A Solar Irradiance Climate Data Record

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**Abstract**: We present a new climate data record for total solar irradiance and solar spectral irradiance between 1610 and present-day with associated wavelength and time dependent uncertainties, and quarterly updates. The data record, which is part of the National Oceanographic and Atmospheric Administration’s (NOAA) Climate Data Record (CDR) Program, provides a robust, sustainable, and scientifically defensible record of solar irradiance that is of sufficient length, consistency, and continuity for use in studies of climate variability and climate change on multiple time scales, and for broad user groups spanning climate modeling, remote sensing, natural resource and renewable energy industries. The data record, jointly developed by the University of Colorado Boulder’s Laboratory for Atmospheric and Space Physics (LASP) and the Naval Research Laboratory (NRL), is constructed from a two-component solar irradiance model that determines the changes from quiet Sun conditions when facular brightening and sunspot darkening features are present on the solar disk, where the magnitude of the delta changes in irradiance are determined from linear regression of proxy indices- the Mg II index and sunspot area, respectively- against the approximately decade-long solar irradiance measurements of the SOlar Radiation and Climate Experiment (SORCE). To promote long-term data usage and sharing for a broad range of user groups, the source code, the dataset itself, and supporting documentation are archived at NOAA’s National Climatic Data Center (NCDC). The dataset is also available through LASP’s Interactive Solar Irradiance Data Center (LISIRD) for user-specified time periods and spectral ranges of interest.

**The Role of the Sun in Climate**

The Sun is the dominant energy source for the Earth, establishing the structure of its surface and atmosphere, defining its external environment, and powering the complex and coupled dynamical, chemical, and land-atmosphere interactions that define its terrestrial habitat. Natural solar variability exhibits time and wavelength dependencies, spanning seconds to minutes and gamma rays (10-10 m) through radio waves (> 100 m).

Put in here how magnetic structures on sun, which can be represented by proxy indicators, cause the temporal variability that is observed.

Because of selective absorption and scattering process in Earth’s atmosphere, the climate system responds in distinct ways to solar energy inputs in different spectral regions. For example, solar radiation at wavelengths shortward of 315 nm is completely absorbed in Earth’s atmosphere and is critical for the formation and destruction of ozone as well as middle atmosphere dynamics and temperature. Longer wavelength visible and near-infrared radiation penetrates to the lower atmosphere and to the Earth’s surface, where roughly half of the globally-averaged incoming solar radiation is absorbed (ref. Fasullo/Trenberth; Gray paper). The role of solar irradiance in Earth’s radiation budget – the balance of absorbed solar radiation to emitted longwave radiation- establishes its position as an *essential climate variable* (GCOS, ref.) whose long-term measurement is necessary for the understanding of past and present climate and the projection of future climate (Bojinsky, BAMS sept, 2014 ref; Holdren, 2014).

Determining the Sun’s role in climate variability and change requires uninterrupted time series of total solar irradiance (TSI) and spectral solar irradiance (SSI) that are of sufficient length, consistency and continuity to be useful for evaluating the natural variability in solar irradiance and for providing the baseline foundation used for evaluating all other forcings of climate change against (Kopp and Lean Report B ref.). The National Oceanographic and Atmospheric Administration (NOAA) Climate Data Record (CDR) program defines a climate data record as the sustained and routine generation of products using observational records that span decades to centuries and assigns a “maturity matrix” level to quantify the reliability of a CDR for use in decision making across many socioeconomic sectors (Bates EOS article). Because the extant space-age observations of TSI and SSI (36 years for TSI, or approximately 3 solar cycles, and less for SSI) lacks the length and, with respect to SSI, the stability to resolve solar variability over multiple 11-year solar activity cycles, solar irradiance models are needed to extend the measurement record and provide the constraints needed for a solar irradiance climate data record.

In this article, we define the solar irradiance climate data record - consisting of extant solar irradiance data sets and a solar irradiance model - which exemplifies community best practices in a robust, sustainable, and scientifically defensible record of solar irradiance. The discussions will also touch on the level of the solar irradiance CDR in each of the six thematic areas of the maturity matrix:

* *Code stability*
* *Metadata and Quality Assurance*
* *Documentation (source code, dataset, supporting documentation)*
* *Validation*
* *Public Availability*
* *Utility for a broad user group*

**Solar Irradiance Datasets**

The solar irradiance model, NRLTSI2 and NRLSSI2, calculates solar total and spectral irradiance, respectively, using an algorithm based on direct solar observations made by the Total Irradiance Monitor (TIM), the SOLar STellar Irradiance Comparison Experiment (SOLSTICE) and the Spectral Irradiance Monitor (SIM) instruments on the NASA satellite, SOlar Radiation and Climate Experiment (SORCE), launched in 2003 and continuing to make daily measurements. The TIM instrument measures the total, spectrally integrated (i.e., bolometric), solar irradiance [Kopp et al solar physics paper] and the SOLSTICE and SIM measurements [Harder, McClintock Rottman solar physics papers] measure irradiance over a spectral range of 115 to 2400 nm at variable spectral resolution[[1]](#footnote-1). The total solar irradiance record, measured since 1978, is currently measured by the SORCE mission.

A new observational dataset of TSI began in late 2013 with the launch of the Joint Polar Satellite System (JPSS) Total solar irradiance Calibration Transfer Experiment (TCTE), on the U. S. Air Force STPSat-3 satellite. The TCTE instrument is a nearly identical copy (i.e. a ground “witness”) of the SORCE TIM instrument and repurposed for quick integration on STPSat-3. The necessity for a quick turn around developed after the Glory mission, containing a next-generation TIM instrument, failed on launch in 2011 putting the long term record of total solar irradiance in jeopardy as the SORCE mission extended far past its design life of 5 years and the follow on mission, the Total and Spectral Solar Irradiance Sensor (TSIS), now scheduled for launch in 2017, experienced a series of launch delays related to changes in programmatic structuring and spacecraft appropriations. The SORCE satellite, whose degrading and extremely limited battery life has long been a source of apprehension for the solar irradiance community, has been operating since February 2014 in a “hybrid” mode of operations where the satellite is placed in safe-hold each orbital eclipse and real-time “wake up” commands are sent from NASA’s Tracking and Data Relay Satellite System (TDRSS) upon exiting each orbital eclipse orbital for measurement collection. Further flight software investigations are pursuing solutions whereby the SORCE mission could potentially survive the loss of an additional battery cell that would put the spacecraft into an under voltage condition. While this would reduce the possibility of a gap in the measurement record between SORCE and TSIS, overlap between the missions is far from a certainty. TCTE, a 1-year mission with an 18-month goal, has met the comprehensive success criteria established by Kopp and Lean (2013) for a 1-year overlap with SORCE TIM, but is unlikely to provide overlap with the future TSIS. Kopp and Lean [2013; study B report] have outlined strategies to assess and mitigate a gap in the long term solar irradiance record.

In addition to measurement continuity, measurement accuracy and precision are also essential. Table 1 outlines measurement requirements for a climate data record of total and spectral solar irradiance. For solar irradiance, variations of less than 0.1% per decade are typical of the kinds of signals that must be extracted from “noisy” time-series measurements. The next-generation TSIS TIM and SIM instruments have been designed, built, and calibrated to meet these requirements. For TSIS TIM, engineering advances in optical and electrical sensors and end-to-end validation of the radiometers in the TSI Radiometer Facility (TRF) contribute to an approximate 3-fold improvement in measurement accuracy compared to SORCE TIM. For TSIS SIM, improvements have been made in the electronic noise of the detectors thereby improving measurement precision, the inclusion of a third-channel improves measurement stability by reducing uncertainties in the correction of degrading prism transmission due to exposure to harsh solar radiation, and pre-launch calibration using the Spectral Radiometer Facility (SRF) improves absolute accuracy. The novel TRF and SRF facilities at the Laboratory for Atmospheric and Space Physics establish ground-based irradiance reference standards and are the only calibration facilities in the world capable of characterizing TSI and SSI instruments at power levels and vacuum conditions experienced on flight. The irradiance standards are achieved through custom-built cryogenic radiometers compared against a National Institute of Standards and Technology (NIST) optical power standard with Système International d’Unités (SI) traceability.

Table 1: CDR Requirements Established for the TSIS TIM and SIM

|  |  |  |
| --- | --- | --- |
| **Parameter** | **TSI CDR Requirement** | **SSI CDR Requirement** |
| Absolute Accuracy | 0.01% | 0.2% |
| Stability | 0.001% / year | 0.05% / year (λ < 400 nm)  0.01% / year (λ > 400 nm |
| Noise | 0.001% | 0.02% |

The SORCE instruments pre-dated the SRF and TRF facilities. The knowledge to be gained from improved accuracy and stability in the TSIS instruments will be transferred *back* in time to the SORCE instruments. The TCTE TIM, which does not meet the CDR requirement for absolute accuracy established in Table 1, does establish continuity with the SORCE TIM record through its 1+ year overlap and, because it has been calibrated in the TRF facility, supplies the connection to the future TSIS TIM albeit with added uncertainty to be attributed to any gap in the measurement data record. Regrettably, there is not an interim spectral irradiance instrument that can play the role SSI record that TCTE plays for the TSI record.

While the algorithm used to calculate TSI and SSI for the Solar Irradiance Climate Data Record uses, as a starting point, SORCE observations, it will be augmented in the future by higher accuracy TSIS observations. The baseline irradiance values and the algorithm coefficients used to calculate the irradiance modulation with time are not expected to change on time scales shorter than a few years, which is the time frame over which new solar irradiance information can be expected from the TSIS measurements.

The extant space-age observations of TSI is 36 years and SSI is 10 years. For climate studies, solar variability needs to be understood over multiple 11-year solar activity cycles. In particular, SSI observations lack the length, and stability, to achieve this goal. Hence, solar irradiance models are needed to extend the measurement record and provide the constraints for a solar irradiance climate data record.

Go into more detail? Further Instrument correction/calibration descriptions?

**Irradiance Variability Model**

The NRLTSI2 and NRLSSI2 model calculates values of the total irradiance and the solar spectral irradiance in 3,785 wavelength bins of variable width spanning 115.5 to 99975 nm when supplied with two inputs; the facular brightening and sunspot darkening indices, each of which varies with time. The facular and sunspot influences on solar irradiance are calculated in irradiance units by applying scaling coefficients to the input facular and sunspot indices, and the resultant irradiance increments are then applied to adjust the specified baseline total irradiance and spectral irradiance which indicate the “quiet” sun (add refs).

The magnitude of the delta changes in irradiance are determined from linear regression of proxy indices of facular brightening and sunspot darkening- the Mg II index and sunspot area, respectively- against the SORCE (and TCTE) TSI and SSI irradiance measurements. As such, while the linear scaling coefficients are dependent upon the measurement record, they are not expected to change on time scales shorter than a few years and are “constant” (fixed). The choice of “quiet” (invariant) Sun is also based on SORCE measurements from a time period during solar minimum conditions when the solar disk was free of both sunspots and faculae. For TSI, this reference value is 1360.45 Wm-2 and is based on SORCE TIM measurements (Kopp and Lean, 2011). For SSI, the reference spectrum is obtained as following: For wavelengths less than 300 nm, the spectrum is exactly that of the Whole Heliosphere Interval (WHI) (ref) SSI reference spectrum garnered from SORCE SIM measurements between March 20, 2008 and April 16, 2008. For wavelengths between 300 nm and 1000 nm, the spectral shape is constrained to that of the WHI, but with the higher spectral resolution of the SOLar SPECtrum (SOLSPEC) instrument measuring spectral absolute irradiance from the COLUMBUS laboratory of the International Space Station (ref. Thullier paper); the SOLSPEC, being a grating spectrometer has higher spectral resolution compared to the Fery prism spectrometer of the SORCE SIM over this wavelength range (refs). Finally, for wavelengths longer than 1000 nm, the WHI spectrum is scaled to make the integral of the quiet sun reference spectrum equal to the adopted quiet sun TSI value from TIM observations. All adjustments to the adopted quiet sun reference spectrum used in the NRLSSI2 model are within the absolute uncertainty of the measurements.

Future changes to scaling coefficients or adopted quiet Sun values would be reflected by an updated model version number (see Section Deliverables).

An additional third component is calculated to estimate the contribution of an assumed long-term facular component speculated to produce secular irradiance change underlying the solar activity cycle on historical time scales (prior to 1950), since 1615, including during the Maunder Minimum of anomalously low solar activity.

* Algorithm Overview – version 2 description
* Processing Outline
* Mg II and USAF sunspot area sources
* Model parameter characteristics –spot and facular contrasts
* Ancillary Data characteristics – Quiet sun, bolometric and spectrally dependent coefficients, beta angle
* Outline Differences from Version 1 model
* Reference more detailed comparison validation in second paper
* Provide web addresses for sources on input data

**Uncertainty Analysis**

**Results and Validation**

**Deliverables**

**Operational Implementation**

**User Applications**

**Future Outlook**

**Conclusions**

**Acknowledgements**

**References**

Holdren, J.P., 2014, National Plan for Civil Earth Observations, 62 pp. Natl. Sci. and Technol. Counc., Washington, D.C. [ Available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/national\_plan\_for\_civil\_earth\_observations\_-\_july\_2014.pdf.]

1. The SORCE Level 3 data is available online at <http://lasp.colorado.edu/home/sorce/data/>. The NRLTSI2 and NRLSSI2 model utilizes TIM Version 13, and combined SOLSTICE/SIM Version 13/21 data. [↑](#footnote-ref-1)