Correlation study of six solar activity indices in the cycles 21 - 23

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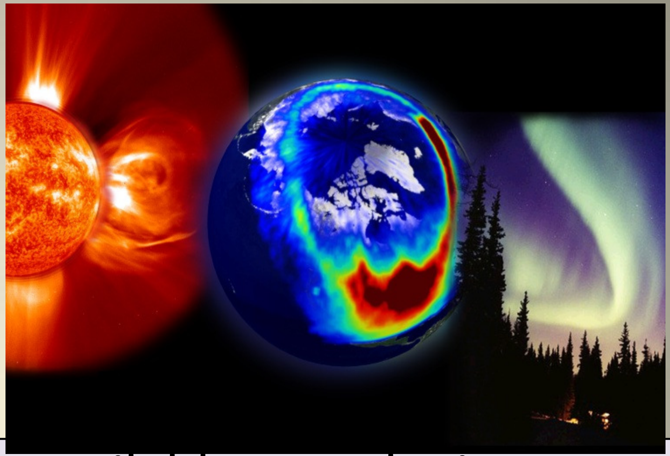
- The indices we've studied are: Wolf numbers – W, radio flux – $F_{10.7}$, 530.3 nm coronal line flux – F_{530}, the total solar irradiance – TSI, Mg II UV – index 280 nm core-to-wing ratio, Flare Index – FI, and Counts of flares.
- The correlation coefficients of the linear regression of six solar indices versus 10.7 cm radio flux $F_{10.7}$ were analyzed in solar cycles 21, 22 and 23.
- The interconnections between these indices and $F_{10.7}$ with help of the approximation by the polynomials of second order were studied.



We use **NASA** and **SGD** data that are available at web-sites

National Geophysical Data Center Solar and Terrestrial Physics

http://www.ngdc.noaa.gov/stp/spaceweather.html

Solar-Geophysical Data Reports. 54 Years of Space Weather Data, 2009,

http://www.ngdc.noaa.gov/stp/solar/sgd.html

We studied the time series of monthly average of W, $F_{10.7}$, F_{530}, TSI, Mg II-index, FI, and Counts of flares.

All the indices are very important not only for analysis of solar radiation formed on the different altitudes of solar atmosphere, but for solar-terrestrial relationships as the key factors of the solar radiation influence (EUV/UV solar radiation is the most important) on the different layers of terrestrial atmosphere also.

The Wolf numbers (W) is a very popular, widely used solar activity index: the series of Wolf numbers observations continue more than two hundred years. Although W are highly correlated with other solar-activity indicators, they are not the best indicator of solar activity because they do not contain information on how magnetically energetic sunspot regions are (Kilcik et al., 2011a).

The solar radio microwave flux at wavelengths 10.7 cm ($F_{10.7}$) has also the longest running series of observations started in 1947 in Ottawa. This radio emission comes from high part of the chromosphere and low part of the corona. $F_{10.7}$ radio flux has two different sources: thermal bremsstrahlung and gyro-radiation. $F_{10.7}$ is the integrated emission from the whole solar disk at the radio wavelength of 10.7 cm. This index is more complex than W because it contains both active regions and bright regions (such as faculae and plages) contributions. If the magnetic-flux emergence is taken into account, the situation will become more complicated (Deng et al., 2013). The strong correlation of F10.7 with plage area and faculae area has been reported earlier (Kilcik et al., 2011b).
The active region's contribution to sunspot-related indicators peaks before that to faculae- and plage-related indicators, so the temporal variation of F10.7 and W behave differently in a solar cycle.

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The Mg II 280 index derived from daily solar observations of the core-to-wing ratio of the Mg II doublet at 279.9 nm provides a good measure of the solar UV variability and can be used as a reliable proxy to model extreme UV (EUV) variability during the solar cycle. The Mg II observation data were obtained from several satellite's (NOAA, ENVISAT) instruments.

Data of GOES observations of the X-ray 0.1-0.8 nm background were taken from Solar Geophysical Data bulletin. This permanent monitoring of solar disk at the 0.1-0.8 nm range is a good indicator of solar corona activity without flares.

Data of the total solar irradiance (TSI) SOHO observations for the 23rd cycle were taken from Solar-Geophysical Data bulletin. Earlier from 1985 to 2000 the total solar irradiance was observed by Earth Radiation Budget Satellite (EBRS).

We also analyzed two activity indices which describe rapid processes on the Sun - Flare Index (*FI*) and monthly Counts of 'grouped' solar flares (Monthly flare count). According to 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 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 used the monthly averaged *FI* values.

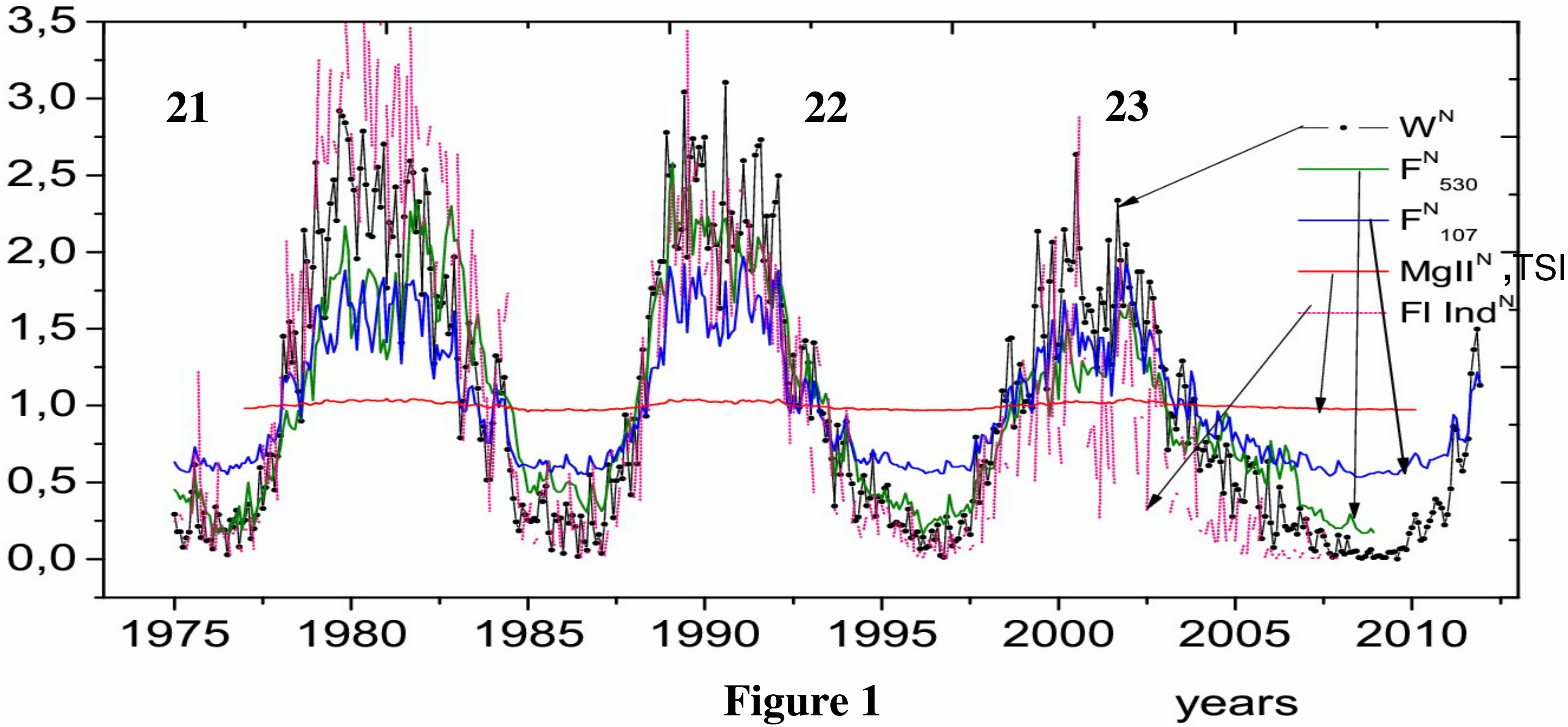

Figure 1

- **The time series of monthly average values of W, $F_{10.7}$, F_{530}, TSI, Mg II-index, 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**
- **We can see that the relative variation of most of solar indexes in activity cycle is about 2-3 times. However, the magnitudes of Mg II - index and TSI change very little - about shares of percent.**

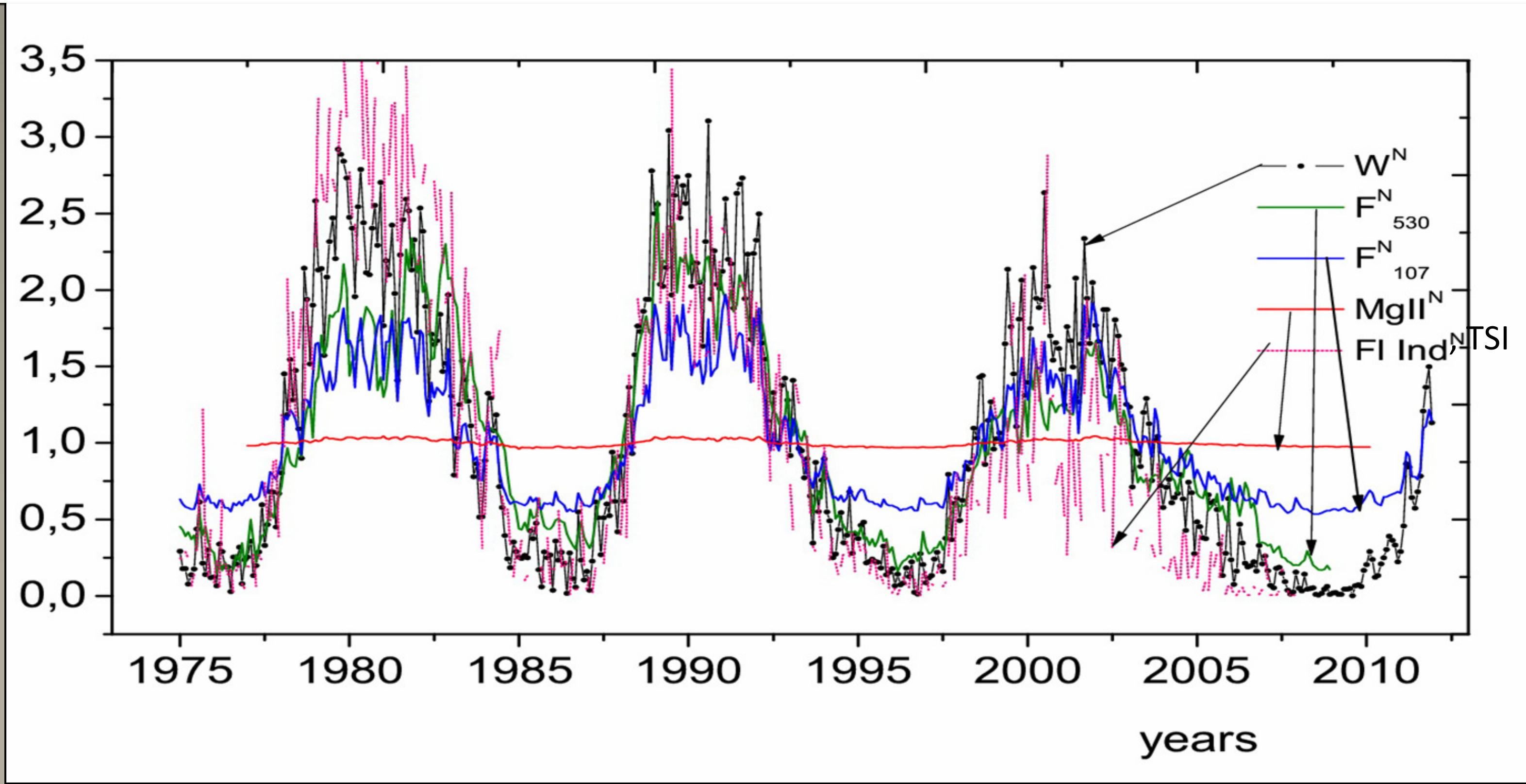

Figure demonstrates that for all activity indices in the solar activity cycle 23 we can see two maximum separated one from another on 1.5 year approximately. We see the similar double-peak structure in the cycle 22 but for the cycle 21 the double-peak structure is not evident.

We can see at Figure that there are displacements in both maximum occurrence time of all these indices in the solar cycle 23.

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

We assume that the probable reason of such double-peak structures is a modulation of the 11-year fluxes variations by both of the quasi-biennial and 5.5 years cyclicity. The different time of the first and second maximum appearance may be caused by the difference in fluxes formation conditions (for our indices) at different atmosphere's altitudes of the Sun.

We found out than the linear correlation was violated not only for maximum of solar activity cycles but for minimum of the cycles too.

Vitinsky et al. (1986) analyzed solar cycles 18 - 20 and pointed out that correlation for spot numbers versus radio flux F10.7 does not show the close linear connection during all the activity cycle.
This conclusion was confirmed by our study (Bruevich, Yakunina, 2011).

- Also it was emphasized the importance of statistical study in our solar activity processes understanding. To achieve the best agreement in approximation of spot numbers values by $F_{10.7}$ observations Vitinsky et al. (1986) proposed to approximate the dependence W - $F_{10.7}$ by two linear regressions: the first one - for the low solar activity (where $F_{10.7}$ less than 150) and the second one - for the high activity ($F_{10.7}$ more than 150).

- We separated out the rise phase, the cycle's maximum phase, the cycle's minimum phase and the decline phase during our studying of solar activity indices in 21, 22 and 23 solar activity cycles .
- In case of linear regression we've 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 in connection between W and $F_{10.7}$. Correlation coefficients K_{corr} for linear regression for TSI versus $F_{10.7}$ are the minimal of all correlation coefficients determined here.

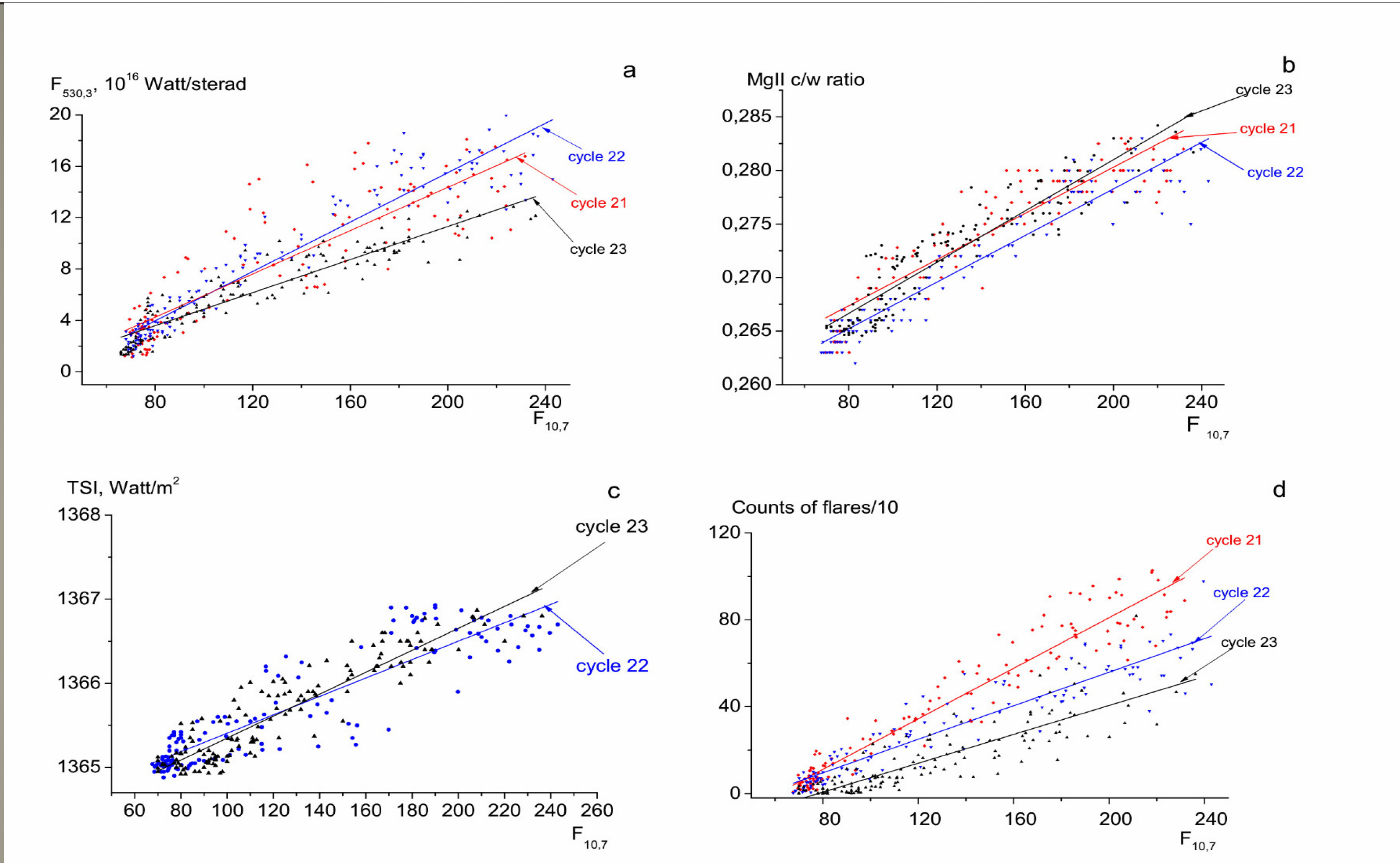

Figure 2.Correlation between monthly averages for solar indices versus $F_{10.7}$ radio flux in the cycles 21 - 23.

Note that the interconnections of solar indices versus $F_{10.7}$ differ significantly for different cycles. In several cycles the regression coefficients (the slope especially) differ significantly also. Especially Counts of flares (in two times) in cycle 23 versus cycle 21.

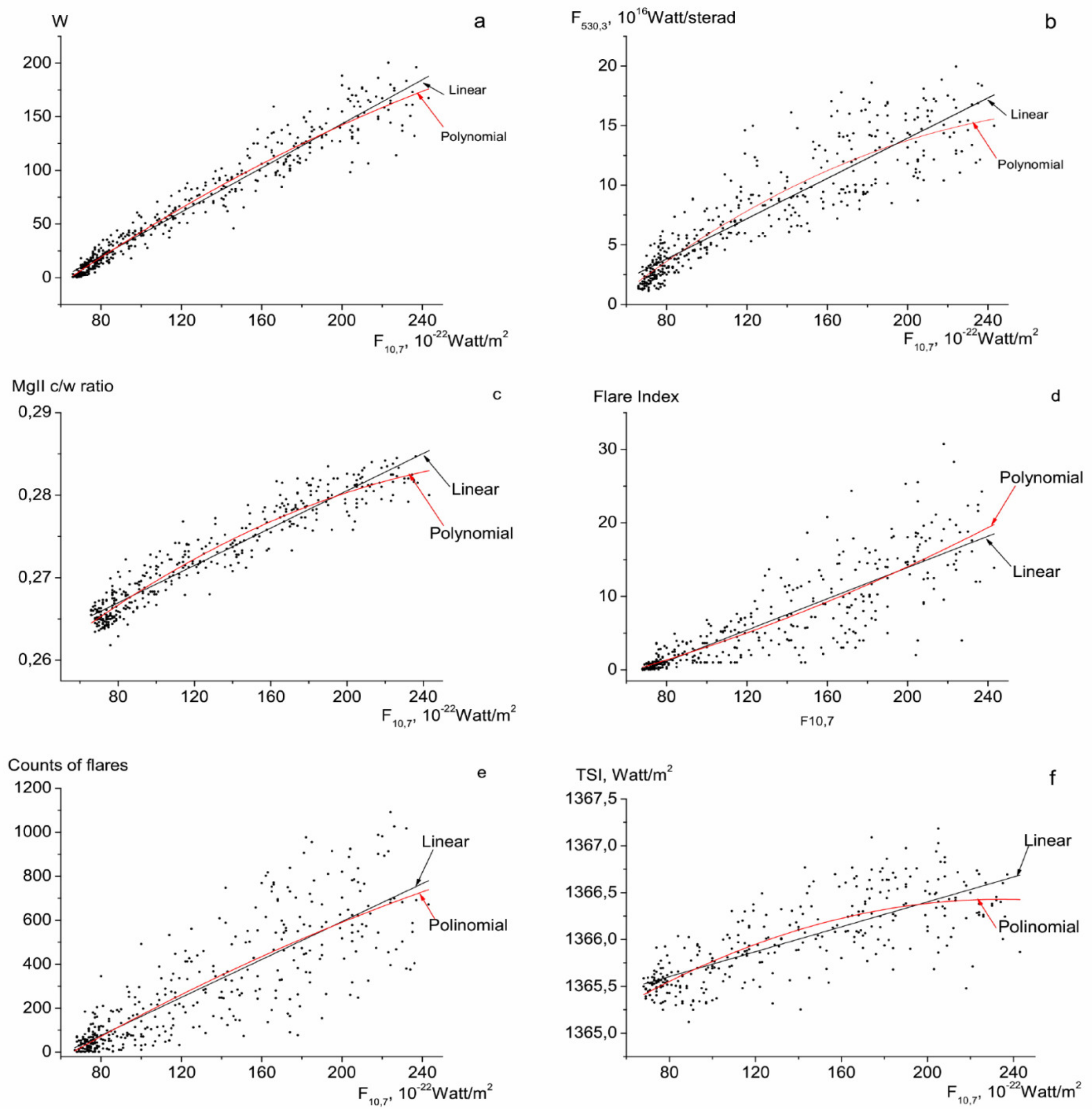

Figure 3. Linear and polynomial interconnection between monthly averages of solar indices versus $F_{10.7}$ in the cycles 21 -23.
(a) Wolf numbers,
(b) F_{530} ,
(c) Mg II index,
(d) Flare Index,
(e) Counts of flares,
and
(f) TSI .

•We study the difference in the linear and polynomial regression for six indices of activity in cycles 21-23, depending on the radio emission.

The linear model corresponds to the linear regression equation:

$$F_{ind} = A_{ind} + B_{ind} \cdot F_{10,7}$$

Table 1 Solar activity indices versus $F_{10,7}$. Coefficients of linear regressions: A, B and their standard errors.

Activity indices versus $F_{10,7}$	A_{ind}	B_{ind}	Error σ_A	Error σ_B
W	-62,28	1,03	1,57	0,011
$F_{530,3}$	-2,93	0,084	0,27	0,002
MgII	0,258	0,00013	0,00026	0,00000018
Flare Index	-7,37	0,106	0,51	0,0036
Counts of flares	-269,03	4,31	20,14	0,146
TSI	1365,07	0,0066	0,044	0,0003

The Table 1 illustrates the linear regression between monthly averages of solar indices versus $F_{10.7}$ in the cycles 21 -23.

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

$$F_{ind} = A_{ind} + B1_{ind} \cdot F_{10,7} + B2_{ind} \cdot F_{10,7}^2$$

Table 2 Solar activity indices versus $F_{10,7}$. Coefficients of polynomial regressions: A, $B1$, $B2$ and their standard errors.

Activity indices versus $F_{10,7}$	A	B1	B2	error σ_A	error σ_{B1}	error σ_{B2}
W	-87,26	1,45	-0,0015	4,86	0,078	0,0003
$F_{530,3}$	-7,38	0,158	-0,00026	0,84	0,013	0,000048
MgII	0,25	0,0002	-0,0000003	0,0007	0,00001	0,00000004
Flare Index	-4,36	0,057	0,00017	1,58	0,024	0,00007
Counts of flares	-361,4	5,83	-0,005	64,01	1,01	0,0035
TSI	1364,4	0,017	-0,000037	0,13	0,002	0,0000007

- **The Table 2 illustrates the polynomial regression between monthly averages of solar indices versus $F_{10.7}$ in the cycles 21 -23.**

- **Note that terms of equation of a second order play considerable part when $F_{10.7}$> 150-200 in accordance with Vitinsky et al. (1986), who examined the regression between the W and the $F_{10.7}$ only.**

We've calculated values K_{corr} of linear regression for solar activity indices versus $F_{10.7}$ *(red)* and versus ***W*** (**black**) for cycles 21-23. Calculations of $K_{corr}(t)$ for each moment of time *t were carried out interval of 3 years with the* center (*t -- 1.5yr <ΔT< t + 1.5yr.*

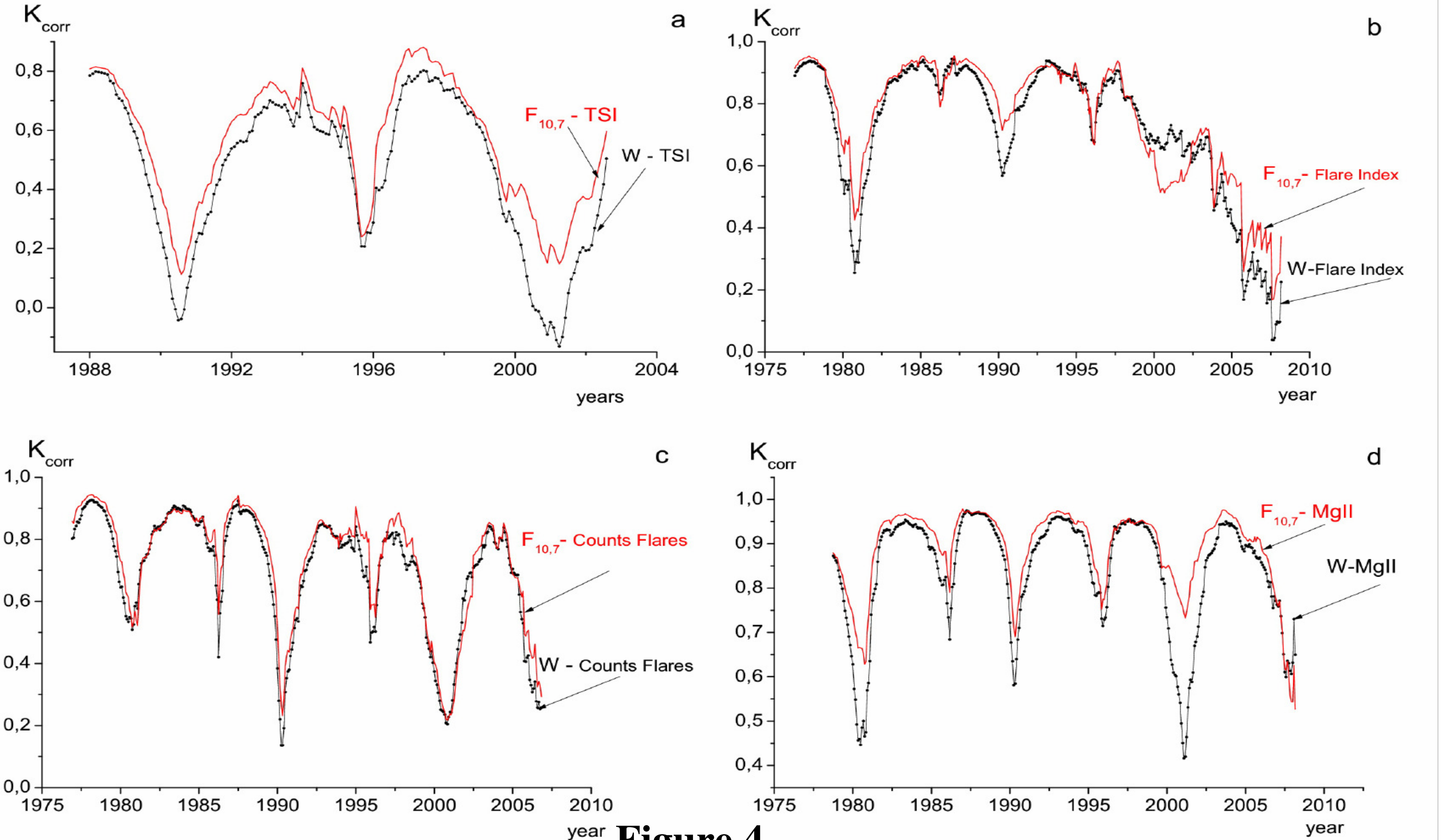

Figure 4

- Figure 4 demonstrates the results of our correlation calculations of these solar activity indices versus $F_{10.7}$ and W (K_{corr} variations during the cycles 21 - 23).

- We can see that all the K_{corr} values have the maximum amounts at rise and at decline phases.

- It's easy to estimate the value of period of K_{corr} cyclic variations as 5.5 years approximately. We assumed that this new cyclicity (characterized with period's value equal to half length of 11-year cycle) is important for the successful forecasts of the solar activity indices fluxes.

- Note that the linear correlation of activity indices versus $F_{10.7}$ is a little stronger than of activity indices versus W. It's a logical result: these indices (as well as $F_{10.7}$) characterize the solar irradiances proceeded from different altitudes of solar atmosphere.

- The linear correlation of Counts of flares (see Figure 4) has no difference versus $F_{10.7}$ or versus W. The Counts of flares index is not connected directly with solar irradiance. This index describes the fast processes on the Sun as well as W is the relatively subjective measure of the total level of solar activity.

Conclusions

• For a long time the scientists were interested in the simulation of processes in the earth's ionosphere and upper atmosphere. It's known that the solar radiance at 30.4 nm is very significant for determination of the Earth high thermosphere levels heating. Lukyanova and Mursula (2011) showed that the for solar 30.4 nm radiance fluxes forecasts (very important for Earth thermosphere's heating predictions) there were more prefer to use MgII 280 nm observed data unlike usual $F_{10.7}$ and Wolf numbers observations.

• We found out that during the rise and decline cycle's phases the forecasts of different solar indices (including MgII 280 nm) with help $F_{10.7}$ observations are good enough and we can use the more available $F_{10.7}$ data when the necessary observations are unavailable.

• The close interconnection between activity indices make possible new capabilities in the solar activity indices forecasts.

• We showed that (Figure 4) 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 W but the linear correlation of Counts of flares has no difference versus $F_{10.7}$ or versus W.

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Thank you for your attention