Correlation study of six solar activity indices in the 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 F10.7 were analyzed in solar cycles 21, 22 and 23. We also analyzed the interconnection between these indices and F10.7 with the help of second order polynomials approximation. The indices we've studied in this paper are: relative sunspot numbers - SSN, 530.3 nm coronal line flux – F530, the total solar irradiance - TSI, Mg II 280 nm core-to-wing ratio UV-index, Flare Index – FI, and Counts of flares. In most cases the regressions of these solar indices versus F10.7 are close to the linear regression except near the minima and maxima of the 11-year solar activity cycles. For the linear regressions we found that the minimum values of correlation coefficients K_{corr} (t) for the solar indices versus F10.7 and SSN occur twice during the 11-year cycle.

Keywords: Solar cycle: observations, solar activity indices;

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 importance is connected with the influence of solar active processes on the Earth's magnetic field. We have studied monthly averaged values of six global solar activity indices in sunspot cycles 21, 22 and 23. Most of the observational data we use 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 the analysis of solar radiation formed at different altitudes in the solar atmosphere, but for solar-terrestrial relations as the key factors of the solar radiation influence (Extreme Ultra Violet and Ultra Violet EUV/UV)solar radiation is the most important) on the different layers of terrestrial atmosphere also. It's known that the various parameters of solar activity correlate quite well with the popular sunspot number index - SSN (or relative sunspot number) and with each other over long time scales. (Floyd al. 2005) showed the mutual relation between sunspot numbers and three solar UV/EUV indices, the $F_{10.7}$ flux and the Mg II core-to-wing ratio. At the end of 2001 these mutual relations dramatically changed due to a large enhancement in solar activity which took place after the actual sunspot maximum of cycle 23 and the intermediate subsequent relative quietness called the Gnevyshev gap. In our study we used the monthly averages values of all indices. Such averages allow us to take into consideration the fact that the major modulation of solar indices contains a periodicity of about 27-28 days (corresponding to the mean solar rotation period). So we reduced the influence of the rotational modulation of the data sets. Vitinsky et al. (1986) analyzed solar cycles 18 - 20 and pointed out that the correlation of the relative sunspot numbers versus radio flux $F_{10.7}$ is not linear during all the activity cycle. Also the importance of statistical studies was emphasized for our understanding of solar activity processes. To achieve the best agreement in the approximation of spot numbers by $F_{10.7}$ observations Vitinsky et al. (1986) proposed to approximate the dependence SSN - $F_{10.7}$ by two linear regressions: the first one - for the low solar activity ($F_{10.7}$ less than 150 *sfu*) and the second one - for the high activity ($F_{10.7}$ more than 150 *sfu*). The solar flux unit (*sfu*) = 10^{-22} W m^{-2} Hz^{-1}. In this paper we found out that the linear correlation was violated not only for maxima of solar activity cycles but for minima of the cycles too. Our analysis of the interconnection between these indices and $F_{10.7}$ with the help of second order polynomials approximation confirmed this fact. We also analyzed the dependence on time of three-year determined correlation coefficients K_{corr} (t) (in linear regression assumption) for solar activity indices versus $F_{10.7}$ and versus SSN. Since the nature of solar activity is very complex, we have to keep in mind that there are different sources which contributie to the values of the indices studied in this paper. For solar energy coming to the atmosphere of the Earth, it is desirable to have solar indices and proxies that vary differently in 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.

Global activity indices

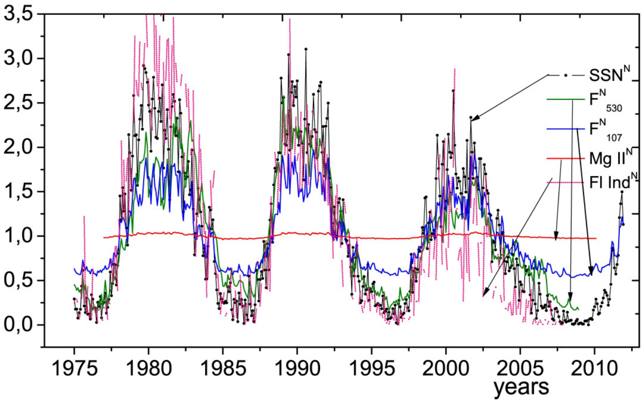

Figure 1: Time series of monthly averaged values of sunspot numbers SSN, F10.7, Mg II core-to-wing ratio, F530, Flare Index and Counts of flares. The upper index N indicates that solar activity indices are normalized to their values averaged over the analyzed time interval.

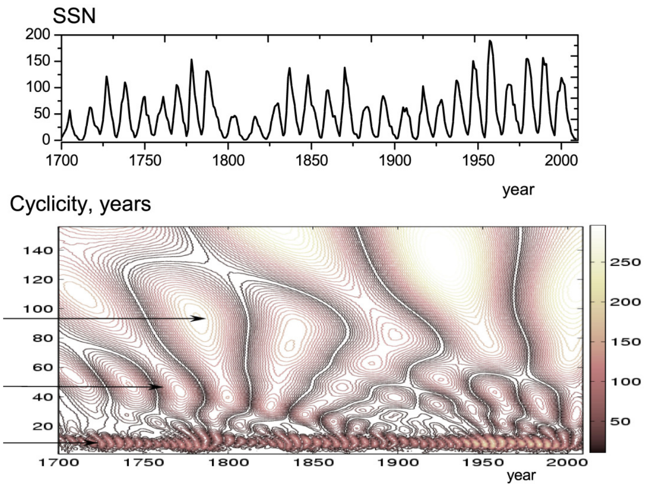

Figure 2: Time series of the annual averaged values of sunspot numbers SSN from 1700 for 2009, and its wavelet image (for wavelet transform calculations we used the Morley mother wavelet).

In Figure 1 we show the activity indices which are normalized to their values averaged over the analyzed time interval. We can see that in most cases the relative variation of an index in a solar cycle is about a factor of 2-3. However, the magnitude of Mg II - index (as well as TSI, not shown in this figure) changes very little - about shares of percent.

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 record was first compiled 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 as R = 10* Number of Groups + Number of Individual Spots visible on the solar disk has stood the test of time. The factor of 10 has also turned out to be a good choice as historically a group contains on average ten spots. Almost all solar indices and solar wind quantities show a close relationship with the SSN, see (Svalgaard et al., 2011; Svalgaard and Cliver, 2010). In our paper we use the proper homogeneity calibrations of SSN from National Geophysical Data Center. Solar Data Service (2013).

The relative sunspot number SSN is a very popular, widely used solar activity index: the series of SSN observations continue more than two hundred years. At Figure 2 we illustrated with the help of wavelet - analysis the fact that the long time series of observations give us very useful information for study of the problem of solar flux cyclicity on long time scales. The result of wavelet – analysis (Morley wavelet) of series of observations of average annual SSN is presented in the form of many of isolines on which the values of the wavelet-coefficients are the same. The maximum value of isolines specifies the maximum value of the wavelet-coefficients, which corresponds to the most likely value of the period of the cycle. We see there three well-defined cycles of activity: the main cycle of activity (approximately equal to 10 - 11 years), 40-50- year cyclicity and 100 to 120-year (ancient) cyclicity.

At present the 10.7- cm solar radio flux is measured by the Solar Radio Monitoring Programme at the Dominion Radio Astrophysical observatory in Penticton, British Columbia. $F_{10.7}$ 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 out the high EUV - $F_{10.7}$ correlation and used this in the Earth's atmospheric density models.

According to Tapping and 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 the cyclic solar activity designated as S-component; (iii) a minimum level below which the intensity never falls - the "Quiet Sun Level". The excellent correlation of S-component at 10.7 cm wavelength with the full-disc flux in Ca II and Mg II 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 and Neupert, 1974; Donnelly et al., 1983; Nicolet and Bossy, 1985; Lean, 1990). This radio emission comes from the upper part of the chromosphere and the 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 (iii) (when SSN is equal to zero as it was in the minimum of cycle 24 and the 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 the solar cycle and sunspots appear, the gyro-radiation source of $F_{10.7}$ radio flux begins to prevail over the free-free one so (i) and (ii) components begin to grow strongly. 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 and Tapping (1988). The relative magnitude of these processes is also a function of observing wavelength. Observations of emissions from active regions over the wavelength range 21-2 cm suggest that at 21 cm, the 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 in importance. At a wavelength of 2-3 cm, the emission is again mainly free-free, possibly with a non-thermal component Gaizauskas and Tapping (1988). The spatial distributions of the two thermal processes are different; the gyroresonant emission originates mainly 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 and 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 the activity is high, they are well-correlated; however, when the 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 10.7 cm flux and full-disc X-ray flux Bruevich and Yakunina (2011) also confirms 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 green and red coronal lines observations were regularly started since 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-borne instruments. These data were modified to the common uniform system and are available as archive data of 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. Instruments of the satellites observe both features. The ratio of the Mg II variable core lines to the nearly non-varying wings is calculated. The result is mostly a measure of the chromospheric solar active region emission that is theoretically independent of instrument sensitivity change through the lifetime of the instrument.

Mg II core-to wing ratio (*crw*) observations were made by NOAA series operational satellites (NOAA-16-18), which host the Solar Backscatter Ultra Violet (SBUV) spectrometer Viereck et al. (2001). This instrument can scatter solar Middle Ultra Violet (MUV) radiation near 280 nm. The Mg II observation data were also obtained by ENVISAT instruments. NOAA started in 1978 (during the 21st, 22nd and the first part of the 23rd solar activity cycles), ENVISAT was launched in 2002 (last part of the 23rd solar activity cycle). Comparison of the NOAA and ENVISAT Mg II index observation data shows that the two Mg II indices agree to within about 0.5% (Viereck et al. 2004; Skupin et al., 2005). We used both the NOAA and ENVISAT observational data of the Mg II index. The Mg II index is an especially 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 lover 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 the other solar indices Tobiska et al. (2008).

The spectral 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 Total Solar Irradiance (TSI) previously known as the solar constant. Regular monitoring of TSI has been carried out since 1978.

We use the NGDC TSI data set from combined observational data of several satellites which were collected in the NASA archive data National Geophysical Data Center, Solar Data Service (2013). The importance of the UV/EUV influence to the TSI variability (Active Sun/Quiet Sun) was pointed out by Krivova and Solanki (2008). There 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 0.1% only. This is due to the increase of amounts of bright and dark features: faculae and network elements on the solar surface on the 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 Earth Radiation Budget Satellite) maxima are fainter than those of the other indices because the solar irradiance variation in the 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 analyzed two activity indices which describe rapid processes on the Sun - Flare Index (FI) and monthly Counts of grouped solar flares (Count of flares). According to the Solar-Geophysical Data Reports (2009), the term 'grouped' means observations of the same event by different sites were lumped together and counted as one.

Kleczek (1952) defined the value FI = *it* to quantify the daily flare activity over 24 hours per day. He assumed that the relationship roughly gave the total energy emitted by the flare and named it flare index (FI). In this relation the value *i* represents the intensity scale of importance of the flare and *t* the duration of the flare in minutes. Here we also used the monthly averaged FI values.

So it should be noted that the data used in our article are not uniform enough but we neglect this. We study the behavior of solar indexes during the activity cycles as a whole. Thus we analyze the general trend in their relationships.

Recent changes in the Sun

The recent solar cycle 23 was an outstanding cycle in authentic observed data since 1849 year. It lasted 12.7 years and was the longest one in two hundred years of direct solar observations. Cycle 23 was the second component of the 22-year Hale magnetic activity cycle but was the first case in modern direct observations (from 1849 to 2008) when the Gnevyshev-Ohl's rule was violated: activity indices in cycle 23 had their maximum values less than the values in the cycle 22 (while according to Gnevyshev-Ohl's rule cycle 23 should have dominated), see Figure 2. Ishkov (2009) pointed that in this unusual cycle 23, the monthly average SSN values exceeded 113 during 8 months and most of the sunspot groups were less in size, their magnetic fields were less composite and characterized by a longer lifetime near the second maximum in comparison with values near the first maximum. SSN reaches its first maximum 3.9 years after the beginning of the cycle. After the first maximum, the index decreased by 14% (of that maximum). The two maxima of this index had the same amplitude.

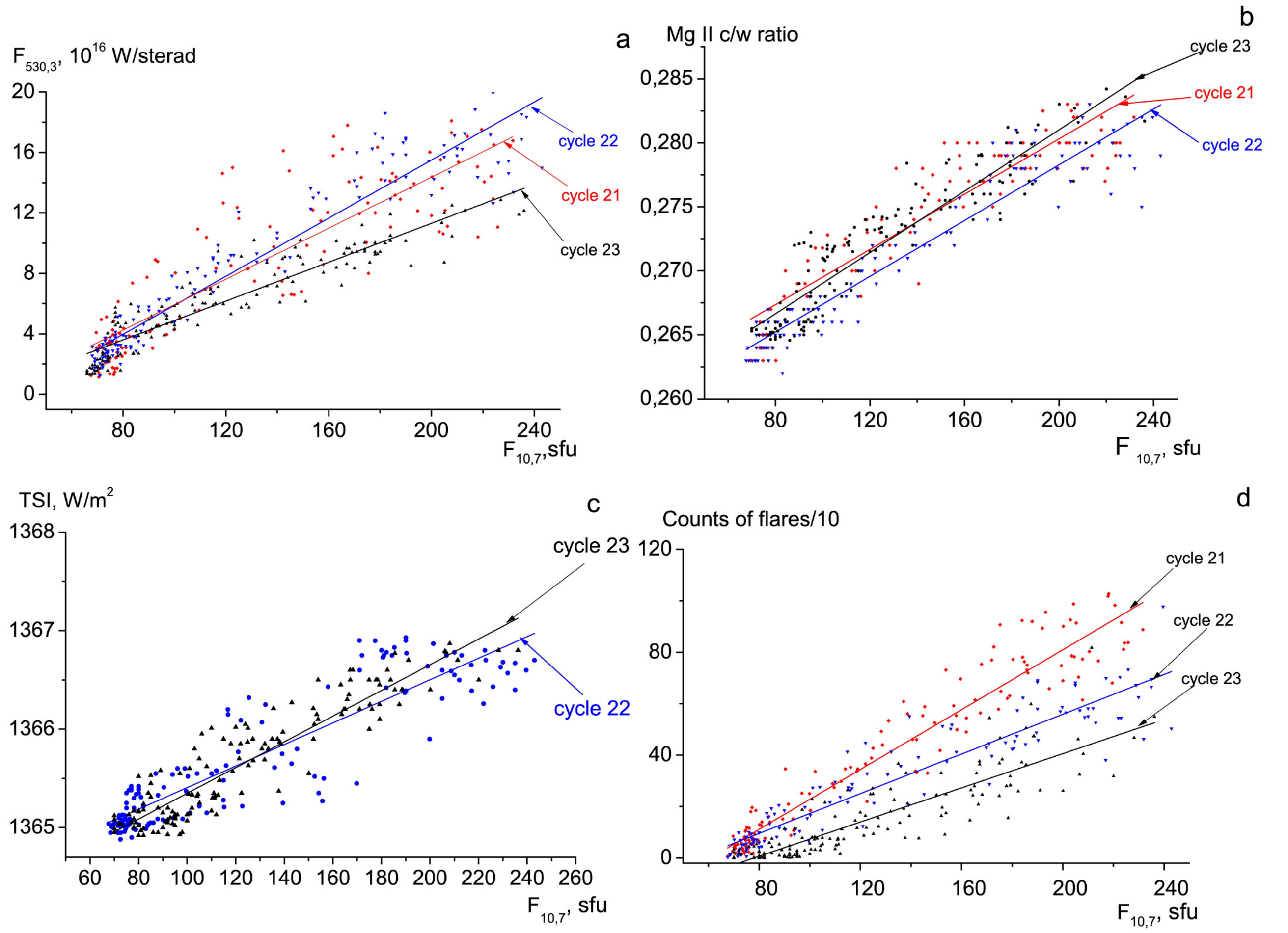

Figure 3: Correlation between monthly averages for solar indices versus $F_{10.7}$ individually determined for the cycles 21, 22 and 23. (a) F_{530}, (b) Mg II core-to-wing ratio, (c) TSI and (d) Counts of flares/10.

Nagovitsyn et al. (2012) analyzed the data set of SSN from (Penn and Livingston, 2006; Pevtsov et al., 2011) and showed that during cycle 23 and the beginning of cycle 24, 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 and Livingston (2006).

From 2007 to 2009 the $F_{10.7}$ radio flux and the TSI have the lowest values over all of these indices observation period. The $F_{10.7}$ radio flux index shows the second maximum is 8.4% stronger than the first one.

It is known that all solar indices have been closely correlated as they all derive from the same source: the variable solar 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 et al. (2012) show that the average magnetic field in sunspots has steadily decreased by 25% since1998. Since their magnetic fields cool sunspots, a decreasing field means that sunspots are getting warmer and that their contrast with the surrounding photosphere is getting smaller, making the spots harder to see. Without the dark spots, TSI might even be a bit higher, see Svalgaard et al. (2011). We can see that the relation TSI/ $F_{10.7}$ is a little lager for cycle 23 (Figure 3c) compared to the previous cycle 22. It is not clear what this will mean for the impact of solar activity on the Earth's environment. 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 compared to previous cycles and also its association with similar behavior in meridional flow speed.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 1 demonstrates that for all activity indices in solar cycle 25 we can see two maxima separated from one another by approximately 1.5 year. We see the 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 maxima occurrence times of all these indices in cycle 23.

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 a very high level of flare activity in cycle 21 and very low level of flare activity in cycle 23. We also confirm (see Figure 3d) that the flare activity (Counts of flares index) in cycle 23 was almost two times weaker than in cycle 21.

Changed relation between $F_{10.7}$ and solar activity indices in the cycles 21-23

Figure 3 illustrates the high level of interconnection between solar activity indices versus $F_{10.7}$. We see that the coefficients of linear regression (slope - A and intercept - B) differ among themselves for the activity cycles 21 - 23. The biggest differences are seen for the Counts of flares index.

We studied the solar activity indices in 21, 22 and 23 solar cycles separately for the cycles' rise phases, maximum phases, minimum phases and decline phases. We've found that the maximum values of linear regression correlation coefficients K_{corr} are reached in the rise and decline phases of the cycles.

According to our calculations, the highest values of correlation coefficients K_{corr} are seen between SSN and $F_{10.7}$. The smallest correlation coefficients K_{corr} determined here for linear regression are for TSI versus $F_{10.7}$.

The cyclic variations of fluxes in different spectral ranges and lines on 11-yr time scale are widely spread phenomenon for F, G and K stars (not only for the Sun), see Bruevich and Kononovich (2011). The chromospheric activity indices (radiative fluxes at the centers of the *H* and *K* emission lines of Ca II - 396.8 and 393.4 nm respectively) for solar-type stars were studied for 45 years, from 1965 to the present time during the HK project at Mount Wilson observational program by Baliunas et al. (1995). The authors of the HK project supposed that all the solar-type stars with well determined cyclic activity remain about 25 % of the time in Maunder minimum conditions. Some scientists proposed that the solar activity in the future cycle 24 will be very low and similar to the activity during the Maunder minimum period. In Figure 2 for the yearly SSN we also see (if we continue the imaginary line, enveloped the maximums) the influence of the century-scale cyclicity onthe 24^{th} cycle's SSN maximum values.

We present our study of the correlation between the activity indices versus 10.7 cm radio flux in Figure 4. We show the results of calculations of the linear regression and also the results of calculations of the polynomial regression (of second order). It is evident that the linear regression is a good approximation for the correlation study of solar indices until the level of solar activity becomes very high (more than 200 *sfu* for $F_{10.7}$).

We also have to point out that a close interconnection between the radiation fluxes characterizing the energy release from different atmosphere's layers is a widespread phenomenon among the stars of late-type spectral classes. Bruevich and Alekseev (2007) confirmed that there is a 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

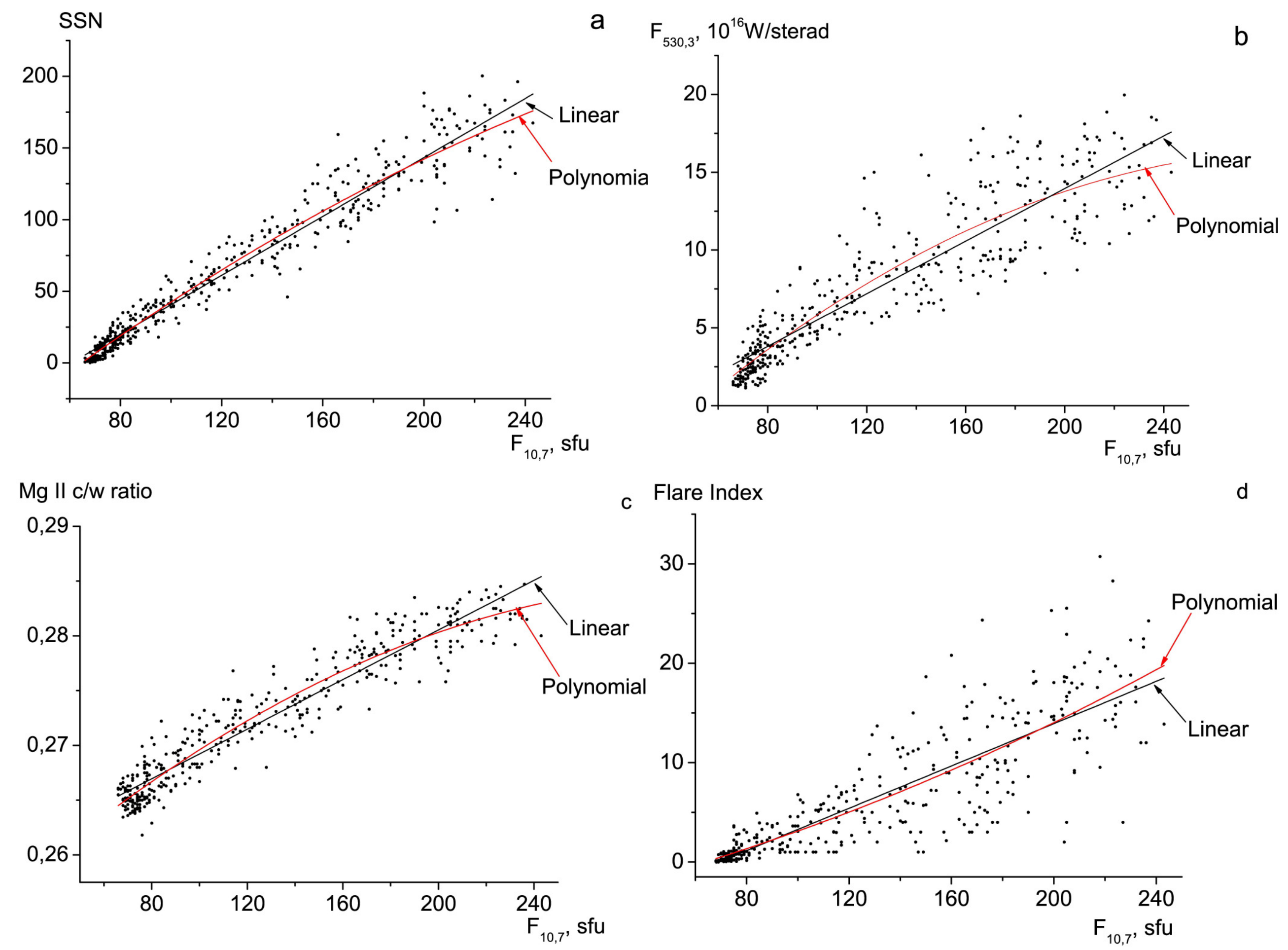

Figure 4: Correlation between monthly averages of solar indices versus $F_{10.7}$ in the cycles 21 - 23 (1975 - 2008). (a) SSN, (b) F_{530}, (c) Mg II *cwr* and (d) Flare Index.

atmospheres. It was shown that the total area of spots and the values of X-ray fluxes increase gradually for the Sun and HK project stars with low spotted discs to the highly spotted K and M-stars for which Alekseev and Gershberg (1996) constructed the zonal model of the spots distributed on the star's disk.

The time variations of correlation coefficient K_{corr} (t) for the linear regression of solar activity indices versus $F_{10.7}$ and versus SSN

We have calculated the three-year intervals linear regression correlation coefficients K_{corr} (t) for solar activity indices versus $F_{10.7}$ and versus SSN for cycles 21, 22 and 23. We used observational data for the period 1975 - 2010. The values K_{corr} (t) were determined for each moment of time t located in the center of the 3-year time interval t-1.5 yr. < ΔT < t+1.5 yr.

Figure 5 demonstrates the results of our correlation calculations of these solar activity indices versus $F_{10.7}$ and versus SSN: K_{corr} (t) variations during the cycles 21 - 23. We can see that all the K_{corr} (t) values have maxima during the rise and he decline phases. The minimum values of the Kcorr (t) are seen during the minimum and the maximum phases of the solar cycles. The minimum values of the correlation coefficients Kcorr (t) for the solar indices versus F10.7 and SSN occurred twice during the 11-year cycle. We assumed that this fact must be considered for the understanding of the solar indices interconnections and for the successful forecasts of different activity indices using F10.7 or SSN observations.

Note that the linear correlation (see Figure 5) of activity indices F530, Mg II index, Flare Index and TSI versus F10.7 is a little stronger than the linear correlation of these indices versus SSN. We assume that this is a logical result: these indices (as well as F10.7) characterize the solar irradiance produced at different altitudes in 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 Figure 5) has no difference versus F10.7 or versus SSN because the Counts of flares index describes the fast flared processes (not irradiance) on the Sun while SSN is the relatively subjective measure of the total level of solar activity.

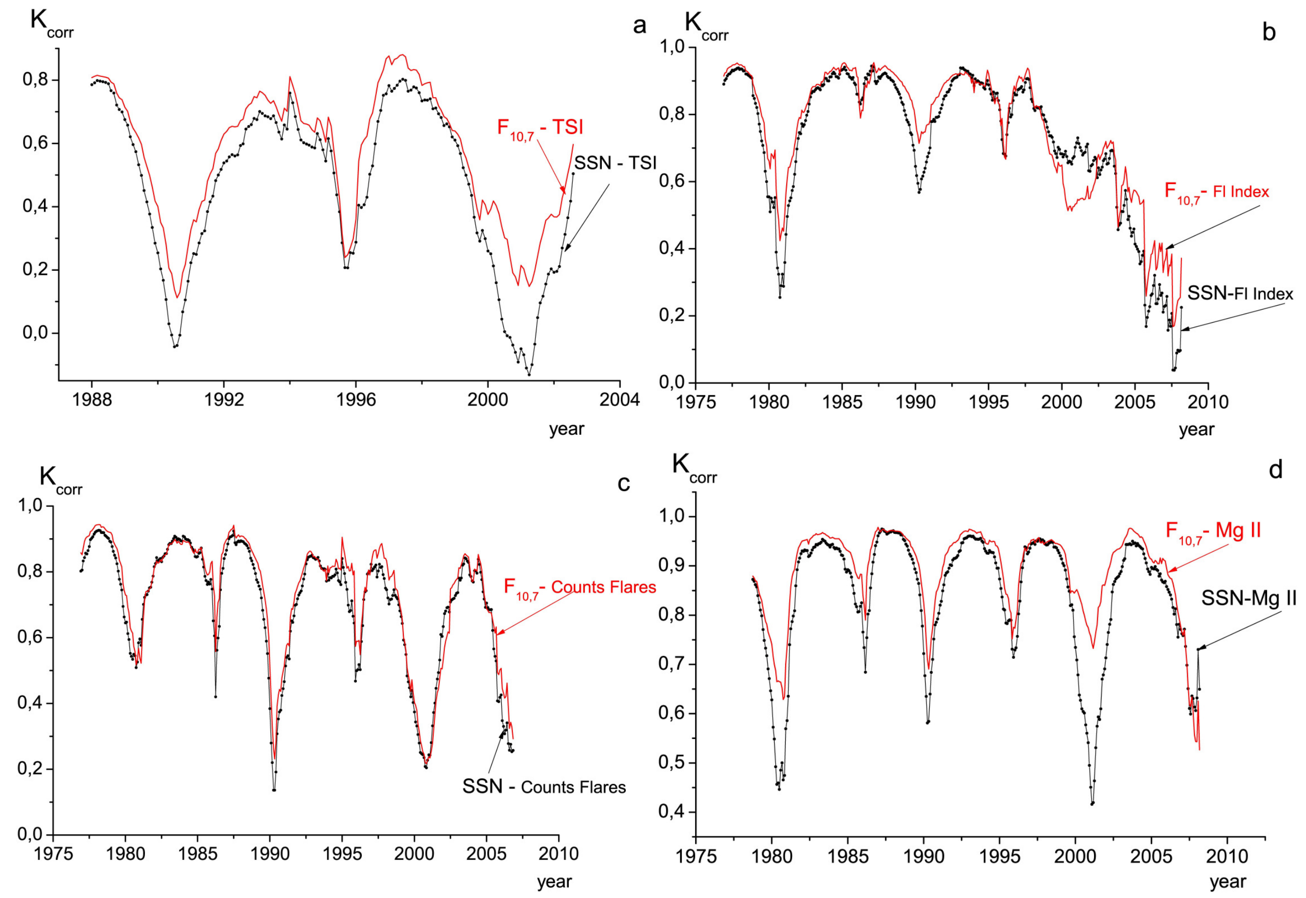

Figure 5: Correlation coefficients of linear regression K_{corr}(t) for (a) TSI, (b) Flare Index, (c) Counts of flares and (d) Mg II UV-index versus SSN and versus $F_{10.7}$.

Summary and conclusion

For a long time scientists have been interested in the simulation of processes in the earth's ionosphere and upper atmosphere. It is known that the solar radiance at 30.4 nm is very significant for determining the Earth's high thermosphere heating. Lukyanova and Mursula (2011) showed that the for forecasts of solar 30.4 nm radiance fluxes (very important for the Earth's predictions of the thermosphere's heating) it is much preferred to use Mg II 280 nm observational data.

Although $F_{10.7}$ does not actually interact with the Earth atmosphere it 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, makes it a good generalized solar proxy for the thermospheric heating. Tobiska et al. (2008) 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 core-to-wing ratio, 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). The model proved the efficiency of the simultaneous use of multiple indexes of solar and geomagnetic activity.

In this paper we found a cyclic behavior of the correlation coefficients *K*corr(*t*) of the linear regression (calculated over three-year time intervals) for TSI, Flare Index, Mg II 280 nm and Counts of flares versus $F_{10.7}$ and SSN during solar activity cycles 21,22 and 23 (see Figure 5). We showed that K_{corr} (t) have the maximum values at the rise and decline phases - the linear connection between indices is stronger in these cases. It means that the forecasts of solar indices, based on $F_{10.7}$ observations will be more successful during the rise and decline cycle's phases. We showed that the linear correlation of activity indices F_{530}, Mg II index, Flare Index and TSI versus $F_{10.7}$ is stronger than the linear correlation of these indices versus SSN but the linear correlation of Counts of flares has no difference versus $F_{10.7}$ or versus SSN. This may be due, in particular, to the fact that all indices have a "Quiet Sun Level" different from zero, except SSN, which has a minimum value equal to zero.

We also determined that for the solar indices versus $F_{10.7}$ and SSN, the three-year interval values of correlation coefficients K_{corr} calculated for the linear regressions assumption, the minimum values were achieved two times during the 11-year cycle.

Our study of linear regressions 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 (characterizing the energy release from different layers of solar atmosphere) increases.

Acknowledgments

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