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Anticipating the Next Decade of Sun-Earth System Variations

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Approximately every decade, the Sun enters a new phase when its magnetic activity increases from quiescent conditions to peak values about 3–5 years later. This intensified solar activity gradually reduces over the next 6–7 years, returning the system to "quiet" conditions. The near-periodic 11-year solar cycle is manifested by the regular presence of large sunspots during high solar activity (solar maximum) and few, if any, sunspots during quiet periods (solar minimum).

This cycle, in turn, creates significant observable effects on Earth and its surrounding environment. During times of peak solar activity, Earth's atmosphere warms globally. In the past decade, the Sun's increased brightness at solar maximum warmed the Earth's atmosphere by about 0.1 degree Kelvin (0.1 K) in the 10 kilometers nearest to the surface (the troposphere), 1 K near 50 kilometers in altitude (at the top of the stratosphere), and 400 K at an altitude of 500 kilometers in the thermosphere. During this time, total ozone concentration increased by a few percent, offsetting for a while the overall decline associated with chlorofluorocarbon (CFC) pollution. Electron densities in the ionosphere and neutral densities in the thermosphere increased by 1–2 orders of magnitude, altering the propagation of radio waves that enable communication and increasing the drag on spacecraft in low-Earth orbits.

Furthermore, the upper atmosphere is also very sensitive to solar eruptions—flares and coronal mass ejections—which are more prevalent during the maximum and declining solar cycle phases than during the minimum. "Space weather" of this nature can have severe and sudden impacts on technology, such as damaging ground-based power systems (e.g., blackouts) and disrupting signals from Global Positioning System (GPS) systems over significant regions. For example, in October 2003, during the declining phase of solar cycle 23, one of the most violent eruptions of the space era degraded GPS horizontal position accuracies over the United States by factors of 10–30 and forced extensive (and costly) rerouting of commercial over-the-pole jet flights to lower latitudes.

Currently the Sun is at solar minimum. With technology increasingly wrapped into daily life and with terrestrial climate change and space weather susceptible to solar conditions, scientists are eager to analyze data from the past and modeled solar cycles to understand the many complex links that couple the Sun and the Earth. Such knowledge can help predict Sun-Earth system variations in the next solar cycle. This article examines what has been learned from analyses of past solar cycles, including regional temperature changes over the previous cycle, and describes predictions of the next solar cycle.

Information From Past Solar Cycles

The 11-year solar cycle was discovered in 1843 by Samuel Heinrich Schwabe, an amateur astronomer from Germany who noticed the periodic variation of the yearly average number of sunspots seen on the solar disk. Rudolf Wolfe, a Swiss astronomer, used Schwabe's data to reconstruct solar cycles back to the middle 1700s. Scientists label Wolfe's reconstruction of the 1755–1766 cycle as "solar cycle 1." Thus, the current solar minimum marks the end of solar cycle 23 and the beginning of cycle 24.

Multiple solar irradiance radiometers on two spacecraft have been monitoring the Sun's brightness during solar cycle 23 and will continue into cycle 24. NASA's Solar Radiation and Climate Experiment (SORCE [*Rottman et al.*, 2005]), launched in 2003, and NASA's Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED [*Woods et al.*, 2005]) spacecraft, launched in 2001, measure, for the first time, the total solar radiative output (total irradiance) and the spectral distribution of this radiation from X rays to the infrared (spectral irradiance).

These spectral irradiance measurements, the most precise to date, show that the solar ultraviolet radiation that is absorbed in Earth's atmosphere (wavelengths shorter than ~315 nanometers) varies significantly more than does the total brightness, which increased by about 0.1% (of ~1361 W m^{-2}) from the minimum

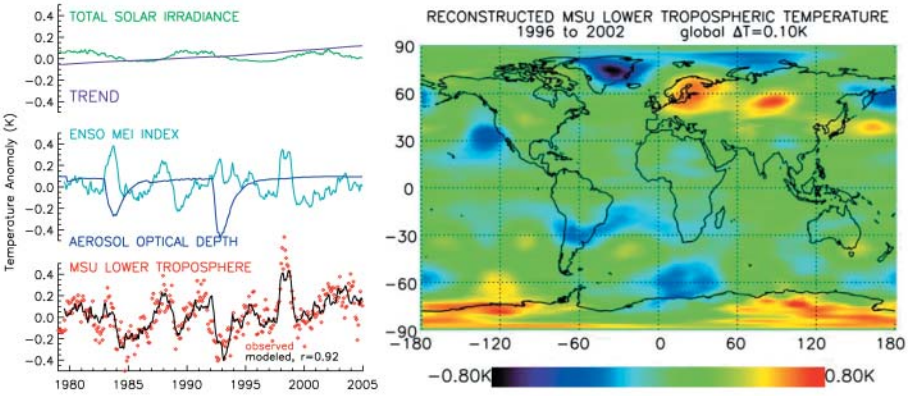

*Fig. 1. The left plots show the monthly mean global microwave sounding unit (MSU) temperature anomalies [*Christy et al., *2007] in the lower troposphere (bottom plot) and the four components that explain 80% of the variance in the observed temperatures. Listed in descending order, these components are (1) solar activity cycle (total solar irradiance), (2) the linear trend attributed to increasing greenhouse gases, (3) the El Niño–Southern Oscillation (ENSO) fluctuations, and (4) irradiance shielding by volcanic aerosols. The right panel shows the spatial distribution of monthly mean tropospheric temperature anomalies, extracted from multiple regression analysis of the 2.5° × 2.5° latitude-longitude arrays of MSU temperature anomalies. The global average increase is +0.1 K.*

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to maximum of solar cycle 23. For example, the solar ultraviolet irradiance near 200 nanometers is about 10% higher near cycle maximum than the irradiance during cycle minimum, and the X-ray irradiance is about 100 times higher at maximum.

Further, as the Sun's photons provide virtually all the energy that warms the Earth's surface and atmosphere (and that in turn drives atmospheric and oceanic circulations), even relatively small changes in the solar photon output could affect the Earth because of potential amplifying effects in how the atmosphere responds to solar changes. Above the troposphere, the Sun's impact on the Earth is now well established even though the assorted and complex physical pathways responsible for the variations are still being explored. However, elucidating and quantifying the role of solar irradiance variations in climate change is proving more challenging.

Empirical evidence abounds for associations of solar variability with climate, especially the tropical hydrological cycle [e.g., *Shindell et al.*, 2006], but also in atmospheric temperature and winds [e.g., *Crooks and Gray,* 2005]. High-fidelity global databases acquired since the 1980s (in the space era) are revealing unmistakable Sun-climate associations in the contemporary epoch on decadal timescales [e.g., *Lean et al.*, 2005].

Figure 1 shows empirical estimates of the primary drivers for the Earth's global temperature anomalies near 2 kilometers measured over the past 25 years by the microwave sounding unit (MSU, aboard a series of NOAA satellites [*Christy et al.*, 2007]). After accounting for the effects of the El Niño–Southern Oscillation (ENSO) and volcanic aerosols, a global temperature anomaly of 0.1 K approximately in phase with the total solar irradiance is apparent. As Figure 1 also shows, the 2-kilometer (and surface) temperature increase is actually the net change from a complex pattern of regional solar-driven warming and cooling, with amplitudes that can exceed the 0.1 K global mean anomaly. For example, the central United States is warmer by about 0.4 K, but there is a cooler region in the eastern Pacific Ocean near southern California.

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 [e.g., *van Loon et al.,* 2007]. These cells, driven in part by warmer temperatures near the equator, create the major wind patterns over the globe. 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 and climate [e.g., *White,* 2006].

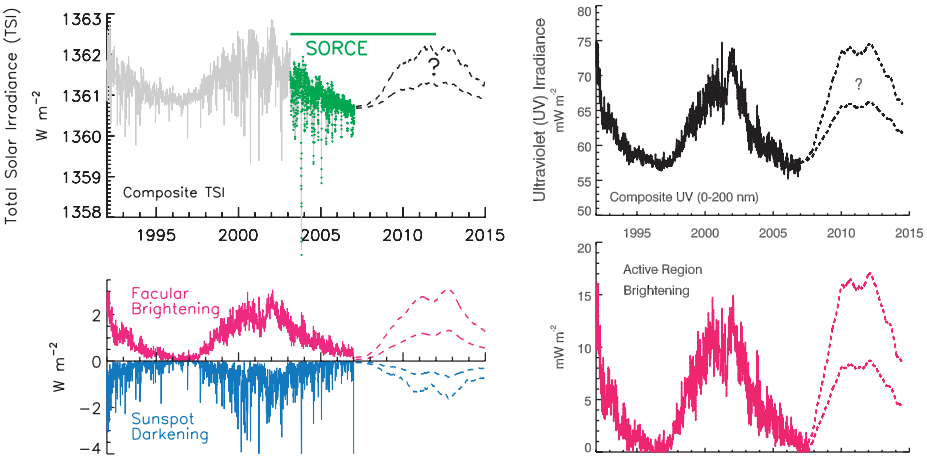

Fig. 2. The solar activity is waning and approaching its next 11-year solar cycle minimum. The dashed curves represent the next solar cycle estimates that correspond to solar activity 40% higher and lower than in the past cycle. The two bottom plots show the primary components for solar variability. The total solar irradiance (TSI), measured in watts per square meter (W m^{-2}), has both a negative component from dark sunspots and a positive component from bright faculae, and the solar ultraviolet, measured in milliwatts per square meter (mW m^{-2}), has just a positive component from bright active regions.

Solar Cycle 24 and Beyond

Three decades of space-based research document dramatic increases in solar photon, particle, and plasma energy output accompanying the increase in sunspot numbers seen at solar maximum. Figure 2 shows the variations in the total solar irradiance since 1992, including the increase of about 0.1% during the maximum of the recent solar cycle 23 relative to solar minimum. This figure also shows the solar ultraviolet irradiance shorter than 200 nanometers, which varies by about 25% over the solar cycle. There is much uncertainty in maximum levels of solar activity, and hence of solar brightness, for the upcoming cycle 24.

A recent NOAA-NASA panel report (D. Biesecker and D. Pesnell, private communication, 2007) forecasts peak activity in cycle 24 for late 2011 or mid-2012, following cycle minimum in 2008. Some researchers argue that solar activity will be 40% stronger in cycle 24 than it was in cycle 23. This is the expectation from a new forecasting approach that simulates the evolution of the Sun's magnetic activity using a flux transport dynamo model [*Dikpati and Gilman,* 2006], which combines a physical model of the subsurface dynamo that drives the solar activity cycle with surface transport of the magnetic flux that alters phenomena such as sunspot numbers. In contrast, *Schatten* [2005] predicts much weaker activity in cycle 24, based on a "precursor" method that relates the strength of the Sun's polar magnetic field during minimum activity with the strength of the subsequent maximum.

While both methods relate solar activity to magnetic field evolution, the flux transport dynamo model has a dynamo cycle time of 30–50 years and the precursor method has a dynamo cycle time of less than 10 years. The validity of this wide difference in dynamo cycles will be tested with the next solar cycle, and the understanding of magnetic field transport is expected to be improved. Because of the ambiguities in current understanding, the NOAA-NASA panel report was unable to state with certainty the expected strength of the next activity maximum.

For assessing the influence of the Sun on Earth, precise knowledge of solar irradiance variability is needed not just during the 11-year activity cycles but also on longer timescales. As Figure 1 shows, solar variability competes with other natural processes (such as volcanic eruptions and the El Niño–Southern Oscillation) and human activity (such as greenhouse gas production from fossil fuel combustion) in altering global temperatures near Earth's surface. The cycle minimum period that we are now entering is a unique opportunity for solar irradiance measurements to elucidate irradiance changes during adjoining minima. Combining SORCE's and TIMED's ongoing precise measurements of the Sun's total and spectral irradiance with prior measurements since 1978 [e.g., *Fröhlich and Lean,* 2004] provides new insights in the long-term solar variations, including possible longer-term irradiance changes that may underlie the 11-year irradiance cycle. Because solar irradiance varies differently at every wavelength and because Earth's atmosphere and climate respond in different ways to solar variations at different wavelengths, measurements of the Sun's energy at individual wavelengths are fundamental for elaborating the mechanisms of terrestrial response to the solar cycle.

Whether the upcoming cycle 24 is more or less active than cycle 23, it affords a unique opportunity to better understand and quantify both the wide-ranging, interrelated terrestrial responses to solar activity

and the solar sources of irradiance variability. An unprecedented array of space-based solar and terrestrial observatories is in place for solar cycle 24. The solar measurements will better clarify the separate relationships of irradiance and its sources. For example, the visible irradiance and total brightness vary because of dimming in dark sunspots and brightening in the more extended "facular" magnetic features; whereas these same active regions show only brightening for the ultraviolet radiation. These relationships between solar activity, magnetic fields, and the sunspot number are expected to improve models of irradiance variations for past, current, and future cycles.

With mounting concern that human activity is altering our environment, not just at the surface but also in the extended atmosphere, it becomes increasingly important to improve our knowledge of all natural "forcings" on the Sun-Earth system and to better characterize and understand the wide range of terrestrial variations that result, from space weather to climate change. In combination with improved models for simulating Sun-Earth system processes, this understanding will ensure the proper interpretation of humans' environmental impact.

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NEWS

In Brief

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Arctic report card A "report card" that tracks multiple changes in the Arctic environment has found that while some indicators show signs of stabilization, other changes are dramatic. In 2007, the central Arctic region lost almost 40 percent of its summertime sea ice, relative to amounts of Arctic sea ice in the 1980s, according to the report card, organized by NOAA and issued on 17 October by an international team of scientists. The report also found that permafrost temperatures are stabilizing in North America and Eurasia but permafrost melt remains a key problem, and that changes in Arctic animal populations have been mixed over decades. "This annual update provides key information to decision makers and the scientific community on changes that are taking place in the Arctic now," said Richard Spinrad, NOAA assistant administrator for oceanic and atmospheric research. For more information, visit the Web site: http://www.arctic.noaa.gov/reportcard/.

Observing the Sun from a giant balloon A solar telescope, borne by a balloon larger than a Boeing 747, was successfully launched to an altitude of 120,000 feet, the National Center for Atmospheric Research (NCAR) announced on 23 October. NCAR, working with a team of research partners, indicated that the test clears the way for long-duration polar balloon flights beginning in 2009 to capture unprecedented details of the Sun's surface. "We hope to unlock important mysteries about the Sun's magnetic field structures, which at times can cause electromagnetic storms in our upper atmosphere and may have an impact on Earth's climate," said Michael Knölker, director of NCAR's High Altitude Observatory and a principal investigator on the project known as Sunrise. "This is a very economical way of rising above the atmosphere and capturing images that cannot be captured from Earth."

Proposed European space missions New candidates for possible future scientific missions were selected by the European Space Agency's Space Science Advisory Committee at its 17–18 October meeting. Among the eight candidates are four solar system missions. The Laplace mission would perform coordinated observations of Europa, the Jovian satellites, Jupiter's magnetosphere, and its atmosphere and interior. Tandem is a mission that would explore two Saturn satellites—Titan and Enceladus—in situ and from orbit to investigate their origins, interiors, and evolution as well as their astrobiological potential. Cross-Scale, with 12 spacecraft, would make simultaneous measurements of plasma on different scales at shocks, reconnection sites, and turbulent regions in near-Earth space. Marco Polo would characterize a near-Earth object at multiple scales and return with a sample. Among other missions, Plato, a photometry mission, would detect and characterize transiting exoplanets, while Spica, a next-generation infrared observatory, would address planetary formation questions. Ultimately, two missions will be proposed for implementation, with launches planned for 2017 and 2018.

—RANDY SHOWSTACK, Staff Writer