GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 5, 1199, doi:10.1029/2002GL016038, 2003

Secular total solar irradiance trend during solar cycles 21–23

Richard C. Willson

Center for Climate Systems Research, Columbia University, Coronado, California, USA

Alexander V. Mordvinov

Institute of Solar-Terrestrial Physics, Russian Academy of Sciences, Irkutsk, Russia

Received 1 August 2002; revised 18 December 2002; accepted 9 January 2003; published 4 March 2003.

[1] A series of satellite total solar irradiance (TSI) observations can be combined in a precise solar magnetic cycle length composite TSI database by determining the relationship between two non-overlapping components: ACRIM1 and ACRIM2. [*Willson and Hudson*, 1991; *Willson*, 1994] An ACRIM composite TSI time series using the Nimbus7/ERB results [*Hoyt et al.*, 1992] to relate ACRIM1 and ACRIM2 demonstrates a secular upward trend of 0.05 percent-per-decade between consecutive solar activity minima. [*Willson*, 1997] A PMOD TSI composite using ERBS [*Lee et al.*, 1995] comparisons to relate ACRIM1 and ACRIM2 [*Fröhlich and Lean*, 1998] differs from the ACRIM composite in two significant respects: a negligible trend between solar minima and lower TSI at solar maxima. Our findings indicate the lower PMOD trend and lower PMOD TSI at the maxima of solar cycles 22 and 23 are artifacts of ERBS degradation. Lower PMOD TSI during the maximum of cycle 21 results from modifications of Nimbus7/ERB and ACRIM1 published results that produces better agreement with a TSI/solar proxy model [*Foukal and Lean*, 1988; *Lean et al.*, 1995; *Fröhlich and Lean*, 1998]. *INDEX TERMS:* 7538 Solar Physics, Astrophysics, and Astronomy: Solar irradiance; 7594 Solar Physics, Astrophysics, and Astronomy: Instruments and techniques; 1650 Global Change: Solar variability; 1694 Global Change: Instruments and techniques; *KEYWORDS:* solar irradiance, ACRIM, climate forcing. **Citation:** Willson, R. C., and A. V. Mordvinov, Secular total solar irradiance trend during solar cycles 21–23, *Geophys. Res. Lett.*, *30*(5), 1199, doi:10.1029/2002GL016038, 2003.

1. Introduction

[2] Monitoring TSI with sufficient precision and persistence for a climate database became possible when a new generation of electrically self-calibrating cavity sensors and opportunities for extended space flight experiments became available in the late 1970's. The TSI record begun by the Nimbus7 Earth Radiation Budget experiment (NIMBUS7/ERB) in late 1978 was continued by the first Active Cavity Radiometer Irradiance Monitor (ACRIM1) during 1980 to 1989, the first experiment designed specifically for high precision TSI monitoring. These were followed by the Earth Radiation Budget Satellite (ERBS) in 1984 and the UARS/ACRIM2 experiment in 1991. The SOHO/VIRGO and ACRIMSAT/ACRIM3 missions began in 1995 and 2000, respectively, and are the only currently operational TSI monitors. [*Fröhlich et al.*, 1997; *Crommelynck and Dewitte*, 1997; *Willson*, 2001].

[3] The uninterrupted series of TSI observations since 1978 can provide a valuable multi-decadal record for climate change and solar physics if the measurement scales of the contributing experiments are related precisely. Key to constructing a composite TSI database is determining the relationship between measurements of two critical non-overlapping experiments: the ACRIM1 on the Solar Maximum Mission (1980–1989) and the ACRIM2 on the Upper Atmosphere Research Satellite (1991–2001). Two TSI experiments, the NIMBUS7/ERB and the ERBS, overlap ACRIM1 and ACRIM2 including the two-year ACRIM gap. NIMBUS7/ERB and ERBS comparisons can therefore be used to link the ACRIM1 and ACRIM2 results at the level of mutual instrument precision and traceability.

[4] The set of satellite TSI monitoring results shown in Figure 1 is a plot of the originally published results by the experiments' science teams. The spread of results in absolute units reflects the bounds of self-calibration uncertainty, which have varied from about ±0.3 to 0.1 percent between 1978 and the present. Results are reported on the experiments' 'native scales', which rely on their independent sensor metrology to represent the absolute radiation scale in the international system of units. The most recent results are considered the most accurate due to continuing improvements in sensor calibrations.

2. TSI Observations During Solar Cycles 21–23

[5] The TSI experiments shown in Figure 1 vary in their ability to sustain instrument precision and relate observations to the international system of units. NIMBUS7/ERB and ERBS were designed to provide TSI results with ±0.5% uncertainty for earth radiation budget investigations. ACRIM and VIRGO experiments were designed for TSI monitoring, implementing features that provide better precision, accuracy and traceability. A concise description of these experiments follows. Additional information can be found in the Supporting Material.

[6] The ACRIM1 experiment originated a combination of features designed to minimize observational uncertainties in long-term satellite experiments. These include three-fold redundancy of its dual-cavity sensors for calibration of degradation, usually the largest single source of uncertainty for TSI monitoring. [*Willson*, 1979] ACRIM1 degradation was calibrated over its 9 1/2 year lifetime with a residual uncertainty of less than 50 ppm. [*Willson and Hudson*, 1991].

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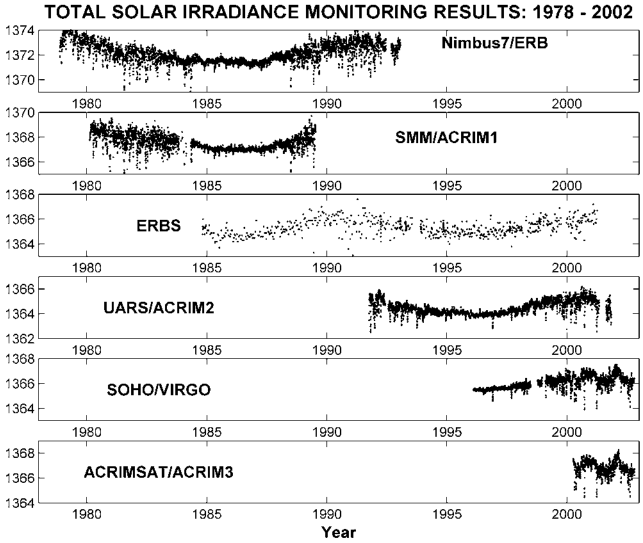

Figure 1. TSI observations by satellite experiments: 1978–2002 (units of watts/meter^2 at 1 A.U.) plotted on each experiment's 'native scale'.

[7] ERBS results are the longest TSI data set but the least precise. NIMBUS7/ERB results are more precise than ERBS, in part because it measures more frequently (by a factor of nearly 200). Results of both are compromised by infrequent observational opportunities, lack of solar pointing and the inability to self-calibrate apparent sensor degradation. A re-evaluation of the NIMBUS7/ERB database carried out by *Hoyt et al.* [1992] significantly improved results.

[8] The ACRIM2 experiment was prevented from overlapping ACRIM1 by the Challenger disaster. Self-calibration of ACRIM2's sensor degradation has provided results with a residual precision uncertainty smaller than 50 parts-per-million (ppm) over its 10 year mission. (See Supporting Material.)

[9] The location of the SOHO spacecraft at the L1 libration point enhances VIRGO results, providing continuous monitoring and eliminating the day-night thermal transients that can degrade observations by TSI monitors in low-earth orbits. This advantage has been partially offset by a combination of instrumentation and satellite problems. These include exceptionally large degradation of the PMO6V monitoring sensor, [*Fröhlich and Finsterle*, 2001] failure of the PMO6V shutters at launch and permanent changes of both DIARAD and PMO6V sensors during the 1998 SOHO hiatus. [See Supporting Material] Results after 1998 are related to pre-hiatus values by comparisons with overlapping ACRIM2 results. [*Fröhlich and Lean*, 1998; *Fröhlich and Finsterle*, 2001].

[10] The ACRIMSAT/ACRIM3, a NASA experiment developed in the 'Better, Faster, Cheaper' modality, was launched in December 1999. ACRIM3 began its TSI monitoring mission in April 2000 following several months of on-orbit fine-tuning the spin-stabilized solar pointing system. ACRIM3 provides TSI results for NASA's Earth Observations System program with accuracy, precision and traceability equaling or exceeding previous ACRIM experiments. Sensor degradation is less than both ACRIM1 and ACRIM2 and has been self-calibrated with a residual uncertainty of less than 10 ppm. [*Willson*, 2001, Supporting Material].

3. The ACRIM Composite TSI Time Series

[11] The most interesting application of this series of satellite monitoring experiments is the compilation of a precise, long-term composite TSI database for studies of climate change and solar physics. Since it will be a combination of the results of a number of individual experiments, each of which reports observations on their 'native scale' they must be related to each other by normalizing to a common scale using comparisons of overlapping results. The accuracy of satellite solar monitors operating at ambient temperature is insufficient to provide adequate traceability for the long-term TSI database. An overlap strategy is required to provide a contiguous database that transfers traceability at the level of TSI observational precision.

[12] ACRIM composite time series have been constructed using various combinations of the TSI data sets. The ACRIM composite shown in Figure 2 includes contributions from NIMBUS7/ERB (16%), ACRIM1, 2 & 3 (73%), and VIRGO (11%). The ACRIM approach uses original results from each experiment provided by the experiments' science teams, unmodified by models or other assumptions. Results are normalized to the 'native scale' of ACRIM3, the best characterized and calibrated ACRIM experiment. The ratio of ACRIM1/ACRIM2 results is derived from their comparisons with NIMBUS7/ERB.

[13] The ACRIM composite TSI is shown in Figure 2. It exhibits a wealth of information useful to both climate change and solar physics. TSI deficits and excesses of sunspot and facular area on the solar rotational time scale cause the highest frequency variations. [*Willson et al.*, 1981; *Willson and Mordvinov*, 1999]. Broad peaks around 1980, 1991 and 2001 correspond to periods of maximum solar magnetic activity during solar cycles 21, 22 and 23. The ~0.1% decreases between maxima are now well-established

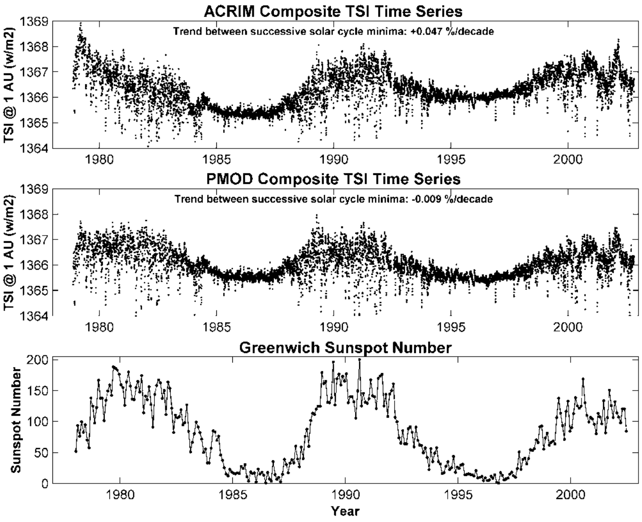

Figure 2. Comparison of the ACRIM and PMOD (Fröhlich/Lean) composite TSI time seriess with the Greenwich Sunspot Number.

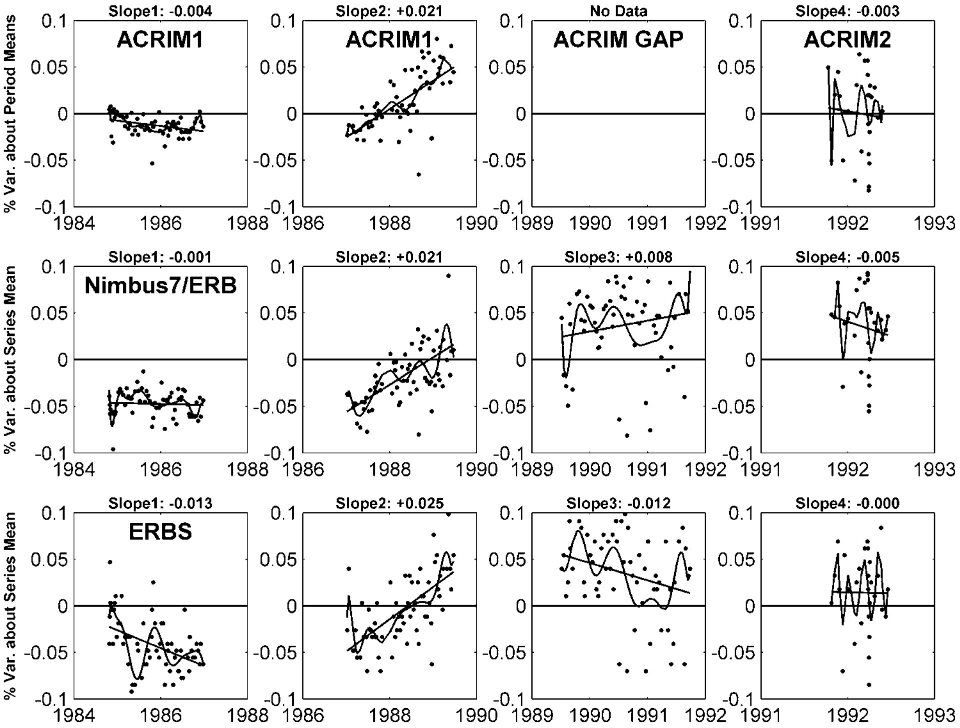

Figure 3. Comparison of ACRIM, Nimbus7/ERB and ERBS results during the ACRIM1, ACRIM2 and ACRIM gap periods. Daily mean results plotted for days when all three experiments had observations.

features of the sunspot cycle. [*Willson et al.*, 1986; *Willson and Hudson*, 1988; *Foukal and Lean*, 1988; *Willson and Hudson*, 1991] Detection of the direct relationship between solar magnetic activity and TSI [*Willson et al.*, 1986] was the key that unlocked the relationships between TSI and historical records of climate and solar magnetic activity. [*Eddy*, 1976, 1977]

[14] The most interesting result of the ACRIM TSI time series for climate change is the +0.05%/decade trend between the minima separating solar cycles 21–22 and 22–23. [*Willson*, 1997] The trend over 9.75 years separating the two minima appears to be significant relative to uncertainty in the time series including comparison computations (±0.001%/decade) and sensor degradation (less than ±0.005%/decade).

[15] ACRIM3 results extend the ACRIM TSI composite into the maximum of solar cycle 23. A larger range of variability is observed there than during the two previous maxima. The high degree of correlation with the Greenwich sunspot number (SNN) shown in Figure 2 ties these variations directly to solar magnetic activity.

4. The PMOD Composite TSI Time Series

[16] The ERBS database also overlaps ACRIM1 and ACRIM2 and has been used by Fröhlich and Lean as the reference during the ACRIM gap to construct what's referred to here as the PMOD composite TSI time series. The PMOD approach alters published NIMBUS7/ERB results during the ACRIM gap by −0.04%, to achieve conformity with ERBS. Adjustments are also made to published ACRIM1 results during 1980–84 and to NIMBUS7/ERB results prior to 1981. [*Fröhlich and Lean*, 1998; *Lean et al.*, 1995] The PMOD composite is shown as panel B of Figure 2.

[17] PMOD's downward adjustments of NIMBUS7/ERB and ACRIM1 results during the solar activity maximum of cycle 21 produces better agreement with solar proxy models, which characteristically predict lower TSI than the measurements provide. [*Foukal and Lean*, 1988; *Lean et al.*, 1995]. NIMBUS7/ERB degradation was justified by extrapolation from similarities with VIRGO/PMO6V. [*Fröhlich and Lean*, 1998] There are significant differences, however, that cast doubt on this rationale. [See Supporting Material] Not the least is that they measured at opposite solar cycle phases. Since NIMBUS7/ERB lacked degradation self-calibration capability it's impossible validate PMOD's proposed degradation corrections.

[18] Degradation of ACRIM1 results in the PMOD composite were based on incorrect assumptions regarding the cumulative solar exposure of its sensors during SMM's 'spin mode'. ACRIM1's 3-fold redundant degradation self-calibration capability provided a precise characterization of sensor degradation before and after the SMM 'spin mode'. [*Willson and Hudson*, 1991] The uncertainty of this process would not accommodate the degradation adjustment proposed by PMOD's authors. [See Supporting Material]

5. Comparison of NIMBUS7/ERB and ERBS as ACRIM Gap References

[19] Simultaneous daily means for the ACRIM, NIMBUS7/ERB and ERBS time series during the ACRIM1, ACRIM2 and ACRIM gap periods are plotted in Figure 3,

along with a polynomial fit to highlight short-term trends and a linear fit to describe the general behavior during each period. The ACRIM1 period is further divided into two parts: the first years of the ERBS experiment and a second part up to the ACRIM gap. The linear slopes of all three data sets show relatively good agreement during the 2nd ACRIM1 and ACRIM2 periods. However ERBS results diverge significantly from those of ACRIM1 and NIMBUS7/ERB during the 1st ACRIM1 and ACRIM gap periods. The most likely explanation of the divergence is uncorrected ERBS degradation.

[20] The significant relative decline of ERBS results during the 1st ACRIM1 period may be the signature of rapid early mission sensor degradation, a common phenomenon for these types of cavities and coatings. It was experienced by ACRIM sensors but corrected using the three-fold redundant degradation self-calibration technique.

[21] The ACRIM gap occurred during a time of increasing and maximum magnetic activity during solar cycle 22. The positive correlation between solar magnetic activity and TSI is compatible with the positive slope of the NIMBUS7/ERB results during this period. The negative slope of the ERBS results is incompatible. The most likely explanation of the divergence of slopes during the ACRIM gap is uncorrected ERBS degradation. The use of ERBS to relate ACRIM1 and ACRIM2 in the PMOD composite would therefore yield systematically lower results following the ACRIM gap and a smaller trend between solar activity minima. [See Supporting Material]

6. Conclusions

[22] The philosophies of the ACRIM and PMOD TSI composite constructions are very different. The ACRIM composite uses results originally published by the science teams of contributory experiments and the NIMBUS7/ERB comparisons to relate ACRIM1 and ACRIM2. This approach is based on our belief that in most cases the science teams had unique knowledge of each experiment that could produce results that most accurately represent their instrumentation's performances.

[23] The PMOD approach modifies published contributory TSI results. Their modifications have the effect of conforming the ACRIM1/ACRIM2 ratio to ERBS during the ACRIM gap and matching composite TSI to the lower values predicted by solar-proxy models during the activity maximum of solar cycle 21.

[24] Construction of TSI composite databases will not be without its controversies for the foreseeable future. However we believe the ACRIM composite and trend represents the best interpretation of the information presently available for solar cycles 21–23.

[25] The ~0.05%/decade minimum-to-minimum trend appears to be significant. If so it has profound implications for both solar physics and climatology. For solar physics it means that TSI variability can be caused by unknown mechanisms other than the solar magnetic activity cycle. Much longer time scales for TSI variations are therefore a possibility, which has obvious implications for solar forcing of climate.

[26] The absence of a minima-to-minima trend in the PMOD composite is an artifact of uncorrected ERBS degradation. ERBS degradation during the gap equals the trend difference and the PMOD offsets (within computational uncertainty).

[27] **Acknowledgments.** The National Aeronautics and Space Administration under contract NAS5-97164 provide support for Dr. Willson at Columbia University. Support for Dr. Mordvinov at the Institute of Solar-Terrestrial Physics is provided by the INTAS project 2001–0550.

[28] ACRIM: http://eosweb.larc.nasa.gov/, http://www.acrim.com/; ERBS: http://eosweb.larc.nasa.gov/; NIMBUS7/ERB: http://daac.gsfc.nasa.gov/; VIRGO: http://www.pmodwrc.ch/.

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A. V. Mordvinov, Institute of Solar-Terrestrial Physics, Russian Academy of Sciences, Irkutsk 664033, Russia.

R. C. Willson, Center for Climate Systems Research, Columbia University, Coronado, CA 92118, USA. (acrim@acrim.com)