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Reconstruction and prediction of the total solar irradiance: From the Medieval Warm Period to the 21st century

V.M. Velasco Herrera [a,*], B. Mendoza [a], G. Velasco Herrera [b]

[a] Departamento de Ciencias Espaciales, Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad Universitaria, Coyoacán, 04510 México D.F., Mexico
[b] Centro de Ciencias Aplicadas y Desarrollo Tecnológico, Universidad Nacional Autónoma de México, Ciudad Universitaria, Coyoacán, 04510 México D.F., Mexico

HIGHLIGHTS

- We present a new method to estimating TSI between the years 1000 and 2100.
- We found a grand minimum for the 21st century.
- We found conspicuous periodicities of 11 and 120 years.
- The solar activity grand minima periodicity is of 120 years.
- To decide when the solar activity is high or low, we using the power of the TSI.

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ABSTRACT

Total solar irradiance is the primary energy source of the Earth's climate system and therefore its variations can contribute to natural climate change. This variability is characterized by, among other manifestations, decadal and secular oscillations, which has led to several attempts to estimate future solar activity. Of particular interest now is the fact that the behavior of the solar cycle 23 minimum has shown an activity decline not previously seen in past cycles for which spatial observations exist: this could be signaling the start of a new grand solar minimum. The estimation of solar activity for the next hundred years is one of the current problems in solar physics because the possible occurrence of a future grand solar minimum will probably have an impact on the Earth's climate. In this study, using the PMOD and ACRIM TSI composites, we have attempted to estimate the TSI index from year 1000 AD to 2100 AD based on the Least Squares Support Vector Machines, which is applied here for the first time to estimate a solar index. Using the wavelet transform, we analyzed the behavior of the total solar irradiance time series before and after the solar grand minima. Depending on the composite used, PMOD (or ACRIM), we found a grand minimum for the 21st century, starting in ~ 2004 (or 2002) and ending in ~ 2075 (or 2063), with an average irradiance of 1365.5 (or 1360.5) $\mathrm{Wm}^{-2} \pm 1\sigma = 0.3$ (or 0.9) Wm^{-2}. Moreover, we calculated an average radiative forcing between the present and the 21st century minima of ~ -0.1 (or -0.2) Wm^{-2}, with an uncertainty range of -0.04 to -0.14 (or -0.12 to -0.33) Wm^{-2}. As an indicator of the TSI level, we calculated its annual power anomalies; in particular, future solar cycles from 24 to 29 have lower power anomalies compared to the present, for both models. We also found that the solar activity grand minima periodicity is of 120 years; this periodicity could possibly be one of the principal periodicities of the magnetic solar activity not so previously well recognized. The negative (positive) 120-year phase coincides with the grand minima (maxima) of the 11-year periodicity.

1. Introduction

Solar radiation is one of the main influences on the Earth's climate. Over the 11-year solar cycle, total solar irradiance (TSI) variations of $\sim 0.1\%$ have been observed between the solar minima and maxima of cycles 22 and 23 (Kopp and Lean, 2012). This modulation is mainly due to the interplay between dark sunspots and bright faculae and network elements (Foukal and Lean, 1988).

Long-term reconstructions of TSI (e.g. Steinhilber et al. (2009), Wang et al. (2005), Krivova et al. (2007), Muscheler et al. (2007), Bard et al. (2000), Fröhlich (2006), Vieira et al. (2011)) showed epochs of maxima and minima when substantial changes in the

* Corresponding author. Tel.: +55 56224113.
E-mail address: vmv@geofisica.unam.mx (V.M. Velasco Herrera).

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TSI occur. These changes can contribute to climate variability (e.g. Gray et al. (2010)).

These TSI reconstructions are based on the evolution of the sun's total and/or open magnetic flux. For instance Wang et al. (2005) used a flux transport model to simulate the evolution of the solar total and open magnetic flux by means of the group sunspot number (GSN). This model obtained two annual TSI reconstructions, one with and one without a secularly varying background. From 1850 onwards these reconstructions are recommended as the solar forcing for the fifth Coupled Model Intercomparison Project 20th century simulations (Taylor, 2009). The Krivova et al. (2010) TSI model used the GSN to reconstruct the evolution of the solar surface magnetic field, relying on time constants representing the decay and conversion of the different photospheric magnetic flux components.

Other reconstructions explicitly used the solar modulation potential (Φ). This potential quantifies the galactic cosmic ray deceleration produced by the solar activity (Gleeson and Axford, 1968): Φ is obtained from cosmogenic isotope time series corrected for geomagnetic field variations. The Steinhilber et al. (2009) reconstruction is based on an observationally-derived relationship between TSI and open magnetic flux (Fröhlich, 2009); the authors obtained the open flux from Φ. Also, Delaygue and Bard (2011) use Φ to reconstruct the TSI.

The Vieira et al. (2011) model derived the relationship between solar-cycle averaged open magnetic flux and TSI from the Krivova et al. (2010) model, and this is used to reconstruct the TSI throughout the Holocene, based on ^{14}C record.

The TSI reconstructions are used in climate models for among other things, to assess the effect of solar radiative forcing on the climate. Because the physical constraints on the amplitude and timing of TSI histories remain a very difficult challenge, we propose that using as many different approaches for TSI reconstructions will lead to a better and objective sensitivity experiments regarding how Earth climate can response to changing TSI.

Studies using cosmogenic isotope data and sunspot data (e.g. Solanki et al. (2004), Abreu et al. (2008), Velasco et al. (2008)) indicate that we are currently within a grand activity maximum, which began after $\sim$ 1930.

However, the behavior of the solar cycle 23 minimum has shown an activity decline not previously seen in the past solar cycles for which spatial observations exist (e.g. Kirk et al. (2009), Lee et al. (2009), Smith and Balogh (2008), McComas et al. (2008)). The descending phase and minimum measurements show that the TSI has fallen below the previous two solar minima values: the mean PMOD composite TSI for September 2008 was 1365.26 ± 0.16 Wm^{-2}, compared to 1365.45 ± 0.1 Wm^{-2} in 1996 or 1365.57 ± 0.01 Wm^{-2} in 1986 (Fröhlich, 2009).

Studying the solar wind, the interplanetary magnetic field strength, and the open solar flux over the past century, Lockwood et al. (2009) found that all three parameters showed a long-term rise peaking around 1955 and 1986 and then declining, yielding predictions that the grand maximum will end in the years 2013, 2014 or 2027, depending on the parameter used. Other studies have indicated that the current maximum will not last longer than two or three more solar cycles more (Abreu et al., 2008). It has been suggested that a Dalton-type minimum already began in the preceding minimum solar cycle 24 reaching to solar cycles 24 and 25 (e.g. Russell et al. (2010), Rigozo et al. (2010)). In addition, a summary and analysis of maximum sunspot number predictions for solar cycle 24 indicate an average of 115 ± 40 (Pesnell, 2012). Moreover, up to now the observed smoothed sunspot maximum number of solar cycle 24 shows less than 70 sunspots (www.sidc.be), consistent with the lower estimate.

Frequency analysis of solar activity series (e.g. Tobias et al. (2004)) showed several significant long-term periodicities whose existence has inspired attempts to predict trends in solar activity. The future estimation of solar activity for the next hundred years is one of the current problems in solar physics because the possible occurrence of a future grand solar minimum will probably have a significant impact on the Earth's climate.

In this paper we modeled the TSI between 1000 and 2100 AD using the Least Squares Support Vector Machines, which is being applied for the first time to estimate a solar activity index. Using the PMOD and ACRIM TSI composites as the original calibration and training set, we produced two TSI reconstructions and future TSI estimates, compared them with previous results, and calculated their main periodicities, power index and radiative forcings for Earth's climate.

2. Data

2.1. Statistical characteristics of the TSI-composites

Since 1978, several independent space-based instruments have measured the TSI. Three main composite series were constructed: the Active Cavity Radiometer Irradiance Monitor (Willson and Mordvinov, 2003; Scafetta and Willson, 2014), the Royal Meteorological Institute of Belgium (RMIB) (Dewitte et al., 2004) and the Physikalisch-Meteorologisches Observatorium Davos (PMOD) (Fröhlich, 2006). The composites employed different calibration techniques and mathematical algorithms.

Here we used the annual TSI mean obtained from the daily PMOD (www.pmodwrc.ch) and ACRIM (www.acrim.com) composites (Fig. 1) between 1979 and 2013.

Figs. 1a and c show the Probability Density Function (PDF) of the PMOD and ACRIM composites respectively, which yields a binomial distribution with the characteristic that the first maximum is greater than the second. In the case of the PMOD composite, these maxima are ~ 1365.7 Wm^{-2} and ~ 1366.3 Wm^{-2} and for the ACRIM-composite: ~ 1361.2 Wm^{-2} and ~ 1362.1 Wm^{-2}, respectively.

We note that the difference between the first and the second peak in the PDF is larger for the ACRIM composite than for the PMOD data (i.e., compare Fig. 1a and c).

2.2. Power index

As an indicator of the level of TSI activity, we defined the following TSI annual power index (P_i):

$$P_i = \sum_{k=1}^{N_i} \frac{(TSI_k)^2}{N_i}$$

where N_i is the total number of data for each year i. The normalized annual power index anomalies can be used to ponder and compare, which then allows us to decide when periods of higher or lower TSI occur; it is defined as:

$$\hat{P}_i = \frac{P_i - \langle P_{TSI} \rangle}{MAX(\|P\|)}$$

where $\langle P_{TSI} \rangle$ is the average PMOD or ACRIM average power index, $MAX(\|P\|)$ is the maximum in absolute value of the power index anomalies and ($\hat{}$) denotes normalization.

According to Fig. 1b and d, the power anomaly signs of both composites have similar time behavior for cycles 21–23: around the minimum of each cycle, the normalized power anomalies are negative; for the rest of the cycle phases, the normalized power anomalies are positive. But we highlight that during the ascending phase of solar cycle 24, the values are negative in both TSI-composites. This empirical evidence would indicate that during the current activity phase, solar cycle 24 has a very low level