

# The Sun's Total Irradiance: Cycles, Trends and Related Climate Change Uncertainties since 1976

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**Abstract.** A composite record of the Sun's total irradiance compiled from measurements made by five independent space-based radiometers since 1978 exhibits a prominent 11-year cycle with similar levels during 1986 and 1996, the two most recent minimum epochs of solar activity. This finding contradicts recent assertions of a 0.04% irradiance increase from the 1986 to 1996 solar minima and suggests that solar radiative output trends contributed little of the 0.2°C increase in the global mean surface temperature in the past decade. Nor does our 18-year composite irradiance record support a recent upward irradiance trend inferred from solar cycle length, a parameter used to imply a close linkage in the present century between solar variability and climate change.

## Introduction

Changes in the Sun's radiation potentially cause climate change. Space-based solar monitoring recorded total irradiance levels increased  $1.3 \text{ Wm}^{-2}$  (0.1%) during the 1980 and 1990 maxima of the Sun's 11-year activity cycle relative to its levels during activity minima in 1986 and 1996 [Willson and Hudson, 1991; Lean, 1997; Fröhlich and Lean, 1998]. The radiative climate forcing of  $\sim 0.2 \text{ Wm}^{-2}$  associated with this irradiance change approximately equals that by increasing greenhouse gas concentrations over the same 5-year period [Hansen and Lacis, 1990]. Whereas the thermal inertia of the oceans is thought to attenuate significantly climate's response to an 11-year cyclic forcing [Wigley and Raper, 1990], longer term solar irradiance variations, if they are occurring in addition to the 11-year cycle, may contribute to global warming on multi-decadal and centennial time scales.

Surface temperatures and solar activity both increased during the past 400 years, with close associations apparent in pre- and post industrial epochs [Hoyt and Schatten, 1993; Lean et al., 1995; Reid, 1997]. However, the inference from correlation studies that Sun-climate relationships can account for a substantial fraction of global warming in the past 150 years is controversial. Since 1850, the climate forcing of  $2.4 \text{ Wm}^{-2}$  by increases in greenhouse gas concentrations exceeds significantly (and is known with greater certainty) than that by solar forcing, thought to be in the

range of  $0.2\text{-}0.8 \text{ Wm}^{-2}$  (or 0.1 to 0.4%) [Hoyt and Schatten, 1993; Lean et al., 1995; Soon et al., 1996; Solanki and Fligge, 1998].

Recently, Willson [1997] has claimed the detection of a significant irradiance increase of  $0.5 \text{ Wm}^{-2}$  (or 0.04%, approximately half the 11-year cycle amplitude) between solar cycle minima in 1986 and 1996 as proof that climatically-relevant long term irradiance changes are occurring. However, our analysis of the space record of solar total irradiance and model comparisons described below cannot support such a change.

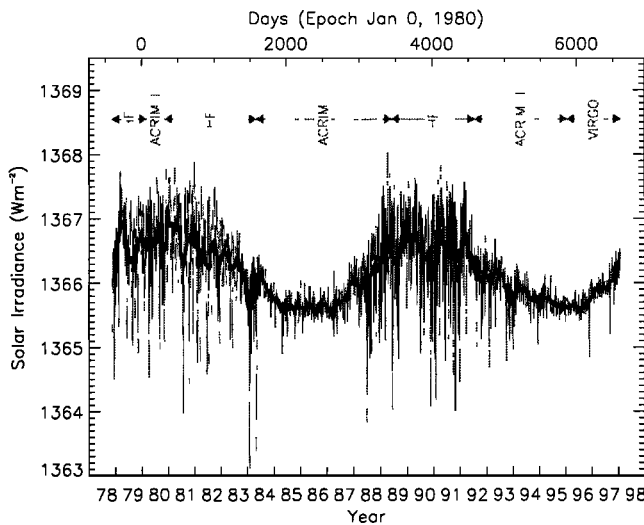
## Composite Solar Irradiance Record

Reliable deduction of true solar irradiance variability requires the construction of a composite record utilizing overlapping data for cross calibration of measurements made by different radiometers. This is needed because absolute levels of the Hickey-Frieden (HF), Active Cavity Radiometer Irradiance Monitor (ACRIM I and II), Earth Radiation Budget Satellite (ERBS) and Variability of solar Irradiance and Gravity Oscillations (VIRGO) radiometers have uncertainties of 'only'  $\pm 0.2\%$ . Corrections for sensitivity drifts must also be made because exposure to high energy solar radiation and particles alters the interior surfaces of the receiver cavities and their electronics, as do fluctuating thermal and aspect environments of the spacecraft platforms [Anklin et al., 1998].

Adjustments [Fröhlich and Lean, 1998] are made for drifts in the radiometric data as follows. We adjust HF data [Hoyt et al., 1992] prior to the end of 1980 downwards, corresponding to a slip in the NIMBUS-7 orientation relative to the sun. Near October 1, 1989 and May 8, 1990 adjustments are made of  $-0.26$  and  $-0.32 \text{ Wm}^{-2}$  respectively to correct for glitches relative to independent ERBS data and also by comparison with ground based evaluations [Lee III et al., 1995; Chapman et al., 1996]. We apply corrections for HF radiometer degradation prior to 1982 by utilizing data from the ACRIM I and considering the degradation of VIRGO's PMO6 radiometers (similar in design to the HF radiometers), presently flying on the Solar and Heliospheric Observatory (SOHO) [Fröhlich et al., 1995; Anklin et al., 1998]. We adjust the 1980 ACRIM I data downward by  $0.22 \text{ Wm}^{-2}$  to account for a total degradation of  $0.47 \text{ Wm}^{-2}$  [Fröhlich and Lean, 1998] compared with  $0.25 \text{ Wm}^{-2}$  (180 ppm) [Willson and Hudson, 1991]. Our assessment recognizes that essentially all ACRIM's degradation happened prior to the repair of the Solar Maximum Mission (SMM) since exposure during the spin mode phase (Dec. 1980 – April 1984) was

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**Figure 1.** Shown is a composite record of solar total irradiance compiled from detailed cross-calibrations of various radiometric measurements from the end of 1978 to the present, and adjusted to the absolute scale of the Space Absolute Radiometric Reference (SARR).

reduced by about a hundred times. We adjust ACRIM II data from the Upper Atmosphere Research Satellite (UARS) [Willson, 1994] upward by  $0.12 \text{ Wm}^{-2}$  after October 3rd 1995 to account for an apparent downward slip on October 2. Moreover, ACRIM II data prior to June 1992 seem to be influenced by the early exposure.

The composite solar total irradiance record displayed in Fig.1 was compiled from the drift-adjusted data as follows. During 1980, after 1984 until 1989 and from September 1991 to January 1996 the data are the ACRIM I and ACRIM II values, scaled by comparison with HF and ERBS data [Lee III et al., 1995; Fröhlich and Lean, 1998]. HF data are inserted prior to March 1980, during the ACRIM I spin-mode period from 1981 to 1984, and in the gap between the ACRIM I and II measurements. VIRGO data are used since January 18, 1996 [Fröhlich et al., 1995]. The absolute value of the composite is adjusted to the Space Absolute Radiometric Reference [Crommelynck et al., 1995] which is considered to provide the most probable value to date of the absolute level of solar total irradiance, with an uncertainty of  $\pm 0.15\%$ .

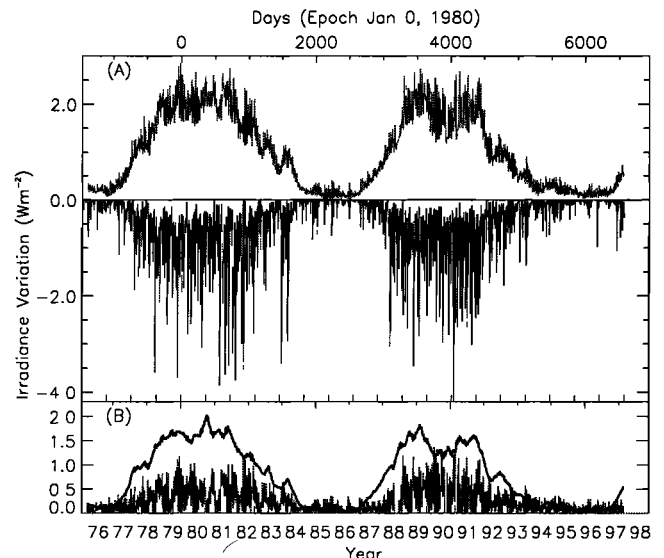
Our composite time series in Fig.1 suggests that levels of solar irradiance were similar during the 1986 and 1996 activity minima, in direct contrast with the analysis of Willson [1997] which indicated an upward irradiance trend of  $0.04\%$  between the two successive minima. The difference between these assessments corresponds closely to the sum of the two corrections applied to the HF data in October 1989 and May 1990 which Willson [1997] neglected.

## Solar Irradiance Variability Model

To assess prospective solar cycle irradiance changes we have developed an empirical model that parameterizes the combined influences of dark sunspots and bright facular features on solar irradiance since 1976, following Foukal and Lean [1988]. We calculate from ground-based visible light images a daily time series of sunspot darkening of irradi-

ance, incorporating results from recent studies of the dependence of sunspot residual intensity contrast on sunspot area [Brandt et al., 1994]. For representing irradiance brightening by faculae we use the chromosphere Mg index (ratio of the emission from the core of the Fraunhofer line near 280 nm to that from the wings) which is known to vary primarily in response to bright faculae (both in active regions and the surrounding network), alone. We construct a composite Mg index using data from the Solar Backscatter Ultraviolet (SBUV) instruments from 1978 to 1992 [Donnelly, 1988], the Solar Stellar Intercomparison Experiment (SOLSTICE) thereafter [de Toma et al., 1997], and the He EW from 1976 to 1978 [Harvey and Livingston, 1994], scaled by linear relationships in periods of overlap.

A linear combination of the sunspot darkening and facular brightening fluctuations, which we show in Fig.2, permits a reconstruction of solar total irradiance that tracks closely the variations in our composite record on time scales from days to the solar cycle with a correlation coefficient of 0.94, thus accounting for 88% of the variance. Recognizing that the chromospheric brightness sources may relate somewhat differently to photospheric facular brightness sources over shorter (rotational) versus longer (solar cycle) time scales, we construct as well a 3-component model by multiple linear regression of the irradiance composite with sunspot darkening, slowly varying Mg II index and short term Mg II index facular proxies. Fig. 3 compares this model with the observational composite. That this model can explain as much as 89% of the variance in our 18-year composite total irradiance record, argues strongly that both the proxy model and composite observational record reflect true solar variability since 1976. Both the measurements and the proxy model agree that solar irradiance levels were similar during the 1986 and 1996 solar cycle minima, contradicting the

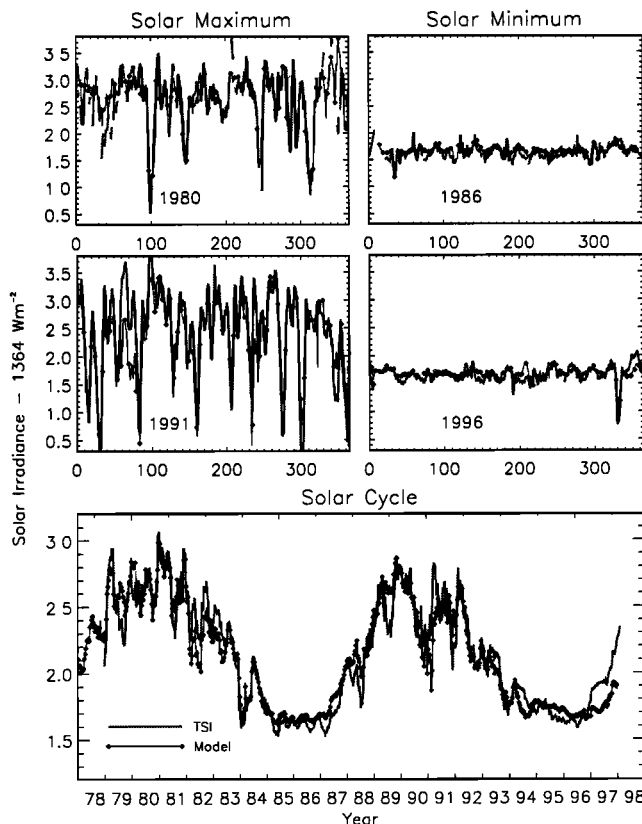


**Figure 2.** Shown in (A) is the time-dependent contribution of facular brightening to solar total irradiance variability, parameterized by a composite of the Mg II index. We compare this total facular brightening (above the line) with our calculated sunspot darkening (below the line) contribution to the total irradiance variability. In (B) we show the longer term of the facular brightening (smooth dark line) and daily components separated.

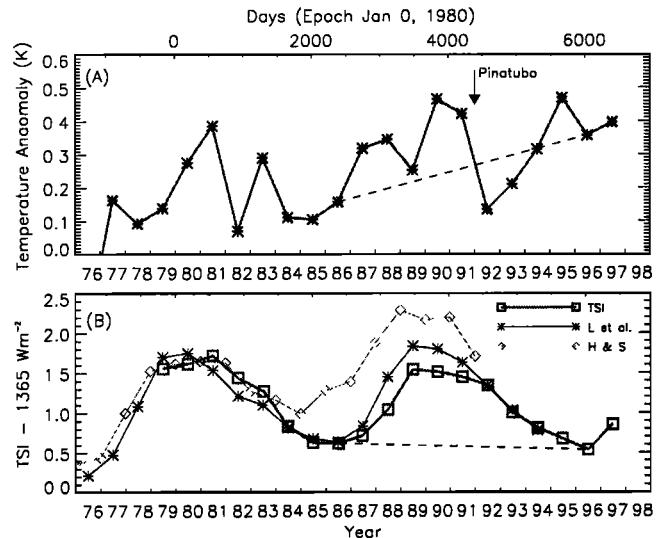
claimed 0.04% trend over this decade. Solar geomagnetic data provide independent confirmation of our results. The average value of the *aa* index in 1997 is similar to that in 1987 which *Cliver et al.* [1998] interpret as a leveling off of the long term component of solar variability.

## Surface Temperature Comparison

Unlike solar irradiance, which we have shown from both our observational composite and empirical model to have similar levels in 1986 and 1996, the global surface temperature of the earth has an upward trend of 0.2°C during this decade [*Hansen et al.*, 1997]. These different trends are evident in Fig. 4. Investigations of climate change attribution over multi-decadal time scales utilize historical irradiance reconstructions [*Hoyt and Schatten*, 1993; *Lean et al.*, 1995], two of which we compare in Fig. 4 with our composite irradiance record. Both irradiance reconstructions assume that solar irradiance varies over the 11-year activity cycle and on longer time scales as well, but their parameterizations differ for these variability components. In one case [*Lean et al.*, 1995] the centennial scale irradiance changes track the overall amplitude of solar activity cycles (as indicated by the direct relationship between irradiance and activity in the contemporary era), while in the other case [*Hoyt and Schatten*, 1993] the length, rather than amplitude, of the



**Figure 3.** Compared with the measured solar total irradiance variations (thick line) are estimates from our empirical model (thin line with diamonds) that utilizes the parameterizations of facular brightening and sunspot darkening shown in Fig. 2. The model replicates the observed variability over both the day-to-day time scales, shown in the upper panels, and over the solar cycle, shown in the lower panel.



**Figure 4.** Globally averaged annual mean surface temperatures compiled by the Goddard Institute for Space Studies (A), exhibit an overall increase of more than 0.2°C from 1986 to 1996, indicated by the dashed line. In contrast, the annual mean values of the composite total irradiance record (B) indicate similar levels over this decade. Compared in (B) with the annual mean composite irradiance (TSI) record are two different irradiance reconstructions by [*Lean et al.*, 1995] and [*Hoyt and Schatten*, 1993] that have been used elsewhere to investigate historical solar forcing of climate change.

activity cycle is adopted as a proxy for long term solar irradiance fluctuations. Our composite irradiance record does not have the upward irradiance trend present in the cycle-length model [*Hoyt and Schatten*, 1993].

## Conclusions

Measurements of total solar irradiance, when corrected for a variety of instrumental effects that we have identified in the historical database, indicate comparable levels during the two most recent solar minima, 1986 and 1996. In contrast, measurements of earth's global surface temperature increased 0.2°C during this decade. While these results indicate that direct solar total irradiance forcing is unlikely to be the cause of global warming in the past decade, the acquisition of a much longer composite solar irradiance record is essential for reliably specifying the role of the Sun in global climate change. Detection of long term solar irradiance trends and validation of historical irradiance reconstructions rely on the acquisition of a much longer irradiance time series than is presently available. Future comparisons of the composite solar irradiance record with historical reconstructions may help resolve speculations about the extent of long term solar irradiance increase since the seventeenth century Maunder Minimum, and the relative roles of direct radiative and indirect (e.g., by changing solar ultraviolet radiation or particle fluxes) solar forcing of climate change.

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## References

- Anklin, M., C. Fröhlich, W. Finsterle, D. A. Crommelynck, and S. Dewitte, Assessment of degradation of VIRGO radiometers onboard SOHO, *Metrologia*, *35*, in press, 1998.
- Brandt, P. N., M. Stix, and H. Weinhardt, Modelling solar irradiance variations with an area dependent photometric sunspot index, *Sol. Phys.*, *152*, 119–124, 1994.
- Chapman, G. A., A. M. Cookson, and J. J. Dobias, Variations in total solar irradiance during solar cycle 22, *J. Geophys. Res.*, *101*, 13541–13548, 1996.
- Cliver, E. W., V. Boriakoff, and J. Feynman, Solar variability and climate change: Geomagnetic aa index and global surface temperature, *Geophys. Res. Lett.*, *25*, 1035–1038, 1998.
- Crommelynck, D., A. Fichot, R. B. Lee III, and J. Romero, First realisation of the space absolute radiometric reference (SARR) during the ATLAS 2 flight period, *Adv. Space Res.*, *16*, (8)17–(8)23, 1995.
- de Toma, G., O. R. White, B. G. Knapp, G. J. Rottman, and T. N. Woods, Mg II core-to-wing index: Comparison of SBUV2 and SOLSTICE time series, *J. Geophys. Res.*, *102*, 2597–2610, 1997.
- Donnelly, R. F., The solar MgII core-to-wing ratio from the NOAA 9 satellite during the rise of solar cycle 22, *Adv. Space Res.*, *8*, (7)77–(7)80, 1988.
- Foukal, P. V., and J. Lean, Magnetic modulation of solar luminosity by photospheric activity, *Astrophys. J.*, *328*, 347–357, 1988.
- Fröhlich, C., and J. Lean, Solar radiative output and its variability: Evidence and mechanisms, *Astron. Astrophys. Rev.*, manuscript in preparation, 1998a.
- Fröhlich, C., and J. Lean, Total solar irradiance variations: The construction of a composite and its comparison with models, in *IAU Symposium 185: New Eyes to See Inside the Sun and Stars*, edited by F. L. Deubner, 89–102, Kluwer Academic Publ., Dordrecht, The Netherlands, 1998b.
- Fröhlich, C., et al., VIRGO: experiment for helioseismology and solar irradiance monitoring, *Sol. Phys.*, *162*, 101–128, 1995.
- Hansen, J., et al., Forcings and chaos in interannual to decadal climate change, *J. Geophys. Res.*, *102*, 25679–25720, 1997.
- Hansen, J. E., and A. A. Lacis, Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change, *Nature*, *346*, 713–719, 1990.
- Harvey, J. W., and W. C. Livingston, Variability of the solar He I 10830 triplet, in *International Astronomical Union Symposium 154: Infrared Solar Physics*, edited by D. M. Rabin, J. T. Jefferies, and C. Lindsey, pp. 59–64, Kluwer Academic Publ., Dordrecht, The Netherlands, 1994.
- Hoyt, D. V., and K. H. Schatten, A discussion of plausible solar irradiance variations, 1700–1992, *J. Geophys. Res.*, *98*, 18895–18906, 1993.
- Hoyt, D. V., H. L. Kyle, J. R. Hickey, and R. H. Maschhoff, The NIMBUS-7 solar total irradiance: A new algorithm for its derivation, *J. Geophys. Res.*, *97*, 51–63, 1992.
- Lean, J., The Sun's variable radiation and its relevance for Earth, *Annu. Rev. Astron. Astrophys.*, *35*, 33–67, 1997.
- Lean, J., J. Beer, and R. Bradley, Reconstruction of solar irradiance since 1610: Implications for climate change, *Geophys. Res. Lett.*, *22*, 3195–3198, 1995.
- Lee III, R. B., M. A. Gibson, R. S. Wilson, and S. Thomas, Long-term total solar irradiance variability during sunspot cycle 22, *J. Geophys. Res.*, *100*, 1667–1675, 1995.
- Reid, G. C., Solar forcing of global climate change since the mid-17th century, *Clim. Change*, *37*, 391–405, 1997.
- Solanki, S. K., and M. Fligge, Solar irradiance since 1874 revisited, *Geophys. Res. Lett.*, *25*, 1–4, 1998.
- Soon, W. H., E. S. Posmentier, and S. L. Baliunas, Inference of solar irradiance variability from terrestrial temperature changes, 1880–1993: An astrophysical application of the sun-climate connection, *Astrophys. J.*, *472*, 891–902, 1996.
- Wigley, T. M., and S. C. B. Raper, Climatic change due to solar irradiance changes, *Geophys. Res. Lett.*, *17*, 2169–2172, 1990.
- Willson, R. C., Irradiance observations from SMM, UARS and ATLAS experiments, in *The Sun as a Variable Star, Solar and Stellar Irradiance Variations*, edited by J. Pap, C. Fröhlich, H. S. Hudson, and S. Solanki, pp. 54–62, Cambridge University Press, Cambridge UK, 1994.
- Willson, R. C., Total solar irradiance trend during solar cycles 21 and 22, *Science*, *277*, 1963–1965, 1997.
- Willson, R. C., and H. S. Hudson, The Sun's luminosity over a complete solar cycle, *Nature*, *351*, 42–44, 1991.

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