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Total Solar Irradiance and the Fe XIV Corona

Milan Minarovjech · Vojtech Rušin · Metod Saniga

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Abstract Analyzing daily values of the total solar irradiance (TSI), the coronal index of solar activity (CI), and the Mg II 280-nm core-to-wing ratio (Mg II index), we have found that the temporal variations of these indices are very similar to each other during the period from 1978 to 2005. The correlation between CI and TSI, with the PSI correction lying within the interval under study, has been found to be 0.699, which is very close to the value of 0.703 of the correlation between Mg II and TSI for 27-day averages (the CI – Mg correlation is 0.824). The regression equation between CI and TSI is almost linear, except for TSI depletions when a large number of sunspots are present on the visible disk. By employing CI, an extrapolation of TSI back to 1947 is presented.

1. Introduction

Our Sun, a magnetic variable star, varies in its electromagnetic output both spectrally and in its aggregate. This finding stems from observations of different solar activity features, emissions at different wavelengths of the spectrum, and total solar irradiance (TSI). Whereas a number of indices of solar activity, such as the sunspot number, the number of faculae, the F10.7/2800 MHz radio flux, the green line (Fe XIV, 530.3 nm) intensity, and EUV and X-ray fluxes, may change by more than 100% between solar maxima and minima, TSI, the integrated solar flux over the entire solar spectrum as inferred from space-borne observations, varies only about ±0.1% over a solar cycle (*e.g.*, Pap, 1997; Fligge *et al.*, 2000; Friis-Christiensen, 2000; Rybanský *et al.*, 2005; Fröhlich, 2003).

Solar activity affects the heliosphere as a whole, including the Earth and its vicinity, our climate and life, as well as sensitive electronic equipment aboard satellites. Analyzing

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M. Minarovjech (✉) · V. Rušin · M. Saniga
Astronomical Institute of the Slovak Academy of Sciences, 05960 Tatranska Lomnica, Slovakia
e-mail: milanmin@ta3.sk

V. Rušin
e-mail: vrusin@ta3.sk

M. Saniga
e-mail: msaniga@ta3.sk

TSI and other variable solar features (spots, flares, CMEs, *etc.*) is of crucial importance for a deeper understanding of solar activity and a better prediction of solar-driven climate changes, as well as for distinguishing the effects of the latter from other climatic drivers. With this end in view, we made a comparison between TSI and the coronal index of solar activity (CI), as the latter, introduced by Rybanský (1975), represents the total energy emitted by the Sun's outermost atmospheric layer (the emission corona) at a wavelength of 530.3 nm (Fe XIV) toward Earth, being usually expressed in 10^{16} $\mathrm{W\,sr^{-1}}$. As stated by Mavromichalaki, Petropoulos, and Zouganelis (2002) "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."

Direct measurements of TSI have only been available within the past three decades. To infer the TSI variations at earlier dates, a proxy measure is used, *e.g.*, the sunspot number. However, the sunspot number is a "non-energetic index" of solar activity that furnishes only quantitative descriptions of solar phenomena. Moreover, there are also indices that are explicitly and directly expressed in energetic units. CI can well be ranked among these in the visible part of the electromagnetic spectrum. Our option for employing CI as a proxy for TSI was motivated by the fact that there is a close relation between the green corona intensities and photospheric magnetic-field strength (*e.g.*, Wang *et al.*, 1997; Zhang *et al.*, 1999; Rušin and Rybanský, 2002; Rušin *et al.*, 2007), even when the CI contribution to TSI is negligible. Both TSI and CI are obviously connected with magnetic fields of active regions on the solar surface. So, it is reasonable to assume that CI can be used as a reliable proxy for TSI variations. Moreover, although CI data are available for the years 1939 – 2005, those of TSI go back only to the end of 1978. To justify the correlation between CI and TSI, we have also compared CI with the Mg II index, given the fact that bright regions in the chromosphere and upper photosphere (which comprise Mg II variations) coincide well with photospheric magnetic fields (*e.g.*, Cook, Brueckner, and Vanhoosier, 1980), and, as was shown by Lean, Mariska, and Acton (1997) and Krivova, Solanki, and Floyd (2006), approximately 30 – 60% of the actual TSI variations over the solar cycle might be produced at wavelengths below 400 nm. So, the Mg II index is a direct measure of the irradiance that provides a substantial part of the TSI variation. Using CI as a proxy makes it possible to reconstruct TSI back to 1939. To make our analysis more complete, a comparison between TSI and F10.7 radio flux has also been made.

The model reproduces observed solar-cycle variations of the irradiance at wavelengths down to 115 nm and indicates an important role of UV irradiance variability: Up to 60% of the total irradiance variations over the solar cycle might be produced at wavelengths below 400 nm.

The CI data were computed from photometric patrol observations made at all ground-based stations observing the emission corona. Patrol measurements are made with different observational methods, at different heights above the solar limb, and with different steps in positional angles. So, all the data collected have first been converted to a common intensity scale by intensity rescaling, shifting position angles of the measurements, and comparing values taken at all the sites. The Lomnický Štít coronal station was taken as the data reference station for calculations of CI; CI created this way is referred to as a "coronal homogeneous data set" (HDS) and is often employed in other fields of solar research. Missing observational data in the HDS were calculated by using a linear interpolation. (For more details about the procedure, see Rybanský *et al.*, 2005.) CI, for a given day, is based on limb observations of the green line for that day and within intervals of six days on either side of that day. The distribution of intensity above the solar surface is obtained by using

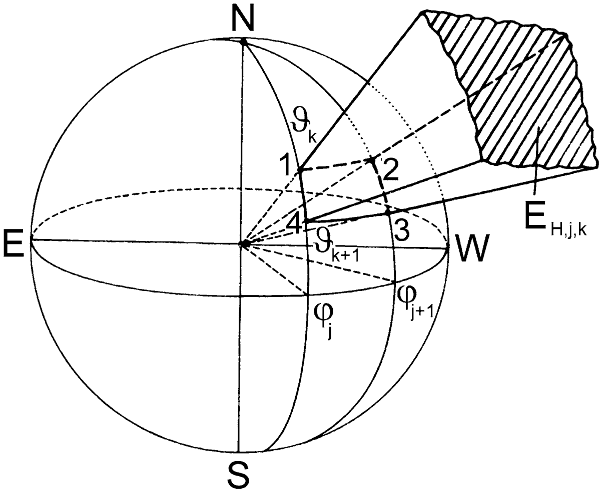

Figure 1 An illustration of a unit volume in front of the solar disk. Integrating the volume emissivity over the visible disk and above the Sun's limb yields CI.

observations at the E-limb (W-limb) from the six days preceding (following) the given day to specify the coronal intensities above the eastern (western) half of the disk. By integrating over the entire solar disk (Figure 1) we obtain the irradiance in front of the visible part of the Sun (E_H); to this we add the irradiance above the solar limb ($0.5E_\mathrm{L}$) (see Figure 2 in Rybanský, 1975) to obtain CI,

$$\mathrm{CI} = E_\mathrm{H} + 0.5E_\mathrm{L}, \tag{1}$$

the total irradiance of the green corona into one sterradian (sr) toward the Earth (see Rybanský, 1975 and Rušin and Rybanský, 2002 for further detail). Some details about the reexamined CI data (Rybanský *et al.*, 2005) are employed for this comparison.

The Mg II core-to-wing ratio is derived by taking the ratio of the H and K lines of the solar Mg feature at 280 nm to the background or wings at approximately 278 and 282 nm. The H and K lines are variable chromospheric emissions whereas the background emissions are more stable. The result is a robust measure of chromospheric activity. This ratio has been shown to be a good measure of solar UV and EUV emissions. Each of the data sets was scaled to the original NOAA TIROS 9 data set with a linear fit of the overlapping data. The nature of the Mg II core-to-wing ratio and the quality of the data resulted in linear correlation coefficients between 0.98 and 0.999 (Viereck and Puga, 1999; Viereck *et al.*, 2001).

This paper can be regarded as an extension of a series (see Rušin *et al.*, 2007, and references therein) where comparisons of CI with the magnetic flux, the sunspot number, the F10.7 radio flux, the X-ray flux, and, indirectly, with cosmic rays have been given.

2. Data Processing

Our work is based on two sets of TSI data: (1) the composite TSI daily data described by Fröhlich and Lean (1998) and downloaded from ftp://ftp.pmodwrc.ch/data/irradiance/composite, version d41_61_0604[1] and (2) the VIRGO TSI daily data version V6.001.0605

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[1] The contiguous TSI database extends from late 1978 to the present, covering more than two sunspot cycles (one solar magnetic activity cycle). It comprises the observations of seven independent satellite experiments:

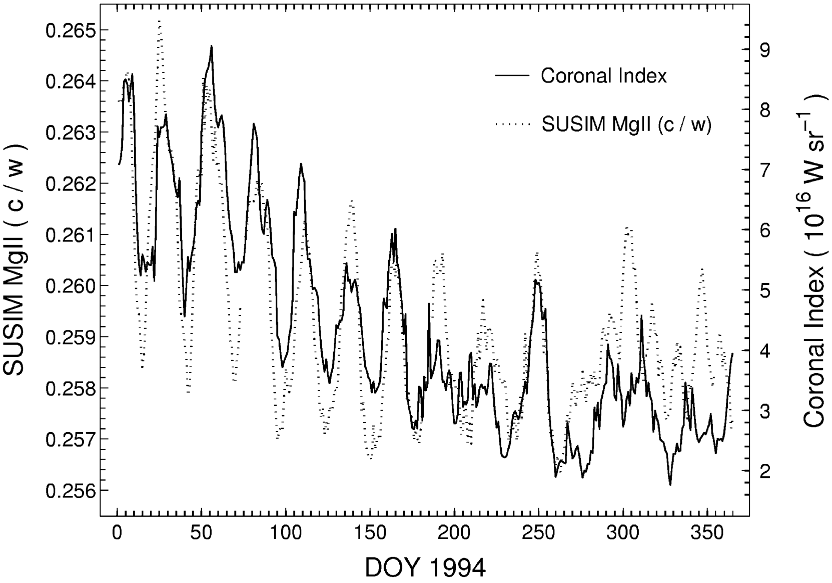

Figure 2 Daily Mg II and CI indices for the descending phase of solar cycle 22.

downloaded from ftp://ftp.pmodwrc.ch/data/irradiance/virgo. The NOAA Mg II daily index version 9.1 was obtained from http://www.sec.noaa.gov/ftpdir/sbuv/NOAAMgII.dat. The reexamined CI data (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_CORONA/LOMNICKY/index/) were used as a comparative proxy for variations related to bright chromospheric plages and the upper photosphere. Daily Mg II and CI data during the declining phase of cycle 22 in 1994 are shown in Figure 2. In Figures 3 and 4, the normalized value Y of the observable U is given by the formula $Y = (U - \bar{U})/\mathrm{std}(U)$, where $\bar{U}$ is the mean value of U.

To directly compare the variations in TSI with the changes in the coronal index of solar activity at 530.3 nm, represented by CI, we have used two data sets:

1. TSI data uncorrected for the effect of sunspots and
2. TSI data corrected for the effect of sunspots by means of the Photometric Sunspot Index (PSI; "sunspot deficit"). The PSI was defined by Hudson *et al.* (1982) and its current data were provided by the San Fernando Observatory; the "sunspot deficit" is discussed in more detail in, *e.g.*, Chapman, Cookson, and Dobias (1996) and Walton *et al.* (1988). The VIRGO TSI and CI daily data plots in the period 1996–2005 are shown in Figure 3. Correlation coefficients between individual parameters for the studied periods are shown in Table 1; here we included also the correlation coefficients from comparisons between Mg II and CI.

Nimbus7/ERB, SMM/ACRIM1, ERBS/ERBE, UARS/ACRIM2, SOHO/VIRGO, ACRIMSAT/ACRIM3, and SORCE/TIM. In general, the behavior of the ACRIM and PMOD TSI composites are very different (see, *e.g.*, Wilson, 1997 and/or Wilson and Mordvinov, 2003). The PMOD composite shows the solar minima immediately before and after the SC 22 maximum at the same level whereas the ACRIM composite shows that the latter minimum is substantially higher. Analyzing the ACRIM composite should thus yield a different result than our analysis of the PMOD composite. This question will be discussed in detail in a forthcoming paper.

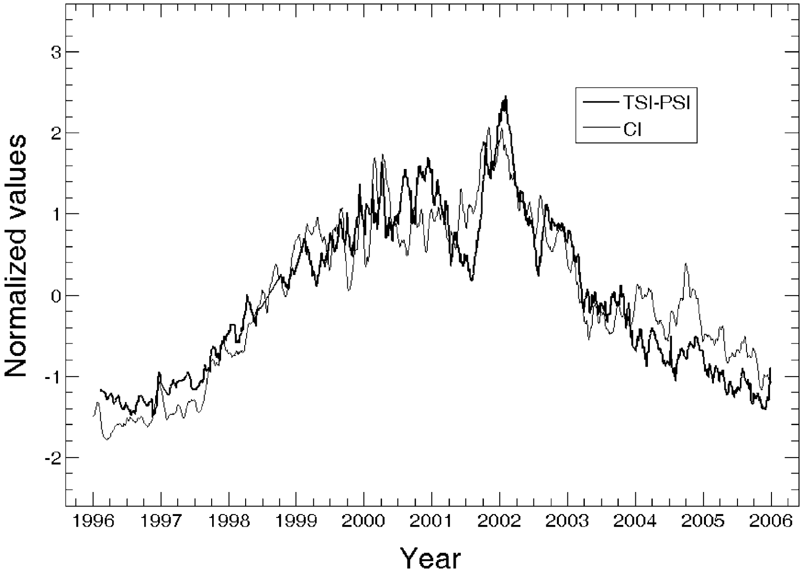

Figure 3 Daily VIRGO TSI corrected by PSI (thick line) and CI (thin line) data in the period 1996 – 2005.

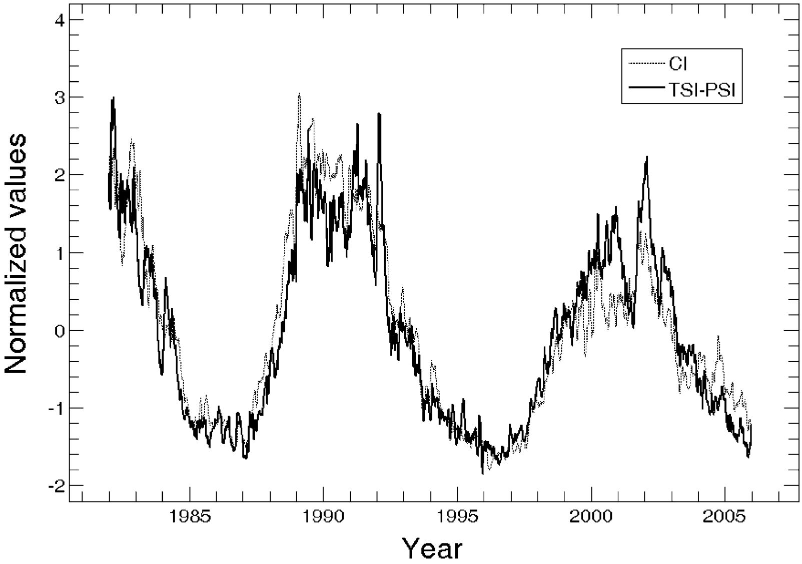

Figure 4 Solar cycle variations of the 27-day mean composite TSI corrected by PSI (thick line) and CI (thin line) in the period 1982 – 2005.

The 27-day-average composite TSI corrected by PSI and CI data during the period 1982 – 2005, covering the descending phase of solar cycle 21, full cycle 22, and an almost entire cycle 23, are shown in Figure 4.

Correlations among CI, the Mg ii index, and composite TSI corrected by PSI, as well as those between Mg ii and TSI (27-day means) are shown in Figures 5, 6, and 7, respectively.

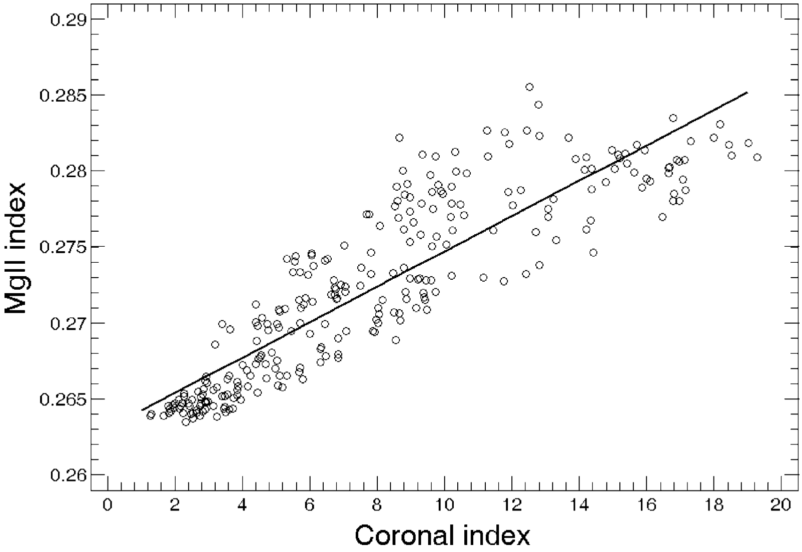

Figure 5 Correlation between CI and Mg II (27-day means). The correlation coefficient is 0.824.

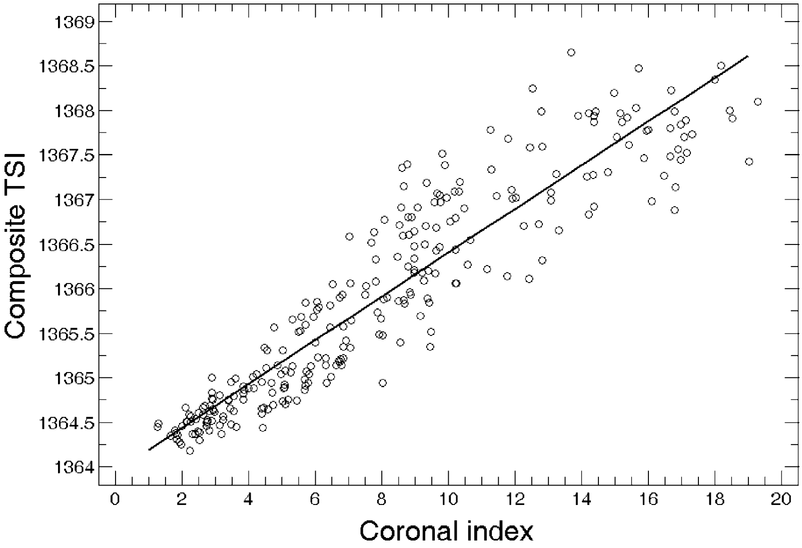

Figure 6 Correlation between CI and composite TSI corrected by PSI. The correlation coefficient is 0.699.

From Figures 3 – 7 we see a good agreement among the variations of CI, Mg II, and composite TSI corrected by PSI for the whole period under study. The Mg II index, beginning in 1978 and continuing to the present, is a generally used proxy. As follows from the computations, the correlation coefficient between the Mg II data and CI in years 1978 – 2005 is 0.791 for daily values and 0.824 for 27-day averages. We note that the correlation coefficient between CI and Kitt Peak magnetic flux is 0.863 and the CI – F10.7 correlation coefficient is 0.900 (Rušin *et al.*, 2007). We have computed, for a comparison, the correlation coefficients

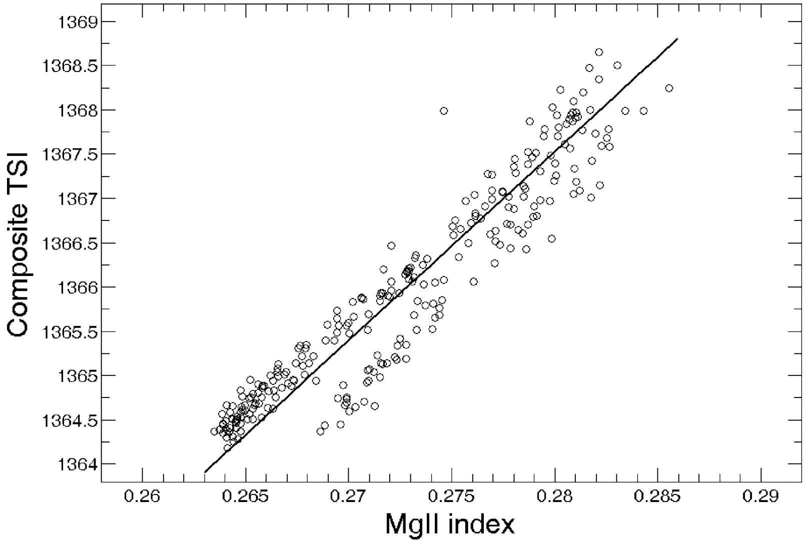

Figure 7 Correlation between Mg II and composite TSI corrected by PSI. The correlation coefficient is 0.703.

Table 1 Correlations among CI, composite TSI, Mg II, and sunspot number (W) in the period 7 November 1978 to 31 December 2005. Correlation coefficients among sunspot numbers, CI, and Mg II are also shown for comparison.

Without PSI corrections			
Index relation	Daily values	27-day means	81-day means
CI – W	0.780	0.887	0.9176
CI – TSI	0.543	0.728	0.90
CI – Mg II	0.791	0.824	0.8328
Mg II – W	0.827	0.866	0.8797
Mg II – TSI	0.467	0.698	0.7785
With PSI corrections in the period of 1 January 1986 to 31 December 2005			
Mg II – TSI	0.692	0.703	0.7057
CI – TSI	0.669	0.699	0.7071

Note. The PSI values in this model set were downloaded from the San Fernando Observatory from http://davinci.csun.edu/~astro.

among the F10.7 radio flux, sunspot number, and TSI. Results are shown in Table 2; one sees that the F10.7 flux, originating in the corona, correlates a bit better with the two than that of CI and/or Mg II. CI thus lends itself as a more appropriate proxy than Mg II during the period of 1947 – 2005 (see Figure 8) and can be employed as a suitable proxy for modeling TSI if we do not have Mg II index data at our disposal.

We have tried to "recover" the behavior of TSI back to 1947 by employing the high correlation between TSI and PSI and CI in the period 1978 – 2005 and 1986 – 2005, respectively. The composite TSI data (W m^{-2}), derived from satellite measurements (see Fröhlich and Lean, 1998, and references therein) are shown in Figure 8 (upper part). The TSI data

Table 2 Correlations among the F10.7 radio flux, sunspot number (W), and composite TSI.

Without PSI corrections				
Index relation	Daily values	27-day means	81-day means	
F10.7 – W	0.938	0.970	0.979	(period 1947 – 2005)
With PSI corrections				
F10.7 – TSI	0.6994	0.7295	0.7412	(period 1986 – 2005)

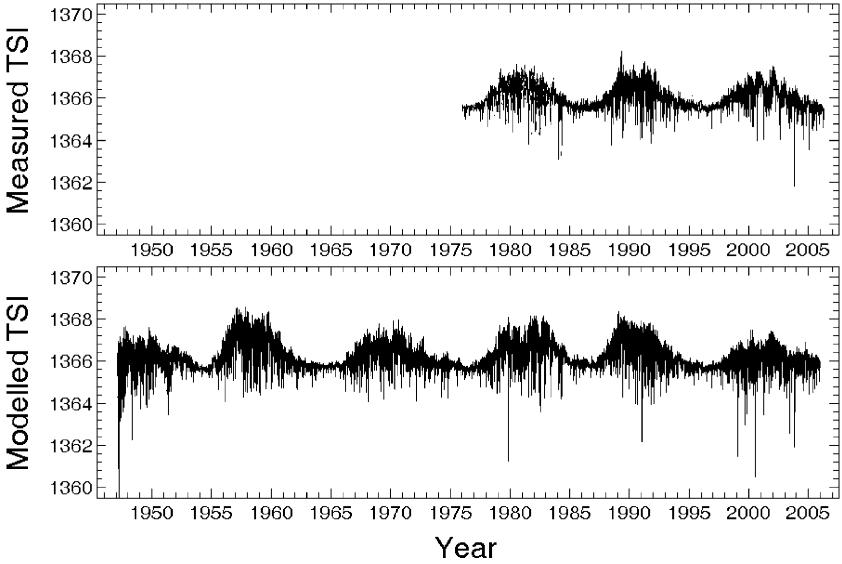

Figure 8 Measured (upper part) and "modeled" daily TSI data (lower part) by employing the distribution of CI within the period of 1947 – 2005 and that of the F10.7 radio flux.

calculated according to our procedure are shown in Figure 8 (lower part). We see a striking similarity between the TSI measured and that inferred from CI in the period from 1978 to 2005.

3. Discussion

The coronal index of solar activity ranks among the most important ground-based indices that express solar activity and may be used to study the relationship between various manifestations of solar activity and its influence on the heliosphere. The Fe XIV (green) corona radiation is produced by forbidden transitions in highly-ionized species that are excited by collisions and high-energy radiation, and the intensity is proportional to the integral of electron density along the line of sight to a power between 1.5 and 2 (*e.g.*, Guhathakurta *et al.*, 1992) and linearly to the temperature (Billings, 1966). Generally speaking, the higher the density and temperature, the higher the intensity of the Fe XIV corona. Increased intensities of the Fe XIV corona are observed above active regions where enhanced magnetic fields are observed as well. Very recently, Rušin and Rybanský (2002) and Rušin *et al.* (2007) have studied relationships between the Fe XIV corona and solar surface magnetic fields (Wilcox Solar Observatory and National Solar Observatory data) in the period of 1976 – 2004. They have found a good similarity between the magnetic-field strength or flux and intensities of the Fe XIV corona. This relation allowed us to extend the overall distribution of the strength of the magnetic field back to 1939, the onset of the Fe XIV corona observations. The magnetic strength and flux shows a variable magnitude in individual solar cycles with its maximum in cycle 19. This finding seems to contradict that of Lockwood, Stamper, and Wind (1999).

TSI is a fundamental parameter that describes the electromagnetic energy output observed from space since 1978 and is currently being used to study climate influence. Both the CI and TSI variations are connected with the occurrence of solar surface magnetic fields. We have compared the composite TSI with CI and the Mg II index over the period 1978 – 2005, where TSI was used in both the observed and PSI-corrected data in the period 1986 – 2005. The relationships between individual parameters in all cases are relatively good, and within the period under study the correlation between TSI and CI is slightly better than that between TSI and Mg II (see Table 1). This conclusion allows us to extrapolate the TSI course/variations (data) back to 1947 when radio F10.7 observations began. A good correlation between CI and TSI might indicate that TSI gradually increased from cycle 18 to 19 in cycle maxima, and from cycle 20 to 22. However, cycles 20 and 23, when compared with their predecessors 18 and 22, yield lower values of TSI.

A striking similarity between the TSI and CI plots, on both short- and long-term scales (see Figures 2, 3, and 4), enables us to do a compensation of positive excesses in the TSI distribution caused by active regions' local magnetic fields on the solar surface. TSI should be nearly constant over a cycle activity if there were no local surface magnetic fields on the Sun.

A very similar result has been obtained by Tobiska (2001) and is discussed by Lean (2001), who extrapolated TSI back to 1939 in the period 1939 – 2001 using EUV proxy. However, from Figure 4 one can discern that the values of TSI were a bit smaller in the minimum of cycle 22/23 when compared with those of cycle 21/22.

4. Conclusions

Having compared the variations of TSI, Mg II, and CI over a few solar cycles, we have found the following:

1. The long-term variations of all three indices are very similar to each other, especially around cycle minima, although each of them represents a different part of the solar atmosphere.
2. Variations of both CI and the Mg II index reflect very well the rotational period (see Figure 2), mainly around cycle minima and especially when just a single active region is present on the visible part of the solar surface.
3. In cycle 23, the values of TSI exceed those of CI data, even though in the preceding cycles they agreed relatively well.

As was stressed by several authors, the magnetic features that emerge from below the photosphere modulate solar radiative output in the solar atmosphere. If there were nonlocal strong magnetic fields in large active regions on the Sun, the TSI values throughout a cycle would remain "constant" and the Sun would not be a magnetically variable star. This statement is also valid for other transient features on the solar surface, because emergence of magnetic features in the solar atmosphere is strongly associated with irradiance variations. To understand physical causes of irradiance variations at different layers of the solar atmosphere, it is necessary to study the evolution of solar magnetic fields with both higher spatial and temporal resolution and in the whole range of the electromagnetic spectrum.

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