GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L20101, doi:10.1029/2009GL040707, 2009

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ACRIM-gap and total solar irradiance revisited: Is there a secular trend between 1986 and 1996?

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Received 27 August 2009; revised 15 September 2009; accepted 17 September 2009; published 16 October 2009.

[1] A gap in the total solar irradiance (TSI) measurements between ACRIM-1 and ACRIM-2 led to the ongoing debate on the presence or not of a secular trend between the minima preceding cycles 22 (in 1986) and 23 (1996). It was recently proposed to use the SATIRE model of solar irradiance variations to bridge this gap. When doing this, it is important to use the appropriate SATIRE-based reconstruction, which we do here, employing a reconstruction based on magnetograms. The accuracy of this model on months to years timescales is significantly higher than that of a model developed for long-term reconstructions used by the ACRIM team for such an analysis. The constructed 'mixed' ACRIM — SATIRE composite shows no increase in the TSI from 1986 to 1996, in contrast to the ACRIM TSI composite.
Citation: Krivova, N. A., S. K. Solanki, and T. Wenzler (2009), ACRIM-gap and total solar irradiance revisited: Is there a secular trend between 1986 and 1996?, *Geophys. Res. Lett.*, *36*, L20101, doi:10.1029/2009GL040707.

1. Introduction

[2] Solar total irradiance has been measured by a number of space-borne instruments without interruptions since 1978 [*Fröhlich*, 2006]. However, no single instrument remained operational over the whole period, and a cross-calibration and construction of a composite of measurements by several radiometers is not trouble-free. A detailed description of individual data sets, their problems and corrections is given by *Fröhlich* [2006] [cf. *Scafetta and Willson*, 2009]. As a consequence, three different composites of the total solar irradiance (TSI) have been constructed: PMOD [*Fröhlich*, 2006], ACRIM [*Willson and Mordvinov*, 2003], and IRMB [*Dewitte et al.*, 2004].

[3] The main disagreement concerns the TSI levels during the minima preceding cycles 22 (which took place in 1986) and 23 (in 1996) and thus the presence of a long-term trend during this period. The origin of the discrepancy lies in the fact that the launch of the ACRIM-2 experiment on UARS, originally planned to overlap with ACRIM-1 on SMM, had to be postponed. Thus for more than 2 years (July 1989 to October 1991; the so-called ACRIM gap) only the data from HF/Nimbus7 and ERBS/ERBSE are available. The ERBS irradiance measurements were made only approximately every 2 weeks. In September 1989, the HF radiometer was switched off for several days due to saturation of its output signal. When it returned to normal operating mode, it apparently showed an abrupt increase in irradiance by about 0.4 W m^{-2} (for more details, see *Lee et al.* [1995], *Chapman et al.* [1996], and *Lockwood and Fröhlich* [2008]). There is also an indication for another either abrupt or gradual increase of a similar magnitude [*Lee et al.*, 1995; *Fröhlich*, 2006]. This change in the HF sensitivity was allowed for in the PMOD composite but not in the ACRIM one, which led to the disagreement in the long-term behaviour mentioned above. The ACRIM composite shows an increase in the TSI of 0.037% (about 0.5 W m^{-2}) between the minima of 1986 and 1996 [*Willson and Mordvinov*, 2003], whereas the PMOD composite gives nearly the same TSI values (difference less than 0.06 W m^{-2} or 0.004%) for both.

[4] Recently, *Scafetta and Willson* [2009] have proposed to use the SATIRE model of TSI variations, in order to bridge the ACRIM gap and thus estimate the long term change independently. The SATIRE models [*Solanki et al.*, 2005; *Krivova and Solanki*, 2008] calculate variations of solar irradiance from the solar surface magnetic field evolution. Several versions of the model have been developed for different applications. Each version is optimised for a different time scale. For reconstructions restricted to the period after 1974, direct full-disc measurements of the solar photospheric magnetic field, i.e. magnetograms, can be employed together with continuum images to identify magnetic features (i.e. sunspots, faculae and the network) [*Krivova et al.*, 2003; *Wenzler et al.*, 2004, 2005]. The brightnesses of the individual types of features are time-independent and are calculated from semi-empirical model atmospheres [*Unruh et al.*, 1999]. Variations of TSI result from the emergence, evolution and decay of magnetic features, which is obtained from the magnetograms and continuum images. Thus variability on all considered time scales is modelled in a self-consistent way, with no additional assumptions on a long-term trend. In the following we refer to this version of the model as SATIRE-S, where the S stands for 'Satellite era'. This model is indeed well suited for a self-contained test of the irradiance trends around the ACRIM gap.

[5] In contrast, the model SATIRE-T (where the T stands for Telescope era) by *Krivova et al.* [2007] that has been employed by *Scafetta and Willson* [2009] is not suited for such an analysis. It has been developed in order to provide an insight into irradiance changes on decadal to centennial time-scales and is, by design, significantly less accurate, particularly on time scales of months. The main challenge of the longer-term models is that the only direct proxy of solar activity going back to the Maunder minimum is the sunspot number. The evolution of the bright magnetic elements

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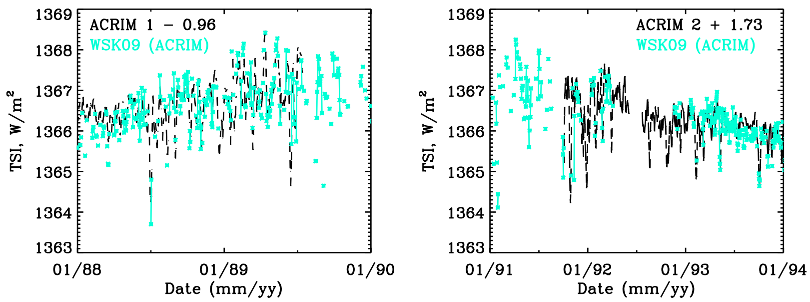

Figure 1. Measured and reconstructed TSI during 1988–1990 and 1991–1994. (left) ACRIM-1 and (right) ACRIM-2 measurements (black dashed line) are shifted by -0.96 W m^{-2} and 1.73 W m^{-2}, respectively, to the level of the WSK09 ACRIM model (asterisks connected by the solid line when there are no gaps).

(faculae, network) has to be derived somehow from the sunspot record. For this, *Krivova et al.* [2007] use the coarse physical model developed by *Solanki et al.* [2000, 2002], which allows a reconstruction of the solar photospheric magnetic field from the sunspot number. Unfortunately, the evolution of the facular and network components cannot be recovered on a daily basis using such a model: only averages over several months can be considered. This is clear from *Krivova et al.* [2007, equations (1)–(7)] and the corresponding values of the involved time scales for the decay and flux transfer in active and ephemeral regions (about 3 months to years). Note that variations of the irradiance on time scales of days to weeks is still well reproduced by this model, since they are driven by the evolution of sunspots, which are adequately represented by the daily sunspot number record.

[6] Thus, by its very conception, the model by *Krivova et al.* [2007] employed by *Scafetta and Willson* [2009] is expected to be relatively accurate on time scales of days to the solar rotation and from the solar cycle to centuries, whereas its accuracy on time scales of several months to years is limited. This is exactly opposite to what *Scafetta and Willson* [2009] assumed. Here we repeat their analysis employing the more accurate SATIRE-S model by *Wenzler et al.* [2006, 2009] based on quasi-daily full-disc magnetograms and continuum images of the Sun recorded by the National Solar Observatory, Kitt Peak (NSO/KP) between 1974 and 2003. We show that employing a more appropriate model gives a rather different result than obtained by *Scafetta and Willson* [2009]. We stress that it is not the aim of this paper to produce a new TSI composite, but rather to show that the approach taken by *Scafetta and Willson* [2009] is completely consistent with a deeper minimum preceding cycle 23 than that preceding cycle 22, if an appropriate model is used.

2. Combining ACRIM With SATIRE-S

[7] We employ exactly the same technique as used by *Scafetta and Willson* [2009]. Thus we compare the measurements by the ACRIM-1 and ACRIM-2 instruments directly with the SATIRE-S model, in order to construct a 'mixed' composite based on ACRIM data when they are available and the model to bridge the gap.

[8] ACRIM-1 and 2 data are taken from the ACRIM web page: http://www.acrim.com/. ACRIM-1 data are available between February 1980 and July 1989, ACRIM-2 between October 1991 and November 2001.

[9] We employ the SATIRE-S model based on NSO/KP magnetograms and continuum images as described by *Wenzler et al.* [2006, 2009]. These data are available between 1974 and 2003. There is a single free parameter in the model which can be adjusted to achieve best agreement with observations. This parameter takes into account the saturation of brightness in regions with concentrations of magnetic elements higher than a threshold (see *Wenzler et al.* [2006] for further details). Note that this single parameter controls the magnitude of the variations on all time scales under consideration and thus cannot be changed arbitrarily, in order to best reproduce variations

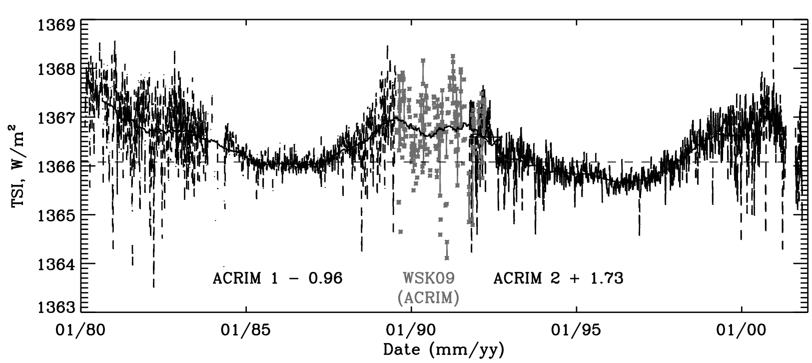

Figure 2. 'Mixed' TSI composite constructed from ACRIM-1 and ACRIM-2 data (black dashed line), with the gap bridged using the WSK09 ACRIM model (asterisks connected by grey solid line when there are no gaps). The heavy solid line is the 1-year smoothed TSI, and the horizontal dashed line shows the level of the minimum preceding cycle 22.

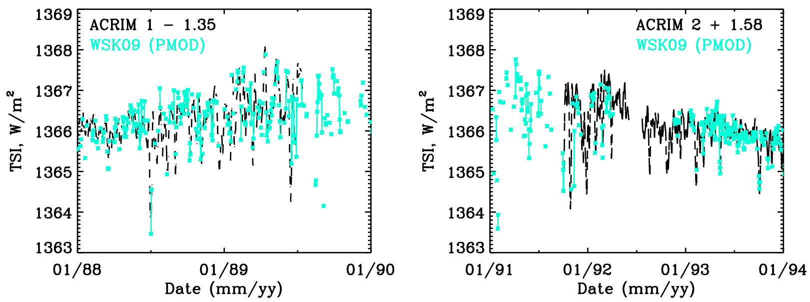

Figure 3. Measured and reconstructed TSI during 1988–1990 and 1991–1994. (left) ACRIM-1 and (right) ACRIM-2 measurements (black dashed line) are shifted by -1.35 W m^{-2} and 1.58 W m^{-2}, respectively, to the level of the WSK09 PMOD model (asterisks connected by the solid line when there are no gaps).

on a selected time scale. *Wenzler et al.* [2009, hereafter referred to as WSK09] ran the reconstruction with different values of the free parameter, in order to find the best possible fit to each of the three existing TSI composites: PMOD (this reconstruction is referred to as WSK09 PMOD), ACRIM (WSK09 ACRIM) or IRMB (WSK09 IRMB). Here we use these three models as they were derived in that paper, i.e. the free parameter is fixed to the values deduced by *Wenzler et al.* [2006] for each of the composites.

[10] In order to compare the model with the data and produce an ACRIM-1 –WSK09 –ACRIM-2 'mixed' composite as proposed by *Scafetta and Willson* [2009], we use 1 year periods of overlap between the model and ACRIM-1 (July 1988 – July 1989) or ACRIM-2 (October 1992 – October 1993). The periods were selected to be exactly the same as in the paper by *Scafetta and Willson* [2009], to avoid bias and to allow a direct comparison to their results. For these periods, we minimise the squared differences between the ACRIM measurements and the SATIRE-S results, in order to derive the shifts between their absolute levels. For WSK09 ACRIM, this comparison is shown in Figure 1 and reveals a good agreement between the model and the data. Figure 2 shows a 'mixed' composite, based on ACRIM data prior to July 1989 and after October 1991 and on the WSK09 ACRIM model during the ACRIM gap. The minimum preceding cycle 23 is 0.38 W m^{-2}, or 0.028%, lower compared to the minimum preceding cycle 22 (as derived from the minima of the 1-yr smoothed record).

[11] In order to test whether this result is solid and is independent of the value of SATIRE's free parameter, we have repeated the same procedure with the WSK09 model optimised to best fit the PMOD and IRMB composites, i.e. the same model, but with different values of the free parameter [see *Wenzler et al.* 2009]. The results for the PMOD composite are shown in Figures 3 and 4. For this model, the TSI at the minimum preceding cycle 23 has a value that is still lower, by 0.15 W m^{-2} or 0.011%, than the TSI in the minimum preceding cycle 22. The difference between the two minima derived using the WSK09 IRMB model is same as for the WSK09 ACRIM version. All results are summarised in Table 1. As a further test, we have also varied the length (between 1 and 3 years) and the dates (1 year within the periods July 1987 – July 1989 and October 1991 – October 1993) of the overlap period. In all cases, the mean TSI during the minimum of cycle 23 is lower than that for cycle 22 by about 0.15 to 0.7 W m^{-2} (0.011–0.05%), in contrast to the result of *Scafetta and Willson* [2009] who found a TSI increase of 0.033% (0.45 W m^{-2}).

3. Conclusion

[12] We have compared the SATIRE-S model of the TSI variations with the measurements by the ACRIM-1 and ACRIM-2 experiments, in order to bridge the so-called ACRIM gap (July 1989 to October 1991), as proposed by *Scafetta and Willson* [2009]. This gap is the source of the on-going debate about the presence of the secular variation in solar irradiance between the minima of cycle 22 and 23. The SATIRE-S model calculates the TSI variations from the continuously evolving distribution of the solar surface magnetic field obtained from NSO/KP magnetograms and continuum images [*Wenzler et al.*, 2009] covering the period 1974–2003. In contrast to the SATIRE-T model by *Krivova*

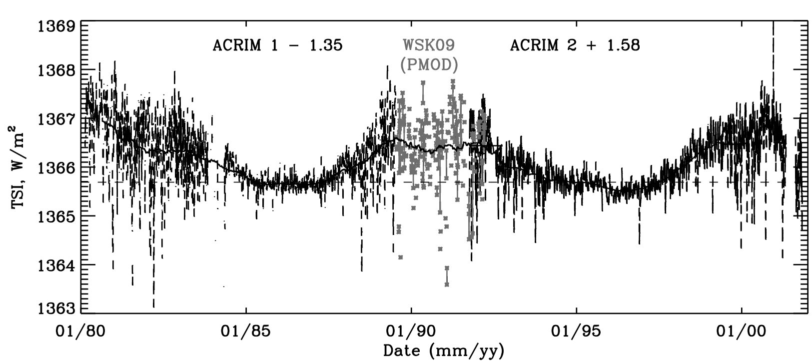

Figure 4. Same as in Figure 2 but using the WSK09 PMOD model.

Table 1. Summary of the Comparison of the SATIRE WSK09 ACRIM, PMOD and IRMB Models With ACRIM Measurements[a]

Model	Shift ACRIM-1	Shift ACRIM-2	Change 23 – 22 (W/m^2)	Relative Change 23/22 – 1 (%)
WSK09 ACRIM	−0.96	1.73	−0.38	−0.028
WSK09 PMOD	−1.35	1.58	−0.15	−0.011
WSK09 IRMB	−0.75	1.95	−0.38	−0.028

[a]Listed are: model versions; derived shifts between ACRIM-1 or ACRIM-2 data and the model for the analysed periods of overlaps; difference in the 1-yr smoothed minimum TSI at the minimum of cycle 23 compared to the minimum of cycle 22; the relative difference in % normalised to the cycle 22 minimum.

et al. [2007] employed by *Scafetta and Willson* [2009], in this model variations on all covered time scales are modelled in a self-consistent way, with no additional assumptions regarding the long term trend. Also the accuracy of the SATIRE-S model is significantly higher than that of the SATIRE-T model since it uses direct measurements of the solar photospheric magnetic flux rather than its modelled evolution. Thus it is best suited for such a test.

[13] The constructed 'mixed' ACRIM-1 – WSK09 – ACRIM-2 composite does not show an increase in the TSI from 1986 to 1996, in contrast to the ACRIM composite. Independently of the value of the model's free parameter, a slight decrease is found. The magnitude of this decrease cannot be estimated very accurately from such an analysis (and therefore such a 'mixed' composite should not be considered as a replacement of real measurements), but it lies between approximately 0.15 and 0.7 W m^{-2} (0.011–0.05%) for different values of the model's single free parameter. Note that irradiance changes due to non-magnetic effects, if any, cannot be revealed by either SATIRE-S used here nor by SATIRE-T employed by *Scafetta and Willson* [2009].

[14] **Acknowledgments.** This work was supported by the Deutsche Forschungsgemeinschaft, DFG project SO 711/2 and by WCU grant R31-10016 funded by the Korean Ministry of Education, Science and Technology.

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