2018 Sun-Climate Symposium

"The State of the TSI and SSI Climate Records at the Junction of the SORCE & TSIS Missions"

Welcome and Introduction

A TSIS & SORCE Status Overview

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Measurements of solar irradiance from space began four decades ago with the launch of the Nimbus 7 satellite that carried the Earth Radiation Budget (ERB) and Solar Backscatter Ultraviolet (SBUV) sensors. Remarkable progress has been made since that time in our ability to monitor ever smaller changes in the Sun's output, integrated over the entire spectrum and in individual wavelength bands, and with increased radiometric accuracy. This has improved our understanding of the Sun's influence in past and present climate, our ability to predict future climate and helped us gain insight into the mechanisms by which the Earth system responds to subtle variations in solar irradiance.

The timing our meeting represents an important juncture in the measurement record of solar irradiance. The Solar Radiation and Climate Experiment (SORCE) recently celebrated the 15-year anniversary of its launch. SORCE not only ushered in advanced capabilities for measuring total and spectral solar irradiance, accompanied by a large number of science achievements, it has persevered for 10 years beyond its scheduled mission lifetime. In so doing, SORCE has helped preserve the 40-year solar irradiance data record from space.

As SORCE winds down, the Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) is just beginning its mission. TSIS-1 was launched to the International Space Station (ISS) on 15 December 2017; commissioning exercises have been underway for the past two-plus months. The SORCE-heritage Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM) on TSIS-1 have both experienced first light. At this meeting, preliminary data from both sensors will be presented. We anticipate that the expected improvements in accuracy, particularly for solar spectral irradiance, will impact Sun-climate studies in the coming decade.

Session 1. The creation, significance, and applications of accurate CDRs

Designing the Climate Observing System of the Future

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Climate observations remain a serious challenge for current and future Earth observations. The number of essential climate variables to measure and monitor is ~ 50, about 10 times the number for weather observations. Observing the critical small decadal changes in those variables commonly requires 10 times the accuracy of weather observations. Maintaining very high accuracy continuous global observations over many decades provides a third challenge. As a result, the world lacks a designed, complete, and rigorous climate observing system. While progress has been made (e.g. WCRP GCOS, NASA Earth Observing System, Copernicus) very serious shortcomings remain (Trenberth et al. 2013).

Given the magnitude of the task, what is the appropriate level of investment? Recent estimates based on narrowing uncertainty in climate sensitivity suggest a value of $10 to $20 Trillion U.S. dollars in net present value at a typical discount rate of 3%. The cost to provide such an advanced climate observing system might require tripling current investments of $4 Billion per year, for 30 years or longer. But compared to its value, the return on investment ranges from 50:1 to 100:1, much higher than typical societal investments.

The need, value, and methods for designing such an observing system have been described in a recently published paper (Weatherhead et al. 2017, AGU Earth's Future). This presentation will summarize that paper as well as interpret the need in terms of the recent U.S. Academy of Sciences Decadal Survey released in January 2018. The Decadal Survey set of quantified climate science objectives allows a measure of how short we remain of the required observations. In most cases, the technology exists, but the resources to apply it do not. How do climate scientists better communicate this need to society as well as the large return on investment it represents?

Continuity and Preservation of Long-Term Synoptic Observations of the Sun

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Heliophysics research community is pushing hard to explore the Sun and its cosmic neighborhood with new instruments in new wavelength bands, with the highest-possible spatial resolution and the fastest time cadence. We justify this by the need to better understand the physics of solar activity and the societal "mandate" to develop a reliable space weather forecast. However, our understanding of solar activity will be incomplete and even distorted, if we do not know how present activity compares with the past and what changes may had been occurring in properties of solar phenomena. The latter necessitates long-term monitoring of solar activity. The success of synoptic observations requires long-term sustainable funding, but unfortunately, we are witnessing an alarming decline in funding levels for these programs. The uniformity of synoptic data also requires careful planning for on-time replacement of aging instruments and their cross-calibration. Equally important is a long-term preservation of existing data, but in absence of proper planning, we may already be witnessing irreversible loss of some important historical datasets. This talk will review the present efforts aimed at addressing the continuity of long-term observations of solar activity including establishing close international collaboration in this area of research.

Properties of Magnetic Elements Derived from HMI Data Compensated for Scattered-Light

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We employ full-disk, scattered-light corrected images from the Helioseismic Magnetic Imager (HMI) to investigate photometric properties of faculae and network. In agreement with results previously obtained from analysis of high spatial resolution observations and simulations on limited fields of view, we find that network regions exhibit in general higher photometric contrast than facular ones. More specifically, for magnetic flux values larger than approximately 300 G, the network is always brighter than faculae and the contrast differences increase toward the limb, where the network contrast is about twice the facular one. For lower magnetic flux values, pixels in network regions appear always darker than facular ones. Contrary to reports from previous full-disk observations, and to synthetic spectra obtained with one-dimensional atmosphere models employed for irradiance reconstructions, we also find that network contrast exhibits a higher center-to-limb variation. We estimate that the facular and network contribution to irradiance variability of the current Cycle 24 is overestimated by at least 11% due to the photometric properties of network and faculae not being recognized as distinctly different.

Climate Data Records – History, Status, and Future

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The NOAA Climate Data Records (CDR) Program began in 2003 by engaging the National Academies to help define a CDR and develop guidelines for establishing an operational CDR program. First funding for the CDR program was received in 2007 and, in collaboration with the scientific community, more than 41 CDRs have now been transitioned to initial operating capability (IOC). The process for attaining IOC status will be outlined as well as a more recent example of transitioning the International Satellite Cloud Climatology Program (ISCCP) to full operating capability (FOC). A key in the progression from research to IOC and then FOC is an ongoing assessment of the qualities that ensure openness and transparency in CDR processing using a maturity matrix. Maturity assessment approaches to data storage and archival are increasingly being used across a range of disciplines including finance, medical records, and the geophysics.

Although the CDR Program was originally created for satellite data, a European program has adapted the CDR maturity assessment matrix approach and demonstrated that it is applicable also to in situ and climate re-analysis data. This expanded assessment approach is called the system maturity matrix and has been used to assess European capabilities for the Copernicus Climate Change Service. Maturity matrix approaches help objectively assess software engineering, metadata and preservation, and usage aspects of a CDR. However, they do not provide a metric of fitness for purpose of a given CDR. An application performance metric has been proposed to assess fitness for purpose and initial results of applying this metric will be presented.

Finally, application of the maturity matrix and application performance metric to global surface temperature records will be shown and discussed with an emphasis on the NOAA products. The use of metrics is applied and assessed using the Global Climate Observing System Essential Climate Variable (GCOS ECV) CDR requirements.

Potential of Satellite Spectral Solar Irradiance (SSI) Measurements in Ground-based Remote Sensing of Atmospheric Aerosols and Trace Gases

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Retrieval of the amounts and properties of atmospheric aerosols and trace gases using direct sun measurements from ground-based instruments, such as sun photometers and spectrometers, requires reliable top of the atmosphere (TOA) solar signal (V0□) values at specific wavelengths (□) to achieve acceptable absolute accuracy in the retrieved quantities. Typically, such V0□ values are determined through instrument calibration such as by pointing to the Sun on a clear day across a wide range of solar zenith angles, preferably from highly elevated locations in order to reduce the effect of the overlying atmosphere on the extraterrestrial solar signal, and deriving V0□ from linear regression fitting to logarithmic transformations of the measured signals through a process known as the Langley calibration method. Another method typically used is to transfer calibration from a reference instrument that has been previously calibrated through the Langley method to another instrument by conducting solar measurements concurrently with both instruments, then deriving V0□ for the new instrument by ratioing between its signal measurements and those of the reference instrument. On the other hand, since 2003, NASA's Solar Radiation and Climate Experiment (SORCE) mission has been measuring V0□ from space (without interference from Earth's atmosphere) using its Spectral Irradiance Monitor (SIM) instrument. These Spectral Solar Irradiance (SSI) measurements cover the wavelength (□) range of 300 to 2400 nm at spectral resolutions of 1–27 nm at relatively high accuracy, which is expected to be further improved by the SIM instrument on the Total and Spectral Solar Irradiance Monitor (TSIS-1) mission that was successfully launched on December 15, 2017 for deployment on the international Space Station (ISS) to continue the SSI data record. In this presentation, we will discuss preliminary results of sensitivity studies to determine how these TOA direct measurements of SSI (i.e. V0□) could be used to improve the calibration of ground-based solar-pointing instruments in order to improve their atmospheric parameter retrieval accuracy.

Sea Ice Concentration CDR at the National Centers for Environmental Information

Ann Windnagel *[ann.windnagel@nsidc.org], Walt Meier, and Florence Fetterer; National Snow and Ice Data Center in CIRES, University of Colorado, Boulder, CO USA*

The NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration is a CDR that provides a consistent daily and monthly-averaged record of the fraction of ocean covered by sea ice for both the North and South poles. It spans 9 July 1987 to present and meets current standards and guidelines for climate data records. It is based on a long-term passive microwave satellite record on a 25 km grid that is superior to other measurement methods such as in situ or ship-based that cannot reproduce the spatial and temporal coverage of these satellites. This talk will present a basic description and characterization of this ice concentration CDR along with the challenges of creating and maintaining such a record. In addition, a discussion of the scientific relevance of this CDR and its validation with other sea ice products will be included.

TSI Data for the CERES Climate Data Record and the FLASHflux Environmental Data Record

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The Clouds and the Earth's Radiant Energy System (CERES) instruments aboard the Terra, Aqua and Suomi-NPP satellites measure energy emanating from the Earth's surface-atmosphere system in the shortwave (wavelengths less than 4.5 micrometers), infrared window (wavelengths between 8 and 12 micrometers), and total (all wavelengths). To balance this energy equation, CERES incorporates measurements of the total solar irradiance (TSI) provided by the Total Irradiance Monitor (TIM) instrument aboard NASA's Solar Radiation and Climate Experiment (SORCE) satellite. This balance allows for an overall accounting of the planetary energy budget, and thus, can reveal imbalances within the system, whether they are local, regional or global.

The CERES measurements are also used in the Fast Longwave and Shortwave Radiative Fluxes (FLASHFlux) sub-project within CERES to provide CERES-like fluxes within 7 days of satellite observations. This rapid response necessitates use of CERES data with calibrations that have not been fully adjusted for changes in the instrument gains and the spectral response functions over the last six to twelve months. Since the FLASHFlux data is a short-term environmental data record, rather than a climate data record, some degree of accuracy can be exchanged for rapid data availability. Moreover, experience has demonstrated that recent changes in the gains and instrument response functions are usually quite small, having negligible impact on the environmental data records. While rapidly available versions of the CERES observations, MODIS-derived cloud properties, and other meteorological parameters are available, the remaining variable, the total solar irradiance (TSI), is only available seven days after being measured. Currently, a simple method is used to predict the total solar irradiances ten days into the future based on running means of the latest TSI data. This method, while reasonably accurate for quiet solar conditions, is incapable of catching significant departures from the nominal trend in the TSI data.

Special Presentation

Big Bear Solar Observatory – Cool Toys for Observing Our Warm Star

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Fundamental discoveries in solar physics rely on advances of instrumentation. This includes observations that advance the state of the art in resolution and cadence, and open new wavelength domains. NJIT (New Jersey Institute of Technology) has built, and now operates the highest-resolution solar telescope ever built − the Goode Solar Telescope (GST, formerly the New Solar Telescope, NST) at Big Bear Solar Observatory (BBSO), California. This 1.6-meter clear aperture, off-axis GST is the first facility class solar telescope built in the U.S. in a generation and will dominate U.S. ground-based solar observations until the 4-meter DKIST comes online. Benefitting from the long periods of local excellent seeing at Big Bear Lake, the GST, equipped with high-order adaptive optics (AO), routinely collects diffraction-limited spatial resolution (~ 0.1″) photometric, spectroscopic and/or polarimetric data, with a high cadence, across the spectrum from 0.4 - 5.0 μm. Since its regular operation in 2010, it has provided the community with open access to observations of the photosphere, chromosphere and up to the base of the corona with the unprecedented resolution, targeting at the fundamental nature of solar activity and the origin of space weather. This presentation reviews the process of design, construction and commissioning of the GST, and reports the up-to-date progress on its next generation instruments including the AO systems (AO-308, GLAO & MCAO), the Near-InfraRed Imaging Spectro-polarimeter (NIRIS), the Visible Imaging Spectrometer (VIS), the Broad-band Filter Imager (BFI), and the Cryogenic Infrared Spectrograph (CYRA). Some significant scientific results from GST will be highlighted.

Session 2. The state of the TSI and SSI climate records near the end of the SORCE Mission

PREMOS/PICARD TSI Data Version 2 and New TSI Absolute Value from First Light of CLARA/NorSat-1

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PREMOS was a PMOD/WRC experiment on the French PICARD mission, which measured Total Solar Irradiance and spectral irradiance in three selected wavelength bands. Here we discuss the PREMOS TSI measurements, which cover almost 4 years. In Ball et al. (J. Space Weather Space Clim., 6, A32, 2016) we evaluated the stability of the PREMOS measurements between October 2011 and February 2014 to be 0.02 W/m^2 over 2.3 years, or 6 ppm per year. This makes the PREMOS measurement accurate enough to assess the diverging trends of the TIM/SORCE and VIRGO/SOHO data series over the PREMOS time period, which is of special interest as TIM had an operational gap at the end of this period. We concluded that the PREMOS data support TIM to have a better stability than VIRGO. For that assessment, we used ratios of ratios of head A to head B, which limited the evaluation to the above mentioned 2.3 years. The new PREMOS data version presented here relies on comparison to measurements by three other instruments operational at the beginning of the PREMOS time, i.e. in July and September 2010, to derive a refined sensitivity change of the PREMOS cavities as a function of exposure time. With an improved sensitivity correction, the PREMOS data can now be compared to other data series over the full PREMOS 3.7 years period from July 2010 to March 2014.

The Compact Lightweight Absolute Radiometer (CLARA) is an absolute radiometer built by PMOD/WRC, which has been launched on July 14, 2017 as payload on the Norwegian micro satellite NORSAT-1. CLARA was end-to-end calibrated against the SI traceable cryogenic radiometer of the TSI Radiometer Facility (TRF) in Boulder (Colorado). The measurement uncertainties for the three SI-traceable TSI detectors are 567, 576, and 912 ppm (Walter et al., Metrologia 54, 674, 2017)), for heads A to C respectively. From first light on August 25, 2017 we derive a new absolute value of the Total Solar Irradiance and compare it to the values measured by VIRGO/SOHO and TIM/SORCE.

Twenty-One Years of Total Solar Irradiance from VIRGO on SoHO

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The experiment VIRGO on the ESA/NASA mission SoHO was launched on December, 5 1995 and the continuous observations of TSI started in late January 1996. Two radiometer PMO6V-A and B and DIARAD with 2 channels observe TSI. PMO6V-A provides a value every minute (in the shuttered during 23 days at the beginning every 2 minutes) and DIARAD every 3 minutes. As SoHO is at a halo orbit around L1 solar observations are never interrupted. In June 1998 SoHO was lost due to an operational mishap and no data are available until October 1998, when it was successfully rescued and observations of the Sun restarted for all but one instrument (C1 of LASCO). In late 1998 the operation of SoHO was reconfigured without needing the giros anymore and no science data could be transmitted during this period. These periods, called the summer (103 days) and winter (43 days) vacations of SoHO, are the only prolonged ones when no science data were available. They were some other shut-downs of SoHO and together with a few switch-offs of VIRGO (mostly due to latch-up) we have lost about 3.8% of the continuous hourly TSI values during the whole mission (half is due to the SoHO vacations).

The level-1 DIARAD data are evaluated at the VDC with only minor changes during the mission. Until the end of 2017 the level-1 PMO6V were evaluated with the level-1 IDL program developed in 1996 by Wolfgang Finsterle. Now a new program is used which takes the temperature dependence of the power measurements into account and treats missing temperatures during the 'keyholes' adequately. More importantly, the evaluation of the open/closed power during the cover operation is now properly treated. The absolute value of VIRGO TSI is based on the new characterization of the PMO6V (see poster) and my earlier one of DIARAD, because the VIRGO value is an average of the two radiometer. The corrections due to degradation (level-2 hourly and daily record) the latest version is still in use.

The TIM Trilogy

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The Total Irradiance Monitor (TIM) now has three versions on-orbit. The first of this modern-era total solar irradiance (TSI) measuring instrument was designed for the SORCE mission and has been producing data since early 2003. The TSI Calibration Transfer Experiment (TCTE), a refurbishment of a SORCE-era TIM, was launched in 2013 to provide overlap between the aging SORCE mission and the future Total and Spectral Solar Irradiance Sensor (TSIS). That “future” commenced in Dec. 2017 with the launch of the refined TSIS/TIM now on the ISS.

I will discuss the results from this trilogy of TIMs over their 15-year measurement period and summarize the performance of and the differences between the three instruments.

Methodology for Creating a TSI Composite

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The production of accurate total and solar spectral irradiance records for long-term Earth-climate or solar-variability studies heavily relies on our ability to merge disparate observations into one single composite. To accomplish this, we have recently developed a new methodology for creating composites that has several advantages over previous methods. Our approach is probabilistic and statistically driven. First, we derive time- and scale-dependent uncertainties from the individual observations. Next, we use weighted contributions from all available data sets at any one time rather than a binary selection, with the weighting determined by those statistically-driven, scale-dependent uncertainties. We are presently using this approach to create the new TSI composite. In this presentation we shall explain its different steps, show what new insight it gives into the uncertainty on long-term variations, and reveal how easily it can be generalized to other solar datasets.

TSIS SIM Solar Spectral Irradiance: First Light and Early Observations

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On December 15, 2017 the *Total and Spectral Irradiance Sensor* (TSIS) was launched to the International Space Station (ISS) and was installed on Dec 31, 2017 with instrument commissioning activities beginning in early January 2018. The TSIS SIM is the next generation SSI instrument that will carry forward the SSI data record (covering 200-2400 nm) that began with SORCE SIM. In this talk we present the very early mission results that marks the beginning of the new era of SSI observations of the TSIS SIM and we also include comparisons to the overlap with SORCE SIM.

Update on the SATIRE Model

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The main goals of the irradiance models are to understand the mechanisms of the irradiance changes and to extend the available records of direct measurements in wavelength and time domains. It is now recognized that the irradiance variability on all observable time scales longer than one day is dominated by the solar surface magnetism. Thus, the most direct way of modelling the irradiance variability is through the employment of the observed surface distribution of the solar magnetic features (i.e. the magnetograms). This underlies the concept of the SATIRE model over the space era, while going back in time is only possible with proxies of solar magnetic activity. We will describe the current status of the model, compare the output with the available observations and alternative models and discuss the remaining uncertainties.

Observational Constraints on Irradiance Models in the Ultraviolet

Romaric Gravet *[romaric.gravet@cnrs-orleans.fr], Matthieu Kretzschmar, and Thierry Dudok de Wit; LPC2E, CNRS and University of Orléans, Orléans, France*

Understanding solar irradiance variations, in particular in the ultraviolet wavelength range, is essential for climate modeling and for space weather. Solar irradiance models are precious for reconstructing the solar spectral irradiance in the absence of observations or when the latter lack stability. However, they come with their assumptions. Here we aim at constraining these in the UV by characterizing the contrast of solar magnetic features at different wavelengths. We consider solar images taken by the Solar Dynamics Observatory between 2010 and 2016. From these we extract the contrast, which we study as a function of position, magnetic field strength and time. We find that photometric thresholds are necessary to properly segment solar structures, mainly in the UV, because of the coexistence of both dark and bright structures for the same value of the magnetic field. Some pixels that are classified as quiet-Sun by the SATIRE-S model actually belong to faculae, but they are too few to have a significant impact on irradiance reconstructions. Our results highlight the importance of having multi-wavelength observations for better constraining the identification of structures. The distinction between network and faculae is essential for such reconstructions, and using a network with magnetically variable contrast and other structures with constant contrast is a valid simplification to reconstruct the solar irradiance. Finally, we find no evidence for solar cycle variations in the contrast.

The Solar Ultraviolet Spectral Slope during the Last 270 Years

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The radiative output of the Sun is variable on different time scales, but the most prominent variability over the last few centuries has been the 11-year cycle. Total Solar Irradiance shows changes of around 0.1% during the 11-year cycle, with different spectral regions (e.g. UV) changing by different amounts. Solar UV variability is extremely important for the stratospheric ozone, which has an impact on Earth's atmospheric structure and dynamics through radiative heating and ozone photochemistry.

We use the SOLSTICE/SORCE data to investigate the variability in FUV and MUV during the descending phase of cycle 23 and ascending phase of cycle 24. We introduce the [FUV-MUV] color index to measure the solar UV spectral slope and study its dependence on solar activity using the Mg II index Bremen composite and the sunspot number. We find a clear correlation between the color and Mg II index, as well as a difference in the UV spectral slope during the descending phase of cycle 23 and ascending phase of cycle 24, which we attribute to a residual uncorrected time-dependent performance of SOLSTICE UV channels. We use the correlation between the color and Mg II index to reconstruct the solar UV spectral slope between 1978 and today, and the correlation between the color and the sunspot number to reconstruct the slope between 1749 and today.

The NOAA/NCEI Solar Irradiance Climate Data Record: Recent Advances and Comparisons with Independent Datasets

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The Naval Research Laboratory's (NRL) solar variability models estimate total solar irradiance (TSI) and solar spectral irradiance (SSI) changes from quiet Sun conditions due to the presence and evolution of bright faculae and dark sunspots are present on the solar disk. The NRLTSI2 and NRLSSI2 models are constructed from linear regression of proxies of solar sunspot and facular features with irradiance

observations from the SOlar Radiation and Climate Experiment (SORCE). These models were transitioned in 2015 as the Solar Irradiance Climate Data Record to the National Oceanographic and Atmospheric Administration's National Centers for Environmental Information Climate Data Record (CDR) Program. This Solar Irradiance CDR, operationally-produced and updated approximately every three months by the Laboratory for Atmospheric and Space Physics (LASP), is made available from 1610 to the present as yearly-average values and from 1882 to the present as monthly- and daily-averages, with associated time and wavelength-dependent uncertainties.

A recently released revision of the Solar Irradiance CDR (v02r01) reduces uncertainties in estimated irradiances due to uncertainties in sunspot darkening, especially prior to 1980. We discuss these improvements and present comparisons between independent sunspot darkening proxies and between modeled irradiance estimates and observations by SORCE, the Ozone Monitoring Instrument (OMI), and the recently launched Total and Spectral Solar Irradiance Sensor (TSIS-1). We have also extended the NRLTSI2 and NRLSSI2 models back in time from 1610 to 850 with cosmogenic irradiance indices, using parameterizations of the Solar Irradiance CDR record during the time period after 1610. We compare these new historical estimates with the irradiances that the Paleoclimate Model Intercomparison Project (PMIP4) recommends for use in simulations of climate change in the pre-industrial millennium. Finally, we discuss new advances in statistical modelling of irradiance variability driven by progress in identifying the causes of differences on solar cycle timescales between the NRL2 models and SORCE observations, relying on the total and Lyman alpha irradiances, which exhibit unprecedented long-term repeatability.

Decoupling Solar Variability and Instrument Trends using the Multiple Same-Irradiance-Level (MuSIL) Analysis Technique

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OBJECTIVE. Understanding the long-term variations of the solar spectral irradiance (SSI) over time scales of the 11-year solar activity cycle and longer is critical for many Sun-Earth research topics. There are satellite measurements of the SSI since the 1970s that contribute to understanding the solar variability, with most of these SSI measurements in the ultraviolet and only recently in the visible and near infrared since 2003. A limiting factor for the accuracy of the previous results is the uncertainties for the instrument degradation corrections, for which there are fairly large corrections relative to the amount of solar cycle variability at some wavelengths. The primary objective of this investigation has been to separate out solar cycle variability and any residual uncorrected instrumental trends in the SSI satellite measurements from the Solar Radiation and Climate Experiment (SORCE) mission and the Thermosphere, Mesosphere, Ionosphere, Energetic, and Dynamics (TIMED) mission.

METHODOLOGY. A new technique called the Multiple Same-Irradiance-Level (MuSIL) analysis has been developed that examines a SSI time series at different levels of solar activity to provide long-term trends in a SSI record, and the most common result is a downward trend that is most likely from uncorrected instrument degradation. The SSI record is then updated with this residual instrumental trend to provide a more accurate solar cycle variability result.

RESULTS. This technique has been applied to each wavelength in the SSI records from SORCE (2003-present) and TIMED (2002-present) to provide new solar cycle variability results between 27 nm and 1600 nm with about 1 nm resolution at most wavelengths. This technique applied to the highly accurate Total Solar Irradiance (TSI) record indicates that this analysis can provide a relative uncertainty of about 5% of the true solar cycle variability. The MuSIL results are further validated with the comparison of the new solar cycle variability results from different solar cycles.

The New Observational Solar Spectral Irradiance Composite, Updates and Related Activities

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Variations in the solar spectral irradiance (SSI) are an important driver of the chemistry, temperature, and dynamics of the Earth's atmosphere and ultimately the Earth's climate. To investigate the detailed response of the Earth's atmosphere to SSI variations, a robust SSI dataset is needed. We present the recently published observational SSI composite that is based on 20 space instruments. It has been built by using a probabilistic approach taking into account the scale-dependent uncertainty of each available SSI observation. We compare the variability of this composite with available SSI reconstructions and discuss the respective modeled responses in the Earth's atmosphere. The next step is to improve and update the composite. A summary of these and related activities will be given.

Improved Long-Term Spectral Irradiance Record from Aura/OMI

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The Ozone Monitoring Instrument (OMI) on the Aura satellite provides global measurements of atmospheric trace gases, also collecting daily solar spectral irradiance measurements over 265-500 nm wavelength range. The long lifetime (13+ years) and exceptional stability of OMI has enabled us to develop a high quality SSI record covering all of the solar cycle 24. We have recently revised the OMI degradation model by utilizing data from multiple on-board diffusers and assuming consistency between solar minima. The improved OMI SSI data now resolve solar variability at the 0.1% (or better) level on both solar rotational and solar cycle time scales. These highly accurate and spectrally resolved (0.5 nm grid) measurements offer new opportunities for evaluating model assumptions.

New Solar Reference Spectrum SOLAR-ISS and Variability from SOLAR/SOLSPEC – Nine Years of Observations of Solar Cycle 24

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For 9 years since April 5, 2008 and until February 15, 2017, the SOLSPEC (SOLar SPECtrometer) spectroradiometer of the SOLAR facility on the International Space Station (ISS) performed accurate measurements of Solar Spectral Irradiance (SSI) from the far ultraviolet to the infrared (165 nm to 3000 nm). These measurements, unique by their large spectral coverage and long-time range, are of primary importance for a better understanding of solar physics and of the impact of solar variability on climate (via Earth's atmospheric photochemistry), noticeably through the "top-down" mechanism amplifying ultraviolet solar forcing effects on the climate (UV affects stratospheric dynamics and temperatures, altering interplanetary waves and weather patterns both poleward and downward to the lower stratosphere and troposphere regions). SOLAR/SOLSPEC, with almost 9 years of observations covering the essential of the unusual solar cycle 24, followed UV temporal variability and established a new reference solar spectra from UV to IR (165-3000 nm). A complete reanalysis of data was possible thanks to revised engineering corrections, improved calibrations and advanced procedures to account for thermal influence, aging (degradation) and pointing corrections. These intensive ground and space calibrations allowed a proper evaluation of uncertainties on these measurements. Results, the new absolute reference spectrum (SOLAR-ISS) and UV variability, are presented and compared with other measurements (WHI, ATLAS-3, SCIAMACHY, SORCE/SOLSTICE, SORCE/SIM) and models (SATIRE-S, NRLSSI2).

Session 3. Next generation of solar and atmospheric observations

Optimizing Climate Observations for Targeted Results

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Solar and climate observations are the critical foundation for understand the current and future Earth. The current observing system is inadequate to address the multitude of questions that need to be addressed about seasonal variability and long-term changes. The scientific community is addressing prioritization in order to assure that the most important climate observations will be gathered in the future. One method for prioritizing observations was presented in Weatherhead et al. (2017) and suggests that observations should be planned around the seven World Climate Research Program's "Grand Challenges." The framework suggests that three types of observations should be considered: long-term observations such as those that can be used for trend detection; short-term observations—including campaigns—that can be used to understand processes; and those observations that are critical to supporting seasonal forecasting.

This prioritization will assure that the most important scientific challenges related to climate will be addressed. The WCRP Grand Challenges include water availability, climate sensitivity, carbon cycle, extreme events, melting ice, seasonal forecasting and coastal impacts remain a serious challenge for current and future Earth observations. These priorities represent the most serious societal and scientific challenges facing the world. Without innovation and careful planning of observations, these challenges will not be met in a timely manner. By identifying the critical observing needs—especially if the appropriate observing capability does not exist—innovation may arise to meet the needs.

This effort to prioritize needed observations should not be limited by current technologies or current budgets. Any proposed technology should, however, be rigorously evaluated by independent evaluation to assure that the observing system is sufficient for the proposed goals. Significant care needs to be taken with spatial coverage and long-term accuracy to meet the needs of climate research and products.

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission: Status, science, advances

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The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission is a strategic climate continuity activity that will not only extend key heritage ocean color, cloud, and aerosol data records, but also enable new insight into oceanographic and atmospheric responses to Earth's changing climate. The primary PACE instrument will be a spectroradiometer that spans the ultraviolet to shortwave infrared region at 5 nm resolution with a ground sample distance of 1 km at nadir. This payload will be complemented by two cubesat-sized multi-angle polarimeters with spectral ranges that span the visible to near infrared spectral region. Scheduled for launch in 2022, this PACE instrument suite will revolutionize studies of global biogeochemistry, carbon cycles, and hydrosols / aerosols in the ocean-atmosphere system. Here, I present a PACE mission overview, with focus on instrument characteristics, core and advanced data products, and overarching science objectives.

Multi-Angle Imager for Aerosols (MAIA): Observations, measurements, and science

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Aerosols are associated with uncertainty in climate prediction and cardiovascular and respiratory disease. The complexity of aerosol impacts is largely due to their heterogeneity in composition and variability in space and time. The past two decades have witnessed major advances in our ability to map aerosol abundances and their radiative impacts from space. Instruments such as the Multi-angle Imaging SpectroRadiometer (MISR) and Moderate resolution Imaging Spectroradiometer (MODIS) have also been used to estimate human exposure to near-surface particulate matter (PM) concentrations.

Current efforts in aerosol remote sensing are aimed at improving our ability to characterize particle type. Recent technology advances enable integrating passive multispectral, multiangular, and high-accuracy polarimetric measurement methodologies into a single sensor. Previous experience with MISR, other satellite instruments (e.g., Polarization and Directionality of Earth's Reflectances, POLDER), and airborne sensors such as JPL's Airborne Multiangle SpectroPolarimetric Imager (AirMSPI), demonstrate the value of spatially resolved multiangular imaging. As part of the Earth Venture Instrument program, NASA selected the Multi-Angle Imager for Aerosols (MAIA) investigation in 2016. The MAIA instrument extends MISR's multiangular visible and near-infrared (VNIR) spectral coverage to 14 bands between the ultraviolet to shortwave infrared; three of the bands are polarimetric to enhance sensitivity to aerosol size and composition.

Unlike MISR, MAIA is a targeting instrument. Its primary focus is on investigating the health impacts of different types of airborne PM, including sulfates, nitrates, organic carbon, black carbon, and dust. Primary targets for epidemiological studies include major cities around the world. Secondary target areas would also be observed for a variety of scientific purposes, including studies of air quality, climate, and the interactions between aerosols and clouds. MAIA launch is expected to occur no earlier than mid-2021. The decision to implement MAIA will not be finalized until NASA completes the National Environmental Policy Act process.

The Compact SIM (CSIM) and Compact TIM (CTIM) 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, has a planned launch in late 2018 and a target two-year operation life. It will monitor solar spectral irradiance from 200-2400nm with an accuracy of <0.25%. To achieve this accuracy, it will be calibrated in the same facility as TSIS SIM, the LASP Spectral Radiometry Facility. TSIS SIM will have been performing solar observations for approximately nine months by the launch of CSIM, so the direct comparison of initial solar observations of CSIM to the concurrent TSIS SIM observations will allow us to independently validate the degradation-correction scheme in place on TSIS SIM. Then, during the 2-year CSIM mission, we can use TSIS SIM as reference to independently test the on-orbit degradation correction scheme of CSIM.

The CTIM instrument, a four-channel 6U CubeSat instrument, is currently in the development phase. 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%. The underlying technology, including the silicon VACNT bolometers, has been demonstrated at the prototype-level. The design of the CTIM instrument and CubeSat are currently being finalized. In 2018-2019 we will build, and environmentally qualify, a CTIM instrument in that will be ready for a future flight opportunity.

The RAVAN CubeSat Mission: On-orbit results

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The small imbalance between the incident solar irradiance and Earth-leaving fluxes of total and shortwave solar-reflected energy is vital to understanding and predicting climate change. Accurately quantifying the spatial and temporal variation of Earth's outgoing energy from space is a challenge—one potentially rendered more tractable with the advent of multipoint measurements from small satellite or hosted payload constellations. The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) 3U CubeSat, launched November 11, 2016 and still operating over a year later, is a pathfinder for a constellation to measure the Earth's energy imbalance. Funded by NASA's Earth Science Technology Office, the objective of RAVAN is to establish that compact, broadband radiometers calibrated to high accuracy can be built and operated in space for low cost. We present a (brief) overview of the mission and on-orbit results demonstrating RAVAN's two key technologies. First, we show measurements of the solar irradiance and Earth's outgoing energy with radiometers that use vertically aligned carbon nanotube (VACNT) absorbers. VACNT forests are some of the blackest materials known and have an extremely flat spectral response over a wide wavelength range. The measurements are made at both shortwave, solar wavelengths and in the thermal infrared. Second, we show the performance of two gallium phase-change cells that are used to monitor the degradation of RAVAN's radiometer sensors. A 3-axis controlled CubeSat bus allows for routine solar and deep-space attitude maneuvers, which are essential for calibrating RAVAN's Earth radiation measurements. RAVAN also demonstrates partnering with a commercial vendor for the CubeSat bus, payload integration and test, and mission operations. This paradigm has allowed us to focus on technology development essential to the new Earth measurement.

Absolute Radiometers on Upcoming TSI and Future EO Missions

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Even though the TSI is an essential climate variable it is often difficult to find suitable space missions for ensuring the continuity of the TSI data record. Solar research missions nowadays focus on high-resolution imaging. With the Davos Digital Absolute RAdiometer (DARA) PMOD/WRC has developed a TSI radiometer to be used in wider range of mission environments. Thanks to its versatile design DARA-type radiometers have been selected to fly on such diverse missions like the ship-tracking micro-satellite NORSAT-1 (Norwegian Space Centre, launched July 2017), the FY-3E meteorological observatory (China Meteorological Administration, 2019) and the PROBA-3 occulter spacecraft (ESA) with its highly eccentric orbit and tight attitude stability requirements. Additionally, a modified version of the DARA will be part of the EAGER mission proposal to ESAs Earth Explorer program to measure the Earths radiation imbalance. We will present the mission concepts and how the DARA can meet the different science requirements, including the long-term continuation of the TSI data record.

A FURST Look at the VUV Sun as a Star

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Hubble Space Telescope spectra for Sun-like stars are of such quality that we now know the input of radiation from α Cen A to our solar system far better than that of the Sun. We have therefore proposed the

Full-Sun Ultraviolet Rocket Spectrometer (FURST) to obtain the first moderate resolution (R > 10^4), radiometrically calibrated VUV spectrum of the Sun-as-a-star. Our immediate science goal is to understand better the processes of chromospheric and coronal heating. The solar spectrum we obtain will enable us to understand the interaction of solar UV radiation with solar system bodies, the nature of magnetic energy dissipation as a Sun-like star evolves, and the dependence of magnetic activity on stellar mass and metallicity. We present the instrument design, scientific prospects, and broader impacts of the mission.

Total and Spectral solar Irradiance Sensor (TSIS) NASA Project Status

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TSIS-1 studies the Sun's energy input to Earth and how solar variability affects climate. TSIS-1 will measure both the total amount of light that falls on Earth, known as the total solar irradiance (TSI), and how that light is distributed among ultraviolet, visible and infrared wavelengths, called solar spectral irradiance (SSI). TSIS-1 will provide the most accurate measurements of sunlight and continue the long-term climate data record.

TSIS-1 includes two instruments: the Total Irradiance Monitor (TIM) and the Spectral Irradiance Monitor (SIM), integrated into a single payload on the International Space Station (ISS). The TSIS-1 TIM and SIM instruments are upgraded versions of the two instruments that are flying on the Solar Radiation and Climate Experiment (SORCE) mission launched in January 2003.

NASA Goddard's TSIS project responsibilities include project management, system engineering, safety and mission assurance, and engineering oversight for TSIS-1. TSIS-1 was installed on the International Space Station in December 2017. At the end of the 90-day commissioning phase, responsibility for TSIS-1 operations transitions to the Earth Science Mission Operations (ESMO) project at Goddard for its 5-year operations.

NASA contracts with the University of Colorado Laboratory for Atmospheric and Space Physics (LASP) for the design, development and testing of TSIS-1, support for ISS integration, science operations of the TSIS-1 instrument, data processing, data evaluation, calibration and delivery to the Goddard Earth Science Data and Information Services Center (GES DISC). TSIS data products will be made available to the public through the GES DISC.

NASA is committed to long-term monitoring of total and spectral solar irradiance and is currently studying implementation alternatives for a follow-on mission, designated TSIS-2, to continue this long-term data record.

Session 4. Impacts of solar variability on the terrestrial environment during SC24

Impact of the 11-year Solar Cycle at the Earth's Surface

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The surface response to the 11-year solar cycle signal over the Atlantic / European sector has been an interesting but controversial research topic. There is evidence for 11-year variability in the North Atlantic Oscillation (NAO), a pattern of pressure anomalies that essentially govern the behavior of the NH mid-latitude jet-stream and hence much of the weather that arrives over Europe. However, skeptics point to the fact that the signal appears to be present in some periods but not others, and suggest the signal may be a random artifact. Analysis of long datasets is therefore required, and a better understanding of the influence mechanism(s) that might explain why it is evident in some periods and not others. An analysis of an extended dataset back to 1660 will be described, that shows an 11-yr signal in mean sea level pressure, related sea surface temperatures and patterns of atmospheric blocking. We confirm the presence of an 11-yr signal throughout the data period, but the amplitude and lag of the response exhibits decadal variations. Mechanisms will be discussed in terms of solar influence via UV changes and their effect on stratospheric temperatures and wind structures. The surface response to this stratospheric forcing is generally synchronous with the 11-year irradiance forcing. An additional mechanism is proposed, involving atmosphere-ocean coupling, that results in a peak response that lags the forcing by ~3-4 years. The overall observed signal is the result of a mixture of these mechanisms and appears to depend on both the amplitude of the solar forcing and the strength of the ocean feedback process which itself exhibits decadal-scale variability.

Lagged Correlation between the NAO and the 11-Year Solar Cycle: Forced response or internal variability?

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Very recently, the North Atlantic Oscillation has been suggested to respond to the 11-year solar cycle with a lag of a few years. The solar/NAO relationship provides a potential pathway for solar activity to modulate surface climate. However, a short observational record paired with strong intrinsic variability of the NAO raise questions about the robustness of the claimed solar/NAO relationship. For the first time, we investigate the robustness of the solar/NAO signal in four different reanalysis data sets, and long integrations from an ocean-coupled chemistry-climate model forced with the 11-year solar cycle. The signal appears to be robust in the different reanalysis datasets. We also show, for the first time, that many features of the observed signal, such as amplitude, spatial pattern, and lag of 2/3 years can be accurately reproduced in our model simulations. However, in both the reanalysis and model simulations, we find that this signal is non-stationary. Most importantly, a lagged NAO/solar signal can also be reproduced in two sets of model integrations without the 11-year solar cycle. We find that this sporadic signal in models and observations is due to internal decadal variability in the NAO, and is not a response to the solar cycle. This has implications towards the interpretation of surface solar signals in observational data.

Solar Cycle Variations in Mesospheric Carbon Monoxide

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As an extension of Lee et al. (2013), solar cycle variation of carbon monoxide (CO) is analyzed with MLS observation, which covers more than thirteen years (2004-2017) including maximum of Solar Cycle 24. Being produced primarily by the carbon dioxide (CO_2) photolysis in the lower thermosphere, the variations of the mesospheric CO concentration are largely driven by the solar cycle modulated ultraviolet (UV) variation. This solar signal extends down to the lower altitudes by the dynamical descent in the winter polar vortex, showing a time lag that is consistent with the average descent velocity. To characterize a global distribution of the solar impact, MLS CO is correlated with the SORCE measured total solar irradiance (TSI) and UV. As high as 0.8 in most of the polar mesosphere, the linear correlation coefficients between CO and UV/TSI are more robust than those found in the previous work. The photochemical contribution explains most (68%) of the total variance of CO while the dynamical contribution accounts for 21% of the total variance at upper mesosphere. The photochemistry driven CO anomaly is further transported to the tropics, extending the solar impact to the summer hemisphere by the meridional residual circulation. The solar cycle signal in CO is further examined with the WACCM experiment by implementing two different modeled Spectral Solar Irradiances (SSIs): SRPM 2012 and NRLSSI. The model simulations underestimate the mean CO amount and solar cycle variations of CO, by a factor of 3, compared to those obtained from MLS observation. Different inputs of the solar spectrum have small impacts on CO variation.

Long-Term Variations in Terra/MISR Angular Radiance Differences: Solar or Aerosol Influences on Polar Cloudiness?

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There has been a long outstanding debate on whether global cloud cover is influenced by solar variability. Detection of such signals has been controversial and challenging, largely because of difficulty and fidelity associated with inter-sensor calibration. In addition, attribution of any quasi-decadal variation to the solar cycle influence requires careful consideration of other internal variabilities in the Earth's system that oscillate with the similar period (e.g., Pacific Decadal Oscillation) or disrupt solar influences (e.g., volcano eruptions). In this paper we present an angular differential analysis of the monthly radiance data from 17-year Terra/MISR (Multi-angle Imaging SpectroRadiometer) sun-synchronous observations. MISR takes simultaneous images from 9 view angles at nadir and 26.1°, 45.6°, 60.0°, and 70.5° angle pairs in the forward and aftward directions. By differencing the radiances between 70.5° forward and aftward, radiometric calibration error is greatly reduced or eliminated and in the meantime reflective cloud signals are enhanced in the polar region where low clouds produce strong forward scattering. There is a significant quasi-decadal variation in the 70.5° forward and aftward radiance differences. The differences do not appear to have any trend at low latitudes where the pair of view angles have roughly symmetric about the solar incidence, indicating systematic errors of instrument radiometric calibration are mostly removed. The quasi-decadal variations are found in the polar region from all four MISR spectral bands, but stronger in the blue and green bands than in the red and near-IR. They are out of phase with the 11-year solar cycle, but these enhancements also appear to correlate with volcanic aerosol activities. By examining the MISR radiances closely, we find that these large angular radiance differences are dominated by the scattering from low-level clouds dominates, compared to the surface contribution.

The 11-Year Solar Cycle Signal in Global NO_2 Measurements from NDACC Stations

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The solar UV variability during 11-year solar cycles has impacts on many important atmospheric chemical species. Understanding and quantifying the variabilities due to the natural solar forcing is critical for an accurate prediction of future atmospheric changes in the context of continuing and complex anthropogenic forcings. In particular, the solar cycle induced variabilities in ozone and its controlling species NO_x (through catalytic reaction cycles involving NO and NO_2 in the lower part of the middle atmosphere) and HO_x (through reaction cycles involving OH and HO_2 in the upper part of the middle atmosphere) have been studied with various observations and model simulations. Puzzling questions or discrepancies between model and observations remain unresolved.

In the present work, we investigate the solar cycle signal in middle atmospheric NO_2 using the long-term data record from NDACC (Network for the Detection of Atmospheric Composition Change) stations. Most of the stations are located at higher altitude or away from urban areas. Local boundary layer pollution has little impact on the variability of NDACC NO_2 vertical columns. The dominant variabilities come from the seasonal cycle, QBO, solar cycle, and a possible long-term trend. We extract the 11-year solar cycle signal from these measurements. The global pattern of this signal is discussed. For those stations with NO_2 data record longer than 20 years, solar cycle signals in SC23 and SC24 are compared. The comparison with results from 3-D global model will also be discussed. The results from this study may have important implications for middle atmospheric ozone variabilities.

Improvements in Coupled Ocean-Atmosphere Model Responses to Solar Activity

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The fidelity and capacity of coupled ocean atmosphere GCMs to respond to changes in solar activity has increased greatly in recent years. Results from the last round of international comparisons (CMIP5 ~2012-2016) showed that some GISS model configurations were able to better capture solar-cycle responses from the stratopause to the ocean surface as a function of interactive ozone and more realistic stratospheric circulation. CMIP6 will additionally feature model configurations that have an internal QBO mode, and sufficient aerosol and cloud microphysics to include hypothesized ion-nucleation mechanisms as well. We will discuss the implications this may have for recent attribution of decadal and longer-term variations in observed temperatures.

Response of the East Asian Monsoon to Solar Cycle

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This study find a special time period within the summer half-year and a special region in the East Asia from 1958 to 2012 when and where precipitation response is sensitive to solar cycle. And the time period has an explicit physical significance. It just corresponds to the typical East Asian monsoon rainy season (mei-yu season), characterized by a largescale quasi-zonal monsoon rainband (i.e., 22 May–13 July). The place is also a special region where the boundary of summer monsoon located during the rainy the season. The statistically significant correlation and the relatively explicit physical significance together strongly indicate a regular response of the East Asian monsoon to the 11-year solar cycle during the last five solar cycles. During the high SSN years, the mei-yu rainband lies 1.2 degree farther north, and the amplitude of its interannual variations increases when compared with low SSN years. The robust response of monsoon rainband to solar forcing is related to an anomalous general atmospheric pattern with an up–down seesaw and a north–south seesaw over East Asia. The up-down seesaw is related to the stratospheric ozone and the tropopause westerly jet and the north-south seesaw to the onset of the tropical monsoon and a SST anomaly in a key region of the western Pacific.

Quasi-biennial Oscillation and Solar Cycle Influences on Arctic O_3 Simulated by the WACCM4 Model

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Observations show that the quasi-biennial oscillation (QBO) and the 11-year solar cycle perturb the polar vortex via planetary wave convergence at high latitudes, a mechanism first proposed by Holton and Tan in 1980. These perturbations lead to an increase of stratospheric sudden warming events, and consequently observable increases in temperature and O_3 abundance at polar latitudes. However, these observations have not been studied in models definitively. Here we test whether the observed O_3 changes can be reproduced in chemistry-transport models. We constrained the Whole Atmosphere Community Climate Model version 4 (WACCM4) with the observed wind fields and 11-year UV variability and ran the model from 1979 to 2014. The simulation was diagnosed in four groups: westerly QBO phase and solar minimum, westerly QBO phase and solar maximum, easterly QBO phase and solar minimum, and easterly QBO phase and solar maximum. We showed that the simulated O_3 changes among these four groups agree very well with the observation. The linkage between the Holton-Tan mechanism and polar O_3 in the model are examined.

The Solar Influence on the Earth's Climate at the Centennial Time Scale

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At the beginning of the 21st century the Earth's global temperature trend leveled off to a plateau, called the climate hiatus. One of the potential contributors to this climate change could be the extended, deep minimum of solar activity associated with the low solar irradiance input to the Earth. The current extended, deep minimum of solar variability 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 reconstructed for over many centuries. We will discuss the latest reconstructions of solar irradiance in this respect. 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 solar influence is mostly seen not globally but as forcing of the Earth's climate patterns, such as NAM and PNA. 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. The timing and spatial pattern of the Earth's climate response allows distinguishing the CGC forcing from other climate forcings.

Terminators: The Death of Solar Cycles and La Niña 2020

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The Sun provides the energy required to sustain life on Earth and drive our planet's weather. Over the past few years a new picture to describe solar variability has developed, based on observing bands of magnetism that belong to the Sun's *22-year* magnetic activity cycle, and migrate from high latitudes towards the equator. The intra- and extra-hemispheric interaction, so-called “magnetic telecommunication,” of these magnetic bands appear to explain the occurrence of decadal scale variability that primarily manifests itself in the sunspot cycle. One of the most important events in the progression of these bands is their death, or termination, at the solar equator that signals a global increase in magnetic activity that becomes the new solar cycle. Their death is NOT dragged out, but abrupt. Indeed, the triggering of growth in the new solar cycle is almost immediate (significantly less than 1 solar rotation). Here we show the particulate and radiative implications of these termination points, their temporal recurrence and signature, from the Sun to the Earth. We show the correlated signature of solar cycle termination events and major oceanic oscillations that extend back many decades. A combined one-two punch of reduced particulate forcing and increased radiative forcing that result from the termination of one solar cycle and rapid blossoming of another correlates strongly with a shift from El Niño to La Niña conditions in the Pacific Ocean. Should current projections of solar magnetic band migration hold, we expect the current solar cycle termination to occur in or around April 2020, and thus we expect to see La Niña conditions develop in the Pacific 2-3 months thereafter. These observations can help us to explore the capability of the Sun to dynamically drive the Earth's atmosphere.

Session 5. Stellar variability and connections to the Sun

The Variability of Sun-like Stars

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The Solar-Stellar Spectrograph (SSS) project at Lowell Observatory has now been in regular operation for 25 years – enough to resolve multiple cycles in a large set of solar analog stars, as well as a full solar Hale cycle. Overlap of some SSS stars with Mount Wilson Observatory (MWO) HK Project targets yields some activity records in excess of fifty years. Contemporaneous Strömgren *b, y* observations from Lowell and Fairborn (Tennessee State) Observatory enables analysis of activity-brightness variations of many of these stars. We therefore now have a reasonably comprehensive picture of solar variability in the stellar context – at least as far as Ca II H&K manifestations of activity are concerned. In this talk, I will review recent progress and key results, including significant progress in cross-calibration of the solar-stellar and SSS-MWO data sets. In particular, I will address the prevalence of flat activity (FA) versus cycling states in solar analog stars, and recent evidence for a FA-cycling transition in one star, with attendant onset of brightness variability: perhaps our first convincing glimpse of a stellar Maunder Minimum transition. I will conclude with a brief review of the status of the now-aging SSS project at Lowell, and our plans for the next stage of synoptic stellar cycles observations.

Magnetic Evolution of Sun-like Activity Cycles

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After decades of effort, the solar magnetic cycle is exceptionally well characterized, but it remains poorly understood. Pioneering work at the Mount Wilson Observatory demonstrated that other Sun-like stars also show regular activity cycles, and identified two distinct relationships between the rotation rate and the length of the cycle. The solar cycle appears to be an outlier, falling between the two stellar relationships, potentially threatening the very foundation of the solar-stellar connection. Recent discoveries emerging from NASA's Kepler space telescope have started to shed light on this perplexing result, suggesting that the Sun's rotation rate and magnetic field are currently in a transitional phase that occurs in all middle-aged stars. We have recently identified the manifestation of this magnetic transition in the best available data on stellar cycles. These observations suggest that the solar cycle is currently growing longer on stellar evolutionary timescales, and that the global dynamo will shut down entirely sometime in the next 0.8-2.4 Gyr. I will review four lines evidence for this unexpected result and discuss future observational tests, both solar and stellar.

Modeling Intrinsic Luminosity Variations Induced by Internal Magnetic Field in the Sun and in Solar-like Stars

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During their main sequence evolution, solar-like stars (M < 1.2 Msun) possess outer convective layers where magnetic fields are generated by dynamo action. As a consequence, these stars are magnetically active and can undergo brightness variations because of two distinct mechanisms. The first is the appearance and disappearance of surface features (starspots, faculae, magnetic network) that enter and leave the visible stellar disk because of stellar rotation and of their own evolution. Secondly, magnetic fields in the interior can induce intrinsic readjustments of the stellar structure and thus affect the stellar luminosity directly.

In this talk, I will present intrinsic magnetic variability models for the Sun and solar-like stars. The models are constructed using an opportunely modified 1D stellar evolution code that takes into account the mechanical, thermal, and energy budget effects of time-dependent magnetic fields, such as, e.g., the inhibition of convective energy transport through magnetized layers. For the Sun, the internal magnetic field profiles are constrained using helioseismic measurements, and prescribed on the basis of the output of state-of-the-art mean-field solar dynamo models. For young, fast-rotating, and therefore strongly magnetically active stars, the magnetic field at the surface is assumed to be in equipartition with the plasma pressure.

The observable predictions of these models, both in the solar and the stellar context (e.g., as a viable explanation for the so-called "radius inflation problem" of low-mass stars) will be discussed.

Long-Term Brightness Variability of Sun-like Stars

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Observations of Sun-like stars revealed stellar brightness variability on multiple time-scales, where variations on the time-scales of rotational periods and of magnetic activity cycles are induced by stellar magnetic features. Similar brightness changes occur on our Sun, where they can be observed in detail and have been extensively studied. Thus, models for solar irradiance variations have been developed for decades and provide accurate agreement with the solar observations. Since stellar variability is based on the same concepts that were used in solar irradiance models, those can be extended to investigate Sun-like stars. In our approach we focus on stars with the same surface distribution of magnetic features as the solar case, but different fundamental stellar parameters, e.g. metallicities and effective temperatures. Our investigation reveals that for such stars the amplitude of the brightness variations has a local minimum in the neighborhood of solar metallicity and effective temperature. This is because brightness variability is caused by a delicate balance between dark and bright magnetic features, which is sensitive to the combination of stellar fundamental parameters. Moreover, we show that even a small change (e.g. within observational error range) of metallicity significantly increases the photometric variability. This allows to explain a long-standing puzzle: The observation that solar brightness variability on the time-scale of the 11-year activity cycle is anomalously low in comparison to variability of Sun-like stars with near-solar level of magnetic activity.

How Typical is the Sun as a Variable Star?

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Solar brightness varies on all timescales that have ever been resolved or covered by space-born instruments. Driven by the climate community’s interest in links between solar variability and climate change, our understanding of solar brightness variations has dramatically improved over the last decade. Concurrently with solar studies, ground-based photometric measurements of Sun-like stars revealed brightness variations similar to solar variability on the 11-year activity timescale but with much wider variety of patterns. Surprisingly, several studies found the variability of solar brightness on the activity cycle timescale to be anomalously low in comparison with Sun-like stars. This posed the oxymoronic question of whether the Sun is actually a Sun-like star.

The interest in this question, and solar-stellar connections in general, was further elevated by the unprecedented precision of stellar brightness measurements achieved by the CoRoT and Kepler space missions. In particular, there have been a number of studies based on Kepler data aimed at understanding whether brightness variations of the Sun at timescales from days to weeks are typical or rather weak compared to the cohort of Sun-like stars. These studies led to a contradictory results and the unambiguous answer to this question is still not found.

We review the progress in the solar-stellar comparison reached over the last few years and discuss the biases which can affect such a comparison.

Magnetic Activity and Flares in the Near-UV of Exoplanet Host Stars

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Flares in the Sun and M dwarfs are thought to result from a common process of sudden reconnection and relaxation of magnetic fields in their coronae. A fraction of M dwarfs are in the saturated magnetic activity regime and on occasion produce flares with energies that are 10,000x larger than typical solar flares. The highly dynamic stellar atmospheric response during flares produces radiation across the electromagnetic spectrum, from the radio to X-rays, on a range of timescales, from seconds to days, which can have important effects on planetary atmospheres in the habitable zones of stars. In this talk, I will review the flare activity of M dwarfs, which are often targets for habitable-zone planet searches. I will then focus on the observed properties of the near-UV flare radiation in M dwarf flares and how we have reproduced some of these properties in recent radiative-hydrodynamic models with very energetic electron beams. I will discuss what is not known about flare spectra in the near-UV between 200 and 350 nm, which is an important wavelength range for planetary surface biology and ozone chemistry in habitable zone planets.

Solar Brightness Variations as they would be Observed by Kepler Telescope

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Recent planet-hunting missions, such as CoRoT and Kepler opened new perspectives for studying stellar photometric variabilities on timescales of stellar rotation and below. They led to considerable efforts aimed at establishing general patterns of stellar photometric variations (e.g. dependences on rotational periods and fundamental stellar parameters). Comparisons of stellar variabilities to that of the Sun are of special interest.

However, due to the special position of the Earth-bound observer, solar brightness variations are measured from the equatorial plane while stars are observed from arbitrary directions. We model solar brightness variations on timescales of the solar rotational period and below as they would be observed out of ecliptic and study the dependence of stellar variability on the inclination angle. The distribution of the magnetic features on the solar surface is calculated with the Surface Flux Transport Model developed at MPS. This allows to decompose solar variability into two components: one caused by transits of magnetic features over the visible solar disk as the Sun rotates and another one due to the evolution of these features.

In the future, we will extend our model to stars with different rotational periods and fundamental parameters. A comparison of observational and simulated data will show which, if any physical concepts of solar brightness variability have to be altered to reproduce the distribution of Sun-like stars variability.

Fast Spectral Synthesis for a New Generation of Solar and Stellar Brightness Variability Models

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Currently a new generation of models of solar and stellar brightness variability based on the realistic three-dimensional magnetohydrodynamic simulations of atmospheres is being developed, in particular when applied to the many pixels in a 3D MHD simulation. The standard procedure used for the radiative transfer is computationally very expensive. This is due to the treatment of the spectral lines: The spectra of the Sun and Sun-like stars contain several millions of molecular and atomic lines that play an important role in the irradiance variability in the UV and visible spectral domains. Therefore, an optimization of the spectral line calculations is urgently required. One possible approach is the employment of the opacity distribution functions (ODFs). They allow taking into account the effect of spectral lines by approximating their complex structure in opacity. We investigate the procedure used for ODF computations and develop a novel approach for fast calculations of a) integrated flux and its variability in passbands of interest, e.g. in Strömgren-, Kepler-, and Plato- filters; b) the total solar irradiance (TSI) and its variability. In particular, we show that it is sufficient to calculate the radiative transfer of just about a hundred frequency points to accurately reproduce the TSI and its variability. Our method and the related speed-up in radiative transfer calculations allows the current models to be taken to a new level, making it potentially possible to investigate a whole range of new phenomena.

Climate and Habitability of Earth-like Extrasolar Planets

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Over the past two decades, the study of planets orbiting around other stars has emerged from relative obscurity to the forefront of modern science. After only a brief glance at the cosmos, extrasolar planets appear to be extraordinarily common. The holy grail of the field remains to detect Earth-like planets orbiting distant stars and to characterize their atmospheres. Ultimately, we hope to confirm the existence of habitable, and possibly even inhabited extrasolar planets. To date *Kepler* and ground based surveys have identified numerous planets that reside within the so-called "habitable zone" (HZ). By definition, the HZ is the region in space surrounding a star where a terrestrial planet can support liquid water on its surface. The inner edge of the HZ is bounded by the runaway greenhouse, where a planet becomes too hot and surface water is irreversibly boiled away to space. The outer edge of the HZ is bounded by runaway glaciation, where the planet becomes too cold and surface water is irreversibly frozen. However, the HZ is not static, but rather varies as a function of the stellar type, the age of the star, and also planetary properties such as the composition of the atmosphere, the planet's rotation rate, and carbonate-silicate weathering cycling rates. In this talk, I will review the basic concepts of climate and habitability for Earth-like extrasolar planets found in and near the HZ. While presently this work remains largely theoretical, upcoming missions such as the *James Webb Space Telescope* and the next generation of thirty-meter class ground based telescopes expected to come online in the mid-2020s, will be able to begin characterizing these worlds.

Session 6. What are the expectations for the next solar minimum and Solar Cycle 25?

140 Years of the "Extended" Solar Cycle: Predictability, expectations for SUNSPOT Cycle 25 and what is to follow

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Starting with 22 years of contemporary observations of the solar corona we readily see bands of activity-long-lived patterns that mark out the 22-year solar magnetic activity cycle. The modulation of these bands can explain the landmarks of the sunspot cycle – that only occurs over about half of the magnetic cycle span. Exploiting routine observations of the green-line corona that go back to the late 1930s and of solar filaments that go back to the dawn of H-alpha photography in the late 1870s we demonstrate that the 22-year magnetic cycle is extremely robust and is predictable through this continuous observational record. Using this record, we explore the "climatology" of the system and the root drivers of solar variability and activity. Given the apparent predictability in the system we look at sunspot cycle 25, how it has evolved since first appearing in 2012/2014, what it may yield in terms of activity, and also what may follow…..

Mechanisms of Solar Cycle Fluctuations

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In this talk I will review the various physical mechanisms having been invoked to explain the patterns of solar fluctuations in amplitude and duration, as inferred from long temporal records.
Working from the dynamo point of view and using a variety of solar cycle models as starting points, I will illustrate the effects of (1) nonlinear magnetic backreaction on large-scale flows,
(2) stochastic forcing due to variability of emerging active region characteristics, and (3) stochastic variability and nonlinear quenching of the turbulent electromotive force.
Based on these representative examples, I will survey and comment critically on the various extant dynamo-based solar cycle prediction schemes, distinguishing ``next-cycle'' prediction from prediction of longer timescale variability, from multidecadal to millenial timescales, presumably more relevant to climate.

Prediction of Solar Cycle 25

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There is growing acceptance of the suggestion by Schatten et al. (GRL 5, 411, 1978) that the Sun's polar fields during a few years leading up to solar minimum is a 'seed' for the next solar cycle, being transported to and amplified in the interior by the solar global dynamo. If so, Predicting the size of the next solar cycle then comes down to predicting [or better: measuring] the polar fields. I use the observations since 1976 from WSO supplemented by the latest data from HMI to determine the solar axial Dipole Moment [DM] comparing it to DM at the previous minimum. Already at this time [≈2 years before minimum] the DM now is larger than the previous DM signaling that solar cycle 25 will be larger than cycle 24. Including the evidence from the recent heliospheric magnetic field [that also is a precursor of the cycle] leads to an estimate for SC25 approximately midway between cycles 20 and 24.

Solar Cycle Activity Related to Local and Global Helioseismology

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The solar activity cycle is thought to arise from dynamo processes occurring in the solar interior below the visible photosphere. The only observational method we currently have that can probe the interior is that of helioseismology, the study of the resonant acoustic-gravity waves trapped inside the Sun. Helioseismology is particularly suited for detecting the motions of the plasma inside the Sun, which is useful in this context since a dynamo is a system of plasma flows that generate a self-sustaining large-scale magnetic field. We now have more than 22 years of high-quality consistent helioseismology data from GONG, SOHO, and SDO; these data are showing that the internal flows are generally more complex than is assumed by dynamo theories. In this talk I will review the current state of knowledge about the zonal (east-west) and meridional (north-south) components of the flow as obtained from global and local helioseismology, and discuss how the temporal evolution of these flows is related to future activity cycles. I will also touch on the solar-cycle related changes in the Sun's global acoustic spectrum and associated evidence for the existence of a second dynamo process.

Morphology and Time Evolution of Dark Facular Regions in Cycle 23 and 24

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This is a study of the contrast of plage and facular regions in the 607nm red continuum spectral region using images produced by the ground-based Precision Solar Photometric Telescope (PSPT) at Mauna Loa Observatory. Additional information is derived from space-based observations from the Helioseismic and Magnetic Imager (HMI) as well as the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO) at 617.3 and 1700nm, respectively. PSPT analysis over the time frame of January 2005 to February 2015 permits the solar cycle characterization of the time evolution of facular regions. Facular regions darker than the center-to-limb variation (CLV) in PSPT exhibit a distinct solar cycle dependence with about 15-30 percent of facula darker than the CLV during times of high solar activity. These dark facular regions have the greatest contrast at disk center and fall off toward the solar limb where they become predominantly bright. Cospatial magnetic field strength dependence can be associated with image contrast using HMI images and co-aligned and cotemporal high contrast AIA images can be used for the identification of bright solar features. Analysis of HMI contrast employing masking of magnetic field strength and AIA brightness provides greater insight into evolution of these dark features. HMI images indicates bright and dark image pixels are highly interleaved in solar regions that can be identified as facular structures. HMI pixels in the $200<|B|<600$ Gauss range show a distinct brightening near the limb resembling the CLV enhancement seen in facula identified in PSPT. This field range is predominately bright relative to the CLV, but for $600<|B|<1200$ Gauss, it is predominately dark. In HMI images, dark facular regions exhibit a higher population than seen in PSPT images. HMI images masked according to AIA brightness indicate a broad range contrast and a similarly broad range of magnetic field strengths.

<u>Galactic Cosmic Ray Intensities during the Space Age and the Holocene</u>

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Both ground-based and space-based measurements have shown clearly that the intensity of galactic cosmic rays (GCRs) measured in the inner solar system varies over the 22-year (Hale) solar cycle. In addition, measurements of radioactive isotopes including ^{14}C found in tree-rings and ^{10}Be in found in ice cores have demonstrated even larger periodic intensity variations on time scales ranging from ~100 years to thousands of years.

During the extended solar minimum of 2009 measurements of GCR heavy-ions from C to Fe reached their highest levels of the space era. At the same time the count rates of many ground-based neutron monitors also reached their highest recorded levels. As of this writing, the ACE GCR heavy-ion intensities have approached within a few percent of the 2009 levels, suggesting that even higher intensities may be in store in the next year or two.

This talk will compare cosmic-ray intensities over the space era with measurements of related solar/interplanetary properties including sunspot number, interplanetary magnetic field and solar wind properties, and the tilt of the interplanetary current sheet. It will also compare the present-day GCR intensities with estimates by others based on ^{14}C and ^{10}Be data, and with forecasts for this and coming solar minima.