THE SUN-CLIMATE RESEARCH CENTER

Summary of the 2015 Sun-Climate Symposium "Multi-Decadal Variability in Sun and Earth during the Space Era" Savannah, Georgia * Nov. 10-13, 2015

The 2015 Sun-Climate Symposium, November 10-13, in Savannah, Georgia, was organized by the Sun-Climate Research Center – a collaboration between NASA Goddard Space Flight Center (GSFC) and the Laboratory for Atmospheric and Space Physics at the University of Colorado (LASP/CU). This conference focused on multi-decadal variations in the Sun and Earth during the space era. There were eight sessions that covered solar irradiance measurements and modeling, solar influences on Earth's atmosphere and climate, variability observed in Sun-like stars, and climate changes and its impact on society. **Gary Rottman** [LASP/CU], the original Solar Radiation and Climate Experiment (SORCE) Principal Investigator, kicked-off with a keynote talk on the solar variability record that started with the sunspot record in the 1600s, progressing to solar irradiance measurements from ground, to the space-based measurements that have continued since 1978.

Session 1: Total Solar Irradiance Measurements and Modeling

This session focused on total solar irradiance (TSI) measurements during solar cycles 23 and 24. It included results from the recently revised Naval Research Laboratory TSI2 (NRLTSI2) empirical proxy model, the semi-empirical Spectral And Total Irradiance REconstruction (SATIRE) model, the San Fernando Observatory's TSI reconstructions using ground-based photometric indices, and historical reconstructions dating back to the Maunder Minimum period in the 1600s. Such reconstructions help determine Earth's climate sensitivity to natural forcing as well as the solar causes of irradiance variations. A potential solar irradiance trend between the 1996 and 2008 solar cycle minima was assessed, because of its implications for long-term solar influences on climate change. The different TSI composites from space-borne measurements exhibit changes in minima that range from 150 parts per million (ppm) decrease (SATIRE model) to little or no decrease (NRLTSI2 model). Stability uncertainties of about 120 ppm limit the long-term variability results from the current TSI measurements and models, so there is not a clear resolution of this important Sun-climate issue.

Reconstructions of TSI generally indicate lower values during the Maunder Minimum in the 1600s that could help explain lower global temperatures during that century, near the end of the Little Ice Age. The sunspot record is the most direct indicator of solar activity back to these times. The new Sunspot Index and Long-term Solar Observations (SILSO) sunspot record, released in July 2015, resolves some issues related to how measurements from different observers are combined and clarifies sunspot group definition. Session speakers estimated TSI levels during the Maunder Minimum to be 0.5 to 1.0 W/m^2 lower than modern cycle minima levels.



Figure 1. Gary Rottman's keynote address to start the 2015 Sun-Climate Symposium reviewed 400 years of the solar climate data record. SORCE has had a direct contribution to this record. The SORCE TIM and other recently calibrated TSI sensors now indicate that the TSI level is actually near 1360 W/m². Image credit: Greg Kopp, CU/LASP, <u>http://spot.colorado.edu/~koppg/TSI/</u>.

All TSI models are based on recent spacecraft measurements. A TSI of 1361 W/m² has clearly been established over the past several years. The TSI community is now focusing on long-term stability provided by linking data from temporally overlapping instruments such as those from SORCE's Total Irradiance Monitor (TIM) and other TSI instruments currently flying. International research teams are working to develop a community-composite TSI record. When complete, this community-composite will provide a new solar record for both solar and climate researchers.

Session 2: Sun-Climate Connection: Top-down and bottom-up couplings

This session explored the links between the Sun and Earth's climate, including top-down and bottom-up couplings, addressing questions about the Sun's influence on the Earth's atmosphere during the satellite era and the skill of climate models to capture these links. The Sun is Earth's primary source of energy, providing a globally averaged irradiance that is four orders of magnitude greater than the next largest energy source, Earth's interior heat flux. Solar spectral variability in the visible drives the bottom-up couplings from surface to atmosphere while the highly variable ultraviolet radiation, absorbed in the atmosphere by ozone and oxygen, drives the top-down couplings to the surface. Even the variability in the Sun's total energy over one solar cycle exceeds the energy of all other energy sources by an order of magnitude. Despite this, one of the difficulties in assessing the atmospheric response to the solar variability is that several internal modes of variability are present, which may inhibit accurate detection. In particular, assessing and distinguishing between natural climate variability, for example the Pacific Decadal Oscillation (PDO) and Quasi Biennial Oscillation QBO), and anthropogenic forcing, and quantifying their relative contributions to climate change is a formidable challenge.

One of these challenges is that Whole Atmosphere Community Climate Model (WACCM) simulations do not find a persistent wintertime solar response in the polar vortex when stratifying by QBO phase, in contradiction to observational data from 1953-2012. The model simulations also indicate solar cycle influences on gravity waves and the wave-driven circulation. At solar maximum, the monthly-mean, zonal-mean temperature in the Southern Hemisphere from July to October is lower (-2 to -5 K) in the stratosphere and higher (+3 to +6 K) in the mesosphere and the lower thermosphere (MLT). Using 13 solar cycles from 1869 to 2009 another model study showed significant differences in the temperature patterns between the phases of four cycles; the clearest pattern of the temperature anomalies is not found during sunspot maximum or minimum, but during the declining phase, when the temperature pattern closely resembles the pattern found during positive North Atlantic Oscillation. In a Goddard Institute for Space Studies (GISS) climate simulation, however, no clear 11-year solar forcing signals are found in surface temperature. However, there are large multi-decadal surface temperature responses, where the planetary albedo is negatively correlated with the surface temperature in these experiments. Another chemistryclimate model study found significant solar cycle signals in lower-stratospheric temperature and ozone time series. It is clear that top-down and bottom-up couplings both play a role, but challenges remain in modeling the solar forcing contributions at the required accuracies.

While the solar cycle impacts are greatest in the upper atmosphere, anthropogenic effects are still significant there. Carbon dioxide (CO₂) observations from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) shows an increasing trend of ~5% per decade at ~80 km and below, consistent with the tropospheric trend observed at Mauna Loa from anthropogenic forcing. Above 110 km, the SABER CO₂ trend is as large as ~12% per decade, requiring more sophisticated chemistry and transport modeling to fully understand the underlying processes.



Figure 2. The measured long-term trend of the CO_2 in the atmosphere below 80 km is consistent with surface measurements, but trend of the CO_2 in the upper atmosphere is faster than the WACCM model expectations. This difference may be an indication of needing 30% more Eddy diffusion in the upper atmosphere. Acronyms: Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), Whole Atmosphere Community Climate Model (WACCM), Atmospheric Chemistry Experiment (ACE). Image credit: Jai Yue, Hampton University, VA.

Session 3: Climate Changes during the Space Era

The various records on multi-decadal timescales during the space era help to put our current knowledge of climate change, including the Sun's role, into perspective. **Drew Shindell's** [Duke University] keynote on *Solar Forcing of Industrial Era Climate Change* established the challenges in isolating solar forcing in observations and climate models due to the overlapping temporal signals from other known climate drivers such as volcanic activity. Earth system models have generally improved over time but not all models fully represent the top-down response of known solar forcing. For example, solar variability in the ultraviolet imparts temperature gradients that modulate upper stratospheric winds that may impact polar processes through dynamical propagation. There is evidence of solar forcing on regional scales in some models used in the Coupled Model Intercomparison Project (CMIP), and some changes, for example, over Europe, can be much larger than the global average.

Another topic in this session was Earth's radiation imbalance that included comparisons of observed and modeled radiative fluxes at Earth's top-of-atmosphere (TOA), and the importance of TSI measurements for estimating the imbalance. The imbalance at TOA determined by the Clouds and the Earth's Radiant Energy System (CERES) instrumental record is 0.6 Wm⁻² (1 σ range is 0.34-0.86 Wm⁻²), with no identifiable long-term trend. Relating the imbalance to atmospheric and surface variables remains a challenge because climate feedbacks and climate forcing are not well known. Improved understanding requires reducing uncertainty in outgoing fluxes to 0.06% (0.2 Wm⁻²), comparable to the current uncertainty in TSI of 0.13 Wm⁻².

Insights were provided into discrepancies between the observational record and models of long-term trends of density and chemical species in the thermosphere, a region of Earth's atmosphere with undeniable links to solar forcing. CO₂ trends related to the solar cycle from measurements made by the SABER instrument (~12% per decade at 110 km) were shown to be larger than model estimates from WACCM. This comparison emphasizes the importance of quantifying the solar cycle signal, which may be embedded within the 12 years of CO₂ observations. These trends, on the order of 8-9% per decade in CO and CO₂ in the mesosphere, exceed the estimated 5% per decade anthropogenic influence of CO₂ and CO at the surface and in the stratosphere. In the thermosphere, because CO and CO₂ are the dominant IR emitters, the thermosphere is cooling as CO and CO₂ increase. Consequently, the density is dramatically increasing near 400 km as the thermosphere cools. For example, the 400 km density decreased by about 30% in 2008 relative to the previous solar cycle minimum in 1996. Solar extreme ultraviolet variability, geomagnetic activity, and changes in CO and CO₂ composition all help explain these decade-long changes in thermosphere density, but the changes are not all well reproduced by thermosphere models. One clear improvement is the WACCM reproduction of SABER CO and CO₂ observations by changing the gravity wave parameterization. Improved understanding of the long-term changes of the thermospheric density has a very practical application for tracking satellites and orbital debris. Currently, there are more than 100,000 objects between 1 and 10 cm in size (7500 objects > 10 cm size) in low Earth orbit (LEO). Calculating atmospheric drag is key to mitigating satellite collisions with debris.



Figure 3. The long-term trend of the thermosphere density at 400 km has been decreasing since the 1970s and is a key indication of long-term changes in the solar ultraviolet irradiance variation (F10.7), geomagnetic activity (Kp), and increase of atmosphere CO₂ that is the primary infrared cooling in the thermosphere. There was a large 30% decrease in the 400 km density during the last solar cycle minimum in 2008, and this decrease is a concern for longer life of orbit debri and thus enhanced chances for satellite-debri collisions. Acronyms: Global Average Mass Density Mode GAMDM. Image credit: John Emmert, Naval Research Laboratory.

Session 4: Solar Spectral Irradiance Measurements and Modeling

Solar spectral irradiance (SSI) is by far the strongest external forcing to the climate system. Understanding the SSI measurement record is essential to understanding Sun-Climate connections. The two main themes of this session were modeling the physics of the Sun that produces spectral irradiance variability and understanding the uncertainties in the SSI observational record.

The magnitude and sign of SSI solar cycle variability during the SORCE mission has been under debate for several years. The presentations examined the SORCE SSI results along with SSI variability models and other verification techniques such as trending of ozone measurements and the relationship between 27-day rotational and 11-year solar cycle variability. These presentations clarified the range of variability of the SSI as a function of wavelength. Although variability in ultraviolet is significantly larger than in the visible, the magnitude of ultraviolet variability was debated. While measurements and models both support out-of-phase variability in the near infrared, they differ in how the variability trends in the visible.

The solar physics presentations ranged from purely theoretical radiative transfer models of the solar atmosphere to analysis of ground-based solar images. One highlight was **Scott McIntosh's** [National Center for Atmospheric Research/High Altitude Observatory] talk on the interaction of bands of activity on the Sun over several solar cycles. This work may lead to a better understanding of the cause of the 11-year irradiance cycle and the 22-year solar magnetism cycle.



Figure 4. The integrated SSI from the SORCE Solar Irradiance Monitor (SIM) agrees well with the TSI time series from the SORCE TIM as shown in the top two panels. However, there remain significant differences of the SSI variability between the measurements and the models for particularly the near ultraviolet and visible wavelengths as shown in the bottom panel. Acronyms: Total Solar Irradiance (TSI), Spectral Irradiance Monitor (SIM), Spectral And Total Irradiance Reconstruction (SATIRE), and Naval Research Laboratory Solar Spectral Irradiance (NRLSSI). Image credit: Jerry Harder and Tom Woods, CU/LASP.

Session 5: Societal Impacts from Climate Change and Solar Variability

Global impacts on the severity and cost of climate change were highlighted in this session. Keynote speaker **Bruce Wielicki** [NASA Langley Research Center] presented the results of detailed economic analyses using accurate climate monitoring methods like those from the future Climate Absolute Radiance and Refractivity Observatory (CLARREO) Mission and varying response scenarios to estimate the value of climate information. Shortened times-to-detection and earlier mitigation strategies revealed the risks and unrealized costs of delays in establishing a global climate program. A presentation on the sea level rise of the Atlantic drove home the severity of increased warming with several examples of impacts around the globe.

Session 6: Variability of the Sun-like Stars

How typical is the cyclic activity of our Sun relative to Sun-like stars? What progress have we made in understanding the physical processes that control the cycle length and activity range of a Sun-like star? In his keynote address, **Jeffrey Hall** [Lowell Observatory], surveying 60 years of monitoring Sun-like stars via photometry and spectrophotometry, vividly illustrated the subtlety of the hidden question – by what criteria do we judge whether a star is Sun-like? At the last level of detail, the Sun is unique. Nevertheless, the advancement of observational techniques, including asteroseismology, precision astrometry, and radial velocity studies—as well as the vital continuity of synoptic measurements—has pinpointed a small number of stars (such as 18 Scorpii) that can fairly be called "solar twins" based on physical parameters and merit close study.

Other speakers in this session considered diverse space- and ground-based data that reveal the range of behavior of Sun-like stars. Some show cyclic activity on timescales roughly comparable to the Sun, while others show no definite variation or hints of multi-periodicity. Some, like the Sun, become brighter at visible wavelengths when they become more active, while others show the reverse behavior, reflecting the relative contributions of bright and dark atmospheric features such as plages and sunspots. But can a Sun-like star transition from weak or absent cycling to definite cycling? Can it transition from a direct to an inverse activity-brightness relation? Could the Sun produce a "superflare" two or more orders of magnitude more energetic than the largest observed solar flare? Could the Sun enter a period of low activity, extending over decades or centuries, even more extreme than the low activity observed during the Maunder Minimum (c. 1645-1715 AD)? We do not have definite answers to these questions. We seek the answers because the Sun alone has not enabled us to develop the theory of regenerative magnetofluid dynamos, thought to underlie the activity of all Sun-like stars, to a degree that confers the predictive power we need both to confirm our physical understanding and for the practical benefit of predicting solar activity and space weather. Although helioseismology has dramatically increased our knowledge of the thermal and velocity structure of the solar interior, we are still far from the ability to construct and test a comprehensive dynamo theory from first principles. In particular, we do not adequately understand how the Sun generates a poloidal (north-south) magnetic field component (" α effect") from the toroidal component generated by differential rotation (" Ω effect"). We do not lack for semi-empirical models of the solar activity cycle; but the Sun alone has not enabled us to choose between them.

By combining data from synoptic ground-based programs with multi-wavelength data from space missions such as SORCE, we can explore the range of activity exhibited by Sun-like stars that have somewhat different masses, ages, rotation rates, and chemical compositions. Our goal is to narrow the range of semi-empirical variability models to those that are capable of producing not only the Sun's behavior but also the behavior of Sun-like stars. In this endeavor, it will be important to create a community resource that enables researchers to easily access and combine data from dozens of space- and ground-based databases. It will also be essential to continue synoptic programs and expand the sample of stars that have been tracked over multiple decades. Although synoptic observations have thus far been made mainly with ground-based programs, long-term monitoring of the Sun and Sun-like stars in soft X-rays is also particularly important because they exhibit a strong cycle response but do not typically disappear during periods of weak activity.



Figure 5. The relationship of a star's intensity cycle period to its rotation period appears to fall into two branches. The Sun appears as an odd star because the Sun's relationship falls in between these two branches. Image credit: Philip Judge, HAO/NCAR.

Session 7: Challenges and Opportunities in Solar Observations

There is a wide variety of upcoming missions, instrument developments, and measurement capabilities that will extend the lessons-learned from previous missions to address needs for Sunclimate and solar physics research. Session presentations described new sensors that span the entire solar spectrum and included advanced technologies in a variety of spectrometers, and innovative smaller and lighter CubeSat designs that meet the same stringent requirements as existing sensors. There was interesting discussion regarding the status of the Total and Spectral Solar Irradiance Sensor (TSIS) and the Geostationary Operational Environmental Satellites – R Series (GOES-R) missions scheduled for launch within the next two years. These missions will ensure the continuity of climate records from the SORCE and GOES programs. Advancements in sensor technology also require advancement in launch facilities and inexpensive launch vehicles. Aside from these space-based assets, profound improvements in our understanding of the Sun will be driven by the sub-arcsecond observation capabilities of the Daniel K. Inouye Solar Telescope (DKIST) now under construction on Haleakala in Hawaii. The session closed with an overview of the NASA Solar Irradiance Science Team (SIST) program that will provide valuable data sets and improved models of TSI and SSI variability for the Sun-climate research community.

Session 8: Next Generation Observing Systems for Climate Records

Next-generation observing systems with advanced sensors and implementation strategies are essential to meet the current and future challenges facing climate change studies. The discussion focused on broad challenges for critical Earth science future observations central to the climate system. Keynote speaker **Hank Revercomb** [University of Wisconsin, Madison] introduced many of these challenges in an overview of the CLARREO Climate Benchmarking Mission. Increased measurement accuracy and spectral resolution required for climate trend detection and attribution were emphasized. Two example next-generation instruments are the Absolute Radiance Interferometer (ARI) to measure the spectrally resolved long-wave infrared emission with increased accuracy (<0.1K brightness temperature uncertainty) and the Earth Climate

Hyperspectral Observatory (ECHO), a proposed pathfinder mission to CLARREO, to provide a more accurate measurement of the spectrally resolved Earth-reflected shortwave radiation. These technology advancements are proving valuable assets toward final implementation on emerging orbital systems to quantify the full Earth radiation budget from the ultraviolet to the far infrared.

Several recently launched missions are now providing important global data of the Earth's climate system with unprecedented coverage of the atmosphere, land, sea and ice. From high cadence atmospheric column-CO₂ profiles to reflectance observations of the diurnal variations of aerosols, clouds, and vegetation we are beginning to refine the needed observational and geo-sampling strategies required of a 21st century climate observational system. While the strategies and technology are mature, funding limitations remains the biggest challenge.

Conclusion

The GSFC-LASP Sun-Climate Research Center and the SORCE Science Team Meeting was a great success. Over 80 scientists and students from around the world gathered to present their findings on solar irradiance variability and climate change and engage in spirited discussions. The NASA Earth Science missions, including the SORCE mission, have been critical for advancing our understanding of the complex Earth systems, and new climate missions are required to continue these valuable climate records. Most of the 2015 Sun-Climate Symposium presentations are available online at http://tinyurl.com/gjfx6zh.

To stay up to date on the latest SORCE news and meeting announcements, read the SORCE newsletter at *lasp.colorado.edu/home/sorce/news-events/newsletter*.



Attendees at the 2015 Sun-Climate Symposium in Savannah, GA. Photo credit: Vanessa George, CU/LASP.