Solar activity, the Earth’s climate and human culture, all undergo change. An increasing number of paleoclimate records, such as in ice-cores, ocean sediments, lake levels and tree-rings, suggest a solar contribution to past climate change because many records correlate strongly with the $^{10}$Be and $^{14}$C cosmogenic isotopes. The cosmogenic isotopes are considered to be proxies of solar activity, because solar modulation of the heliosphere alters the flux of incoming galactic cosmic rays which produce the isotopes. Furthermore, comparisons of paleoclimate records with archeological evidence of past human cultures suggest that solar-driven climate change may have contributed to the prosperity and demise of various civilizations, for example in the Yucatan and East Africa.

The 2005 SORCE meeting focused on both the empirical evidence and physical processes that link the sun, climate and culture in the distant past. This includes understanding the relationship between solar irradiance and cosmogenic isotopes, which are typically assumed to reflect changes in solar brightness since this energy modulation is a million times larger than that of cosmic rays themselves. The lack of global climate records makes it difficult to discern the spatial pattern of the apparent climate response to past solar variability, which can provide clues about possible mechanisms. Nevertheless, from assorted paleo evidence at equatorial, mid- and high-latitudes, sometimes in combination with more recent datasets, a number of processes have been suggested. These include changes in the location of the intertropical convergence zone and in various dynamical modes including the North Atlantic Oscillation, the El Niño Southern Oscillation, and in the Hadley and Walker Circulations. Civilizations most susceptible to solar-driven climate change appear to be those located in regions where rainfall and drought are especially vulnerable to changes in these climate variability modes and circulation patterns. This emphasizes the need to understand the role of the hydrological cycle in the sun, climate, and culture connection.

The third annual SORCE science meeting was held in Durango, Colorado on 14-16 September 2005. About 80 scientists attended this meeting that concentrated on the paleo-connections between the sun, climate, and culture. In addition to the many oral and poster presentations, attendees enjoyed a special dinner speaker who discussed the rich history of early inhabitants and the archeology of western Colorado. The meeting concluded with an optional field trip to the Mesa Verde National Park to view the Anasazi ruins that are a result of sudden culture changes influenced by severe droughts at about 1300 AD.

Between special keynote speakers, the meeting was arranged into five sessions to address the meeting topic:

- SORCE Observations of Solar Radiation – New Science Results
- Reconstruction of Past Solar Irradiance and Modeled Climate Responses
- Evidence for Climate Responses to Solar Variability
Interpreting the Solar and Climate Sources of Cosmogenic Isotope Variations, and their Relationship to Solar Irradiance

- Linkages of Climate Cultural Responses and Solar Variability

Most of the presentations are available on the SORCE Meeting website at – http://lasp.colorado.edu/sorce/2005ScienceMeeting.html.

**Wednesday, 14 September 2005**

Judith Lean began the meeting with a keynote talk in the morning, discussing the current understanding of secular changes in the Sun-Earth system. She introduced many of the workshop topics concerning solar variability and possible climate effects over the past 1000 years. As shown in Figure 1, Judith presented a new estimate of solar irradiance variability obtained from modeling the transport of magnetic flux on the Sun. For comparison, prior reconstructions have been based on variations in sun-like stars or on cosmogenic isotopes (\(^{14}\)C and \(^{10}\)Be) and geomagnetic activity which are sensitive to long-term variations in the heliosphere. The new estimates of long-term solar irradiance variations are smaller than prior estimates, having about one quarter of the increase from the Maunder Minimum (~1650) to the modern maximum (today's solar irradiance level).

![Figure 1. Estimates of solar irradiance variability over the past 400 years (from J. Lean).](image)

The remainder of the morning was a session highlighting the Solar Radiation and Climate Experiment (SORCE) observations of the total solar irradiance (TSI) and the spectral solar irradiance (SSI). Gary Rottman first gave an overview of the SORCE mission and some of its results. Gary also discussed his retirement; the role of Principal Investigator has officially been transferred to Tom Woods at LASP. Tom has been the LASP Project Scientist for the SORCE mission.

Greg Kopp summarized results of the TSI observations by the SORCE Total Irradiance Monitor (TIM). He discussed TSI variations, including the first measurements of flares detected in the TSI time series, and some of the issues concerning TIM's absolute value of total solar irradiance which is about 5 W/m\(^2\) lower than the previous measurements, as shown in Figure 2. A TSI Validation Workshop was held at NIST in July to begin to address this issue. Joe Rice discussed the workshop results later in the Wednesday morning session. Some of the conclusions of the TSI validation workshop are that the TSI uncertainties should be increased for most measurements and that instrumental corrections, such as aperture diffraction effects and scattered
light off baffles, are not consistently applied by different instrument teams, and should be studied in more detail.

![Figure 2](image_url). Total solar irradiance (TSI) measurement record for 3 solar cycles (from G. Kopp).

Other talks in the SORCE morning session addressed the spectral solar irradiance. Jerry Harder presented new results from the Spectral Irradiance Monitor (SIM) regarding solar variability from the near ultraviolet (NUV) near 300 nm, through the visible, and into the near infrared (NIR) near 2500 nm. Jerry related the measured spectral variability to the modeled irradiance expected from the presence of solar features, such as sunspots and faculae, as identified from solar images. Bill McClintock presented the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) results of solar irradiance from the far ultraviolet (FUV) near 120 nm to the NUV. He showed that the SOLSTICE results from both UARS and SORCE are consistent within their respective calibration uncertainty (accuracy) of about 5%. Tom Woods presented flare observations from the SORCE XUV Photometer System (XPS), compared with the TIM's TSI detection of the flares. Tom showed that the XUV radiation from 0.1 to 27 nm is about 30% of the TSI variation during large flares and that the TSI total energy from a flare is 110 - 150 times the total energy measured by the GOES X-Ray Sensor (XRS) in the 0.1 to 0.8 nm band (a factor of 10 higher than past studies have assumed).

The session concluded with a presentation by Rodney Viereck regarding NOAA’s plans for future solar irradiance measurements. These plans include TSI and NUV-Visible-NIR SSI measurements from the series of NPOESS satellites, solar UV irradiance and the Mg II core-to-wing ratio (solar proxy for chromospheric variability) from the POES SBUV and NPOESS OMPS instruments, and extreme ultraviolet (EUV) and X-ray solar irradiance measurements from the series of GOES satellites.
Session 2, *Reconstructions of Past Solar Irradiance and Modeled Climate Responses*, was on Wednesday afternoon. Two talks, by **Natalie Krivova** and **Sami Solanki**, discussed solar irradiance reconstructions. Natalie presented estimates of the total solar irradiance (TSI) and solar spectral irradiance (SSI) from the 4-component SATIRE model over the past 3 solar cycles. Sami presented a reconstruction of TSI and SSI variations from the present back to the Maunder Minimum. The other talks in this session addressed simulations of the climate response to solar forcing. **Caspar Ammann** showed that paleo-records suggest a solar influence on climate and that the NCAR Climate System Model (CSM 1.4) predicts global temperature changes of about 0.5 °C over the past 1000 years due to solar variations, consistent with the paleo temperature records. **Drew Shindell** presented results from the fully coupled chemistry-climate GISS Model E, simulating temperature, winds, and photochemical responses, such as for ozone, to solar forcing. Two talks about the stratosphere-troposphere dynamical processes ended this session. Like Drew, both **Kunihiko Kodera** and **Katja Matthes** stressed the importance of the solar UV irradiance variability that forces ozone changes in the stratosphere which dynamically couple to the troposphere. They showed data and general circulation model (GCM) predictions of temperature, winds, and ozone global and regional response to solar variability. As presented by Katja, Figure 3 shows the predicted temperature changes from lower solar irradiance values during the Maunder Minimum, noting that there is a slightly colder global temperature and much larger regional temperature changes (both hotter and colder).
The poster session for the SORCE science meeting occupied the remaining part of Wednesday afternoon. The session commenced with a summary by Dick White of the 14 posters in the Solar Variability poster session, followed with a summary by Peter Pilewskie of the 5 posters in the Sun-Climate poster session. Lively discussions of the results in these posters ensued, several continuing long after the poster session into the dinner conversations.

Thursday, 15 September 2005

Peter deMenocal’s keynote talk commenced the second day of the meeting. Peter dedicated this morning session to Gerard Bond, who passed away this year. Well known for his innovative research involving ocean sediment analysis and results concerning paleoclimate changes, Gerard had attended the 2003 SORCE meeting and was hoping to also participate in the Durango meeting. Peter presented an overview of the late Holocene solar and ocean circulation variability observed in the North Atlantic Ocean sediments. The sediment records indicate temperature variations of 1-2 °C that appear related to small solar variations over the past 3000 years. A probable mechanism for these changes is deep ocean convection changes in response to solar forcing. This mechanism also supports the observed ocean salinity changes (fresher during colder periods).
Session 3, *Evidence for Climate Responses to Solar Variability*, on Thursday morning comprised eight talks. A common theme during this session was the relationships of long-term regional climate proxies, especially those for drought and rainfall, with the cosmogenic isotope records of solar variability. It is important to note that regional changes are much more dramatic than the globally averaged changes. Harry van Loon presented compelling evidence for the impact of the solar cycle on Pacific Ocean circulation and temperature decadal changes. Curt Stager revisited a long-standing, sun-climate puzzle – that of the relationship between rainfall in East Africa at Lake Victoria and solar variability over the past century and past 1000 years. The variations are related to ENSO and Indian Ocean circulation changes, but their linkages with solar activity are intermittent (sometimes uncorrelated). Two other talks by Subarna Bhattacharyya and Ashish Sinha also showed correlations between solar variability and the Indian Ocean circulation changes and associated droughts and rainfall in India.

Paul Mayewski provided a longer term perspective in his discussion of the Greenland ice core records of climate variations over the past 110,000 years. These climate variations indicate large temperature variations of about 20 °C in Greenland prior to 10,000 before present (BP). Paul showed that the temperature variations appear to be caused by significant changes in the polar circulation patterns and that disruptions to Asian civilization occur during the coldest periods. He also presented instrumentally calibrated proxies for atmospheric circulation developed from Antarctic ice cores. Comparison with the $^{10}\text{Be}$ proxy of solar activity demonstrates significant correlations between solar variability and the strength of zonal winds forced via solar induced changes in stratospheric ozone. Further aspects of the hydrological cycle were the focus of the next two talks, namely possible relationships between river levels (rainfall) and solar variations. Charles Perry presented Mississippi River flow results over the past 140 years and showed how the Pacific Ocean heating and circulation pattern changes are a possible lagged driver of the rainfall that affects the Mississippi River flow. Alexander Ruzmaikin analyzed the Nile River flow records over the past 1400 years, relating these changes to solar variations at 11 years, 88 years, and 260 years. He also connected solar variability to changes in the Northern Annular Mode (NAO), affecting the Hadley circulation and thus the rainfall in Africa. Alexander showed support for the hypothesis that rainfall increases in equatorial Africa during periods of less solar irradiance (such as during the Maunder Minimum). David Lund presented the final talk in this session, showing that Gulf Stream salinity level increased during the Little Ice Age (LIA: 1200-1850 AD).
and that this increase could be explained by the Inter-Tropical Convergence Zone (ITCZ) having southward migration in response to lower solar irradiance values.

The focus of the Thursday afternoon session was Interpreting the Solar and Climate Sources of Cosmogenic Isotope Variations, and their Relationship to Solar Irradiance. The five talks in this session discussed the geomagnetic field and how the cosmic rays are modulated by geomagnetism as well as solar activity. The first two talks by Monika Korte and Cathy Constable provided overviews of the long-term and short-term changes of the geomagnetic field. As shown in Figure 6, there are significant long-term changes in the geomagnetic dipole moment.

The following three talks described how the cosmic rays are modulated, how this modulation affects the production of cosmogenic isotopes, and the implications for long-term climate changes.
of the cosmogenic isotope records. Horst Fichtner pointed out that the long-term temperature changes could be due to changes in the solar irradiance or cosmic rays (or both) and that these different forcings potentially could be isolated by examining the 22-year variations as the cosmic ray variations has a stronger 22-year cycle than the solar irradiance. He further showed that cloud, rainfall, and temperature data do have a 22-year signal, suggesting the importance of cosmic ray forcing on the climate. Raimund Muscheler re-emphasized the importance for the cosmogenic isotope production of both the geomagnetic field variations and the solar magnetic / particle modulation, driven by solar activity impacts on the heliosphere. He showed a reconstruction of solar irradiance for the past 1000 years assuming that the heliospheric modulation and solar irradiance changes are related. Raimund also pointed out that the $^{10}$Be isotope has more simple processes compared with the $^{14}$C isotope processes, which are complicated by its interaction with the biosphere and oceans. As shown in Figure 7, the $^{10}$Be and $^{14}$C records over the past 12,000 years are very similar and indicate long-term solar variations. Christy Field presented results using the GISS Model E on how the climate itself modulates the $^{10}$Be deposition, suggesting that the $^{10}$Be record may be expected to overestimate solar variations when used to model climate responses to solar forcing.

![Figure 7. Cosmogenic isotope records for the past 12,000 years (from R. Muscheler).](image)

That evening meeting participants enjoyed the Fort Lewis College's Center of Southwest Studies cultural history museum which hosted viewing and a reception. Later that evening, the group dined at the historical Strater Hotel. The dinner speaker, Mark Varien, presented a fascinating talk about the history of the Pueblo Indian settlements in the local area and how the historical ecology (e.g. drought) impacted their culture. Mark's talk was a great introduction for Friday's tour of Mesa Verde National Park.
The archeological sites found in Mesa Verde national Park are some of the most notable and best preserved in the United States. (Photo by M. Snow)

Friday, 16 September 2005

In his keynote talk on Friday morning, Scott Lehman, also paid tribute to Gerard Bond, then discussed the responses of the Norwegian Sea to solar forcing. As shown in Figure 8, Scott introduced first the linear relationship between solar proxies and the $\delta^{18}O$ isotope record in the ocean sediments, which is related to air temperature when it is deposited. He then showed longer term records over the past 10,000 years and discussed how the North Atlantic Oscillation (NAO) could be a mechanism for causing sea surface temperature (SST).

The topic of the remainder of the meeting, Session 5, was Linkages of Climate Cultural Responses and Solar Variability. The five talks in this session presented evidence for cultural changes plausibly related to climate changes associated with solar forcing. Ray Bradley first talked about possible secular changes in solar activity derived from the $^{14}C$ record then showed that glacier advances are correlated with lower solar activity, as is regional rainfall. Ray presented a geographical synopsis of evidence supporting climate responses to solar variations. Bas van
Geel talked about several different regional climate and culture changes during the past 10,000 years that are correlated with solar activity. In a graphic illustration of how the sun, climate and culture may be connected, Sultan Hameed showed an increased frequency of peasant rebellions and cannibalism during severe droughts (as based on China's written records and example shown in Figure 9) and suggested that the fall of the Ming Dynasty in 1644 is probably linked to the severe drought in 1628-1643, which occurred during the Sun’s Maunder Minimum. In an excellent demonstration of the impact of droughts on present-day society, Connie Woodhouse showed the importance of water flow records for the Colorado River basin for State managers, and discussed how the 22-year drought periods in Colorado dominate the river flow and water resources in the area. Joan Feynman concluded the session with a talk about agriculture development – its history, driving factors for its development, and how the dramatic changes in climate (solar activity) about 12,000 years ago might have enabled agricultural development.

Figure 9. Map showing peasant rebellions and drought areas (from S. Hameed).

To conclude the SORCE Meeting, Dick White and Peter Pilewskie provided brief overall summaries. Dick pointed out the success of the meeting in reviewing and discussing many of the interesting links between climate and solar activity and possible impacts on cultural changes, and in raising new questions and encouraging future collaborations. Peter introduced the concept for the next SORCE science meeting, planned for the fall of 2006 on the topic of the many outstanding radiative energy issues of the Sun-Climate system relating to, for example, clouds, aerosols, solar radiation, and dynamical transport of energy. Everyone is welcome and details will be posted on the SORCE website as they become available -- http://lasp.colorado.edu/sorce/. 
Dan Yeloff from the University of Amsterdam discusses his poster presentation with Connie Constable from Scripps Institution of Oceanography in San Diego, California.

**Poster Sessions**

**Session 1. Solar Variability:**

*Connecting Inferred Solar Microvariability over the Past 200ky with Observed Microvariability of 582 Solar-Class Stars from the ESA Hipparcos Program,* by Aden & Marjorie Meinel, University of Arizona, Tucson and Jet Propulsion Laboratory, Pasadena, California and Santa Barbara, California

*What was the Probable State of the Solar Chromosphere and Corona during the Maunder Minimum?* by Phil Judge, HAO, National Center for Atmospheric Research, Boulder, Colorado

*Cyclic and Secular Activity Changes in Solar Analog Stars,* by Jeffrey Hall, Lowell Observatory, Flagstaff, Arizona

*Variability and Redundancy across the Solar Spectrum,* by Peter Fox, HAO/ESSL/National Center for Atmospheric Research, Boulder, Colorado

*Spectral Irradiance Modeling and Long-Term Trends,* by Juan Fontenla, LASP, University of Colorado, Boulder

*Accuracy of Solar Radius Determinations from Solar Eclipse Observations, and Comparison with SDS and SOHO Data,* by David Dunham, Johns Hopkins University, Applied Physics Laboratory, Laurel, Maryland

*Observing the Solar Photosphere from Space using the MDI and HMI Instruments,* by Rock Bush, Stanford University, California

*Empirical Orthogonal Function Analysis of Observed and Modeled Solar Spectral Irradiances,* by Guoyong Wen, Goddard Earth Sciences and Technology Center and NASA Goddard Space Flight Center

*The NOAA MgII Core-to-Wing Ratio,* by Larry Puga, NOAA, Space Environment Center, Boulder, Colorado
Preliminary Estimate of the Mg II Index from 1932 to 1974, by Jeff Morrill, Naval Research Laboratory, Washington, DC

SORCE SOLSTICE High-Time Cadence Magnesium II Observations, by Marty Snow, LASP, University of Colorado, Boulder

Absolute Calibration of SORCE SOLSTICE, by Marty Snow, LASP, University of Colorado, Boulder

The LASP Interactive Solar Irradiance Database (LISIRD), by Marty Snow, LASP, University of Colorado, Boulder

SORCE Data Processing and Data Products, by Chris Pankratz, LASP, University of Colorado, Boulder

Session 2. Sun-Climate:

The Fossil Record of UV-B in Juncus Seeds and the Relation with Climate Change, by Dan Yeloff, University of Amsterdam, The Netherlands

A Model for Investigating Sun-Climate Questions, by E. J. Zita, Evergreen State College, Olympia, Washington

Solar Variability, Climate, and Human Response: A view from the Southwest, by David Gregory and Fred Nials, Center for Desert Archaeology, Pinetop, Arizona

A Climatological Spectral Study for Diagnosing the Solar 11-Year Signal in the Northern Hemisphere Atmosphere, by Ming Chen, IMSG at NOAA/NESDIS, Camp Springs, Maryland

Connecting the Inverse Correlation between 10Be and GRIP Temperature and Snowfall Accumulation over the Past 200 Ky with Relevance to the Variation of 10Be during the past 80 Ky and to the 40-Ky BP Surge, by Aden & Marjorie Meinel, University of Arizona, Tucson and Jet Propulsion Laboratory, Pasadena, California and Santa Barbara, California