Total Solar Irradiance Trend During Solar Cycles 21 and 22

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Results from Active Cavity Radiometer Irradiance Monitor (ACRIM) experiments show an upward trend in total solar irradiance of 0.036 percent per decade between the minima of solar cycles 21 and 22. The trend follows the increasing solar activity of recent decades and, if sustained, could raise global temperatures. Trends of total solar irradiance near this rate have been implicated as causal factors in climate change on century to millennial time scales.

Total solar irradiance (TSI), a measure of the climate-driving radiative energy received by Earth from the sun, has been monitored by satellite experiments with adequate precision to detect intrinsic solar variability since 1978 (*1*). A direct association between solar magnetic activity and climate has been inferred from historical records of climate, solar activity indicators, and time series analyses of cosmogenic isotopes (*2, 3*). Data from the first ACRIM experiment (ACRIM I) on the Solar Maximum Mission (SMM) showed that solar activity during a solar cycle was directly related to TSI. This was confirmed by the Nimbus 7 Earth Radiation Budget (ERB) and Earth Radiation Budget Satellite (ERBS) experiments during solar cycles 21 and 22 (*4–6*). On the basis of this result, it has been suggested that the a TSI decrease during the Maunder Minimum of solar activity (1650–1715) may have been a contributing factor to the Little Ice Age climate anomaly (*2, 7*).

The ERB, ACRIM I, ERBS, and Upper Atmosphere Research Satellite (UARS) ACRIM II (*1*) experiments have provided the overlapping, complementary data essential for establishing and sustaining a precision, long-term TSI database (Fig. 1) (*8*). Of these experiments, only ACRIM I and II are able to calibrate degradation of their monitoring sensors (9). The larger uncertainties of the ERB and ERBS are the result of their limited observing opportunities and their inability to calibrate sensor degradation (*10*).

The ACRIM II experiment has provided a highly precise component of the TSI database since 1991. ACRIM II was launched in September 1991 as part of the science payload of UARS nearly 2 years after the end of the SMM. The delay of its launch prevented planned on-orbit comparisons between ACRIM I and ACRIM II. The absolute uncertainty of flight-qualified TSI sensors—about 0.1% in the laboratory and larger in space flight experiments—is inadequate to sustain a useful long-term TSI database. Evidence for this is clearly seen in Fig. 1, where the spread of results from the ERB, ACRIM I, ACRIM II, and ERBS experiments covers ~±0.25% about their mean, exceeding the 0.08% peak-to-peak TSI variation observed during solar cycle 21. The two ACRIM experiments were overlapped by the ERB and ERBS observations, and it is possible to relate ACRIM I and ACRIM II using these comparisons.

The ACRIM II results (Fig. 2) show variations resulting from solar rotation (~28 days) and active-region lifetimes (3 to 6 months). The large, short-term decreases are caused by the TSI deficit of sunspots in magnetically active regions as they rotate through our view from Earth. The peaks preceding and following these sunspot dips are caused by the TSI excess of faculae in solar active regions, whose larger areal extent causes them to be seen first as the region rotates onto our side of the sun and last as they rotate over the opposite solar limb. These effects are evident in the ACRIM I and ERB results as well. The downward trend through the 1991–1997 period is similar in slope and amplitude to that observed by ACRIM I during the declining activity phase of solar cycle 21. From the peak of solar cycle 21 to its minimum, the TSI decreased by ~0.08%. The similar appearance of the ACRIM I and II results during the declining activity phases of solar cycles 21 and 22 indicates that a cycle 22 TSI minimum could occur during 1997, about 11 years after the cycle 21 minimum (*11*).

The results of electrically self-calibrating TSI experiments are initially reported on the "native scale" of their instrument calibration, which relates the observations to SI units. The spread of results in SI units seen in Fig. 1 is an artifact of native-scale reporting. A common reference scale based on instrument precision must be adopted to produce a long-term database because of the need to relate the observations of many TSI experiments at high precision. Here, I relate the observations of the ACRIM I and ACRIM II experiments, using mutual comparisons with the ERB results.

The ACRIM I/ACRIM II ratio derived from the ERB comparisons is nearly twice as precise as the ratio derived from ERBS (Table 1) because of ERB's larger number of comparison days, smaller measurement uncertainties, and daily mean measurement correspondence with ACRIM results. The ERB observations are made on every orbit

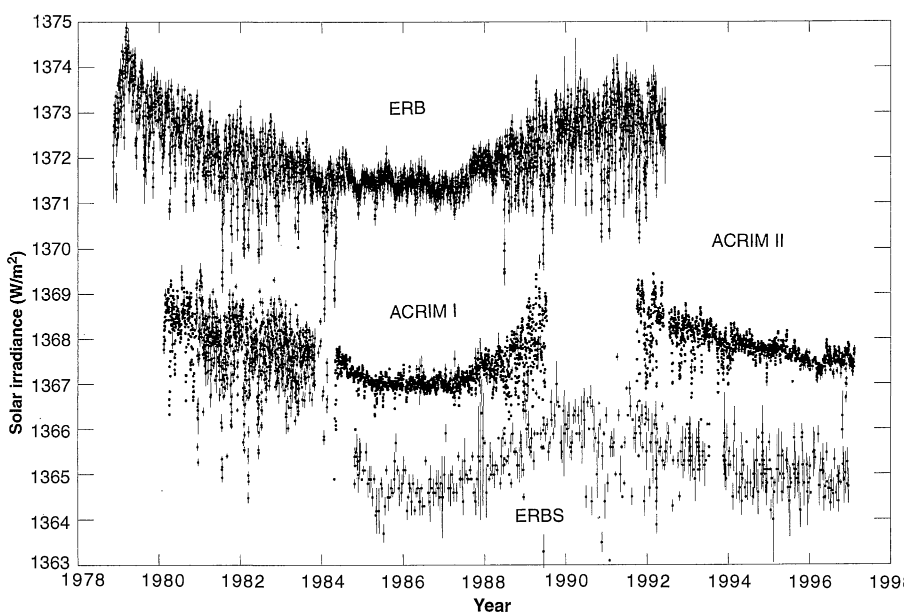

Fig. 1. TSI monitoring results during solar cycles 21 and 22. Daily mean values and uncertainties are shown for the ERB, ACRIM I, ERBS, and ACRIM II experiments.

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of its operational days, whereas the ERBS operates for only one orbit every 14 days. ACRIM and ERB results are integrated over each comparison day, whereas the ERBS results could produce a more variable result on a given day, depending on the rate of TSI variation. There is a systematic difference of 331 parts per million between the ACRIM I/ACRIM II ratio derived from ERB and that derived from ERBS. The ERB/ERBS ratios for the ACRIM I and ACRIM II periods confirm this difference, which indicates a systematic shift in sensitivity for one or both of the ERBS and ERB sensors between the ACRIM I (1984–1989) and ACRIM II (1991–1993) comparison periods.

There were several trends in the ERB/ERBS ratio during the years these experiments overlapped. These trends are believed to be caused by differing rates of degradation of their sensors, which in turn are dependent on the flight history of each experiment and the extent of solar activity (*5, 6, 12–14*). The ERB, ACRIM I, ERBS, and ACRIM II experiments all experienced rapid initial degradation (*1, 5, 6, 8, 15*). The effects on ACRIM results were removed by their degradation self-calibrations (*1, 4, 9*). The effects on the ERB and ERBS remain convoluted with their data and can be seen in Fig. 1 as rapid decreases in their early results.

Increasingly intense solar activity beginning in 1988, approaching the maximum of solar cycle 22, produced large increases in high-energy, short-wavelength solar radiation. The rate of degradation of ACRIM I's sensors increased during this time (*4*). The degradation rates of the ERB and ERBS sensors undoubtedly increased as well (*16*).

Table 1. Relation between ACRIM I and ACRIM II results derived from comparisons with ERB and ERBS. Uncertainties in least significant digits are shown in parentheses.

Comparison	Samples	Ratio
ACRIM data vs. ERB		
ACRIM I	2714	1.003138 (05)
ACRIM II	368	1.004832 (14)
ACRIM I/ACRIM II		1.001689 (15)
ACRIM data vs. ERBS		
ACRIM I	138	0.998400 (22)
ACRIM II	221	0.999756 (19)
ACRIM I/ACRIM II		1.001358 (29)
Weighted mean ACRIM I/ACRIM II ratio		1.001621 (13)
ERB/ERBS ratio		
During ACRIM I (1985–1989)	254	1.004833 (25)
During ACRIM II (1991–1993)	50	1.005146 (31)
Ratio change		0.000313

The increase in the ERB/ERBS ratio during the 1989–1991 gap between ACRIM I and ACRIM II could result from increased ERBS degradation relative to ERB, a relative increase in the sensitivity of the ERB sensor, or both. The ERB data were reviewed in 1993 and corrected for a 1987 sensor response increase of 0.03%. It is unlikely that other similar increases were overlooked (*12*).

Increases in the ERB results, relative to regression fits to ERBS data in 1989 and 1990 against solar activity indices, have been attributed to uncorrected increases in ERB sensitivity (*6, 10*). Although regression analyses can provide qualitative views of measurement trends, the multiple regression of Lee *et al.* (*6*) is based on solar indices that are less well calibrated than are the TSI data. Moreover, the relations between these indices and TSI are not well understood. These regressions cannot determine whether the ERB or ERBS experiment is principally responsible for the shift in their ratio between the ACRIM I and ACRIM II periods. The weight of evidence indicates that the increase in the ERB/ERBS ratio between the ACRIM I and ACRIM II periods was not caused by an increase in ERB sensitivity, but rather by the accelerated degradation of ERBS as it responded to its first exposure to heightened solar ultraviolet (UV) flux during the rising activity phase of solar cycle 22 (*5, 12, 14*).

For the above reasons, I have selected the ACRIM I/ACRIM II ratio derived from ERB data (1.001689) to relate the results of the ACRIM I and ACRIM II experiments. Similar TSI trends between successive solar minima are found in the results of both the ACRIM and ERBS databases if the ERB ratio is used. If the ERBS ratio is used instead, this is not the case—another indication of uncorrected degradation in the ERBS data (*17*).

The ACRIM and ERBS databases both include results near the activity minima of two successive solar cycles, 21 and 22 (Figs. 1 and 2). The rapidly varying active-region phenomena that drive large TSI fluctuations are largely absent during these minima, and therefore they are the likeliest source of evidence for long-term TSI trends. If we assume that the TSI was near a min-

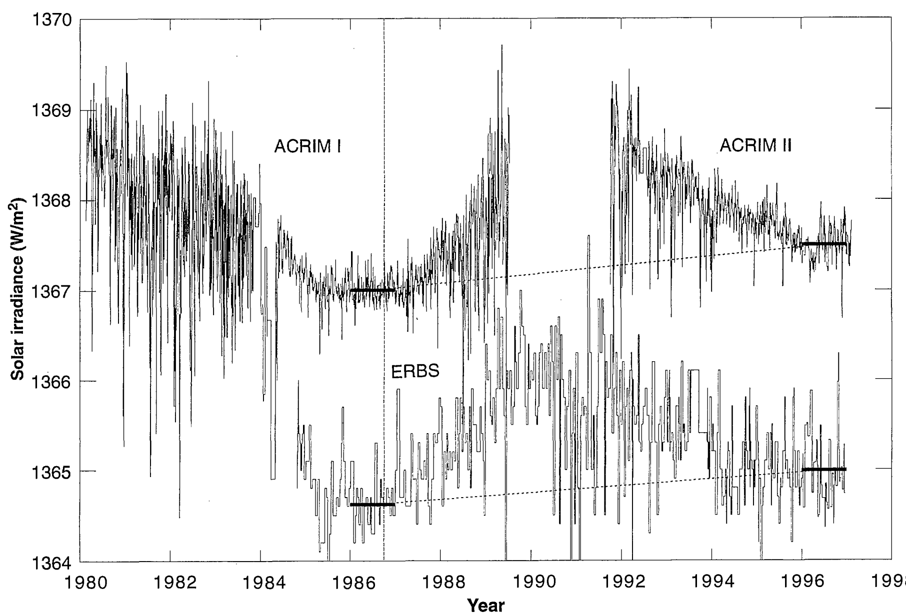

Fig. 2. TSI trends in ACRIM and ERBS results between the minima of solar cycles 21 and 22.

Table 2. Multidecadal TSI trend detected in results of the composite ACRIM and ERBS experiments near the minima of solar cycles 21 and 22.

Parameter	ACRIM*	Uncertainty (prob. error)	ERBS	Uncertainty (prob. error)
1986 mean TSI (W/m²)	1367.009	0.007	1364.624	0.050
1996 mean TSI (W/m²)	1367.502	0.011	1364.994	0.071
Ratio (1996/1986)	1.000361	0.000006	1.000271	0.000036
Degradation corrections (%)	0 to 0.100	<0.0050	0	Unknown
Slope of trend (% per decade)	0.036	<0.005	0.027	Unknown

*ACRIM I/ACRIM II ratio = 1.001689.

imum for solar cycle 22 during 1996, then the ACRIM mean TSI was 0.0361 ± 0.0006% higher for the current minimum than for cycle 21 (Table 2 and Fig. 2). Degradation corrections for the ACRIM experiments are uncertain by less than ±0.005% per decade (*4*). The total root-mean-square uncertainty of the trend is also less than ±0.005%, which indicates that the difference in ACRIM TSI between the solar minima in 1986 and 1996 is well resolved.

Similarly, the corresponding mean ERBS results changed by 0.0271 ± 0.0036% between 1986 and 1996 (Fig. 2). The ERBS uncertainty does not include sensor degradation, and significant changes of ERBS results can be observed in the record when no comparable signals are present in other TSI data (Figs. 1 and 2). Accelerated degradation during the rising activity phase of solar cycle 22 is likely, with an amplitude ranging up to the shift in the ERB/ERBS ratio (~0.03%). The ERBS trend is corroborative, but its degradation uncertainty limits it to qualitative interpretations.

The TSI trend is significant for direct solar climate forcing. The response of climate to TSI variation is complex, but a sensitivity is predicted by global circulation models at ~1 K per 1% change in TSI (*18*). If sustained, the ACRIM TSI trend is near that required to produce, on 200-year time scales, a climate change comparable to (but in the opposite sense of) the estimated 0.4 to 1.5 K average temperature decrease during the Little Ice Age climate anomaly (*3*, *19*). The climatic effect of greenhouse warming over the next 50 to 100 years is estimated to be 1.5 to 4.5 K (*19*). By comparison, the TSI trend could produce additional warming of ~0.4 K in 100 years, a potentially significant contribution.

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10. The ERB and ERBS experiments view the sun as it passes through their fields of view for only a few minutes per orbit, whereas the ACRIM experiments are solar-pointed for at least 10 shutter cycles per orbit, every orbit, every day. During most of the ERB mission, observations were made every orbit on 3 of every 4 days. The ERBS experiments observe the sun for a few minutes during one orbit every 2 weeks.
11. UV irradiances, their surrogates (HeI 1083 and F10.7 cm fluxes), and the Zurich sunspot number were at a minimum in mid-1996. ACRIM II results showed a local minimum near the same time. The broad TSI minimum of solar cycle 21 was centered about 6 months before solar minimum, as defined by reversal of active-region magnetic polarity in September 1986. Definition of the actual location of the cycle 22 TSI minimum must await analysis of the 1997 ACRIM II results.
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14. H. L. Kyle *et al.*, *Nimbus-7 Earth Radiation Budget Compact Solar Data Set User's Guide* (NASA Ref. Pub. 1346, NASA, Greenbelt, MD, 1994).
15. Degradation of the cavity sensors of TSI experiments is a phenomenon that usually occurs in two phases. The first is rapid degradation that occurs when the cavity's solar flux–absorbing surface is modified by its initial exposure to space and the radiation environment. The sensors then settle into a "mission" degradation modality as further exposure to solar flux slowly alters the cavity's absorbing surfaces. The rates of initial and mission degradation vary between experiments, but the degradation phenomena are common to most of them. It was further observed in the ACRIM I experiment that the rate of degradation was proportional to both the amount of solar exposure and the relative abundance of high energy, short-wavelength flux. During periods of intense solar magnetic activity, the enhanced amounts of high-energy, short-wavelength solar radiation increase the rate of degradation.
16. A lower susceptibility for ERB to accelerated degradation would be expected because of its longer history of solar exposure, including the peak activity period of solar cycle 21. Its sensor surfaces may have been near their degradation saturation point during solar cycle 22.
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20. I thank J. Hansen, L. Kyle, A. Mecherikunnel, R. Lee III, and R. Wilson for providing helpful discussions, documentation, data, and advice. The ACRIM II experiment is supported by NASA at Columbia University under NASA contract NAS5-97164. The ACRIM II results are available from the NASA Goddard Space Flight Center and Langley Research Center Distributed Active Archive Centers.

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Increased Compressibility of Pseudobrookite-Type $MgTi_2O_5$ Caused by Cation Disorder

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Compressibilities were determined for four pseudobrookite-type magnesium titanate ($MgTi_2O_5$) samples with different degrees of Mg-Ti disorder. Compressibilities of *a* and *c* axes in disordered $MgTi_2O_5$ were 10% and 7% greater, respectively, than those of a relatively ordered sample. The estimated bulk moduli for fully ordered and disordered $MgTi_2O_5$ are 167 ± 1 and 158 ± 1 gigapascals, respectively. This difference is an order of magnitude greater than that predicted by bulk modulus–volume systematics. Cation order, in addition to composition and structure information, is thus important when documenting the elasticity of crystalline phases. Elastic constants of mantle silicates that are subject to pressure-induced cation ordering must be reevaluated.

Pressure-volume equations of state (EOS) of crystalline solids impose important constraints on models of interatomic bonding, and they provide an essential foundation for interpreting seismic data from Earth's deep interior. Conventional wisdom suggests that EOS are principally dependent on only two variables: structure and composition. Summaries of mineral EOS parameters (*1*), for example, are tabulated according to these two variables. Details on the state of order-disorder—which may be important in characterizing the thermochemistry and transport properties of minerals as well as those of alloys, ceramics, and other crystalline phases—are usually omitted in discussions of EOS. Recent studies demonstrate that order-disorder phenomena may be affected by pressure in phases that display a nonzero volume of disordering $\Delta V_{dis} = V_{disordered} - V_{ordered}$ (*2*). Silicate minerals commonly display ΔV_{dis} up to 0.5% (*3*, *4*), and values exceeding 1% have been observed in oxides and sulfides (*5*). However, the extent to which differing states of order affect the physical properties of phases at high pressure is not known.

The comparative compressibility technique, in which several crystals are mounted in the same diamond-anvil cell experiment, can be used to discern subtle differ-

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