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Changed Relation between Solar 10.7-cm Radio Flux and some Activity Indices which describe the Radiation at Different Altitudes of Atmosphere during Cycles 21–23

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Abstract. The correlation coefficients of the linear regression of six solar indices versus 10.7 cm radio flux $F_{10.7}$ were analysed in solar cycles 21, 22 and 23. We also analysed the interconnection between these indices and $F_{10.7}$ with help of approximation by polynomials of second order. The indices we have studied in this paper are: the relative sunspot numbers – SSN, 530.3 nm coronal line flux – F_{530}, the total solar irradiance – TSI, Mg II 280 nm core-to-wing ratio UV-index, the Flare Index – FI and the counts of flares. In most cases the regressions of these solar indices vs. $F_{10.7}$ are close to the linear regression except the moments of time near the minimums and maximums of the 11-year activity. For the linear regressions, we found that correlation coefficients $K_{\text{corr}}(t)$ for the solar indices vs. $F_{10.7}$ and SSN dropped to their minimum values twice during each 11-year cycle.

Key words. Solar cycle: observations—solar activity indices.

1. Introduction

Magnetic activity of the Sun is called the complex of electromagnetic and hydrodynamic processes in the solar atmosphere. The analysis of active regions (plages and spots in the photosphere, flocculae in the chromosphere and prominences in the corona of the Sun) is required to study the magnetic field of the Sun and the physics of magnetic activity. This task is of fundamental importance for astrophysics of the Sun and the stars. Its applied meaning is connected with the influence of solar active processes on the Earth's magnetic field.

We have studied monthly averaged values of six solar activity indices in magnetic activity cycles 21, 22 and 23. Most of these observed data we used in our paper were published in Solar-Geophysical Data Reports 2009 and National Geophysical Data Center, Solar Data Service 2013.

All the indices studied in this paper are very important not only for analysis of solar radiation formed on different altitudes of solar atmosphere, but also for solar-terrestrial relationships as key factors of solar radiation influence (Extreme Ultra

Violet and Ultra Violet EUV/UV solar radiation are the most important) on different layers of terrestrial atmosphere too.

It is well known that various parameters of solar activity correlate quite well with the popular sunspot number index – SSN (or relative sunspot numbers) and with each other over long time scales. Floyd *et al.* (2005) showed that the mutual relationship between sunspot numbers and three solar UV/EUV indices, the $F_{10.7}$ flux and the Mg II core-to-wing ratio 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 and the subsequent relative quietness intermediate called the Gnevyshev gap.

Here we have used the monthly average values for all the indices. Such averages allowed us to take into consideration the fact that the major modulation of solar indexes contains a periodicity of about 27–28 days (corresponding to mean solar rotation period). So we reduced the unwanted influence of the rotational modulation.

Vitinsky *et al.* (1986) have analysed solar cycles 18–20 and pointed out that correlation for relative sunspot numbers vs. radio flux $F_{10.7}$ does not show the close linear connection during all the activity cycle. The importance of statistical study in our understanding of solar activity processes was also emphasized. To achieve the best agreement in approximation of SSN values with the use of 10.7 cm flux data, it (Vitinsky *et al.* 1986) was proposed to approximate the dependence of SSN vs. $F_{10.7}$ by two linear regressions: (1) for the low solar activity (where $F_{10.7}$ is less than 150 sfu) and (2) for the high activity ($F_{10.7}$ is more than 150 sfu). A solar flux unit (sfu) $= 10^{-22} \cdot \mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{Hz}^{-1}$.

In this paper, we found out that the linear correlation was violated not only for maximums of solar activity cycles but for minimums of the cycles also, twice during each 11-year cycle. Our analysis of the interconnection between these indices and the 10.7 cm flux with the help of approximation by polynomials of second order confirmed this fact.

We also analysed the dependencies of time of correlation coefficients of linear regression $K_{\mathrm{corr}}(t)$ which were calculated on the three-year time interval. These $K_{\mathrm{corr}}(t)$ dependencies were calculated for solar activity indices vs. $F_{10.7}$ vs. SSN.

For solar energy coming to the atmosphere of the Earth, it is desirable to have some solar indices and proxies that vary differently through time. This strategy of using multiple solar indices has significantly improved the accuracy of density modeling of the atmosphere of the Earth as reported by Bowman *et al.* (2008). Use of these solar indices in their thermospheric density model produces significant improvements in previous empirical thermospheric density modeling.

2. Global activity indices

We have to say a few words about solar indices studied in this paper.

Figure 1 shows the activity indices which are normalized to their values averaged over the analysed time interval. We can see that the relative variations of solar indices during the solar cycle is about 2–3 times. However, the magnitude of variations of Mg II – index (as well as TSI, not shown in this figure) changes very little – about shares of per cent.

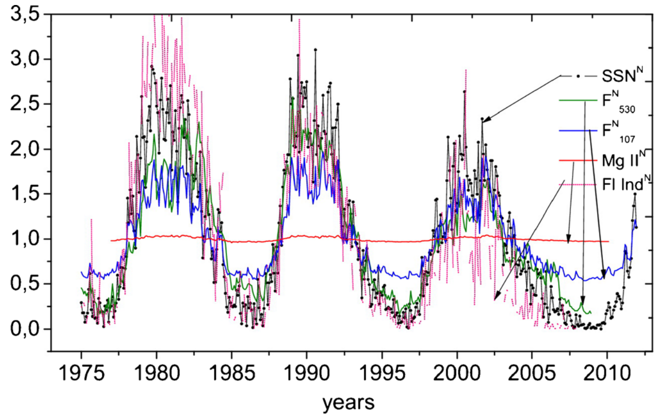

Figure 1. The time series of monthly average values of sunspot numbers SSN, 10.7 cm flux, Mg II core-to-wing ratio, 530.3 nm flux, flare index and counts of flares. The upper index N indicates that solar activity indices are normalized to their values averaged over the analysed time interval.

The sunspot number SSN (also known as the International sunspot number, relative sunspot number or Wolf number) is a quantity that measures the number of sunspots and groups of sunspots present on the surface of the Sun.

The historical sunspot recorded was first put up by Wolf in 1850s and has been continued later in the 20th century until today. Wolf's original definition of the relative sunspot number for a given day is $R = 10 \cdot$ number of groups + number of spots visible on the solar disk that has stood the test of time. The factor of 10 has also turned out to be a good choice as historically a group contained on average ten spots. Almost all solar indices and solar wind quantities show a close relationship with the SSN (Svalgaard *et al.* 2011; Svalgaard & Cliver 2010). Here, we use the proper homogeneity calibrations of SSN from National Geophysical Data Center.

At present, the 10.7-cm solar radio flux $F_{10.7}$ is measured at the Dominion Radio Astrophysical Observatory in Penticton, British Columbia by the Solar Radio Monitoring Programme. $F_{10.7}$ is a useful proxy for the combination of chromospheric, transition region and coronal solar EUV emissions modulated by bright solar active regions whose energies at the Earth are deposited in the thermosphere. Tobiska *et al.* (2008) pointed the high EUV–$F_{10.7}$ correlation and used this in the Earth's atmospheric density models.

According to Tapping & DeTracey (1990), the 10.7-cm emission from the whole solar disc can be separated on the basis of characteristic time-scales into 3 components: (i) transient events associated with flare and similar activity having duration less than an hour; (ii) slow variation in intensity over hours to years, following the evolution of active regions in cyclic solar activity designated as the S-component; (iii) a minimum level below which the intensity never falls – the 'Quiet Sun Level'. An excellent correlation of the S-component at 10.7-cm wavelength with full-disc flux in Ca II and MgII was discussed by Donnelly *et al.* (1983). The 10.7-cm flux resembles the integrated fluxes in UV and EUV well enough to be used as their proxy (Chapman & Neupert 1974; Donnelly *et al.* 1983; Bruevich & Nusinov 1984; Nicolet & Bossy 1985; Lean 1990).

This radio emission comes from the higher part of the chromosphere and lower part of the corona. $F_{10.7}$ radio flux has two different sources: thermal bremsstrahlung (due to electrons radiating when changing direction by being deflected by other charged participles – free–free radiation) and gyro-radiation (due to electrons radiating when changing direction by gyrating around magnetic fields lines). The minimum level component (when SSN is equal to zero as it was at the minimum of the cycle 24 and local magnetic fields are negligible) is defined by the free–free source. When the local magnetic fields become strong enough at the beginning of the rise phase of solar cycle and solar spots appear the gyro-radiation source of $F_{10.7}$ radio flux begins to prevail over the free–free source and the (i) and (ii) components begin to grow stronger.

The S-component comprises the integrated emission from all sources on the solar disc. It contains contribution from free–free and gyroresonance processes, and perhaps some non-thermal emission (Gaizauskas & Tapping 1988). The relative magnitude of these processes is also a function of the observing wavelength. Observations of emission from active regions over the wavelength range 21–2 cm suggest that at 21 cm, free–free emission is dominant, whereas at 6 cm, the contribution from gyroresonance is larger. At a wavelength of 10 cm, the two processes are roughly equal. At a wavelength of 2–3 cm, the emission is again mainly free-free, possible with a non-thermal component (Gaizauskas & Tapping 1988). The spatial distributions of two thermal processes are different; the gyroresonant emission originates chiefly in the vicinity of sunspots, where the magnetic fields are strong enough, while the free–free emission is more widely-distributed over the host region complex (Tapping & DeTracey 1990).

The intensities of the Ca II and Mg II spectral lines are primary functions of chromospheric density and temperature, while the soft X-rays are produced in the corona. The high degree of correlation of the 10.7 cm flux with all these quantities suggests some dependence upon common plasma parameters and that their sources are spatially close. Another strong correspondence is between 10.7 cm flux and full-disc X-ray flux. When activity is high, they are well-correlated; however, when activity is low, the X-rays are too weak to be detected, while some 10.7 cm emission in excess of the 'Quiet Sun Level' is always present (Kruger 1979). Our study of the connection between the 10.7 cm flux and the full-disc X-ray flux (Bruevich & Yakunina 2011) also confirm the conclusions of Kruger (1979).

Thus we have enhanced 10.7 cm radiation when the temperature, density and magnetic fields are enhanced. So $F_{10.7}$ is a good measure of the general solar activity.

The observation of the green and red coronal lines was regularly started from 1960 and the new solar index F_{530} – the averaged intensity of coronal flux at 530.3 nm was introduced. We used NASA data from several observatories and from satellite's instruments. These data were modified to the common uniform system and are available as archive data of the National Geophysical Data Center, Solar Data Service 2013.

The 280-nm Mg II solar spectrum band contains photospheric continuum and chromospheric line emissions. The Mg II h and k lines at 279.56 and 280.27 nm, respectively, are chromospheric in origin while the weakly varying wings or nearby continuum are photospheric in origin. The instruments of the satellites observe both features. The ratio of the Mg II variable core lines to the nearly non-varying wings (cwr) is calculated. The result is mostly a measure of chromospheric solar active region emission that is theoretically independent of instrument sensitivity change through time.

Mg II cwr observations were made at NOAA series operational satellites (NOAA-16-18), which host the Solar Backscatter Ultra Violet (SBUV) spectrometer (Viereck *et al*. 2001, 2004). This instrument can scatter solar Middle Ultra Violet (MUV) radiation near 280 nm. The Mg II observation data were also obtained from ENVISAT instruments. NOAA started in 1978 (during the 21st, 22nd and the first part of the 23rd solar activity cycles), and ENVISAT was launched in 2002 (last part of the 23rd solar activity cycle). Comparison of the NOAA and ENVISAT MgII index observation data shows that both the Mg II indexes agree to within about 0.5% (Viereck *et al*. 2004; Skupin *et al*. 2005). We used both the NOAA and ENVISAT Mg II index observed data.

The Mg II index is especially a good proxy for some Far Ultra-Violet (FUV) and Extreme Ultra-Violet (EUV) emissions (Skupin *et al.* 2005). It well represents photospheric and lower chromospheric solar FUV Schumann-Runge continuum emission near 160 nm that maps into lower thermosphere heating due to O2 photodissociation (Bowman *et al.* 2008). Since a 160 nm solar index is not produced operationally, the Mg II index proxy is used for comparison with other solar indices (Tobiska *et al.* 2008).

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 (EBRS). We use the NGDC TSI data set from combined observational data of several satellites which were collected in NASA archive data (National Geophysical Data Center, Solar Data Service 2013). The importance of UV/EUV influence to TSI variability (active Sun/quiet Sun) was pointed out by Krivova & Solanki (2008). They indicated that up to 63.3% of TSI variability is produced at wavelengths below 400 nm. Towards activity maxima SSN grows dramatically. But on average the Sun brightens about 0.14% during the 11-year activity cycle. This is due to the increase in the amount of bright and dark features: faculae and network elements on the solar surface on one hand and spots on the other hand. The total area of the solar surface covered by such features rises more strongly as the cycle progresses than the area of dark sunspots. The TSI (from ERBS) maxima are fainter than those of the other indices because the solar irradiance variation in solar cycle is approximately equal to 0.14%. This value seems very small but is normal. Some TSI physics-based models have been developed using the combined proxies describing sunspot darkening (sunspot number or areas) and facular brightening (facular areas, Ca II or Mg II indices) (see Fontenla *et al*. 2004; Krivova *et al*. 2003).

We also analysed two activity indices which describe rapid processes on the Sun – Flare Index (FI) and monthly counts of grouped solar flares (count of flares). The term 'grouped' means observations of the same event by different sites lumped together and counted as one (Solar-Geophysical Data Reports 2009).

Kleczek (1952) defined the value $FI = it$ to quantify the daily flare activity over 24 h per day. He assumed that relationship roughly gave the total energy emitted by the flare and named it Flare Index (FI). In this relation i represents the intensity scale of importance of the flare and t the duration of the flare in minutes. In this issue we also used the monthly averaged FI values from National Geophysical Data Center, Solar Data Service 2013.

So it should be noted that the data used in our article are not absolutely homogeneous because of observations made using different equipments at different satellites and observatories. But all data sets have been adjusted and reduced to a common base (National Geophysical Data Center, Solar Data Service 2013) as a result of comparisons and more accurate definitions of absolute calibration of equipments at different observatories and satellites. So the mistakes are relatively small. We neglected these mistakes because we study the behavior of solar indexes during cycles of activity as a whole. Thus we analyse the general trend in their relationships.

3. Recent changes in the Sun

Recent solar cycle 23 was the outstanding cycle for authentic observed data from the year 1849. It lasted 12.7 years and was the longest one for two hundred years of direct solar observations. This cycle is the second component in the 22-year Hale magnetic activity cycle but the 23rd cycle was the first case of modern direct observations (from 1849 to 2008) when Gnevyshev-Ol's rule was violated: activity indices in cycle 23 had their maximum values less then the values in cycle 22 (but according to Gnevyshev-Ol's rule, cycle 23 must dominate).

Ishkov (2009) pointed that in this unusual cycle 23 the monthly average values for SSN during 8 months exceeded 113 and most of the sunspot groups were smaller in size, their magnetic fields were less composite and characterized by the greater lifetime near the second maximum in comparison with values near the first maximum. SSN reaches its first maximum 3.9 years after the beginning. After the first maximum, the index decreases by 14% (of that maximum). The two maxima of this index have the same amplitude.

Nagovitsyn *et al.* (2012) showed that for sunspot numbers SSN we see the opposite long-scale trends (which influence to increase or decrease SSN) during the last several solar cycles. In Nagovitsyn *et al.* (2012), it was analysed the data set of SSN from Penn & Livingston (2006) and Pevtsov *et al.* (2011) shown during cycle 23 and the beginning of cycle 24 that the number of large sunspots gradually decreased, while the number of small sunspots steadily increased. It was suggested that this change in the fraction of small and large sunspots (perhaps, due to changes in the solar dynamo) can explain the gradual decline in average sunspot field strength as observed by Penn & Livingston (2006).

In cycle 23, the 10.7-cm radio flux and the TSI have the lowest values from 2007 to 2009 (the beginning of cycle 24) all over the indices observation period. The $F_{10.7}$ radio flux index shows the second maximum is 8.4% stronger than the first one.

It is well-known that all solar indices have been closely correlated as they all derive from the same source: the variable magnetic field. But while there has long been a stable relationship between the 10.7-cm flux and SSN, this relationship has steadily deteriorated in the past decade to the point where the sunspot number for a given flux has decreased by about a third.

Observations by Livingston since 1998 until the present showed that the average magnetic field in sunspots has steadily decreased by 25% (Livingston *et al.* 2012).

Svalgaard *et al.* (2011) noted that decreasing of the average magnetic field in sunspots means that sunspots are getting warmer and that their contrast with the surrounding photosphere is getting smaller, making the spots harder to see. It was also noted that without the dark spots, the TSI might even grow slightly.

We can see that the relation TSI/$F_{10.7}$ is a little larger for cycle 23 compared to the previous cycle 22 (see Fig. 2c). It is not exactly clear what this will mean for the impact of solar activity on the Earth's environment.

In cycle 23, the flare index has a higher first maximum. This shows that the flares can be more efficiently generated during the first maximum, and it seems that the generation is decreasing towards the end of the cycle.

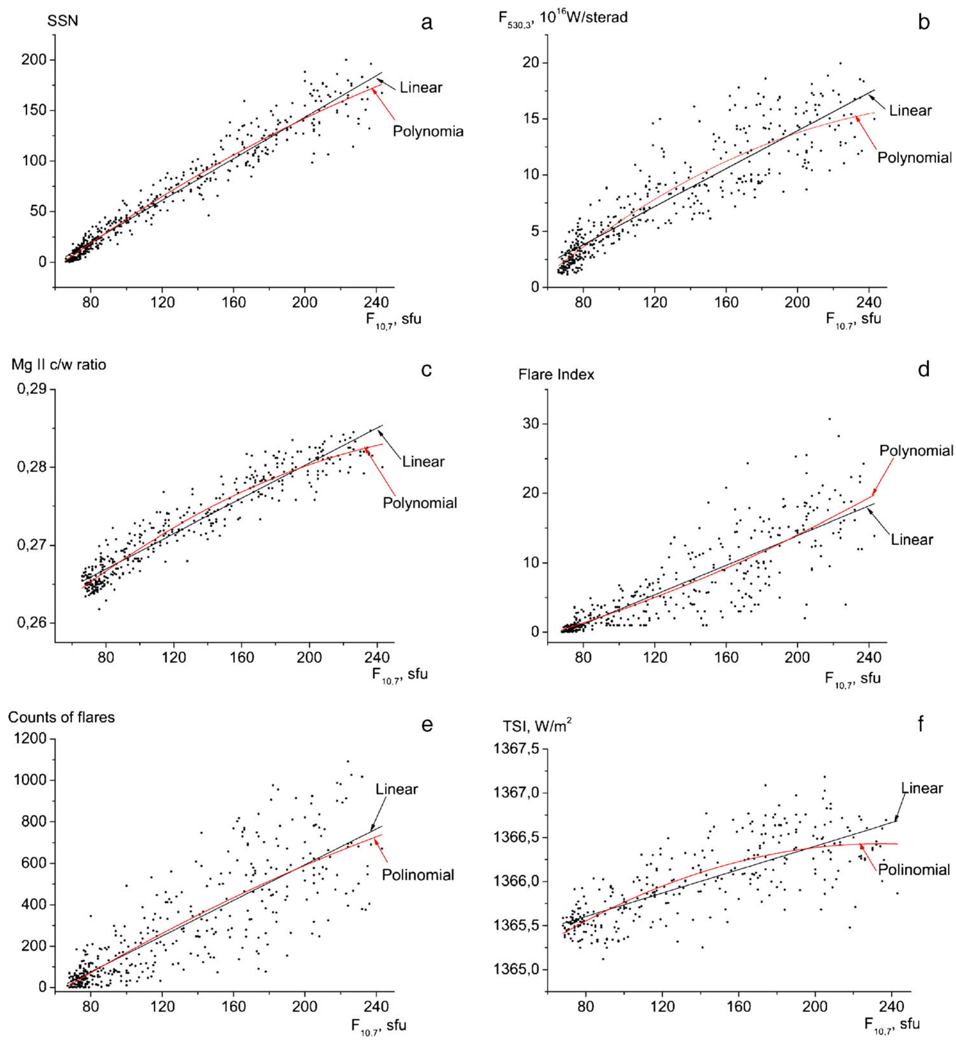

Figure 2. Correlation between monthly averages of solar indices vs. $F_{10.7}$ in cycles 21–23 (1975–2008). (**a**) SSN, (**b**) F_{530}, (**c**) Mg II core-to-wing ratio, (**d**) flare index, (**e**) counts of flares and (**f**) TSI.

Figure 1 demonstrates that for all activity indices in the 23rd solar activity cycle we can see two maximums separated one from another on 1.5-year approximately. We see a similar double-peak structure in cycle 22 but for cycle 21 the double-peak structure is not evident. We see that there are displacements in both maximum occurrence time of all these indices in the 23rd solar cycle.

Figure 1 also shows that for all solar indices in cycle 23 the relative depth of the cavity between two maximums is about 10–15%.

Ishkov (2009) pointed that there was very high level of flaring activity in cycle 21 and very low level of flaring activity in cycle 23. We also confirm this fact (see Fig. 3d) that the flaring activity (counts of flares index) in the 23rd cycle is almost twice weaker in comparison to the 21st cycle.

Janardhan *et al.* (2010) have examined polar magnetic fields for the last three solar cycles 21, 22 and 23 using NSO Kitt Peak synoptic magnetograms and showed a large and unusual drop in the absolute value of the polar fields during cycle 23 as compared to previous two cycles and also its association with similar behavior in meridional flow speed.

An important result was obtained by Janardhan *et al.* (2011). It has been shown here that rms electron density fluctuations in the solar wind according to 1983–2009 measurements of Interplanetary Scintillation (IPS) have been reducing in sync with the declining polar fields. The decline in both cases i.e. polar fields and rms electron density fluctuations started around the same time in the mid 1990's. It has

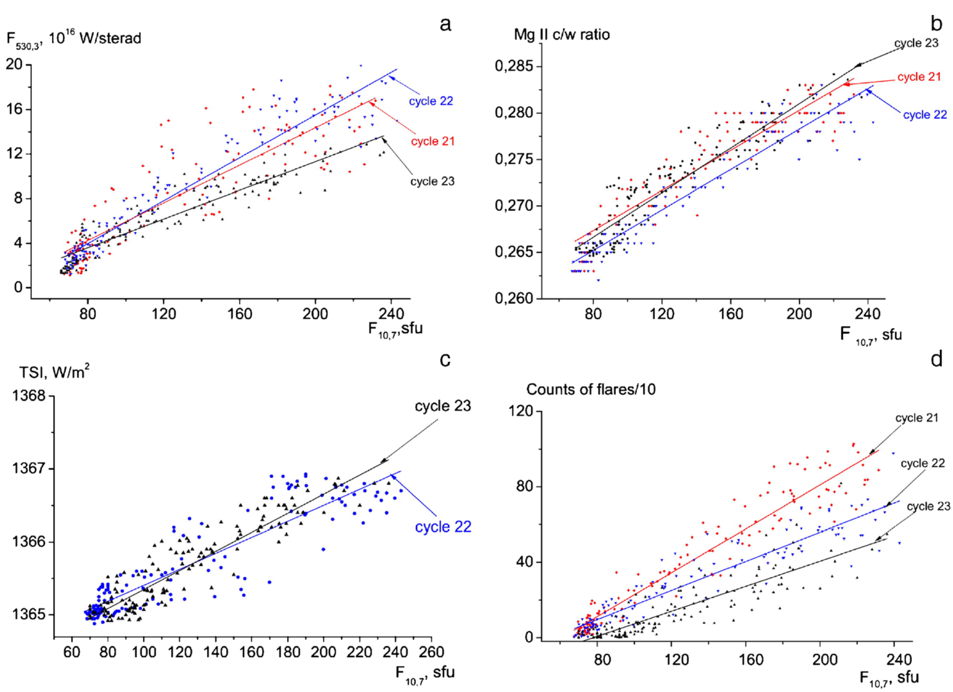

Figure 3. Correlation between monthly averages for solar indices vs. 10.7-cm flux. Individually studied for cycles 21, 22 and 23. (**a**) F_{530}, (**b**) Mg II core-to-wing ratio, (**c**) TSI and (**d**) counts of flares/10.

been assumed that this large-scale IPS signature, in the inner heliosphere coupled with the fact that solar polar fields have also been declining since mid 1990's was the result of changes in the solar dynamo around the mid-1990's that triggered the unusual and deep solar minimum at the end of cycle 23. Thus it can be argued that the deepest minimum at the end of cycle 23 actually begun more than a decade earlier.

4. Changed relation between $F_{10.7}$ and solar activity indices in cycles 21–23

Figure 3(a)–(d) illustrates the high level of interconnection between solar activity indices vs. $F_{10.7}$. We see that coefficients of linear regression (slope – A and intercept – B) differ among themselves for the activity cycles 21–23. The most differences show the counts of flares index.

We studied solar activity indices in cycles 21, 22 and 23 and separated out rise phases, cycle's maximum phase, cycle's minimum phase and declining phase. In case of linear regression we have found that the maximum values of correlation coefficients K_{corr} reached for the rise and decline phases of the cycles. According to our calculations the highest values of correlation coefficients K_{corr} we see is in connection between SSN and $F_{10.7}$. Correlation coefficients K_{corr} of the linear regression for the TSI vs. $F_{10.7}$ are the minimal of all correlation coefficients determined here.

The cyclic variation of fluxes in different spectral ranges and lines at the 11-year time scale are a widely spread phenomenon for F, G and K stars (not only for the Sun) (see Bruevich & Kononovich 2011). The chromospheric activity indices (radiative fluxes at the centres of the H and K emission lines of Ca II – 396.8 and 393.4 nm respectively) for solar-type stars were studied during HK-project by Baliunas *et al.* (1995) at Mount Wilson Observational Program for 45 years, from 1965 to the present time. The authors of the HK-project supposed that all the solar-type stars with well determined cyclic activity of about 25% of the time remain in the Maunder minimum conditions. Some scientists proposed that the solar activity in cycle 24 will be very low and similar to activity during the Maunder minimum period. We can see now that although the new cycle of activity is not characterized by very high SSN values, however, the activity in cycle 24 is significantly higher than in the Maunder minimum period.

In Fig. 2 we have presented the interconnection between solar indices and radio flux $F_{10.7}$ in cycles 21–23. We analysed the interconnection between $F_{10.7}$ and six activity indexes – SSN, F_{530}, Mg II cwr, flare index, counts of flares and TSI, using the data of observations for the 21st, 22nd and 23th solar cycles. We have studied both the linear and polynomial dependencies.

The linear model corresponds to the linear regression equation:

$$F_{\text{ind}} = A_{\text{ind}} + B_{\text{ind}} \cdot F_{10.7}\,, \tag{1}$$

where F_{ind} is the activity index flux, A_{ind} is the intercept of a linear regression and B_{ind} is the slope of a linear regression.

In Table 1, we present the coefficients of the linear regressions and their standard errors σ of intercept and slope values.

Table 1. Solar activity indices vs. $F_{10.7}$. Coefficients of linear regressions: A, B and their standard errors. Observational data 1975–2010.

Activity indices vs. $F_{10.7}$	A_{ind}	B_{ind}	Err. (σ_A)	Err. (σ_B)
SSN	−62.28	1.03	1.57	0.011
F_{530}	−2.93	0.084	0.27	0.002
Mg II cwr	0.258	$1.3 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$	$1.8 \cdot 10^{-7}$
Flare index	−7.37	0.106	0.51	0.0036
Counts fl/10	−269.03	4.31	20.14	0.146
TSI	1365.07	0.0066	0.044	$3 \cdot 10^{-4}$

The polynomial model corresponds to the following equation of a second order polynomial:

$$F_{\text{ind}} = A_{\text{ind}} + B1_{\text{ind}} \cdot F_{10.7} + B2_{\text{ind}} \cdot F_{10.7}^2 , \tag{2}$$

where F_{ind} is the activity index flux, A_{ind} is the intercept of a polynomial regression, and $B1_{\text{ind}}$ and $B2_{\text{ind}}$ are the coefficients of a polynomial regression.

In Table 2, we present the coefficients of polynomial regressions: A, $B1$, $B2$ and their standard errors σ of intercept and slope values.

We have to point out that close interconnection between radiation fluxes characterized the energy release from different atmospheric layers which is the widespread phenomenon among the stars of late-type spectral classes. Bruevich & Alekseev (2007) confirmed that there exists close interconnection between photospheric and coronal fluxes variations for solar-type stars of F, G, K and M spectral classes with widely varying activity of their atmospheres. It was shown that the summary areas of spots and values of X-ray fluxes increase gradually from the Sun and HK-project stars with low spotted discs to highly spotted K and M-stars for which Alekseev & Gershberg (1996) constructed the zonal model of the spots distributed at the star's disks.

5. Time variations of correlation coefficient $K_{\text{corr}}(t)$ for linear regression of solar activity indices vs. $F_{10.7}$ and vs. SSN

We have calculated values $K_{\text{corr}}(t)$ of linear regression for solar activity indices vs. $F_{10.7}$ for cycles 21, 22 and 23. The values $K_{\text{corr}}(t)$ were determined for each moment

Table 2. Solar activity indices vs. $F_{10.7}$. Coefficients of polynomial regressions: A, $B1$, $B2$ and their standard errors. Observational data 1975–2010.

Activity indices vs. $F_{10.7}$	A	$B1$	$B2$	Err. (σ_A)	Err. (σ_{B1})	Err. (σ_{B2})
SSN	−87.26	1.45	−0.0015	4.86	0.078	$3 \cdot 10^{-4}$
F_{530}	−7.38	0.158	$-2,6 \cdot 10^{-4}$	0.84	0.013	$4.8 \cdot 10^{-5}$
Mg II cwr	0.25	$2 \cdot 10^{-4}$	$-3 \cdot 10^{-7}$	$7 \cdot 10^{-4}$	$1 \cdot 10^{-5}$	$4 \cdot 10^{-8}$
Flare Index	−4.36	0.057	$1.7 \cdot 10^{-4}$	1.58	0.024	$7 \cdot 10^{-5}$
Counts fl/10	−361.4	5.83	−0.005	64.01	1.01	0.0035
TSI	1364.4	0.017	$-3,7 \cdot 10^{-5}$	0.13	0.002	$7 \cdot 10^{-7}$

of time *t* from $K_{\text{corr}}(t)$ calculation during the 3-year time interval $t - 1.5$ yr $< \Delta T <$ $t + 1.5$ yr.

Figure 4(a)–(d) demonstrates the results of our correlation calculations of these solar activity indices vs. $F_{10.7}$ and vs. SSN – $K_{\text{corr}}(t)$ variations during cycles 21–23. We can see that all the $K_{\text{corr}}(t)$ values have maximum amounts at the rise and at the decline phases of 11-year cycles. We see the minimum values of $K_{\text{corr}}(t)$ at the minimum and the maximum phases of 11-year cycles.

We can see that the minimum values of correlation coefficients $K_{\text{corr}}(t)$ for solar indices vs. $F_{10.7}$ and SSN occurred twice during the 11-year cycle. We assumed that this fact must be considered for the understanding of solar indices interconnections and for successful forecasts of different activity indices using $F_{10.7}$ or SSN observations.

Note that the linear correlation (see Fig. 4) of activity indices F_{530}, MgII index, flare index and TSI vs. $F_{10.7}$ is a little stronger than the linear correlation of these indices vs. SSN. We assumed that it is a logical result: these indices (as well as $F_{10.7}$) characterize the solar irradiance proceeded from different altitudes of the solar atmosphere. But SSN and counts of flares are not connected directly with solar irradiance at different wavelengths or spectral intervals. So the linear correlation of counts of flares (see Fig. 4) has no difference vs. $F_{10.7}$ or vs. SSN because the counts of flares index describes the fast flaring processes (not irradiance) on the Sun while SSN is the relatively subjective measure of the total level of solar activity.

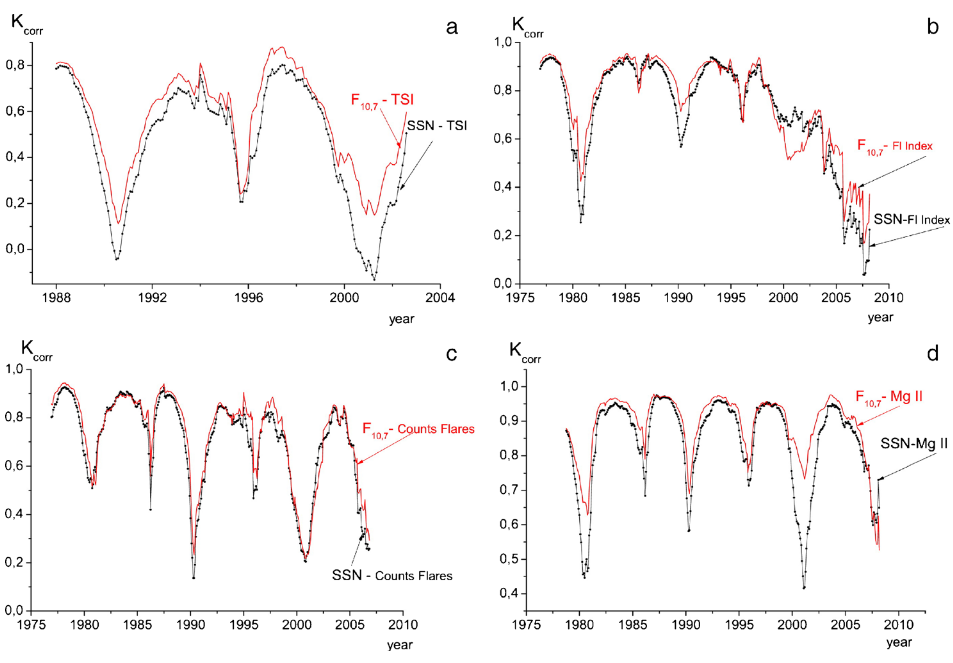

Figure 4. Correlation coefficients of linear regression $K_{\text{corr}}(t)$ for (**a**) TSI, (**b**) flare index, (**c**) counts of flares and (**d**) Mg II UV-index vs. SSN and vs. $F_{10.7}$. $K_{\text{corr}}(t)$ was calculated during the three-year interval. Observational data (1975–2010).

The cyclic behavior of K_{corr} can be explained by the following assumption: we imagine that some activity index flux depends on time t by the expression:

$$F_{\mathrm{ind}}(t) = F_{\mathrm{ind}}^{\mathrm{background}}(t) + \Delta F_{\mathrm{ind}}^{\mathrm{AR}}(t), \tag{3}$$

where $F_{\mathrm{ind}}^{\mathrm{background}}(t)$ is the background flux which continuously rises with increasing solar activity. Background flux consists of two components – (1) slow variation in intensity over hours to years, following the evolution of active regions in cyclic solar activity and (2) a minimum level below which the intensity never falls – the 'Quiet Sun Level'. In case of the radio flux $F_{10,7}$, the component (1) is (ii), the component (2) is (iii) respectively. It can be note that all indices have the 'Quiet Sun Level' different from zero except SSN, which at the minimum of the cycle has the 'Quiet Sun Level' value equal to zero. $\Delta F_{\mathrm{ind}}^{\mathrm{AR}}(t)$ is the additional flux to the overall flux from the active regions.

The previous correlation study allows us to consider that $F_{\mathrm{ind}}^{\mathrm{background}}(t)$ and $\Delta F_{\mathrm{ind}}^{\mathrm{AR}}(t)$ are the linear functions of the background and activity regions levels of the solar activity. In our case, we choose the radio flux $F_{10,7}$ as the best basal indicator of solar activity levels:

$$F_{\mathrm{ind}}^{\mathrm{background}}(t) = a_1 + b_1 \cdot F_{10.7}^{\mathrm{background}}(t), \tag{4}$$

$$\Delta F_{\mathrm{ind}}^{\mathrm{AR}}(t) = a_2 + b_2 \cdot \Delta F_{10.7}^{\mathrm{AR}}(t). \tag{5}$$

The coefficients a_1 and b_1 vary from a_2 and b_2 in different powers for different activity indices. For SSN this difference is small, but for counts of flares index the difference between a_1, b_1 and a_2, b_2 is more significant than for SSN.

During the rise and decline cycle's phases the dependence of $F_{\mathrm{ind}}(t)$ vs. $F_{10.7}(t)$ is approximately linear and relative addition flux from active regions $\Delta F_{\mathrm{ind}}^{\mathrm{AR}}(t)$ is neglected with respect to $F_{\mathrm{ind}}^{\mathrm{background}}(t)$. So additional flux from active regions cannot destroy a balance in the correlation close to linear between $F_{\mathrm{ind}}(t)$ and $F_{10.7}(t)$. And we see that respective values of $K_{\mathrm{corr}}(t)$ reach their maximum values all over the cycle.

During the minimum of activity cycle both values $F_{\mathrm{ind}}^{\mathrm{background}}(t)$ and $\Delta F_{\mathrm{ind}}^{\mathrm{AR}}(t)$ are small, but additional flux from active regions is not neglected in relation to background flux that has minimum values during all over the cycle.

During the maximum of activity cycle, $\Delta F_{\mathrm{ind}}^{\mathrm{AR}}(t)$ often exceeds $F_{\mathrm{ind}}^{\mathrm{background}}(t)$ and so disbalance in linear regression between activity indices increases and values of $K_{\mathrm{corr}}(t)$ also reach their minimum values during all over the cycle too.

6. Conclusions

Currently, scientists are very interested in imitation processes in the Earth's ionosphere and upper atmosphere. It is well-known that the solar radiance at 30.4 nm is very significant for determination of the Earth's high thermosphere levels heating. Lukyanova & Mursula (2011) showed that for solar 30.4-nm radiance fluxes forecasts (very important for Earth thermosphere's heating predictions) Mg II 280 nm observed data was more preferable.

Although $F_{10.7}$ does not actually interact with the Earth's atmosphere, $F_{10.7}$ is a useful proxy for the combination of chromospheric, transition region and coronal solar EUV emissions modulated by bright solar active regions whose energies at the Earth are deposited in the thermosphere (Tobiska *et al.* 2008). $F_{10.7}$ dependence on few processes, combined with it localized formation in the cool corona, i.e. region that is closely coupled with magnetic structures responsible for creating the XUV-EUV irradiances, make this a good generalized solar proxy for thermospheric heating. Tobiska *et al.* (2008) proved the efficiency of the simultaneous use of multiple indexes of solar and geomagnetic activity. There was presented the improved thermospheric density model, where four solar and two geomagnetic indices were used. Solar indices are $F_{10.7}$, 26–34 nm EUV emission, Mg II *cwr* and X-rays in the 0.1–0.8 nm. The geomagnetic indices are 'ap' index (amplitude of planetary geomagnetic activity – which is derived from geomagnetic field measurements made at several locations around the world) and 'Dst' index (Disturbance storm time – as indicator of the storm-time ring current in the inner magnetosphere). We also point out the importance of simultaneous study of solar indices in the cycle of activity for the successful modelling of processes in the solar-terrestrial physics.

In this paper we found out the cyclic behavior of correlation coefficients $K_{\rm corr}(t)$ of linear regression (calculated on the three-year time interval) for the TSI, flare index, Mg II 280 nm index and counts of flares vs. $F_{10.7}$ and SSN during solar activity cycles 21, 22 and 23 (see Fig. 4). We showed that $K_{\rm corr}(t)$ have the maximum values at the rise and decline phases – the linear interconnection between indices is more strong in these cases. It means that the forecasts of solar indices, based on 10.7-cm observations will be more successful during the rise and decline of cycle's phases. We showed that the linear correlation of activity indices F_{530}, Mg II index, flare index and TSI vs. $F_{10.7}$ is stronger than the linear correlation of these indices vs. SSN but the linear correlation of counts of flares has no difference versus $F_{10.7}$ or vs. SSN. This may be due, in particular, that all indices have the 'Quiet Sun Level' which is different from zero except SSN which has the minimum value equal to zero.

We have also showed that values of correlation coefficients $K_{\rm corr}(t)$ of linear regressions for the solar indices vs. $F_{10.7}$ and SSN which were calculated during three-year interval have two minimums during the 11-year cycle.

Our study of linear regression between solar indices and $F_{10.7}$ confirms the fact that at minimum and at maximum cycle's phases the nonlinear state of interconnection between solar activity indices (characterized the energy release from different layers of solar atmosphere) increases.

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