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Modified Coronal Index of the Solar Activity

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Abstract The original coronal index of the solar activity (CI) has been constructed on the basis of ground-based measurements of the intensities of the coronal line of 530.3 nm (Rybanský in *Bull. Astron. Inst. Czechoslov.*, **28**, 367, 1975; Rybanský *et al.* in *J. Geophys. Res.*, **110**, A08106, 2005). In this paper, CI is compared with the EUV measurements on the CELIAS/SEM equipment based on the same idea as the original idea of the coronal index. The correlation is very good for the period 1996 – 2005 ($r = 0.94$ for daily values). The principal result of this paper is the introduction of the modified coronal index (MCI) which in all uses and contexts can replace the existing CI index. Daily MCI values extend over a time period of six solar activity cycles. Future MCI measurements will be derived from more reliable measurements made by space-based observatories that are not influenced by the weather. MCI measurements are and will continue to be archived at the web site of the Slovak Central Observatory in Hurbanovo (http://www.suh.sk/obs/vysl/MCI.htm).

Keywords Corona · Solar cycle

1. Introduction

By constructing an index of the solar activity we seek to quantify a phenomenon, the essence of which is not known and which is actually defined only generally. It is a sort of a sum of variable phenomena which have a synchronous time sequence with a varying number and intensity during the so-called solar activity cycles. Previous observations showed that its length varies between 9 and 14 years.

Sunspots were the first variable phenomenon observed and the first index – Wolf number – was also derived from their observation. A number of variable phenomena followed from

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spectral observations, *e.g.* prominences and flares in the Hα line, some emissions in the core of absorption lines and emission lines of the corona, mainly the 530.3 nm line. Sporadic observations of this line have been carried out since 1939 and from 1947 onwards the observations have been conducted on a regular basis. Solar radio flux was discovered in the 1940s and from 1948 there have been regular solar observations of the total radio flux at the frequency of 2800 MHz. Sporadic solar observations in UV and X-ray regions of the spectrum have been carried out from the beginning of the 1960s. From 1986, regular observations in solar X-ray radiation with time resolution of 1 minute at two wavelengths (0.05 – 0.4 nm and 0.1 – 0.8 nm) have been conducted by stationary GOES satellites.

In addition to the observations at 2800 MHz (http://sidc.oma.be/sunspot-data/), there are also regular observations of solar radiation at many other radio and microwave frequencies between 100 and 15 400 MHz. Variability at the mentioned X-ray frequencies is much higher; 1:5000 and 1:10 000.

Elske, Smith, and Gottlieb (1974) and Dupree (1973) analyzed UV radiations of the Sun and they observed its increase in the variability in the solar activity cycle towards shorter wavelengths. At $\lambda = 10$ nm the ratio between the minimum and the maximum values is about 1:20, at $\lambda = 50$ nm about 1:5, at $\lambda = 100$ nm about 1:1.5; only sections without strong emission lines were taken into consideration. The results of these analyses show that long-term measurements of the intensity in any part of the UV section of the solar spectrum would be a suitable index of the solar activity. During the 1980s, measurements at NIMBUS and SMM satellites showed the variability of the overall irradiance of the Sun during the solar activity cycle at the level around 0.1% (in 81-day running mean). This discovery shows that solar activity may be one of the agents that has an impact on climate changes. A more suitable index than the Wolf number was sought for a more detailed study of the relation between the irradiance of the Sun and the level of solar activity. Minarovjech, Rušin, and Saniga (2007) presented a survey of literature where CI was proved to be the most suitable index for this purpose.

There are, however, also some disadvantages of CI.

i) It was constructed from ground-based patrol observations (for details see Section 2) and thus the completeness of the data depends on weather condition.
ii) For low CI values, the relative magnitude of its mean square deviation increases thus causing CI to be highly uncertain during minimum periods.
iii) Increases in the number of satellite observations has, for financial reasons, led to fewer ground observatories and, accordingly, increasing gaps in time between successive CI observations.
iv) CI values can only be calculated after the overall data assembly from all existing stations, that is, usually after a year. The index cannot be used for operative evaluation of the solar activity and a short-term forecast.

Therefore, we looked for a suitable measurement from a Sun-observing space-based probe, which might replace CI in the future and the whole time sequence of CI might be used thereby. We found it in the measurements conducted by CELIAS/SEM apparatus in the SOHO observatory.

In Section 2, we give a brief account of the construction of CI, Section 3 contains a comparison of CI with the measurements done on the CELIAS/SEM instrument and the construction of the modified coronal index of the solar activity (MCI), and Section 4 contains a summary of the main results.

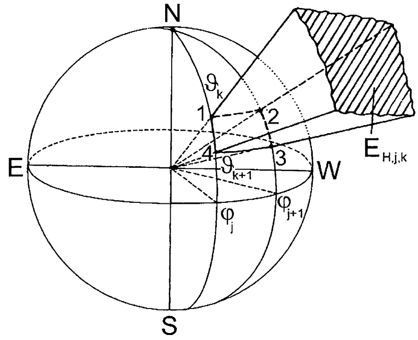

Figure 1 The construction of CI from ground-based intensity measurements of the coronal line 530.3 nm in coronal observatories (adopted from Rybanský, 1975).

2. Coronal Index of Solar Activity

The coronagraph was invented in 1930 by Lyot (1939); since then coronographs have been used for observing variations of the intensities of the coronal emission line of 530.3 nm around the solar disc. The main advantage of these observations is that they help us describe the solar activity also in high heliographic widths. After WWII a network of coronal stations was built up with the agenda of such observations. The most complete survey of them was given by Rybanský *et al.* (2005) and works cited therein. The measurements were used, among others, for determining the total irradiance of the Sun of the corona in the 530.3 nm line, which was later named the coronal index of the solar activity (CI). The way of calculation, displayed in Figure 1, is based on two assumptions:

i) That limb observations may be extrapolated to the solar disc.
ii) That there exists a mean height-gradient in intensity of the emission line. It means that the intensity of the green line in every height above the solar limb can be found out from measurements of its intensity at the standard height, what is around 50″.

It has been established that both assumptions are fulfilled only approximately and on average. No improvements to this calculation method have yet been found.

CI is then determined as the volume integral of volume luminosity in the area of the observable corona. Since observations of the green line of the corona are done only once a day, we need 13 days of observations for calculating the daily value of CI: six days after the given day for the western hemisphere values to be obtained from the west limb observations and six days before the given day for the eastern hemisphere values to be obtained from the east limb observations. Daily CI values were determined between 1939 and 2005 and their electronic form is available on the web site of the world data center (WDC-A, http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarcorona.html#green). Before 1943 there were only annual or monthly mean values available because there were only few real observations. The values of the measurements in the missing days are determined for the calculation of CI by interpolation.

Figure 2 shows monthly average CI values from the years 1939 – 2007, the last two years being based on the results obtained in this paper.

3. Coronal Index and SOHO/CELIAS/SEM

The SOHO/CELIAS/SEM (*Solar Extreme Ultraviolet Monitor*) contains a grating spectrometer designed to measure the absolute solar EUV flux of the Sun restricted by the aluminum

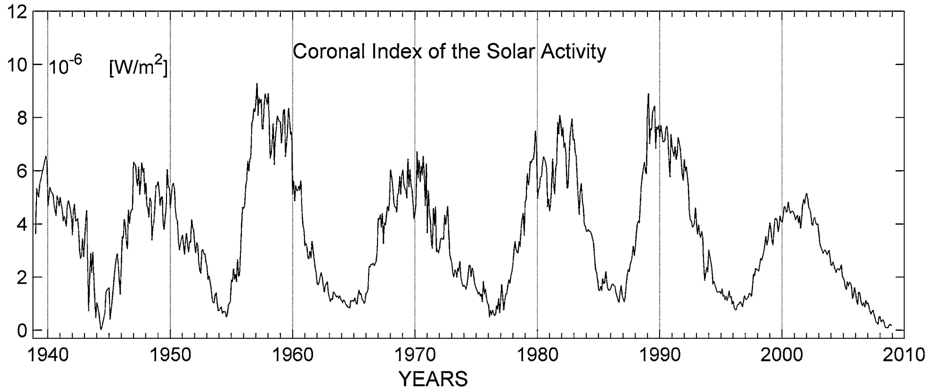

Figure 2 Coronal index of solar activity (monthly averages).

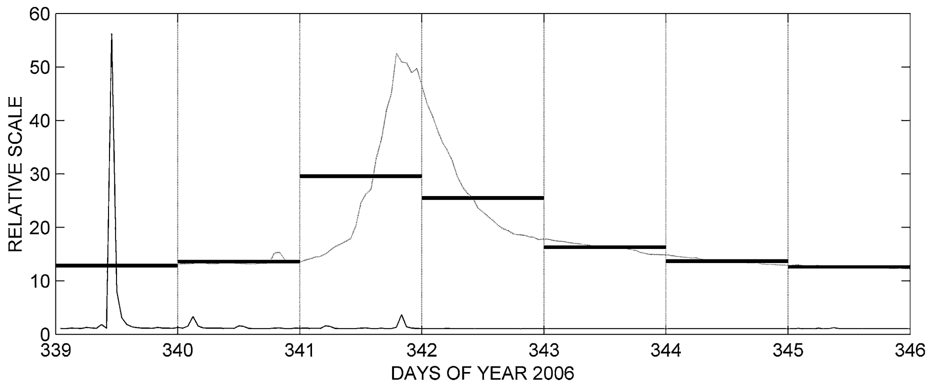

Figure 3 The mode of the reduction of "bursts". A solar flare is indicated by an impulse in X-rays in day 339 (full line), the burst on SEM occurs only about two days later (dotted line), when CME passes around the measurement equipment.

filters with different bandpasses and time resolution of 15 s. For the purpose of the comparison with CI, we selected daily averages of EUV flux in the bandpass 26 – 34 nm for the whole period of common observations: 1996 – 2005, that is 3653 days altogether. We chose the bandpass 26 – 34 nm because inside of it there are strong spectral lines He II (30.4 nm), Fe XIV (28.4 nm) and several lines of Fe XIV (26.79, 27.42 and 33.42 nm). In the intensity dominate the He II line, which arise in the chromosphere and in the transition region, but we do not have another choices because the second bandpass of the SEM instrument is much wider (0.1 – 50 nm). Before comparing, we adjusted both time sequences, CI and a series of measurements in the selected bandpass SEM(CE) as follows:

i) in CE we have eliminated the days when the instrument did not work (221 days) and the days with strong eruptions, when in some cases a short-term increase can be more than ten-fold. Such data are denoted in the data set as "adjusted for burst" and the increase in the level is removed by interpolation. Some increases are not connected directly with eruption but they are connected with the passage of high-energy protons in the vicinity of the measurement equipment or directly through it (for an example, see Figure 3). These cases were adjusted in the same way. Over the whole period studied

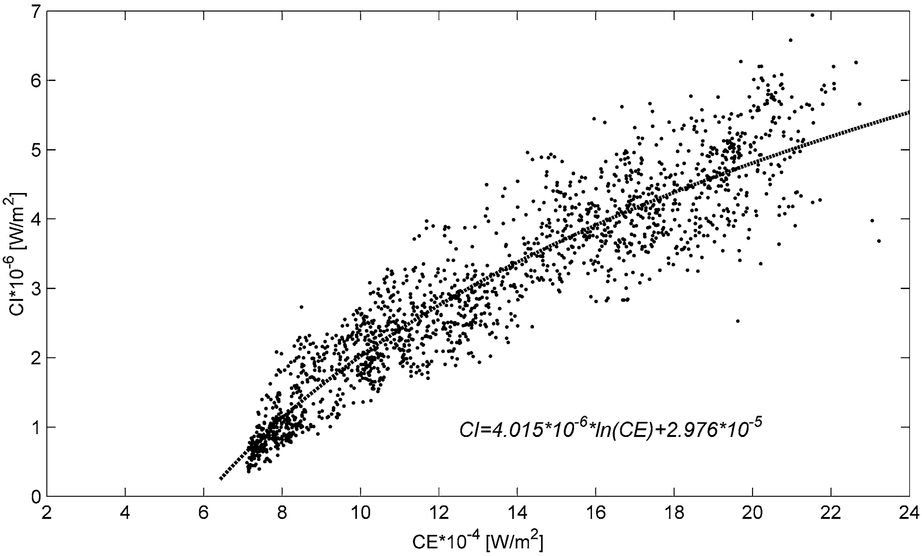

Figure 4 Scatter plot between CE and CI. The curve indicates the approximate relation of Equation (1).

there were 35 such cases and their list will be in the data archive that is under preparation (http://www.suh.sk/obs/vysl/MCI.htm).

ii) in CI for the purpose of comparison, we only selected the days when CI was determined on the basis of at least nine real measurements, *i.e.* of necessary 13 measurements. The values obtained by interpolation are for four days at most.

After these adjustments, there remained 1735 values to be compared. Both time sequences were transformed to equal units: $\mathrm{W\,m^{-2}}$ at a distance of 1 AU. CI was originally given in the so-called coronal units, which is the power emitted by the corona at the 530.3 nm line (in 10^{26} $\mathrm{W\,str^{-1}}$) and CE is given in the number of photons $\mathrm{cm^{-2}\,s^{-1}}$ at the distance of 1 AU (CI [$\mathrm{W\,m^{-2}}$] = 4.468 × 10.7 CI [coronal units]; CE [$\mathrm{W\,m^{-2}}$] = 6.622 × 10.14 CE [photons $\mathrm{cm^{-2}\,s^{-1}}$]).

Figure 4 shows the scatter plot between CE (abscissa) and CI (ordinate). For the approximating function we chose the logarithm for convenience and quality of fit without exploring its physical meaning. Then, using the least-square method we found the relation:

$$\mathrm{MCI} = 4.015 \times 10^{-6} \ln(\mathrm{CE}) + 2.976.10^{-5}, \tag{1}$$

if $\mathrm{CE} \geq 6.35 \times 10^{-4}\ \mathrm{W\,m^{-2}}$,

$$\mathrm{MCI} = (602.31 \times \mathrm{CE})^{16}, \tag{2}$$

if $\mathrm{CE} < 6.35 \times 10^{-4}\ \mathrm{W\,m^{-2}}$.

Expression (2) is an extension of the approximation expression (1) for low values of CE, where we have no corresponding values of CI, and it is based only on the assumption that both CE and CI values go to zero as solar activity decreases. Like the spline functions, the derivative of Equations (1) and (2) is identical for the value of $\mathrm{CE} = 6.35 \times 10^{-4}\ \mathrm{W\,m^{-2}}$.

Figure 5 shows the linearized CE – CI relation and the correlation coefficient $r = 0.94$ shows correlation in daily values higher than that obtained in comparison with radio emission at 2800 MHz with 81-day running average (Rybanský *et al.*, 2005).

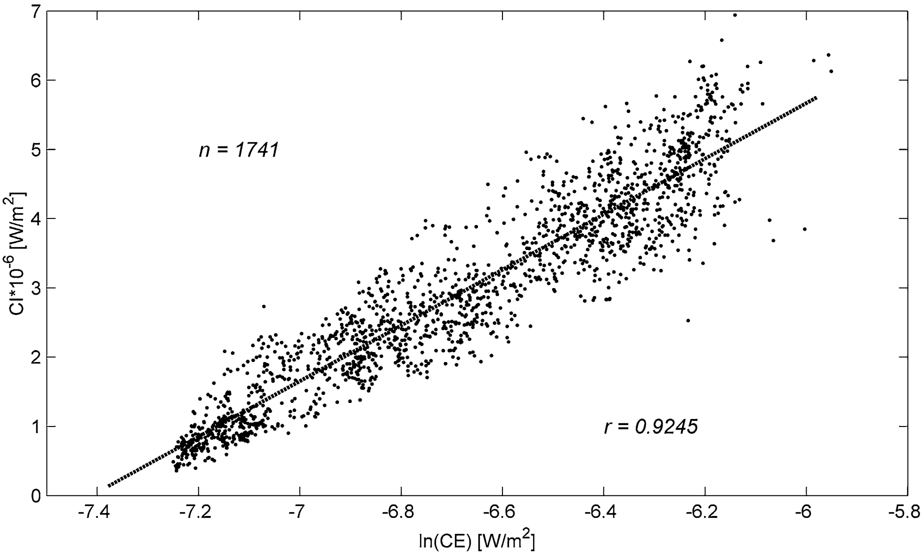

Figure 5 Scatter plot between ln(CE) and CI. Now the correlation looks linear.

SOHO/CELIAS/SEM measurements correlate very well with CI and after transforming according to the correlation relation found they can replace it very well.

The resulting modified coronal index of the solar activity (MCI) is available at http://www.suh.sk/obs/vysl/MCI.htm for every day in the years 1947 – present. Until 1995, it was the original CI transformed to units [W m^{-2}], from 1996, MCI represents CELIAS/SEM measurements transformed according the approximate relation of Equations (1) and (2) and adjusted in the presence of bursts. The missing data from the years 1998 and 1999, when observations at SOHO were interrupted, are also added. We found the values from the values of CI by inversely converting the approximate relation. Only monthly averages are reported for the years 1939 – 1946 because the observation days were only few.

4. Results and Conclusion

The advantage of CI is the long time sequence (from 1939 monthly averages and from 1943 daily values) and the fact that CI represents a comparable physical quantity. However, recently there is a lack of necessary observations due to the declining number of coronal observatories and deteriorating observation conditions (cirrus) caused by an increase in air transport. Here it is shown that solar extreme ultraviolet observations from above the absorbing atmosphere can serve as a viable alternative. Such observations are currently conducted by the CELIAS/SEM equipment aboard SOHO. We assume that identical observations will be routinely available in the future. The correlation with CI is very high. Considering additional extensions of the MCI into the future, EUV observations in the region surrounding He II 30.4 nm emission line are likely to continue to become available. Calibrated irradiance measurements having similar EUV wavelength bandpasses are ongoing (SORCE, TIMED SEE, and SOL-ACES) or are planned (GOES-R and SDO EVE). Where these measuring conditions (*e.g.* bandpass) are not identical, different transformation processing will most likely be required for their seamless integration into an extended MCI index data set. Daily values MCI for the years 1943 – 2008 are available at http://www.suh.sk/obs/vysl/MCI.htm.

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