

SORCE Science Meeting Addresses “Decadal Variability in the Sun and Climate”

— *Judith Lean, jlean@ssd5.nrl.navy.mil, Naval Research Laboratory*
 — *Greg Kopp, kopp@lasp.colorado.edu, Laboratory for Atmospheric and Space Physics, University of Colorado*
 — *Mark Baldwin, mark@nwra.com, Northwest Research Associates*
 — *Gary Rottman, gary.rottman@lasp.colorado.edu, Laboratory for Atmospheric and Space Physics, University of Colorado*
 — *David Rind, drind@giss.nasa.gov, Goddard Institute for Space Studies, Columbia University*
 — *Peter Pilewskie, peter.pilewskie@lasp.colorado.edu, University of Colorado*
 — *Tom Woods, woods@lasp.colorado.edu, Laboratory for Atmospheric and Space Physics, University of Colorado*
 — *Robert Cahalan, robert.cahalan@gssc.nasa.gov, NASA Goddard Space Flight Center*

After 18 extremely successful months in orbit, the SOLAR Radiation and Climate Experiment (SORCE) continues to engage the scientific community. EOS’s SORCE mission is measuring the Sun’s total and spectral irradiance with unprecedented accuracy and spectral coverage. SORCE data are providing new information to the science community to address solar variability relating to climate effects and potential climate response mechanisms. The SORCE program is fostering a unique venue for ongoing scientific exchange about the Sun and climate.

The SORCE team and interested scientists recently met in Meredith, New Hampshire to discuss *Decadal Variability in the Sun and Climate*. Approximately 75 people attended the meeting held October 27-29, 2004. The meeting was an opportunity to further understand the evidence for, and mechanisms involved in, decadal variability in the Sun and climate, with emphasis on their possible connections.

Discerning the role of the Sun in climate variations on time scales of decades is a challenging task. It is now relatively well established that climate forcing is well correlated with total irradiance and UV irradiance measurements obtained from high-precision

space-based solar measurements spanning more than two decades. When the Sun is near the maximum of its activity cycle, it is about 0.1% brighter overall, with an order of magnitude greater increase at UV wavelengths. SORCE measures these variations with unprecedented accuracy, precision, and spectral coverage across the UV, visible, and IR. But how—and if—climate responds to these measured solar variations presents a major puzzle. The meeting sessions focused on detecting and understanding plausible mechanisms both through direct surface heating and indirectly through the stratosphere.

Widespread empirical evidence from the extensive Earth climate data sets suggests the presence of an 11-year solar signal on the order 0.1 K in surface, atmospheric, and ocean temperatures. But general circulation models (GCMs) underestimate this response by as much as a factor of five. The GCMs account primarily for direct forcing by changing incoming total radiation and assume that the response time for climate feedback processes to this external forcing is on the order of 100 years. Processes and pathways not included in the GCMs may help facilitate the larger than predicted climate response to decadal solar variability. Solar variations in the UV spectrum modulate

stratospheric ozone concentrations, which may couple to climate via radiative and dynamical pathways. These pathways may involve the Northern and Southern annular modes, allowing a solar signal to be amplified and reach Earth’s surface. Internal atmosphere-ocean oscillations such as the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO) may also play a role. Clouds may expedite the feedback process, as they appear to also exhibit variability with the solar cycle. Stochastic climate variability may amplify the relatively small solar variations. Other, non-linear, climate processes are speculated.

With almost 60 abstracts submitted, attendees enthusiastically shared information, ideas, and opinions over the two-and-one-half days of oral and poster presentations. Most of the presentations are available on the SORCE Meeting website at: lasp.colorado.edu/sorce/2004ScienceMeeting/Meeting_Review.html.

The scientific organizing committee, **Mark Baldwin** from Northwest Research Associates, **Greg Kopp** from the Laboratory for Atmospheric and Space Physics (LASP), and **Judith Lean** from NRL, arranged the meeting into four sessions:

1. Solar Radiation—Status of Current
SORCE Measurements
2. Decadal Variability in the Atmo-
sphere and Oceans
3. Mechanisms and Modes of Decadal
Solar Variability
4. Climate Variability Modes, e.g.,
ENSO, NAO/ Arctic Oscillation
(AO), Pacific Decadal Oscillation
(PDO) and Nonlinear Response

An invited keynote speaker began each day with a thoughtful and enlightening overview talk, and meeting attendees enjoyed a provocative science dinner lecture.

Keynote Talks

Meeting Chair, **Mark Baldwin** (Northwest Research Associates, Bellevue, Washington) began the meeting with a tutorial on *The Stratospheric Link Between the Sun and Climate*. He intro-

duced the main Earth atmospheric modes such as the Quasi-Biennial Oscillation (QBO) and AO and discussed possible mechanisms whereby changes to the circulation of the lower stratosphere can affect surface climate. Possible stratospheric polar-vortex sensitivity to solar forcing may provide an indirect mechanism for climate change due to solar variability (see **Figure 1**).

On Thursday morning, **Vikram Mehta** (The Center for Research on the Changing Earth System, Columbia, Maryland) spoke on *“Decadal Climate Variability: Societal Impacts, Phenomena, Problems, and Prospects.”* He provided fascinating anecdotal evidence of how decadal and multi-decadal climate variability has influenced societies throughout history by affecting localized rainfall, fires, drought, fish catch, and hurricanes. But he noted that current climate predictions are not very accurate, partly due

to a limited time range of high-quality data. Mehta considered how the results would be used by society if climate variability prediction were reliable. Meeting attendees also learned about the Center for Research on the Changing Earth System (www.crces.org) for which decadal-to-century-scale climate variability is a special focus.

Madeleine Nash (*TIME* magazine contributor and book author, San Francisco, California) was a special guest at the meeting. She brought a new perspective to the SORCE Meeting on Friday morning when she presented *Chasing El Niño: A Science Writer's Walk on the Wild Side of Climate*. She discussed the effects the 1997-98 El Niño had on individual societies and people (a topic she explores in her recent book, *El Niño: Unlocking the Secrets of the Master Weather-Maker*), and speculated about the effects that long-term climate change might have on societies collectively over the next century. Her insightful comparisons of the characteristics of scientists and journalists proved especially interesting. The science-based audience had several questions on improving interactions with the public, and a lively discussion ensued.

Session 1—Solar Radiation—Status of Current SORCE Measurements

Chair: Robert Cahalan (NASA Goddard Space Flight Center)

Gary Rottman, SORCE Principal Investigator, commenced Session 1 with an overview of the SORCE mission (see **Figure 2**). He reported that SORCE is in excellent health and providing daily total solar irradiance (TSI) and solar spectral irradiance data from the soft X-rays, through the ultraviolet, visible, and into the infrared. All aspects of the

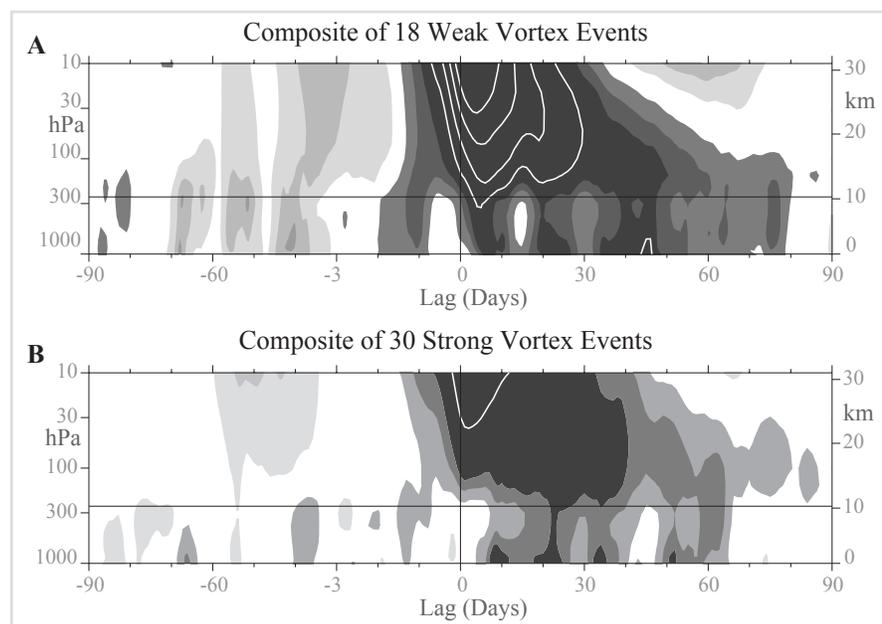
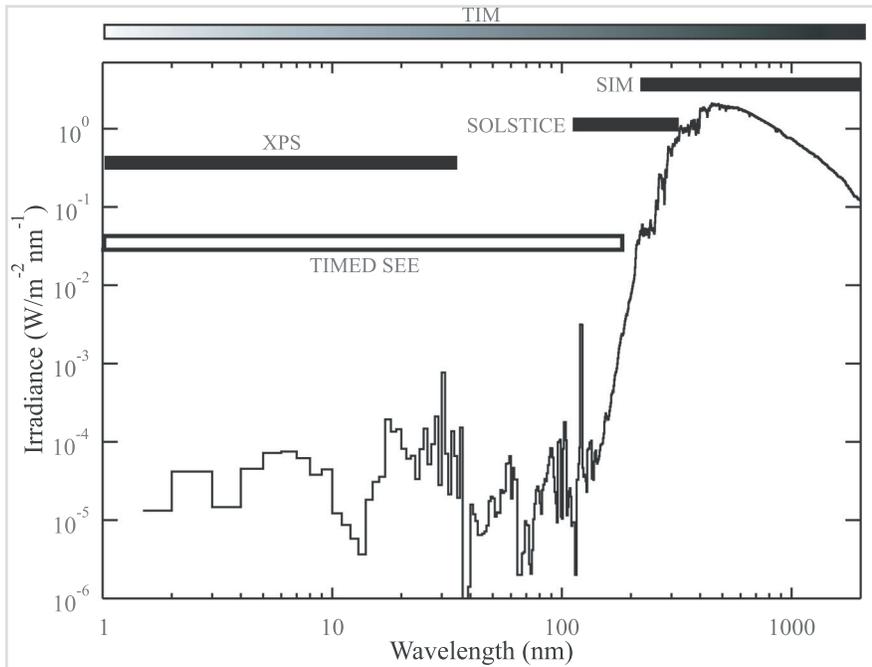


Figure 1: Composites of time-height development of the northern annular mode for (A) 18 weak vortex events and (B) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular-mode values cross -3.0 and $+1.5$, respectively. The indices are nondimensional; the contour interval for the shading is 0.25 and 0.5 for the contours. Values between -0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and the stratosphere. (Baldwin, M.P. and T.J. Dunkerton, Stratospheric Harbingers of Anomalous Weather Regimes, *Science*, 244, 581-584, 2001)

Figure 2: SORCE instruments and their wavelength coverage. (Gary Rottman)



mission exceed expectations with the spacecraft and instruments continuing to function flawlessly. Rottman concluded by stressing how very important it is to Sun-climate science to ensure the continuity of the solar data sets.

Following an introduction by Session Chair **Bob Cahalan**, each of the SORCE instrument scientists presented results from the first 18 months of the SORCE mission. A special focus was the observations of the dramatic flare, of almost unprecedented strength (in the space era) that occurred during the intense solar storm in October-November 2003 (shown in **Figure 3**). SORCE instruments are also providing excellent characterizations of solar rotational variability, which modulates the entire solar spectrum, and underlies the rapid surges of brightening seen during flares. As the SORCE mission continues, the instrument scientists expect to see reduced rotational modulation because solar activity is

declining. There is high anticipation that SORCE will eventually be able to characterize the Sun's 11-year cycle in irradiance at all wavelengths.

The Total Irradiance Monitor (TIM) instrument on SORCE measures total solar irradiance, continuing a database that extends without interruption back to 1978. **Greg Kopp** (LASP, University of Colorado) discussed the TIM results (see **Figure 3**). A crucial radiometric development is the offset of about -4 W/m^2 in the TIM absolute solar-irradiance value, as compared with other TSI measurements. After careful examination of all TIM calibration parameters and re-evaluation of data-processing algorithms, the SORCE scientists are now confident the new, lower values are correct. NASA and NIST calibration experts will convene a workshop(s) to address the differences between the various data sets, and hopefully in early 2005, a recommendation can be made to the climate community. *If solar irradiance is as low as 1361 W/m^2 , rather than the currently accepted value of 1365.5 W/m^2 , climate models may need revising.* TIM's beautiful observations of the

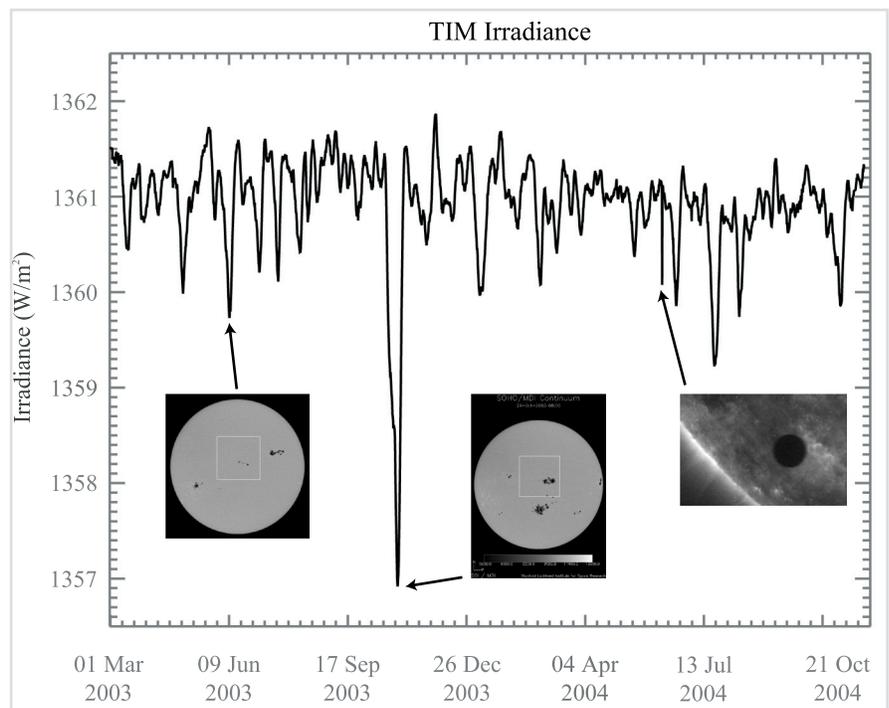


Figure 3: Over the life of the SORCE mission to date, the TIM has recorded the largest short-term decrease in TSI since space-borne measurements began, and has observed the transit of Venus across the Sun. (Greg Kopp)

Venus transit are exciting *serendipitous science*.

SORCE has a unique new capability to make precise measurements of spectral-irradiance variations that compose the changes in total irradiance. SORCE's Spectral Irradiance Monitor (SIM) is observing fluctuations in the entire solar spectrum from 0.2-2 μm . SIM instrument scientist, **Jerry Harder** (LASP, University of Colorado) reviewed the visible and near-infrared results. Harder pointed out important differences between the SIM measurements and models of solar spectral-irradiance variability that various climate model studies have used. He emphasized the need to refine solar models in the infrared region. He concluded that solar images, TSI, and solar modeling in conjunction with SIM spectral irradiance measurements provide an effective and unprecedented suite of research tools to investigate solar variability and achieve new understanding of its nature and causes.

Discussing the ultraviolet results from the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) instrument, **Bill McClintock** (LASP, University of Colorado) presented new information about solar variability evident in the Magnesium-II (Mg II) core-to-wing index. SORCE SOLSTICE data continue to validate and refine the UV spectral-irradiance observations made by SOLSTICE on the Upper Atmosphere Research Satellite (UARS). Achieving a long-term database of high-quality solar UV irradiance is crucial for clarifying solar influences on ozone concentrations, and possible stratospheric forcing of climate. Like TIM, SOLSTICE is also providing exciting *serendipitous science*, including occultation measurements of ozone and molecular oxygen,

and lunar observations that suggest a lower lunar UV albedo (reflectivity) than previously thought.

The soft X-ray results from the Extreme Ultraviolet (XUV) Photometer System (XPS) instrument were covered by **Tom Woods**, LASP's SORCE Project Scientist. Woods talked about the latest XPS calibrations and additional flare measurements in June 2003 and July 2004. Woods' instruments on the simultaneously operating Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission combine with the SORCE XPS to extend the spectral-irradiance coverage of SIM to the XUV region.

All SORCE science data are processed, analyzed, validated, and distributed through LASP's Mission and Science Operations Center in Boulder, Colorado. Processed data are distributed to the science community through the Goddard Earth Sciences (GES) Distributed Active Archive Center (DAAC). For additional information on obtaining SORCE data from the DAAC and reading the SORCE HDF data files, see: lasp.colorado.edu/sorce/data_access.html.

Session 2—Decadal Variability in the Atmosphere and Oceans

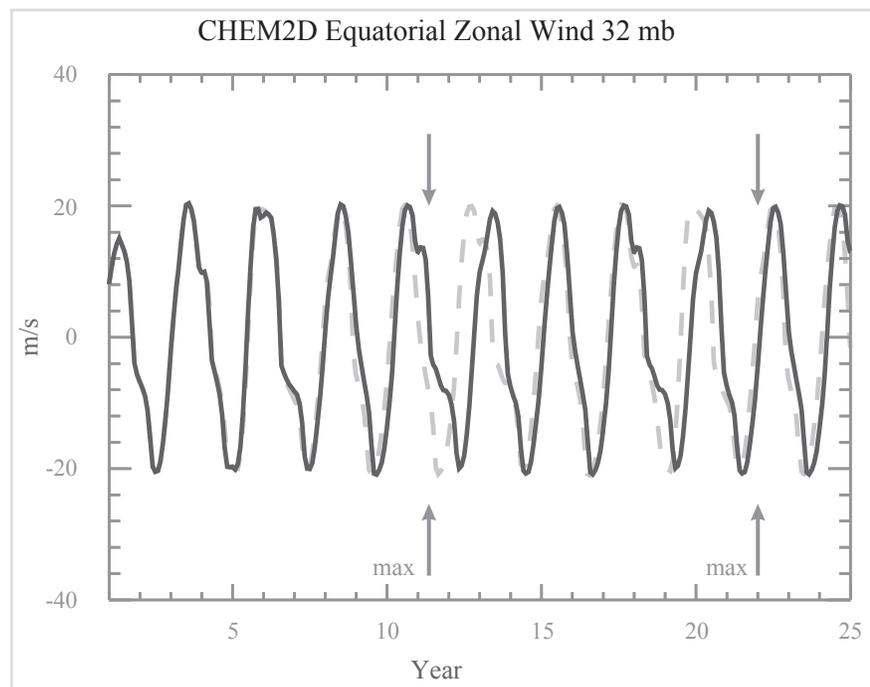
Chair: David Rind (Goddard Institute for Space Studies, Columbia University)

Session 2, chaired by climate-change expert **David Rind**, examined evidence for decadal variability in the Earth's atmosphere, with emphasis on exactly how solar-cycle effects might influence the stratosphere and troposphere. This is a continuing source of interest to the Sun-climate community, motivated by recent studies that appear to demonstrate a possible stratospheric influence

on climate. The direct solar heating in the stratosphere is becoming better observed, and a response is also detectable in the troposphere. The solar-cycle impact on the stratospheric circulation is increasingly seen as an interaction between the solar cycle, ozone, QBO, and the semi-annual oscillation (SAO) (which Mark Baldwin described in his keynote talk) in complicated ways, usually involving planetary-wave interactions. The effect on tropospheric dynamics may also involve synoptic-scale waves, although tropospheric responses are typically determined to be quite small.

Discussing empirical detection of the 11-year cycle as derived from observations of the lower troposphere, **David Douglass** (University of Rochester, NY) shared his findings of a solar-cycle-related temperature change of order 0.1°C . From this he inferred a climate sensitivity of $0.1^\circ\text{C}/\text{W}/\text{m}^2$, with a lower sensitivity to the seasonal variation in solar irradiance ($0.03\text{ C}/\text{W}/\text{m}^2$). Both sensitivities are much lower than GCMs produce and seem to imply a negative feedback relative to the decadal cycle. He combined the observations with the observation (now-disputed) that Microwave Sounding Unit (MSU) sensors show a cooling in the upper troposphere—in contrast to GCM-produced warming—to conclude that GCMs have inappropriate positive feedbacks and long response times. However, the sensitivity of the system depends on the time-scale of the forcing. The decadal cycle of five years up and five years down is too quick to incite most of the ocean warming and water vapor response. This is even more true of the seasonal cycle, which has an even lower sensitivity than the decadal cycle. Thus the full feedback response

Figure 4: When solar UV variations are included (dotted line), westerly QBO phase tends to be shorter near solar maximum (arrows). This effect is only present when zonal wind SAO is also included. (John McCormack)



requires consistent forcing lasting longer than a decade.

Particularly exciting are new developments in the detection and interpretation of solar signals in high-quality atmospheric databases that have existed for many decades. **Joanna Haigh** (Imperial College, London, UK), a leader in this area of work, presented her results from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) data. She related changes in the solar cycle to changes in the tropospheric zonal wind field, both in NCEP/NCAR observations and in a GCM. In both model and observations the subtropical tropospheric jets moved poleward as solar activity increased, although the model effects were somewhat smaller. The model response was related to a change in tropical upwelling and Hadley Cell strength (the Hadley Cell weakened and expanded poleward). To

investigate the mechanism involved, heating was added to a simplified GCM, changing the stratospheric temperatures at various latitudes. Uniform or high-latitude warming weakened the jets and moved them equatorward, while tropical warming produced changes in accord with the observations. The warming of the lower stratosphere affected the height of the tropopause, and the life cycle of baroclinic waves, explaining part of the response. While the variations involved are small—changes in the jet of 1 m/s—they are detectable at the 95% confidence level in the observations.

There is emerging evidence, both from analysis and modeling, that solar variability can influence the Earth's atmosphere by affecting its various modes of variability. **John McCormack** (Naval Research Laboratory [NRL], Washington, DC) discussed the relationship of the solar cycle to the QBO (and SAO).

Of particular interest was uncertainty as to the altitude at which the main interactions occur—in the lower stratosphere or the upper stratosphere. McCormack used the NRL CHEM2D model with full chemistry, a lower boundary forcing of the QBO, and the SAO forced by gravity-wave drag, to investigate possible interactions. His results are shown in **Figure 4**. The QBO was found to increase the variation in zonal wind from solar maximum to solar minimum by a factor of two (although it was still 2.5-times too weak). A shorter-phase westerly QBO at solar maximum in the model was found to be due to the SAO (although the difference in phase was less than half the observed). The conclusion was that both the QBO and SAO are needed and both altitudes are important. One problem is that the model (like others) was not able to reproduce in detail the observed variation of ozone with the solar cycle (model values have smaller amplitude changes and peak at lower altitudes). McCormack also noted that the Halogen Occultation Experiment (HALOE) observations don't seem to indicate the same ozone/solar-cycle effects as had been previously observed, underscoring an issue that would emerge again during the meeting—namely our relatively poor understanding of the solar-cycle variation of ozone.

To investigate the variability of the winter stratosphere with respect to the solar cycle, **Lesley Gray** (Reading University, UK) examined the last 20 years of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40). A multiple-regression analysis was performed with respect to the solar cycle (10.7 cm flux), volcanic aerosols, the NAO, ENSO, and the QBO. As **Figure 5** shows, a clear solar cycle is observable in temperature,

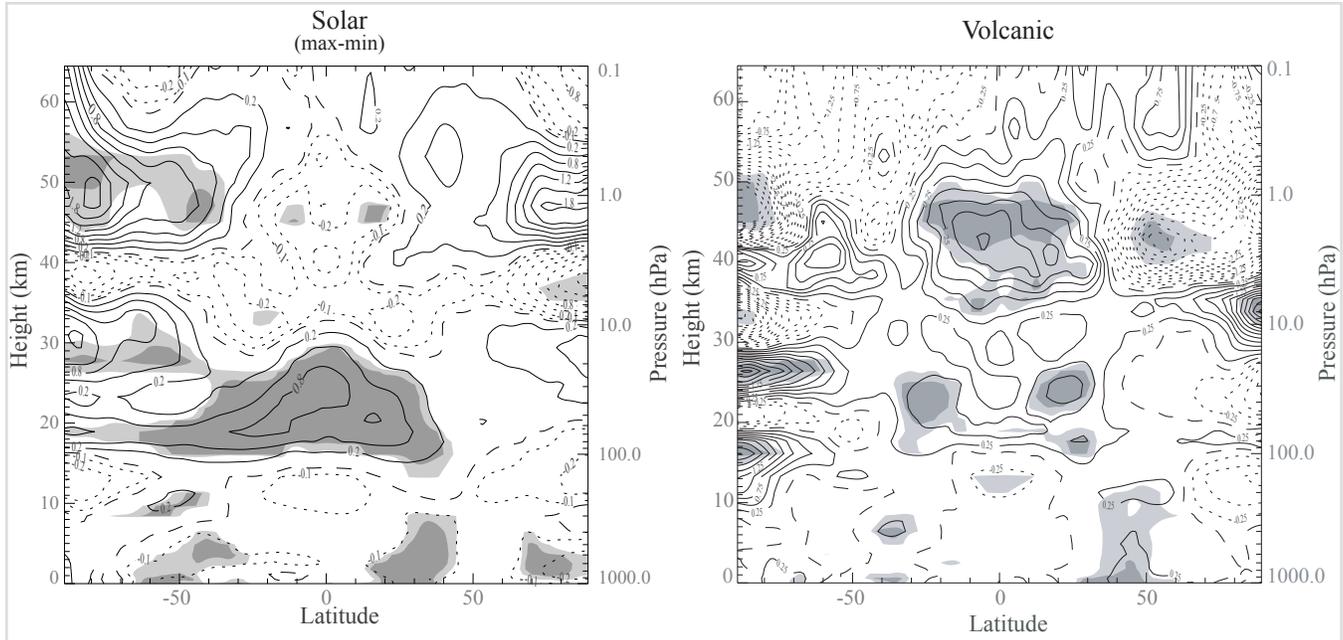


Figure 5: Latitude - height distribution of the zonally-averaged, annual-average amplitude of the 11-year solar cycle and volcanic signal in temperature (K) from a multiple regression analysis of the ERA-40 dataset for the period 1979-2001 (S. Crooks and L.J. Gray, *J. Clim.*, 2005, in press). The other components in the multiple regression included a long-term trend, seasonal variations, and representations of the NAO, ENSO and QBO.

on the order of 2 K at 40-50 km, with a secondary maximum at 20-25 km in the subtropics (in agreement with observations of Labitzke and van Loon). A zonal-wind response, of up to 6 m/s was found peaking at 50-60 km in the subtropics. This anomaly was associated with a tendency for stratospheric warmings to occur earlier with the east phase of the QBO and solar-minimum conditions. It was reproduced in a simple model, in which subtropical easterlies were pulled in around the polar vortex and used to build up the Aleutian High, leading to the earlier breakdown of the vortex. For this to happen, the anticyclones had to be coherent with depth, which means it also depends on the phase of the SAO. Hence both this and the previous talk emphasized the interaction of the solar cycle with oscillations throughout the depth of the stratosphere.

An understanding of the response of stratospheric ozone to changes in solar UV radiation is crucial for quantifying

mechanisms to explain the results presented by both Joanna Haigh and Lesley Gray. **Terry Nathan** (University of California, Davis) focused on how solar-cycle-induced perturbations to stratospheric ozone could impact the vertical propagation and downward reflection of forced planetary waves—a topic also discussed later in the meeting by his colleague Eugene Cordero. Nathan used a mechanistic (quasi-geostrophic) model of the extratropical atmosphere to account for the interactions between ozone, radiation, and dynamics. The results indicated that solar-cycle-induced ozone perturbations could change the refractive index of the planetary waves via two mechanisms: 1) by changes in the zonal-mean temperature gradient, which affects the zonal-mean wind via thermal-wind balance; and 2) by changes in the diabatic heating associated with wave-ozone interactions. The former mechanism has been considered in previous studies and represents an incomplete picture of how the solar cycle might af-

fect planetary wave reflection. The latter mechanism has not been considered before and represents a new pathway for communicating solar-cycle-induced changes in ozone heating to the lower atmosphere. Indeed, the second mechanism produces changes in the refractive index that cause the planetary waves to reflect downward into the troposphere where the poleward heat fluxes are altered.

Also focusing on wave motions, using a 2-level baroclinic model, **Alfred Powell** (NOAA/NESDIS/Office of Research Applications [ORA], Camp Springs, MD) investigated how the solar cycle might alter the planetary-wave spectrum. The basic idea is that static stability is changed during the solar cycle, and the critical wavelength for instability is affected by the static stability. In addition, as the temperature gradient is altered during the solar cycle, so is the vertical shear of the zonal wind, which also affects instability. The results showed that there was more energy at

solar maximum for short waves, and more energy during solar minimum for long waves, a combination of shear and static stability influence. The response also differed as a function of month. Overall, the change in energy was greatest during the maximum gradient of the solar flux. The conclusion was that both synoptic-scale and planetary-scale wave generation can be affected by solar-cycle influences, although it was estimated that the resulting changes were small (on the order of 3%).

Session 3—Mechanisms and Modes of Decadal Solar Variability

Chair: Stephen Walton (San Fernando Observatory, California State University)

A primary cause of solar-irradiance variations is the occurrence of bright active regions, called *faculae* (Latin for *torch*) on the Sun's disk. In fact, during the solar activity cycle, facular brightening dominates—by a factor of two—the darkening by sunspots to cause overall total-irradiance brightening at cycle maxima. Faculae have lower contrasts, are more spatially dispersed, and are not nearly as well understood as sunspots. Session 3 focused on recent research into solar mechanisms that cause variations in the Sun's output on decadal time scales, with particular emphasis on observations and models of faculae.

Commencing the session, **Dick White** (LASP, University of Colorado) examined current knowledge of the Sun's radiative output, based on measurements of various proxies of activity—the F10.7, Mg II, and sunspots—in relation to the rapid increase in global temperature over the last 50 years. He stressed the importance of the last 30 years specifically in measuring and understanding the total- and spectral-ir-

radiance variations, and for comparing solar variability to the Earth's global temperature. The current solar cycle 23 is an important case study. Whereas the prior solar activity cycles (numbers 21 and 22) were comparable in the strength of their activity (as indicated by similar sunspot numbers), cycle 23 is of overall lower activity. Facular indices such as the Mg II core-to-wing ratios don't appear to follow the sunspot numbers as well as they did in prior solar cycles, and TSI is comparable in the three cycles. Like many others, White concluded that solar-output changes cannot account for the rapid increase in global warming.

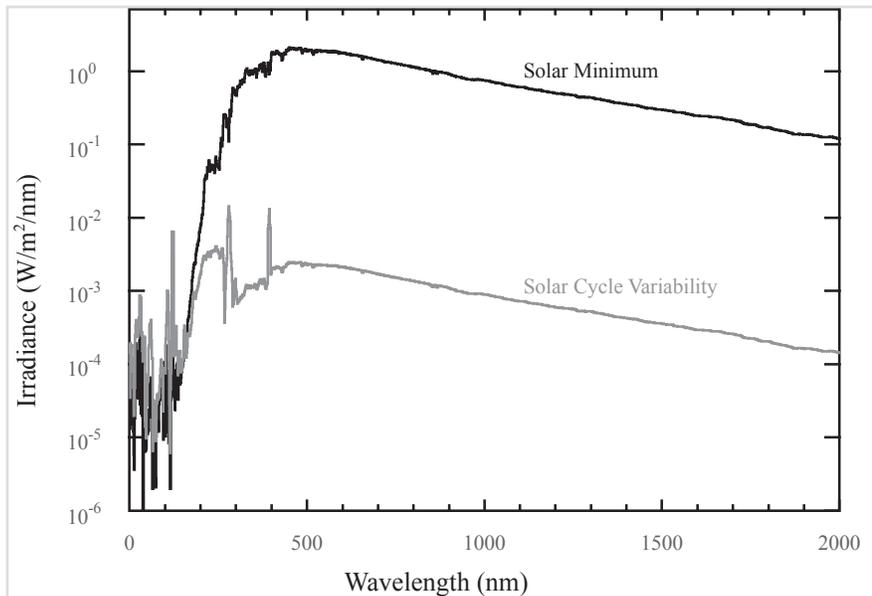
The San Fernando Observatory (SFO) has been making 5x5" full-disk photometric images in 3 wavelength bands since 1985 with higher resolution images and additional wavelength bands starting in 1992. Analysis of these images helps in understanding the sunspot and facular influences on TSI. **Stephen Walton** (San Fernando Observatory, California State University, Northridge) explained how daily photometric sums are computed, with contributions from high-relative-intensity pixels attributable to faculae and low-intensity pixels to sunspots. These sums correlate well with spacecraft measurements of TSI. He finds no solar-cycle variation in the broadband photometric sum in the *red* region of the solar spectrum. This suggests that visible-wavelength continuum radiation has no solar-cycle component, and that changes in the line blanketing by the solar atmosphere dominate the solar-cycle change in TSI. The SFO results also show that solar features larger than 10^{-4} of the solar hemisphere account for the majority (80%) of the solar-cycle variations in irradiance. Particularly interesting were Walton's preliminary comparisons of

the SFO image on September 1, 2003 converted to *bolometric* brightness maps (thus mimicking TSI) with new images that measure this quantity directly using the Solar Bolometric Imager, which Peter Foukal discussed later in the session.

Following from the 2002 SORCE meeting, in which there was considerable discussion of the constructions of composite records of TSI, **Claus Fröhlich** (Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Switzerland) reported on his refined TSI composite. Fröhlich's composite now includes a re-analysis of: 1) the Solar Maximum Mission/Active Cavity Radiometer Irradiance Monitor (SMM/ACRIM-I) observations for an early sensitivity increase; and 2) the degradation of the Hickey-Frieden radiometer on NIMBUS-7 to remove sudden discontinuities not present in the Mg II record. Degradation in early solar radiometers is difficult to quantify, as many did not have multiple channels for on-orbit tracking. To overcome this liability, Fröhlich fits a degradation correction to the early measurements by the Hickey-Frieden solar radiometer that is similar to the quartz siliconizing parameterization that he uses to account for analogous sensitivity changes detected in the more-recent Variability of Solar Irradiance and Gravity Oscillations (VIRGO)/Physicalish-Meteorologisches Overvatorium Savos (PMOD) radiometer. The new composite, similar to the prior ones, shows no significant secular change in irradiance, but does show a somewhat different behavior of cycle 21.

Secular changes in irradiance are an important area of on-going research. **Tom Woods** (LASP, University of Colorado) discussed possible changes

Figure 6: The solar irradiance spectrum is shown shortward of 2000 nm along with the estimated variability of the irradiance over the 11-year solar cycle. At the short ultraviolet wavelengths, the solar variability is larger than the solar minimum irradiance value, and the variability at the visible and infrared wavelengths is about 0.1% of the irradiance value. As listed in the table, the ultraviolet irradiance is a small amount of the total solar irradiance (TSI), but the ultraviolet variability is a more significant part of the TSI variability.



Range	Fraction of TSI	Fraction of TSI SC Variation
0-400 nm	7.7%	24%
0-300 nm	1.1%	12%
0-200 nm	0.008%	1.2%

in solar irradiance during the Maunder Minimum period of the late 1600s, when sunspots were absent from the Sun for long periods. Based primarily on analysis of solar Ca K images (which indicate regions of facular brightness), Woods pointed out that solar active regions alone, as indicated by sunspot numbers, cannot account for the expected lower irradiances that are obtained by removing known brightness sources present in the Ca K images even during solar-cycle minima. He suggests that an absence of the active network caused lower irradiances at this time. Estimated irradiance variations between the most recent 1996 solar minima and the Maunder Minimum are as follows: the Ly-alpha irradiance was lower by 25%; the UV (<400 nm) irradiance was lower

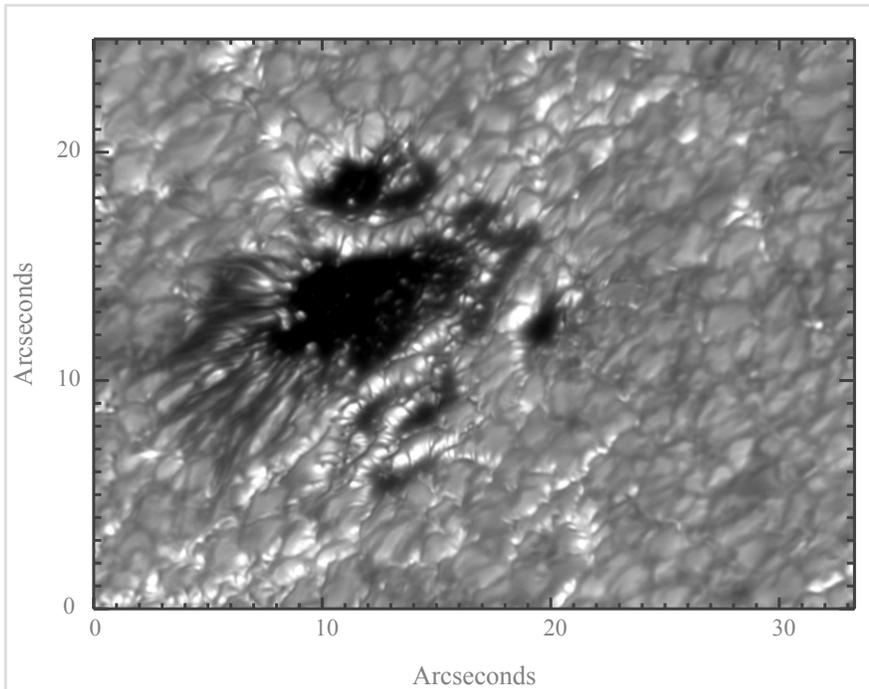
by 0.32 W/m², and TSI was lower by 1.3 W/m².

Continuing the topic of the role of faculae, **Ken Schatten** (ai-solutions, Inc., Lanham, MD) described his *Ion-Hurricane Model* for sunspots and faculae, and compared it to the conditions that create hurricanes on the Earth. He contrasted the fluid-dynamical solar-ion hurricane model to a quite different facular model—that of Spruit’s field-inhibition hot-wall model. Two basic differences are that: 1) in the fluid-dynamical model the magnetic field enhances energy transport whereas in the field-inhibition model the field reduces it; and 2) faculae in the fluid-dynamical model appear as *hillocks* on the Sun’s surface (uplifted structures with bright sides) rather than depressions or wells.

Thus, in the fluid-dynamical model, the Sun’s magnetic field enhances the solar irradiance by allowing the Sun to shed its luminosity through a second energy transport mechanism, very much as a hurricane enhances energy transport from the oceans. This helps explain the overall effect of solar activity to enhance the Sun’s luminosity. It is a challenging observational question to ascertain whether faculae are *uplifted* features, when there is no *sea level* on the Sun to measure the relative heights of features.

Wonderful new high-resolution images of the Sun’s surface have been recently recorded, and may afford the possibility of clarifying mechanisms of faculae formation. **Tom Berger** (Lockheed Martin Solar and Astrophysics Laboratory, Palo Alto, CA) showed some of the best images and movies of faculae ever recorded. He compared images of solar faculae and magnetic field strengths with 0.1” resolution from the Swedish Solar Telescope. He described the observational challenges behind measuring facular area and center-to-limb variations. His high-resolution facular images will help validate whether the hot-wall field-inhibition model or that predicting *hillock* faculae is more realistic. 3-D compressible magneto-hydrodynamic simulations do well replicating the morphology of the observations, but currently lack the detail and the dynamic effects on short time scales seen in his movies. Mechanisms besides sunspots and faculae have been speculated to contribute to solar-irradiance variations on multi-decadal to millennial time scales. **Peter Foukal** (Heliophysics, Inc., Nahant, MA) showed that the evidence used over the past 10 years to argue for such additional variation is no longer valid. He also pointed out that satisfactory

Figure 7: Active Region 10377 taken on June 6, 2003 in the G-band 430.5 nm bandpass at a disk position of N5 E43 degrees heliographic. The image shows the three-dimensional form of bright faculae surrounding the central sunspot: faculae are the walls of granulation seen through the transparency caused by the small-scale magnetic field outside of sunspots. (Tom Berger)



physical explanation of the spot- and facular-induced irradiance fluctuations requires that the enormous thermal inertia of the Sun's convective envelope be taken into account. In Foukal's view, this inertia limits any additional irradiance variations associated with conceivable solar structural changes to relatively shallow layers. More-precise solar photometry will be required to search for such—as yet undetected—mechanisms. In this regard, Foukal described the recent balloon flight of the Solar Bolometric Imager which was used to obtain the first wide-band (0.2-3 μm) facular contrasts. These new contrasts should enable construction of more-accurate empirical irradiance models using the long time series of facular areas compiled at San Fernando Solar Observatory, a topic he is pursuing with Steve Walton of CSUN. In contrast with Tom Wood's earlier discussion (see Figure 6) he concluded

that, at present, evidence favors long-term solar output variations of amplitudes limited ($<0.1\%$) and comparable to those observed over recent decades.

Session 4—Climate Variability Modes, e.g., ENSO, NAO/AO, PDO, and Non-linear Response

Chairs: Lesley Gray (Reading University, UK) and Peter Pilewskie (LASP, University of Colorado)

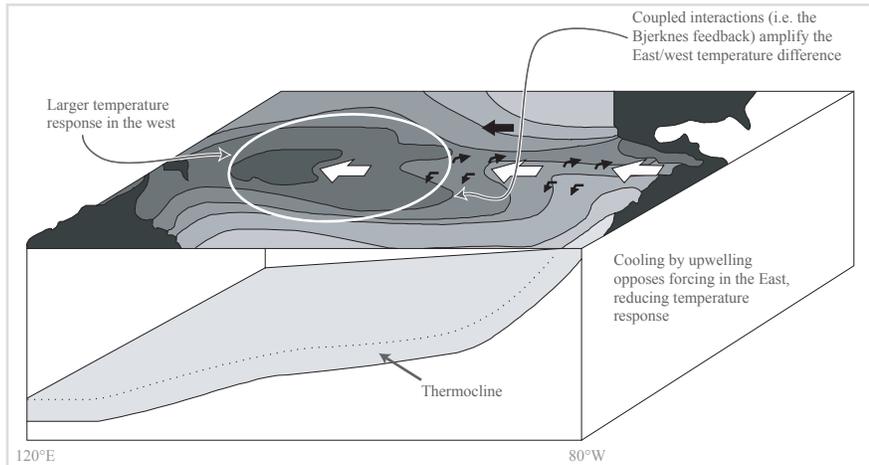
Session 4 began with **Mark Cane** (Lamont-Doherty Earth Observatory of Columbia University) providing an excellent overview of the basic mechanisms of the El Niño/Southern Oscillation (ENSO) and its impacts around the globe. He addressed the Bjerknes feedback, (see Figure 8) potentially a key amplifying mechanism in the climate's response to solar variability. ENSO influence goes well beyond the tropical Pacific, affecting

worldwide patterns. The response is mediated by the *thermostat mechanism* whereby a positive forcing leads to a colder eastern equatorial Pacific and an increased zonal temperature gradient on the equator. He concluded with a long-term perspective on ENSO that comes from paleoclimate records and models that show a response to natural solar and volcanic forcing.

Amy Clement (Rosenstiel School of Marine and Atmospheric Sciences, FL) explained her investigation into the response of El Niño to volcanic and solar forcing over the past 1000 years. She found that very small decadal sea-surface temperature (SST) anomalies can have large impacts on climate. A combination of responses to past changes in volcanic and solar radiative forcing closely reproduces changes in the mean state and interannual variability in El Niño in past centuries which have been recorded in fossil corals. She suggested that droughts in the American west are directly related to small anomalies in tropical Pacific sea SSTs and raised the question, "Can these anomalies be related to variability in solar irradiance?"

Evidence exists for decadal time-scale periodicities in the instrumental and proxy climate records that may be related to solar forcing, according to **Michael Mann** (University of Virginia, Charlottesville). A leading expert in the statistical description of climate variability, Mann reviewed work looking at both the statistical connections and underlying dynamical mechanisms for solar forcing of climate on decadal-through-multicentennial time scales. The decadal time-scale signals suggest both thermodynamic and dynamical responses of the climate to solar radiative forcing. Proxy-based climate reconstructions suggest persistent

Figure 8: This figure is a schematic of the mechanism by which a heating of the tropical Pacific ocean can lead to a cooling in the eastern equatorial Pacific. The heating produces a larger temperature response in the western basin than in the eastern basin. This is because the effect of upwelling of cold water into the surface offsets the forcing. As a result, there is a slight increase in the east-west temperature gradient that in turn accelerates the trade winds. The stronger trade winds lead to increased upwelling and a shallower thermocline, both of which cool in the east. This feedback between the surface temperature gradient, winds and thermocline is known as the Bjerknes feedback, which is the fundamental mechanism leading to El Niño events. As a result of this feedback, there is a cooling in response to a heating at the surface of the tropical Pacific ocean. (Amy Clement)



decadal and multidecadal relationships with solar forcing over centuries and millennia. Mann concluded that forced changes in large-scale atmospheric circulation such as the NAO, and internal dynamics related to El Niño, may play an important role in explaining regional patterns of response to solar forcing.

Atmospheric Centers of Action (COA) at the surface are extended regions of high and low pressures that dominate atmospheric circulations over large areas. It is useful to study the variations of the COA because they are strongly coupled to regional climate, as **Sultan Hameed** (Stony Brook University, NY) described in his talk at the 2003 SORCE meeting. This year, Hameed showed that two such COA, the Icelandic Low and the Azores High, are strongly related to regional climates in North America, Europe and North Africa while the Aleutian Low and the Hawaiian High are strongly related to regional climates in East Asia and

North America. The surface pressures and the positions of the Aleutian Low (see **Figure 9**), the Icelandic Low, the Hawaiian High, and the Azores High systems have significant correlations with the solar cycle when they are classified by the East and West phases of the QBO. The responses in the surface conditions of the COA are found to lag the stratospheric wind direction by zero to four months.

In an excellent complementary discussion to Mark Baldwin's keynote talk, **David Thompson** (Colorado State University, Fort Collins) addressed the impact of stratospheric ozone depletion on climate change at the Earth's surface. He suggested that recent southern hemisphere climate change can be interpreted as a bias towards the high-index polarity of the fluctuations in the strength of the circumpolar vortex pattern. The largest and most significant trends at Earth's surface can be traced to recent trends in the lower stratospheric polar vortex, which are largely

due to photochemical ozone losses. He concluded that stratospheric ozone depletion in the Southern Hemisphere is associated with substantial changes in climate at Earth's surface.

To explore mechanisms by which solar variability influences climate, **Alexander Ruzmaikin** (Jet Propulsion Laboratory [JPL], California Institute of Technology, Pasadena), investigated how the dynamics of the interaction between planetary waves and zonal flow responds to changes in solar UV flux. Using the assimilated data from the NCEP re-analysis, he showed that the extratropical signature of the QBO is seen mostly in the North Annular Mode (NAM). To understand these findings, Alexander researched earlier suggested mechanisms for extratropical manifestation of the QBO, and the time dependence of the QBO-NAM coupling.

Past and ongoing research (as John McCormack and Murry Salby described at the meeting) suggests that a solar-cycle influence in the lower atmosphere may be linked to the QBO, which is generated primarily by small-scale gravity waves. **Hans Mayr** (NASA Goddard Space Flight Center) recently initiated a 3D study where the QBO under the influence of the solar cycle was simulated. Preliminary results indicate that the Numerical Spectral Model (NSM) can produce a relatively large modulation of the QBO related to the solar cycle. Mayr discussed ideas about how the effect might be generated, but cautioned that further numerical experiments are needed to explore and more fully understand the mechanism that may amplify the solar-cycle influence. In addition, parametric studies with improved vertical and temporal resolution must be implemented to determine

whether the effect is real and the results are robust.

Zonal-mean ozone perturbations can affect the QBO. **Eugene Cordero** (San Jose State University, CA), examined this association during the 11-year solar cycle by using a model of the tropical stratosphere. The model accounts for wave-driven changes in the zonal-mean circulation and thus can simulate the zonal wind, temperature, and ozone QBOs in the tropical stratosphere. He concluded that solar-cycle-like perturbations to the ozone field affect the QBO in a way that resembles observations. Wave-induced ozone perturbations are apparently responsible for a majority of these changes. Future work is needed that will include upper stratospheric responses, the annual cycle, and eventually a global model.

Building on his recent seminal work on the role of the QBO in facilitating

solar forcing of the middle atmosphere, **Murry Salby** (Program in Atmospheric and Oceanic Sciences [PAOS], University of Colorado, Boulder) discussed the detection of a solar-cycle influence on the general circulation of the stratosphere, with subsequent interaction with the troposphere. Modulation of the QBO's phase during winter can explain the large amplitude of the solar signature when polar temperature is stratified against equatorial wind. Stratifying data rectifies the high-frequency oscillation, leaving a systematic drift through all phases of the solar cycle. The accompanying structure resembles interannual changes of the residual mean circulation of the stratosphere. The latter is characterized by anomalous downwelling over the winter pole, which penetrates well into the troposphere. Compensating it at subpolar latitudes is anomalous upwelling, accompanied by an apparent intensifi-

cation of the Hadley circulation. Similar structure characterizes changes that operate coherently with the QBO and solar activity.

Opening the Friday morning portion of this session, **Jose Rial** (University of North Carolina, Chapel Hill) began by discussing the (nonlinear) causes of abrupt climate change during the last Ice Age, and demonstrated with a simple model that variability in the Greenland Ice core Project (GRIP) short-period time series can be explained by non-linear oscillations externally forced by astronomically induced changes in incoming solar radiation. The model reproduced the Younger Dryas episode very well (see **Figure 9**) and thus may provide useful predictions of global warming at the millennial scale. The next challenge is to incorporate as many physical processes as possible by using the relevant climate variables, including geography, to demonstrate that the sea-ice/ocean/atmosphere thermal system is equivalent to a forced, self-sustained, nonlinear relaxation oscillator.

In his talk on the effect of ENSO on the dynamical and thermal structure of the middle atmosphere, **Fabrizio Sassi** (NCAR, Boulder, CO) presented a simulation using a General Circulation Model (GCM) forced with observed SST for the period 1950-2000. He showed that circulation anomalies in the middle atmosphere are accompanied by large temperature anomalies that are of opposite sign in the stratosphere and mesosphere. The findings were corroborated by an annular-mode analysis which showed that the strongest coupling between stratosphere and troposphere occurred during El Niño events when stratospheric sudden warmings were more frequent.

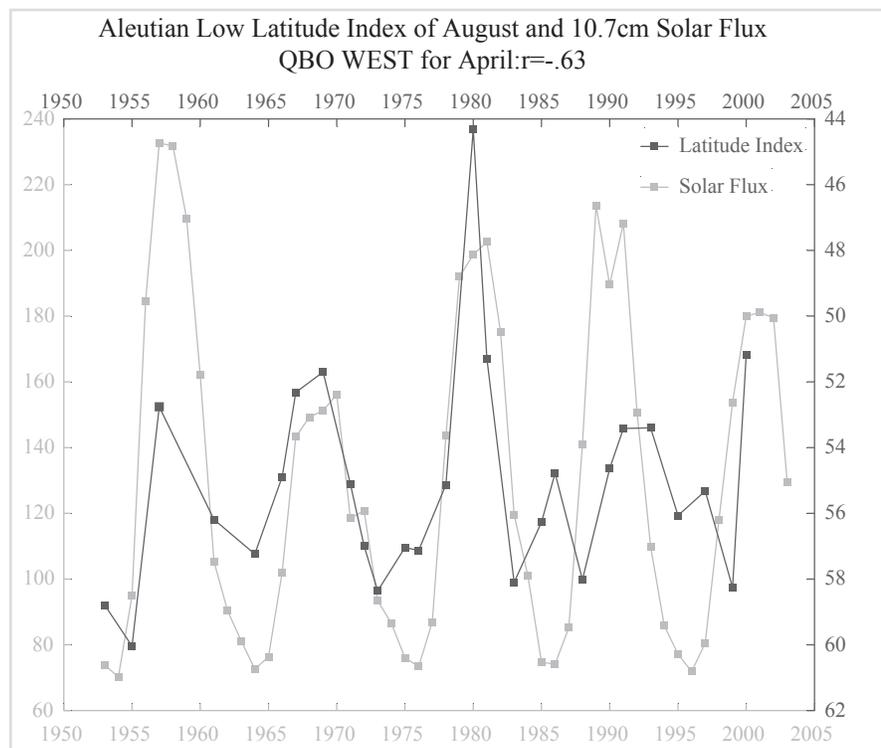
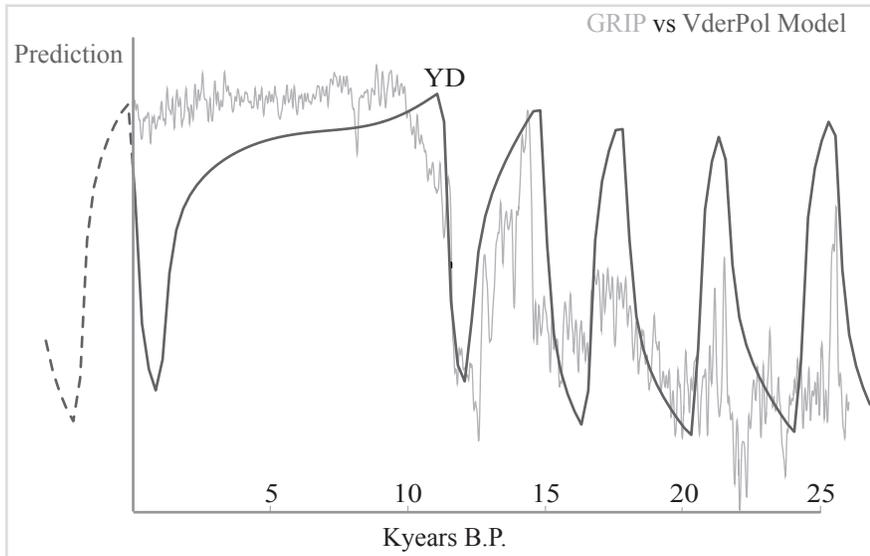


Figure 9: The correlation of the Aleutian Low latitude position in August with the 10.7 cm Solar Flux when the winds at 30 mb are westerly. Significant correlations exist for westerly wind directions in August, July, June, May and April, and the last case is shown in this figure. (Sultan Hameed)

Figure 10: Detail of the comparison between the van der Pol model and the GRIP time series. The model is the result of forcing a 2.75ky nonlinear thermal oscillator (sea ice-ocean-atmosphere) with the theoretical insolation. The period of the oscillator was extracted from the data by frequency demodulation. The model reproduces the phases and some of the amplitudes closely, and is robust to changes in the parameters. The “prediction” for the next 2,000 years is suggestive. Work is in progress to confirm the existence of the 2.75ky oscillation using a general circulation model. YD marks the Younger Dryas episode. (Jose Rial)



Using the moon to monitor terrestrial albedo was the theme of **Enric Pallé's** (Big Bear Solar Observatory, CA) paper on changes in the Earth's albedo over the past two decades. Observations from the illuminated and dark sides of the moon obtained at Big Bear Solar Observatory were correlated with satellite-measured global cloud cover to derive a proxy for solar reflectance. The results indicate a decrease in reflectance from 1984-2000. Since 2001 this trend appears to have reversed. New measurements of lunar-reflected earthshine are spectrally resolved and thus may reveal global trends in absorbing species such as ozone and water vapor.

Shuntai Zhou (NOAA/NCEP, Camp Springs, MD) examined a Sun-climate link through the response of stratospheric zonal wind and other dynamical factors to solar-cycle variations, determined using 24 years of observed data. While the zonal-wind sensitivity to solar-cycle variations was found to

be relatively small compared to other factors, it was significant in the tropical upper stratosphere and in the extratropics of the southern hemisphere.

The 2004 SORCE Science Meeting concluded with **Shaopeng Huang** (University of Michigan, Ann Arbor) reporting a fascinating concept to retrieve information about past solar irradiance from lunar regolith temperatures, as well as the radiation budget of Earth. Temperature time series at the Apollo 15 landing site revealed the diurnal cycle and trends in near-side lunar-surface temperature driven by direct solar irradiance during the day and reflected solar radiation and longwave emission from Earth at night. Huang suggests that subsurface temperature measurements from boreholes on the Moon can provide valuable extensions of the length of the lunar-surface temperature history, and of its relationship to radiative variations in both the Sun and the Earth.

Science Dinner

On Thursday evening **Dan Schrag** (Harvard University) entertained attendees following dinner at a ski lodge by talking about “*Snowball Earth and Other Climate Tales of Earth and Her Neighbors.*” Many lines of evidence support a theory that the entire Earth was ice-covered for long periods 600-700 million years ago. Each glacial period lasted for millions of years and ended abruptly under extreme greenhouse conditions. These climate shocks triggered the evolution of multicellular animal life and challenge long-held assumptions regarding the limits of global change. The geological record hosts multiple extraordinary observations that can all be explained by the *snowball Earth* hypothesis. The appeal of the hypothesis is that it simultaneously explains all of these salient features of the geologic record, none of which had satisfactory independent explanations.

Poster Sessions

Session 1. Solar Radiation—Status of Current SORCE Measurements

A Comparison of the VIRGO and TIM Data, by Claus Fröhlich, Physikalisches-Meteorologisches Observatorium Davos, Switzerland

The SOLSTICE Observing Technique, by Marty Snow, LASP, University of Colorado, Boulder

SORCE Science Data Processing and Availability, by Christopher Pankratz, LASP, University of Colorado, Boulder

Session 2. Decadal Variability in the Atmosphere and Oceans

Figure 11: Marty Snow from LASP discusses his poster on the role of spectral resolution in measuring the solar magnesium II index. There were 17 posters featured during the meeting, with a special poster reception on Wednesday afternoon.



Global Measurements of the Earth's Visible Spectral Albedo, by Pilar Montanes-Rodriguez, Big Bear Solar Observatory (New Jersey Institute of Technology), California

Vertical Propagating Wave Diagnostic Analysis, by Alfred M. Powell, NOAA/National Environmental Satellite, Data, and Information Service/Office of Research Applications (NESDIS/ORA), Camp Springs, Maryland

Relationships Between Solar Activity, Earth Rotation and Atmospheric Angular Momentum, by David Salstein, AER, Inc., Lexington, Massachusetts

A Solar-Cycle Influence on New England's Climate?, by Richard Wolfson, Middlebury College, Vermont

Response of the O(1S) Dayglow to the Solar Zenith Angle and Solar Irradiance: An Empirical Model by WINDII on UARS, by Shengpan P. Zhang, CRESS, York University, Toronto, Canada

Session 3. Mechanisms and Modes of Decadal Solar Variability

Measurement of the Long-Term Total Solar Irradiance Trend: What is Needed Versus What is Achieved, by Steven Dewitte, Royal Meteorological Institute of Belgium, Brussels

Some Thoughts about the Reliability of Reconstructions of Total Solar Irradiance into the Past, by Claus Fröhlich, Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Davos Dorf, Switzerland

Inferring Total Solar Irradiance from Sunspot Areas Only, by Dora G. Préminger, San Fernando Observatory, California State University, Northridge

Direct and Indirect Thermospheric Heating Sources for Solar Cycles 21-23, by D. J. Knipp, U.S. Air Force Academy, Colorado Springs, Colorado

The SUSIM MgII Core-to-Wing Ratio Index, by Linton E. Floyd, Interferometrics, Inc. and Naval Research Laboratory, Washington, DC

The Role of Spectral Resolution in Measuring the Solar Magnesium II Index, by Marty Snow, LASP, University of Colorado, Boulder (see **Figure 11**)

Center-to-Limb Variation of the Solar UV Spectrum Observed by SKYLAB, by Jeff Morrill, Naval Research Laboratory, Washington, DC

Empirical Orthogonal Function Analysis of Solar Spectral Irradiance from SIM, by Guoyong Wen, NASA Goddard Earth Sciences and Technology Center (GEST)/University of Maryland Baltimore County (UMBC)

NOAA NESDIS Data Rescue Solar Image Scanning Project, by Helen E. Coffey, NOAA National Geophysical Data Center, Boulder, Colorado

Plans for the next *SORCE* Science Meeting are already underway. The next meeting will vastly extend the time domain to paleoclimate and the very-longest-term changes in the solar output. Everyone is welcome! Please mark your calendar for September 14-16, 2005 and stay tuned to the *SORCE* website: lasp.colorado.edu/sorce/meetings.html for details. We plan to meet in southwest Colorado.

Acknowledgements

The authors are pleased to acknowledge the following individuals for their contributions to the *SORCE* mission and this Science Team Meeting:

Vanessa George was responsible for all details of the meeting—both large

and small. She arranged the location and insured that weather cooperated beautifully.

SORCE Team Members: **Jerry Harder, Greg Kopp, George Lawrence, Bill McClintock, Tom Woods.** All are at LASP, University of Colorado, Boulder.

Session Chairs: **Robert Cahalan**, NASA Goddard Space Flight Center; **David Rind**, Goddard Institute for Space Studies, Columbia University; **Stephen Walton**, San Fernando Observatory, California State University, Northridge; **Lesley Gray**, Reading University, Reading, United Kingdom; **Peter Pilewskie**, LASP, University of Colorado, Boulder

Meeting speakers, presenters, and attendees whose shared enthusiasm and expertise contributed much to the meeting's success.

For additional information on the SORCE Mission, see the SORCE website at lasp.colorado.edu/sorce/ for the latest news and updates.



The island of Phuket on the Indian Ocean coast of Thailand is a major tourist destination, with inviting white sand beaches and warm sunny skies. Unfortunately for those living and visiting there to escape the Northern Hemisphere's winter gloom, it was also in the path of the Asian tsunami that washed ashore on December 26, 2004. This Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite image shows how the island appeared on December 27, 2000, well before the wave of destruction.

It was the beaches that bore the brunt of the massive waves, which probably struck the west coast (left side) within an hour of the undersea earthquake. Devastation was particularly severe in Patong and Karon Beaches.

NASA image created by Jesse Allen, Earth Observatory, using data obtained from the University of Maryland's Global Land Cover Facility.

