Jean-Philippe Montillet[1], J.-P Montillet[2], M Haberreiter[2], and E Rozanov[2]

[1]Affiliation not available
[2]Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC)

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Preface to Monitoring the Earth Radiation Budget and its Implication to Climate Simulations: Recent Advances and Discussions

J.-P. Montillet[1], M. Haberreiter[1], E. Rozanov[1]

[1]Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC), Davos, Switzerland

Key Points:

- Preface to the JGR-Atmospheres special section "Monitoring the Earth Radiation Budget and its Implication to Climate Simulations: Recent Advances and Discussions"
- Some introduction to solar irradiance, the Earth's radiation budget and the Earth energy imbalance
- Some discussions on the current state of the solar forcing within climate simulations

Corresponding author: J.-P. Montillet, `jean-philippe.montillet@pmodwrc.ch`

Abstract

This article acts as an introduction to the JGR-Atmospheres special section titled Monitoring the Earth Radiation Budget and its Implication to Climate Simulations: Recent Advances and Discussions. It outlines the major findings of the articles published in the special section as well as discusses ongoing research within the field of research of monitoring the Earth Radiation Budget.

1 Introduction

A high precision and accurate measurement record of the spectrally-integrated solar flux at Earth, i.e., the Total Solar Irradiance (TSI) arriving at ToA and normalized to the distance of 1 Astronomical Unit (AU) is essential for understanding both the energy balance of the Earth's climate system and the impact of TSI variations on decadal and centennial timescales relevant for climate studies. Specifically, these timescales are essential to understand the relative contribution of solar variability to recent estimates of anthropogenic, and future, climate change. Comprehensive reviews of the potential influences of solar variability of climate have been presented in recent years by Solanki et al. (2013), Gray et al. (2016) and Schmutz (2021).

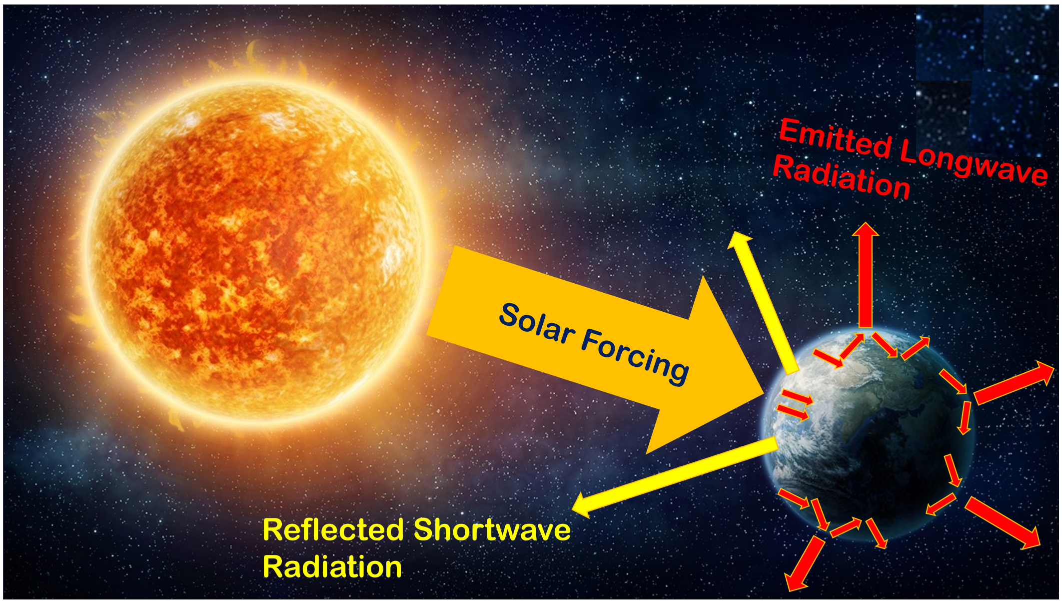

Figure 1: Artistic view of the direct contribution of the Sun's power to the Earth's energy budget.

It has been shown that the Sun is not the main contributor to recent changes in global temperatures (Stocker et al., 2000; Forster et al., 2021). However, modelling studies suggest that solar cycle (about decadal) timescales, and variations over the 90-year Gleissberg cycle and longer changes between grand minima and maxima, have an influence on the climate through modification of the hydrological cycle (Feynman & Ruzmaikin, 2014), ocean circulation (Knudsen et al., 2014), and radiative forcing and global surface temperatures (Egorova et al., 2018; Schmutz, 2021). Compared to recent anthropogenic influences, the effect of solar variation is small (Stocker et al., 2000; Forster et al., 2021). Moreover, there is evidence for a surface response on regional scales to solar cycle variability (Gray et al., 2016), though the magnitude, spatial extent and robustness of the signal are still under consideration.

Global temperature and TSI are linked by the energy equilibrium equation for the Earth system (Schmutz, 2021; Montillet et al., 2022). Climate modelers have defined various scenarios making assumptions and varying the input observations to study the influence of solar activity on climate. As summarized by Schmutz (2021), the derivation of this equation with respect to a variation of the solar irradiance has two terms: a direct forcing term, which can be derived analytically and quantified accurately from the Stefan-Boltzmann law, and a second term, describing indirect influences on the surface temperature. If a small TSI variation should force a large temperature variation, then it has to be the second indirect term that strongly amplifies the effect of the direct forcing. This amplification mechanism has been debated in the scientific community for the past two decades (Shapiro et al., 2011; Egorova et al., 2018; Schmutz, 2021; Montillet et al., 2022), because it will most likely call for a strong modification of the models that describe the Earth's climate response to variations in the solar radiative output. On shorter time scales (e.g., monthly), the existence of a trend (or multiple trends) in the measurements could significantly bias the analysis of solar phenomena (e.g., estimation of a new solar minima) on longer timescales (e.g., yearly). Therefore, it is important to produce robust and reliable TSI observations and composite time series using all the observations available recorded by successive space instruments spanning 4 decades. Climate modelers have defined various scenarios by making assumptions on the long-term variability of total and spectral solar irradiance (Matthes et al., 2017). Available TSI composite datasets serve as important validation of the irradiance reconstruction datasets.

This JGR-Atmospheres special section has been a venue for contributions to shed light on the understanding and modeling of the Sun-Earth climate interaction and the ongoing research work within the Monitoring the Earth Radiation Budget.

2 Total solar irradiance

TSI provides nearly all the energy powering the Earth's climate system. The high-precision absolute radiometry needed to measure TSI is very challenging. To avoid atmospheric effects, such measurements must be obtained by space-born instruments, which adds considerably to the difficulties of calibrating these instruments to the desired accuracy and maintaining the required long-term stability of those calibrations. The technology on board of various spacecrafts has continuously evolved over the past 4 decades to meet these requirements. These measurements are critical inputs to help understand the effects of solar variability on climate. Various space missions have measured the TSI since 1978. Among them the experiments Precision Monitoring of Solar Variability (PREMOS) on the PICARD satellite (2010–2014) (Schmutz et al., 2013), the SORCE/TIM instrument (2003-2020) (Kopp & Lean, 2011), the TSI Calibration Transfer Experiment (TCTE)/TIM (2013-2019), TSIS-1/TIM (2018 to present) (Kopp, 2016) and the Variability of Irradiance and Gravity Oscillations (VIRGO) on the mission Solar and Heliospheric Observatory (SOHO), which started in 1996 and is still operational (Fröhlich et al., 1997; Finsterle et al., 2021). These instruments employ various approaches to track and correct the inevitable degradation of their radiometers (Finsterle et al., 2021).

Following the SORCE/TIM instrument, the Compact Lightweight Absolute RAdiometer (CLARA) (Finsterle et al., 2014; Walter et al., 2017; Walter et al., 2020) onboard the Norwegian NorSat-1 micro satellite also uses 3 cavities. Any of the three cavities can serve as active, reference, or back-up channel in order to monitor the degradation of the active cavity due to long exposure to UV/EUV radiation. The latest generation of TSI instrument is the Davos Absolute Radiometer (DARA) series. The first instrument has been embedded on the Fengyun 3E (FY-3E) spacecraft launched the 4th of July 2021, part of the Joint Total Solar Irradiance Monitor (JTSIM) built by the Changchun Institute of Optics, Fine Mechanics and Physics Chinese Academy of Sciences in Changchun, China (Song et al., 2021). Later in 2024, another instrument will be launched on the PROBA-3 mission operated by the European Space Agency (Montillet et al., 2023). The objective in building an absolute radiometer is to decrease the level of measurement uncertainty by addressing or minimizing the impact of instrumental factors, such as lead heating, diffraction, and scattered light (Suter, 2014). This can be achieved through the calibration of both the basic radiometer properties and the combined effects of these factors at a component-level (instrument characterization) traceable to the International System of Units (SI) to implement the so-called SI 'native scale' (Suter, 2014), or at a system level by end-to-end calibration against an SI-traceable primary-standard cryogenic radiometer to implement an SI cryogenic 'laboratory scale' (Walter et al., 2017). The ultimate goal is to compare the TSI observations recorded by instrument after launch with the nominal TSI value of 1361 W/m^2 as recommended by the IAU 2015 Resolution B3 (Prša et al., 2016).

The nominal TSI value was defined based on the measurements with SORCE/TIM and independently confirmed by the Picard/PREMOS instrument. The PREMOS instrument was the first TSI instrument to be operated on-orbit after end-to-end irradiance calibrations provided by the NIST-traceable ground-based TSI Radiometer Facility (Kopp et al., 2007), and confirmed the new lower irradiance value (Schmutz et al., 2013), as did the subsequent NOAA and NASA (TCTE) launched in 2013. This work is continuously ongoing with the sequel mission TSIS/TIM and the recent launch in July 2021 of the FY3E/JTSIM mission by the Chinese Meteorological Administration with two radiometers (including DARA) (Song et al., 2021).

Timescale variations can be classified in subdaily (minutes to hour), daily to weekly, and yearly to one solar cycle. It is commonly understood that TSI variations on timescales of hours to solar cycle time scales are a combination of sunspot blocking and an intensification due to bright features such as active network, faculae and plage on the solar disk (Haberreiter et al., 2005; Kopp & Lean, 2011; Coddington et al., 2019; Yeo et al., 2017; Lean et al., 2022; Chatzistergos et al., 2023) of which the driver is understood to be the magnetic field (Yeo et al., 2017). Overall, two key approaches to model the solar irradiance have been established. On the one hand the empirical models such as the NRLSSI models (Coddington et al., 2019; Lean et al., 2022) and the EMPIRE model (Yeo et al., 2017) use solar activity proxy data such as the Mg-II index and sunspot blocking indices to account for solar variability. On the other hand, semi-empirical models use solar images and determine the area covered by solar activity features such as network, plage, and sunspots. In addition, the intensity contrast of the solar activity features is determined from synthetic spectra (Haberreiter et al., 2005, 2021; Yeo et al., 2014). Both approaches lead to different trends from solar minimum to minimum, while the overall solar cycle variation is comparable (Matthes et al., 2017). Only a few attempts have been used to forecast solar irradiance, see e.g., Fontenla et al. (2009).

As all space instruments have finite lifetimes and space observations therefore cover limited time intervals, constructing composites is a key aspect to the investigation of TSI over several decades. Merging all available observations is a difficult exercise with both a scientific and a statistical challenge (Dudok de Wit et al., 2017). Several authors (Wilson, 1997; Fröhlich & Lean, 2004; Mekaoui & Dewitte, 2008) produced TSI composite time series by daisy chaining all the available TSI observations, but without including any models of the stochastic noise properties. The first methodology which relied on some knowledge of the underlining noise characteristics was developed by Schöll et al. (2016) and Dudok de Wit et al. (2017) including a data-driven noise model and a multiscale decomposition, and later also applied to spectral irradiance by Haberreiter et al. (2017). In this JGR-Atmospheres special section, Montillet et al. (2022) developed a methodology to further advance the data-driven approach first adopted by Dudok de Wit et al. (2017) based on data fusion, including a stochastic noise model to take into account short and long-term correlations in the observations (See Figure 2).

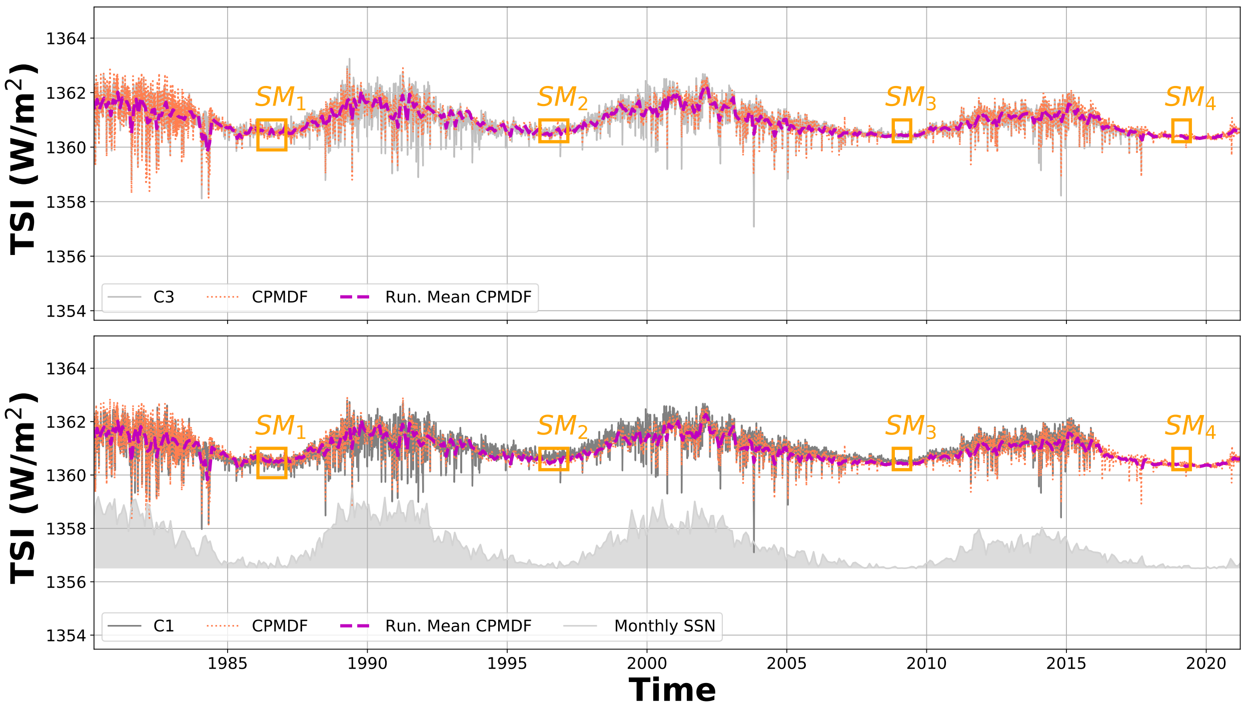

Figure 2: New composite (*CPMDF*, orange) based on merging 41 years of TSI measurements. For comparison, *C3* (Fröhlich, 2006) and *C1* (Dudok de Wit et al., 2017) are also shown (grey line). A 30-day running mean of *CPMDF* is shown as a yellow/purple dashed line. The orange boxes are associated with the solar minima (SM) for each solar cycle described in (Montillet et al., 2022). For context, the monthly sunspot number is also displayed.

3 Determining the Earth Energy Imbalance from Space

The terrestrial energy budget is determined by the net balance between the incoming and outgoing radiation terms at the top of the atmosphere (ToA). On the incoming side it is the TSI, i.e., the spectrally integrated solar radiation at the ToA. The outgoing term is composed of the Outgoing Shortwave Radiation (OSR) i.e., the spatially and spectrally integrated reflected solar radiation, plus the spatially and spectrally integrated Outgoing Longwave Radiation (OLR), i.e., the thermal emission of the Earth's surface and atmosphere. The OSR and OLR build the total outgoing radiation (TOR), which is the spatially and spectrally integrated emission at the ToA. If the incoming and outgoing energies are at equilibrium the Earth's climate does not change, only a relative short-term internal variability, but no long-term warming or cooling of the Earth's system is observed. However, this is not the case for the present-day climate. It has been shown that the net energy, i.e., the Earth Energy Imbalance (EEI), is of the order of 0.5 to 1 Wm^{-2}, for reviews see e.g., Allan et al. (2014); Dewitte and Clerbaux (2017); Wild et al. (2017); Kramer et al. (2021); Forster et al. (2021) and references therein.

There are two key methods to determine EEI. First, there is the approach to measure the all components of the EEI at the ToA by scanning the globe and integrating the solar and thermal outgoing radiation along with the measurement of TSI. This has been started with the Earth Radiation Budget Experiment (Shrestha et al., 2014) on-board the Earth Radiation Budget Satellite (ERBS), and is currently undertaken with the Clouds and the Earth's Radiant Energy System (CERES) mission (Loeb et al., 2018). The second approach uses in-situ measurements of the ocean heat uptake, as it is currently done with the Argo float system (Argo, 2020; Riser et al., 2016), measuring the oceans heat uptake in absolute terms.

While there is some uncertainty on the absolute value of EEI there is indication that it is not constant but increasing. Schuckmann et al. (2020) show that from 2010 – 2018 the value of the EEI is 0.87 ± 0.12 $\mathrm{W/m^{-2}}$ and that it has increased with respect to the time frame of 1972 – 2018, for which they give a value of EEI of 0.47 ± 0.1 $\mathrm{W/m^{-2}}$. This trend (but not the absolute level) had been independently confirmed by Loeb et al. (2021) using CERES observations.

Both, the remote-sensing and in-situ methods, have pros and cons. The challenge of the determination of EEI from space is the absolute calibration of the radiometer and which has not yet been achieved to the required level. The outstanding challenge of the in-situ measurements is to have sufficient coverage of the ocean and land. Here, outstanding achievements have been made in the past (Schuckmann et al., 2020; Hansen et al., 2022). For a robust quantification of the absolute level of EEI an independent validation of the in-situ measurements would be required. One step in that direction is to measure the ERB components, i.e., the TSI, OLR and OSR with a high-precision state-of-the-art SI-traceable absolute radiometer. The CLARA instrument (Finsterle et al., 2014; Walter et al., 2017, 2020) onboard of NorSat-1 currently measures TSI and OLR and can be seen as a demonstration mission towards determining EEI from space.

Recently, (Meftah et al., 2021) presented first measurements of the OLR and OSR with the UVSQ-SAT, launched 24 January, 2021, and shortly after than (Meftah et al., 2022) present a comparison of the ERA5 reanalysis data with the UVSQ-Sat OLR and OSR measurements, as well as OLR and OSR simulations for the follow-on INSPIRESat-7 Cubesat. The monthly mean data show a scatter by up to 20 Wm−2 for the OSR and 30 Wm−2 for the OLR.

As part of this special section, Li et al. (2023) analyze 56 global climate models that participated in CMIP6. Specifically, they compare the regional scales of the ToA, atmospheric and surface energy budgets of with two reference data sets, i.e., the NASA Energy and Water cycle Study (NEWS) and the Clouds and the Earth's Radiant Energy

System (CERES) Energy Balanced and Filled (EBAF) data (Loeb et al., 2018). While improvement of the model performance compared to CMIP5 is found, the authors conclude that substantial deficiencies and spreads are present on the regional scale in the CMIP6 models.

4 Earth Climate simulations

Solar activity variations on different time scales can affect Earth's climate via modulation of the electromagnetic radiation flux in the ultraviolet (UV), visible (VIS), and near-infrared (NIR) spectral regions as well as by precipitating energetic particles of solar, galactic or magnetospheric origin. The response of the climate is realized through different physical and chemical mechanisms (Gray et al., 2010) Electromagnetic radiation in UV, VIS, and NIR can directly affect climate if it reaches the surface (Misios et al., 2016) Short-wave UV radiation is strongly absorbed above the tropopause and can impact tropospheric climate modulating ozone distribution, temperature structure, atmospheric wind field, and atmospheric wave patterns (Mitchell et al., 2015). Energetic electrons and solar protons initiate similar mechanisms of downward solar signal propagation but affect ozone and temperature inside the polar vortex via reactive nitrogen and hydrogen oxides production and transport down to the ozone layer (Rozanov et al., 2012). Galactic cosmic rays and extreme energetic solar protons have the potential to modulate chemical processes, aerosol composition, atmospheric conductivity, and global electric circuit with possible implications for the cloud fields and climate (Golubenko et al., 2020; Tinsley, 2022). This special section is aimed at the discussion of all these problems.

During the last decade there has been a substantial increase in our understanding of these processes. The climate efficacy of weakly absorbed solar electromagnetic radiation is limited by the magnitude of the TSI variability (see section 2). It was pointed out by several groups that the upper limit of the TSI changes cannot exceed 2 W/m^{-2} (Yeo et al., 2020; Lockwood & Ball, 2021) which cannot explain observed warming pattern in the Early Twenties Century (Egorova et al., 2018) and some evidences of solar related climate change obtained from paleo reconstructions (Schmutz, 2021). The application of very conservative solar irradiance treatment for the solar forcing calculations for the case with hypothetical drop of the solar magnetic activity (Matthes et al., 2017) led to low (up to 0.75 W/m^{-2}) magnitude of the future TSI decline. The influence of this scenario on the Earth climate and ozone layer has been evaluated by (Sedlacek et al., 2023). They concluded that the most changes at the surface and higher altitudes during 2080-2100 relative to the reference case are not significant. Even for the solar activity maxima, when the difference in solar irradiance is the largest, a noticeable climate response was not found.

The influence of short-wave UV radiation and energetic particles on the middle atmospheric is visible in observation data and model simulations (Szelag et al., 2022). The recent publications (Edvartsen & et al., 2023) confirmed previously suggested dependence of the stratospheric forcing (either from solar UV irradiance or different energetic particles) efficiency on the state of the polar vortex. However, the influence of stratospheric forcing on the Earth's climate via top-down mechanism is established only on regional and seasonal/monthly scales, which makes these factors potentially important to increase the quality of seasonal forecast (Drews et al., 2022), but does not help to explain long term global climate changes.

Taking account new upper limit of TSI variability and localized character of the stratospheric (solar UV and energetic particles) forcing we think that the major efforts should be undertaken on the additional forcing related to galactic cosmic rays and extreme energetic solar protons events, which has a potential to modulate cloud fields and climate via different mechanisms (Tinsley, 2022; Harrison & Lockwood, 2020). This topic is not covered in this JGR-Atmospheres special section, but we hope more attention will be paid to this problem in the nearest future.

5 Conclusions

The special section "Monitoring the Earth Radiation Budget and its Implication to Climate Simulations: Recent Advances and Discussions" has proposed to review global climate variability and solar forcing observations. We have emphasized the recent technological improvements of the satellite-based absolute radiometers recording the solar irradiance and which started to be used to also observe the terrestrial emission. This is a first step towards inferring EEI from space. Measuring the EEI allows us to better analyse climate changes and constrain climate models. Climate modelers have defined various scenarios making assumptions using the TSI composite time series to study the influence of solar activity on climate. It should include reconstructions of the past where simulated solar activity is tested against historical grand minima (e.g., Maunder, Dalton minima). This special section has welcomed contributions in line with the framework defined by the International Panel on Climate Change (IPCC) which motivates research work on future scenarios considering various variables (e.g., probability to reach new grand minimum, return to conditions similar as past historical minima) and their impact on climate . We hope that this research will contribute to spur different ways (including the exploration of geoengineering solutions) to mitigate climate change by modelling more precisely the Sun-Earth interaction and by simulating the variations of some important parameters (e.g., TSI, CO_2 concentration). Certainly, the reduction of greenhouse gases is the most effective way to slow down or stop the increase of CO_2 concentration in the atmosphere. Another type of approach, geoengineering, involves deliberate interventions in the Earth's natural systems to counteract the effects of greenhouse gases. For instance, Schaller et al. (2013) investigate a scenario where the rise in atmospheric CO_2 levels is balanced by reducing downwelling solar radiation through aerosols emitted to the atmosphere through geoengineering techniques, which could potentially mitigate the climate warming in the long-run (National Research Council, 2015). These potential solutions cannot be a substitute for reducing greenhouse gas emissions, which remains the most important and effective way to mitigate climate change. Geoengineering should be considered as a complementary approach to emissions reductions, rather than a replacement (Ho, 2023).

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