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A reevaluation of the solar constant based on a 42-year total solar irradiance time series and a reconciliation of spaceborne observations

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ABSTRACT

A reevaluation of the solar constant is undertaken here to take into account the progress in space radiometry that has occurred since the early 2000s. Various sources of spaceborne total solar irradiance (TSI) observations are investigated here, including the long-term ACRIM and PMOD composites, as well as recent observations from the SORCE-TIM, TCTE-TIM, and PICARD-PREMOS instruments. A proxy model is constructed using daily data of sunspot number, radio flux at 10.7 cm, and MgII index, as predictors for TSI over the 42-year period 1976–2017. These daily estimates are used to fill in 9.7% of missing TSI observations during that period. By comparison with these proxy estimates, the PMOD composite appears generally more reliable than the ACRIM composite before 2003, and particularly before 1981. The 42-year time span is separated into nine periods, each defining the revised TSI daily values from one or more sources that are selected based on the trend of their resemblance with the proxy model. A final correction is added to emulate the highly accurate absolute calibration of PREMOS. Based on the resulting TSI reconstruction, a revised solar constant value of 1361.1 W/m^2 is obtained, with a standard uncertainty of 0.5 W/m^2. The revised solar constant is ≈5 W/m^2 less than the previous values promulgated in ASTM and ISO standards. A revision of these standards is thus highly recommended.

1. Introduction

The magnitude of the solar output and its variability over various time scales condition virtually all geobiological processes on Earth. Among many other important phenomena, this planet's weather and climate are directly affected by the energy received from the Sun at each instant, and in the long-term. Among the numerous terrestrial energy-related applications that are dependent on the Sun's output, solar power is of course at the forefront. The exploration of space also requires solar power as a reliable energy source for satellites and spacecraft.

The early days of solar radiation research were directly related to the quantification of the solar power output and its variations. This solar output is still usually referred to as the "solar constant" (SC), even though it is now known to actually fluctuate due to solar activity. In 1837, the first acknowledged pioneer, Pouillet, reported measurements with an early type of pyrheliometer and obtained a value of 1230 W/m^2 (after unit conversion using the thermochemical calorie definition, 1 cal = 4.184 J). In the early 1900s, Abbot continued the work of Langley and developed the Smithsonian Institution's Solar Constant Program (1902–1957), aimed at finding a link between sun's cyclical activity and its power output (Hoyt, 1979; Hoyt and Schatten, 1997). Abbot (1911) mentions 13 SC estimates (between 1185 and 2371 W/m^2) that were published between 1837 and 1908. His own estimate at that time was 1340 W/m^2, which is remarkably close to the current observations, despite the large experimental uncertainties that existed then. Based on elaborate measurements from high mountains or balloonsondes, the values he obtained over the years ranged between about 1320 and 1550 W/m^2. These variations were mostly attributed (wrongly for the most part) to solar activity. Hoyt and Schatten (1997) listed 36 SC values that were proposed between 1838 and 1993. A shorter list, covering the period 1940–2004, can be found in Gueymard (2006), with 16 SC values in the range 1322–1429.5 W/m^2. The most recent value, 1366.1 W/m^2 was initially proposed by ASTM (2000), thus updating the previous value of 1353 W/m^2 originally proposed by Thekaekara (ASTM, 1974), and was then confirmed by (Gueymard, 2004; hereafter G04).

To account for the temporal variability in the sun's instantaneous output, it is now termed *total solar irradiance* (TSI). In what follows, the term "solar constant" is used only to describe the long-term *mean value* of TSI. Using spaceborne instruments, the continuous monitoring of TSI has started in 1978 and has shown that TSI was indeed somewhat variable over time, as a consequence of the sun's 27-day rotation cycle and of complex mechanisms behind the 11-year solar cycle (Fröhlich

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and Lean, 2004; Kuhn and Armstrong, 2004). What was referred to as the "solar constant" in the past will be evaluated below by calculating the long-term average TSI at the Earth's top of atmosphere for the average sun-earth distance (1 ua).[2]

As G04 mentioned, a discrepancy existed between the 1366.1 W/m^2 SC value just mentioned and the TSI measurements made with the Total Irradiance Monitor (TIM) radiometer. That instrument had just started collecting data, as part of the Solar Radiation and Climate Experiment (SORCE) mission (http://lasp.colorado.edu/home/sorce/), and was reporting values typically ≈ 5 W/m^2 lower than older instruments in space. Since the publication of G04, a small number of new estimates of SC were proposed, sometimes based on data from new spaceborne instruments. In 2007, ISO Standards 14222 (ISO, 2013) and 21348 (ISO, 2007) recommended a value of 1366 W/m^2, almost identical to ASTM's. ASTM E490 was reapproved in 2014, and ISO 21348 was reapproved in 2015, even though significantly lower SC values had been proposed in the mean time. For instance, Kopp and Lean (2011) suggested a "most probable value" of 1360.8 W/m^2 for the representation of TSI at *solar minimum*, based on a few years of measurement with the SORCE-TIM instrument. Gueymard (2012) used the older data time series from G04 and scaled it to the newer observations from the PREMOS instrument onboard the PICARD satellite, obtaining an SC value of 1361.2 W/m^2. In parallel, Fehlmann et al. (2012) indicated that PREMOS was the best understood and calibrated radiometer of its category ever sent to space. In 2015, the International Astronomical Union (IAU) adopted a resolution suggesting a solar constant value of 1361 W/m^2 (IAU, 2015), based on available measurements during solar cycle 23 only. This value was confirmed by Prša et al. (2016), but may be understood as provisional, since not based on an in-depth study.

The new developments in precision space radiometry that followed the publication of G04 show that the newer radiometer design of TIM removed sources of bias that were impacting the older ones—based on which the 1366.1 W/m^2 value was derived. Even with older radiometer designs, such as that of PREMOS, advanced pre-flight calibration and characterization techniques allowed a substantial decrease in uncertainty. In an effort to improve accuracy in solar or other applications, these developments justify a revision of the standard SC values that were stipulated in ASTM (2000) or ISO (2007, 2013), for instance. Moreover, the solar energy literature still frequently refers to even older (and obsolete) SC determinations, such as 1367 or 1373 W/m^2. This contribution aims at alerting the scientific community involved in terrestrial or space applications about the recent evolution in the observation of TSI, justifying a lower value for SC, and proposing a long-term reconstruction of the TSI time series using the best possible absolute calibration.

2. TSI observations

Following many decades of attempts at estimating SC from terrestrial observatories (e.g., by Abbot) and high-altitude balloons, aircraft or rockets (Thekaekara, 1965, 1973, 1976), a new era started in November 1978 with the launch of Nimbus-7, which allowed the continuous monitoring of TSI with spaceborne radiometers without any interference from atmospheric constituents. During its first nine years of measurement, the mean annual TSI varied between 1370.2 and 1371.3 W/m^2 in good synchronicity with solar activity, which established the reality of this connection (Fox, 2004; Hickey et al., 1988; Willson et al., 1981). In turn, the Earth climate impacts caused by this variability started to be studied extensively (Fröhlich and Lean, 1998; Lean, 2010; NRC, 2012; Schatten and Arking, 1990; Solanki et al., 2013). Spaceborne measurements made from the satellites that followed Nimbus-7 indicated significantly lower TSI values, even under "calm sun" conditions. This was caused mainly by differing absolute calibrations of the radiometers, which prompted the need to reconcile the time series from different platforms, using elaborate corrections and time-dependent scaling factors. This arduous process, which is documented in a number of publications (e.g., Dewitte et al., 2004; Fröhlich, 2004, 2006, 2012a,b; Mekaoui and Dewitte, 2008; Willson, 2014; Willson and Mordvinov, 2003), led to the development of composite time series based on combined TSI observations from different instruments, depending on period and estimated data quality.

In what follows, the PMOD and ACRIM composites are used extensively. (An earlier version of the PMOD composite was used in G04.) The latest versions of the extended PMOD composite,[3] covering the period to 1976-01-11 to 2017-09-20,[4] and of the ACRIM composite,[5] covering the period 1978-11-17 to 2013-09-17, are used here. These two composites differ because they use different observations from different platforms during some periods, and differing reduction processes. Moreover, the latest versions used here include appropriate corrections of about -5 W/m^2 compared to their older versions, in order to compensate for the systematic overestimation of the measurements made with older radiometers, as a result of two sources of error: (i) stray light impacting the radiometer's reading (Kopp and Lean, 2011); and (ii) difference of $\approx 0.3\%$ between the World Radiometric Reference (WRR) used to calibrate older radiometers and the absolute calibration method based on the SI realization of the watt (with cryogenic radiometers) used for the TIM and PREMOS instruments (Fehlmann et al., 2012; Kopp et al., 2012; Walter et al., 2017). In the case of the PMOD composite, the correction process included a downward correction of –0.362%, as explained in its accompanying online documentation.[6] To complement these composites, three recent, single-source time series of measurements made during recent, or still ongoing, missions are added for reference. These are SORCE-TIM (2003-02-25 to 2017-12-31), TCTE-TIM (2013-12-16 to 2017-12-31) and PICARD-PREMOS (2010-07-27 to 2014-02-11). (In the present nomenclature, the satellite name comes first, followed by the instrument acronym.)

A comparison of the latest versions of the PMOD and ACRIM composites is shown in Fig. 1. There are obvious differences between the two time series, most particularly during 1978–79, when ACRIM's TSI appears systematically larger than PMOD's TSI (or vice versa, PMOD appears lower than ACRIM). Another source of concern is their discrepancy during the solar minima between cycles 22 and 23 and cycles 23 and 24, as underlined before (Kopp, 2014). More generally, the differences between the two datasets have been the object of intense debate in the literature (Fröhlich, 2006; Scafetta and Willson, 2014; Willson and Mordvinov, 2003), due to differing views on the radiometers' calibration, stability, degradation, and need for correction. The disagreement also fueled controversy regarding the reality of long-term trends in the solar output and their possible impact on climate change (NRC, 2012; Scafetta, 2013). One of the objectives of the present study is to reconsider these differences from another standpoint and find a way to reconcile the datasets.

Similar to Fig. 1, Fig. 2 shows the temporal evolution of TSI as observed by SORCE-TIM, TCTE-TIM and PICARD-PREMOS. The time series are shorter here, particularly for PREMOS and TCTE-TIM. The differences between them are also typically smaller than in Fig. 1. A comparison between the two composites (PMOD and ACRIM) and SORCE-TIM is shown in Fig. 3 during their common period

[2] The abbreviation to be used for the *astronomical unit* is somewhat confusing: ISO stipulates "ua" whereas the International Astronomical Union (IAU) favors "au", and ASTM reports it as "AU". The ISO nomenclature is used here.

[3] ftp://ftp.pmodwrc.ch/pub/data/irradiance/composite/ext_composite_42_64_1508.dat.

[4] According to the data documentation, the extended version used here contains additional data obtained with a proxy model from 1976-01-11 until 1978-11-16 to prolong the time series so that it starts at the onset of solar cycle 21.

[5] http://www.acrim.com/RESULTS/data/composite/acrim_composite_131130_hdr.txt.

[6] ftp://ftp.pmodwrc.ch/pub/Claus/VIRGO-TSI/VIRGO_Char2Space.pdf.