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Modulation in the solar irradiance due to surface magnetism during cycles 21, 22 and 23

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Abstract. Magnetic field indices derived from synoptic magnetograms of the Mt. Wilson Observatory, i.e. Magnetic Plage Strength Index (MPSI) and Mt. Wilson Sunspot Index (MWSI), are used to study the effects of surface magnetism on total solar irradiance variability during solar cycles 21, 22 and 23. We find that most of the solar cycle variation in the total solar irradiance can be accounted for by the absolute magnetic field strength on the solar disk, if fields associated with dark and bright regions are considered separately. However, there is a large scatter in the calculated and observed values of TSI during solar cycle 21. On the other hand, the multiple correlation coefficients obtained for solar cycles 22 and 23 are 0.88 and 0.91 respectively. Furthermore, separate regression analyses for solar cycles 22 and 23 do not show any significant differences in the total solar irradiance during these cycles. Our study further strengthens the view that surface magnetism indeed plays a dominant role in modulating solar irradiance.

Key words. Sun: solar-terrestrial relations – Sun: activity – Sun: photosphere – Sun: magnetic fields

1. Introduction

The study of solar irradiance has evoked considerable interest in recent years. Several space borne experiments in the last two and a half decades clearly show that it varies in phase with the solar magnetic activity cycle over time scales of from minutes to years and decades (Wilson & Hudson 1988). It is believed that these variations are associated with the evolution of magnetic fields (e.g. Lean et al. 1998, and references therein) and the models based on such an assumption have been successful to some extent in explaining the irradiance variability. Most of these models are based on measurements of various solar features which represent the magnetic activity at different heights in the solar atmosphere. In particular, chromospheric proxies have been widely used to estimate the enhancement in irradiance due to brightening (Lean & Foukal 1988; Foukal & Lean 1988, 1990; Brandt et al. 1994; Fligge et al. 1998; Fröhlich & Lean 1998; Lean 2000a; de Toma et al. 2001; Preminger et al. 2002; Foukal 2002; Fröhlich 2003a; Ermolli et al. 2003; Jain & Hasan 2004). On the other hand, the reduction in irradiance due to dark regions on the solar surface is generally estimated by the photometric sunspot index (PSI), which depends on the location and contrast of sunspots on the solar disk. However, not much effort has been made to use direct measurements of magnetic field strength on the solar surface to model the observed irradiance and finally, to understand the role of the evolutionary surface magnetic field in irradiance variability. Also, the empirical models emphasizing the contributions of photospheric magnetic structures seem to provide better prospects for an improved physical understanding of sun-climate links (Foukal 2002).

Synoptic observations of the solar magnetic field are now available for more than three decades, thus providing a reasonably long data base that has sufficient overlap with the irradiance measurements to carry out studies based on direct observations of fields. In an earlier attempt, Chapman & Boyden (1986) separated out the regions of absolute magnetic fields between 10 and 100 Gauss, and the regions of fields above 100 Gauss on magnetograms taken at the Mount Wilson Observatory (MWO). The magnetic field strengths of these regions were used to model irradiance variations as measured by the Active Cavity Radiometer Irradiance Monitor I (ACRIM I) for the period 1980–84, which covered the analysis during the declining phase of the solar cycle only. It was emphasized that the decrease in irradiance observed during this period was caused by the declining magnetic activity. Later, Parker et al. (1998) used a similar index derived from MWO magnetograms, commonly known as the magnetic plage strength index, to model solar UV and EUV irradiances and obtained a high correlation between variations in the magnetic plage strength index and variations in the UV indices and the 10.7 cm radio flux. In a different approach, the total and spectral solar irradiances were successfully reconstructed by combining a time series of daily magnetograms from the Michelson Doppler Imager (MDI) on SoHO along with empirical models of the thermal structure of magnetic features (sunspots and faculae) for cycle 23 (Solanki & Fligge 2002; Krivova et al. 2003).

Thus, these studies along with those by Fröhlich & Lean (1998; see also Fröhlich 2003a), using indirect proxies of the magnetic field, were strongly indicative of the influence of surface magnetism in modulating the total and spectral solar irradiance.

On the other hand, it was argued by de Toma et al. (2001) that the solar irradiance at the current cycle maximum is very similar to that at the previous maximum while various indicators of solar magnetic activity are much lower in cycle 23 than in cycle 22, implying that surface magnetism is not the sole cause for irradiance change. Later, Jones et al. (2003) confirmed this discrepancy between cycles 22 and 23 using spectromagnetograph (SPM) data of the National Solar Observatory (NSO) for the period 1992–2000; these authors carried out analyses for cycles 22 and 23 and obtained substantially different regression parameters. However, inter-cycle trends remained unexplained in this study as the residuals of a linear multiple regression of the total solar irradiance against SPM observations over the entire period showed an increasing linear time variation with a rate of about 0.05 W/m^2 per year. Thus, the magnetic association of the solar irradiance variability, in particular the cycle-to-cycle variations in TSI, needs to be re-examined carefully in the light of the above mentioned studies. This is the main objective of the present investigation.

In our earlier study (Jain & Hasan 2004), we showed that various chromospheric proxies for facular brightenings contribute differently to the solar irradiance. We demonstrated that the facular term in current empirical models (using facular area or radio flux proxies) on short time scales needs to have a non-linear component in order to obtain a better correlation with the observed irradiance. Now, with the availability of direct measurements of the magnetic field from various sources with a long overlap with irradiance observations from space, it is necessary to re-assess the role of surface magnetism on irradiance variability on time scales from days to years and decades. Furthermore, understanding and successfully modeling the irradiance variations are important for the reconstruction of irradiance in the pre-satellite period, which may play a crucial role in understanding climatic changes in past centuries.

In the present paper, we employ a simple bivariate regression analysis based on direct measurements of the magnetic field on the solar surface and the total solar irradiance. Our approach is similar to that of Chapman & Boyden (1986); however, it considers a much longer TSI time series of about 25 years. Based on the evolution of the solar surface magnetic field, here represented by field measurements by the MWO, we obtain a good agreement between the reconstructed irradiance and the composite time series of the total solar irradiance for the period 1978–2003. We also carry out separate regression analyses for solar cycles 21, 22 and 23 to study the differences, if any, in cycles 22 and 23, as reported in earlier studies (de Toma et al. 2001; Jones et al. 2003); these are important for studying the sources of irradiance variability.

The plan of the paper is as follows: in Sect. 2, we briefly outline the irradiance and magnetic field measurements which are used in the analysis. In Sect. 3 we discuss our results using irradiance measurements from individual experiments and also using composite time series for the entire period of irradiance observations. A comparison of our results for solar cycles 21, 22 and 23 is also made to study the differences between them. Finally, the discussion on the importance of surface magnetism in modulating the daily solar irradiance in different solar cycles and the summary of the results are given in Sect. 4.

Table 1. Summary of the irradiance data sets.

TSI data source	Period	Entries
ERB/NIMBUS-7	Nov. 16, 1978–Dec. 13, 1993	4584
ACRIM I/SMM	Feb. 16, 1980–Jun. 1, 1989	3053
ACRIM II/UARS	Oct. 4,1991–May 5, 2001	3275
VIRGO/SOHO	Feb. 7, 1996–Oct. 1, 2003	2624
Composite time-series	Nov. 17, 1978–Oct. 1, 2003	8405

2. The data: Irradiance and magnetic field measurements

The present study is based on two data sets. One of these is the total solar irradiance (TSI) measurements from space by various radiometers for the last two and a half decades. The description of individual observations is summarized by Fröhlich & Lean (1998) along with the technique to combine them into a single data set. This composite time series provides consistent data to study the TSI variability during the last two solar cycles. In the present study we use data on solar irradiance variability from individual observations as well as from composite time series. Table 1 summarizes each data set, including the time period of data collection, and the total number of days in the data record. We use version $d25\_07\_0310a$ for the composite TSI time series and version $v5\_007\_0310a$ for VIRGO data with updated TSI data till October 1, 2003 (Fröhlich 2003a,b).

The other data set comprises the magnetic field measurements taken at the 150-Foot solar tower of the Mount Wilson Observatory (Ulrich et al. 1991), where daily magnetograms have been obtained using the magnetically sensitive Fe I 525.0 nm line for more than thirty years. For each magnetogram taken, two indices are calculated: the Magnetic Plage Strength Index (MPSI) and the Mount Wilson Sunspot Index (MWSI). The MPSI is defined as the sum over the absolute value of the magnetic field strengths for all pixels where the absolute value of the magnetic field strength is between 10 and 100 Gauss. This number is then divided by the total number of pixels (regardless of the magnetic field strength) in the magnetogram. The MWSI is determined in a similar way as the MPSI, though the summation is done only for pixels where the absolute of the magnetic field strength is greater than 100 Gauss. These magnetic levels were earlier determined by Chapman & Boyden (1986) where sunspots and faculae were defined solely on the basis of intensity of the magnetic field. To obtain the boundaries of sunspots and faculae, these authors made iso-gauss contours which provide the best fit to the outlines of these solar features as seen on white light photographs. They tried several different levels near these regions and finally determined the best match for sunspots at 100 Gauss and for faculae at 10 Gauss. Further, the cut-off level of 10 Gauss is chosen to prevent the inclusion of

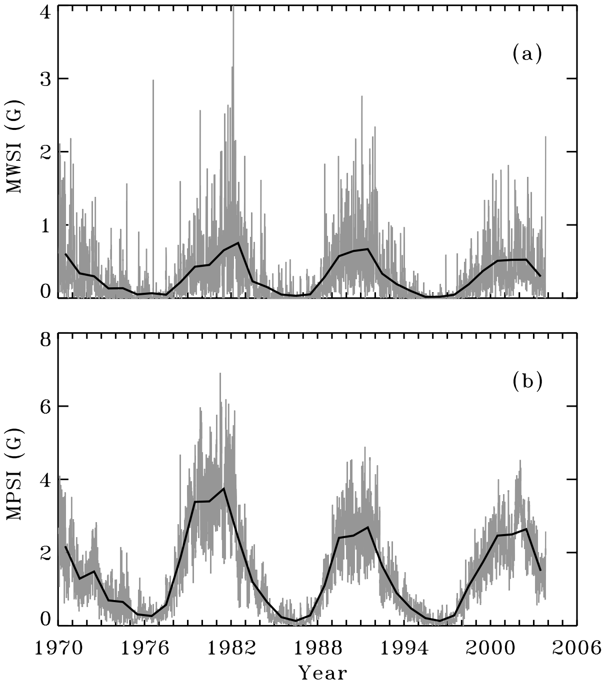

Fig. 1. A time series of **a)** Mt. Wilson Sunspot Index, MWSI and **b)** Magnetic Plage Strength Index, MPSI, where the daily variations are shown in grey. The dark lines show the bin averages over 365 days.

system noise. Thus, the MPSI and the MWSI provide magnetic field strengths of the bright and the dark regions on the solar disk which are primarily responsible for the TSI variability. The daily variations of MPSI and MWSI since 1970 are shown in grey in Fig. 1, and the annual variation is shown by the dark line.

3. Analysis and results

Our analysis is based on the assumption that the variations in TSI are entirely caused by the changes in solar surface magnetic fields. This allows us to fit the daily values of TSI with linear regression of the form

$$\mathrm{TSI} = C_{\mathrm{quiet}} + C_1 A_{\mathrm{MPSI}} + C_2 A_{\mathrm{MWSI}} \tag{1}$$

where the contribution from the quiet Sun, C_{quiet}, is assumed to be a constant over the period considered in this analysis and the other two terms refer to the contribution due to variations in the magnetic field strength. The coefficients C_1 and C_2 are related to changes in surface magnetism due to bright and dark regions on the solar disk respectively whereas A_{MPSI} and A_{MWSI} are measures of the magnetic field strength as defined in Sect. 2.

3.1. TSI data from individual observing missions

In Fig. 2, we show the reconstructed solar irradiance for three different solar activity periods using TSI data from the Hickey-Frieden (HF) radiometer of the Earth Radiation Budget (ERB) experiment on the NIMBUS-7 spacecraft for the period 1978–1993 (Hoyt et al. 1992). The multiple correlation coefficient, R, for all of the ERB/NIMBUS data is determined to be 0.78. Figures 2a and c show variations in the modeled TSI (shown by asterisks) for the high activity periods in solar cycles 21 and 22 respectively, while Fig. 2b is for the period of minimum activity. The ERB total irradiance measurements are also shown by a solid line. It is evident from the figure that the irradiance variations are overestimated by the magnetic field indices during the high activity period in cycle 21. However the calculated values are in better agreement with the observations in cycle 22 (as shown in Fig. 2c). We obtained similar results with a low multiple correlation coefficient ($R = 0.79$) for TSI observations from ACRIM I operated on the Solar Maximum Mission (SMM), which span the periods of high activity in cycles 21 and 22 (Wilson & Hudson 1991). In an earlier attempt, Chapman & Boyden (1986) also obtained $R = 0.65$ using five years of data from ACRIM I, i.e. 1980–84 together with the measurements of MWO. This value is much lower than our value obtained for the entire TSI observation period by the ACRIM I satellite.

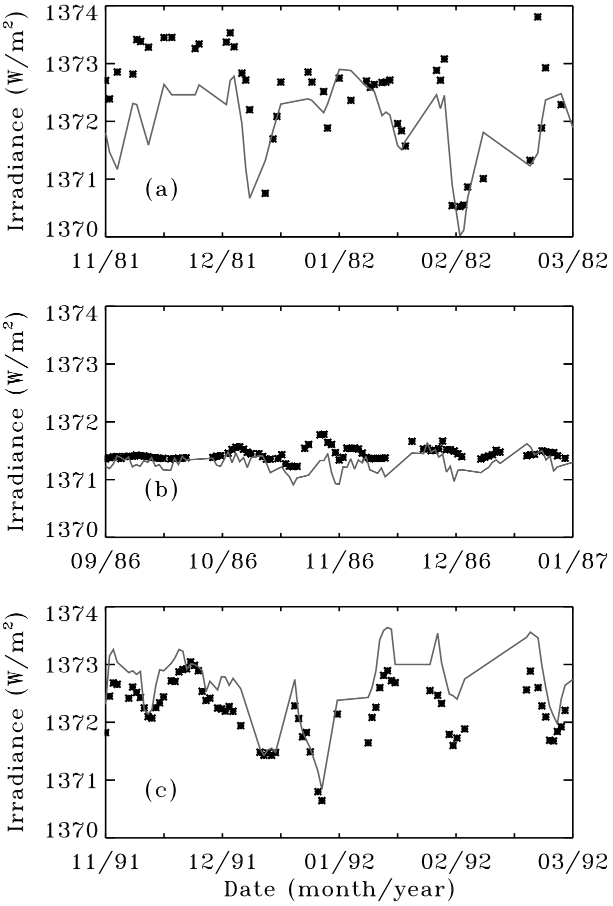

Fig. 2. The modelled total solar irradiance based on the magnetic field measurements of MWO, i.e. MPSI and MWSI, using TSI data from ERB on NIMBUS-7 satellite for the period 1978–1993. The daily variation in the reconstructed irradiance at three different activity periods, i.e. **a)** high solar activity during cycle 21, **b)** lower solar activity, and **c)** high solar activity during cycle 22 is shown by the asterisks and the variations in the observed TSI are shown by the solid line.

We now consider TSI observations with ACRIM II on the Upper Atmosphere Research Satellite (UARS), which began in the high activity period of cycle 22 and continued till the maximum activity period of cycle 23 (Wilson 1994). In Fig. 3 we

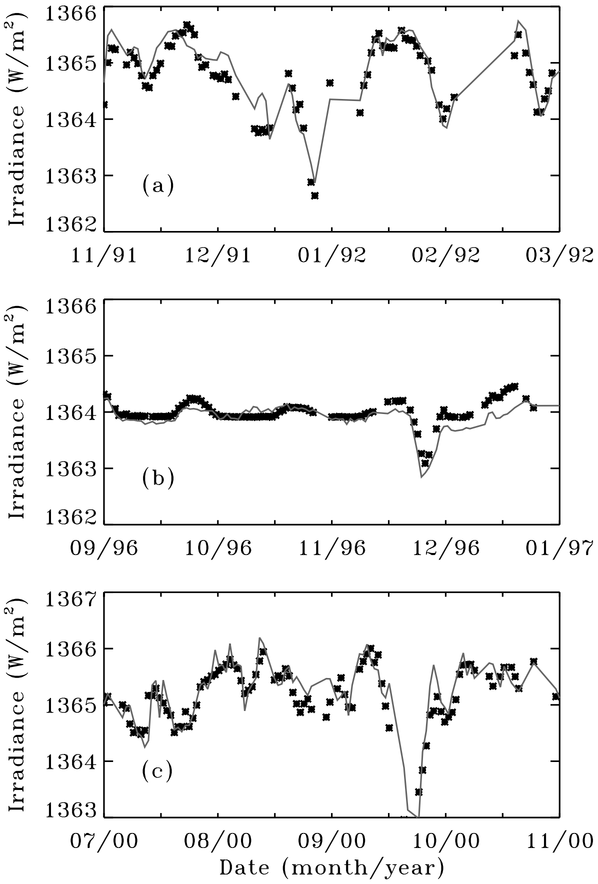

Fig. 3. The daily variation in the modeled and observed total solar irradiance at **a)** high solar activity during cycle 22; **b)** lower solar activity; and **c)** high solar activity during cycle 23. The solid line is for the TSI observations from ACRIM II on the UARS satellite and the asterisks show the modeled values.

show observed and reconstructed irradiance variations for three different activity periods during the ACRIM II observations. In contrast to our results discussed earlier for the ERB/NIMBUS and ACRIM I/SMM data sets, we obtain a good correlation between observed and calculated values, with a multiple correlation coefficient $R = 0.91$. Figure 3a shows the variations in reconstructed and observed TSI for the high activity period in cycle 22, which can be directly compared with Fig. 2c where we show the variations using ERB/NIMBUS data set for the same period. It is evident that the exclusion of cycle 21 improves the correlation significantly. Figure 3b shows the variation during the period of minimum activity and Fig. 3c for the maximum activity period in cycle 23, confirming that small fluctuations in irradiance can be accounted for by surface magnetic field variations.

In Fig. 4, we illustrate results for four different solar activity periods in cycle 23 using data from VIRGO (Fröhlich et al. 1995) on board SOHO. VIRGO started observations at the beginning of 1996 and still continues to provide uninterrupted daily values of the TSI except during two major break downs in mid 1998 and early 1999. We fit the TSI values as measured by VIRGO for the period 1996–2003 and obtain an excellent correspondence between the data and the model, yielding a multiple correlation coefficient $R = 0.94$. Figures 4a and c demonstrate this behaviour during the minimum and the maximum activity periods respectively while Figs. 4b and d correspond to the rising and declining periods of solar activity. It should be noticed that the variations in TSI on a time scale as short as 1 day are clearly reproduced by the magnetic field strength on the solar surface. Our results for the VIRGO measurements are in good agreement with those obtained by Krivova et al. (2003) using a four-component model for the solar photosphere with a single free parameter based on daily images of full-disk daily magnetic fields and continuum recorded by MDI during the period 1996–2001. However, the study of Krivova et al. (2003) was confined to the irradiance variations solely in solar cycle 23 and did not address intercycle trends, which are important for studying the long-term behaviour of solar irradiance. These trends are discussed in the next section using a composite time series of total irradiance for the entire period of the TSI observation since 1978.

3.2. Composite time series and comparison of solar cycles 21, 22 and 23

We first carry out a regression fit to Eq. (1) using a composite time series for the entire period of irradiance measurements, i.e. 1978–2003, similar to Fröhlich & Lean (1998), though using a different set of indices. We find that a good correlation is obtained in the observed and modeled time series for a period of about twenty five years, providing strong support for the assumption that a readjustment in solar surface magnetism regulates the short-term as well as the long-term variations in irradiance. However, we obtain significantly different values of the reconstructed total irradiance for the maximum phase of solar cycle 21, which is in agreement with our finding using TSI data from a single instrument, as discussed in the previous subsection. A more detailed analysis of the composite time series is presented in Fig. 5 where we show results of our fit to irradiance data with MWO magnetic field indices for solar cycles 21, 22 and 23 separately. The dark line indicates a 27-day running mean of the daily values of TSI obtained using the regression parameters, C_1 and C_2 as described in Eq. (1), while the grey line shows the running mean variation in the observed values.

The calculated coefficients $C_{\rm quiet}$, C_1 and C_2 for individual solar cycles and the full data set of composite time series are given in Table 2 along with fitting statistics. It should be noted that the coefficients C_1 and C_2 obtained for solar cycles 22 and 23 are within 1σ. On the other hand, the calculated coefficients for solar cycle 21 are significantly different from those for the other two cycles. To best reproduce the observed TSI values in cycle 21, one needs to have a lower C_1, which is finally used to calculate the enhancement in brightening due to a variable magnetic field. In other words, the net contribution due to brightening in solar cycle 21 is compensated by the higher/overestimated values of MPSI. Furthermore, the agreement between calculated and observed short-term variations in the total irradiance is much higher in cycles 22 and 23 than in cycle 21. We note that the correlation obtained for cycle 23 using the TSI composite time series is lower than that obtained

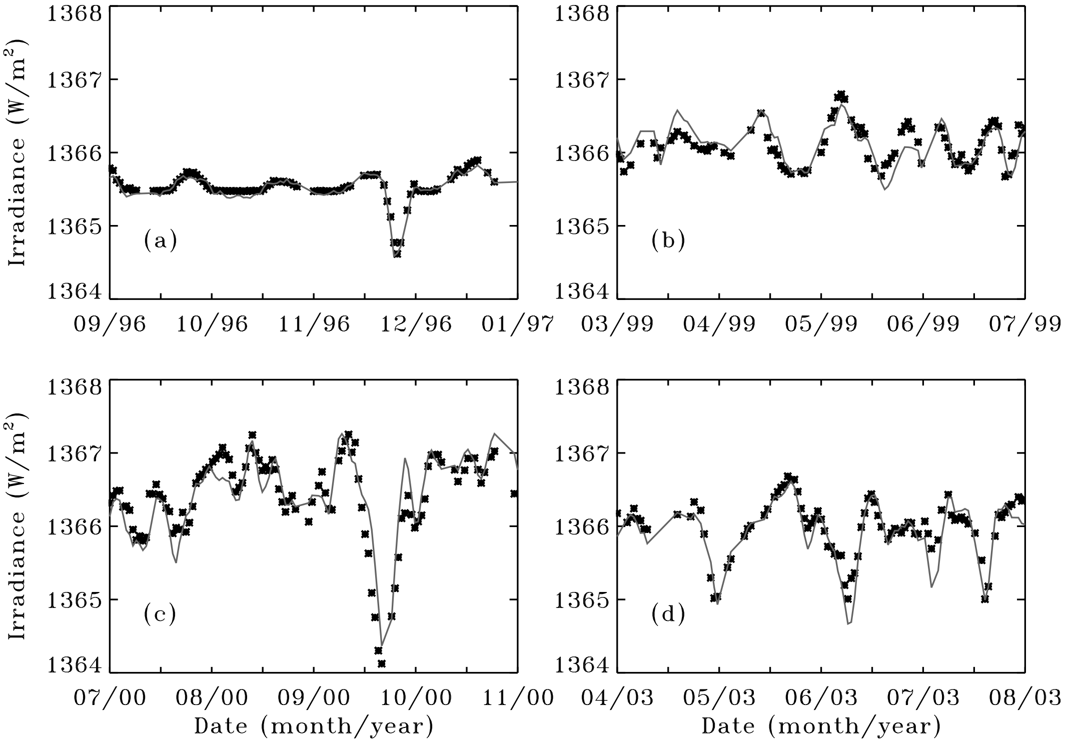

Fig. 4. The daily variation in the modeled and observed total solar irradiance at **a)** low solar activity; **b)** rising solar activity; **c)** high solar activity; and **d)** declining solar activity during cycle 23. The solid line is for the TSI observations from VIRGO on board SOHO and the asterisks are for modeled values.

Table 2. Regression fits between the composite time series of total solar irradiance, the magnetic plage strength index and the Mt. Wilson sunspot index for four different periods from 1978 to mid 2003. The coefficients C_{quiet}, C_1 and C_2 are defined in Eq. (1), R and χ^2 are the multiple correlation coefficient and reduced chi-square values. The 1σ error in the regression is also given below each coefficient.

Period	Solar cycle	C_{quiet} (W/m^2)	C_1 (W/m^{2}G)	C_2 (W/m^{2}G)	R	χ^2
1978–1985	21	1365.75	0.384	−1.002	0.75	0.16
			±0.090	±0.036		
1986–1995	22	1365.51	0.725	−1.706	0.89	0.06
			±0.071	±0.021		
1996–2003	23	1365.48	0.646	−1.709	0.91	0.04
			±0.068	±0.021		
1986–2003	22-23	1365.50	0.667	−1.644	0.89	0.06
			±0.056	±0.016		
1978–2003	21-23	1365.59	0.534	−1.343	0.83	0.09
			±0.052	±0.016		

with the VIRGO data for the same period. In our analysis, we obtain $R = 0.94$ using TSI data from the VIRGO instrument for the period 1996–2003, while this value reduces to 0.91 for the composite time series of total solar irradiance. Krivova et al. (2003) also obtained a slightly higher value of the correlation coefficient (0.96) using VIRGO TSI measurements using a shorter data set (1996–2001) with a model having a single free parameter. The accuracy obtained in our analysis is comparable to that achieved by Krivova et al. The high correlations obtained in our analysis for cycles 22 and 23 with similar values of the calculated coefficients emphasize that no additional component is required to reproduce the inter-cycle irradiance variations. Thus we find that the direct measurements of the magnetic field strength on the solar surface are able to explain the short-term as well as the inter-cycle variations in irradiance with high correlation. These findings are in contrast to those obtained by de Toma et al. (2001) using sunspot and facular indices of the San Fernando Observatory with Mg II core-to-wing ratio for the ascending phases of cycles 22 and 23. These authors found an increase of 33% in the brightening term to account for the TSI variations in cycle 23 as compared to cycle 22, thus they emphasized that the cycle to cycle variability in TSI cannot be explained by such a set of indices. However, in our study we find a decrease of 10% in the brightening coefficient from solar cycle 22 to cycle 23, which is within the 1σ error limit. Our findings are also in contradiction to those discussed by Jones et al. (2003), where significantly different parameters for cycles 22 and 23 were obtained.

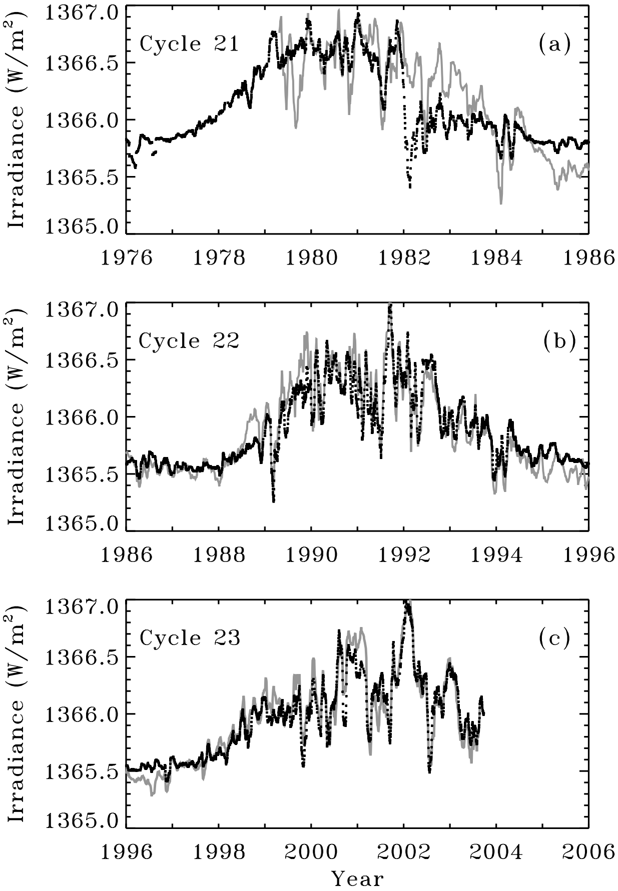

Fig. 5. The 27-day running mean of the reconstructed total solar irradiance using regression models based on the magnetic field measurements for **a)** solar cycle 21; **b)** solar cycle 22; and **c)** solar cycle 23 is shown by a dark dotted line. The models are developed for each cycle independently. The 27-d running mean of the observed TSI is shown by the grey line.

4. Discussion and summary

The main focus of the present investigation was to re-examine whether surface magnetism can reproduce the solar irradiance variability. Earlier work by Chapman & Boyden (1989) using indices taken from magnetograms had demonstrated for a limited data set (1980–84) that such indices provide a reasonable representation for irradiance. Subsequent studies based on a composite time series over a much larger duration showed that a good reconstruction for TSI could be obtained using a different set of proxies i.e. PSI and the Mg II core-to-wing ratio (Fröhlich & Lean 1998). In their reconstruction these authors separated out the facular proxy (Mg II ratio) into short- and long-term components. Later, Fröhlich (2003a) updated the reconstruction and also studied the possible differences in the TSI during different cycles. In separate regession analyses for cycles 21, 22 and 23, Fröhlich did not find any significant change in the calibration factors. The above investigations provided evidence in support of the idea that surface magnetism is indeed an important factor in influencing solar irradiance. However, some doubt on this conclusion was cast recently by the work of de Toma et al. (2001) and Jones et al. (2003), which motivated us to investigate this issue using essentially the same data set as above but using direct field measurements as opposed to proxies.

In the work by de Toma et al. (2001), the TIRR index derived from the photometric indices of the San Fernando observatory is used with the Mg II core-to-wing ratio for the ascending phases of cycles 22 and 23. They showed that cycle 23 is magnetically weak compared to cycle 22. Therefore, the indices depicting the solar magnetic activity for cycle 23 have lower values than those for cycle 22. As a result, to obtain a better fit with the observations of TSI, a higher coefficient in the brightening term is required for the cycle 23. On the other hand, we have shown in Fig. 1 that the relative magnitudes of the solar surface magnetic field strength for these two cycles are comparable, hence the regression coefficients obtained in our analysis are also within the error limit. It is further noticed that the discrepancy between our work and the earlier work by Jones et al. (2003) arises mainly from the phases of the solar cycle included in the analysis. If we regress the TSI data for the period considered by these authors, we also find different coefficients for cycle 22 (1992–1995), i.e. $C_1 = 0.640$ W/m^{2}G and $C_2 = -1.540$ W/m^{2}G, and the correlation drops to 0.77. Furthermore, the regression of the TSI data for the ascending phases of both cycles leads to similar values of the regression coefficients.

Since our analysis of the solar irradiance basically depends on the time series of the MPSI and the MWSI, the uncertainties involved in the reconstruction therefore reflect the uncertainties in the measurements of these quantities. We found a major discrepancy in the reconstructed and the observed irradiance for solar cycle 21. It is noticed that the MPSI is substantially stronger in cycle 21 than in cycles 22 and 23 unlike the 10.7 cm radio flux, sunspot number or other activity-sensitive indices. The possible reasons for this discrepancy were discussed by Parker et al. (1998) and the preliminary analysis indicated that the inclusion of fastgrams in the calculation of MPSI at the end of cycle 21 yielded systematically lower values (around 5%). Thus, the higher values of MPSI estimate the higher values of the irradiance in cycle 21 while a close agreement is obtained for the cycles 22 and 23, showing a good correlation between the surface magnetism and the solar irradiance.

The present work does not take into account the variation of facular contrast with position on the solar disk. The center-to-limb variation of facular brightness contrast has been discussed in detail by Unruh et al. (2000). At this stage it is difficult to assess the errors introduced in our analysis due to its neglect, but we feel that this assumption can perhaps be justified to some extent a posteriori given the good agreement of our reconstruction with irradiance observations. However, a more rigorous analysis including this effect would be desirable; we postpone this to a future investigation.

In brief, we have reconstructed the total solar irradiance for the last three solar cycles using direct measurements of the magnetic field strength at the Mount Wilson Observatory. On the basis of empirical models using the magnetic field indices derived from synoptic magnetograms, i.e. Magnetic Plage Strength Index (MPSI) and Mt. Wilson Sunspot Index (MWSI), we find that most of the daily variations in the total solar irradiance can be accounted for by the absolute magnetic field strength on the solar disk, if fields associated with dark and bright regions are considered separately.

We have also carried out a separate regression analysis for solar cycles 21, 22 and 23 to study the sources of irradiance variability and also to understand the inter-cycle trends in irradiance modulation. We obtained high multiple correlation coefficients for cycles 22 and 23, i.e. $R = 0.89$ and 0.91, respectively. This suggests that the solar irradiance was modulated by similar sources during these two cycles and no additional factor may be required to explain the inter-cycle trends in the irradiance variability. We also find similar regression parameters for these cycles, in contrast to the earlier findings of de Toma et al. (2001) and Jones et al. (2003), where significantly different parameters for cycles 22 and 23 were obtained. A more detailed study, however, is required to clarify this difference by using complete data sets for these solar cycles, which would be only possible after the present solar cycle arrives at the minimum activity period.

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References

Chapman, G. A., & Boyden, J. E. 1986, ApJ, 302, L71
Chapman, G. A., Cookson, A. M., & Dobias, J. J. 1996, J. Geophys. Res., 101, 13541
de Toma, G., White, O. R., Chapman, G. A., et al. 2001, ApJ, 549, L13
Ermolli, I., Berrilli, F., & Florio, A. 2003, A&A, 412, 857
Fligge, M., Solanki, S. K., Unruh, Y. C., Fröhlich, C., & Wehrli, C. 1998, A&A, 335, 709
Foukal, P. 2002, Geophys. Res. Lett., 29(23), 2089
Foukal, P., & Lean, J. 1988, ApJ, 328, 347
Fröhlich, C. 2003a, in International Solar Cycle Studies – 2003 Symp., ESA-SP, 535, 183
Fröhlich, C. 2003b, Solar Irradiance Variability, in Geophysical Monograph Series, 111, American Geophysical Union, in press
Fröhlich, C., & Lean, J. 1998, Geophys. Res. Lett., 25, 4377
Fröhlich, C., Romero, J., Roth, H., et al. 1995, Sol. Phys., 162, 101
Hoyt, D. V., Kyle, H. L., Hickey, J. R., & Maschhoff, R. H. 1992, J. Geophys. Res., 97, 51
Jain, K., & Hasan, S. S. 2004, J. Geophys. Res., 109, A03105
Jones, H. P., Branston, D. D., Jones, P. B., & Popescu, M. D. 2003, ApJ, 589, 658
Krivova, N. A., Solanki, S. K., Fligge, M., & Unruh, Y. C. 2003, A&A, 399, L1
Lean, J., Cook, J., Marquette, W., & Johannesson, A. 1998, ApJ, 492, 390
Lean, J., & Foukal, P. 1988, Science, 240, 906
Parker, D. G., Ulrich, R. K., & Pap, J. M. 1998, Sol. Phys., 177, 229
Preminger, D. G., Walton, S. R., & Chapman, G. A. 2002, J. Geophys. Res., 107, SSH 6-1
Sofia, S., & Li, L. H. 2001, J. Geophys. Res., 106, 12969
Solanki, S. K., & Fligge, M. 2002, Adv. Space Res., 29, 1933
Spruit, H. 2000, Space Sci. Rev., 94, 113
Ulrich, R. 1991, Adv. Space Res., 11, 217
Unruh, Y. C., Solanki, S. K., & Fligge, M. 2000, Space Sci. Rev., 94, 145
Wilson, R. C. 1994, in The Sun as a Variable Star: Solar and Stellar Irradiance Variations, ed. J. M. Pap, C. Fröhlich, S. K. Solanki, & H. S. Hudson (New York: Cambridge University Press), 54
Wilson, R. C., & Hudson, H. S. 1988, Nature, 332, 810
Willson, R. C., & Hudson, H. S. 1991, Nature, 351, 42