LONG-TERM VARIATIONS IN TOTAL SOLAR IRRADIANCE

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Abstract. For more than a decade total solar irradiance has been monitored simultaneously from space by different satellites. The detection of total solar irradiance variations by satellite-based experiments during the past decade and a half has stimulated modelling efforts to help identify their causes and to provide estimates of irradiance data, using 'proxy' indicators of solar activity, for time intervals when no satellite observations exist. In this paper the variations in total solar irradiance observed by the Nimbus-7/ERB, SMM/ACRIM 1, and UARS/ACRIM II radiometers are compared to the changes in sunspot darkening and the enhanced emission of bright magnetic elements, including faculae and the magnetic network. Quantitative indices of sunspot darkening have been derived from the area and position of sunspots published in the NOAA-WDC Solar Geophysical Data catalogoue. The Mg core-to-wing ratio, derived from the irradiance observations of the Nimbus-7 and NOAA9 satellites, is used as a proxy for the bright magnetic elements. It has been found that a model, calculated from the Mg II core-to-w'ing ratio underestimates the observed total irradiance at the time of maximum and during the beginning of the declining portion of solar cycle 22 similar to behaviour just before the maximum of solar cycle 21. Similar results are found using the He-line equivalent width and 10.7 cm radio flux which indicates that the current irradiance models are in general not capable to reproducing the changes observed in total solar irradiance.

Key words: Total solar irradiance - solar activity - sunspots - faculae - network

1. Introduction

The precise and continous determination of the value of the total solar energy flux impinging on the Earth and its variation is one of the principal concerns for both climatic and solar physics studies, since the solar radiative output, is the main driver of the physical processes within the Earth's atmosphere. Thus the monitoring and study of the changes in total irradiance are extremely important. There are indications that changes in the solar output influence the Earth's climate on time scales ranging from the Gleissberg cycle (Reid, 19S7, l~riirx-Christensen & Lanssen, 1991) up to the Maunder

Minimum type of climate anomalies (Lean et al., 1992, Ribes, 1993). Further, to understand the human effect in the global than.gc of the climate, it is essential to reveal the role of the solar irradiance variations in the terrestrial and atmospheric processes.

For more than a decade total solar irradiance has been monitored from space by different satellites, These observations have revealed variations in total irradiance ranging from minutes to the 11-year solar cycle (Willson & Hudson, 1991). It has been shown that the very small, rapid irradiance fluctuations are due to solar oscillations (e.g. Fröhlich, 1992). The short-term variations (from days to months) are directly produced by the passage of active regions (Willson, 1982, Pap, 1985, Fröhlich & Pap, 1989) with dark sunspots and bright faculae (Chapman, 1987). The most important discovery of irradiance observations was the enhancement of solar luminosity during the high activity part of the solar cycle (Willson & Hudson, 1991, Hoyt et al., 1992) that is attributed to the enhanced emission of bright faculae and the magnetic network (Foukal & Lean, 1988).

Although considerable information exists about the variations in total solar irradiance, their physical origin is not well understood. Results of multivariate spectral analysis show that considerable variation in total irradiance remains unexplained after removing the effect of dark sunspots and bright magnetic elements, and the residual variability changes with the phase of the solar cycle (Pap & Fröhlich, 1992). Furthermore, empirical models of total solar irradiance, developed from various solar activity indices, such as the full disk equivalent width of the He-line at 1083 nm (HeI), the behaviour of various Fraunhofer lines, and the 10.7 cm radio flux (Foukal & Lean, 1988, Livingston et al., 1988, Pap et al., 1992, Fröhlich, 1993), disagree significally with the irradiance observations at the maximum of solar cycle 21. The main purpose of this paper is to estimate total solar irradiance at the maximum of solar cycle 22 to clarify whether the disagreement between irradiance observations and the proxy estimates has an intrinsic solar or instrumental origin. The uncertainties in the proxy data used for irradiance modelling and the resulting limitation of the models are also discussed.

2. Observational Data

Measurements of total solar irradiance used in this study were performed by the Nimbus-7/ERB, SMM/ACRIM 1, and UARS/ACRIM 11 radiometers. The irradiance observations on board the Nimbus-7 satellite began in November 1978 and data are available through November 30, 1992 (Hoyt et al., 1992). The high precision irradiance observations of the Solar Maximum Mission satellite started in February 1980 and ended with re-entry of the SMM spacecraft in November 1989 (Willson & Hudson, 1991). The daily ACRIM 1 irradiance data. are available from February 1980 through June

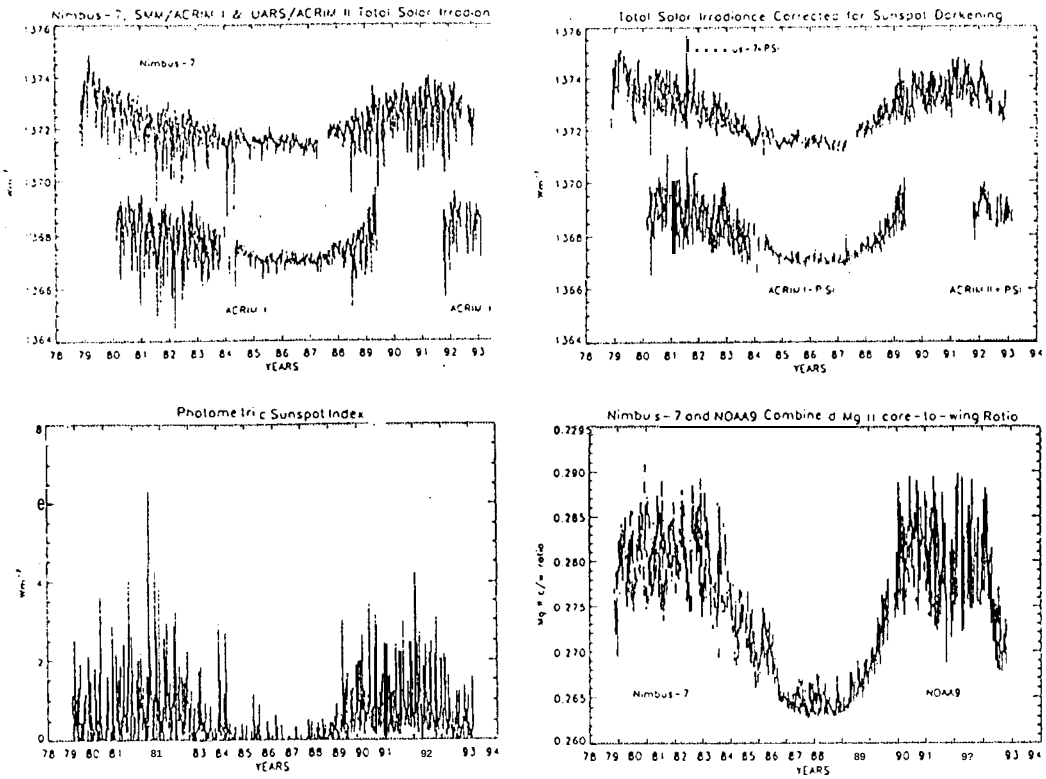


Fig. 1. Time series of total solar irradiance measured by the Nimbus-7/ERB, SMM/ACRIM 1 and UARS/ACRIM II radiometers (a), the Photometric Sunspot Index (b), total solar irradiances corrected for sunspot darkening (c), and the combined Nimbus-7 and NOAA9 Mg c/w (d).

1989. The second ACRIM radiometer began to operate on board the Upper Atmospheric Research Satellite on October 4, 1991 and continues into the present. The UARS/ACRIM II irradiance data are available for this study from October 1991 through, February 1993. The daily values of the three total irradiance data sets are presented in Fig. 1a. Note that the SMM/ACRIM 1 and UARS/ACRIM II data are adjusted to each other through their mutual intercomparisons with Nimbus-7/ERB. A detailed information on this topic is given by Willson, 1993.

The Photometric Sunspot Index (*PSI*) has been developed to study the effect of sunspots on total solar irradiance (e.g. Hudson et al., 1982). However, results of direct sunspot photometry discovered the dependence of the contrast of the sunspots on their area (Steinegger et al., 1990, Chapman et al., 1992). It has also been found that the former *PSI* models overestimate the sunspot effect on total irradiance by about 40% (Chapman et al.,

1992) . Therefore, a new PSI model has been developed by Fröhlich et al., 1993 taking into account the area dependence of the sunspot contrast among other *effects, such* as screening, daily mean values and different limb darkening functions, Mainly the screening for outliers improves significantly the homogeneity of the data set. The newly calculated PSI, used in this study, is shown in Fig. 1b. The daily values of total solar irradiance corrected for the sunspot darkening by adding PSI are presented in Fig.] c.

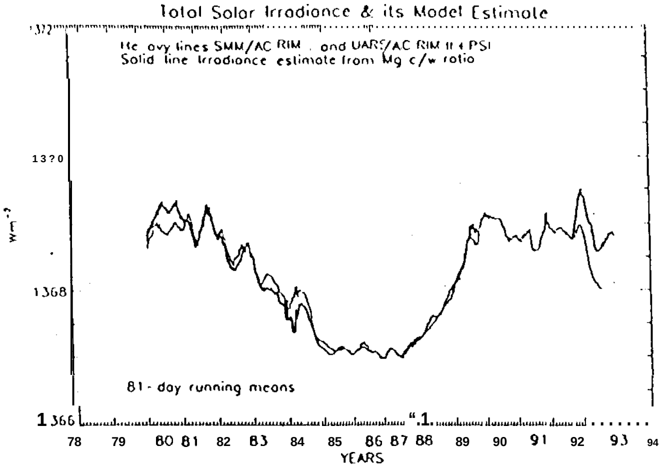
'l'he Mg 11 h & k core-to-wing ratio (Mg c/w) is used as proxy for the bright magnetic elements, including plages and the magnetic network (Fig. 1 d). 'l'his quantity is calculated from the observations of the SBUV experiments on the Nimbus-7 and NOAA9 stallites (Heath & Schlesinger, 1986, Donnelly, 1991). The Nimbus-7 and NOAA9 Mg c/w were made consistent by the means of their overlapping observational time period in 1986, and also by the means of the full disk Ca 11 index. Since the formation of the Mg line is very similar to that of the Ca 11 K line, the Mg c/w provides a reasonable good index for. the plage and network radiation.

3. Empirical Models of Total Solar Irradiance

'l)ot al solar irradi ance corrected for sunspot darkening is est i mat ed from the Mg c/w ratio using linear regression analysis. The estimated irradiance data arc calculated from the equation $y = a + b, x$, where a and b arc the regression coefficients, x contains the daily mean values of the Mg c/w ratio and y gives the best-fit linear relationship (by minimizing χ^2) between total irradiance corrected for sunspot darkening and the bright magnetic elements represented by Mg c/w, Since the correlation between total irradiancc and solar activity indices depends on the phase of the solar cycle (Pap & Fröhlich, 1992, l'ap et al., 1992), the irradiance models were developed for the maximum, declining portion and minimum of solar cycle 21 and for the rising portion and maximum time of solar cycle 22, respectively. in a first step, the models are calculated for the period of the SMM/ACRI M 1 observations from February 1980 to June 1989. This period is devided in the following intervals:

- (1) February 1980 **to June** 19S4 (maximum and declining portion of solar cycle 21),
- (2) July 1 984 to August 1986 (minimum of solar cycle 21),
- (3) September 1986 to June 1989 (rising portion of solar cycle 22).

To extend the irradiance models after June 1, 1989 the regression coefficients calculated for the time interval from February 1980 to June 1984 has been used. Fig. 2a shows the 81-day running means of the SMM /ACRIM 1 and UARS/ACRIM II total irradiance data after the correction by PSI. The solid line shows the 81-day running means and of the irradiance model estimates developed from the Mg c/w with linear regression analysis. The



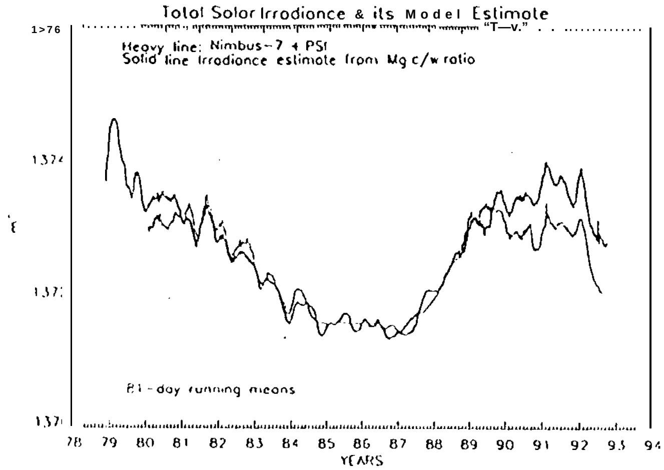


Fig. 2. 81-day running mean of the SMM/ACRIM I and UARS/ACRIM II total solar irradiance corrected by PSI (heavy line in a) and of the irradiance estimates calculated from the Mg c/w ratio (solid line in a). (b) same as (a) but for Nimbus-7/ERB irradiance data.

same model has been developed for the Nimbus-7/ERB total solar irradiance corrected by PSI, and is shown in Fig. 2b.

As can be seen from Figs. 2, the estimated values of total solar irradiance corrected for sunspot darkening considerably underestimate the observed irradiance values at the maximum time and the beginning of the declining portion of solar cycle 22. Note that irradiance models calculated from the full disk He-line equivalent width at 1083 nm and 10.7 cm radio flux (Brandt et al., 1993, Fröhlich, 1993) show the similar discrepancy between the observations and model estimates. These results clearly show that the current irradiance models underestimate the real amplitude of the solar-cycle-related long-term changes in total solar irradiance and the models cannot reproduce the observed changes in total irradiance.

4. Uncertainties in the Models of Total Solar Irradiance

The breakdown between the observed total irradiance and its model estimates during solar maximum is one of the current outstanding problems in solar physics and is indicative of the fact that we do not understand the physical origin of the variability observed in the solar radiative output. The uncertainties in the proxy data used to construct these statistical irradiance models are surely part of the problem. The usefullness of these irradiance models for climate studies is limited by their inherent uncertainties.

One of the largest, uncertainties in the irradiance models, especially on long time scales, originates from the lack of knowledge of the effect of faculae principally because of the lack of high quality synoptic data. While more than 90% of total solar irradiance is emitted from the photosphere, most of the irradiance variations related to the bright magnetic elements are modelled by chromospheric proxy data, such as the Ca II K plages, HeI, Mg c/w and 10.7 cm radio flux. However, the conversion factor between the area and intensity of the chromospheric plages and photospheric faculae is not known; the center-to-limb behavior of the contrast of white light faculae is quite different from that of Ca **K** plages (e.g. Chapman et al., 1992, Schatten & Mayr, 1992). The situation is far more difficult since the spatially resolved Ca K plage data observed at the Big Bear Solar Observatory does not include the remnants of plages and other network elements that give a significant contribution to the changes in total (and also in UV) solar irradiance (Pap et al., 1990). It should also be noted that the available resolved Ca K plage data are from three different sources:

- (1) from December 1970 till September 1979 observed at the McMath Observatory,
- (2) from October 1979 till August 1982 observed at the Mt. Wilson Observatory,
- (3) from September 1982 till November 1987 observed at the Big Bear Solar Observatory.

This indicates that no homogenous spatially resolved plage data set is available for studying irradiance variations, and after November 1987 no plage area and intensity data are measured and published on a routine basis (Marquette, 1992).

It has also been shown that the evolution of active regions plays an important role in the irradiance changes (e.g. Willson, 1982, Pap, 1985, Fröhlich & Pap, 1989), but the evolutionary effects arc not really included in the irradiance models. The additional sources of the Ca II K data (White et al., 1992), the Mg c/w ratio, the He-line equivalent width at 1083 **nm**, and the 10.7 cm radio flux are full disk indices, therefore, these proxies cannot provide information either on the evolutionary effects or the contribution of the plage and network radiation to the changes in solar irradiance. On the other hand, the variation of the He-line equivalent width and the 10.7 cm radio flux is rather complex and not well-understood (Harvey, 1984, Tapping, 1987). It has been shown that while most of the variations in the He-line equivalent width is related to the Ca K plages, a substantially large fraction of its variability is related to the filaments (Harvey & Livingston, 1993) that do not effect total solar irradiance. Furthermore, it is not clear whether the irradiance effect of the small network elements is included in the plage-related variation of the He-line equivalent width (Harvey & Livingston, 1993). The variability of the 10.7 cm radio flux is attributed to gyroresonant absorption and free-free (bremsstrahlung) emissions (Tapping, 1987). The latter is supposed to be related to weaker magnetic fields concentrated in plages and in the m agnetic network, while the former one is related to the strong magnetic field of the sunspots, These results clearly show that the above proxies used in the current irradiance models give only a rough estimate for the behavior of the faculae and their effect on total solar irradian ce.

The lack of the good synoptic data sets for sunspots has to be mentioned too. The publication of the high precision area and position of the sunspots in the Greenwich Catalogue ended in 1976. Since then the sunspot observations are reported in the NOAA-WDC Solar Geophysical Data catalogue. The current precision of the measurements of the area of sunspots is about 20-25% for large sunspots and it can be as high as 50% for small spots (Sofia et al., 1982). Fröhlich et al., 1993 show that the irregularities in the sunspot area reports cause the largest uncertainty in the PSI. Furthermore, no observational information exists on the area and intensity of the umbrae and penumbrae of sunspots, Part of the observed change of contrast with time (Fröhlich et al., 1993) could be due to changes in the umbra- penumbra intensity and/or area ratio. The results of sunspot photometry also show that the contrast changes with even during the passage over the visible disk and is normally overestimated in PSI calculations (Steinegger et al., 1990, Chapman et al., 1992). Moreover, the contrast of sunspots changes over the solar cycle (Maltby et al., 1986) and all these details are not incorporated in the irradiance models.

Another important aspect to be pointed out is that the current observat ions of total solar irradiance cover only 14 years, not much more than one solar cycle, From this short observing period it is hard to establish accurate irradiance models, mainly because it is difficult to judge the representativeness of the proxies, even if their quality is good. It must also be underscored that the current irradiance models are only empirical models developed with simple linear regression analysis and no adequate physical model of irradiance variations exists as yet. The large uncertainties in the irradiance proxies, the lack of adequate irradiance models, and the existing disagreements between the observed changes in total irradiance and its model estimates emphasize the need to provide continuous total solar irradiance monitoring while extending and expanding investigations aimed at better understanding the physical origin of irradiance changes.

5. Conclusions

A simple empirical model of total solar irradiance corrected for sunspot darkening has been developed from the Mg II h & k core-to-wing ratio with linear regression analysis. The newly calculated Photometric Sunspot Index (Fröhlich et al., 1993) was used for removing the effect of sunspots from total solar irradiance. It has been found that the models underestimate the observed irradiance values at the maximum time and the beginning of the declining phase of solar cycle 22, similar to solar cycle 21. These results show that the disagreement between irradiance models and observations, found first by Foukal & Lean, 1988 for the maximum of solar cycle 21, seems to be more of a problem with the models than with the instruments.

Part of the found discrepancies can be due to the uncertainties in the proxy data. The inherent limitation of these simple empirical models must have to be kept in mind when irradiance models are used. Considering the significance of irradiance variations as a causal mechanism for climate change, continuous observations of total irradiance from space are necessary to maintain a long-term, high precision irradiance data base for climatic studies. In parallel with the direct irradiance observations, advanced theomtical and statistical studies of the observed irradiance validations are required. The ultimate goal is to understand (1) why, **(2) how,** and **(3)** on what time scale the total solar irradiance varies in order to reconstruct and predict the solar induced climatic. changes.

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