The Sun Approaches Its 11 Year Minimum and Activity Cycle 24

Tom Woods, Laboratory for Atmospheric and Space Physics, University of Colorado, woods@lasp.colorado.edu
Judith Lean, Naval Research Laboratory, Washington, DC, judith.lean@nrl.navy.mil

Observations reveal that magnetic activity on the Sun varies dramatically over time, with a near periodic 11-year cycle. Large dark s*unspots* are frequently observed on the Sun during *solar maximum* and few, if any, sunspots are seen during *solar minimum*. **Figure 1** compares images of the Sun's visible disk during high (*left*) and low (*right*) solar activity. Sunspot occurrence is an indicator of a change in the Sun's energy output. In addition to the sunspots, large bright prominences called *faculae—faculae* is a Latin word that means small torches—are more commonly observed during *solar maximum*. The occurrence of sunspots and faculae changes the total energy output from the Sun—*total solar irradiance*. As **Figure 2** shows, the Sun's brightness is higher during *solar maxima*; in recent cycles it increased by about 0.1% relative to *solar minima*. **Observations suggest that faculae increase radiance considerably more than sunspots decrease radiance from the Sun.** Scientists continue to work to more precisely quantify how much each factor contributes to the observed changes in solar irradiance. Since, as **Figure 2** shows, the magnitude of sunspot dimming and facular brightening both increase with solar activity, predicting their specific balance, which determines total solar irradiance, is difficult.

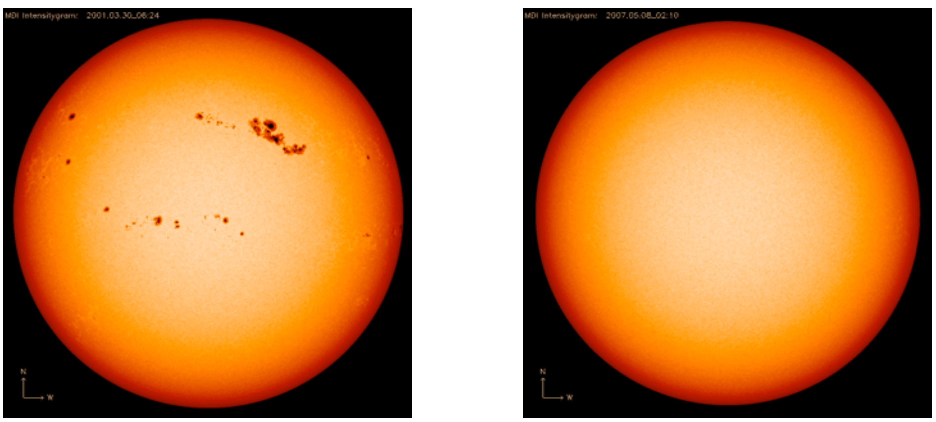

Figure. 1. Near the peak of the solar activity cycle many sunspots appear regularly on the Sun, as seen in the left image on 30 March 2001 in Cycle 23. Currently, solar activity is near the minimum of the 11-year cycle and sunspots may be absent entirely, as seen on 8 May 2007, in the right image. The images are of the intensity of a narrow band of visible light, made by the MDI instrument on SOHO.

Since 2003, scientists have had a powerful tool to help them observe variations in the Sun's energy output. NASA's Solar Radiation and Climate Experiment (SORCE) [Rottman et al., 2005] has been making precise measurements of the Sun's total and spectral irradiance, which are being combined with prior measurements [e.g., Fröhlich and Lean, 2004] to provide new insights in the long term solar variations. Onboard SORCE, the Total Irradiance Monitor (TIM) measures the total solar irradiance (TSI), denoted by the top image in **Figure 2**. Because solar activity influences the Sun's output differently at every wavelength, SORCE also includes three other instruments, which measure the Sun's energy at individual wavelengths: XUV Photometer System (XPS) for soft-X-ray irradiance; Solar Stellar Irradiance Comparison Experiment (SOLSTICE) for solar ultraviolet irradiance; and Spectral Irradiance Monitor (SIM) for visible/near infrared irradiance. This unique and unprecedented combination of instruments monitors simultaneously both the total solar energy reaching our planet (the single most important contributor to natural climate variability) and how the Sun's energy output changes at different wavelengths. These latter measurements are used to determine the atmosphere's response to the Sun's changes. Changes occurring in the ultraviolet portion of the spectrum alter the amount of ozone in the atmosphere, which can impact large-scale atmospheric motions that couple the stratosphere and troposphere. Changes occurring at longer wavelengths, in the visible and near-infrared part of the spectrum, impact climate more directly by changing the heating at the Earth's land and ocean surface, and lower atmosphere.

The solar irradiance measurements from SORCE confirm earlier results and show similar variability for Cycle 23 to that which has been observed in previous solar cycles. The increase in total irradiance reflects not just the effects of sunspots, whose presence on the solar disk actually decreases total irradiance, but the additional effects of bright faculae as well. **Facular brightening more than compensates (by about a factor of two) for sunspot dimming during the solar cycle, with the result that total irradiance varies in phase with solar activity.**

Currently, solar activity is entering a new minimum, and a new cycle known as Cycle 24 will soon begin. During the previous cycle (Cycle 23) the *solar minimum* occurred in 1996, followed by the *solar maximum* in 2000-2002. Solar activity has waned during 2007, as has the total irradiance, signaling the impending onset of the next *solar minimum*—expected to occur in 2008. According to a recent NOAA-NASA panel report [D. Biesecker and D. Pesnell, private communication, 2007] peak activity in Cycle 24 is forecast for late 2011 or mid-2012. That much is fairly certain, but there is still considerable debate over the strength of the next activity maximum. Some computer simulations of solar activity using a model suggest that solar activity will be 40% stronger in Cycle 24 than in Cycle 23 [e.g., Dikpati and Gilman, 2006], while others suggest much weaker activity in Cycle 24—e.g., Schatten [2005]. **Either way, the upcoming Cycle 24 affords a unique opportunity to observe the cycle from start to finish and better understand and quantify sources of irradiance variability, especially the separate relationships of sunspot dimming and facular brightening with solar activity and the sunspot number.** Improved understanding of solar variability sources and their evolution on time scales longer than the 11-year cycle are needed to improve reconstructions of past irradiance changes that are used to asses natural climate change in both pre-industrial and present eras.

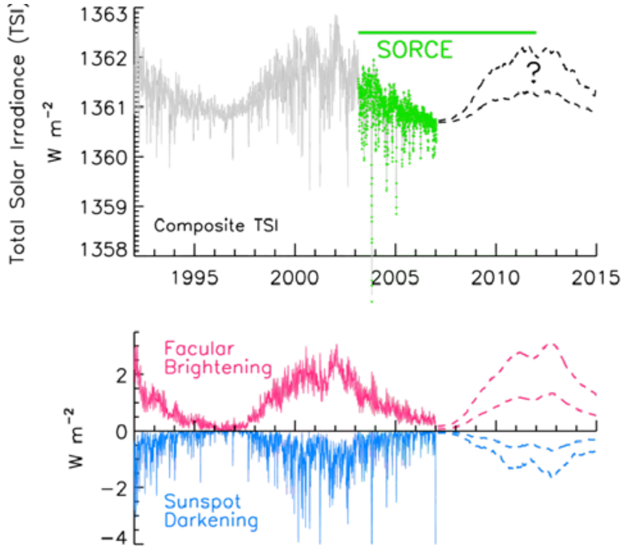

Figure 2. The solar activity is waning and approaching its 11-year solar cycle minimum. The dashed curves represent the next solar cycle estimates that correspond to solar activity 40% higher and lower than in the past cycle. The lower panel shows the two primary components for variability of the total solar irradiance (TSI) that is shown in the upper panel.

Elucidating and quantifying the role of solar irradiance variations in climate change continues to be a challenging task. Empirical evidence abounds for associations of solar variability with climate, especially the tropical hydrological cycle [e.g., Shindell et al., 2006], but also in temperature and winds [e.g., Crooks and Gray, 2005]. The high fidelity global databases acquired since the 1980's (i.e., in the space era) reveal unmistakable Sun-climate associations in the contemporary epoch, on decadal time scales [e.g., Douglass and Clader, 2002; Lean et al., 2005]. **Figure 3** shows empirical estimates of the primary factors that drive the Earth's global temperature anomalies near 2 km over the past 25 years. A global temperature anomaly of 0.1 K is associated with solar activity, approximately in phase with the irradiance cycle. Analysis of the surface temperature datasets yield analogous results with a solar-driven temperature anomaly cycle of slightly smaller amplitude [Lean et al., 2005]. As **Figure 4** shows, the 2-km (and surface) temperature increase is actually the net change from a complex pattern of regional solar-driven warming and cooling, with amplitudes even reaching ±0.7K in some locations.

Climate response to decadal solar forcing has previously been expected to be too small to be detected. (Scientists reasoned that the amount of change caused by solar forcing would be too small to change the ocean temperatures significantly—i.e., any change would be dampened by the ocean's *thermal inertia*.) However, recent empirical results associating decadal solar variability and climate, such as those shown in **Figures 3 and 4**, contradict this expectation, and recent studies are beginning to shed light on how this may take place. The National Center for Environmental Prediction (NCEP) reanalysis database [van Loon et al., 2007] and fossil coral records during the past 1000 years [Mann et al., 2005] reveal a cooling of the tropical Pacific not unlike the pattern observed during a La Niña. This cooling may be caused by differential solar heating in the east and west tropical Pacific Ocean, as a result of their different mixed layer depths. Positive solar forcing may increase the trade winds and induce upwelling of cooler waters that produce a La Niña-like pattern. More generally, solar activity appears to alter the interactions between the surface and atmosphere that drive the fundamental circulation cells (especially the north-south Hadley and Ferrell cells and the east-west Walker circulation) and generate atmospheric centers of action [e.g., Christorofou and Hameed, 1997]. Other mechanisms may involve the cloudy lower atmosphere, which absorbs more visible and near infrared radiation than previously thought (25% rather than 20%) [e.g., Zastawny, 2006]. This impacts convection, clouds, and latent heat in water vapor. Over relatively

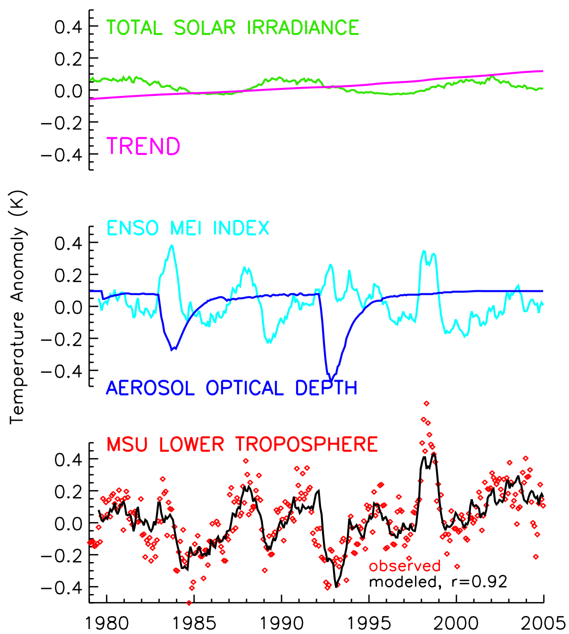

Figure 3. Compared in the top panel are monthly mean global temperature anomalies in the lower troposphere (~ 2 km) associated with the solar activity cycle and with a trend attributed to increasing greenhouse gases. In the middle panel are the 2 km temperature anomalies arising from the El Niño Southern Oscillation (ENSO) and volcanic aerosols. The associations are extracted from multiple regressions analysis of the global MSU (microwave sounding unit) lower troposphere temperatures (with ENSO and volcanic influences, lagged by 7 and 9 months, respectively), following the approach of Douglass and Clader [2002]. An empirical model that combines the solar, trend, ENSO and volcanic effects, shown as the dark line in the bottom panel, explains 80% of the variance in the observed temperatures, shown as the symbols.

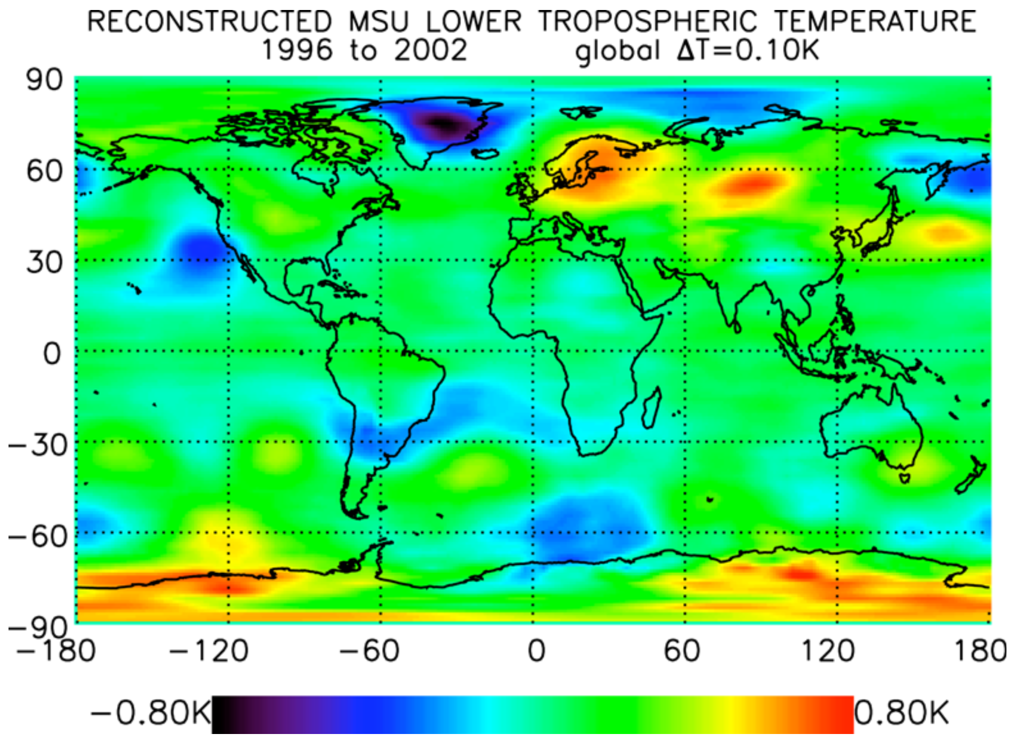

Figure 4. Shown is the spatial distribution of monthly mean 2-km temperature anomalies, extracted from multiple regression analysis of the 2.5°×2.5° latitude-longitude arrays of MSU temperature anomalies (including ENSO, volcanic activity and a trend, in addition to solar irradiance) that together comprise the global variations in **Figure 3**. The global average is +0.1K.

cloud-free regions, increased evaporation from enhanced solar forcing produces moisture that intensifies the regional monsoon and the Hadley and Walker circulations [Meehl et al., 2003; van Loon et al., 2007]. Also, the solar ultraviolet radiation, which varies far more than the total solar irradiance, influences stratospheric chemistry and dynamics, which in turn appears to couple to the troposphere and provide an indirect forcing of surface temperatures [e.g., White, 2006] and climate [e.g., Geller, 2006].

Crucial for assessing the influence of solar variability and other natural processes—i.e., volcanic eruptions and El Niño and Southern Oscillation (ENSO)—and human activity—i.e., greenhouse gas production from fossil fuel combustion—on climate change are precise, long-term records of solar irradiance that extend over a much longer period than the observational databases—which commenced only in 1978. Depending on amplitude and spectral composition, long-term solar irradiance changes may alter climate in different ways than during the recent activity cycles. Model simulations of the transport of magnetic flux in the Sun (by differential rotation, diffusion and meridional flow) [Wang et al., 2005], shown in **Figure 5**, suggest that long term irradiance changes may accrue from the accumulation of magnetic flux during times of overall increasing solar activity, as witnessed during the past century. Solar irradiance measurements during cycle minimum periods, such as the present, are uniquely important because connecting levels during adjoining minima provides knowledge and quantification of possible longer-term irradiance changes that may underlie the 11-year irradiance cycle.

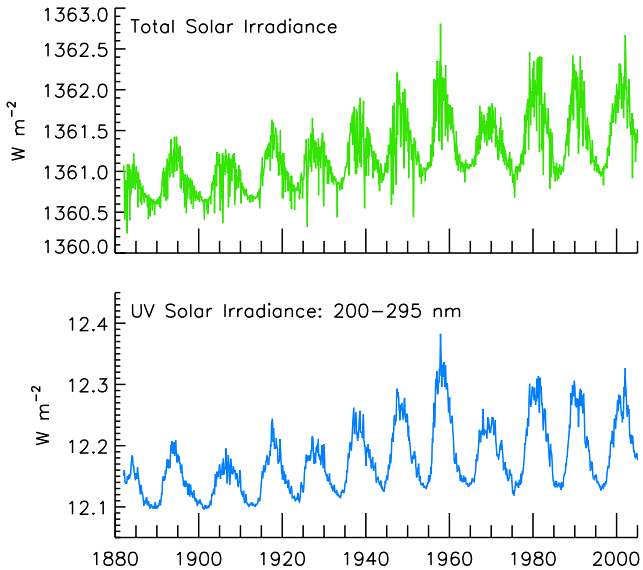

Figure 5. Shown in the top panel are monthly mean values of total solar irradiance, based on the magnetic flux transport calculations of Wang *et al*. [2005] that predict a small but significant accumulation of magnetic flux during the first half of the twentieth century, associated with the steadily increasing solar activity cycle amplitudes. In the bottom panel are the changes in UV irradiance at wavelengths from 200 to 295 nm (absorbed in the atmosphere), also based on the flux transport model simulations.

The measurements made by SORCE are the most fundamental of data needed to understand Earth's climate because the Sun provides virtually all the energy that warms the atmosphere and surface, evaporates water, and drives the general circulation of the atmosphere, oceans, and water cycle. Even relatively small changes in the Sun's output could impact the Earth because of potential amplifying effects in how the atmosphere responds to those changes. The unexpectedly large (by current understanding) solar-driven global decadal cycle of 0.1 K in 2-km temperatures exemplifies this. As models for simulating climate processes improve, sensors with exceptional accuracy and precision, such as those on SORCE, will be critical to resolve the smallest of solar irradiance changes. These data are needed to understand the state of climate now, why climate varied in the past, and to predict how climate may change in the future. Before we can truly interpret the role that human's are having in changing Earth's climate we must first more accurately assess the role that natural "forcings" have on the climate system, and the Sun is by far the most significant of those natural "forcings".

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