2020 Sun-Climate Symposium
"What is the Quiet Sun and What are the Subsequent Climate Implications"

Welcome/Introduction – TSIS & SORCE Status Overview

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The theme of the 2018 Sun-Climate Symposium was *The State of the TSI and SSI Climate Records at the Junction of the SORCE and TSIS Missions*. At the meeting we symbolized the connection and continuity between SORCE and TSIS with a relay baton being passed from SORCE to TSIS. It is almost two years since that meeting and SORCE has steadfastly refused to relinquish its grip on the baton. Despite a recurrence of battery problems that have plagued SORCE for years, initially triggering an acceleration of the SORCE decommissioning plan, NASA decided to extend SORCE operations first into January and then February, 2020, based solely upon the compelling science that SORCE continues to provide.

As planned, the Total Solar Irradiance Calibration Transfer Experiment (TCTE) ended on June 30, 2019, acquiring measurements of total solar irradiance (TSI) for five and a half years. TCTE met its primary mission requirement to ensure continuity of what is now a 41-year long TSI climate data record, confirming the TSI value of 1361 W/m^2.

As TCTE has finished its journey, linking the SORCE TSI calibration scale with TSIS-1, and SORCE looks to conclude its historic mission next month, TSIS-1 continues to produce high quality solar irradiance data on its perch aboard the International Space Station. The TSIS-1 Total Irradiance Monitor (TIM) has provided further validation of the SORCE and TCTE calibration scales. Meanwhile, the TSIS-1 Spectral Irradiance Monitor (SIM) has reduced uncertainties from SORCE SIM by approximately one order of magnitude in the visible and even more in the near-infrared. TSIS-1 is nearing the end of the second year of a 5-year prime mission. Preparations for TSIS-2 have already begun, with a launch-readiness date of February, 2023.

Session 1. *The Sunset of SORCE*

SORCE – Important Factors of Concept and Development
Gary Rottman *[gary.rottman@lasp.colorado.edu], Tom Woods, and Tom Sparn; LASP / University of Colorado, Boulder*

Among other topics this Science Meeting celebrates the many accomplishments of the SORCE Mission since launch in 2003 — scientific discoveries and new insights into the Sun as documented in papers and meeting proceedings. This particular talk will harken all the way back to 1988 and LASP's original proposal to NASA's Earth Observing System (EOS) to provide a spectrometer to measure the solar ultraviolet irradiance. That proposed instrument would be the second Solar Stellar Irradiance Comparison Experiment, SOLSTICE. The first having not yet flown was being prepared for NASA's Upper Atmosphere Research Satellite UARS, and would launch 3 years later in 1991.

The EOS SOLSTICE as proposed in 1988 would languish on the ground 15 years until finally being launched on SORCE in 2003. (Fortunately the UARS Mission was extended and the two versions of SOLSTICE did have two years of overlap). Meanwhile besides SOLSTICE the SORCE carried two additional spectral instruments that measured not only the solar ultraviolet irradiance but almost all wavelengths from the shortest X-rays all the way to the far infrared, and in addition a third, new instrument concept to revolutionize the measurement of total solar irradiance, TSI. What transpired in those years from 1988 to 2003 to advance and evolve the single EOS SOLSTICE to this complement of functionality? Such new devices didn't materialize overnight but were a slow and directed evolution and extension. While SOLSTICE delayed there were many twists and turns of fate, some surprises and some planned that expanded SORCE to its full capability. In this talk we describe and detail the impact of these most favorable occurrences and thereby connect some of the dots.

Celebrating SORCE

Robert Cahalan *[bob@chears.org], NASA Goddard Space Flight Center (Emeritus), Greenbelt, MD*

Personal and professional reflections as SORCE Project Scientist from 1999 to 2015, include the build, launch, Halloween X-rays, a "Great Minimum" during the "Great Recession," evolving from "Outlier" to "Gold Standard," dual Venus transits, a "gap year," dual Sol maxima, and a fitful winding down of cycle 24, as TSIS takes the baton and Sol begins anew.

Highlights from the SORCE / TIM

Greg Kopp *[greg.kopp@lasp.colorado.edu], LASP / University of Colorado, Boulder*

The first Total Irradiance Monitor (TIM) was launched on the SOlar Radiation and Climate Experiment (SORCE) in 2003. This new space-borne instrument incorporated several innovations over its predecessors to more accurately and more precisely measure the total solar irradiance (TSI), the spatially- and spectrally-integrated radiant energy from the Sun (normalized to one astronomical unit) and thus the net energy powering the Earth's climate system.

Over the TIM's 17-year measurement duration, its accomplishments include:

- Establishing the new, more accurate, lower TSI value of 1361 W m^{-2} and thereby improving estimates of the Earth's energy (im)balance
- Achieving the best inherent stability and the lowest noise of any TSI instrument, improving measurements of short- and long-term solar variability, which provide important natural forcings for Earth-climate models
- Detecting the first solar flare in TSI, thus providing the first direct measurement of the net radiant energy released by a flare
- Observing two Venus and four Mercury transits, thereby giving insights into discovering exoplanets orbiting Sun-like stars via the planetary-transit method
- Recording the largest short-term decrease in the TSI during the spacecraft era
- Creating one of the longest-duration TSI measurement records from a single instrument

The SORCE/TIM has been succeeded by two follow-on TIMs, namely those flown on the TSI Calibration Transfer Experiment (TCTE) and the Total and Spectral Solar Irradiance Sensor (TSIS). The absolute accuracies of these three instruments are such that all agree within their stated uncertainties to the new, lower TSI value established by the SORCE/TIM. While the SORCE ends operations in early 2020, its TIM's legacy and the uninterrupted 41-year-long space-borne TSI measurement record continue into the foreseeable future with the TSIS/TIM.

In this presentation, I will describe the instrument innovations of the SORCE/TIM, its most important accomplishments, and comparisons to other past and present TSI instruments.

SORCE SIM Instrument Highlights for Middle Ultraviolet, Visible, and Near Infrared

Jerald Harder *[jerry.harder@lasp.colorado.edu], Stéphane Béland, and Thomas Woods; LASP / University of Colorado, Boulder*

The SORCE Solar Irradiance Monitor (SIM) instrument has played an important part in our understanding of the nature of solar spectral variability and how these variations affect the Earth climate system. SORCE SIM was the first instrument to provide an uninterrupted record of daily solar variability in the visible and infrared spanning the descending phase of Solar Cycle 23 and Cycle 24 maximum, and is now concluding its 17-year mission in Cycle 24/25 minimum. Over its full operating range, SIM observed the solar spectral variability of about 97% of the total solar output. Herein we briefly discuss the highlights of the SORCE SIM: 1) its reported solar variability over the full wavelength range, 2) its importance to modeling solar activity, 3) its importance as input to Sun-Earth climate modeling, and 4) the innovative technological advances made in the development of the SIM that have been passed on to the next generation of solar spectral radiometers.

Highlights from 17 Years of SORCE / SOLSTICE Observations

Martin Snow *[marty.snow@lasp.colorado.edu], William McClintock, and Thomas Woods; LASP / University of Colorado – Boulder*

The SOLar-STellar Irradiance Comparison Experiment (SOLSTICE) has been measuring solar spectral irradiance (SSI) since early 2003. SOLSTICE observes from 115-300 nm with a spectral resolution of 0.1 nm. In addition to the daily solar measurements, we have also observed spectral irradiance from bright stars, the Moon, and comets. Stellar occultations at 140 and 240 nm have measured atmospheric O2 and O3. SOLSTICE has even measured the evolution of the South Atlantic Anomaly. This talk will summarize the highlights of the SOLSTICE data record over the last seventeen years.

SORCE X-ray Ultraviolet Photometer System (XPS) Highlights

Tom Woods *[tom.woods@lasp.colorado.edu], Gary Rottman, and Joshua Elliott; LASP / University of Colorado, Boulder*

The XUV Photometer System (XPS) aboard SORCE measures the X-ray Ultraviolet, or XUV, energy input to Earth's atmosphere. The XPS instrument is measuring the solar XUV irradiance with 7-10 nm resolution shortward of 34 nm and the bright hydrogen emission at 121.6 nm. During the SORCE mission from 2003 to 2020, the solar activity has evolved from near solar maximum conditions in solar cycle 23, through the cycle 23/24 minimum, over the full range of activity of solar cycle 24, and now into cycle 24/25 minimum. The solar irradiance varies on all time scales, seconds to years, and this variation is very dependent on wavelength. During the SORCE mission, the XPS instrument has observed 17 years of solar cycle activity, more than 200 solar rotations with an average period of about 27 days, and several thousand flares which last from minutes to hours. The XUV radiation, being mostly from coronal emissions, varies more than other wavelengths in the solar spectrum. The XPS measurements indicate variations by a factor of more than 100 for the largest flares during the October-November 2003 solar storm period and the September 2017 solar storm period; those being the most intense periods of solar activity for solar cycle 23 and 24, respectively. The XUV contribution to the total energy of a flare is about 20% as determined with comparisons with total solar irradiance (TSI) flare variations recorded by the SORCE Total Irradiance Monitor (TIM) instrument. The variations of the solar XUV irradiance will be discussed in the context of the SORCE mission.

SORCE's Flexible Satellite Architecture Allows Science to Continue Despite Hardware Challenges

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The SORCE satellite, with a planned 5-year mission, is currently in its 16th year of operation. Several critical events during the mission have resulted in unexpected changes in order to continue successful science operations.

The first of these occurred during instrument commissioning phase, only one week after launch. Housekeeping data and the ability to consistently command the instruments was lost. Initially a brute force method was deployed, and eventually flight software upgrades were made to enhance science operations and data collection.

A degrading battery in 2013 caused the Flight Operations Team extensively redesigning the way the spacecraft was flown. As the capacity of the battery decreased over time, instruments were phased out of operations in eclipse while strategies were tested to improve battery performance and longevity. Flight software changes were developed for the Attitude and Power Electronics (safemode computer) and the On-Board Computer (main spacecraft computer) and Microprocessor Unit (instrument computer).

SORCE now successfully operates in daylight-only mode where the only components powered on in eclipse are the Attitude and Power Electronics computer and the receiver. Despite the decreased power load, most orbits the APE now browns out in eclipse. Cleverly designed automation sequences have allowed the mission to continue with greatly reduced battery capacity.

Re-defined science objectives are being met through the use of updated spacecraft and ground automation, and new planning and scheduling software. Special calibration activities are performed through the use of temporary on-board command sequences that are loaded by the Flight Operations Team. A final set of special calibrations and experiments are scheduled to be performed in December 2019 during the last mini-eclipse prior to spacecraft passivation in February 2020. These activities will complete a very successful SORCE mission.

SORCE Management in a Civilized Time

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This talk will reflect on the history of the management processes and experience that brought the successful implementation of the SORCE mission, on schedule and within budget. Specifically it will focus on the teamwork between Academia (LASP), Government (NASA GSFC), and Industry (Orbital Sciences Corporation) that allowed the SORCE program to be successful. Many times during the development of the SORCE program, it was called "lucky", but this luck was not chance but made by the excellent working relations between the three strong partners.

The talk will discuss structure, agreement and relationship that created the success of the hardware implementation that fulfilled the science requirements of SORCE. This is not a technical presentation but a historical reflection put into perspective based on years of experience since the launch of SORCE.

Session 2. *Recent/Space-Era Solar Cycle Timescales*

What is the TSI value at solar minima in the space age?

Bo Andersen *[bo.andersen@spaceagency.no], Norwegian Space Agency, Oslo, Norway*

The value of the TSI at solar minima historically back to the Maunder Minimum is to a large degree not known to the level of accuracy needed for understanding the potential coupling with global Climate change. Sophisticated proxy models have been developed by several authors, but all of them rely upon the measured TSI value from space since 1979. Due to the gap in high quality measurements between ACRIM1 and ACRIM2 there are several conflicting time series for this measurements period, this leads to a built in uncertainty in the historical reconstructions. I will present a method to construct a coherent time series in this period with reference to latest calibrated measurements.

Modern and Historical Reconstructions of Solar UV Irradiance Variability

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It has been for long known that UV solar radiation affects the Earth's atmosphere and its climate. Similarly, UV radiation of the hosting star plays a key-role in determining the habitability of exoplanets, and it affects the interpretation of bio-markers measurements. We present a method to reconstruct irradiance UV indices on the secular temporal scales. The method combines semi-empirical and proxy approaches and assimilates the Sunspot number, full-disk observations, and modern UV irradiance measurements by SORCE. It allows to reconstruct the UV color index, as well as the area coverage of facular and network regions, from which it is possible to reconstruct irradiance variability at different wavelengths. We present here reconstructions from 1749 to 2015 of UV solar indices, namely the UV color, and core-to-wing ratio of MgII and CaII lines. The agreement between our reconstructions and modern composites measurements makes us optimistic about the use of the proposed approach to reconstruct irradiance variability in the past, at times when full-disk measurements were not available, or when studying active star hosting exoplanets that cannot be resolved spatially.

Solar Spectral Irradiance Measurements from the TSIS-1 SIM: Data continuity and comparisons to other records

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The Total and Spectral Solar Irradiance Sensor (TSIS-1) launched on December 15th, 2017 and was integrated on the International Space Station (ISS). The TSIS-1 SSI observations began in March 2018 with an improved version of the LASP Spectral Irradiance Monitor (SIM). Extensive advances in both instrument design and new spectral irradiance calibration techniques have resulted in the TSIS-1 SIM being the most accurate space-borne SSI radiometer to date (continuous 200 – 2400 nm *SI*-traceable spectral absolute uncertainties < 0.5%). We now have nearly two years of continuous operations during a time period of solar minimum conditions. This has provided a unique opportunity to compare to the SORCE SIM end-of-mission SSI data as well as other SSI data records, including the European SOLAR SSI data and new Compact Spectral Irradiance Monitor (CSIM) CubeSat mission record. With the improvements in the long-term stability corrections of TSIS SIM over the previous SORCE SIM we have an SSI data record that will improve solar spectral irradiance models.

<u>SORCE/TSIS Overlap Analysis</u>

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TSIS was launched in December 2018 and the SIM instrument started its nominal operations in March 2018. With over 22 months of overlap with the SORCE SIM instrument, we are presenting preliminary results of the absolute scale comparison and the relative stability of these measurements over the 240-2400 nm spectral range. We will address the controversy of the absolute irradiance at the 1.6 micron measured on SORCE by taking advantage of the high fidelity absolute ground calibration of TSIS SIM. Differences in the two datasets over the time of overlap will also be presented over various spectral regions.

<u>Satellite Overlap Requirements for Building Long-term Continuous Records – SORCE/TSIS Case Study</u>

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The amount of satellite overlap needed to create a useful long-term dataset depends on the agreement between the two satellites and the level of accuracy needed in the final product. The expected factors affecting overlap time were outlined in a Weatherhead *et al.* paper in 2017. With the TSIS/SORCE overlap period, we now have the ability to look at impacts of overlap time by wavelength for this important datasets, testing the assumptions put forward in Weatherhead *et al.* Results show that initial burn-in period, long-term drift, offsets and unexplained spikes all impact overlap requirements. Results of this effort are applicable to many other long-term observational datasets. However, the need for appropriate overlap is most important when the satellite data have little or no additional observational sources for validation.

<u>TSIS Measurements from NORSAT-1/CLARA</u>

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Total Solar Irradiance (TSI) is the main energy source at Earth. For a correct evaluation of the Earth's energy budget it is key to measure the short- and long-term variations of TSI continuously and with high precision from space. The Compact Lightweight Absolute Radiometer (CLARA) on board the Norwegian satellite NORSAT-1 was launched 14 July 2017 and is PMOD's latest operational active cavity Electrical Substitution Radiometers (ESR). Nominal operation of CLARA started 21 August, 2017, however in May 2018 the satellite experienced a spinning wheel failure and subsequently pointing problems occurred. Meanwhile, reasonable solar pointing with 2 spinning wheels could be restored and CLARA saw its second "first light" 8 November 2019. We will present the latest status of the TSI measurements by CLARA and how they compare to previous and ongoing measurements, such as SOHO/VIRGO, PICARD/PREMOS, SORCE/TIM and TSIS/TIM.

Estimating the Precision of TSI Measured from VIRGO, SORCE, TCTE, and TSIS-1 Using the Triple Differencing Technique

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Since the launch of SORCE in 2003, we have entered an era where multiple instruments have been making high-cadence (~hourly or less) measurements of total solar irradiance (TSI). The launch of TCTE in late 2014 increased the number of near-simultaneous high-cadence (six-hourly) TSI measurements to three, while the launch of TSIS-1 in late 2017 and the near-coincident end of the VIRGO mission have kept this number at three for the past 4.5 years. Using the pairwise differencing analysis, it becomes feasible to glean out the precision information of each sensor from these sets of overlapping measurements.

By differencing all three overlapping (and de-trended) datasets with each other (VIRGO, SORCE, TCTE; and SORCE, TCTE, TSIS-1), three difference datasets are generated. Assuming that the sampling difference uncertainties between these three sets of measurements are small and that the instrumental uncertainties are uncorrelated with each other, the problem simplifies into one of adding uncorrelated errors. We organize the variances (rolling multi-day window) of these difference datasets as a series of linear equations with three knowns (the difference dataset variances) and three unknowns (the squared instrumental precisions). Because this technique relies on three overlapping datasets, it is quite complementary to the standard auto-regression technique, which only relies on the dataset being tested. We will present comparisons over both the TSIS-1, SORCE, and TCTE overlap, as well as the longer time-period corresponding to the VIRGO, SORCE and TCTE mission overlap.

A Comparative Examination of SORCE and TSIS-1 TSI Data during the Overlap Period

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Daily TSI measurements are being used to process data acquired from CERES instruments onboard Terra and Aqua satellites for deriving CERES Edition-4 TOA and surface radiation budget parameters. Combined CERES Terra and Aqua period extends from 01 March 2000 to the present. Daily SORCE measurements have been available over most of this period with a latency of seven days making it eminently suitable for timely processing of CERES data. SORCE Version-15 was used at the start of CERES Edition-4 processing. The period prior to the start of SORCE was covered with WRC data. The period of SORCE interruption during 2013-14 was covered with TSI data from the RMIB-composite dataset. Use of SORCE data was resumed after the interruption though with later versions. Data from later versions of SORCE and other datasets were normalized to Version-15 level. Gaps in SORCE and other dataset were filled by linear interpolation.

Starting in January 2018, another parallel stream of TSI data, namely TSIS-1, became available with a latency of five days. Simultaneous availability of two low latency streams allowed development of an innovative method of filling gaps that frequently occur in both streams. The gap-filling method makes use of the high temporal coherence exhibited by both streams allowing to fill gaps in one stream when a good value for that day is present in the other. Gaps simultaneously present in both streams are still filled by linear interpolation. Comparison of the two streams also showed that mean of TSIS-1 values was about 0.48 Wm^{-2} higher than that for SORCE Version-15.

On the Decay of Sunspots

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Sunspots are stable magnetic flux tubes in the solar photosphere. They are embedded in a flow cell, known as the moat. We will present our study on the stability and evolution of a (MHD) simulated sunspot in an extended box (98 x 98 x 18 Mm^{3}). The extension of the box enables to take into account the surrounding plasma motions, at the surface and underneath the solar photosphere. In addition, we use HMI/SDO data to study the radial flow evolution within sunspots and in their surroundings in the decay phase. We find that the evolution and decay of the sunspot is influenced by the surrounding plasma motions. A few megameters below the surface, interchange instability and a radial inflow lead to the destabilization of the geometrical structure of the sunspot. The initially roundish sunspot magnetic flux tube becomes then ragged.

The evolution of sunspots and their surrounding moat flow, studied in HMI data, shows an inflow towards the sunspot in its final stage of evolution. When the penumbra has dissolved, the inflow becomes visible in the photosphere. We also find that the moat flow evolves into a supergranular flow when sunspots decays. The evolution of the sunspot cell depends on the interaction with surrounding supergranules. In some cases, the supergranular cell remains when the sunspot disappears. However, in some other cases, the competing effect can also squeeze the whole cell after the sunspot disappearance. In both cases, the remnant magnetic flux feeds the quiet Sun network eventually becoming part of it.

Solar Irradiance Variations in Chromospheric Spectral Lines

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The chromospheric activity of the Sun is governed by the magnetic field anchored at the photosphere. We study the dependence of chromospheric activity on magnetic field of the Sun-as-a-star by using observations by Integrated Sunlight Spectrometer (ISS) and Vector Spectromagnetograph (VSM) of Synoptic Optical Long-term Investigations of the Sun (SOLIS) instrument. The chromospheric activity is measured as the line depth and equivalent width (EW) of spectral lines in Hα, He I 10830 nm, Ca II 854.2 nm, Ca II H and K, and Na D I 589.6 nm obtained with the ISS. The full disk mean total magnetic flux (FDMTMF) observed with the VSM is used as the measure of magnetic activity of the Sun. The equivalent width of Ca II K and He I 10830 nm measured by Livingston along with the Magnetic Plage Strength Index (MPSI) value and a Mount Wilson Sunspot Index (MWSI) obtained with 150-foot Solar Tower in Mt. Wilson Observatory are used to further study the relationship between the magnetic field and chromospheric activity.

Solar Activity and Responses Observed in Balmer Lines

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The ~daily solar irradiance measurements made by the Aura/OMI and Sentinel-5P/TROPOMI instruments are capable of observing subtle variations in solar absorption features such as hydrogen Balmer lines, using the core-to-wing ratio method that provides stable measurements despite possible instrument

degradation, as previously developed for the Mg II and Ca II features. Analysis of these data shows that, on 27-day solar-rotational timescales, the upper-Balmer series lines closely follow changes in the total solar irradiance, thus diverging from the behavior observed in other chromospheric-sensitive transitions. This behavior persists through both active- and quiet-Sun epochs.

Response of Solar Irradiance to Solar Proxies: Is it instantaneous?

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Most models for reconstructing solar irradiance from solar proxies do so by assuming the existence of some instantaneous (but possibly nonlinear) relationship between the two. This assumption often turns out to be wrong because the relationship is convolutional. The proper approach for handling such processes involves transfer functions. Here, we 1) Show by how much linear transfer functions improve the reconstruction of solar irradiance variations; 2) What such transfer functions tell us about the underlying physics; 3) Investigate whether long-term variability (i.e., on timescales of years and beyond) can be reconstructed by means of models that describe short-term variability using as input solar proxies such as the daily sunspot number.

Session 3. *Solar Variability and Climate Trends on Secular Timescales (formerly Session 4)*

Solar Activity over the Last Four Billion Years

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The action of dynamo generates magnetic field in the solar interior. This field then travels through the convective zone and emerges on the solar surface, leading to a various manifestations of solar magnetic activity. One of the most appealing among them is the variations of solar brightness. We review recent theoretical progress in understanding solar variability on timescale from hours to the millennia. We utilize recent observations of Sun-like stars younger than the Sun to reconstruct solar activity and brightness variability over last four billion years.

Re-evaluations of the 400-Year Sunspot Record

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The sunspot record is the longest continuous directly-observed solar record in existence and gives indications of solar variability on daily, solar-rotational, solar-cycle, and multi-century timescales with commensurate resulting inputs for studies of solar activity, the solar dynamo, and Earth climate. Creating a composite sunspot record by merging the many hundreds of observers contributing to the 400-year observational time range requires correcting for offsets, trends, and non-linearities in the individual time series. In creating the Sunspot Indices and Long-term Solar Observations (SILSO) V2.0 sunspot number and a new group sunspot number composite, released in July 2015, several new composite-creation methods were explored and many observer's historical sunspot records were recovered and updated. The methods, approaches, and results were described in a topical collection of *Solar Physics* (**291**, 2016) and have applicability to the creation of other time-series composites, such as solar irradiances and Earth-climate records.

With work continuing subsequent to the release of the SILSO V2.0 series, these newly-recovered observational records and composite-creation methodologies will provide even further improvements to future sunspot-record versions. An International Space Science Institute (ISSI) team (http://www.issibern.ch/teams/sunspotnoser) is coordinating these future-version updates. We present a summary of this ISSI team's efforts, giving an overview of the advantages of and differences between various methodologies for creating sunspot-record composites, progress on newly-recovered observational records, and recommended composite-creation approaches for both imminent and more distant future data versions.

Reconstructing Historical Solar Activity with the Advective Flux Transport Model

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Historical reconstructions of total solar irradiance (TSI) rely on calculations of flux emergence and transport based primarily on sunspot-number records. In 2015, the Sunspot Indices and Long-term Solar Observations (SILSO) released version 2.0 of the sunspot-number time series, including monthly sunspot numbers from 1749 to the present. These revisions produce a sunspot record that differs notably from prior versions and are thus expected to significantly impact estimates of solar open and closed magnetic flux and historical TSI reconstructions. We are using the Advective Flux Transport (AFT) model estimate the impacts of sunspot number revisions on extant historical reconstructions of TSI based on the empirical, proxy-based NRLTSI2 model. AFT is, a realistic surface flux transport model that has demonstrated its predictive capability on both short (active-region evolution) and long (solar-cycle) timescales. We present our method for generating synthetic active-region databases based on the revised sunspot-number record. These synthetic databases include the timing, position, and strength of solar active regions, which are then used as the magnetic input sources to AFT to create simulations of the evolution of the Sun's magnetic fields, from which historical TSI variations (since 1749) will be estimated. We also show examples of AFT-generated historical and recent solar cycles, the latter of which we use to validate the model's ability to generate realistic solar cycles.

Validation of the Group Sunspot Series

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Solar activity e.g. as measured by the number of active regions (sunspot groups) on the disk at any time varies on time scales ranging from solar rotation to centuries. Solar activity (telescopically observed for four centuries) manifests itself both by variations of wave radiation (e.g., EUV flux and TSI) and of particle emission (e.g., solar wind and energetic particles). These variations influence the Earth's environment (e.g., the ionosphere and the Van Allen Belts) with consequences that are observable on the ground as variations in the geomagnetic field. Two centuries of systematic (and an additional earlier century of more sporadic) observations serve as direct measurements of solar activity influence and can reliably be employed to reconstruct said activity for centuries past. These reconstructions validate the recent revisions of the (difficult to calibrate) telescopic observations (the Sunspot and the Group Numbers) that show no significant long-term trend over the past three hundred years. This is particularly important for historical reconstructions of total solar irradiance, such as the recently released Climate Data Record which shows a trend not compatible with the neither the geomagnetic record nor with the revised sunspot records.

On the Contribution of Quiet Sun Magnetism to Solar Irradiance Variations

Matthias Rempel *[rempel@ucar.edu], National Center for Atmospheric Research / High Altitude Observatory (NCAR/HAO), Boulder, CO*

While the quiet Sun magnetic field shows only little variation with the solar cycle, long-term variations cannot be completely ruled out from first principles. We investigate the potential effect of quiet Sun magnetism on spectral solar irradiance through a series of small-scale dynamo simulations with varying levels of small-scale magnetic field and one weak network case with an imposed vertical mean field of 100G. From these setups we compute the dependence of the outgoing radiative energy on the unsigned vertical magnetic flux density in the photosphere at continuum optical depth $\tau=1$. We find that a quiet Sun setup with an unsigned vertical magnetic flux density of 69 G is about 0.7% brighter than a non-magnetic reference case. We find a linear dependence of the outgoing radiative energy flux on unsigned magnetic flux density (TSI sensitivity) of 0.017%/G. With this sensitivity, only a moderate change of the quiet Sun field strength by 10% would lead to a total solar irradiance variation comparable to the observed solar cycle variation. While this does provide strong indirect constraints on possible quiet Sun variations during a regular solar cycle, it also emphasizes that potential variability over longer time scales could make a significant contribution to longer-term solar irradiance variations.

Reduced Caribbean Hurricane Activity during the Maunder Solar Minimum

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Assessing the impact of future climate change on North Atlantic tropical cyclone (NATC) activity is of crucial societal importance, but the limited quantity and quality of observational records interferes with the skill of future NATC projections. In particular, NATC response to radiative forcing is poorly understood and creates the dominant source of uncertainty for 21st century projections. Here, we study NATC variability during the Maunder Minimum (MM; 1645-1715 CE), a period defined by the most severe reduction in solar irradiance in documented history. For this purpose, we combine a documentary time series of Spanish shipwrecks in the Caribbean (1495–1825 CE) with a tree-growth suppression chronology from the Florida Keys (1707–2010 CE). We find a 75% reduction in decadal-scale NATC activity during the MM that indicates modulation of the influence of reduced solar irradiance by the cumulative effect of cool North Atlantic sea surface temperatures, El Niño-like conditions, and negative phases of the Atlantic Multi-decadal Oscillation and the North Atlantic Oscillation. Our results emphasize the need to enhance our understanding of the response of these oceanic and atmospheric circulation patterns to radiative forcing and climate change in order to improve the skill of future NATC projections.

The Earth Climate at Deep Minima of the Solar Activity

Alexander Ruzmaikin *[alexander.ruzmaikin@jpl.nasa.gov] and Joan Feynman, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA*

The recent extended and deep minimum of solar variability (cycles 23-34) and the extended minima in the 19th and 20th centuries (1810-1830 and 1900-1920) are consistent with minima of the Centennial Gleissberg Cycle (CGC), a 90-100 year variation of the amplitude of the 11-year sunspot cycle observed on the Sun, solar wind, and at the Earth. The CGC has been identified in the Total Solar Irradiance (TSI) reconstructed for over three centuries. The Earth's climate response to the prolonged low solar irradiance involves heat transfer to the deep ocean with a time lag longer than a decade.

The CGC minima, sometimes coincidently in combination with volcanic forcing, are associated with severe weather extremes. Thus the 19th century CGC minimum, coexisted with volcanic eruptions, led to especially cold conditions in United States, Canada and Western Europe (called “a year without summer”). Using the reconstructed solar forcing and modeled and reconstructed Earth’s temperature data we identify the timing and spatial pattern of the Earth’s climate response to the Sun’s Grand Minima.

The Sun in Stellar Context: Stellar Windows into Solar Magnetic Evolution

Jennifer van Saders *[jlvs@hawaii.edu], University of Hawaii, Honolulu*

The last 10 years have seen sudden and dramatic improvements in our understanding of stars, thanks to the launch of space photometry missions such and Kepler and TESS. These missions have enabled asteroseismology of hundreds of Sun-like stars, and the measurement of starspot modulation in tens of thousands. Rotation and magnetism are inextricably linked in the Sun, and these datasets have now enabled us to explore that link in other stars at other phases of stellar evolution with unprecedented precision. The results have been surprising: we have evidence that middle-aged stars undergo a transition in their magnetic properties, manifested in both their rotational behavior and magnetic activity. I will discuss the lines of evidence for this midlife magnetic crisis, and the possible implications for our own middle-aged star.

Seeking the Quiet Sun Among the Stars

Thomas R. Ayres *[Thomas.Ayres@Colorado.edu], Center for Astrophysics and Space Astronomy, University of Colorado, Boulder*

How does one judge the state of the Quiet Sun, if by that is meant the barest minimum of solar activity? Some possibilities include: (1) construct histograms of spatially resolved solar measurements (e.g., UV and X-rays) and evaluate the activity properties of, say, the lower portions of the distribution; (2) follow global "irradiance" tracers over multiple sunspot cycles, to identify empirical minima; or, (3) collect large samples of stellar observations to sketch out a lower activity bound among stars of solar type. These approaches all have advantages and drawbacks.

I have developed a way to jointly leverage the positive aspects of such methods, exploiting datasets from IRIS (spatially resolved Mg II); SORCE (disk-average UV spectra over recent solar cycles); and long-term HST-STIS UV monitoring of Alpha Cen AB, two nearby stars that closely bracket the Sun's activity extremes. A curiosity on the solar side involves flux-flux correlations between different diagnostics say, X-rays vs. Mg II. The well-behaved stellar power laws at moderate activity give way to broken power laws at low activity in SORCE. This offers a way to extrapolate global activity indices into the regime below that sampled by the existing solar irradiance records, to examine consequences of a Sun in its quietest possible state.

Session 4. *Solar Influence on the Atmosphere and Climate (formerly Session 3)*

Navigating the Causes of Modern Climate Change

Judith Lean *[judith.lean@icloud.com], LASP / Univ. of Colorado, Boulder; and Naval Research Laboratory, Washington, DC (emeritus)*

Climate change detection and attribution have proven unexpectedly challenging during the 21st Century thus far. Earth's global surface temperature increased less rapidly from 2000 to 2015 than during the last half of the 20th Century, even though greenhouse gas concentrations continued to increase. Simulations made with state-of-the art general circulation climate models did not replicate this lack of global surface temperature increase, which in 2013 the IPCC termed a "global warming hiatus". This motivated over a decade of climate change research focused on elucidating the causes of a so-called "pause". Amplified by media commentary, the suggestion that "missing" mechanisms are influencing climate exacerbated confusion among policy makers, the public and other stakeholders about the causes and reality of modern climate change. Did global warming really pause during the beginning of the twenty-first century and does record-breaking warmth in recent years signify its resumption? How well do observations track Earth's global temperature changes and how reliable are physical climate models at replicating these changes? A statistical analysis of surface temperature observations suggests answers to these questions and provides quantitative interpretation of modern climate change as a mix of both anthropogenic and natural influences, including the Sun's irradiance cycle. Plausible climate change scenarios in future decades are explored using a range of anthropogenic and natural projections. Understanding and communicating the causes of climate change in the next 20 years may be more challenging than in the recent past, in part because predictions of the modulation of projected anthropogenic warming by natural processes have limited skill and in part because of emerging feedbacks and tipping points that even the most sophisticated physical climate models do not yet replicate, nor statistical models based on past observations include.

Based on "Observation-based detection and attribution of 21st century climate change", J. Lean, WIREs, 2016.

Ozone Change and Its Influence on Climate

Summary of Chapter 5: "Stratospheric Ozone Changes and Climate" from the Scientific Assessment of Ozone Depletion [2018]

Karen Rosenlof *[karen.h.rosenlof@noaa.gov], NOAA Earth System Research Laboratory (ESRL), Chemical Sciences Division, Boulder, CO*

Ozone is important in the climate system and its changes can influence both the troposphere and the stratosphere. Past increases in ozone depleting substances and associated decreases in stratospheric ozone have been an important driver of past stratospheric cooling trends and increases in the strength of the Brewer Dobson circulation in the lower stratosphere. At the surface, the largest climate impacts identified to date are in the Southern hemisphere in summer. The climate impacts of ozone depletion both in the troposphere and stratosphere are expected to reverse over coming decades as atmospheric abundances of ozone depleting substances decline due to the Montreal Protocol and stratospheric ozone recovers. The relative importance of ozone recovery for future Southern hemisphere climate will depend on the evolution of atmospheric greenhouse gas concentrations. This presentation will discuss these and other key findings regarding ozone changes and climate reported in Scientific Assessment of Ozone Depletion: 2018.

Top-down Solar Influences on the Madden-Julian Short-Term Climate Oscillation

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The tropical Madden-Julian Oscillation (MJO) is the strongest of the intra-seasonal climate oscillations and has important effects on extratropical circulation, including effects on storminess and temperature in the United States and Europe. Beginning about three years ago, it was realized that the stratospheric quasi-biennial oscillation (QBO) exerts a significant influence on the amplitude and occurrence rate of MJO events during boreal winter (DJF). More events occur in the easterly QBO phase (QBOE) than in the westerly phase (QBOW). The main candidate mechanism is the decrease in static stability in the tropical upper troposphere / lower stratosphere (UTLS) resulting from relative upwelling and adiabatic cooling under QBOE conditions.

In this work, we examine whether strong MJO occurrence rates are also influenced by solar variability on the 27-day and 11-year time scales. On both time scales, there is observational evidence that increased solar UV heating in the tropical upper stratosphere accelerates the lower mesospheric subtropical jet, which modifies wave propagation such that the stratospheric meridional circulation is slowed. The net effect is that temperatures in the tropical UTLS are reduced under 27-day or 11-year solar minimum (SMIN) conditions relative to those under SMAX conditions.

It was found that, under 11-year SMAX conditions when 27-day UV variations are largest, the mean occurrence rate of strong winter-spring MJO events is increased and tropical UTLS static stabilities are decreased following 27-day solar UV minima; the opposite occurs after 27-day solar UV maxima (Hood, *J. Atmos. Sci.,* 75, 857, 2018). Although only 3-4 solar cycles of high-quality MJO data are available, there is also evidence for an increase in strong MJO events and decreased static stabilities under 11-year SMIN conditions ([Hood, *GRL,* 44, 3849, 2017). Occurrence rates are largest under combined QBOE/SMIN conditions and are smallest under QBOW/SMAX conditions.

Solar EUV Irradiance and Thermospheric Composition Trends Retrieved from FUV Dayglow Observations

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The advent of routine thermospheric/ionospheric remote sensing missions such as GUVI, and now GOLD and ICON, provide a long-term database of atmospheric composition retrieved from observed far ultraviolet (FUV) thermospheric emissions. Algorithms that extract composition from dayglow observations ingest a solar irradiance spectrum provided either from direct measurements such as those made by SORCE or EVE, or empirical models thereof that adjust for solar activity, and egest altitude-dependent thermospheric densities (Earth limb viewing) and/or the integrated column O/N_2 ratio (Earth disk and limb viewing). A product of the retrieval methodology is also information about the absolute magnitude of the solar extreme ultraviolet (EUV) irradiance required to reproduce the FUV dayglow. This quantity, designated Q_{euv} (W/m^2), is obtained by scaling the magnitude of the ingested solar spectrum to optimize the retrieval process. Q_{euv} is the integral of the scaled spectral irradiance from 0 to 45 nm, the range of photon energy that is required to produce photoelectrons with sufficient energy to collisionally excite thermosphere species to electronic states that radiate in the FUV. Following a brief review of the retrieval techniques, the Q_{euv} values derived from thermospheric FUV emissions are compared with direct measurements of this energy band, and trends are examined in both Q_{euv} and thermospheric composition.

A New Clock for the Sun: Sun-Climate Implications & What May Be Looming

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The Sun's variability is controlled by the progression and interaction of the magnetized systems that form the 22-year magnetic activity cycle as they march from their origin at ~55° latitude to the equator, over ~19 years. We will discuss the end point of that progression, dubbed "terminator" events, and our means of diagnosing them. These approximately decadal scale events *simultaneously* mark the end of magnetic cycles and are the trigger for the growth of the sunspot cycle (the butterfly pattern of sunspots) at mid-latitudes and the rush to the poles at high latitudes. We will briefly explore the consequences of such events for what we know about the Sun's interior. We will then show that these events provide a new clock to frame the Sun's activity proxies before we demonstrate how that clock translates into significant terrestrial impact that has gone unnoticed, largely because we have been using the landmarks of the sunspot cycle ("max" and "min") as our translative clock. We will show when the next terminator will happen (in 2020) and discuss the signature that it may have. Finally, developing a longer baseline for terminator events in the 270+ years of the sunspot record, we will present a look at the upcoming sunspot cycle based on currently visible indicators – the result will be of great interest to the group.

Atmosphere and Ocean Responses to Extreme Low Solar Activity and Their Hemispheric Differences

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The total solar irradiance (TSI) changes by ~0.1% during solar cycles. The impact of the change on tropospheric climate is small in comparison with the large climate variability. While the solar cycle variation of ultraviolet (UV) is larger, its downward effect on climate is also rather weak. It is thus challenging to clearly quantify the solar signal, and to investigate the processes involved in sun-climate connection. As a result, the climate sensitivity to solar forcing is poorly quantified and understood. In this study, we seek to overcome this difficulty by driving a coupled whole atmosphere-ocean model—the NCAR CESM Whole Atmosphere Community Climate Model (WACCM) with the interactive ocean model (POP2)—with an extreme low solar forcing. The TSI and solar spectral irradiance (SSI) are obtained from MHD simulations using the MURaM code, and the TSI/SSI values obtained can be regarded as a lower theoretical limit as allowed by known solar physics principles. With this hypothetical low solar forcing, significant and complex changes are seen throughout the atmosphere and also in the ocean circulation. While the surface generally cools during the 200-year simulation, the evolution path of the cooling and the cooling rates are very different between the two hemispheres. Our analysis suggests that the interplay between the radiative forcing and dynamical feedback determines the response, and the dynamical feedback from atmosphere and ocean coupling, in particular in the form of atmospheric waves, differ between the two hemispheres. Additional simulations with extreme low SSI forcing in the ultraviolet (UV) only and in the visible/infrared (VIR) only show that they can cause troposphere/ocean responses similar to the full forcing case, albeit with different magnitudes. The results unambiguously demonstrate the importance of middle atmosphere/lower atmosphere/ocean coupling in sun-climate connection and in studying the climate sensitivity to solar forcing.

Possible Solar Cycle Responses of Eddy Diffusion in the Mesosphere and Lower Thermosphere as Inferred from SABER CO_2

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This work presents a possible solar cycle response of eddy diffusion in the MLT region. We utilize global-mean SABER CO_2 to first derive global-mean eddy diffusion coefficients (K_{zz}) that span at least one solar cycle. Then, a multiple-linear regression is used to determine the response of these K_{zz} profiles to the solar cycle. It is found that K_{zz} decreases during solar maximum and increases during solar minimum (hereafter referred to as a negative solar cycle response). These are compared with simulations from the Specified Dynamics – Whole Atmosphere Community Climate Model – eXtended (SD-WACCM-X). Model simulations also indicate a negative solar cycle response in K_{zz}. To explain these solar cycle responses in global-mean K_{zz}, we analyzed the solar cycle response of zonal-mean CO_2 as well as the role of K_{zz} per season. Results show that all seasons show consistently a negative solar cycle response in zonal-mean K_{zz}. We did further analysis on June solstice and found that the negative solar cycle response of K_{zz} can be attributed to anomalies in gravity wave propagation.

Solar Cycle Modulation of MLS Nighttime Ozone near the Secondary Ozone Maximum Layer

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Solar cycle variation of nighttime ozone near the secondary ozone maximum layer is analyzed with Aura Microwave Limb Sounder (MLS) observation, which covers most of the SORCE era (2004 – present). Being produced primarily from the recombination of molecular oxygen (O_2) with single oxygen (O) transported from the lower thermosphere, the variation of the mesospheric nighttime ozone concentration is modulated by the solar cycle driven UV changes. MLS measured nighttime ozone and Solar Radiation and Climate Experiment (SORCE) Solar-Stellar Irradiance Comparison Experiment (SOLSTICE) measured UV show positive in-phase correlations between mesospheric nighttime ozone and UV. The nighttime ozone correlations with temperature is not monotonously positive nor negative but depend on location and season. They are positively correlated with each other except the boreal winter in the NH high latitude region. Similarities in solar cycle variation between nighttime ozone and Carbon Monoxide (CO) in the upper mesosphere is originated from the in-phase solar cycle variation of oxygen (O) and its downward transport.

For this study, MLS nighttime ozone is re-defined by sub-setting MLS ozone product only when the solar zenith angle is greater than 90 degrees from both ascending orbit (10:30 AM local time) and descending orbit (10:30 PM local time). Even though MLS observation does not provide a full coverage of the secondary maximum ozone layer in the upper mesosphere and lower thermosphere, MLS ozone clearly shows solar cycle associated variations in the lower part of the maximum at 0.002 hPa. To confirm the ozone variation at this level, the variation of MLS radiance 25-channel spectral band at 235.71 GHz is also shown.

The North American Monsoon in a Changing Climate

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The North American monsoon is a period of enhanced convective precipitation that occurs in late summer in the Desert Southwest. This presentation will provide a climatological overview of the monsoon and its role in producing extreme weather. Some unique hazards to the region include flash flooding and dust storms (haboobs). Monsoon precipitation associated with organized convection is now becoming less frequent and more extreme, due to long-term observed changes in atmospheric circulation and increases in atmospheric moisture. Such changes can be well represented with high resolution, convective-permitting atmospheric modeling. Recent changes in the North American monsoon appear broadly consistent with how extreme precipitation is changing globally in a warming world.

Session 5. *A New Reference Spectrum for Remote Sensing (formerly Session 6)*

GSICS Applications and the Need of a Solar Irradiance Reference Spectrum

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GSICS is an international organization designed to promote calibration best practices across satellite dataset providers. By radiometrically scaling a target sensor reflected solar band to a well-calibrated contemporary reference sensor such as MODIS and VIIRS. This in turn allows for consistent channel reflectances across a large constellation of sensors, which are necessary to provide uniform cloud, aerosol and land retrievals. Similarly, a reference solar reference spectrum is necessary to assign consistent band radiances among sensors. This can be easily accomplished if sensor agencies use the same solar spectrum. However, the MODIS and VIIRS dataset providers, have used the MCST, Modtran, and Thuillier solar spectrum for MODIS, NPP-VIIRS and NOAA-20-VIIRS, respectively. GSICS and ISCCP next generation projects, would like to promote the use of a recommended solar spectrum used by all dataset providers. Can the solar community provide the state of the art static (outside of the UV) solar spectrum based on measurements and high resolution modeled data? Can continuity be achieved between an existing and a more accurate future solar spectrum by means off a "scaling factor"?

The potential sensor band radiance differences based on several solar spectrum will be presented to illustrate the need for a recommended solar spectrum. The presentation will summarize the GSICS solar spectrum web meetings designed to achieve consensus within the solar community. An example of the NASA-Langley spectral band adjustment factor tool will be presented, to highlight how sensor band spectral differences are taken into account.

The Impact of the TSIS-SIM Data on the OCO-2/OCO-3 Data Analysis

David Crisp *[david.crisp@nasa.gov], Jet Propulsion Laboratory, Cal. Inst. of Technology, Pasadena*

Space-based measurements of shortwave-infrared solar radiation reflected by the Earth and its atmosphere are providing new insights into the sources that are emitting carbon dioxide (CO_2) and methane (CH_4) into the atmosphere as well as the natural sinks that remove these gases. Accurate measurements of the top-of-atmosphere solar spectrum play two critical roles in the analysis of the space-based CO_2 and CH_4 measurements. First, observations of the solar spectrum provide the primary on-orbit radiometric and spectroscopic calibration standard for both individual instruments and for cross-calibrating instruments on different platforms. An accurate, high-resolution description of the solar spectrum is also critical for use in the remote sensing retrieval algorithms needed to estimate the column averaged CO_2 and CH_4 dry air mole fractions from the reflected solar spectra (XCO_2 and XCH_4, respectively.

For OCO-2, a high-resolution solar spectrum is constructed by combining a high resolution solar "transmission spectrum" derived from ground based and airborne FTS measurements (G. Toon personal communication) with a solar continuum derived from space-based instruments. Until recently, we used a solar continuum derived from the data derived from the ATLAS 3 SOLSPEC experiment. However, recent measurements from the Solar ISS and TSIS SIM instruments showed significant discrepancies with the ATLAS 3 SOLSPEC estimates. TSIS SIM results (E. Richard, personal communication) were adopted as the new standard in the latest algorithm build. This changed the continuum level by ~1.3% near 760 nm, 3% near 1610 nm, and 6.5% near 2060 nm. These changes introduced a small reduction in the retrieved surface pressure over land and an increase in the surface pressure retrieved over ocean. The associated changes in XCO_2 were small (< 0.3%) but were positive over land and negative over water. While the changes were small, they were still significant source-sink inversion studies due to their spatial structure.

AERONET – the Ground-based Aerosol Satellite

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AERONET is a global ground-based sun photometer network for characterizing aerosol optical, microphysical and radiative properties at approximately 600 sites supporting satellite aerosol retrieval assessments and global aerosol model validation research. Aerosol optical depth based on direct spectral solar observations in the UV to near-infrared are obtained nominally at 5 minute intervals during daylight hours and from waxing to waning gibbous of the lunar cycle. Sky radiance measurements allows inversion of the radiative transfer equation to retrieve the column integrated absorption and particle size distribution. Twenty-six years of measurement has provided a remarkably consistent, highly accurate and comparable record of aerosol trends over the planet. Likewise with improved processing and automatic quality assurance algorithms near real-time assessment of aerosol properties is possible. This talk will trace the development of the AERONET project from the era of atmospheric correction to remotes sensing of aerosols influence on the climate system, air quality and the role of the solar spectrum in creating this database.

Requirements for a Reference Solar Spectrum for Lunar Calibration Applications

Thomas C. Stone *[tstone@usgs.gov], U.S. Geological Survey, Flagstaff, AZ*

Creating global climate records from space-based Earth observations requires inter-consistency and stability of the satellite sensors' calibrations. The Moon is an ultra-stable diffuse reflector of sunlight that can be used to quantify sensor response changes over time with very high precision and to realize sensor inter-calibrations at reflected solar wavelengths. The fundamental property of the Moon that enables its use as a radiometric reference is the invariant nature of the lunar surface reflectance. Thus, the solar spectral irradiance is a key component of the lunar calibration reference, which constrains its absolute accuracy and defines the spectral content. Recent advances in absolute SSI measurements have opened the possibility of achieving SI-traceable lunar radiometry; however, the lunar calibration application requires higher spectral resolution than these instruments provide. A reference solar spectrum is needed that is scaled to high-accuracy SSI measurements and also retains sufficient solar spectral structure to be used with remote sensing spectrometer instruments. Efforts by the USGS lunar calibration project toward constructing such a reference spectrum have found some additional needs regarding the constituent solar data, which potentially could drive specifications for future SSI measurements.

Progress toward a New, High-Resolution, High-Accuracy Solar Reference Spectrum based on TSIS-1 SIM

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A new, state-of-the-art, daily record of solar spectral irradiance (SSI) commenced in 2018 with the Spectral Irradiance Monitor (SIM) on the Total and Spectral Solar Irradiance Sensor (TSIS-1) mission. Technological advances of TSIS SIM, based on lessons learned from the heritage SIM on the SOlar Radiation and Climate Experiment (SORCE) mission, provide a SSI dataset of higher precision, accuracy, and stability than previously attained. The TSIS SIM absolute scale has been validated to much better than 0.5% accuracy over the majority of the spectrum during robust and extensive pre-launch characterization and calibration efforts.

In this presentation, we focus on incorporating our new understanding of the absolute scale of the solar spectrum into a new reference spectrum for atmospheric radiative transfer and remote sensing applications. Motivation for this development is demonstrated by results showing irradiance differences between TSIS SIM SSI and other, commonly used, reference spectra that reach 8%, particularly in the near-infrared portion of the spectrum. However, some remote sensing applications, such as trace gas retrievals, also require much higher spectral resolution than obtained by TSIS SIM alone. This necessitates renormalizing a high-resolution spectrum, measured at lower radiometric accuracy, to the absolute irradiance scale of TSIS SIM. We apply established techniques to perform this normalization and show initial results of our analysis for the Kitt Peak Solar Flux Atlas and the Solar Pseudo-Transmittance Spectrum.

Thoughts on the Application of TSIS/SORCE SSI in the IPCC CMIP Modeling Efforts: Why the coupled model must be used

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All the modeling centers that participated in the IPCC CMIP modeling effort adopted the same SSI data set, the one by Lean et al. (2011). We compared it (hereafter, L11) with three other SSI data sets, namely the EMPirical Irradiance REconstruction (EMPIRE) by Yeo et al. (2017), the TSIS 1.5-year SSI measurement, and the 14-year SSI measurements by SORCE (MuSIL). While the L11 and EMPIRE agree with each other within 0.8Wm^{-2} for the total solar irradiance, the agreement indeed is achieved by a large offset between the visible and the near-IR bands. At the RRTMG-SW bandwidth, the L11 – EMPIRE difference can be as large 6 Wm^{-2}. Compared to the TSIS and MuSIL SSI, L11 underestimated the irradiance over 0.44-0.63um by 4 Wm^{-2} and overestimated that over 0.76-1.24um by 2-4Wm^{-2}. At higher spectral resolution, it becomes even clear that, in the visible portion of the spectrum, the SSI differences between TSIS and MuSIL is a factor of ten smaller than those between CESM and EMPIRE.

The opposite discrepancies of L11 and TSIS/MuSIL between the visible and near-IR cast a doubt on the use of prescribed-SST runs to assess the solar impact on the climate, as the spectral albedo of snow and ice has a distinctive dichotomy behavior across such two spectral regions. Only fully-coupled run with sea ice interactively responding to the imposed SSI can fully reflect such impact. We used TSIS and MuSIL SSI to constrain the SSI used NCAR CESM, then run different configurations to further elaborate on this point.

Solar Spectral Irradiance during WHPI and Comparison to WHI and WSM

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Solar Spectral Irradiance (SSI) has been measured on a daily basis by the Solar Radiation and Climate Experiment (SORCE) since 2003 and by the Thermosphere Ionosphere Mesosphere Energetics Dynamics (TIMED) mission since 2002. This includes observations during the solar cycle minimum campaigns in 2019 for the Whole Heliosphere Planetary Interactions (WHPI) as well as in 2008 for the Whole Heliosphere Interval (WHI) during the previous minimum (Woods et al., 2009, GRL, 36, L01101). SSI measurements in 1996 during the Whole Sun Month (WSM) campaign are also available from the SSI instruments on the Upper Atmosphere Research Satellite (UARS). In addition to the SORCE and TIMED observations for the WHPI campaign, we will also show data from the Total and Spectral Irradiance Sensor (TSIS) Spectral Irradiance Monitor (SIM) in the 240-2400 nm range. The SSI during these minimum activity levels provide knowledge of the long term changes in the quiet Sun over three solar cycles.

Near Infrared Ground-based Spectrum

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The near-infrared (NIR) part of the solar spectrum is of prime importance for solar physics and climatology, directly intervening in the Earth's radiation budget. Despite its major role, available solar spectral irradiance (SSI) NIR datasets, space-borne or ground-based, present discrepancies caused by instrumental or methodological reasons. We present results obtained from the PYR-ILIOS SSI NIR ground-based campaign carried out at the Mauna Loa Observatory (MLO) in Hawaii (3397 m a.s.l.) during 20 days in July 2016.

The top-of-atmosphere (TOA) NIR SSI is obtained with the Langley-plot method, derived from the Beer-Bouguer-Lambert law. The NIR SSI dataset obtained with the Langley-plot method is presented as well as a detailed error budget and atmospheric sensitivity study.

We demonstrate that the most recent results, from PYR-ILIOS and other space-borne and ground-based experiments, namely TSIS on the ISS, agree and show a NIR SSI lower than the previous reference spectrum, ATLAS3, for wavelengths above 1.6µm.

New Absolute Reference Spectrum SOLAR-ISS2 at 2008 Solar Minimum and its Extension at Very High Resolution (0.01 nm) from 500 nm up to 4200 nm for Atmospheric Modeling and Remote Sensing

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Since April 5, 2008 and up to February 15, 2017, the SOLar SPECtrometer (SOLSPEC) instrument of the SOLAR payload on board the International Space Station (ISS) has performed accurate measurements of solar spectral irradiance (SSI) from the middle ultraviolet to the infrared (165 to 3088 nm). SOLAR-ISS (representative of the 2008 solar minimum) is a solar spectrum based on SOLAR/SOLSPEC data, which has a resolution better than 0.1 nm below 1000 nm and 1 nm in the 1000—3000 nm wavelength range. A new version has been developed, the SOLAR-ISS2 spectrum (SOLAR-ISS v2.0) improved for FUV (<180 nm), MUV near 220 nm and NIR (2.4 to 3 µm). SOLAR-ISS2, extending from 165 to 3000 nm is the more elaborated spectrum presently (with uncertainties evaluated). It is compared with other recent spectra and models. SOLAR-ISS2 was further developed in a very high resolution version (SOLAR-ISS2-HR, 0.01 nm resolution) to serve as a reference for climate models, atmospheric observations (MicroCarb O2, CO2 mission) and planetary atmosphere measurements from 500 to 4200 nm. There are four methods to determine the solar spectrum: theoretical, exo-atmospheric, zero airmass extrapolation, and telluric subtraction. Based on the telluric subtraction approach, an empirical solar linelist has been generated by simultaneous fitting of ATMOS, MkIV, Kitt Peak, Denver U, and TCCON spectra (Toon *et al.*, 2014). The telluric absorptions were fitted using the HITRAN linelist and any remaining airmass-independent absorptions were attributed to the Sun. Together, with a simple lineshape function, this linelist allows the computation of a solar pseudo-transmittance spectra for disk-integrated. From this solar pseudo-transmittance spectra (high resolution) and from the SOLAR/SOLSPEC spectrum (absolute determination at lower resolution), we determine this new reference spectrum at very high resolution (better than 0.01 nm).

Session 6. *Observational Predictions (formerly Session 5)*

How Well Can We Predict Solar Cycle 35?

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Solar Cycle 24 has faded and signs of Solar Cycle 25 are appearing at the solar surface. The number of active regions of the new cycle will begin a rapid rise next year. We have learned much about predicting solar activity in Solar Cycle 24, especially with the data provided by SDO and STEREO. Short-term predictions of solar flares and coronal mass ejections have benefited from applying machine learning techniques to the new data. Mid-range predictions like the arrival times of coronal mass ejections have benefited from a steady flow of data from SoHO, STEREO, and SDO. Longer-term (greater than a year) predictions of solar activity have benefited from helioseismic studies of the plasma flows in the Sun. But predictions made long before the next cycle begins still rely on precursors. I will describe the prediction of the SODA polar field precursor method, which has accurately predicted the last three cycles, for Solar Cycle 25. I will also describe our understanding of the polar regions of the Sun --- the seeds of the next cycle. Some ideas on even longer-term predictions will be presented. These predictions are limited by the growth of the forecast error, which increases until a simpler forecast becomes more accurate. Versions of the climatological average forecast are examples of the simpler forecast.

The Next Five Decades Under the Sun

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The IPCC considers the Sun to be a minor player in recent century-long global warming, the consensus reached after several decades of multi-disciplinary research. But how robust is this consensus? In this overview we will try to condense the complicated series of arguments to reveal the minimal foundations upon which the arguments are made. We then focus on how decadal to millennial solar variations, induced by familiar yet poorly understood hydro-magnetic effects, can be constrained by solar and stellar data in the absence of credible models based upon first principles. Finally, we argue that new solar and stellar observatories combined with machine learning methods will enable the present generation of scientists to predict with more confidence the solar-terrestrial effects that are of concern to modern society.

Session 7. *Looking Ahead – Future Observations of the Sun and Earth*

CLARREO Pathfinder: Mission Overview

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The Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder mission began in 2016 and will demonstrate essential measurement technologies required for climate observations. The mission includes the flight of a reflected solar (RS) spectrometer that will be installed on the International Space Station (ISS) in the 2023 timeframe. CLARREO Pathfinder will demonstrate the ability to calibrate the spectrometer on orbit to a high accuracy with SI-traceability and to inter-calibrate other orbiting instruments. The spectrometer is based on the University of Colorado/LASP's HyperSpectral Imager for Climate Science (HySICS) instrument and is being designed to have a radiometric uncertainty of 0.3% (1-sigma), providing a 3 to 10 times improvement over existing RS instruments. By measuring spectral reflectance with high accuracy the CPF instrument will serve as an on-orbit radiometric reference for operating Earth-viewing sensors, such as CERES and VIIRS. Two-axis pointing, a spectral range from 350 nm to 2300 nm, and a spectral resolution ≤6 nm enable the CLARREO Pathfinder instrument to provide temporal, spatial, angular, and spectral matching of inter-calibration targets, with sampling sufficient to reduce random errors. The inter-calibration method will refine knowledge of target sensor effective offset, gain, non-linearity, spectral response, and polarization sensitivity (as is relevant). We will present an overview of the CLARREO Pathfinder mission and its current status.

SIMBA, Measuring the Earth's Radiation (im)Balance

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The Sun-earth IMBAlance (SIMBA) satellite is a 3U CubeSat that will be launched in Q1 2019. The in orbit demonstration mission's objective is to study the feasibility of monitoring with the same instrument both the incoming solar radiation and the earths outgoing radiation. To achieve this, the main payload sensor is an electrical substitution cavity radiometer designed for absolute measurement of total radiation. To study performance of the instrument in orbit, we will switch between pointing towards the earth, deep space and the Sun. To separate the two different kinds of radiation emitted by the Earth, the payload further consists of black and white flat spectral sensors.

Depending on the outcome of the mission, SIMBA and successors will contribute to the monitoring of the Essential Climate Variables of Total Solar Irradiance and the Earth Radiation Budget. As a long term objective, this should lead to the direct measurement of the Earth radiation (im)balance. This long-term objective is very challenging both in terms of instrument design, characterization and temporal and spatial sampling and at the very least requires measurement from a satellite constellation.

In this talk we will first discuss the general design of the SIMBA CubeSat and the payload. Then we will address the challenges met during the construction and testing phase of the satellite. Finally, we will discuss the mission itself.

Calibrating Space Radiometers to Ground-based TSI Standards

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PMOD/WRC has a long tradition of maintaining standards for ground-based solar irradiance measurements, such as the World Radiometric Reference (WRR). The radiometric scale defined by the WRR has also been transferred to several space radiometers, including the PMO6 on SOVA2, VIRGO, and SOVIM. Special care needs to be taken when transferring the WRR scale to space, as the sensitivity of the radiometer might change in vacuum. On the other hand, using the sun as a source for the calibration reduces the uncertainty of cross-channel calibrations. Moreover, if properly set up the calibration procedure implicitly includes corrections for diffraction, scattering, and spectral sensitivity. We will describe the calibration facilities at PMOD/WRC, present the calibration procedures, as well as discuss its advantages and how it can complement laboratory experiments to calibrate space TSI radiometers.

TSIS-2: Continuing the Solar Irradiance Data Record

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NASA Goddard Space Flight Center is developing the Total and Spectral solar Irradiance Sensor-2 (TSIS-2) as a Class-D mission for launch in 2023. It will provide continuity to the Total Solar Irradiance (TSI) data that extends back more than 40 years as well as the more recent Spectral Solar Irradiance (SSI) data. As emphasized in the 2017 NAS Decadal Survey for Earth Science and Applications from Space, accurate TSI and SSI measurements over many decades are required to understand the Earth's energy balance and detailed processes that affect the climate system. This paper describes the TSIS-2 mission concept and the challenges of carrying out Goddard's first Class-D free-flyer science mission. The two instruments on TSIS-2, the Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM), will be identical to those on TSIS-1 and are being developed by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado. In contrast to TSIS-1, which launched in December 2017 and is currently operating on the International Space Station (ISS), TSIS-2 will be a 3-year mission on a dedicated spacecraft operating in a Sun-synchronous orbit.

The Compact SIM (CSIM), Compact TIM (CTIM), and Future Compact Earth Radiation Budget Instruments

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The Compact Spectral Irradiance Monitor (CSIM) and the Compact Total Irradiance Monitor (CTIM) are CubeSat instruments to demonstrate next-generation technology for monitoring spectral and total solar irradiance. Both instruments include novel silicon-substrate room temperature vertically aligned carbon nanotube (VACNT) bolometers. CSIM, a two-channel 6U CubeSat instrument similar in design to the SORCE and TSIS SIM instruments, was launched in December 2018 and has been operating on-orbit since. The first-light CSIM spectra, taken in April 2019, provided an independent validation of the TSIS SIM solar spectral measurements. Additionally, the CSIM spectral measurements extend to 2.8 μm, providing the first solar-spectral measurements beyond 2.4 μm with <1% radiometric accuracy. The continued observations since first-light are currently being analyzed to investigate on-orbit stability of CSIM.

The CTIM instrument, an eight-channel 6U CubeSat instrument, is currently begin built for a flight in 2021. Like CSIM, the basic design is similar to the SORCE, TCTE and TSIS TIM instruments. It will measure the total irradiance of the sun with an accuracy of <0.01%. An engineering model of the CTIM instrument has been built and tested under flight conditions, and the flight instrument build is in process.

The VACNT bolometer development initiated on the CSIM and CTIM program continues with Black Array of Broadband Absolute Radiometers (BABAR) project. The goal of BABAR is to develop a linear array of miniature bolometers for integration into a future broadband Earth radiation imager. Each element of the BABAR array is operated, like the CTIM and CSIM detectors, as closed-loop electrical substitution radiometers providing high accuracy, stability, and fast response.

TSIS-2 and Beyond

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Following the successful implementation of TSIS-1 on the International Space Station, the follow-on mission, TSIS-2, will continue the space-based solar irradiance record without interruption. While TSIS-2 utilizes the same instrument design and observation concept dating back to SORCE, continuity of the long-term data record requires an updated, agile and flexible approach to these making these measurements.

Miniaturization of the SIM and TIM instruments is being demonstrated through the ESTO Projects CSIM-FD and CTIM-FD with on-orbit verifications of these designs enabling smaller, lower cost missions beyond TSIS-2. This reduces the risk to the TSIS Climate Data Record through leveraging all aspects of the mission with LASP's existing instrument and CubeSat spacecraft designs, satellite operations center, and takes advantage of the increasing number of launch opportunities for small spacecraft.

The FURST Mission

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We describe a new sounding rocket mission, the Full-disk Ultraviolet Rocket SpecTrograph (FURST), planned for launch in 2022. FURST will obtain the first high resolution (R > 20,000), radiometrically calibrated VUV spectra of the Sun as a star, from 120-180 nm. FURST spectra will have applications to solar and stellar physics, climate science, and the interaction of solar UV radiation with comets, moons, and planets. We summarize the scientific priorities, optical design, calibration plan, and status of the FURST mission.