{obs}}}{SSN_{\text{syn}}} \) in recent years was 25% (Fig. 2b). Annual averages of \( \frac{SSN_{\text{obs}}}{SSN_{\text{syn}}} \), shown by asterisks in Figure 2a, were taken from Svalgaard (2013). It is seen that the Svalgaard’s ratio \( \frac{SSN_{\text{obs}}}{SSN_{\text{syn}}} \) has reduced by 35 % by 2012.

The difference with our results is due to the fact that in the period from 2013 to 2015, which were not included in earlier papers, the number of spots \( SSN_{\text{obs}} \) has increased noticeably and the main trend was changed. Therefore the value \( \frac{SSN_{\text{obs}}}{SSN_{\text{syn}}} \) decreased only by 20 - 25% in our analysis.

We also analysed the ratio of the monthly averaged number of spots to the radio flux \( (F_{10.7}) \) taking into account only the variable components of the radio flux: \( \frac{SSN_{\text{obs}}}{(F_{10.7} - F_{10.7}^{\text{min}})} \).

As we can see in Fig. 3 a decrease in the relative number of sunspots after 1990, in the case of linear regression, the reduction is about 15%, and in the case of a polynomial (it is more suitable for the analysis of cross-correlation between solar indices) - about 25%.

Note to the cyclical nature of \( \frac{SSN_{\text{obs}}}{(F_{10.7} - F_{10.7}^{\text{min}})} \) dependence. The deviations from regression lines reach maximum values in the minima of the 11-year cycles, when the relative error of observations of indices of activity increases. Because of this fact we have to exclude from consideration the months when \( SSN < 10 \).

On the other hand, the dispersion of the deviations decreases and the relationship \( \frac{SSN_{\text{obs}}}{(F_{10.7} - F_{10.7}^{\text{min}})} \) becomes closer to the regression line on the rise and decline phases of the 11-year cycles, which is consistent with the findings obtained by us earlier Bruevich et al. (2014b) about the maximum correlation between solar indices during these periods.

Our analysis showed that the assumption Livingston et al. (2012) and Svalgaard (2013) about the desire of the average annual values of sunspot numbers to zero, and in the near future is waiting for another Maunder minimum, is not confirmed.

We have tried to reveal the effect of increasing the radiation flux from the solar photosphere, and with it the increase in TSI as a result of the reduction of deficit of brightness of photospheric radiation in dark spots. A comparison
Figure 3: The time dependence of the ratios of the observed monthly averaged values of the sunspot numbers to the variable component of radio flux values: $SSN_{obs}/(F_{10.7} - F_{10.7}^{min})$. Observations from 1950 to 2015.

was made of TSI in cycle 22 with TSI in the cycle 23 and the rising phase of cycle 24 relatively to resistant solar index - radiation flux ($F_{10.7}$).

In Fig. 4a and Fig. 4b we present the dependence of TSI from the radio flux at 10.7 cm. We used the observations of the total solar irradiance TSI from the entire solar disk, integrated over the entire solar spectrum. The data of TSI monitoring from 1978 to 2013, observed by various instruments during the flight of multiple satellites that is standardized to the uniform observational data, which are presented in National Geophysical Data Center Solar and Terrestrial Physics data of observations, see NGDC (2013).

In Fig. 4c we show a set of observations of TSI used to analyse. Separately for the cycles 22 and 23+24 we built regression: in Fig. 4a - linear, in Fig. 4b - polynomial for the cycle 22 and linear for the cycles 23+24. It is known that polynomial regression best describes the relationship between the activity indices in the maxima of the cycles. Fig. 4 shows that for large values of
Figure 4: The dependence of TSI from radio flux $F_{10.7}$ for 22, and 23+24 cycles of solar activity: a) - linear regression for 22 and (23+24) cycles; b) - linear regression for (23+24) cycles and polynomial regression for 22 cycle; c) - the set of TSI observations from 1978 to 2013.

$F_{10.7}$ the TSI values in the different cycles are different: the value of the solar constant during the periods 2000 to 2013 is higher than in 1985 - 1996.

The rms (mean-square) deviation of the TSI values from regression lines for linear and polynomial is about 0.1 Watt/m². When $F_{10.7} = 240$ sfu the difference between TSI in the 22-nd cycle and TSI in the cycles 23+24 is about 0.4 Watt/m² for the dependencies in Fig. 4a and 0.6 Watt/m² for the dependencies in Fig. 4b.

Thus, the difference between the two regression dependencies in Fig. 4a and in Fig. 4b are statistically significant with a significance level of 0.05 when $F_{10.7}$ is equal to 220 sfu, and with a significance level of 0.01 in the maximum cycle when $F_{10.7}$ is equal to 240 sfu.

This effect was predicted in Svalgaard (2013). It was assumed that the value of the solar constant should be increased when reducing the number of
sunspots and the magnetic field strength in them.

It increases the radiation flux from the photosphere due to the decreasing of deficit of bright photosphere’s flux in dark spots. Moreover, the relative amplitudes of the total areas of spots in the cycle’s maximums decrease in the cycles 23+24 compared to the cycle 22, and the ratio of total areas of faculae to total areas of spots in the cycle 24 is growing according to Chapman et al. (2014). This also leads to an increase of the radiation flux from the photosphere.

It is obvious that the detection of this effect is difficult, as the maximum variation of TSI in the cycle of activity is not more than 0.1 - 0.15% of the average value in the cycle.

3 Conclusions

The analysis of relationship of mean monthly observed values $SSN_{obs}$ (NOAA Sunspots Numbers) depending on $SSN_{syn}$ from 1950 to 2015 which were calculated using the coefficients of the polynomial regression between SSN and the radio flux $F_{10.7}$ according to the observations 1950 - 1990, showed that for the monthly averages $SSN_{obs}/SSN_{syn}$ the scatter of the deviations from the regression line is greater than in the case of yearly averages $SSN_{obs}/SSN_{syn}$ from Svalgaard (2013). We also show the cyclical nature of $SSN_{obs}/(F_{10.7} - F_{10.7}^{min})$ dependence. The period of this cycle is equal to half part of 11 yr, see Fig. 3. The deviations from regression lines reach maximum values in the minima of the 11-year cycles, when the relative error of observations of indices of activity increases.

While observations show marked increase in 2013 - 2014 of the numbers of sunspots we received a reduction in the amount $SSN_{obs}/SSN_{syn}$ only 20% (Fig. 2a), and this value is less than 35% of Livingston et al. (2012)and Svalgaard (2013).

As we noted earlier in Bruevich et al. (2014b) the relationships between the indices are much stronger in the moments related to the rising and declining phases of the 11-year cycle and worse in moments of maximums and minimums of the cycle, which is confirmed by Fig. 3.

Our detailed analysis of the variation of TSI fluxes in the cycles 22 - 24 showed that the assumption in Svalgaard (2013) which was done on observational data of Penn and Livingston (2006), (2011) and Chapman et al. (2014) is true: at one and the same level of $F_{10.7}$ the value of TSI at the
cycles 23 - 24 increases, see Fig. 4. This assumption is based on the following effect: when reducing the average number of spots and with reducing of their contrasts the deficit of the overall flux of radiation from the solar photosphere is slightly increased, and with it the TSI grows.

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