GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L11102, doi:10.1029/2009GL037519, 2009

Reconstructed and measured total solar irradiance: Is there a secular trend between 1978 and 2003?

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Received 24 February 2009; revised 23 April 2009; accepted 5 May 2009; published 5 June 2009.

[1] Total solar irradiance reconstructed between 1978 and 2003 using solar surface magnetic field distributions is compared with three composites of total solar irradiance measurements. A good correspondence is found with the total solar irradiance composite from PMOD/WRC, with no bias between the three cycles. The agreement with the other composites (the ACRIM composite, mainly based on the Active Cavity Radiometer Irradiance Monitors I, II, and III, and the IRMB composite from the Institut Royal Meteorologique Belgique) is significantly poorer. In particular, a secular increase in the irradiance exhibited by these composites is not present in the reconstructions. Hence any secular trend in total solar irradiance between 1978 and 2003 is not due to magnetic fields at the solar surface. **Citation:** Wenzler, T., S. K. Solanki, and N. A. Krivova (2009), Reconstructed and measured total solar irradiance: Is there a secular trend between 1978 and 2003?, *Geophys. Res. Lett.*, *36*, L11102, doi:10.1029/2009GL037519.

1. Introduction

[2] Regular monitoring of total solar irradiance (TSI) by space-based radiometers started in 1978 and has continued without major interruptions since then, although no single instrument so far managed to survive longer than a single solar activity cycle. Crosscalibrating and combining the data from the different radiometers into one record is not without problems, and three independent groups have constructed distinct composites of the Sun's total irradiance from the measurements [*Fröhlich*, 2000, 2003b, 2006; *Willson*, 1997; *Willson and Mordvinov*, 2003; *Dewitte et al.*, 2004]. These time series show substantial differences, in particular regarding the long-term trend of the irradiance. This is best seen as the difference between the TSI during the minima preceding solar cycles 22 and 23 [*Fröhlich*, 2006].

[3] Here we compare a reconstruction of TSI based on magnetograms and model atmospheres with the irradiance composites. Since such reconstructions have turned out to be highly successful in reproducing the irradiance on the solar cycle time scale [*Krivova et al.*, 2003; *Wenzler et al.*, 2006] this comparison provides an independent test of the composites and in particular of whether any secular trends in the irradiance can be due to solar surface magnetic fields. The precent paper does not address the lower irradiance in the minimum between cycles 23 and 24 [*Lockwood and Fröhlich*, 2008] since the instruments that recorded the data on which the present reconstructions are based stopped operating in 2003.

2. Data and Model

2.1. Composite Records of Total Solar Irradiance Measurements

[4] We consider here three different composites, which are compiled from multiple, cross-calibrated independent radiometric measurements since 1978 November 16. We use the newest PMOD composite of TSI (version 41) from the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC) in Switzerland [*Fröhlich*, 2000, 2003b, 2006], the ACRIM composite [*Willson*, 1997; *Willson and Mordvinov*, 2003] and the IRMB composite from the Institut Royal Meteorologique Belgique [*Dewitte et al.*, 2004; S. Dewitte, private communication, 2004]. The three composite time series are quite different in their longer term trends. The PMOD composite has a negligible trend between the two solar minima of 1986 and 1996 (cycles 22 and 23) and has lower TSI values at the three solar maxima of the cycles 21, 22 and 23 than the other two composites [*Fröhlich and Lean*, 2004; *Fröhlich*, 2003a; *Willson and Mordvinov*, 2003; *Dewitte et al.*, 2004]. The ACRIM composite shows the largest difference between the two minima. It is important to note that the differences between the composites not only change gradually, but also display significant jumps.

2.2. Magnetograms and Continuum Images

[5] The TSI model employs sets of full-disk magnetograms in Fe I 8688 Å and continuum images obtained daily at the Kitt Peak Vacuum Tower (KPVT) [*Livingston et al.*, 1976] of the National Solar Observatory (NSO). Data recorded by the NASA/NSO spectromagnetograph (henceforth referred to as NSO-SPM) between 1992 November 21 and 2003 September 21 and by the NASA/NSO 512-channel Diode Array Magnetograph (henceforth referred to as NSO-512) between 1978 November 16 and 1992 April 4 were used for irradiance reconstructions on a total of 3528 days. The NSO-512 magnetograms need to be divided by a factor f in order to make them compatible with the NSO-SPM data. The standard factor recommended by NSO is $f = 1.46$. However *Wenzler et al.* [2006] have shown that different cross-calibration techniques give different factors between 1.38 and 1.63. A detailed description of the data and their treatment is given by *Wenzler et al.* [2004, 2006].

2.3. Model

[6] We use the SATIRE model (Spectral And Total Irradiance REconstructions) [*Solanki et al.*, 2005] described by *Fligge et al.* [2000a, 2000b], *Krivova et al.* [2003], and

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0094-8276/09/2009GL037519$05.00

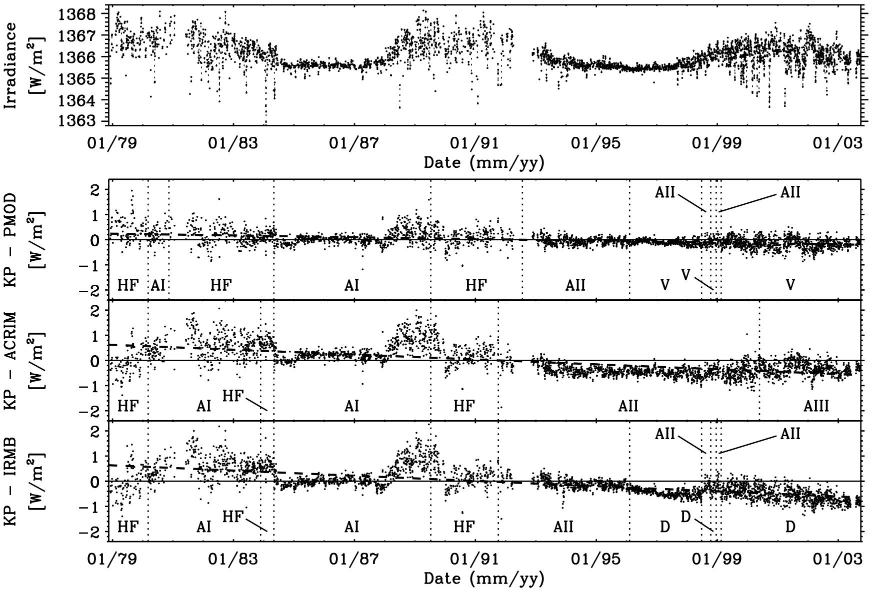

Figure 1. The *top panel* shows the reconstructed daily total solar irradiance based on both NSO-512 and NSO-SPM data for 3528 days between 1978 and 2003, i.e. from the rising phase of cycle 21 to the declining phase of cycle 23. The three *lower panels* show the difference between the reconstructed TSI and the PMOD, ACRIM and IRMB composites, respectively. Each dot represents a daily value. The horizontal solid lines indicate difference = 0, the thick dashed lines are linear regressions. The dotted vertical lines indicate periods, when the individual data sets from HF, AI, AII & AIII (ACRIM I, II & III), V (VIRGO: Variability of solar IRradiance and Gravity Oscillations experiment on SoHO) and D (DIARAD: DIfferential Absolute RADiometer) were used for the composites.

Wenzler et al. [2004, 2005, 2006]. It is based on the assumption that all irradiance changes on time scales of a day and longer are caused by the evolving distribution of the magnetic field on the solar surface. It makes use of two elements: full disk data (magnetograms for identifying bright magnetic features and continuum images for sunspots and pores) and model atmospheres for each of these components. The model has a single free parameter, $B_{\rm sat}$, the value of the magnetogram signal at which magnetic field in the solar photosphere fills the whole magnetogram pixel. $B_{\rm sat}$ is varied until the best representation of the full considered TSI composite is obtained. We have carried out two sets of TSI reconstructions, those using the standard f value of 1.46, called standard reconstructions (discussed in Sect. 3.1) and those allowing f to vary within the allowed range of 1.38 and 1.63, called optimized reconstructions (discussed in Sect. 3.2). A detailed description of the TSI model used here is given by *Wenzler et al.* [2006].

[7] The length of the reconstructed time series is determined by the length of time for which the Kitt Peak magnetograms are available. For this study we decided against combining these reconstruction with those from MDI on SoHO, in order to maintain homogeneity in the reconstructed time series. A combination with MDI would have entailed employing conversion factors between Kitt Peak magnetograms and MDI magnetograms [e.g., *Wenzler et al.*, 2004], which would have introduced further uncertainty in the long-term trend.

3. TSI Reconstructions in Cycles 21, 22, and 23

[8] We now compare the reconstructed TSI with the three TSI composite records: PMOD, ACRIM and IRMB.

3.1. Standard Reconstruction

[9] Here we compare the standard reconstructions of TSI [*Wenzler et al.*, 2006] with all TSI composites. This is illustrated in Figure 1, which in the top panel displays the reconstructed TSI, while the lower panels show the difference between measured and reconstructed TSI for all three composites. The best agreement is achieved with the PMOD composite (second panel). Not only is the scatter larger in the two lowermost panels, but also the slopes of the regression lines are noticeably larger, indicating a significant difference between the long-term trends of these composites and the reconstruction.

[10] The corresponding correlation coefficients, $r_{\rm c}$, between the reconstructed and measured irradiance, the slopes and χ^2 of the linear regressions as well as the $B_{\rm sat}$ values are listed in Table 1 under "Standard Reconstructions". For all three composites we find that the correlation coefficient is lower for the NSO-512 period than for the NSO-SPM period, probably due to the lower quality of the SPM-512 magnetograms, but also of the early TSI data. The correlation coefficients obtained when comparing the reconstructions with the ACRIM and IRMB composites are always significantly lower than those for the PMOD compilation. This is true for all intervals of time considered, but is most striking for the full period.

[11] The ACRIM composite displays a difference of roughly 0.8 W/m^2 between the minima of cycles 22 and 23 [*Willson and Mordvinov*, 2003], while *Dewitte et al.* [2004] obtain a smaller difference of 0.15±0.35 W/m^2. On the other hand, both the PMOD composite and the reconstructed irradiance show no trend significantly different from zero [*Fröhlich and Lean*, 2004; *Wenzler et al.*, 2006]. The main reason for the differences during the period

Table 1. B_{sat} of the Reconstructed TSI, Correlation Coefficients Between Reconstructed and Composite TSI, r_{c}, Slopes, and χ^2 of the Linear Fits to the Scatterplots of Modelled Total Solar Irradiance Based on NSO-512 and NSO-SPM data Versus PMOD, ACRIM, and IRMB Composite Measurements for Different Periods[a]

Comp.	Years	Magnetogram	B_{sat} (G)	r_{c}	Slope	χ^2
Standard Reconstructions (Sect. 3.1)						
PMOD	1978–2003	NSO-512/1.46 and NSO-SPM	340	0.89	1.003 ± 0.009	0.077
PMOD	1978–1992	NSO-512/1.46	340	0.88	1.023 ± 0.015	0.111
PMOD	1992–2003	NSO-SPM	340	0.93	0.937 ± 0.008	0.031
ACRIM	1978–2003	NSO-512/1.46 and NSO-SPM	270	0.71	0.782 ± 0.013	0.277
ACRIM	1978–1992	NSO-512/1.46	270	0.82	0.868 ± 0.017	0.247
ACRIM	1992–2003	NSO-SPM	270	0.91	0.981 ± 0.010	0.057
IRMB	1978–2003	NSO-512/1.46 and NSO-SPM	260	0.74	0.798 ± 0.012	0.269
IRMB	1978–1992	NSO-512/1.46	260	0.81	0.943 ± 0.018	0.268
IRMB	1992–2003	NSO-SPM	260	0.90	0.812 ± 0.009	0.072
Optimized Reconstructions (Sect. 3.2)						
PMOD	1978–2003	NSO-512/1.6 and NSO-SPM	320	0.91	0.978 ± 0.008	0.056
PMOD	1978–1992	NSO-512/1.6	320	0.89	0.968 ± 0.014	0.091
PMOD	1992–2003	NSO-SPM	320	0.94	0.983 ± 0.008	0.032
ACRIM	1978–2003	NSO-512/1.63 and NSO-SPM	250	0.79	0.815 ± 0.011	0.189
ACRIM	1978–1992	NSO-512/1.63	250	0.82	0.810 ± 0.015	0.205
ACRIM	1992–2003	NSO-SPM	250	0.91	1.041 ± 0.011	0.067
IRMB	1978–2003	NSO-512/1.63 and NSO-SPM	250	0.82	0.805 ± 0.010	0.166
IRMB	1978–1992	NSO-512/1.63	250	0.82	0.858 ± 0.016	0.204
IRMB	1992–2003	NSO-SPM	250	0.90	0.842 ± 0.009	0.075

[a] The reconstructed TSI values are calculated with different *f* factors in the upper and lower halves of the table.

before ACRIM-I starts is that in the PMOD composite *Fröhlich* [2006] corrects the data of the Hickey-Frieden (HF) radiometer on NIMBUS-7 for changes he attributes to an early increase, degradation and other long-term changes. Next, all three lower panels of Figure 1 show a jump in 1984 which coincides with the repair of the Solar Maximum Mission (SMM) Spacecraft and the re-start of the ACRIM I data. We cannot rule out problems in the NSO-512 magnetograms as the cause [see *Wenzler et al.*, 2006], but the timing suggests that it could at least partly be due to a change of ACRIM I after its extended switch-off during the repair of SMM.

[12] Another obvious difference between the PMOD and the other composites is seen during the gap between ACRIM I and II. It is manifested as a very steep drop at the end of September 1989. This is most likely due to a slip in HF which was already detected by *Lee et al.* [1995] by comparison with their Earth Radiation Budget Satellite (ERBS) data and later by *Chapman et al.* [1996] relative to their model. In the IRMB composite the tracing of ACRIM II to ACRIM I is performed with ERBS data, which do not have the slip in September 1989. This is responsible for the fact that the ACRIM I and II differences to the model lie at the same level (close to zero) in the composite. The data during the ACRIM gap, however, are from HF and so obviously show that step.

[13] Also, between 1992 and 2003 with the more reliable NSO-SPM data the reconstructed TSI values agree best with the PMOD composite (second panel of Figure 1 and Table 1). During this period the ACRIM composite is generally higher than the reconstructed TSI. *Fröhlich* [2004] has removed steps in the TSI from the PMOD composite in July 1992 and in March 1998, that, he argued, were produced when the radiometers A and B of ACRIM II were switched. No such compensation was made in the other composites. After 1996, when the VIRGO data started, IRMB uses a different method to determine the degradation corrections of DIARAD than underlies the PMOD composite.

3.2. TSI Reconstruction With Optimized Factor Between NSO-512 and NSO-SPM

[14] Next, we repeated the analysis, but now allowed *f* to vary within the allowed range of 1.38 and 1.63 in order to optimize the reconstructions to the different composites.

[15] To best reproduce the PMOD composite irradiance time series (i.e. achieve the highest r_{c} and lowest χ^2), we need a slightly higher *f* of 1.6 compared with the official factor of 1.46 (see column 3 of Table 1), whereas for the ACRIM and IRMB composites a significantly higher factor of 2.0 is required, which lies well outside the allowed range (1.38–1.63). Within this allowed range we receive the best possible reproduction of the ACRIM and IRMB composites using a factor of 1.63. The correlation coefficients etc. between the reconstructions and ACRIM and IRMB composites are given in the lower half of Table 1. Note that the correlation coefficients for the ACRIM and IRMB composites are significantly lower in all of the three considered periods (even for $f = 2.0$) than for the PMOD time series.

4. Conclusions

[16] We have compared the TSI reconstructed between 1978 and 2003 with three different composites of measured TSI (PMOD, ACRIM and IRMB). Our model, based on the assumption that the solar irradiance changes are entirely caused by the evolution of the solar surface magnetic fields, suggests similar levels of the solar irradiance during the three minima of the solar cycles 21, 22 and 23 [*Wenzler et al.*, 2006]. With a single free parameter fixed for the whole period, the model reproduces the observed irradiance variations in all three cycles 21, 22 and 23 as represented by the PMOD composite. However, the reconstructed irradiance displays large deviations from the other two compo-

sites (ACRIM and IRMB), as can be judged from Figure 1 and Table 1. This implies that any secular trend in the irradiance between 1978 and 2003 (e.g., found in the ACRIM and IRMB composites) cannot be due to the surface magnetic field as sampled by ground-based magnetograms. Such magnetograms do miss very small-scale fields in the quiet Sun [see *Solanki*, 2009; *de Wijn et al.*, 2009]. The influence of these weak fields on irradiance, if any, still has to be established.

[17] **Acknowledgments.** We thank M. Fligge, D. M. Fluri, and C. Fröhlich for helpful discussions. This work was partly supported by the Deutsche Forschungsgemeinschaft, DFG project SO 711/1-1, and partly by the WCU grant (R31-10016) from the Korean Ministry of Education, Science and Technology.

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