1. INTRODUCTION

A contiguous total solar irradiance (TSI) database of satellite observations extends from late 1978 to the present, covering 30 years, that is, almost three sunspot 11-year cycles. This database comprises the observations of seven independent experiments: NIMBUS7/ERB (Hoyt et al., 1992), SMM/ACRIM1 (Willson and Hudson, 1991), ERBS/ERBE (Lee et al., 1995), UARS/ACRIM2 (Willson, 1994, 1997), SOHO/VIRGO (Crommelynck and Dewitte, 1997; Fröhlich et al., 1997), and ACRIMSAT/ACRIM3 (Willson, 2001). Another TSI satellite record,
SORCE/TIM (Kopp et al., 2003), exists but it is not studied here because its mission started in February 2003 and this TSI satellite record is still too short for our purpose. None of these independent datasets cover the entire period of observation; thus, a composite of the database is necessary to obtain a consistent picture about the TSI variation. In this paper we use the TSI records depicted in Fig. 1 as available by 2008.

Three TSI satellite composites are currently available: ACRIM composite (Willson and Mordvinov, 2003), PMOD composite (Fröhlich and Lean, 1998; Fröhlich, 2000, 2006), and IRMB composite (Dewitte et al., 2004), respectively (see Fig. 2). Each composite is compiled by using different models corresponding to different mathematical philosophies and different combinations of data.

For example, one of the most prominent differences between ACRIM and PMOD composites is due to the different way of how the two teams use the NIMBUS7/ERB record to fill the period 1989.53—1991.75, the so-called ACRIM-gap between ACRIM1 and ACRIM2 records. Consequently, these two composites significantly differ from each other, in particular about whether the TSI minimum during solar Cycles 22—23 (1995/96) is approximately 0.45 W/m² higher (ACRIM composite) or approximately at the same level (PMOD) as the TSI minimum during the previous solar Cycles 21—22 (1985/96).

The difference among the TSI satellite composites has significant implications not only for solar physics, where the correctness of the theoretical

![FIGURE 1 TSI satellite records. ERBS/ERBE and SOHO/VIRGO TSI records are shifted by −5 W/m² and −10 W/m², respectively, from the ‘native scale’ for visual convenience. (Units in Watts/meter² at 1 A.U.)](image)
models has to be tested against the actual observations and not vice versa, but also for the current global warming debate. Phenomenological analyses (Scafetta and West, 2007, 2008; Scafetta, 2009) using TSI proxy, satellite composites, and global surface temperature records of the past 400 years show that solar variation has been a dominant forcing for climate change during both the pre- and industrial periods. According to these analyses, the sun will likely be a dominant contributor to climate change in the future. However, the solar contribution to the global warming during the last three decades remains severely uncertain due mostly to the difference between the TSI satellite composites.

The phenomenological solar signature on the global temperature is found to match quite well 400 years of global climate reconstructions since 1600 (Scafetta and West, 2007, 2008; Scafetta, 2009), but such an almost continuous matching would be abruptly interrupted since 1975 if the PMOD composite is adopted. Instead, by adopting the ACRIM composite it is still possible to notice a significant correlation between temperature data and the reconstruction of the solar effect on climate. Thus, a significant fraction of the $+0.4 \, \text{K}$ warming observed since 1980 can be ascribed to an increase of solar activity if ACRIM composite is adopted, but almost none of it would be linked to solar activity if PMOD composite is adopted. Evidently, if the solar contribution is uncertain, the anthropogenic contribution to the global warming observed during the last three—four decades is uncertain as well. Hence, determining the correct TSI composite during the last three decades should be considered of crucial importance.

**FIGURE 2** ACRIM, IRMB, and PMOD TSI satellite composites.
The general circulation climate models adopted by the Intergovernmental Panel on Climate Change (IPCC, 2007) do not agree with the above phenomenological findings and predict a minor solar contribution to climate change during the last century and, in particular, during the last 30–40 years. However, such climate models assume that the TSI forcing is the only solar forcing of the climate system and usually use TSI proxy records such as those proposed by Lean (Lean, 2000; Wang et al., 2005), which are compatible with the PMOD TSI composite since 1978. This choice would be evidently problematic and misleading if PMOD TSI composite is flawed.

In any case, the small climate sensitivity to solar changes predicted by the current climate models is also believed to be due to the absence in the models of several climate feedback mechanisms that may be quite sensitive to several solar related changes, in addition to TSI changes alone. Some of these phenomena include, for example, the UV modulation of ozone concentration that would influence the stratosphere water-vapor feedback and the modulation of the cloud cover due to the variation of cosmic ray flux that is linked to changes of the magnetic solar activity (Pap et al., 2004; Kirkby, 2007). These climate mechanisms are expected to magnify the influence of solar activity changes on climate. Because all solar related observables have similar geometrical patterns, TSI satellite records and proxy reconstructions can also be used as geometrical solar proxies in phenomenological and holistic models, instead of just using them as radiative forcings alone in analytical computer climate models. Indeed, this empirical methodology may circumvent the current limitation of our knowledge in the microscopic mechanisms involved in the climatic phenomena.

The original ACRIM composite (Willson and Mordvinov, 2003) has been constructed by simply calibrating the three ACRIM datasets and the NIMBUS7/ERB record on the basis of a direct comparison of the entire overlapping region between two contiguous satellite records. This composite uses the actual observations as published by the original experimental groups without any alteration. However, if some degradation or glitches do exist in the data, this composite is flawed for at least two reasons: (1) the mathematical methodology used for merging two contiguous satellite records, which uses just the average estimate of the residual during the entire overlapping regions between two records, may easily give biased estimates; (2) if the NIMBUS7/ERB record presents some glitches, or degradation did occur during the ACRIM-gap, the relative position of ACRIM1 and ACRIM2 would be erroneous.

The IRMB composite (Dewitte et al., 2004) is constructed by first referring all datasets to space absolute radiometric references, and then the actual value for each day is obtained by averaging all available satellite observations for that day. Thus, IRMB composite adopts a statistical average approach among all available observations; evidently, because the daily average estimate is based on a small set of data (1, 2, or in a few cases 3 data per day), it is not statistically robust, and this may easily produce artificial slips every time data from a specific record are missing or added.
The PMOD composite (Fröhlich and Lean, 1998; Fröhlich, 2000, 2004, 2006) is constructed with altered published experimental TSI satellite data. In fact, the PMOD team claims that the published TSI data are corrupted. Thus, PMOD claims that the published TSI satellite records need to be “corrected” before merging them into a TSI composite. Data corruption is claimed to be caused by sudden glitches due to changes in the orientation of the spacecraft and/or to switch-offs of the sensors, or because of some kind of instrumental degradation. Some TSI theoretical model predictions (Lee et al., 1995; Fröhlich and Lean, 1998; Chapman et al., 1996) have been heavily used by the PMOD team to identify, correct and evaluate these presumed errors in the published records, and these models have been changed constantly during the last 10 years. PMOD composite is claimed to be consistent with some TSI theoretical proxy models (Wenzler et al., 2006; Krivova et al., 2007). However, differences between the model and the PMOD TSI composite can be easily recognized: for example, Wenzler et al. (2006) needed to calibrate the model on the PMOD composite itself to improve the matching, and several details are not reproduced. Also, it cannot be excluded that an alternative calibration of the parameters of these TSI proxy models may better fit the ACRIM TSI satellite composite. Evidently, if the above theoretical models and/or the corrections of the satellite records implemented by the PMOD team are flawed, PMOD would be flawed as well. In any case, an apparent agreement between some theoretical TSI model, which depends on several calibration parameters and a TSI satellite composite does not necessarily indicate the correctness of the latter because in science theoretical models should be tested and evaluated against the actual observations, and not vice versa.

In this paper, alternative TSI satellite composites are constructed using an approach similar to that adopted by the ACRIM team, that is, we do not alter the published satellite data by using predetermined theoretical models that may bias the composite. However, contrary to the original ACRIM team’s approach we use a methodology that takes into account the evident statistical relative differences that are found in the published satellite records. The three ACRIM records are preferred and the ACRIM-gap is filled by using the measurements from the NIMBUS7/ERB and the ERBS/ERBE satellite experiments. Finally, we use these alternative TSI satellite composites in conjunction with a recent TSI proxy reconstruction proposed by Solanki’s team (Wenzler et al., 2006; Krivova et al., 2007) to reconstruct the signature of solar variation on global climate using a phenomenological model (Scafetta and West, 2007, 2008; Scafetta, 2009).

2. SMM/ACRIM1 vs. NIMBUS7/ERB

The first step is to merge SMM/ACRIM1 and NIMBUS7/ERB. Note that the relative accuracy, precision, and traceability of these two databases are radically different. In particular, the average error for the NIMBUS7/ERB measurements is $\pm 0.16 \text{ W/m}^2$ while the average error for the SMM/ACRIM1
measurements is $\pm 0.04$ W/m$^2$; thus, SMM/ACRIM1 is significantly more precise than NIMBUS7/ERB. Moreover, NIMBUS7/ERB instrumentations were not able to self-calibrate their sensor degradations as well as ACRIM1. NIMBUS7/ERB radiometer was calibrated electrically every 12 days. For the above reasons, ACRIM1 measurements are supposed to be more accurate than the NIMBUS7/ERB ones and, when available, they are always preferred to the NIMBUS7/ERB values.

It is necessary to adopt the NIMBUS7/ERB record for reconstructing the TSI record for a few days and during three prolonged periods: (1) before 17/02/1980, (2) from 04/11/1983 to 03/05/1984, and (3) after 14/07/1989. To accomplish this goal the position of NIMBUS7/ERB is evaluated relative to SMM/ACRIM1 and plotted in Fig. 3. The black smooth curve is a 91-day moving average.

The data shown in Fig. 3 have an average of 4.3 W/m$^2$. The original ACRIM TSI composite (Willson and Mordvinov, 2003) is constructed using the above average value to merge SMM/ACRIM1 and NIMBUS7/ERB. However, if the differences between SMM/ACRIM1 and the NIMBUS7/ERB were only due to random fluctuations around an average value, the error associated to the 91-day moving average values would have been about $\pm 0.02 - 0.03$ W/m$^2$, as calculated from the measurement uncertainties. Because the standard deviation of the smooth data shown in Fig. 3 is significantly larger, $\pm 0.17$ W/m$^2$, the difference between SMM/ACRIM1 and NIMBUS7/ERB measurements is not due just to random fluctuations, but it is due to biases and trends in the data, which are probably produced by the poorer sensor calibration of NIMBUS7/ERB.

![FIGURE 3](image-url) Relative difference between NIMBUS7/ERB and SMM/ACRIM1 TSI records.
Under the theoretical assumption that SMM/ACRIM1 measurements are more accurate than NIMBUS7/ERB ones, the black 91-days moving average smooth curve depicted in Fig. 3 suggests that NIMBUS7/ERB measurements could gradually shift during a relatively short period of time, a few months, by an amount that on average is about 0.2 W/m². In a few cases, this shift can also be as large as 0.5 W/m². In fact, irregular large oscillations with periods ranging from 5 to 12 months are clearly visible in Fig. 3.

The above finding suggests that the original methodology adopted by the ACRIM team to merge SMM/ACRIM1 and NIMBUS7/ERB records may be inappropriate because it assumes that NIMBUS7/ERB data are statistically stationary relative to the ACRIM1 measurements, while this is not what the data show. By not taking into account this problem the ACRIM team’s methodology can introduce significant artificial slips in the TSI satellite composite at the chosen merging day.

To reduce the errors due to the above irregular large oscillations of NIMBUS7/ERB measurements, we use the black 91-days moving average smooth curve shown in Fig. 3 to reduce NIMBUS7/ERB record to the level of SMM/ACRIM1 during the overlapping period. Then, we use the NIMBUS7/ERB corrected record to fill all days that SMM/ACRIM1 record misses. Before 17/02/1980 NIMBUS7/ERB record is shifted by $-4.5$ W/m², while after 14/07/1989 it is shifted by $-4.12$ W/m² as indicated in the figure. This means that relative to the original ACRIM composite, our composite is 0.2 W/m² lower before 17/02/1980, and 0.18 W/m² higher after 14/07/1989.

However, these values do depend on the adopted moving average window. In fact, by increasing the window the two above levels approach the average level at $-4.3$ W/m², which is the value used by the ACRIM team to merge the two records. Thus, our proposed merging methodology can have an error as large as 0.2 W/m² (Fig. 4).

On the contrary, the PMOD team significantly alters both SMM/ACRIM1 and NIMBUS7/ERB records before 1986 (see Fig. 4). These corrections are not justified by the data themselves, but by theoretical models, which may be erroneous and/or have their own large uncertainties. About the SMM/ACRIM1 data, PMOD team assumes that the SMM/ACRIM1 record from 1984 to 1986 significantly degraded. In fact, as Fig. 4 shows, the position of NIMBUS7/ERB relative to SMM/ACRIM1 gradually increased from 1984 to 1986. However, this pattern could have been caused by a degradation of SMM/ACRIM1, as the PMOD team interprets, or by an increase of sensitivity of NIMBUS7/ERB sensors due to undetermined factors. From 1988 to 1989.5, the position of NIMBUS7/ERB relative to SMM/ACRIM1 gradually decreased of the same amount of the gradual increase observed from 1984 to 1986. This suggests that NIMBUS7/ERB record can gradually vary by these large amounts.

In any case, ACRIM team has never published an update of their SMM/ACRIM1 record and, they have publicly disagreed with the PMOD team on numerous occasions (Willson and Mordvinov, 2003; Scafetta and Willson, 2009).
arguing that no physical explanation could explain the PMOD’s claimed degradation of the SMM/ACRIM1 record. Herein, we believe that the ACRIM team’s opinion cannot be just ignored and lightly dismissed. In fact, they are the authors of the data. The correction implemented by the PMOD team on the SMM/ACRIM1 record should be considered just as based on a hypothesis not taken for granted. In any case, this proposed correction would not alter the position of the TSI minimum in 1985/1986 relative to the minimum in 1996, which herein is a more important issue. PMOD team’s correction would only lower the TSI maximum in 1981/1982 by about 0.2 W/m\(^2\) relative to the TSI satellite composite after 1986.

About the NIMBUS7/ERB record before 1980, although NIMBUS7/ERB trend appears to be quite uncertain, the PMOD team’s proposed correction should be considered hypothetical as well. In particular, PMOD team believes that the large NIMBUS7/ERB peak occurred during the first months of 1979 (see Figs. 1 and 2) is an artifact due to changes in the orientation of the spacecraft. However, we observe that the TSI theoretical reconstruction proposed by Solanki (Wenzler et al., 2006) shows that a large TSI peak occurred during the first months of 1979. In fact, a careful look at their Figs. 14 and 15, where the TSI proxy reconstruction is compared against the PMOD composite reveals that during the first months of 1979 there is a discrepancy of about 1 W/m\(^2\) between the proposed TSI proxy records and the PMDO TSI composite. This is a sufficient evidence for considering the PMOD team’s corrections of NIMBUS7/ERB questionable. Moreover, from 2000 to 2004 large peaks in TSI have been

![Figure 4: Relative difference between ACRIM and PMOD TSI satellite composites.](image-url)
recorded by all available instruments: see Figs. 1 and 2. These TSI peaks, in particular the one occurred in 2002, do not seem particularly different from the peak recorded by NIMBUS7 during 1979.

In any case, the exact TSI patterns before 17/02/1980 and during the ACRIM-gap are highly uncertain because they are obtained from lower quality satellite measurements.

### 3. THE ACRIM-GAP: 15/07/1989—03/10/1991

SMM/ACRIM1 and UARS/ACRIM2 records can only be bridged by using two low quality satellite records: NIMBUS7/ERB and ERBS/ERBE. Figure 5 shows the two records from 1988.5 to 1993. Note that NIMBUS7/ERB and ERBS/ERBE present opposite trend. From 1990 to 1991.5, NIMBUS7/ERB record shows an increasing trend while ERBS/ERBE record shows a decreasing trend (Willson and Mordvinov, 2003). Thus, these two satellite records are not compatible with each other, and at least one of the two may be corrupted. Note that ERBS/ERBE too was unable to properly calibrate its sensor degradations and a direct comparison with the ACRIM records reveals that the discrepancy between local ACRIM smooth trends and ERBS/ERBE smooth trends could be as large as $0.2 \text{ W/m}^2$. The amplitude of these non-stationary biases is smaller than that observed in the NIMBUS7/ERB measurements, but they are still

![Figure 5](image-url)  
**FIGURE 5** NIMBUS7/ERB and ERBS/ERBE TSI records during the ACRIM-gap. The smooth curves are 91-day moving averages calculated on the TSI values only for those days available in both records.
significant. Moreover, the average error of ERBS/ERBE’s measurements is the largest among all satellite observations: ±0.26 W/m².

The PMOD team claims that NIMBUS7/ERB record must be severely corrected during the ACRIM-gap. The justifications for the proposed corrections can be found in the scientific literature. Lee et al. (1995) compared the NIMBUS7/ERB dataset with a TSI model based on a multi-regression analysis of March 1985 to August 1989 ERBS/ERBE irradiance measurements, and they concluded that after September 1989 NIMBUS7/ERB time series appeared to, and have abruptly increased by +0.4 W/m² after a switch-off of NIMBUS7/ERB for 4 days. Another +0.4 W/m² upward shift appeared to have occurred on April 1990. Thus, this study suggested a two-step shift correction that, once combined, moves down the NIMBUS7/ERB record by 0.8 W/m² at the end of April 1990.

Later Chapman et al. (1996) reviewed the finding by Lee et al. (1995) and concluded that on 29/09/1989 NIMBUS7 experienced a sudden increase by +0.31 W/m² and on 9/05/1990 there was another upward shift by +0.37 W/m²: the combined two-step correction shift had to be −0.68 W/m² after 9/05/1990. Afterward, Fröhlich and Lean (1998) suggested a different two-step shift correction, that is, the NIMBUS7/ERB record had to be adjusted by −0.26 W/m² and −0.32 W/m² near October 1, 1989 and May 8, 1990, respectively: the combined correction shift of NIMBUS7/ERB during the ACRIM-gap was estimated to be −0.58 W/m².

**FIGURE 6** Relative difference between NIMBUS7/ERB original record and PMOD TSI satellite composite.
Finally, Fröhlich (2000, 2004) revised significantly his previous model correction of NIMBUS7/ERB data. He first acknowledged that the supposed slip on May 1990 was indeed difficult to identify. Then, he substituted the two-step correction model with a new model in which there was only one sudden slip on September 29, 1989 followed by a upward linear trend. Figure 6 shows our analysis of these new corrections in their latest version: on 29/09/1989 there is a sudden jump of $+0.47 \text{ W/m}^2$, which is significantly larger than what was previously estimated, which is followed by an upward trend of $+0.142 \text{ W/m}^2$/year. The total downward shift forced on NIMBUS7/ERB record from 1989.5 to 1992.5 is about $-0.89 \text{ W/m}^2$, which is significantly larger than what Fröhlich himself and the other groups had previously estimated.

From the above studies, it is evident that several opinions have been formulated to solve the ACRIM-gap, even by the same research team, and they quantitatively disagree with each other. The above conflicting solutions indicate that it is not so certain how NIMBUS7/ERB should be corrected, if some corrections were truly needed.

Figure 7 shows our analysis of the comparison between NIMBUS7/ERB and ERBS/ERBE. The 91-day moving average curve of the relative difference between NIMBUS7/ERB and ERBS/ERBE decreases until August 1989.
around the time when SMM/ACRIM1 merges with NIMBUS7/ERB at the level 6.29 W/m$^2$, as shown in the graph. Since the beginning of September 1989 to the beginning of 1990 the curve rises rapidly, but, in contrast with the PMOD’s claims, no sudden one-day jump by about 0.65 W/m$^2$ due to an instrumental glitch is observed. From 1990 to 1991.5 the curve rises by about 0.40 W/m$^2$. Finally, from 1991.5 to 1993 the curve decreases slightly by about 0.05 W/m$^2$.

The total shift from 1989.5 to 1993 is about 0.72 W/m$^2$. Note that the error related to the single measurements is about $\pm 0.11$ W/m$^2$. Thus, the observed difference between NIMBUS7/ERB and ERBS/ERBE is significant and must be interpreted as due to biases in the data. These are likely due to uncorrected problems in one or both the satellite instrumentations.

Figure 7 shows also the correction implemented by the PMOD team on NIMBUS/ERB record (Fröhlich, 2000, 2004), which approximately reproduce the divergence between NIMBUS7 and ERBS. It is evident from the figure that the PMOD team believes that the observed difference between the two TSI satellite records is due to uncorrected problems occurring only on NIMBUS7/ERB’s sensors. Even so, the correction of NIMBUS/ERB record implemented by the PMOD team (0.89 W/m$^2$ from 1989.5 to 1992.5) appears to be overestimated at least by about 0.12 W/m$^2$ because the total shift observed during the ACRIM-gap period is about 0.77 W/m$^2$. The difference seems to be due to the fact that PMOD team did not take into account that the real comparison must be done with the level when SMM/ACRIM1 merges with NIMBUS7/ERB around the middle of 1989, and the level during this period, as indicated in the figure, is about 6.29 W/m$^2$. Thus, if on 29/09/1989 a shift really occurred in the NIMBUS7/ERB record, its magnitude has to be by about 0.30 W/m$^2$, as previously estimated by Chapman et al. (1996) and Fröhlich and Lean (1998).

Finally, the PMOD team’s correction with a linear increase from 29/09/1989 to 1992.5 is also poorly observed in data depicted in Fig. 7; indeed, the PMOD linear correction during this period appears to be just a linear simplification of the complex pattern observed in the figure.

However, the theoretical studies (Lee et al., 1995; Fröhlich and Lean, 1998; Fröhlich, 2000, 2004; Chapman et al., 1996) claiming that NIMBUS7/ERB is erroneous during the ACRIM-gap may be questionable. In fact, although these authors did notice a difference between NIMBUS7/ERB and ERBS/ERBE records, they have interpreted such a difference as only due to a corruption of the NIMBUS7/ERB record. This interpretation was preferred despite the fact that ERBS/ERBE too was unable to continuously calibrate its sensor degradations and its data had larger uncertainties than NIMBUS7/ERB data. Indeed, the increase observed in Fig. 7 during the ACRIM-gap could result from increased ERBS/ERBE degradation relative to NIMBUS7/ERB, a relative increase in the sensitivity of the NIMBUS7/ERB sensor, or both (5).

It is important to stress that in 1992, the experimental team responsible of the NIMBUS7/ERB record (Hoyt et al., 1992) corrected all biases in the data they could find and afterward they ever come up with a physical theory for the
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. 4. The correction of the Nimbus7 TSI values for 1979–1980 proposed by Frohlich is also puzzling. The raw data was run through the same algorithm for these early years and the subsequent years and there is no justification for Frohlich’s adjustment in my opinion.

Indeed, it is not possible to exclude that the TSI increase between 1989 and 1991, or part of it, observed in Fig. 7 is an indication of ERBS losing sensitivity rather than Nimbus7 gaining sensitivity. In fact, a careful look at the pattern depicted in Fig. 7 reveals a rapid but gradual increase immediately after September 1989, which lasted for two months. This pattern suggests that the discrepancy between Nimbus7 and ERBS during that period is not due to a one-day glitch event on 29/9/1989 causing a sudden upward increase in the sensitivity of Nimbus7’s sensors, as claimed by PMOD. There are several physical reasons to believe that ERBS/ERBE could degrade more likely than Nimbus7/ERB, in particular during the ACRIM-gap. For example: a) The Nimbus7/ERB cavity radiometer was in a relatively high altitude (about 900 km), while ERBS/ERBE was in a low earth orbit (ca. 200 km). It is possible that ERBS would degrade much faster than Nimbus7/ERB due to more atmospheric bombardment of its sensor. b) During the ACRIM-gap ERBS/ERBE was experiencing for the first time the enhanced solar UV radiation, which occurs during solar maxima, and this too may have caused a much faster degradation of the cavity coating of ERBS than of Nimbus7/ERB.
because NIMBUS7 already experienced such degradation during the previous solar maximum. c) From spring 1990 to May/June 1991, when according to Fig. 7 the difference between NIMBUS7/ERB and ERBS/ERBE increased by about 0.40 W/m², there was a rapid increase of cosmic ray flux, as Fig. 8 shows. In addition, the above phenomena could have more likely damaged ERBS/ERBE’s sensors than NIMBUS7/ERB’s ones, which already experienced a solar maximum 10 years earlier.

The cosmic ray count is negative-correlated to TSI and magnetic flux, and its minima correspond to solar activity maxima. Fig. 8 shows that the minimum around 1991.5 was lower than the minimum around 1989.8–1990.5. This implies that according to this record, the solar activity was likely higher around 1991.5 than around 1989.8–1990.5. This contradicts the pattern observed in ERBS/ERBE and confirms the NIMBUS7/ERB pattern, as Fig. 5 shows. However, other solar indexes, such as the sunspot number index, present the opposite scenario. It is unlikely that solar proxy indexes can be used to definitely and precisely solve this issue.

We believe that unless the experimental teams find a physical theory for explaining the divergences observed in their own instrumental measurements and definitely solve the problem, there exists only a statistical way to address the ACRIM-gap problem by using the published data themselves. This requires just the acknowledgment of the existence of a still unresolved uncertainty in the TSI satellite data. This can be done in the following way:

![Climax cosmic ray of the University of New Hampshire (Version 4.8 21 December 2006). Data from http://ulysses.sr.unh.edu/NeutronMonitor/](http://ulysses.sr.unh.edu/NeutronMonitor/)
Assuming that NIMBUS7/ERB is correct and ERBS/ERBE is erroneous; this would imply that during the ACRIM-gap, ERBS/ERBE record degraded and should be shifted upward by $0.72 \pm 0.77$ W/m$^2$.

Assuming that ERBS/ERBE is correct and NIMBUS7/ERB is erroneous; this would imply that during the ACRIM-gap NIMBUS7/ERB increased its sensitivity to TSI and should be shifted downward by $0.72 \pm 0.77$ W/m$^2$.

Assuming that both ERBS/ERBE and NIMBUS7/ERB records need some correction. Note that there is no objective way to implement method # 3 and infinitely different solutions may be proposed, as those proposed by Fröhlich and other authors. Herein, we propose that all configurations between case # 1 and case # 2 may be possible, and for case # 3 we just propose an average between methods 1 and 2 stressing that this arithmetic average should not be interpreted as a better physical solution for the ACRIM-gap problem.

FIG. 9 Depicts the three reconstructions of NIMBUS7/ERB record during the ACRIM-gap in agreement with three alternative scenarios. (A) NIMBUS7/ERB data are unaltered; (C) the data are adapted in such a way that their smooth component matches exactly the smooth component of ERBS/ERBE; (B) the data are adapted in such a way that their smooth component matches exactly the average between the smooth components in (A) and (C). The smooth component is a 91-day moving average.

(1) Assuming that NIMBUS7/ERB is correct and ERBS/ERBE is erroneous; this would imply that during the ACRIM-gap, ERBS/ERBE record degraded and should be shifted upward by $0.72-0.77$ W/m$^2$.

(2) Assuming that ERBS/ERBE is correct and NIMBUS7/ERB is erroneous; this would imply that during the ACRIM-gap NIMBUS7/ERB increased its sensitivity to TSI and should be shifted downward by $0.72-0.77$ W/m$^2$.

(3) Assuming that both ERBS/ERBE and NIMBUS7/ERB records need some correction.

Note that there is no objective way to implement method # 3 and infinitely different solutions may be proposed, as those proposed by Fröhlich and other authors. Herein, we propose that all configurations between case # 1 and case # 2 may be possible, and for case # 3 we just propose an average between methods 1 and 2 stressing that this arithmetic average should not be interpreted as a better physical solution for the ACRIM-gap problem.
91-day moving average curve in Fig. 9 matches exactly the 91-day moving average curve of ERBS/ERBE shown in Fig. 5. (B) NIMBUS7/ERB data are altered in such a way that their 91-day moving average curve matches exactly the average between the two 91-day moving average curves of NIMBUS7/ERB and ERBS/ERBE shown in Fig. 5.

4. SMM/ACRIM1 vs. UARS/ACRIM2

To align SMM/ACRIM1 and UARS/ACRIM2 records we proceed as follows. First, we merge NIMBUS7/ERB record and its two alternative records shown in Fig. 9 with the SMM/ACRIM1 record. The merging is done by guaranteeing a continuity of the 91-day moving average curves at the merging day, 03/10/1991.

Second, we use the finding shown in Fig. 10. This figure depicts the overlapping period between NIMBUS7/ERB and UARS/ACRIM2 records. This interval is quite short, and it is made of two separated intervals during which both satellite measurements were interrupted for several months. Note that the two intervals are not aligned: there is a difference of about 0.2 W/m² between the two levels. Because the standard deviation of the data is about 0.26 W/m², which is significantly larger than the statistical error of measure 0.16 W/m², the figure indicates that the data are not statistically stationary.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Relative difference between NIMBUS7/ERB and UARS/ACRIM2 TSI satellite records according to the three hypotheses discussed in the article. Note that NIMBUS7/ERB record has been already merged with SMM/ACRIM1 record. Thus, the value reported in the figure refers to the position SMM/ACRIM1 relative to UARS/ACRIM2 in the three alternative cases.}
\end{figure}
However, it is not evident which record is performing poorly: NIMBUS7/ERB and ERBS/ERBE or UARS/ACRIM2. Because the difference observed between NIMBUS7/ERB and UARS/ACRIM2 records in (A), and between the adapted NIMBUS7/ERB and UARS/ACRIM2 records in (C) (where NIMBUS7/ERB record is adapted to reproduce ERBS/ERBE smooth trending) are almost equal, the first impression is that UARS/ACRIM2 sensors experienced a downward slip between the two intervals by about 0.2 W/m². However, because both NIMBUS7/ERB and ERBS/ERBE were less able to calibrate their sensor degradation, it is still uncertain whether it is UARS/ACRIM2 record that has to be corrected and, if so, how large this correction should be. Indeed, given the short time period and that both NIMBUS7/ERB and ERBS/ERBE are characterized by non-stationary biases as large as ±0.2 W/m², it is possible that during 1992 the two latter records experienced a similar upward bias. Thus, here we decided to keep UARS/ACRIM2 record unaltered and merge the two sequences using the average of the relative differences during the entire overlapping period in all three cases, as shown in Fig. 10. The error associated with this merging is about ±0.1 W/m². However, if UARS/ACRIM2 record needs a correction, its global implication would be that the TSI satellite composite before 1992.5 should be shifted downward by about 0.1 W/m² in all three cases.

5. UARS/ACRIM2 vs. ACRIMSAT/ACRIM3

The merging between UARS/ACRIM2 and ACRIMSAT/ACRIM3 is done by using the information shown in Fig. 11 that depicts the relative difference between ACRIMSAT/ACRIM3 and UARS/ACRIM2, and for comparison, the relative difference between SOHO/VIRGO and UARS/ACRIM2. Note that UARS/ACRIM2 measurements were interrupted from 05/06/2001 to 08/16/2001.

The latter comparison is necessary for studying the discrepancy observed between ACRIMSAT/ACRIM3 and UARS/ACRIM2, which is significantly larger than the statistical error of the measurements. In fact, the average statistical error of UARS/ACRIM2 data is 0.01 W/m², while the average statistical error of ACRIMSAT/ACRIM3 data is 0.008 W/m². The average statistical error of the relative difference between ACRIMSAT/ACRIM3 and UARS/ACRIM2 is 0.018 W/m². However, the data in the figure have a standard deviation of 0.3 W/m², which is significantly larger than their statistical errors. Thus, the observed difference between ACRIMSAT/ACRIM3 and UARS/ACRIM2 records is not due to random fluctuations, but to non-stationary trends in the data.

Because a similar pattern appears when UARS/ACRIM2 is compared against both SOHO/VIRGO and ACRIMSAT/ACRIM3 records, it appears that UARS/ACRIM2 sensors may have experienced some problem. Perhaps an annual cycle has been filtered off in some way. However, these problems
appear to have significantly modified a natural variation in the TSI data characterized by a time scale close to 1 year. Because the difference between ACRIMSAT/ACRIM3 and UARS/ACRIM2 appears to present a cyclical pattern, an accurate way to merge the two sequences is to evaluate the average during an entire period of oscillation. The period from 04/05/2000 to 05/06/2001 covers approximately one period of oscillation, and during this period the average difference between ACRIMSAT/ACRIM3 and UARS/ACRIM2 is 1.86 W/m²: we use this value for the merging. As the figure shows, the averages during the first and the second half of the cycle are 1.70 W/m² and 2.02 W/m², respectively. This suggests that our merging has an uncertainty of ±0.18 W/m².

6. THREE UPDATED ACRIM TSI COMPOSITES

The satellites records are merged and our three TSI composites are shown in Fig. 12. Table 1 summarizes how SMM/ACRIM1 and UARS/ACRIM2 records are adjusted and aligned with ACRIMSAT/ACRIM3.

The composite (A) shows that the 1996 minimum is about 0.67 ± 0.1 W/m² higher than the 1986 minimum. The composite (B) shows that the 1996 minimum is about 0.28 ± 0.1 W/m² higher than the minimum in 1986. The composite (C) shows that the 1996 minimum is about 0.11 ± 0.1 W/m² lower

![Graph showing relative differences between satellite records](image-url)
than the minimum in 1986. Thus, only in the eventuality that during the ACRIM-gap ERBS/ERBE record is uncorrupted the two solar minima would almost coincide. However, on average the composites indicate that the TSI minimum in 1996 is 0.28 ± 0.4 W/m² higher than the minimum in 1985/6.

**TABLE 1** Position in W/m² of SMM/ACRIM1 (A1) and UARS/ACRIM2 (A2) relative to ACRIMSAT/ACRIM3 (A3) in the three scenarios (A), (B), and (C) as discussed in the test. The errors are calculated by taking into account the highest uncertainty due to the statistical non-stationarity of NIMBUS7/ERB and UARS/ACRIM2 when they merge and when UARS/ACRIM2 merges ACRIMSAT/ACRIM3. Note that the error of the position of SMM/ACRIM1 compared to UARS/ACRIM2 is ±0.1 W/m². The error associated to the non-stationarity of NIMBUS7/ERB during the ACRIM-gap is described by the three scenarios (A), (B), and (C).

<table>
<thead>
<tr>
<th></th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>−1.90 ± 0.19</td>
<td>−1.51 ± 0.19</td>
<td>−1.12 ± 0.19</td>
</tr>
<tr>
<td>A2</td>
<td>+1.86 ± 0.16</td>
<td>+1.86 ± 0.16</td>
<td>+1.86 ± 0.16</td>
</tr>
<tr>
<td>A3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**FIGURE 12** The three TSI satellite composites: see text for details. The composites (B) and (C) are shifted by −4 W/m² and −8 W/m², respectively, for visual convenience.
Note that if UARS/ACRIM2 record needs to be corrected during its merging with NIMBUS7/ERB, as explained above, the TSI 1996 minimum relative to the TSI 1986 minimum would be about 0.1 W/m² higher than the above three estimates. In this case, according to the satellites data the difference between the two minima would be about $0.38 \pm 0.4$ W/m². This would further stress that the TSI satellite measurements indicate on average that TSI likely increased during solar cycles 21–23 (1980–2002).

7. TSI PROXY SECULAR RECONSTRUCTIONS

It is necessary to use reconstructions of the solar activity as long as possible, at least one century, for determining the effect of solar variations on climate. The TSI record that is possible to obtain from direct TSI satellite measurements covers the period since 1978, and this period is far too short to correctly estimate how the sun may have altered climate. The reason is because the climate system is characterized by a slow characteristic time response to external forcing that is estimated to be about 8 years (which, theoretically, can be as large as 12 years) (Scafetta, 2008; Schwartz, 2008). This decadal time response of the climate requires several decade long records for a correct evaluation of the climatic effect of an external forcing on climate. Thus, it is necessary to merge the TSI satellite composites together with long TSI secular reconstructions, which are quite uncertain because they are necessarily based on proxy data, and not direct TSI measurements.

Long-term TSI changes over the past 400 years since the 17th-century Maunder minimum have been reconstructed by several authors, for example: Hoyt and Schatten (1997), Lean (2000), Wang et al. (2005), and Krivova et al. (2007). These TSI proxy reconstructions are based on the sunspot number record, the long-term trend in geomagnetic activity, the solar modulation of cosmogenic isotopes such as $^{14}$C and $^{10}$Be records, and other solar related records. These observables are used because they are supposed to be linked to TSI variations. However, it is not known exactly how the TSI can be reconstructed from these historical records, nor whether these records are sufficient to faithfully reconstruct TSI changes. In fact, the proposed TSI secular proxy reconstructions are quite different from each other and show different patterns, trends and maxima, as depicted in Fig. 13. Nevertheless, they reproduce similar patterns: in particular, note the minima during the Maunder Minimum (1645–1715) and the Dalton Minimum (1790–1820), and the TSI increase during the first half of the 20th century.

The TSI increase during the first half of the 20th century is particularly important. In fact, because the characteristic time response of the climate to external forcing is about 8–12 years, an increase of TSI during the first half of the 20th century would have induced a warming also during the second half of the 20th century, even if the TSI have remained almost constant during the second half of the 20th century (16).
The four TSI proxy reconstructions shown in Fig. 13 present different trends since 1975. The TSI reconstruction proposed by Hoyt and Schatten (1997) suggests that TSI increased during this period, as shown in our TSI satellite composites (A) and (B), and in the original ACRIM TSI satellite composite. However, the other three TSI proxy reconstructions (Lean, 2000; Wang et al., 2005; Krivova et al., 2007) suggest that TSI did not change on average since 1978, as shown in our TSI satellite composite (C) and in the PMOD TSI satellite composite. Thus, the uncertainty that we have found in composing the TSI satellite records appears unresolved also by using the TSI proxy reconstructions because different solar proxies do suggest different TSI patterns as well.

Because TSI satellite composites refer to actual TSI measurements, we propose their merging with TSI proxy reconstructions for obtaining a TSI secular record. Here, we chose a recent TSI proxy reconstruction (Krivova et al., 2007), which has a daily resolution, and merge it to the TSI satellite composites in such a way that their 1980–1990 average coincides. Other choices and their implications by using the original ACRIM and the PMOD TSI satellite composites with the TSI proxy reconstructions of Lean (2000) and Wang et al. (2005) can be found in Scafetta and West (2007). The three TSI merged records herein proposed are depicted in Fig. 14. The figure shows that during the last decades the TSI has been at its highest value since the 17th century in all three cases.
The phenomenological solar signature on climate can be estimated with a phenomenological energy balance model (PEBM) (Scafetta and West, 2007; Scafetta, 2009). PEBM assumes that the climate system, to the lowest-order approximation, responds to an external radiative forcing as a simple thermodynamical system, which is characterized by a given relaxation time response $\tau$ with a sensitivity $\alpha$. The physical meaning of it is that a small anomaly (with respect to the TSI average value) of the solar input, measured by $\Delta I$, would force the climate to reach a new thermodynamic equilibrium at the asymptotic temperature value $\alpha \Delta I$ (with respect to a given temperature average value). Thus, if $\Delta I(t)$ is a small variation (with respect to a fixed average) of an external forcing and $\Delta T_s(t)$ is the Earth’s average temperature anomaly induced by $\Delta I(t)$, $\Delta T_s(t)$ evolves in time as:

$$\frac{d\Delta T_s(t)}{dt} = \frac{\alpha \Delta I(t) - \Delta T_s(t)}{\tau}.$$ (1)

A simple thermal model equivalent to (1) has been used as a basic energy balance model (Douglass and Knox, 2005; North et al., 1981), but in this paper we use TSI records as a proxy forcing. We implement the PEBM by imposing

**FIGURE 14** Merging of the secular TSI proxy reconstruction by Krivova et al. (26) (black) with the three TSI satellite composites proposed in Fig. 12 (gray). The TSI reconstructions (B) and (C) are shifted by $-5 \text{ W/m}^2$ and $-10 \text{ W/m}^2$, respectively, for visual convenience. The merging is made by shifting the original secular TSI proxy reconstruction by Krivova et al. (26) by $-0.5174 \text{ W/m}^2$, $-0.1295 \text{ W/m}^2$, and $+0.2584 \text{ W/m}^2$ in the cases (A), (B), and (C) respectively.
that the global peak-to-trough amplitude of the 11-year solar cycle signature on the surface temperature is about 0.1 K from 1980 to 2002, as found by several authors (see IPCC, 2007, page 674 for details). This implies that the climate sensitivity $Z_{11}$ to the 11-year solar cycle is $Z_{11} = 0.11 \pm 0.02 \text{ K/W/m}^2$, as found by Douglass and Clader (2002) and Scafetta and West (2005).

In addition, the characteristic time response to external forcing has been phenomenologically estimated to be $\tau = 8 \pm 2$ years (28, 29). Note that Scafetta (28) has also found that climate is characterized by two characteristic time constants $\tau_1 = 0.40 \pm 0.1$ year and $\tau_2 = 8 \pm 2$ years, with the latter estimate that may be a lower limit (the upper limit being $\tau_2 = 12 \pm 3$ years), but an extensive discussion about the consequences of this finding is present in another study (18).

The value of the parameter $\alpha$ is not calculated theoretically by using the TSI as a climate forcing as usually done in the traditional climate models. The value of $\alpha$ is calculated by using the phenomenological climate sensitivity to the 11-year solar cycle found in Eq. (2) by means of the following equation

\[
\alpha(\tau) = \sqrt{1 + \left(\frac{2\pi \tau}{11}\right)^2},
\]  

(2)

which solves Eq. (1). Thus, we find that the phenomenological climate sensitivity to TSI changes is $\alpha = 0.51 \pm 0.15 \text{ K/W/m}^2$. This value is the phenomenological climate sensitivity to irradiance changes where the TSI record is used only as a geometrical proxy of the total solar forcing on climate. Thus, the parameter $\alpha$ has a very different meaning than the climate sensitivity to solar irradiance as estimated in the traditional physical models. In our case, for example, the parameter $\alpha$ would include also other effects such as, for example, that of a cloud modulation by means of cosmic ray flux, which is regulated by solar activity and presents a geometrical form approximately similar to that of the TSI reconstructions.

With the above value of $\tau$ and $\alpha$, Eq. (1) can be numerically solved by using as input the TSI records shown in Fig. 14. The phenomenological solar signatures (PSSs) are shown in Fig. 15 where the three PSSs are plotted since 1600 against a paleoclimate Northern Hemisphere temperature reconstruction (Moberg et al., 2005) and since 1850 against the actual instrumental Northern Hemisphere surface record (Brohan et al., 2006).

The figure shows that there is a good agreement between the PSSs and the temperature record. The patterns between 1600 and 1900 are well recovered such as the cooling during the Maunder (1650–1730) and Dalton (1790–1840) minima. The warming during the first half of the 20th century is partially recovered. The observed discrepancy around 1940–1950 could be due to an error in the used TSI proxy model. A better matching would occur by using Hoyt TSI model because it peaks during 1940–1950. Finally, since 1978 the output strongly depends on the TSI behavior. If the TSI reconstruction (A) is adopted, a significant portion of the warming, about 66% observed since 70s
has been induced by solar variations, while if the TSI reconstruction (C) is adopted, almost all warming, about 85% observed since 70s has been induced by factors alternative to solar variations. If the average TSI reconstruction (B) is adopted, about 50% of the warming observed since 70s has been induced by solar variations.

9. CONCLUSION

We have reconstructed new TSI satellite composites by using the three ACRIM records and have shown that different composites are possible, depending on how the ACRIM-gap problem from 1989.5 to 1992 is solved. Our three TSI composites indicate that the TSI minimum in 1996 is $0.30 \pm 0.40$ W/m$^2$ higher than the TSI minimum in 1986. On the contrary, the two TSI minima in 1986 and 1996 would be located at the same level only in the eventuality that the TSI ERBS/ERBE satellite record is uncorrupted during the ACRIM-gap, a fact that has been questioned by our analysis. For example, in Fig. 7 we did not notice a sudden one-day jump at the end of September 1989 in the sensitivity of NIMBUS7 sensors, as claimed by PMOD. On the contrary, we noticed a rapid, but gradual divergence between NIMBUS7 and ERBS that occurred during

![Graph showing temperature anomalies](image-url)
October and November 1989. This gradual divergence may also imply a rapid degradation of ERBS sensors.

None of the TSI satellite composites proposed by the ACRIM, IRMB, and PMOD teams can be considered rigorously correct. All three teams have just adopted alternative methodologies that yield to different TSI composites, but these teams have also ignored the unresolved uncertainties in the data that yields to an unresolved uncertainty in the TSI composites as well.

The comparison with theoretical TSI proxy models, for example Wenzler et al. (2006) and Krivova et al. (2007), cannot be used to resolve the issue, as the PMOD team assumes. In fact: (1) in science, theoretical models have to be tested against the observations, not vice versa, (2) the TSI proxy models adopt a reductionistic scientific approach, that is, they assume that some given solar observable that refers to a particular solar measure (for example measurements from magnetograms or measurements of the intensity of a given frequency of the spectrum) can be used to faithfully reconstruct a global solar measure such as the TSI, and (3) the TSI proxy models do depend on parameters that opportunely calibrated give different outcomes that may, eventually, fit alternative satellite composites.

Because it is not possible to reconstruct with certainty the TSI behavior during the ACRIM-gap, the TSI decadal trend during the last three decades is unfortunately uncertain, and any discussion that needs to use the TSI record has to take into account this unresolved uncertainty.

However, because the uncertainty in the data indicates that the TSI minimum in 1996 is at least approximately 0.30 ± 0.40 W/m² higher than the TSI minimum in 1986, on average the satellite records do suggest that TSI may have increased from 1980 to 2000. Therefore, the sun may have significantly contributed to the warming observed during the last three decades, as suggested by the phenomenological model simulations herein proposed. This result has been further confirmed by Scafetta (2010) where it was shown that the warming observed from 1970 to 2000 has been mostly induced by a 60-year modulation of the climate during its warm phase. This 60-year modulation appears to be present in the climate records for centuries and it appears to be correlated to a correspondent and clear 60-year heliospheric cycle which is also revealed in several solar proxy records.

Note that a recent paper by Lockwood (2008) concluded that even with the adoption of the original ACRIM composite, the sun’s contribution to the global surface warming would be negligible during the last three decades, in contrast with the findings of Scafetta and West (2007, 2008) and those presented here. However, Lockwood’s findings derive from his evaluation of the characteristic time response of the climate to solar variation: \( \tau = 0.8 \) years. This value strongly differs from the value herein adopted of \( \tau = 8 \) years and recently measured by Scafetta (2008) and Schwartz (2008). The problem with Lockwood’s short time constant is that according to the climate physics implemented in most climate models, the characteristic time response of the climate
varies from a few months to several years and even decades, as Lockwood himself acknowledges in his own paper. For example, the linear upwelling/diffusion energy balance model adopted by Crowley (2000) uses about $\tau = 10$ years. In addition, Scafetta (2008) and Schwartz (2008) have found that climate is characterized by at least two characteristic time constants, one short with a time scale of several months and one long with a decadal time scale. The climate processes with a fast response are usually responsible for the fast fluctuations seen in the data. Instead, the climate processes with a slow response are those that drive the decadal and secular trends observed in the global temperature. This slow climate response derives from the fact that the processes that regulate the decadal and secular variation of the climate (most of all energy exchange with the deep ocean and changes of the albedo due to the melting of the glaciers and forestation and desertification processes) are very slow processes, and they work as powerful climate feedbacks. Thus, we believe that Lockwood’s analysis is inappropriate because it failed to take into account the climate processes with a slow time response that would be responsible for a strong climate response to solar changes. However, a more detailed discussion about this issue, which would imply also an update of the PEBM presented here, is present in another dedicated study (2009).

REFERENCES


Pap J.M. et al., 2004 (Eds.), Solar Variability and Its Effects on Climate: Geophysical Monograph Series Volume 141 American Geophysical Union, Washington, DC.


