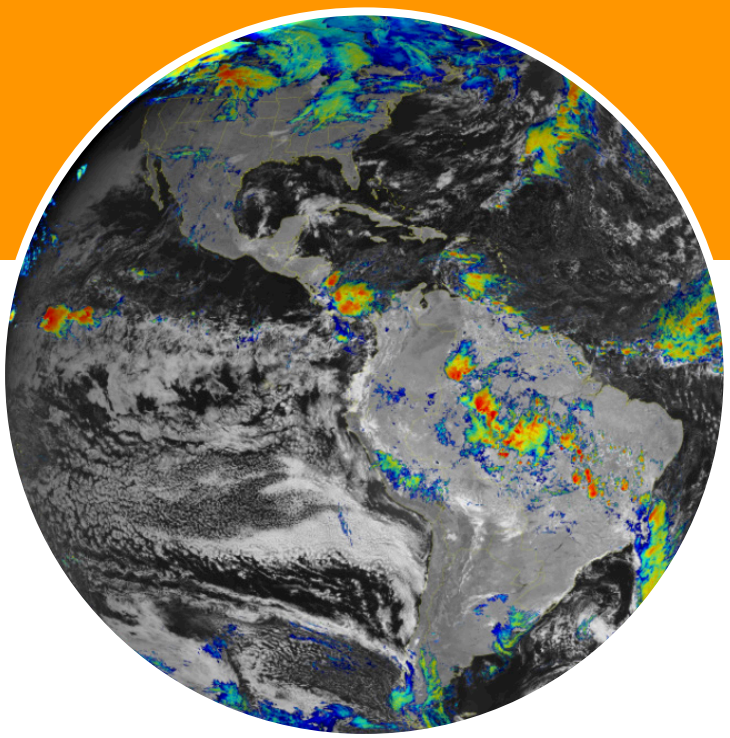
Solar Irradiance Specification for Attribution of Natural Earth-system Variability



SUMMARY

Key Points

- Solar irradiance variability drives natural Earth-system change on time scales from months to millennia
- The natural Earth-system response of fundamental climate parameters to solar irradiance variability has been identified in statistical analyses of observations and in physical climate model simulations
- The reliable detection and attribution of natural Earth-system variability is therefore key to isolating anthropogenic-drive change

Service

- Energy
- Protocol monitoring

End users

- Government agencies
- Industry
- Policymakers
- Researchers

Intermediate User(s)

- Governmental assessments
- Industry
- Research institutes
- Academia

Application(s)

- Solar irradiance is a fundamental variable for specifying Earth's radiation budget, the balance between the incoming solar energy and the energy that Earth returns to space via shortwave scattering and longwave emission.
- Changes in Earth's energy balance drive the Earth-system to a new equilibrium state causing, among other things, a different climate.
- The incoming solar irradiance and its variability must be specified for the attribution of natural Earth-system variability, which occurs concurrently with anthropogenic change. In addition to ongoing national and international assessments of climate change and monitoring ozone layer recovery, applications dependent on Earth's energy balance include renewable energy research, satellite-, air-, and ground-based remote sensing, satellite calibration and inter-calibration, atmospheric chemistry and dynamics modeling, and regional and global climate modeling.

Essential Climate Variables
—Atmosphere

- Earth Radiation Budget

Models

Version 2 of the Naval Research Laboratory (NRL) total solar irradiance (TSI) and solar spectral irradiance (SSI) variability models, referred to as NRLTSI2 and NRLSSI2.

Climate Data Records

Total Solar Irradiance: http://doi.org/10.7289/V55B00C1. It is listed in the ECV Inventory, RecordID is 10552.

Solar Spectral Irradiance: http://doi.org/10.7289/V51J97P6. It is listed in the ECV Inventory, RecordID is 10550.

Agencies

- Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder

Satellite Observations

- NASA SORCE, NASA TSIS-1

Sustainability

Operational solar irradiance TSI and SSI CDR daily- and monthly- products are available from 1882 to the present day and annual irradiances are available from 1610 to present day. Preliminary updates of the records are provided quarterly and replaced with final files at year end. Sustainability depends on the ongoing availability of the NRL models' input facular and sunspot proxies. In the event that one of the two input indices is unavailable, the CDR may be specified by including direct observations of TSI. An observational composite record of TSI is also part of the CDR and is updated quarterly; its sustainability depends on ongoing space-based solar irradiance monitoring, such as currently undertaken by TSIS-1.

DESCRIPTION

Solar irradiance is Earth's dominant energy source and its variability is a primary driver of natural Earth-system change on times scales from months to millennia (Ramaswamy et al., 2018). A balance between incoming, primarily visible-wavelength, solar radiation and outgoing infrared terrestrial radiation establishes Earth's surface temperature and the radiative, chemical and dynamical state of its atmosphere. As recently as fifty years ago the total solar irradiance was referred to as the solar "constant" but forty years of space-based solar irradiance monitoring established unequivocal variability on multiple timescales, including a dominant 11-year cycle, shown in Figure 1. Recognizing the broad need for reliable specification of solar irradiance variability in support of Earth science applications, especially climate change detection and attribution, in 2015 NOAA implemented the Total Solar Irradiance and Solar Spectral Irradiance Climate Data Records (Coddington et al., 2016).

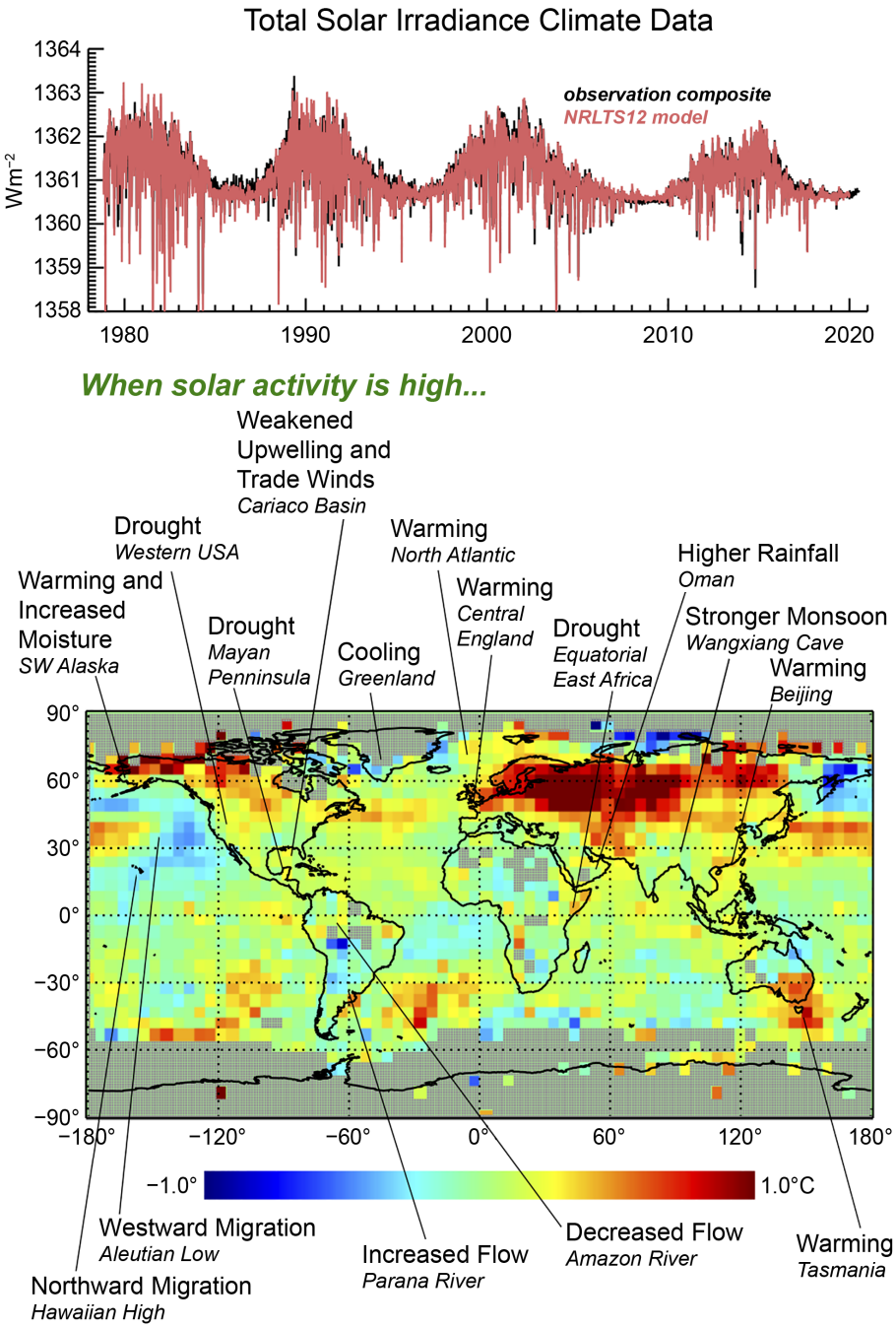


Figure 1. The total solar irradiance space-based observational record has a prominent 11-year cycle which the NOAA CDR model closely captures (upper panel). Regional surface temperature responses to 11-year solar cycle forcing (lower panel) are distinctly inhomogeneous, and consistent with extensive site-specific evidence linking climate change and solar variability.

Multiple empirical associations and physical climate model simulations indicate that solar irradiance variability impacts fundamental climate parameters. Figure 1 shows regional surface temperature responses to the 11-year solar irradiance cycle, statistically extracted from contemporary observations (Lean, 2017). The inhomogeneous response pattern, which differs markedly from that of the received solar radiation itself, arises from dynamical responses to the solar radiative forcing that alter circulation patterns such as the transport of heat from the Equator to the Poles. Multiple site-specific paleoclimate records, also shown in Figure 1, are consistent with the surface temperature response pattern.

The Earth reflects 30% of incoming solar irradiance; the remaining 70% is redistributed and absorbed by atmospheric and terrestrial surfaces process that are strongly wavelength-dependent (Loeb et al., 2009). For example, atmospheric absorption of solar ultraviolet (UV) radiation at wavelengths less than~310 nm creates the ozone layer and establishes the radiative, chemical and dynamical state of the stratosphere. Solar UV irradiance varies an order of magnitude more than does the visible radiation that penetrates to the lower atmosphere and surface. 11-year cyclic changes in solar UV irradiance produce corresponding cycles in total atmospheric ozone which Figure 2 shows are comparable in magnitude to the anthropogenic influences of hydrofluorocarbons and greenhouse gases in the recent past (Lean, 2017). As solar radiation at visible and longer wavelengths transits the Earth's atmosphere, wavelength-dependent processes alter the solar energy at a given height in the atmosphere and at the Earth's surface. Consequently, the spectrum of downwelling shortwave radiation at Earth's surface differs markedly from that of the solar irradiance at the top of the atmosphere (TOA, Figure 3).

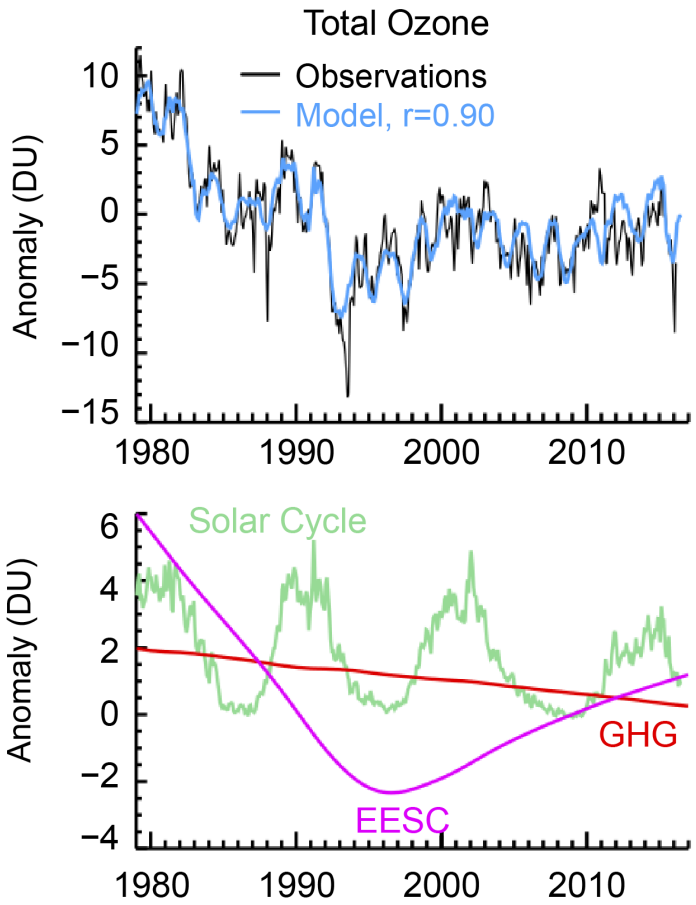


Figure 2. (top) Observed and modeled stratospheric global total ozone anomalies in Dobson units (DU) and (bottom) the amount of the anomaly explained by simultaneous (i.e., with no lag) ultraviolet solar irradiance variability, changing greenhouse gases (GHG) and equivalent effective stratospheric chlorine concentrations (EESC). The model also includes lagged El Nino Southern Oscillation, Quasi Biennial Oscillation and volcanic aerosol components (not shown), with all lags chosen to maximize the observed variance that the model explains.

Heated by incoming solar radiation, the Earth-system then emits longwave, thermal energy. The balance – or imbalance - between the fraction of incoming solar irradiance absorbed by the Earth-system and the total outgoing thermal energy defines Earth's radiation budget (Loeb et al., 2009). Present-day Earth energy imbalance is estimated as 0.6 Watts m^2 with an uncertainty of similar magnitude (Stephens et al., 2012). As a fundamental component of Earth's radiation budget, the Solar Irradiance Climate Data Record supports a wide and comprehensive range of Earth Science uses in pursuit of the detection and attribution of natural Earth-system variability. Recently cited examples include attribution of recent climate change (Lean, 2018), inputs to Earth-system models (Giorgetta et al., 2018; Hogan & Bozzo, 2018; Kelley et al., 2020), IPCC assessments and climate change (Hansen et al., 2017), interpretation of paleo precipitation records (Scroxton et al., 2017) and ozone variability (Chipperfield et al., 2018; Polvani et al., 2017), solar energy technology and production (Ahmed et al., 2019) and urban planning (Wootton-Beard et al., 2016). Specifically, it is crucial for determining the efficacy of the Montreal protocol (WMO, 2015) to ensure that an ozone increase caused by the solar ultraviolet irradiance cycle not be mistaken for ozone's recovery from ozone-depleting gases.

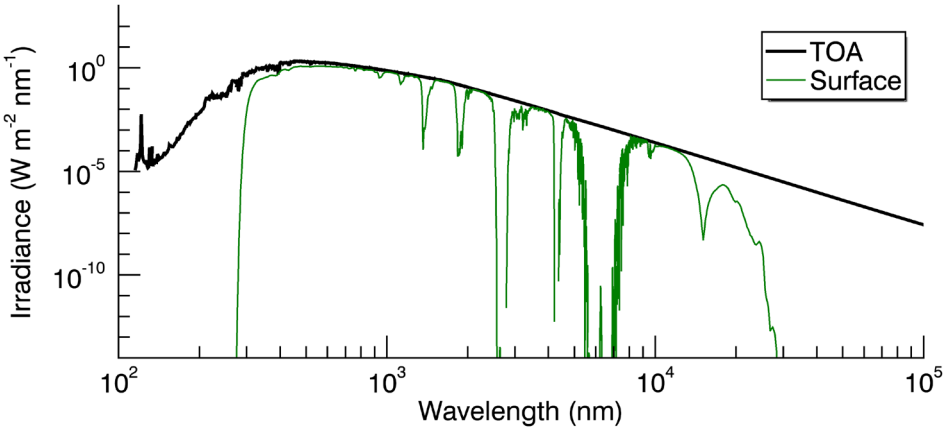


Figure 3. The solar spectral irradiance at the top of Earth's atmosphere (TOA) and the downwelling shortwave irradiance at the surface, on a log-log scale. The surface downwelling shortwave irradiance is computed using the MODerate resolution atmospheric TRANsmission (MODTRAN5) radiative transfer code.

Background: Origins of Solar Irradiance Variability; the Sun's Magnetic Cycle

The Sun's radiative output varies in response to the occurrence of magnetic features such as bright faculae and dark sunspots that alter the emission of radiation from its surface and atmosphere. A subsurface dynamo drives solar magnetic activity cycles that alter the number, size and distribution of these features. At any given time, solar irradiance is the net of the competing effects of irradiance enhancements in bright faculae and reductions in dark sunspots. At most wavelengths, the irradiance enhancement from faculae dominates the reduction from sunspots over the course of the 11-year solar cycle, causing total solar irradiance and ultraviolet and visible solar spectral irradiance (SSI) to increase during solar cycle maxima. The magnitude of solar irradiance variability during the solar cycle depends strongly on wavelength, with larger, multiple percent changes in the UV compared with of order a tenth of a percent at visible wavelengths and for total solar irradiance (TSI) (Coddington et al., 2016; 2019; Lean et al., 2020).

Current understanding of TSI relies on a 43-year satellite record and, for SSI between 200 nm and 2400 nm, a 18-year satellite record. The space-era observations lack, however, the length and broad spectral coverage to characterize true solar variability over the multiple solar activity cycles that comprise the Sun's natural forcing of the Earth-system and climate. Therefore, without exception, solar irradiance variability models are integral in standardizing solar irradiance observations into long, homogeneous records from daily to millennial timescales and from 115 nm to 100 microns.

The NOAA/NCEI Solar Irradiance Climate Data Record (CDR) uses Version 2 of the Naval Research Laboratory models of total and spectral solar irradiance (NRLTSI2 and NRLSSI2) to specify the changes in solar irradiance that occur with changes in solar magnetic activity. The modeled irradiances are computed by relating changes in observed facular and sunspot indices to an equivalent irradiance change. Multiple linear regression of the proxy indices with observations of TSI and SSI prior to 2015 quantify these relationships and comparisons with subsequent observations validate the models' performance. The NOAA Solar Irradiance CDR extends prior to the spacecraft era as the models estimate solar irradiance using proxy records of solar activity that span longer time periods, such as sunspot numbers and cosmogenic isotopes archived in ice cores and tree rings (Figure 4).

Attribution of natural Earth-system variability generally proceeds either by inputting the Solar Irradiance CDR to physical models that seek to simulate the resultant changes in geophysical parameters or by using statistical analyses in which the Solar Irradiance and selected geophysical CDRs are numerically examined for their common signatures. The two different approaches typically yield somewhat different spatial patterns of the responses of quantities such as surface temperature and ozone to changing solar irradiance (e.g., Ramaswamy et al., 2019). Reconciliation of the two different approaches promises to advance understanding of the variable Earth-system but for this to occur will likely require guidance beyond individual research endeavors.

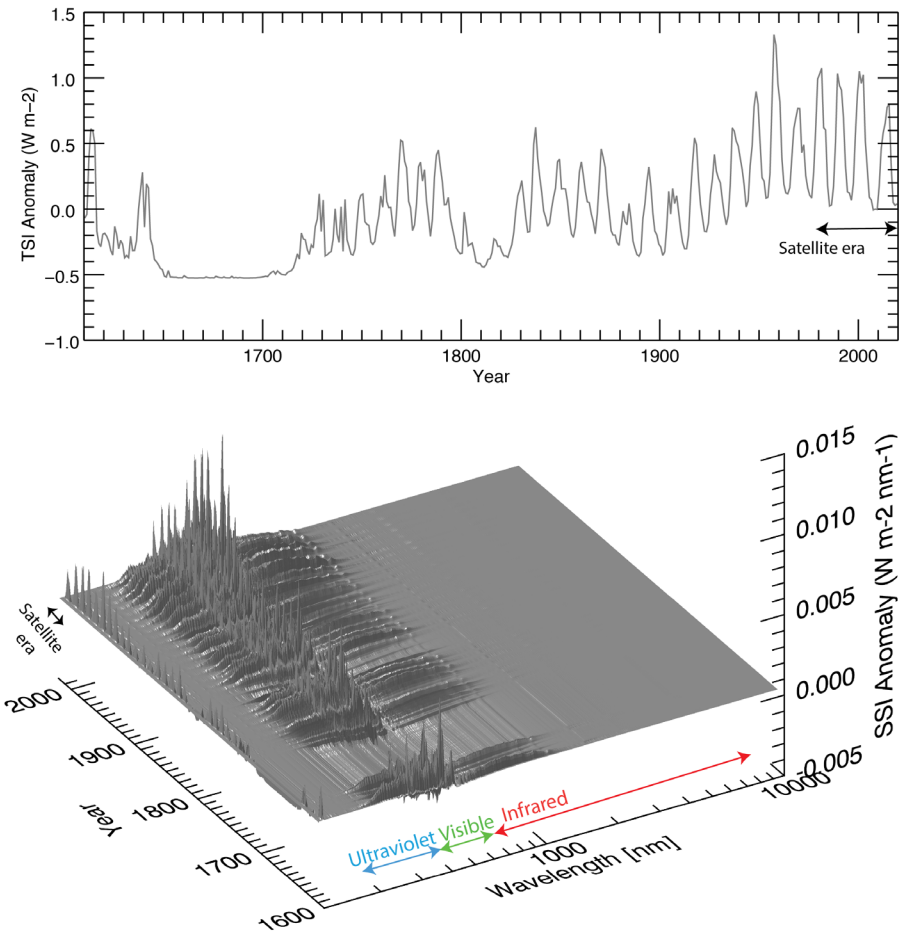
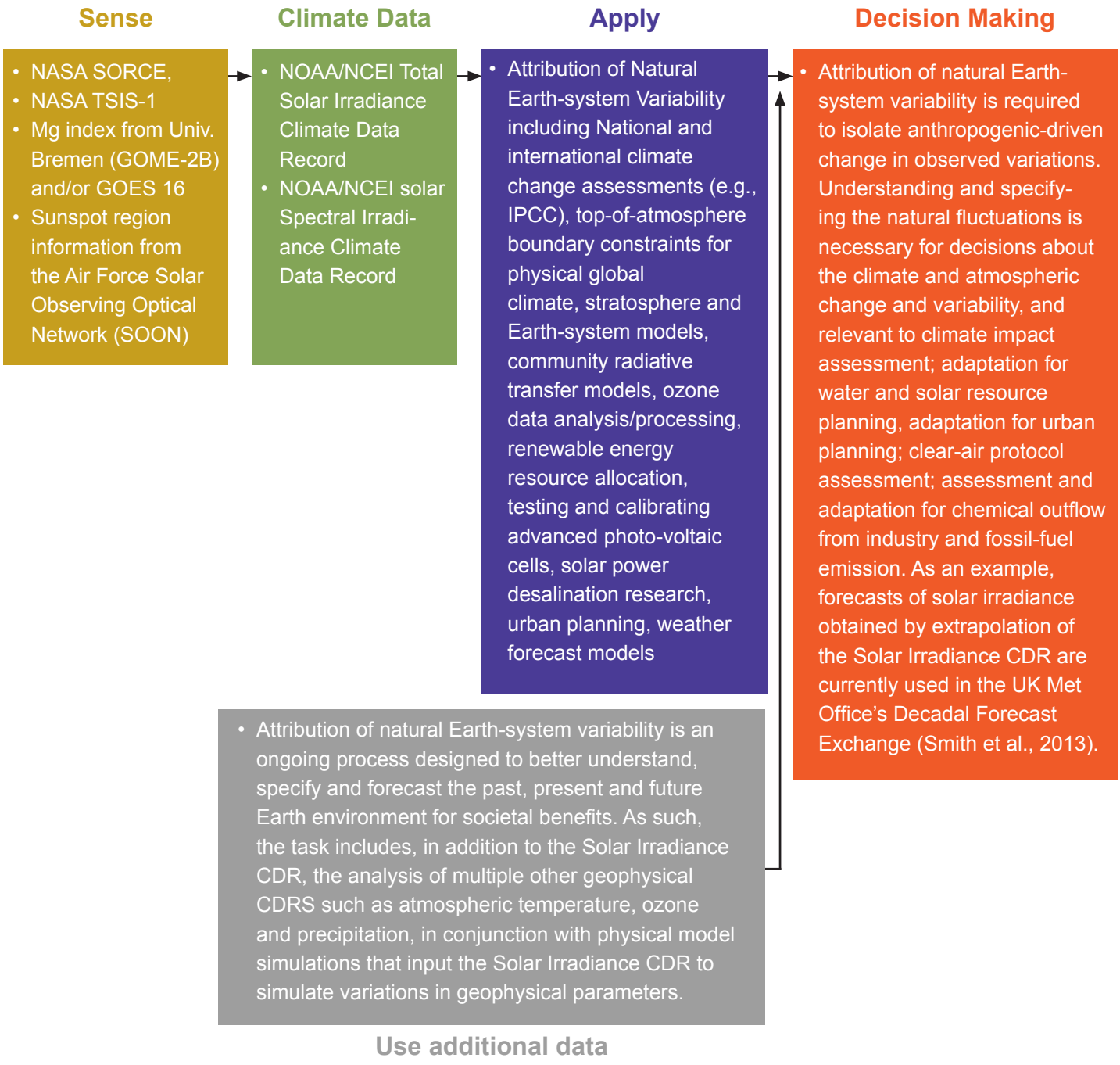


Figure 4. Yearly-averaged TSI anomalies (upper panel) and SSI anomalies (lower panel) spanning 1610 through the present day of the NOAA/NCEI Solar Irradiance Climate Data Record. The anomalies are computed as the TSI and SSI difference from the July, 2008 time period of minimum solar activity.

INFORMATION FLOW



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