LONG-TERM MODULATION OF THE CORONAL INDEX OF SOLAR ACTIVITY

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Abstract. Monthly mean values of the coronal index of solar activity and other solar indices are analyzed for the period 1965–1997 covering three solar cycles. The coronal index is based upon the total irradiance of the coronal 530.3 nm green line from observations at five stations. The significant correlation of this index with the sunspot number and the number of the grouped solar flares have led to an analytical expression which can reproduce the coronal index of solar activity as a function of these parameters. This expression well explains the existence of the two maxima during the solar cycles taking into account the evolution of the magnetic field that can be expressed by a sinusoidal term with a 6-year period. The agreement between observed and calculated values of the coronal index on a monthly basis is high enough and reaches the value of 92%. It is concluded that the coronal index can be used as a representative index of solar activity in order to be correlated with different periodic solar–terrestrial phenomena useful for space weather studies.

1. Introduction

It is well known that solar activity dominates the entire heliosphere including the Earth, influences our lives and may damage sensitive electronics aboard satellites. It may be expressed with many indices such as the sunspot number, the 2800 MHz radio flux, the green-line emission intensity and various other indices. The cosmic ray flux is also used to express solar activity. This is based on the assumption that the modulation of the cosmic ray flux is governed by the solar magnetic field (Cane *et al.*, 1999).

As the origin of solar activity is one of the basic problems of solar physics, it is not clear which index is best suited to help us to understand the physics of the solar cycle and to study solar–terrestrial relations, as each of them has its own advantages and disadvantages. Rybanský (1975) proposed a coronal index (CI) as a general index of solar activity. This is a full-disk index and represents the averaged daily power (irradiance) emitted by the green corona (530.3 nm) into one steradian towards the Earth. The input data for the coronal index computation are ground-based data obtained at different observatories with coronal measurements around the world (Rušin and Rybanský, 1992; Rybanský *et al.*, 1994a; 1996; Altrock *et al.*, 1999).

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The existence of two maxima in the solar activity parameters during an 11-year cycle was first shown by Gnevyshev (1967, 1977). In our days the study of different solar phenomena has confirmed the fact that the 530.3 nm coronal line intensity, which reveals a basic feature of solar activity, has indeed two distinct maxima for every 11-year solar cycle with different physical properties (Gnevyshev and Antalová, 1965; Rušin, Rybanský, and Scheirich, 1979; Rušin, 1980; Xanthakis, Petropoulos, and Mavromichalaki, 1982; Sýkora, 1994). Coronal index data also presents two maxima in each 11-year cycle contrary to the sunspot number R, which exhibits only one distinct maximum. Rušin, Rybanský, and Scheirich (1979) reported that it is not easy to obtain general conclusions for the relationship between coronal emission and sunspot number or other manifestations of solar activity because of the existence of two maxima.

Many investigators have attempted to find empirical relations between the coronal green-line intensity and the classical indices of solar activity like the relative Wolf number (Leroy and Trellis, 1974) and the areas index $I_a(R)$ (Xanthakis, 1969) in order to estimate the values of the coronal green-line intensity, when data of this intensity are not available. A theoretical relation for the green-line intensity I_{5303}, the index $I_a(R)$ and the number of proton events N_p for the time interval of 19th and 20th solar cycles has been also given by Xanthakis, Petropoulos, and Mavromichalaki (1982). A theoretical justification of this empirical relation on the basis of semi-annual data was given taking into account the evolution of the coronal magnetic field during the solar cycle.

In this work we try to find an empirical relation for the green-line intensity expressed by the coronal index of solar activity using the most appropriate independent parameters of solar activity, such as sunspot number and grouped solar flares, on a monthly basis. The residuals between the observed and calculated values of the coronal index that appear in the solar cycle maxima can be explained, in our model, by the contribution of the solar magnetic field in connection with its polarity reversals. This study has been performed in the time period 1965–1997 covering three solar cycles and gives a very good agreement between the observed and the calculated values of the coronal index. The results will be useful for the calculation of the coronal index in future cycles contributing to the space weather studies.

2. Data Analysis

Monthly values of the coronal index of solar activity used in the present analysis have been obtained from the NOAA NGDC website *(http://www.ngdc.noaa.gov/stp)*.

The coronal index of solar activity (CI) presents the total energy emitted by the Sun's outermost atmosphere (the E-corona) at the wavelength of 530.3 nm (Fe XIV, the green corona). It is expressed in 10^{16} W sr^{-1} or 4.5×10^{-7} W m^{-2} or 1.2×10^{8} photons cm^{-2} s^{-1} at the Earth (Rybanský *et al.*, 1994a).

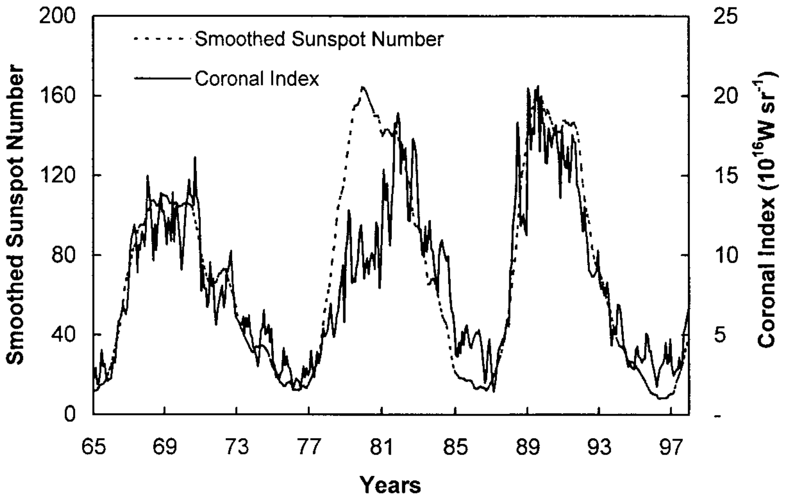

Figure 1. Monthly values of the coronal index of solar activity and smoothed sunspot number for the cycles 20, 21, 22.

The values of the coronal index are derived from ground-based observations of the corona made around the solar limb with a spacing of 5 deg. Before computing the coronal index, intensities from other coronal stations were converted to the same photometric scale of Lomnický Štít Coronal Station in the Slovak Republic. Differences in the height measurement above the solar limb and shifts in positional angles were removed. Numerical values of the 530.3 nm irradiance are in W sr^{-1} units, with the basic intensity obtained at 40″ above the solar limb. The method of computation and final results have been published by Rybanský (1975) and Rybanský *et al.* (1996).

Homogeneous coronal data sets are used for calculating the coronal index of solar activity (Rybanský, 1994a; Altrock *et al.*, 1999). Several coronal stations such as Sacramento Peak, Arosa, Pic du Midi, Kislovodsk, etc. were used in this database with Lomnický Štít being the reference station from 1965 (Rybanský *et al.*, 1994b). According to Rybanský *et al.* (1994a) some of the important advantages of this index are the length of the time sequence ($\sim$ 60 years to date), the relationship with the X-ray flux in regards to the mechanism of their origin and the possibility to study variability of solar activity not only around the solar equator, but around the entire Sun (from a homogeneous coronal data set). On the other hand, disadvantages of the coronal index are the uncertainty of limb data extrapolation onto the solar disk and the errors that result from different methods of observation at different coronal stations.

The time distribution of monthly mean values of the coronal index for cycles 20, 21 and 22 appears in Figure 1. The long-term modulation of this index is obvious (Quinn and Frölich, 1999). This was expected as many investigators have reported similar modulation of the green-line intensity (Storini *et al.*, 1995). The highest

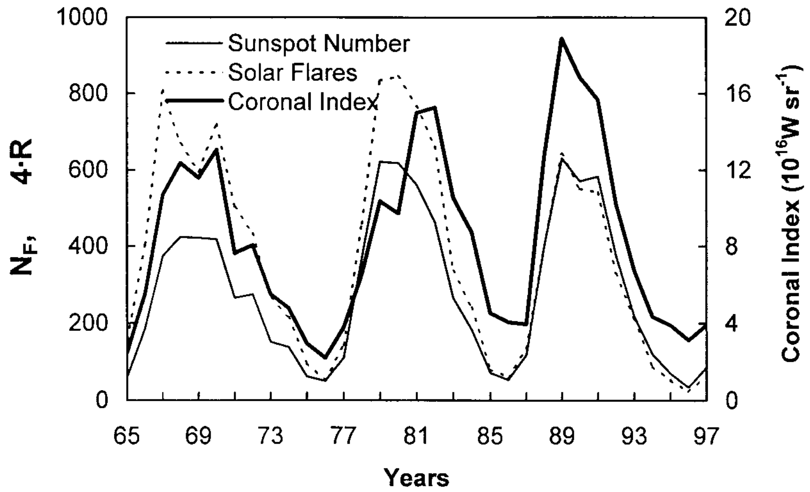

Figure 2. Annual values of sunspot number, grouped solar flares and coronal index for the time period 1965–1997.

values of the coronal index were observed in cycle 22 and continuously grew from cycle 18 as it is noted by Rybanský *et al.* (1996). The peak value in the odd cycle (21st) is higher than that obtained in the previous one according to the well-known Gnevyshev/Ohl rule (Gnevyshev and Ohl, 1948). It is interesting to note that two maxima are observed in each 11-year cycle of the coronal index, although there is no clear indication for a second maximum of this index in the last solar cycle (22nd) (Rybanský, Rušin, and Minarovjech, 2001).

Smoothed sunspot number values, which present only one distinct maximum, are also shown in Figure 1. The first coronal index maximum coincides with the sunspot number during the cycles, while the second one is observed nearly two years after the sunspot number maximum (Gnevyshev, 1977). Rušin, Rybanský, and Scheirich (1979) showed that the first maximum can be observed at the heliographic latitudes of around $\pm 25°$ and almost in coincidence with the occurrence of the Wolf number maximum. The second maximum of coronal intensities is observed at heliographic latitudes around $\pm 10°$ and appears 2–3 years after the occurrence of the first one in the corona. It is consistent with the polarity reversals of the solar magnetic field occurring 2–3 years after the sunspot maximum (Mavromichalaki, Belehaki, and Rafios, 1998). Kopecký and Kotrč (1974) investigated the contribution between the two maxima in sunspots and calculated that the first maximum is that of the sunspot number and the second one is the maximum of their sizes. A hypothetical explanation of the problem of two maxima in the corona is presented by Yoshimura (1977a) in connection with the development of the general magnetic field of the Sun.

Monthly values of sunspot number R and grouped solar flares N_F are obtained from *Solar Geophysical Data* Bulletins. The term 'grouped solar flares' means ob-

TABLE I
Correlation coefficients obtained in this analysis.

	R	N_F	$\sqrt{R}$	$\sqrt{N_F}$	$\sqrt{RN_F}$
CI	0.85 ± 0.03	0.75 ± 0.03	0.86 ± 0.02	0.77 ± 0.03	0.82 ± 0.03

servations of the same event by different sites were lumped together and counted as one. Monthly counts of grouped solar flares are available only after 1965, which is the begin year of our analysis. Annual values of coronal index, sunspot number and grouped solar flares, illustrated in Figure 2, indicate the existence of two maxima in the parameters CI and N_F. This is important evidence to use the solar flares in our relation in order to reproduce the CI values and namely the secondary maximum. The solar magnetic field data are provided by observations of the magnetic field intensity of the Sun ‘as a star’ (Kotov and Severny, 1983; Belov, 2000).

Comparisons between coronal index values and sunspot number as well as between coronal index and grouped solar flares are illustrated in Figure 3. It is noted that there is a bigger dispersion in the high values of all these indices than in the low ones. All the correlation coefficients are presented in Table I, where it is observed that the coronal index is better correlated with $\sqrt{R}$ and $\sqrt{RN_F}$, instead of R and N_F.

This result suggests using the term $\sqrt{R}$ and not R for the calculation of the coronal index. This is also obtained theoretically from the definition of the areas index $I_a(R)$ by Xanthakis and Poulakos (1978), which depends on the sunspot sizes and is proportional to $\sqrt{R}$.

3. Empirical Formulation

In order to estimate the green-line emission measured at the Pic du Midi Observatory for the time period 1946–1972, Leroy and Trellis (1974) gave the following empirical relation with respect to the sunspot number:

$$I_{5303} = \left(1 + \frac{R}{110}\right) 28 \times 10^{-8} I_0, \tag{1}$$

where I_0 is the solar constant and R the sunspot number.

In a previous work Xanthakis, Petropoulos, and Mavromichalaki (1982) found a relation for the green-line intensity for cycles 19 and 20 with respect to the number of proton events and the index $I_a(R)$ introduced by Xanthakis and Poulakos (1978) using data from the Pic du Midi Observatory on a semi-annual basis. The use of the number of proton events has given an explanation of the secondary maximum

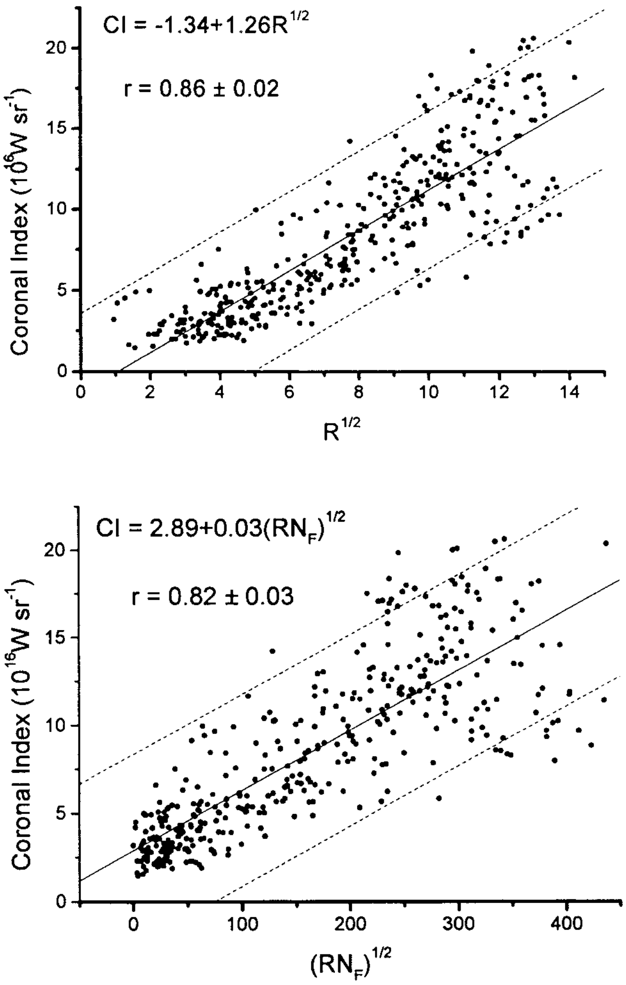

Figure 3. An example of the scatter diagrams of the coronal index with $\sqrt{R}$ and $\sqrt{RN_F}$ is given. In each panel, the 95% of the points are included between the *dashed lines*.

of these cycles. The addition of a sinusoidal term $P(t)$ related to the solar magnetic field has improved the accuracy of this computation.

In this work using monthly data of the coronal index, we try to give a more representative expression for the calculation of the green-line intensity over the three last solar cycles. Taking into account the correlation expressions, we can find the following empirical relation for the coronal index:

$$\text{CI} = 0.78 + 0.63\left(1 + 0.24\sqrt{N_F}\right)\sqrt{R}. \tag{2}$$

Calculating the coronal index by this expression we have an accuracy of 85% between observed (CI_{obs}) and calculated (CI_{cal}) values, as we can see in Figure 4.

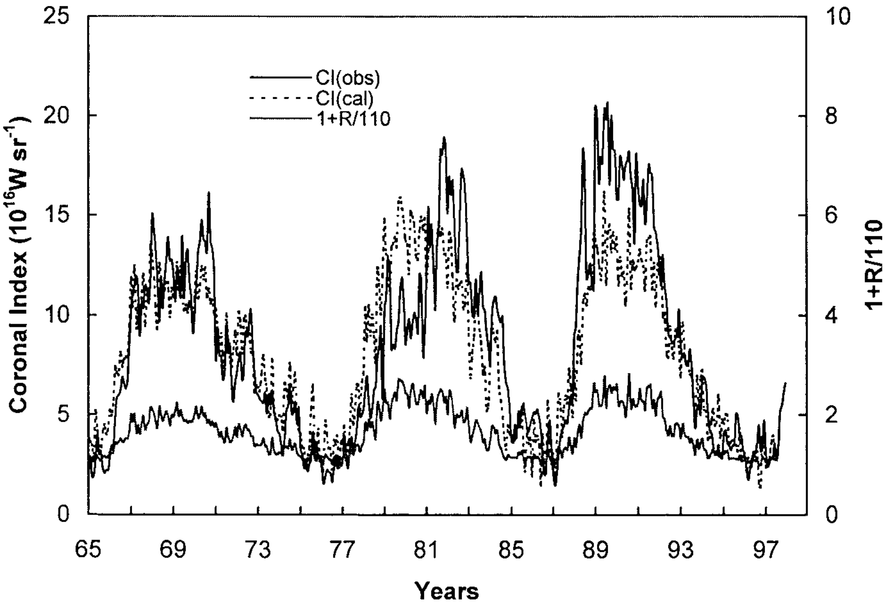

Figure 4. Observed (CI_{obs}) and calculated (CI_{cal}) by Equation (2) values of the coronal index of solar activity are presented. The term $1 + R/110$ is also illustrated.

In the same figure the values obtained from expression (1) are also indicated. If we estimate the correlation coefficients between the observed and calculated values in the ascending and descending phases of the cycles separately and in the period of maxima, the latter presents a large deviation, while the values during the other phases are very well correlated. For example, the correlation coefficients during the ascending and descending phases of the cycle 22 reach values of 83% and 89%, respectively, while during the maximum period it is only 40%. In order to get a better approximation we can deduce that in the maxima of the solar cycles the residuals have a sinusoidal form $P(t)$ with a 6-year period given by the expressions

$$P(t) = \begin{cases} +1\sin\left(\dfrac{\pi}{72}\right)t, & t = 0, 1, \ldots, 72 \quad (1968 - 1974), \\ -4\sin\left(\dfrac{\pi}{36}\right)t, & t = 0, 1, \ldots, 36 \quad (1978 - 1981), \\ +4\sin\left(\dfrac{\pi}{36}\right)t, & t = 0, 1, \ldots, 36 \quad (1981 - 1984), \\ +5\sin\left(\dfrac{\pi}{72}\right)t, & t = 0, 1, \ldots, 72 \quad (1987 - 1993). \end{cases} \tag{3}$$

Taking into account in our analytical expression these $P(t)$ values, the calculation of the coronal index is corrected by the relation

$$\mathrm{CI} = 0.78 + 0.63\left(1 + 0.24\sqrt{N_f}\right)\sqrt{R} + P(t). \tag{4}$$

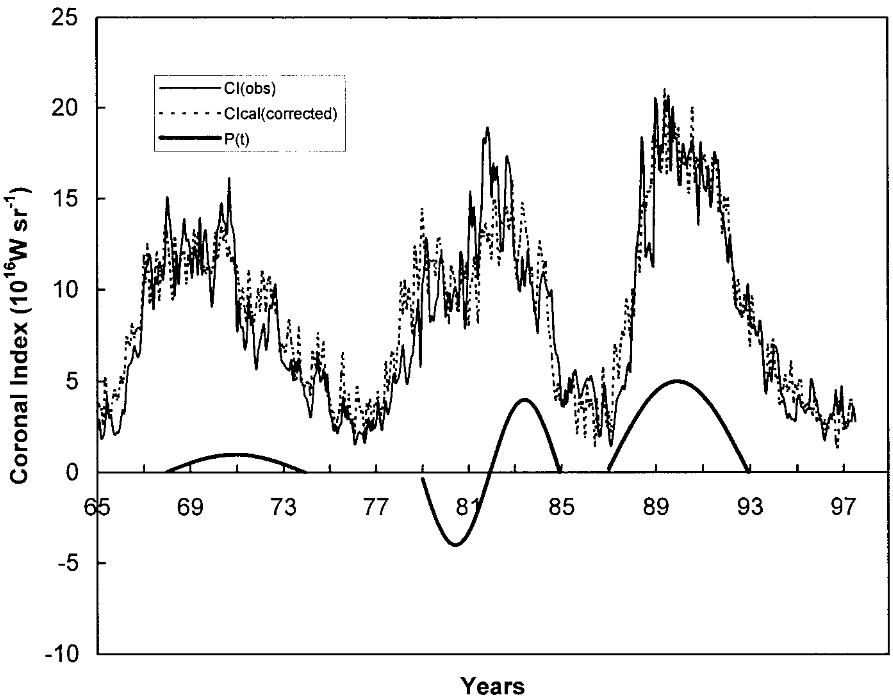

Figure 5. Observed and calculated by Equation (4) values of the coronal index taking into account the solar magnetic field. $P(t)$ terms are also indicated.

The observed values of the coronal index ($\mathrm{CI}_{\mathrm{obs}}$) and the ones calculated by Equation (4) ($\mathrm{CI}_{\mathrm{cal}}$), as well as the $P(t)$ terms, are illustrated in Figure 5. The accuracy of this approximation is $(92.1 \pm 1.8)\%$. The $P(t)$ term has a complete sinusoidal form in cycle 21 (odd cycle) and a semi-periodical one in cycles 20 and 22 (even cycles).

4. Theoretical Interpretation

Leroy, Poulain, and Fort (1973) gave the following equation for each emission line that can be applied for the coronal index (CI) as well:

$$\mathrm{CI} = \int_{-\infty}^{+\infty} A(T_e) N_e^{1+a}\, \mathrm{d}x, \tag{5}$$

where $A(T_e)$ is a contribution function of the electron temperature estimated theoretically as

$$A(T_e) = K_i T_e^{-1/2} e^{-W/kT_e} \frac{N_z}{N_0}, \tag{6}$$

where N_e is the local electron density; T_e, the electron temperature; N_0, the total number of the atoms of the element; N_z, the population of the upper level; W, the transition energy; k, the Boltzmann constant; K_i, a, constants, and $0 \leq a \leq 1$.

According to Dollfus (1971), the coefficient a can be well approximated by the value of 0.5. Taking into account that $I_a(R) \sim \sqrt{R}$ (Xanthakis and Poulakos, 1978), the function $A(T_e)$ can be expressed as

$$A(T_e) = \sqrt{R} F(T_e), \tag{7}$$

where $F(T_e)$ is a function of the electron temperature that can be obtained by relation (6).

According to Xanthakis, Petropoulos, and Mavromichalaki (1982) the variation of the electron density is proportional to the production of proton events N_p which are associated only with intense Hα flares (Perez-Enriquez and Mendoza, 1995). Furthermore, the fact that the correlation between solar proton events with energy > 10 MeV and the solar flares with importance $>$ M4 is very high ($r = 0.94$) gives evidence that these flares are the main sources of solar proton events (Belov *et al.*, 2001). Performing a quick analysis of the relation between the number of proton events and solar flares for the last three solar cycles, we can accept that $N_p \sim N_F^{\beta}$, where $\beta \leq 0.5$. For the purposes of this work, the exponent β can be approximated by the value 0.5, as the coronal index is better correlated to $\sqrt{N_F}$ (Table I). In other terms, the electron density variation can be given by the following relation:

$$\Delta N_e = \overline{N}_e \sqrt{N_F}, \tag{8}$$

where $\overline{N}_e$ is the electron density in the corona of the quiet Sun.

Taking into account that $\Delta\mathrm{CI} = \mathrm{CI} - \mathrm{CI}_0$, where CI_0 is the coronal index corresponding to the quiet solar corona, and with the help of assumptions (7) and (8) and relation (5), the coronal index can be reproduced by the relation

$$\mathrm{CI} = \mathrm{CI}_0 + \sqrt{R} \int_{-\infty}^{+\infty} \Delta F(T_e) N_e^{3/2}\, \mathrm{d}x + 1.5\sqrt{R}\sqrt{N_F} \int_{-\infty}^{+\infty} F(T_e) \overline{N}_e \sqrt{N_e}\, \mathrm{d}x. \tag{9}$$

If we identify the above relation with empirical relation (2), we find that

$$\mathrm{CI}_0 = 0.78, \tag{10}$$

$$\int_{-\infty}^{+\infty} \Delta F(T_e) N_e^{3/2}\, \mathrm{d}x = 0.63, \tag{11}$$

and

$$\int_{-\infty}^{+\infty} \overline{N_e} \sqrt{N_e} F(T_e)\, \mathrm{d}x = 0.1. \tag{12}$$

It is noteworthy that Xanthakis, Petropoulos, and Mavromichalaki (1982) had found approximately the same values using semi-annual data of the green-line intensity. This fact confirms the reliability of this proposed coronal index of solar activity. It will be very useful for space weather studies as the green-line intensity can be considered as an integrated index of solar activity (Xanthakis, Petropoulos, and Mavromichalaki, 1990; Sýkora, 1992).

5. Contribution of the Solar Magnetic Field

It is known that large-scale solar magnetic fields play an important role in the global organization of solar activity and formation of the heliosphere. Their structure, evolution and rotation have been thoroughly studied during the past 30 years (Ivanov, Obridko, and Ananyev, 2001). Especially, the green-line intensity is shown to be closely related to the underlying photospheric magnetic field strength (Wang *et al.*, 1997). Badalyan, Obridko, and Sýkora (1999) have recently shown that the coronal magnetic fields influence the formation of the green-line polarization. Xanthakis, Petropoulos and Mavromichalaki (1982) have used the solar magnetic field in order to calculate the green-line intensity during the years 1954–1972. In that work, the magnetic field is simulated by a periodic term that has the same phase for the ascending branches of the solar activity and inverse phase for the descending ones. Now, in this work, the residuals ΔCI between observed and calculated values of the coronal index seem to be quite similar to the solar magnetic field during the maxima, as is illustrated in Figure 6.

It is known that the evolution of the magnetic field intensity does not change the profile of the coronal green line by the Stark effect, but changes only the electron temperature and density of corona (Unsöld, 1970). So, the coronal magnetic field can be used as a parameter for the study of the variations of the green-line intensity and, consequently, of the coronal index. According to this the variation of the function $F(T_e)$ can be given by the relation

$$\Delta F(T_e) = F_1(T_e) F_2(T_e), \tag{13}$$

where

$$F_1(T_e) = \frac{\mathrm{d}F(T_e)}{\mathrm{d}B} \quad \text{and} \quad F_2(T_e) = \int \frac{\mathrm{d}B}{\mathrm{d}T_e} \mathrm{d}T_e. \tag{14}$$

This assumption is based on the measurements by Dollfus (1971), who has found no displacement of the green line for a long time of observations.

According to Yoshimura (1977b), the coronal magnetic field intensity B can be considered as the sum of two components: the toroidal component $B_{\theta,\varphi}$ and the radial one B_r. The radial component can be developed into a series of Legendre polynomials, normal-modes (Stix, 1977):

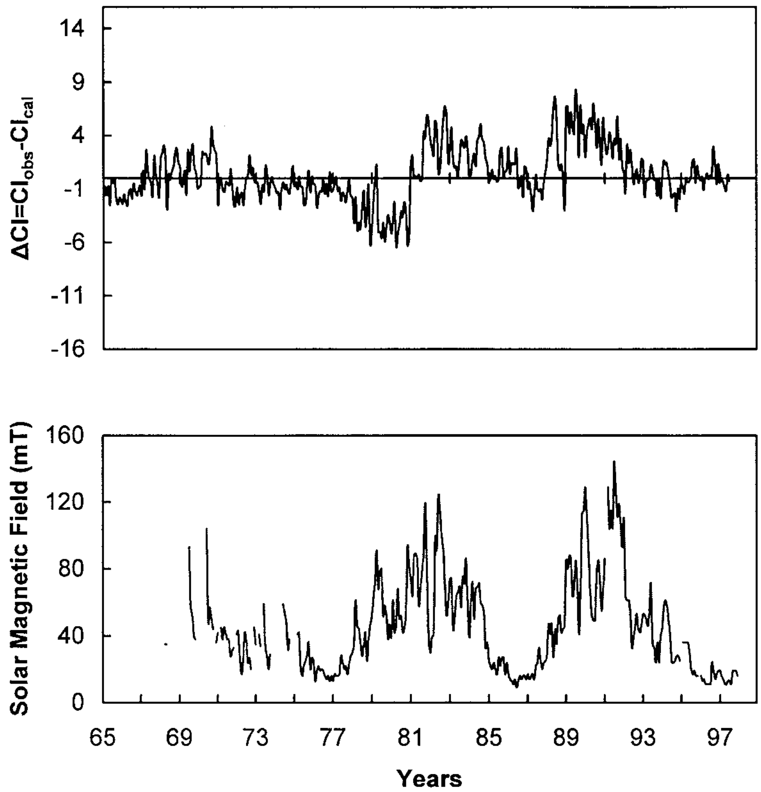

Figure 6. Coronal index residuals (ΔCI) between observed and calculated by Equation (2) values (*upper panel*) and solar magnetic field (*lower panel*) are shown for the time period 1965–1997.

$$B = B_{\theta,\phi} + B_r = B_{\theta,\phi} + \sum_{i=0}^{n} (A_i + S_i), \tag{15}$$

where A_i are the axisymmetric and with respect to the equator antisymmetric parts of the field (E–W asymmetry) and S_i are also axisymmetric but symmetric with respect to the equator (N–S asymmetry). Ivanov, Obridko, and Ananyev (2001) observed a noticeable asymmetry with respect to the equator both in the zonal, and in the sector structure of large-scale solar magnetic fields. This asymmetry changes from cycle to cycle, as well as with the phase of the activity cycle. N–S and E–W asymmetries have also been observed in Pic du Midi Observatory data of the green-line intensity for the period 1954–1972 (Mavromichalaki *et al.*, 1994).

Taking into account the above assumption, and if we identify the relation (9) with the empirical one (4), we can finally find that

$$P(t) = \left[\Delta B_{\theta,\phi} + \sum_{i=1}^{n} \Delta(A_i + S_i) \right] \sqrt{R} \int_{-\infty}^{+\infty} \frac{\mathrm{d}F(T_e)}{\mathrm{d}B} N_e^{3/2}\, \mathrm{d}x, \tag{16}$$

where Δ designates the variation of each component in relation to its value in the period of low solar activity. From the above equation, it can be clearly seen that $P(t)$ is negligible for the periods around the solar minimum, which, in our case, justifies the addition of $P(t)$ terms only in the maximum of the solar cycles.

As was mentioned above, the $P(t)$ terms are different in odd and even cycles. In the odd cycle 21 a complete sinusoidal term has been considered, instead of a semi-periodical one in the even cycles 20 and 22. This is in agreement with the polarity reversals of the solar magnetic field occurring around the maxima. The difference between the odd and the even cycles can be explained by the transition from parallel to antiparallel states of the magnetic field with respect to the angular velocity of the rotation of the Sun (Page, 1995; Mavromichalaki, Belehaki, and Rafios, 1998). Storini and Sýkora (1995) have also noticed differences of the corona brightness in even and odd cycles.

6. Discussion and Conclusions

The coronal index is derived for the period 1939–1998 and belongs to the class of ground-based indices used to study solar activity and its influence on the heliosphere. Comparative studies have shown relatively good agreement with similar solar indices. The coronal index can be used to study, among other things, the rotation of the Sun as a star, and long-, intermediate-, and short-term periodicities. The coronal index is inferred from a homogeneous coronal data set that can be used to study such topics as the 2D distribution of the green corona, and the relationship between the green corona and cosmic rays (Rybanský, Rušin, and Minarovjech, 2001).

Gnevyshev (1967) has shown that each 11-year cycle consists of two different maxima that are seen in photosphere, chromosphere and corona with optical and radio observations. Gnevyshev (1977) proved that the two maxima in the 11-year cycle of solar activity are very different events and not two simple fluctuations. As the physical conditions during the two maxima are very different, the theory and forecasting of solar activity, investigations of solar-terrestrial relations and investigations of individual solar events must be taken into account, in order to determine the features of the 11-year cycle.

In this work a relation between the coronal index, the sunspot number and the grouped solar flares has been found. This relation gives a physical meaning of the coronal index of solar activity and can be used in order to verify the reliability of the coronal index measurements. It can also be used in order to reproduce the coronal index values with a very good approximation and to predict the maxima of next cycles, if the modulation of the solar magnetic field is known. The secondary maximum of the coronal index has been explained very well by the use of the number of solar flares, while the magnetic field intensity has given a better precision around the maxima of solar activity.

Summarizing we can say that the coronal index of solar activity may give a better measure of solar-terrestrial effects than sunspots, because it can be modulated by both solar flares and sunspots, as well as with the magnetic field. All these parameters are very important for space weather studies. The results of these studies may be improved by the use of this index, instead of the green-line intensity, as it is derived using data from more than one station. Further investigation for the next solar cycles could improve our understanding about this modulation and its related physical processes.

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