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Research Article

Comparison of Decadal Trends among Total Solar Irradiance Composites of Satellite Observations

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We present a new analysis of the two-decade-old controversy over interpretation of satellite observations of total solar irradiance (TSI) since 1978 and the implications of our findings for TSI as a driver of climate change. Our approach compares the methods of constructing the two most commonly referenced TSI composites (ACRIM and PMOD) that relate successive observational databases and two others recently constructed using a novel statistical approach. Our primary focus is on the disparate decadal trending results of the ACRIM and PMOD TSI composite time series, namely, whether they indicate an increasing trend from 1980 to 2000 and a decreasing trend thereafter (ACRIM) or a continuously decreasing trend since 1980 (PMOD). Construction of the four-decade observational TSI composites from 1978 to the present requires the use of results from two less precise Earth Radiation Budget experiments (Nimbus7/ERB and ERBS/ERBE) during the so-called ACRIM-Gap (1989.5–1991.8), between the end of the ACRIM1 and the beginning of the ACRIM2 experiments. The ACRIM and PMOD composites used the ERB and ERBE results, respectively, to bridge the gap. The well-established paradigm of positive correlation between Solar Magnetic Field Strength (SMFS) and TSI supports the validity of the upward trend in the ERB results and the corresponding decadal upward trend of the ACRIM composite during solar cycles 21 and 22. The ERBE results have a sensor degradation caused downward gap trend, contrary to the SMFS/TSI paradigm, that biased the PMOD composite decadal trend downward during solar cycles 21 and 22. The different choice of gap bridging data is clearly the cause of the ACRIM and PMOD TSI trending difference, agreeing closely in both magnitude and direction. We also analyze two recently proposed statistical TSI composites. Unfortunately their methodology cannot account for the gap degradation of the ERBE experiment and their resulting uncertainties are too large to uniquely distinguish between the trending of the ACRIM and PMOD composites. Our analysis supports the ACRIM TSI increasing trend during the 1980 to 2000 period, followed by a long-term decreasing trend since.

1. Introduction

Satellite total solar irradiance (TSI) composite databases, using observations from different satellites covering different segments of time since November 1978, have been constructed by several research teams (e.g., [1–9]). TSI composites are important for investigating both solar physics and the effects of TSI variations on the earth's climate. The currently accepted mean TSI value for last complete solar cycle 23 (1996–2009) is near 1361 W/m^2 [7]. The most important feature of a TSI composite for earth climate studies on decadal to multidecadal timescales is the solar magnetic cycle-to-cycle trending that provides valuable information for evaluating solar models and investigating the relative significance of natural and anthropogenic forcing of climate change [7, 10–12]. The two mostly frequently cited TSI composites, compiled by the ACRIM [3, 7] and PMOD [2, 13, 14] science teams, are shown in Figure 1.

1.1. ACRIM and PMOD Composites. ACRIM combines the published and archived NASA records collected and processed by the ACRIM science teams responsible for the Solar Maximum Mission/ACRIM1 (1980–1989), the Upper Atmosphere Research Satellite/ACRIM2 (1991–2001), and the

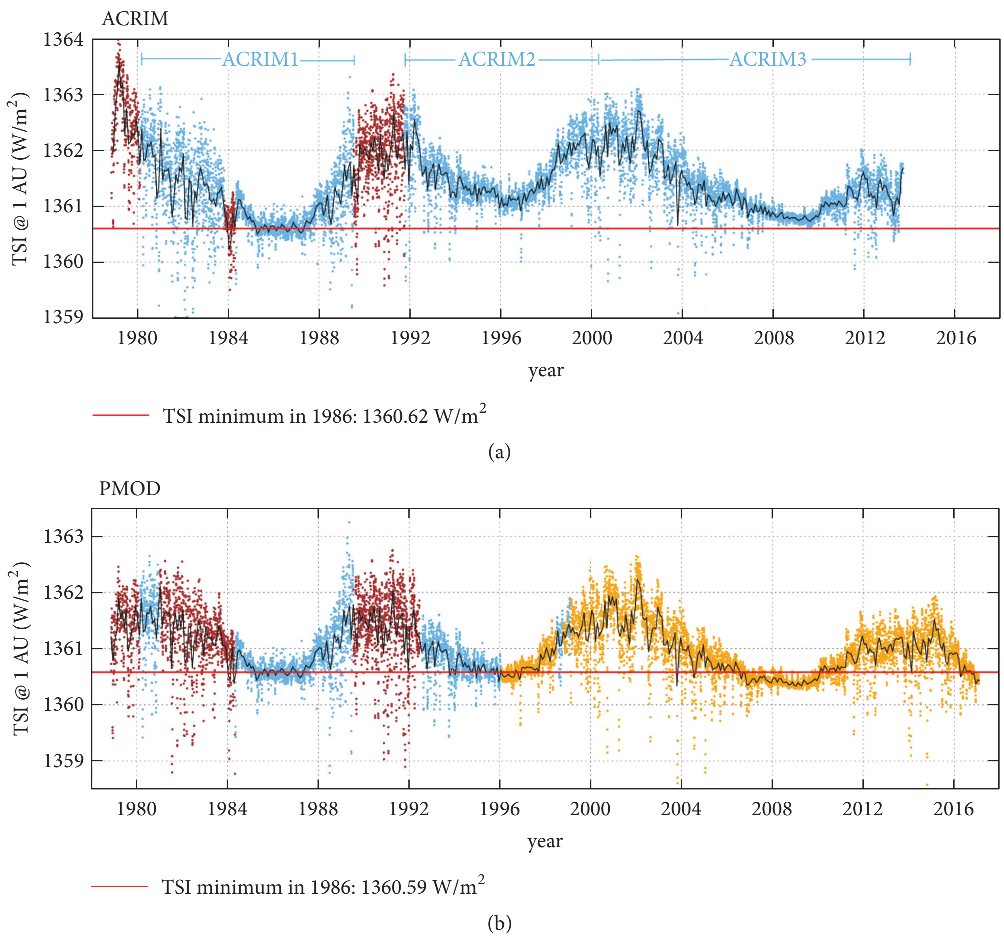

Figure 1: (a) ACRIM TSI composite. (b) PMOD (v. 1702) TSI composite [7, 14]. Components of each composite are ACRIM123 (blue), Nimbus7/ERB (brown), and VIRGO (orange).

ACRIMSAT/ACRIM3 (1999–2013) mission, together with the original ERB science team results from the Nimbus7/ERB (1978–1993) experiment prior to the launch of ACRIM1 (1878–1980) and during the about 2-year gap between ACRIM1 and ACRIM2 results (the so-called ACRIM-Gap from 1989.5 to 1991.8).

The PMOD composite uses their model-modified versions of the ACRIM1, ACRIM2, Nimbus7/ERB and Earth Radiation Budget Satellite/ERBE (1984–2003) records from late 1978 to 1996, together with the Solar and Heliospheric Observatory/VIRGO observational record (1996 to present).

Other TSI composites have been proposed. The RMIB [4, 8] is based on daily averaged TSI data from all available instruments once they are first put on a common absolute scale. Scafetta [6] proposed three alternative composites based on an optimal merging of the TSI records where the ACRIM-Gap was resolved either by Nimbus7/ERB results, by ERBS/ERBE results, or by their average.

The most significant difference between the ACRIM and PMOD composites is their multidecadal trending during solar cycles 21-24. This can be seen clearly in Table 1 where the solar cycle minima in 1986, 1996, and 2009 are compared. ACRIM shows a 0.46 W/m^2 increase between 1986 and 1996 followed by a decrease of 0.30 W/m^2 between 1996 and 2009. PMOD shows a continuous, increasing downward trend with a 1986 to 1996 decrease of 0.05 W/m^2 followed by a decrease of 0.14 W/m^2 between 1996 and 2009. The RMIB composite agrees qualitatively with the ACRIM trend by increasing between the 1986 and 1996 minima and decreasing slightly between 1996 and 2009.

Table 1: Mean values of the TSI composite solar cycle activity during the year of their minima. The error bar of the annual mean values is less than σ=0.01 W/m^2.

	1986 (W/m^2)	1996 (W/m^2)	2009 (W/m^2)
ACRIM	1360.62	1361.08	1360.78
PMOD (v. 1702)	1360.59	1360.54	1360.40
de Wit - Unmodified	1360.32	1360.66	1360.54
de Wit - Modified	1360.52	1360.68	1360.54
Satire-T2	1365.63	1365.50	missing
Satire-S	1360.98	1360.75	1360.55

The different methodologies and components of the TSI records used to construct the ACRIM and PMOD composites cause subtle but important differences between them. The most significant of these, the opposite trends in TSI minima between 1986 and 1996, is caused by their different approaches to bridging the ACRIM-Gap (1989.5–1991.8):

(1) The ACRIM composite uses the original overlapping Nimbus7/ERB results to link ACRIM1 and ACRIM2 results.

(2) The PMOD has produced several composites (cf.: [2, 13, 14, 17, 18]) using different models of the available TSI data during the gap. It bases the results during the gap on the Nimbus7/ERB data sampling frequency but "conformed" to the lower TSI level and negative trend slope of the ERBS/ERBE results, essentially recalibrating and altering the trend in the ERB data to agree with the magnitude and trend of the sparse ERBE results and of some TSI proxy models. This approach is followed mostly by Lee III et al. [19] claiming that during the ACRIM-Gap period Nimbus7/ERB sensitivity increased anomalously. Their proposed evidence supporting this claim was that the Nimbus7/ERB record diverged from a simple TSI proxy model based upon the 10.7-cm solar radio flux (F10) and the photometric sunspot index (PSI). Thus, PMOD used overlapping comparisons of ACRIM1 and ACRIM2 with ERBE observations and proxy models to construct their first composite. Other PMOD composites [17, 18] used different models of the ERBE-ACRIM-Gap degradation. The result of these various modifications during the ACRIM-Gap was that PMOD introduced a downward trend in the Nimbus7/ERB TSI data that decreased results by 0.8 to 0.9 W/m^2 (cf. [18, 20]).

The PMOD rationale for using models to alter the Nimbus7/ERB data was to compensate for the sparsity of the ERBS/ERBE data and conform their gap results more closely to the proxy predictions of solar emission line models of TSI behavior. In fact, the ERBS/ERBE record is too sparse and affected by uncalibrated degradation to provide a useful bridge of the gap between the ACRIM1 and ACRIM2 records using only its observational data.

The trending difference between the two composites has been the subject of a lengthy controversy. ACRIM contends the following:

(1) PMOD's modifications of the published ACRIM and ERB TSI records are questionable because they are based on conforming satellite observational data to proxy model predictions rather than an original analysis of the ACRIM, ERB, and ERBE data [3, 20].

(2) The PMOD trend during 1986 to 1996 is biased downward by scaling ERB results to the rapidly degrading ERBE results during the ACRIM-Gap using the questionable justification of agreement with some TSI proxy predictions first proposed by Lee III et al. [19] (cf.: [3]).

(3) PMOD misinterpreted and erroneously corrected ERB results for an instrument power down event (Sep. 25-28, 1989) as an instrument "glitch" and sensitivity change and for a presumed drift (cf.: [13, 20]).

(4) The fabrication and endorsement of the PMOD composite by some might have been influenced by the fact that TSI proxy models popular at the time predicted a TSI decreasing trend similar to that in the PMOD composite (e.g., [2, 15, 16, 21–25]). However, the proxy data used by these models are derived from observations of the solar active regions, sunspots, and faculae, which nearly disappear during solar cycle minima and are therefore poorly suited for modeling quiet solar brightness variability.

Regarding the Nimbus7/ERB data modification implemented by PMOD during the ACRIM-Gap, it is important to stress that Dr. Hoyt, who was the director of the Nimbus7/ERB mission, disregarded Fröhlich's claims from an experimental perspective (see the supplement files published in [26]). In that occasion Hoyt stated: *"Concerning the supposed increase in Nimbus7 sensitivity at the end of September 1989 and other matters as proposed by Frohlich's PMOD TSI composite: (1) There is no known physical change in the electrically calibrated Nimbus7 radiometer or its electronics that could have caused it to become more sensitive. At least neither Lee Kyle nor I could never imagine how such a thing could happen and no one else has ever come up with a physical theory for the instrument that could cause it to become more sensitive. (2) The Nimbus7 radiometer was calibrated electrically every 12 days. The calibrations before and after the September shutdown gave no indication of any change in the sensitivity of the radiometer. Thus, when Bob Lee of the ERBS team originally claimed there was a change in Nimbus7 sensitivity, we examined the issue and concluded there was no internal evidence in the Nimbus7 records to warrant the correction that he was proposing. Since the result was a null one, no publication was thought necessary. (3) Thus, Frohlich's PMOD TSI composite is not consistent with the internal data or physics of the Nimbus7 cavity radiometer"* (https://agupubs.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1029%2F2008GL036307&file=grl25417-sup-0002-txts01.txt).

The consistent downward trending of the PMOD TSI composite is negatively correlated with the global mean temperature anomaly during 1980–2000. This has been viewed with favor by those supporting the CO_2 anthropogenic global warming (CAGW) hypothesis since it would minimize TSI variation as a competitive climate change driver to CO_2, the featured driver of the hypothesis during the period (cf.: [10, 11, 24]).

ACRIM composite trending is well correlated with the record of global mean temperature anomaly over the entire range of satellite observations (1980–2018) [12]. The climate warming hiatus observed since 2000 is inconsistent with CO_2 anthropogenic global warming (CAGW) climate models [27, 28]. This points to a significant percentage of the observed 1980–2000 warming being driven by TSI variation [6, 7, 12]. A number of other studies have pointed out that climate change and TSI variability are strongly correlated throughout the Holocene including the recent decades (e.g., [12, 20, 27, 29–36]).

The paradigm of positive correlation between Solar Magnetic Field Strength (SMFS) and TSI, first established by ACRIM1 observations [1, 3, 20, 37–41], supports the validity of the upward trend in the ERB results during the ACRIM-Gap and the corresponding decadal upward trend of the ACRIM composite during solar cycles 21 and 22.

The above empirically based studies provide a strong indication that TSI variability resulting from solar magnetic activity variation is the main driver of the earth's climate. Proxy TSI results, derived from the SMFS/TSI paradigm, correlate with the global mean temperature anomaly both during and prior to the satellite TSI observations [7, 20].

It has been shown that the solar cycle amplitude from 1980 to 1989 and the trending from 1992 to 2002 of a proxy model represented as supporting the PMOD TSI composite [22] were actually contradicted by the unmodified TSI satellite data in these periods (see Figures 8 and 9 published in [20]). When the proxy model was empirically adjusted to fit the original TSI data, it conformed much more closely to the multidecadal ACRIM trending than that of the PMOD. Similar conclusions were implied by alternative magnetic field strength measurements ([20], Figures 7, 10, 11 and 13).

1.2. Alternative Statistical Composites. More recently, a novel TSI composite has been constructed using a wavelet transform algorithm that simultaneously uses all available TSI records [9]. This methodology is statistically based, which means that the differences between the TSI values reported by the various TSI satellite databases are assumed to have a solely statistical rather than a physical origin. The authors claim that their proposed composite is "in closer agreement with the trending of the PMOD than the ACRIM or RMIB." Yet, herein we show the opposite to be the case. Their novel approach produced average TSI composites that agree more closely with the ACRIM TSI composite trending during solar cycles 21- 24 [1] than with the PMOD.

Composing a TSI database using a solely statistical methodology has a fatal flaw in that it fails to account for the physical limitations of observation, such as degradation of the TSI sensors. Such composites will have uncertainties so large that they have limited ability to uniquely discriminate between the ACRIM and PMOD TSI composites. The methodology proposed by Dudok de Wit et al. [9] cannot improve our knowledge regarding the TSI trending difference between ACRIM and PMOD. The RMIB composite by Mekaoui and Dewitte [5] used a more simplistic statistical model than Dudok de Wit et al. [9] but was afflicted by the same problem, namely, a failure to account for possible observational flaws of the original TSI records.

Moreover, it is important to clarify that the uncertainty produced by the TSI composites proposed by Dudok de Wit et al. [9] is further stressed by the fact that a wavelet merging methodology uses short overlapping periods which poorly take into account the statistics of the overall records. It is well known that to cross-calibrate two records one needs to compare their average values during their overlapping period. The statistical error of this procedure scales with the root of the number of the overlapping points. For example, if the statistical error associated with a single measure is σ and there are 100 overlapping points, then the statistical error associated with the merging between two such records would be $\sigma/10$, where 10 is the root of 100. However, by using a wavelet methodology the statistical error associated with the merging would be significantly larger. For example, if the wavelets are made of 4 points, the statistical error of the merging would be just s/2, where 2 is the root of 4.

Dudok de Wit et al. [9] claim that the uncertainty in the TSI records appears to be so large that it would not be possible to discriminate between the ACRIM and PMOD composites actually discovered by Scafetta twelve years earlier, in 2005 [42]. Scafetta compared ACRIM and PMOD total solar irradiance satellite composites during solar cycles 21-23 and assumed only random uncertainties of the TSI satellite data sets. The TSI record overlapping comparisons assumed the maximum statistical error derived from a point to point comparison. In this way, Scafetta determined the maximum statistical uncertainty of two simple satellite composites, which were statistically equivalent to ACRIM and PMOD composites. The evaluated uncertainty was just slightly larger than those evaluated in Dudok de Wit et al. [9]. It was found that the secular upward trend of +0.047%/decade between the minima of solar cycles 21-22 and 22-23 presented by the ACRIM satellite composite is statistically equivalent to the -0.009%/decade trend between the same minima presented by the PMOD composite. However, this happens only if the merging among the various TSI records is made using very short overlapping intervals, which is what the wavelet methodology by Dudok de Wit et al. [9] does. However, when all overlapping data are used at once and one distinguishes between Nimbus7/ERB and ERB/ERBE, the uncertainty is greatly reduced since it scales with the root of the number N of overlapping points between each couple of records: see the detailed discussion in Scafetta [6]. However, the optimum approach is the use of observational analysis to test data versus models as discussed in Scafetta and Willson [20].

In the following we provide a detailed analysis of the alternative TSI composites recently proposed by Dudok de Wit et al. [9] by taking into consideration the discussion contained in Scafetta and Willson [20]. It should be noted that de Wit et al. [9] ignored the arguments presented by Scafetta and Willson [20].

2. Comparisons of TSI Reconstructions

2.1. Observational Data Based Composites. The ACRIM and the PMOD composites shown in Figure 1 display two alternative TSI trending patterns during solar cycles 21-24 as discussed above. The values of the irradiance at the solar minima are marked. The data are depicted with different colors to indicate the satellite experiment results used for different composite segments.

The cause of the primary difference in trending between the ACRIM and PMOD during solar cycles 21–23 is shown in Figure 2. The results from the ACRIM1, ACRIM2, Nimbus7/ERB, ERBS/ERBE TSI experiments and Kitt Peak Solar Magnetic Field Strength (SMFS) are plotted before, during and after the approximately two-year gap between the end of the ACRIM1 and beginning of ACRIM 2 experiments.

The TSI results and Solar Magnetic Field Strengths are all correlated except for the ACRIM-Gap where the ERBE results trend downward while the others trend up. This occurs during the increasing phase of solar magnetic activity leading to the peak of solar cycle 22 during 1990–1992. The most likely

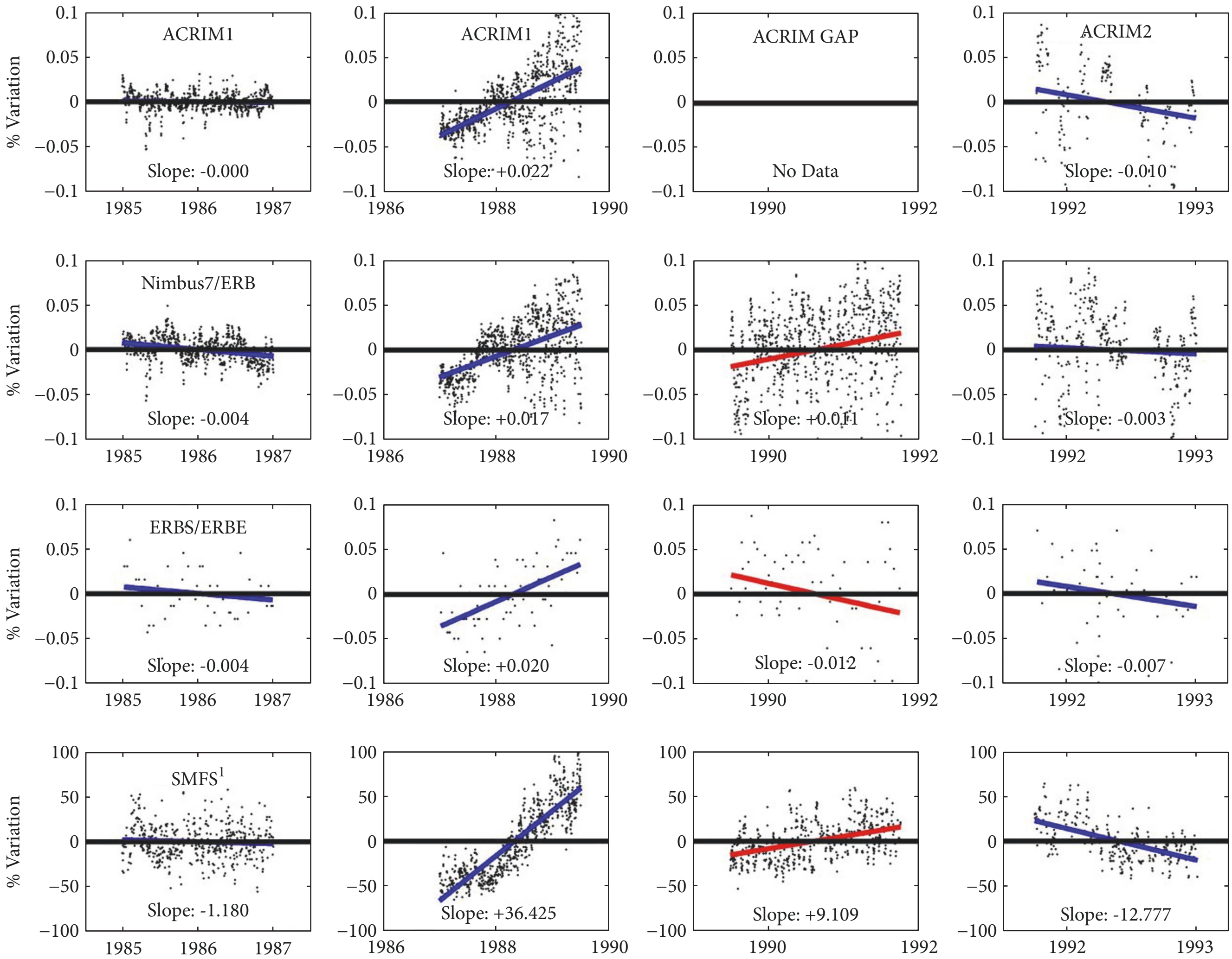

Figure 2: Comparison of the TSI results from the ACRIM1, Nimbus7/ERB, ERBS/ERBE experiments and the NSO/Kitt Peak Solar Magnetic Field Strength (SMFS) during the solar cycle 21-22 minimum and the upward trend to and through solar cycle 22 maximum. The effect of degradation for the ERBE sensors during the 1989–1992 maximum is seen in the downward trend of its results relative to the trends of the ERB results and the SMFS that is anticorrelated with the SMFS–TSI paradigm.

explanation is that the ERBE solar TSI detectors degraded from "bleaching" of their absorptive sensor coatings by the higher levels of short wavelength radiation and particle flux that occur during peaks of solar activity maxima. This effect had been observed in the ACRIM1 experiment during the high but descending SMFS phase of solar cycle 21 from its peak and was self-calibrated precisely using ACRIM1's multisensor approach [43].

Sensor degradation caused by mission exposure to high SMFS solar fluxes has been observed in the performances of all satellite TSI experiments to date. Rapid detector degradation occurs during exposure to the enhanced solar short wavelengths and ionized particulate during peak levels of solar activity and reaches a saturation level, an asymptotic limit or a more slowly varying, more linear rate of degradation thereafter. The timing and shape of the degradation curve depends on the details of the solar sensor surfaces, geometries, and exposure rates [3]. Characteristic sensor degradation can be seen in Figure 3 for the ACRIM3 experiment. The ratios of the observations by sensor C (primary reference sensor) to sensors B (secondary reference sensor) and A (continuously observing sensor) are shown. The reference sensors are exposed to the sun infrequently and the constancy of the C/B ratio is a measure of the precision of the calibration of sensor A's degradation. The C/A ratio changes rapidly during the initial exposure of the sensor to the solar maximum levels of solar flux before saturating and settling into a more slowly varying, more linear slope throughout the mission.

The ERB experiment exhibited rapid sensor degradation during the peak of solar cycle 21 but responded in correlation with the SMFS and, hence, the SMFS-TSI paradigm during the gap. This would be expected from the ACRIM1 degradation experience, since its initial sensor "saturation" degradation had occurred during the peak of solar cycle 21 and its subsequent rate of degradation would be slower. On the contrary, a rapid degradation of the ERBE observations during the ACRIM-Gap was likely caused by the highly

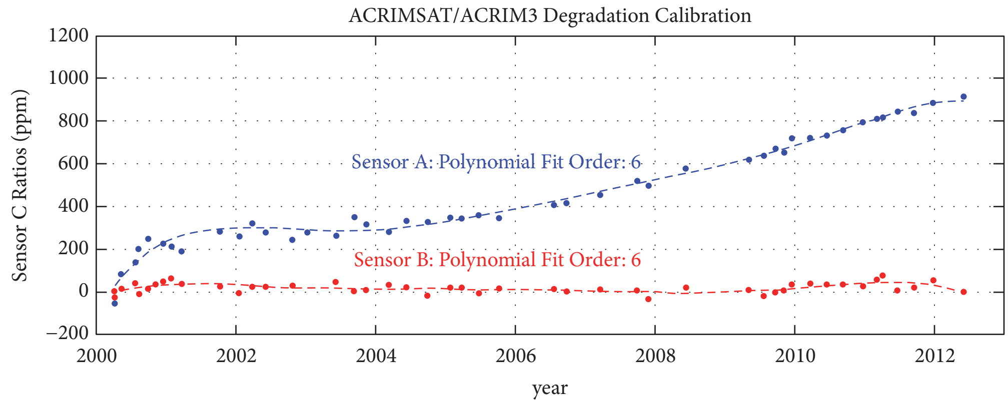

Figure 3: Degradation of the ACRIMSAT/ACRIM3 sensors over the mission.

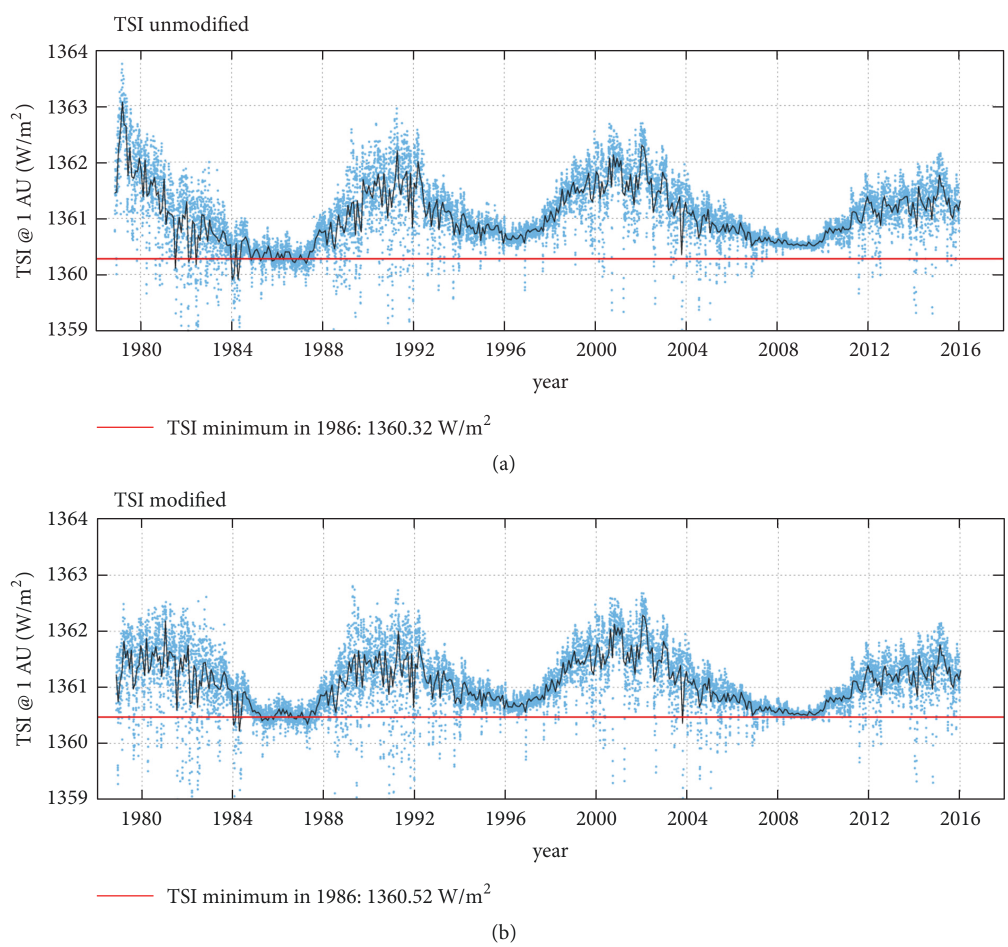

Figure 4: TSI composites proposed by Dudok de Wit et al. [9]. (a) Using the original published TSI satellite data. (b) Using the TSI satellite data modified by PMOD. Daily values (blue), monthly mean (black).

energetic solar maximum fluxes it experienced for the first time during the gap since it was launched during the initial rising phase of SMFS for solar cycle 22.

2.2. Statistically Derived Composites. Figure 4 shows the two TSI composites proposed by Dudok de Wit et al. [9]. In (a) the composite is made using the original unmodified TSI satellite records, while in (b) the PMOD-modified TSI records are used. In both cases trends qualitatively similar to those of the ACRIM composite are found among the TSI minima in 1986, 1996, and 2009 (see Table 1). Both the original and modified TSI composites show an upward trend during 1980–2000 and downward trend thereafter similar to ACRIM trending.

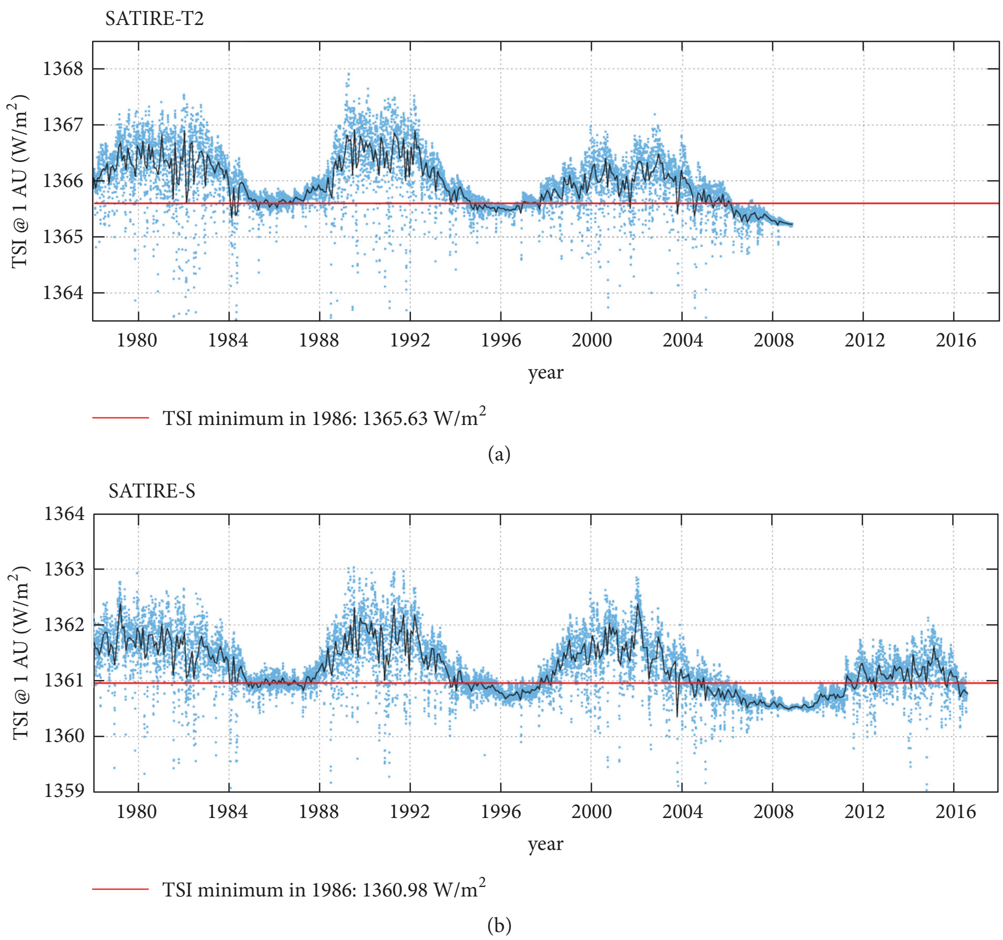

Figure 5: (a) SATIRE-T2 TSI proxy reconstruction [15]. (b) SATIRE-S TSI proxy reconstruction [16]. Daily values (blue), monthly mean (black).

The composite in Figure 4(a) shows a high degree of similarity to the ACRIM composite. The composite in Figure 4(b) shows a smaller upward trend between the minima of 1986 and 1996, followed by a downward trend to the minimum in 2009, making it positively correlated with the ACRIM composite during this period but with smaller amplitudes. Both composites in Figure 4 are negatively correlated with the PMOD composite trend between the 1986 and 1996 minima.

Figure 5 depicts two additional, recently developed TSI proxy models: (a) the SATIRE-T2 TSI reconstruction [15] and (b) the SATIRE-S TSI reconstruction [16]. In both models there is a consistent downward trend among TSI minima in 1986, 1996, and 2009. During these three solar cycle minima the TSI values are as shown in Table 1 for SATIRE-T2 and SATIRE-S. The continuous downward trending makes SATIRE-T2 and SATIRE-S incompatible not only with the ACRIM composite, but also with both TSI models proposed by Dudok de Wit et al. [9].

In Figure 6 and Table 2 we analyze and compare the deviation of the ACRIM, PMOD, and SATIRE-S model from the two TSI composites proposed by Dudok de Wit et al. [9]. The purpose of this analysis is to determine which of the former three records agrees better with the latter composites. Dudok de Wit et al. [9] claim that their proposed TSI composites agree better with PMOD. However, this conclusion was not based on analysis but on a visual inspection of their Figure 3. Here these authors appear to have misinterpreted the fact that ACRIM and PMOD are characterized by slightly different scales because ACRIM3 and VIRGO (the bases of the two composites) were independently recalibrated against the TSI cryogenic radiometer facility of the Laboratory for Atmospheric and Space Physics (LASP) and it is unclear whether later VIRGO was empirically recalibrated to agree better with the TIM/SORCE scale. In fact, Fröhlich [44] claimed that the new absolute value of VIRGO record was 0.86 W/m^2 lower than TIM/SORCE during the period 2008/09/20–2009/05/05. Thus, the better agreement between PMOD and the TSI composites proposed by Dudok de Wit et al. [9] refers to their absolute scales which might have been coincidental. However, such a slight difference in TSI scales is irrelevant because the important issue is how well the TSI decadal trends agree among the various records. This analysis is proposed below.

Figure 6(a) depicts monthly time scale functions of the difference between the ACRIM TSI composite and the unmodified and PMOD-modified TSI by Dudok de Wit et al. [9] from 1980 to 2013. Figures 6(b) and 6(c) depict the same but using the PMOD TSI composite and the SATIRE-S TSI

Table 2: Mean and standard deviation of the curves depicted in Figure 4 in the reported time intervals.

	ACRIM (W/m^2)	PMOD (W/m^2)	SATIRE-S (W/m^2)
Original Unmodified TSI Results			
1980-2013	0.38 ± 0.13	−0.01 ± 0.24	0.21 ± 0.31
1980-1990	0.40 ± 0.15	0.31 ± 0.18	0.01 ± 0.10
1992-2013	0.37 ± 0.12	−0.16 ± 0.05	0.01 ± 0.10
PMOD Modified TSI Results			
1980-2013	0.33 ± 0.19	−0.07 ± 0.12	0.15 ± 0.21
1980-1990	0.16 ± 0.16	0.07 ± 0.06	0.38 ± 0.14
1992-2013	0.38 ± 0.13	−0.15 ± 0.04	0.02 ± 0.11

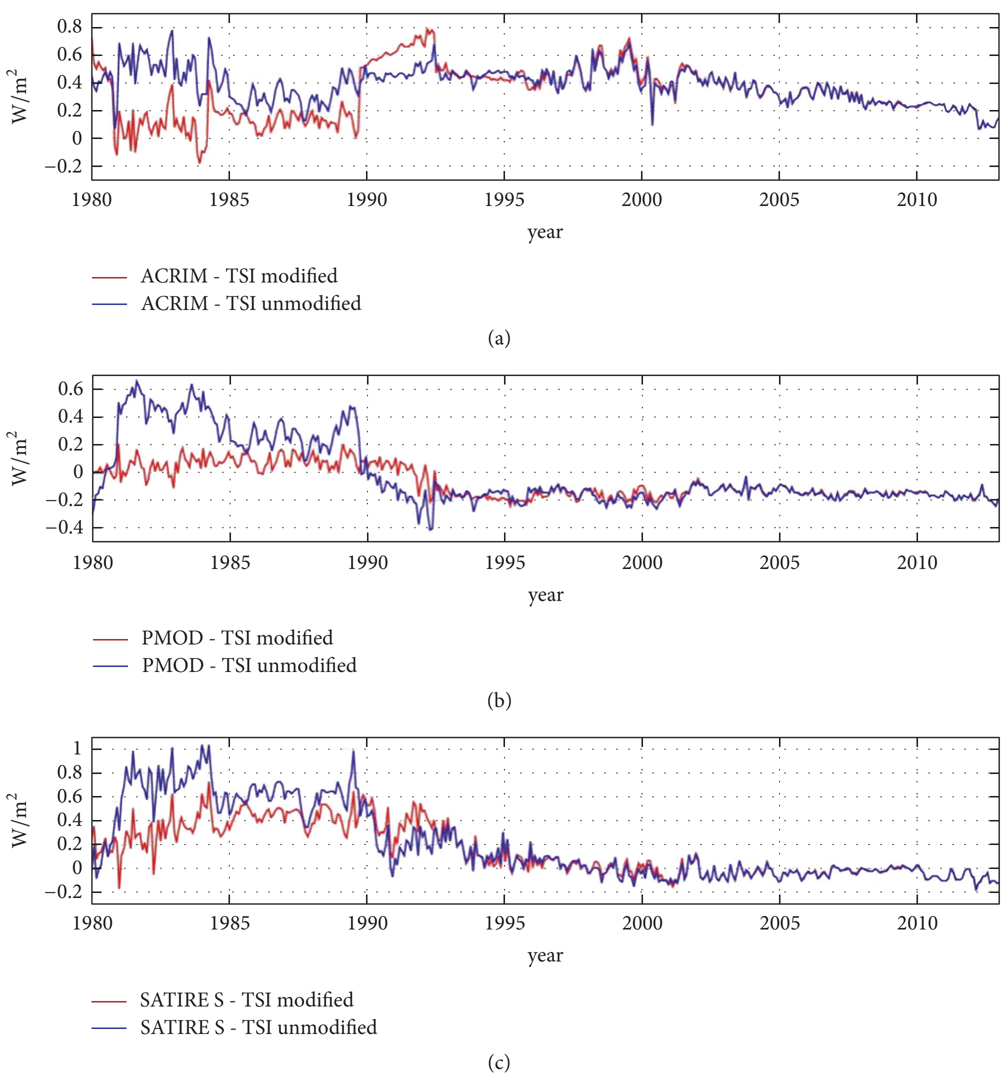

Figure 6: (a) Variation between the ACRIM TSI composite and the unmodified and modified TSI by Dudok de Wit et al. [9] from 1980 to 2013. (b) and (c) The same using the PMOD TSI composite and the SATIRE TSI proxy model. Plots are based on monthly means.

Table 3: The TSI composite data.

ACRIM	http://acrim.com/RESULTS/data/composite/acrim_composite_131130_hdr.txt
PMOD	ftp://ftp.pmodwrc.ch/pub/data/irradiance/virgo/TSI/virgo_tsi_d_v6_005_1702.dat
SORCE	https://spot.colorado.edu/~koppg/TSI/Thierry_TSI_composite.txt
SATIRE-S	http://www2.mps.mpg.de/projects/sun-climate/data/SATIRE-T_SATIRE-S_TSI_1850_20160802.txt
SATIRE-T2	http://www2.mps.mpg.de/projects/sun-climate/data/TSI_SATIRE-T2_1878-2008.dat

model, respectively. Table 2 reports the mean values in the intervals 1980-2013, 1980-1990, and 1992-2013.

The level of agreement between two records is measured by the standard deviation σ of their mutual difference on a given time interval: smaller σ means a better agreement between the two chosen records. This choice makes the slight different absolute scales among the TSI composites irrelevant.

The relative standard deviation of the deviation functions for the periods shown in Table 2 indicates the ACRIM composite agreement with the unmodified TSI composite is nearly identical to the PMOD composite agreement with the modified TSI composite: $\sigma = 0.13$ W/m^2 versus $\sigma = 0.12$ W/m^2, respectively. However, during the 1980-2003 period, the ACRIM composite agreement with the modified TSI composite is 25% superior to that of the PMOD with the unmodified TSI composite: $\sigma = 0.19$ W/m^2 versus $\sigma = 0.24$ W/m^2, respectively. The variations of the SATIRE-S model and both Dudok de Wit et al. [9] composites are significantly larger: $\sigma = 0.31$ W/m^2 versus $\sigma = 0.21$ W/m^2, respectively.

Comparing the intervals 1980-1990 and 1992-2003 using Table 2, ACRIM is essentially balanced with the unmodified TSI composite because the two mean values of the difference are compatible (Figure 6(a), blue curve): 0.40 ± 0.15 W/m^2 and 0.37 ± 0.12 W/m^2, respectively. Conversely, PMOD is not balanced with the modified TSI composite because the two mean values of the difference are incompatible, showing a clear downward trend (Figure 6(b), red curve): 0.07 ± 0.06 W/m^2 and -0.15 ± 0.04 W/m^2. Therefore PMOD would appear to be erroneously composed.

Regarding the large error bars reported for the TSI composites proposed by Dudok de Wit et al. [9], it is important to stress that they are nearly irrelevant for the above discussion. In fact, we have compared means covering 1-year and longer periods. When the means are considered, the original statistical error reported by these authors, which refers to the single daily measure, needs to be reduced at least by a factor of about 20 (the root of 365 is about 19). That is, because their largest reported error is less than 0.7 W/m^2, the relative annual and multiannual means would be affected by an error equal to or less than about 0.035 W/m^2, which are significantly smaller than the observed mean value differences reported in the Tables 1 and 2. The TSI composite data are available at the websites listed in Table 3.

3. Discussion

Today there exists general agreement among various science teams that the mean TSI during solar cycle 23 is near 1361 W/m^2 but differences have persisted about the decadal solar activity cycle-to-cycle trending of the ACRIM and PMOD composites. ACRIM contends that the original data from satellite measurements, as processed and published by the original science teams, are the best representation of the experimental results and demonstrate that the TSI increased from 1980 to 2000 and decreased afterwards. PMOD modifies the original science teams' satellite results using proxy models causing the TSI to gradually decrease since 1980. Resolving this controversy has important implications for understanding climate change and assessing the usefulness of TSI proxy models.

We have shown that the average value of the statistical TSI composite models proposed by Dudok de Wit et al. [9] actually demonstrates better agreement with the ACRIM composite than with the PMOD from 1980 to 2013. Their large error bars are irrelevant because it is the TSI mean values on scales of 1-year or larger which need to be taken into account. When this is done their error bars are reduced by a factor of 20 or more. This is in direct disagreement with the Dudok de Wit et al.'s assessment that their composite most closely agrees with the PMOD composite. We contend that the Dudok de Wit et al.'s conclusion was not based on technical arguments but on a qualitative impression derived from their Figure 3 where a larger divergence of the ACRIM composite is observed. This conclusion is incorrect, however, because they failed to recognize that the larger ACRIM divergence is caused by ACRIM having a larger mean value than PMOD because its absolute scale was based on the ACRIM3 measurements.

The large divergence of the SATIRE TSI proxy models suggests they are inadequate to reproduce the cycle-by-cycle decadal TSI trending with useful precision, as discussed in a previous paper by Scafetta and Willson [20].

It is important to consider whether the satellite records require corrections not made by the original experiment teams. We label the second TSI composite proposed by Dudok de Wit et al. [9] as "PMOD modified" whereas they label it "corrected". The "corrected" label is misleading since the modifications proposed by Fröhlich discussed above are proxy model based and have not been validated by an in-depth reanalysis of the satellite experiment data. In particular, regarding the claims that Nimbus7/ERB sensors drastically increased their sensitivity at the end of September 1989, Dr. Hoyt, the scientist responsible for the ERB instrument and data processing, examined those claims from an experimental point of view and disregarded them ([26], supplement). The dangers of utilizing ex-post-facto corrections by those who did not participate in the original science teams of satellite experiments are that (1) erroneous interpretations of the data can occur because of a lack of detailed knowledge of the experiment and (2) unwarranted manipulation of the data can be made based on a desire to support a particular solar model or some other nonempirical bias. We contend that the PMOD TSI composite construction is compromised in both these ways.

Analysis has disproved the validity of most of Fröhlich's modifications to the satellite TSI records published by the original ACRIM and Nimbus7/ERB science teams he used in constructing the PMOD composite [20]. The first and most important one for trending was Fröhlich's modification of ERB results during the ACRIM-Gap by -0.47 W/m^2, based on a misinterpretation of a three-day ERB instrument power cycle event. Here Fröhlich corrected for what we now know was a nonexistent "step function increase" of instrument sensitivity ([20], Figure 5). A second important erroneous modification derives from Fröhlich's claim that the TSI instrumental sensitivity of Nimbus7/ERB gradually increased during the ACRIM-Gap, in an apparent effort to justify the relative decrease in the ERBE results ([20], Figure 4). These modifications are not supportable by the original TSI experiment results and are responsible for the most important cycle-by-cycle differences between the ACRIM and PMOD TSI composites: the 1986 to 1996 trend divergence. The analysis and TSI composite of Dudok de Wit et al. [9] did not consider the PMOD "correction" errors documented in our 2014 paper [20] which negates the usefulness of their results.

The use of unverified modified data has fundamentally flawed the PMOD TSI satellite composite construction. Composite TSI time series would have greater scientific credibility if the most flawed records, such as the Nimbus7/ERB before 1980 (cf. [20]) or the ERBE data during the ACRIM-Gap [3], were ignored. This is the plausibility argument used in Table 2 to limit our statistical analysis to the period 1980-2013.

There is another important issue regarding the appropriateness of the algorithm proposed by Dudok de Wit et al. [9]. It treats all TSI records as physically reliable although a statistical instrument weighting assumption was taken into account. This methodology would only be appropriate when processing stationary TSI records from stable experiments whose results differ from each other only because of statistical errors of measure.

In general, modifying high quality records with those of lesser quality will not provide the most accurate representation of the data in particular when the low quality of a dataset has a physical rather than a statistical origin. This is certainly a concern with the TSI satellite databases. ACRIM 1, 2 & 3 made up to 720 30-second averaged, self-calibrated, shuttered measurements per day [3]. Nimbus7/ERB observed for a few minutes during each of an average of 14 orbits per day, three days out of every four, most of its lifetime [45]. ERBS/ERBE was limited to one shuttered observation on an average of every 14 days [19]. Moreover, the quality of the ERB and ERBE observations was further constrained by (1) a lack of degradation self-calibration capability and (2) a lack of independent solar pointing in which measurements were made while the sun moved through their fields of view, degrading knowledge of the average cavity absorptance of TSI by their sensors. The latter deficiencies are physical rather than statistical and therefore cannot be addressed by Bayesian statistics as in the approach proposed by Dudok de Wit et al. [9].

The difference between Nimbus7/ERB and ERBS/ERBE during the ACRIM-Gap is too large to be due to statistical fluctuation and so at least one of the two records erroneously represents the TSI variation trends during the ACRIM-Gap. In such a situation it is required to determine which of the two records is the most reliable (compare the various arguments proposed in [3, 13, 18, 20]). Ignoring such a fundamental issue has only the consequence of producing a TSI composite with an anomalously large uncertainty. This is clearly demonstrated by the central panel of Figure 3 in Dudok de Wit et al. [9]. The standard deviation error of their composites reaches the value of $\pm$ 0.45 W/m^2 during the 1980-1989 ACRIM1 interval while during the same period the ACRIM composite has on average a precision of less than $\pm$ 0.1 W/m^2. Such a large uncertainty appears to make the Dudok de Wit et al. [9] TSI composite inclusive of both ACRIM and PMOD TSI composites and, therefore, it is unable to provide any insight on, or solution to, the ACRIM-PMOD contention. In any case, as explained above, any comparison must involve some moving average curve of the data whose statistical error will be scaled down with the root of the smoothing algorithm order.

The statistical issue of the variability of TSI composites resulting from the choice of the Nimbus7/ERB or ERBS/ERBE during the ACRIM-Gap was discussed in Scafetta [6]. The proposed composites were built in such a way to approximately force a merging continuity among the various TSI records based on a 91-day smooth curve. The composites were made using ACRIM1, ACRIM2,and ACRIM3 while the ACRIM-Gap was bridged using (A) the unaltered Nimbus7/ERB record or (B) the Nimbus7/ERB altered in such a way to exactly reproduce the ERBS/ERBE trending during the ACRIM-Gap. The two alternative composites provide the maximum range of uncertainty related to the available TSI database as produced by the divergence between Nimbus7/ERB and ERBS/ERBE during the ACRIM-Gap.

Figure 7 shows these two composites updated to 2018 by extending the most recent ACRIM3 data with the VIRGO record after 2013 and then with SORCE/TIM record. Note that VIRGO and TIM are quite similar after 2013, but the SORCE/TIM record suffers of a serious gap lasting several months in 2013 and 2014 caused by spacecraft battery problems.

These composites show a slight decrease between the TSI minima in 1996 and 2009 as do the ACRIM and PMOD. However, their variation between the 1986 and 1996 TSI minima depend on the specific record used to bridge ACRIM1 and ACRIM2 during the ACRIM-Gap period. As Table 1 shows, this variation varies between +0.67 $\pm$ 0.1 W/m^2 (using Nimbus7/ERB) and -0.11 $\pm$ 0.1 W/m^2 (using ERBS/ERBE). Since the discrepancy between the two results is 0.78 W/m^2 which is significantly larger than their statistical error, then, during the ACRIM-Gap, at least either Nimbus7/ERB or ERBS/ERBE is proven to be physically flawed. Thus, it is

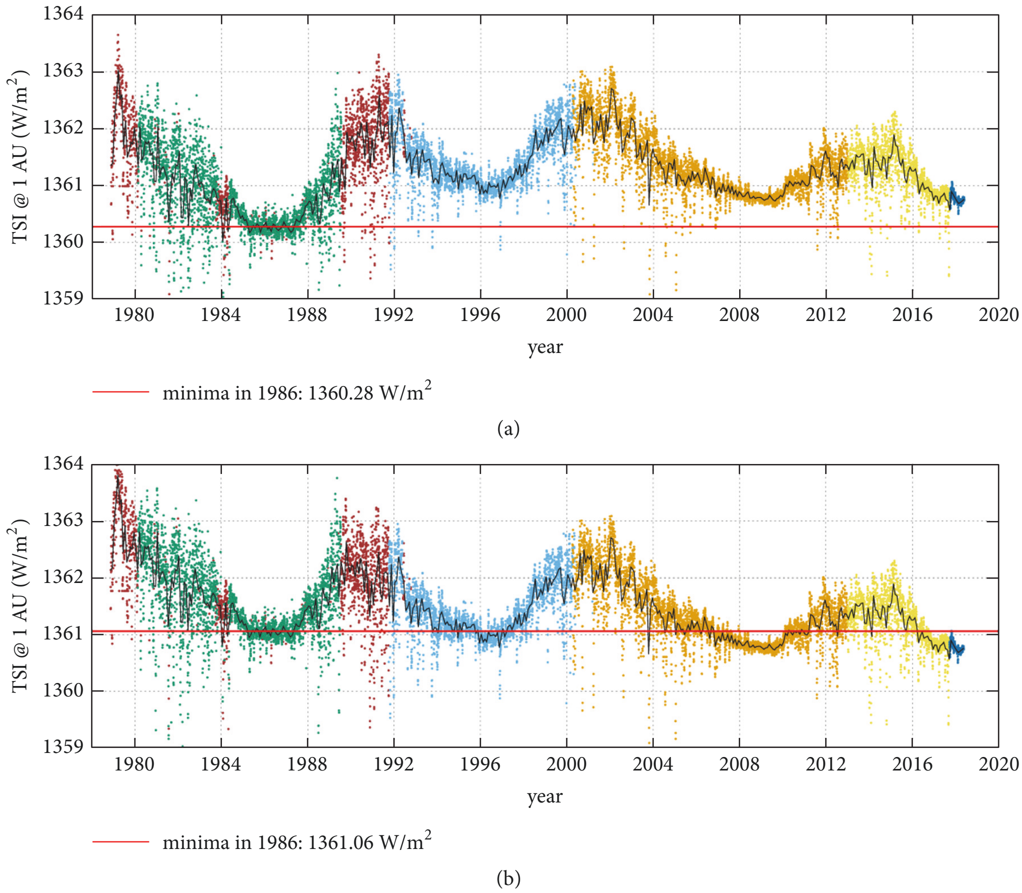

FIGURE 7: Updates of the TSI composites proposed in Willson and Mordvinov [3], Scafetta [6], and Willson [7]. (a) Unaltered Nimbus7/ERB data are used during the ACRIM-Gap; (b) Nimbus7/ERB data are altered to agree with the ERBS/ERBE trending during the same period. Data from Nimbus7/ERB (brown), ACRIM1 (green), ACRIM2 (cyan), ACRIM3 (orange), VIRGO (yellow), and TIM (blue).

inappropriate to adopt solely a statistical methodology using both Nimbus7/ERB and ERBS/ERBE results as proposed by RMIB [4, 8] and more recently by Dudok de Wit et al. [9]. If the physical issue is not solved first, it is only possible to conclude that between 1986 and 1996 TSI varied between the two above estimates.

The full maximum range of possible TSI composites suggests that the TSI minimum in 1996 was about 0.3 ± 0.4 W/m^2 higher than that in 1986. Thus, once all available TSI records are used, the ACRIM upward 1986-1996 trending (0.46 ± 0.02 W/m^2) is statistically favored above the downward trending of PMOD (-0.05 ± 0.02 W/m^2) even if the ACRIM-Gap Nimbus7/ERB increased its sensitivity for some amount, e.g., for about 0.2 W/m^2. The latter value falls within the observed divergence between Nimbus7/ERB and ACRIM1 between 1981 and 1989 on an annual time scale ([6], Figure 3), which is likely due to Nimbus7/ERB's lack of solar pointing and sensor degradation self-calibration as well as other instrumental instabilities. Note that the measured mean range increase of TSI between 1986 and 1996 (0.38 ± 0.41 W/m^2) is nearly identical to that obtained by Dudok de Wit et al. [9] when the original TSI satellite database is used (0.34 ± 0.05 W/m^2).

The downward trending of PMOD between 1986 and 1996 would be acceptable only if it were experimentally demonstrated that ERBS/ERBE trending during the ACRIM-Gap was highly accurate. However, as Willson and Mordvinov [3] noted, this scenario would be experimentally unlikely since the ERBE sensor degraded significantly during the ACRIM-Gap as its sensor first experienced the enhanced short wavelength solar radiation which is known to excessively degrade the coatings of TSI sensors. Moreover, Scafetta and Willson ([20], Figure 5B) showed that the Solar Magnetic Field Strength increased during the ACRIM-Gap. This fact clearly supports the greater reliability of the Nimbus7/ERB record showing upward trending between 1989 and 1991 during the ACRIM-Gap further emphasizing the ERBS/ERBE downward trend during the same period: see Figure 2.

4. Conclusion

The Dudok de Wit et al. [9] approach failed to make the best use of the satellite TSI database by not including the quality and sampling rates of each experiment in their evaluation. Moreover, the different trending and sampling rates of ERB and ERBE records during the ACRIM-Gap were not just statistical but physical. Therefore, it cannot be properly handled using data-driven estimates of the uncertainties, as in the approach of Dudok de Wit et al. [9]. More precise results would require a detailed analysis of the local trends with a preference for the higher quality records, as proposed in Scafetta [6]. Because of known uncorrected degradation issues, it would be preferable to ignore ERB results before 1980 and ERBE results during and before the ACRIM-Gap. Failure to take into account the detailed physical characteristics of the various data sets will only have the effect of considerably increasing the uncertainty of a TSI composite time series.

Therefore, we contend that using a purely statistical methodology to compose TSI records that could contain a physically unreliable one is improper. Such an approach neither produces a more authentic composite nor improves our knowledge regarding a given phenomenon: it can only produce a composite affected by an anomalously large uncertainty that encloses all possibilities.

Improvement of the physical knowledge of TSI behavior since 1978 requires the determination of which of the Nimbus7/ERB and ERB/ERBE experiment results were least defective during the ACRIM-Gap (1989.5-1991.8). Then, our scientific knowledge could be improved by excluding the more flawed record from the composite. This was the logic applied by the ACRIM team. In point of fact PMOD failed to do this, instead selecting the ERBE results that were known to be degraded and sparse, because that made the solar cycle 21–22 trend agrees with TSI proxy models and the CAGW explanation of CO_2 as the driver of the global warming trend of the late 20th century.

We note that the considerable evidence discussed by Scafetta and Willson [20] which clearly favors the TSI composites proposed by Willson and Mordvinov [3], Scafetta [6] and Willson [7] is not challenged by the statistical approach of Dudok de Wit et al. [9]. The large errors of their composites are an artifact of their adoption of a wavelet merging methodology and of their simultaneous adoption of the ERB and ERBS records during the ACRIM-Gap when they diverge significantly. In any case, such large uncertainty is significantly attenuated by a factor of 20 or more when annual or longer averages are adopted. This smoothing makes the composites clearly distinguishable.

Our summary conclusion is that the objective evidence produced by all of the independent TSI composites [3, 5, 6, 9] agrees better with the cycle-by-cycle trending of the original ACRIM science team's composite TSI that shows an increasing trend from 1980 to 2000 and a decreasing trend thereafter. The continuously downward trending of the PMOD composite and TSI proxy models is contraindicated. This contradicts Dudok de Wit et al.'s [9] claim that their proposed composite is "in closer agreement with that from PMOD than those from ACRIM or RMIB."

Note that the apparent agreement of some TSI proxy models with the PMOD trending between 1986 and 1996 solar cycle minima can be coincidental because these proxy models rely on proxy data that are mostly representative of the active regions of the sun such as photospheric sunspots and faculae ([2, 19]; and others). These data poorly model the variability of the quiet sun brightness that involves global solar changes. On the contrary, a TSI increase between 1986 and 1996 would be supported by the following:

(1) The solar cycle length model (e.g., [46–48]) which predicts that short solar cycles correlate with increased TSI (in fact, solar cycle 22 (1986-1996) was only 9.9-years long and was shorter than both solar cycle 21 (1976-1986, 10.5 year) and solar cycle 23 (1996-2008, 12.3 year).

(2) A model of solar variability driven by planetary tidal harmonics [49, 50].

(3) The global surface temperature of the Earth increased from 1970 to 2000 and remained nearly stable from 2000 and 2018. This pattern is not reproduced by CO_2 AGW climate models but correlates with a TSI evolution with the trending characteristics of the ACRIM TSI composite as explained in Scafetta [6, 12, 27] and Willson [7].

Data Availability

All data can be downloaded from the websites listed in Table 3.

Conflicts of Interest

The authors do not have any conflicts of interest to declare.

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