The Effects of Solar Variability on Earth's Climate

A Workshop Report

Committee on the Effects of Solar Variability on Earth's Climate
Space Studies Board
Division on Engineering and Physical Sciences

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Preface

Experts on solar physics, solar variability, climate science, climate models, paleoclimatology, atmospheric science, and experts on other stars came together on September 8-9, 2011, at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, to discuss how the Sun's variability over time has affected Earth's climate. The National Research Council was asked by program managers at the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) to organize an interdisciplinary public workshop to examine the state of knowledge of Earth's climate response to solar variability and to explore some of the outstanding science questions that might guide future research endeavors. As noted above, this particular topic touches upon a number of diverse research areas; a workshop such as this brings together scientists that do not always have an opportunity to interact as a group.

A Committee on the Effects of Solar Variability on Earth's Climate was formed and met on April 25, 2011, at the National Academies Keck Center in Washington, D.C., to develop an agenda for the workshop. Speakers were invited to submit abstracts, and these talks were organized into sessions by the committee. The workshop was advertised to the public through various media. During the workshop, the audience was encouraged to interact with the speakers and discuss the issues from different viewpoints. A final panel discussion was lead by chairs of the sessions, and the entire group was encouraged to share their thoughts on open research questions in these fields.

A complete statement of task and workplan for the project can be found in Appendix A. The workshop featured presentations on a variety of topics related to solar variability and climate change, organized as follows:

- *The Sun and Solar Variability: Past and Present*
  —Overview of solar and heliospheric variability
  —Observations of the Sun's variable outputs
  —Techniques for revealing past solar changes

- *Sun-Climate Connections on Different Timescales*
  —Evidence of solar influences in the troposphere and stratosphere
  —How the climate system works and how it might respond to solar influences
  —Indications of influence based on paleoclimate records

- *Mechanisms for Sun-Climate Connections*
  —Mechanisms connecting variations in total solar irradiance directly to the troposphere
  —Mechanisms that influence upper parts of the atmosphere, such as variations in solar ultraviolet radiation and possibly solar energetic particles
  —Mechanisms that link variations in galactic cosmic rays to climate change.

This workshop report contains no recommendations, findings, or statements of consensus. Instead, this workshop report summarizes the views expressed by individual workshop participants (invited speakers and guests). Also included is background information intended to provide context to the reader on both the solar and climate science topics presented at the workshop; however, this is not intended to be an exhaustive review of the current state of the science. Although the committee is responsible for the overall quality and accuracy of the report as a record of what transpired at the workshop, the views contained in the report are not necessarily those of all workshop participants, the committee, or the National Research Council.

The committee thanks the NCAR Mesa Laboratory, in particular, Gerald Meehl, Stephanie Shearer, and Eron Brennan, for providing meeting space and excellent technical support.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Lennard Fisk, University of Michigan,
Philip Judge, National Center for Atmospheric Research,
Fabrizio Sassi, Naval Research Laboratory, and
Nathan Schwadron, University of New Hampshire.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse any of the viewpoints or observations detailed in this report, nor did they see the final draft of the report before its release. The review of this report was overseen by Joyce Penner, University of Michigan. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Overview

Solar irradiance, the flux of the Sun's output directed toward Earth, is Earth's main energy source.[1] The Sun itself varies on several timescales—over billions of years its luminosity increases as it evolves on the main sequence toward becoming a red giant; about every 11 years its sunspot activity cycles; and within just minutes flares can erupt and release massive amounts of energy. Most of the fluctuations from tens to thousands of years are associated with changes in the solar magnetic field. The focus of the National Research Council's September 2011 workshop on solar variability and Earth's climate, and of this summary report, is mainly magnetically driven variability and its possible connection with Earth's climate variations in the past 10,000 years. Even small variations in the amount or distribution of energy received at Earth can have a major influence on Earth's climate when they persist for decades. However, no satellite measurements have indicated that solar output and variability have contributed in a significant way to the increase in global mean temperature in the past 50 years.[2,3,4] Locally, however, correlations between solar activity and variations in average weather may stand out beyond the global trend; such has been argued to be the case for the El Niño-Southern Oscillation, even in the present day.

A key area of inquiry deals with establishing a unified record of the solar output and solar-modified particles that extends from the present to the prescientific past. The workshop focused attention on the need for a better understanding of the links between indices of solar activity such as cosmogenic isotopes and solar irradiance. A number of presentations focused on the timescale of the solar cycle and of the satellite record and on the problem of extending this record back in time. Highlights included a report of progress on pyroheliometer calibration, leading to greater confidence in the time history and future stability of total solar irradiance (TSI), and surprising results on changes in spectral irradiance over the last solar cycle, which elicited spirited discussion. New perspectives on connections between features of the quiet and active areas of the photosphere and variations in TSI were also presented, emphasizing the importance of developing better understanding in order to extrapolate back in time using activity indices. Workshop participants' reviews highlighted difficulties as well as causes for optimism in current understanding of the cosmogenic isotope record and the use of observed variability in Sun-like stars in reconstructing variations in TSI occurring on lower frequencies than the sunspot cycle.

The workshop succeeded in bringing together informed, focused presentations on major drivers of the Sun-climate connection. The importance of the solar cycle as a unique quasi-periodic probe of climate responses on a timescale between the seasonal and Milankovitch cycles was recognized in several presentations. The signal need only be detectable, not dominant, for it to play this role of a useful probe.

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[1] G. Kopp, LASP, University of Colorado, "Overview and Advances in Solar Radiometry for Climate Studies," presentation at the Workshop on the Effects of Solar Variability on Earth's Climate, September 8, 2011.

[2] S. Solomon, D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, et al., Technical Summary in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds.), Cambridge University Press, Cambridge, U.K., and New York, N.Y., 2007.

[3] National Research Council, *America's Climate Choices*, The National Academies Press, Washington, D.C., 2011.

[4] National Research Council, *Advancing the Science of Climate Change*, The National Academies Press, Washington, D.C., 2010.

Some workshop participants also found encouraging progress in the "top-down" perspective, according to which solar variability affects surface climate by first perturbing the stratosphere, which then forces the troposphere and surface. This work is now informing and being informed by research on tropospheric responses to the Antarctic ozone hole and volcanic aerosols. In contrast to the top-down perspective is the "bottom-up" view that the interaction of solar energy with the ocean and surface leads to changes in dynamics and temperature. During the discussion of how dynamical air-sea coupling in the tropical Pacific and solar variability interact from a bottom-up perspective, several participants remarked on the wealth of open research questions in the dynamics of the climatic response to TSI and spectral variability.

The discussion of the paleoclimate record emphasized that the link between solar variability and Earth's climate is multifaceted and that some components are understood better than others. According to two presenters on paleoclimate, there is a need to study the idiosyncrasies of each key proxy record. Yet they also emphasized that there may be an emerging pattern of paleoclimate change coincident with periods of solar activity and inactivity, but only on long timescales of multiple decades to millennia. Several speakers discussed the effects of particle events and cosmic-ray variability. These are all areas of exciting fundamental research; however, they have not yet led to conclusive evidence for significant related climate effects. The key problem of attribution of climate variability on the timescales of the Little Ice Age and the Maunder Minimum were directly addressed in several presentations. Several workshop participants remarked that the combination of solar, paleoclimatic, and climate modeling research has the potential to dramatically improve the credibility of these attribution studies.

1
Background

THE POTENTIAL SUN-CLIMATE CONNECTION

The Sun varies over a broad span of timescales, from its brightening over its lifetime to the fluctuations commonly associated with magnetic activity over days to years. The latter activity includes most prominently the 11-year sunspot cycle and its modulations. The September 2011 workshop summarized in this report explored the connection between this kind of activity and Earth's climate variability.

Research on the connection between solar magnetic activity and Earth's climate spans the subdisciplines involved in heliophysics, climate science, and the science and engineering of space-borne observatories. Intended to briefly introduce the workshop's topics, the background information provided here is not a product of the workshop itself.

Variations in the total solar irradiance (broad spectral band irradiance: TSI) incident on Earth's atmosphere can cause imbalances in Earth's radiation budget that can induce temperature shifts near the surface. The temperature of Earth can be understood to a first approximation as controlled by the balance between the radiative energy received from the Sun and Earth's thermal emission of radiative energy to space.[1] Thermal emission increases with increasing temperature, and Earth can be thought of as settling into an equilibrium by adjusting its temperature so that this thermal radiation balances the solar energy absorbed by the planet. An increase or a decrease in the TSI is expected on this basis to increase or decrease the temperature of Earth. For example, the TSI changes over an 11-year cycle in step with the cycle of sunspots with an amplitude of nearly 0.1 percent, and this variation's small effects (perhaps an amplitude of a few hundredths of a degree centigrade) on temperatures can be detected, albeit with considerable imprecision, in climate records.[2]

The sunspot cycle amplitude varies, and during the 17th century the Sun was virtually without spots for about 70 years. This observation has bolstered research on the theoretical underpinning of the solar cycle and the roles played by different features of the Sun's face (photosphere). These features include the sunspots themselves, the faculae (bright regions surrounding the spots), and the network of magnetic field features over the Sun's surface.[3] Interest is focused on the quantitative relationship between these features and the TSI.[4] How can the TSI be extrapolated to past (or future) periods when the Sun appeared to be (or might be) more or less active than now? Related studies include the

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[1] S. Solomon, D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, et al., Technical Summary in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds.), Cambridge University Press, Cambridge, U.K. and New York, N.Y., 2007.

[2] C.D. Camp and K.K. Tung, Surface warming by the solar cycle as revealed by the composite mean difference projection, *Geophysical Research Letters*, 34:L14703, 2007.

[3] J. Eddy, *The Sun, the Earth, and Near-Earth Space: A Guide to the Sun-Earth System,* NP-2009-1-066-GSFC, NASA, Washington, D.C.

[4] P. Foukal, C. Fröhlich, H. Spruit, and T.M.L. Wigley, Variations in solar luminosity and their effect on the Earth's climate, *Nature* 443:161-166, 2006.

astronomical work on Sun-like stars, whether they exhibit quiet periods, and whether their brightness is diminished during quiet periods.[5]

The observed sunspot number has been demonstrated to be negatively correlated with the cosmic-ray flux. The cosmic-ray flux reaching Earth's surface is modulated by the strength of the solar wind. It is now understood that this decrease in cosmic rays is due to changes in the magnetic field geometry in the heliosphere, the bubble blown in the interstellar medium by the solar wind.[6] Higher levels of solar activity lead to a decrease in the cosmic-ray flux at Earth. Cosmic rays are potentially implicated in climate change on Earth because as they penetrate Earth's atmosphere they leave behind an ionized path that could serve as a source of condensation centers that in turn affect cloudiness and Earth's albedo (reflectivity of solar radiation).[7] Cosmic rays may also have an effect on the global electric circuit of Earth's atmosphere that is caused by thunderstorms separating charge from the surface to the troposphere.[8] Research is being conducted on these potential mechanisms and their possible relevance as a climate-forcing agent. Furthermore, solar energetic particle (SEP) events, created at the shock front of coronal mass ejections (CMEs), for example, can influence the composition of the upper atmosphere. During a SEP event, solar protons and electrons follow Earth's magnetic field lines toward the poles. The higher-energy particles can penetrate well into the stratosphere where they ionize the atmosphere, producing nitrogen oxides, whereas lower-energy particles can create nitrogen oxides in the lower thermosphere and mesosphere that then descend into the polar stratosphere. These nitrogen oxides can destroy ozone, thus altering not only the chemistry but also the radiative balance of that region.

THE MEASUREMENT RECORD FROM SPACE

The TSI and the spectral solar irradiance are the two most important measurements of the Sun's output as it impacts climate. The continuous 33-year record of total solar irradiance from space-based observations is shown in Figure 1.1. This data record is the result of overlapping measurements from several instruments flown on different missions. Measurements made by individual radiometers providing the data shown in Figure 1.1 exhibit a spread of nearly 1 percent that is of instrument rather than solar origin (the upper panel) and far exceeds the 11-year or rotational solar variability. These radiometers' measurements have a reproducibility of roughly 0.03 percent over decadal timescales.[9] A 2005 workshop conducted at the National Institute of Standards and Technology in Gaithersburg, Maryland,[10] sparked investigations into the effects of diffraction, scattered light, and aperture area measurements on the differences between instrument results.

Evident in this combined, recalibrated record is an 11-year cycle with peak-to-peak amplitude of approximately 0.07 percent and variations greater by a factor of two to three that are associated with short-term transits of sunspots due to solar rotation (the lower panel of Figure 1.1). Measurement continuity has enabled successive radiometric time series obtained from different space missions to be intercalibrated to produce a 33-year-long composite TSI record. The need for such intercalibration makes

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[5] P.G. Judge, and S.H. Saar, The outer solar atmosphere during the Maunder Minimum: A stellar perspective, *The Astrophysical Journal* 663:643, 2007.

[6] L.A. Fisk, K.P. Wenzel, A. Balough, R.A. Burger, A.C. Cummings, P. Evenson, B. Heber, J.R. Jokipii, M.B. Krainev, and J. Kota, et al., Global processes that determine cosmic ray modulation. *Space Science Review* 83:179-214, 1998.

[7] R. Harrison, The global atmospheric electric circuit and climate, *Surveys in Geophysics* 25:441-484, 2004.

[8] L.I. Dorman and I.V. Dorman, Possible influence of cosmic rays on climate through thunderstorm clouds, *Advances in Space Research* 35(3):476-483, 2005.

[9] M. Fligge and S.K. Solanki, The solar spectral irradiance since 1700, *Geophysical Research Letters* 27:2157, 2000.

[10] J. Butler, B.C. Johnson, J.P. Rice, E.L. Shirley, and R.A. Barnes, Sources of differences in on-orbital total solar irradiance measurements and description of a proposed laboratory intercomparison, *Journal of Research of National Institute of Standards and Technology* 113:187-203, 2008.

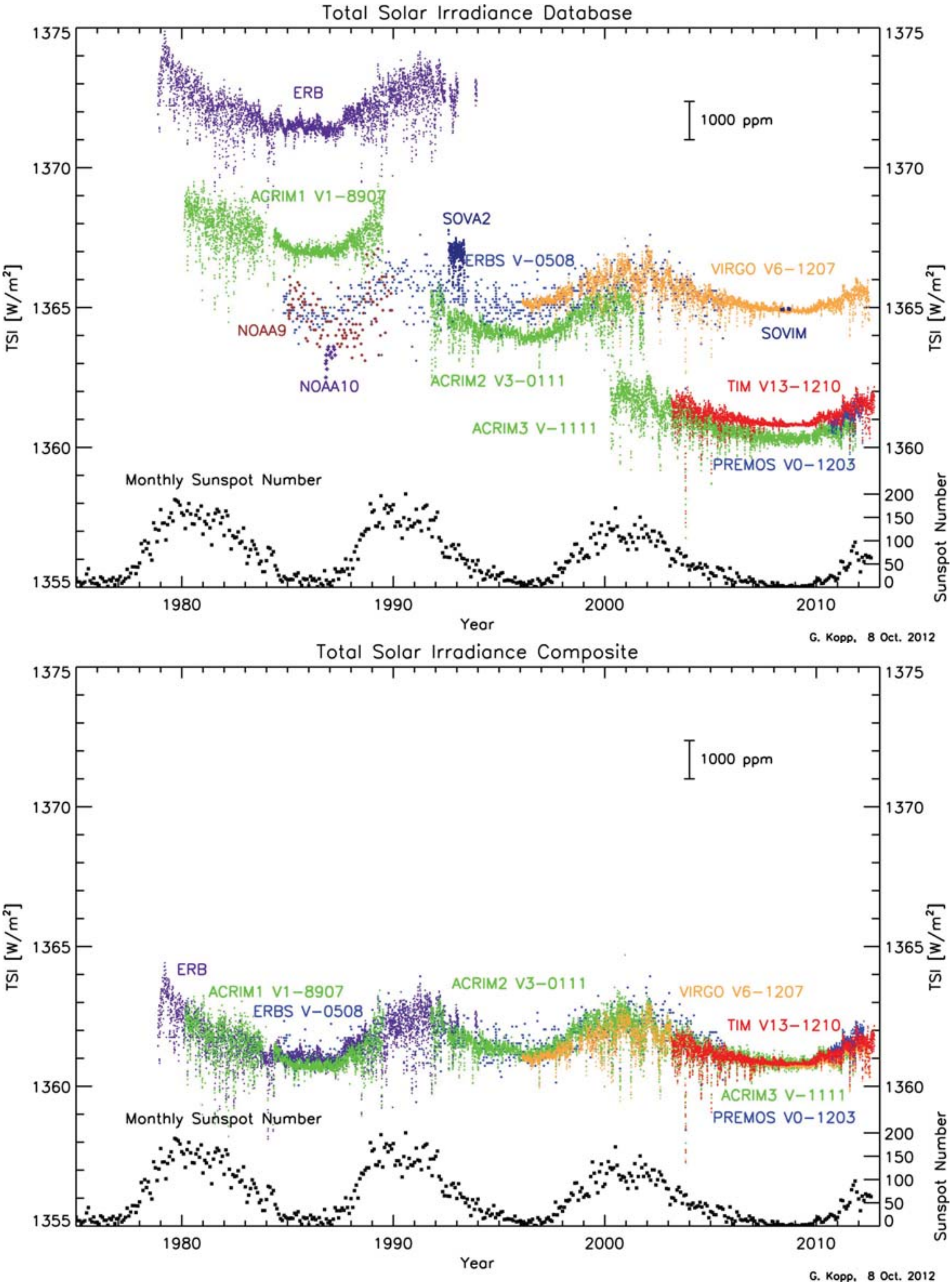

FIGURE 1.1 Space-borne measurements of the total solar irradiance (TSI) (*top*) span the last 34 years. Offsets between measurements are the result of calibration differences between instruments. Measurement continuity allows construction of a composite solar climate data record (*bottom*) showing ~0.1 percent variations with solar activity on 11-year and shorter timescales. SOURCE: Courtesy of Greg Kopp, University of Colorado; high-resolution EPS plots are available at http://spot.colorado.edu/~koppg/TSI.

this record vulnerable to loss in the event of a gap in measurements. Proxy records of radioisotopes provide evidence of long-term change in solar activity, but these must be tuned and extrapolated from the existing TSI data record; however, based on present understanding, the irradiance variations inferred from them are no greater than those observed radiometrically over recent solar cycles. New evidence now suggests that secular variations of larger amplitude may have occurred on multi-decadal to millennial timescales. The *Intergovernmental Panel on Climate Change Fourth Assessment Report* estimated the direct radiative forcing due to changes in solar output since 1750 to be ~0.12 W m^{-2} (0.06 to 0.30); corresponding to a change in TSI of ~0.5 W m^{-2} from its baseline value of 1360 W m^{-2}) with a factor-of-two uncertainty.[11] Shortly before 1750, the Maunder Minimum may have caused greater changes in solar forcing.

Continuous measurements of solar ultraviolet radiation began in 1978 with the Nimbus-7 Solar Backscatter Ultraviolet (SBUV).[12] These measurements were followed by those from the Solar Mesosphere Explorer,[13] NOAA-9 SBUV/2, NOAA-11 SBUV/2, the Upper Atmosphere Research Satellite Solar Stellar Intercomparison Experiment (SOLSTICE),[14] and the Solar Ultraviolet Spectral Irradiance Monitor.[15] The present-day Solar Radiation and Climate Experiment (SORCE) SOLSTICE and SORCE Spectral Irradiance Monitor (SIM) extend this continuous (albeit differing in spectral coverage, resolution, and instrument accuracies and stabilities) record of the solar ultraviolet and its variability.

Although the ultraviolet region of the spectrum provides only a small fraction of the TSI, ultraviolet irradiance can change by several percent over the solar cycle, and thus represents an important source of modulation of the energy deposition and composition in the middle and upper atmosphere. Ultraviolet irradiance both changes the radiative balance of the atmosphere and affects the shape of the spectrum of radiation reaching the lower atmosphere. Such variations are thought to drive the top-down coupling mechanism.

The record of measurement of the continuous, full solar irradiance spectrum, which is much shorter than the record of TSI, commenced with measurements by the SIM on the SORCE satellite in 2003. Results have indicated that ultraviolet trends during cycle 23 were larger than those observed in previous cycles, and were compensated by trends in other bands that increased with decreasing solar activity.[16] Spectral observations from SIM suggest a very different response in Earth's atmosphere because of this compensating spectral behavior, suggesting that further modeling studies and analysis of existing atmospheric observations may be needed, as well as continued validations of these new observations.

POTENTIAL PERTURBATIONS OF CLIMATE DUE TO SOLAR VARIABILITY

Research into possible mechanisms of Sun-climate coupling has taken several paths. Progress is hampered by incomplete understanding of solar variability, climate, and their complex interaction.

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[11] S. Solomon et al., Technical Summary in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007.

[12] B.M. Schlesinger and R. P. Cebula, Solar variation 1979-1987 estimated from an empirical model for changes with time in the sensitivity of the solar backscatter ultraviolet instrument, *Journal of Geophysical Research* 97:119-10,134, 1992.

[13] G.J. Rottman, Observations of solar UV and EUV variability, *Advances in Space Research* 8:53-66, 1988.

[14] G.J. Rottman, T. Woods, M. Snow, and G. DeToma, The solar cycle variation in ultraviolet irradiance, *Advances in Space Research* 27:1927-1932, 2001.

[15] L.E. Floyd, D. K. Prinz, P. C. Crane, and L. C. Herring, Solar UV irradiance variation during cycles 22 and 23, *Advances in Space Research* 29:1957-1962, 2002.

[16] J. Harder, J.M. Fontenla, P. Pilewskie, E.C. Richard, T.N. Woods, Trends in solar spectral irradiance variability in the visible and infrared, *Geophysical Research Letters* 36: L07801, 2009.

The changes in TSI over the solar cycle provide a good starting point for discussing these challenges. Periodic, or quasi-periodic, forcing[17] provides invaluable information on climate dynamics. Other than the seasonal variability on a yearly scale and the precession of the equinoxes (the change of the season in which the minimum Sun-Earth distance occurs) with scales of 20,000 years, the only quasi-periodic forcing term is the 11-year solar cycle. Based on the climate community's best estimates of global climate sensitivity, the solar stimuli are much smaller than would be required to dominate the temperature record on decadal timescales.[18] The search for the solar cycle signal in the temperature record, albeit small, continues to motivate much of the climate research in this area, and so far two basic mechanisms have been modeled. In the first, the 11-year cycle may affect the climate system via the bottom-up total solar irradiance path through which solar cycle effects can manifest themselves at the surface and its nearby environment. In general, this bottom-up driver is strongest in the tropics, where there are feedbacks (from clouds, ocean currents, sea surface temperature, and so on) present in the climate system that strengthen the effect and even show up at higher latitudes.

A second avenue of inquiry is the top-down mechanism that makes use of the modulated absorption of ultraviolet radiation in the stratosphere. Top-down mechanisms operate through changes in the more energetic, shorter-wavelength components of the solar spectrum that influence stratospheric temperatures and winds directly and through absorption by stratospheric ozone. Early work by Karen Labitzke and Harry Van Loon on interactions of the solar cycle and the quasi-biennial oscillation of the equatorial stratosphere helped direct attention to the top-down pathway.[19,20] The modulation of stratospheric temperatures is clear from observations. Climate models also take this modulation as input and have demonstrated significant perturbations on tropospheric circulations. If borne out by future studies and shown to be of sufficient magnitude, this mechanism could be an important pathway in the Sun-climate connection, particularly in terms of regional impacts. However, it is important to realize that, unlike the bottom-up mechanism, it can in itself contribute very little to global temperature variations.

The effects on climate of centennial timescale variations in TSI have been an even more difficult and contentious issue. Since the work of Jack Eddy in 1976,[21] the claim that the lower temperatures of the Little Ice Age from roughly 1600 to 1850 are connected to the secular changes in the Sun, as reflected in paleoclimate data derived from cosmogenic isotopes in sediments and the observed record of sunspots, remains an unresolved research topic (Figure 1.2). Recent findings that removal of small-scale photospheric fields could dim the Sun more than previously expected increase the likelihood of such variations in secular irradiance.[22] It remains to be shown whether or not the field decreased significantly below levels observed during normal 11-year activity minima. Ongoing discussion of the role of solar variations in the early 20th century has given rise to the unfounded conjecture that the observed increase in temperature in the last half century could also be due to changes in TSI rather than to anthropogenic

[17] Forcing, or radiative forcing, denotes an externally imposed perturbation in the radiative energy budget of Earth's climate system. As defined in S. Solomon et al., Technical Summary in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007.

[18] D.R. Marsh and R.R. Garcia, Attribution of decadal variability in lower-stratospheric tropical ozone, *Geophysical Research Letters,* 34: L21807, 2007.

[19] H. van Loon and Labitzke, The Southern Oscillation. Part V: The anomalies in the lower stratosphere of the northern hemisphere in the winter and a comparison with the Quasi-Biennial Oscillation, *Monthly Weather Review* 115:357-369, 1987.

[20] K. Labitzkeand and H. van Loon, Associations between the 11-year solar cycle, the QBO and the atmosphere, Part I: The troposphere and stratosphere in the northern hemisphere in winter, *Journal Atmospheric and Solar-Terrestrial Physics*, 50:197-206, 1988.

[21] J.A. Eddy, The Maunder Minimum, *Science* 192:1189-1202, 1976.

[22] P. Foukal, A. Ortiz, and R. Schnerr, Dimming of the 17th Century Sun, *The Astrophysical Journal Letters* 733:L38, 2011.

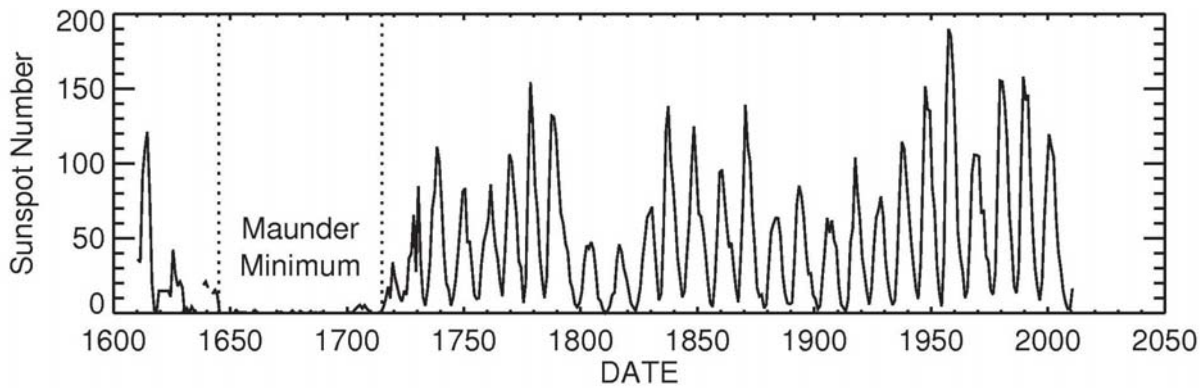

FIGURE 1.2 The yearly averaged sunspot number for a period of 400 years (1610-2010). The Maunder Minimum is shown during the second half of the 16th century. SOURCE: Courtesy of NASA Marshall Space Flight Center.

influences. The Intergovernmental Panel on Climate Change Fourth Assessment[23] and the recent National Research Council report on climate choices[24] agree that there is no substantive scientific evidence that solar variability is the cause of climate change in the past 50 years.[25] However, the mechanisms by which solar variations can affect climate over longer timescales remain an open area of research.

THIS WORKSHOP REPORT

Chapter 2 of this report summarizes the workshop presentations, ordered according to broad science topics. Chapter 3 summarizes the panel discussion session. Appendix A contains the statement of task and work plan for the project. The full workshop agenda is included in Appendix B, and workshop presentation abstracts, prepared by the workshop speakers, are included in Appendix C.

This report summarizes the views expressed by individual workshop participants. Although the committee is responsible for the overall quality and accuracy of the report as a record of what transpired at the workshop, the views contained in the report are not necessarily those of all workshop participants, the committee, or the National Research Council.

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[23] S. Solomon et al., Technical Summary in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007.

[24] National Research Council, *America's Climate Choices*, 2011.

[25] National Research Council, *Advancing the Science of Climate Change*, 2010.

2
Workshop Presentations

THE SUN AND SOLAR VARIABILITY—PAST AND PRESENT

Over the past 30 years substantial advances have been made in understanding variability in solar output. Perhaps most dramatic has been the improved insight into the classic question posed by William Herschel two centuries ago: Does the Sun's brightness vary?[1] Information on total solar irradiance (TSI) behavior has advanced from inferential knowledge for times prior to 1980 to the current understanding of its variation on scales from minutes to the 11-year cycle.

Solar variability is closely related to the structure and magnitude of the solar magnetic field, and so the ability to reconstruct past solar outputs, or predict them, is only as good as the understanding of how the solar magnetic field varies in time and location on the Sun. The past 20 years have seen great strides in the ability to model the large- and smaller-scale structure and variability of the solar magnetic field.[2] These developments in models have been supported by the ability to make measurements of the solar magnetic field.

Precise helioseismic measurements reveal the complex depth dependence of solar rotation throughout the convection zone and well into the radiative core. However, translation of these advances into improved understanding of the dynamo processes that generate solar magnetism has proven more difficult.[3] There is still no precise predictive model of the dynamo that drives solar magnetism over the 11-year cycle or of its modulation envelope over centuries and millennia.

The most rapid advances in this area are coming from simulations of magneto-convection on small scales in relatively shallow layers.[4,5] Their extension to the much deeper layers of the convective and tachocline zones that are most likely to generate the 11-year sunspot cycle is not yet possible with today's computing power.

At the September 2011 workshop, presentations on this topic included discussions of advances in solar radiometry, an assessment of solar influences on Earth's climate change, heliospheric phenomena responsible for cosmic ray modulation, and the behavior of quiet Sun contributions to solar irradiance on timescales ranging from years to thousands of years.

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[1] W. Herschel, Observations tending to investigate the nature of the Sun, *Philosophical Transactions of the Royal Society of London* 91:265-318, 1801.

[2] Y.-M. Wang, A.G. Nash, N.R. Sheeley Jr., Magnetic flux transport on the Sun, *Science* 245:712, 1989.

[3] P. Foukal, *Solar Astrophysics,* Wiley Online Library, 2nd edition, available at http://onlinelibrary.wiley.com/doi/10.1002/9783527602551.fmatter/summary, 2004.

[4] M. Carlsson, R.F. Stein, A. Nordlund, and G.B. Scharmer, Observational manifestations of solar magnetoconvection: Center-to-limb variation, *Astrophysical Journal Letters* 610:137, 2004.

[5] M. Rempel, Penumbral fine structure and driving mechanism of large-scale flows in simulated sunspots, *The Astrophysical Journal* 729(1):5, 2011.

Overview and Advances in Radiometry for Solar Observations

Greg Kopp, University of Colorado, Boulder

Greg Kopp began by listing the potential climate-relevant changes in Earth's radiation budget ranging from volcanic dust veils to heating from radioactive decay in Earth's interior. Solar irradiance is the dominant energy source for Earth, four orders of magnitude greater than the next largest contributor, radioactive decay. Although the Sun's irradiance can change significantly during the passage of features on its surface, such changes are of sufficiently high frequency as to not affect climate. More relevant are trends of a decade or longer. As Kopp explained it, the challenge is to delineate these longer-term solar changes and to discriminate them from other causes of climate change. Statistical studies have suggested that natural influences—including the Sun, effects from volcanic eruptions, and changes in Earth-atmosphere-ocean coupling—together explain roughly 15 percent of the past century's temperature anomaly. Although small, the contribution from the Sun must be determined with a high degree of accuracy in order to reliably quantify the other contributors to climate change (Figure 2.1).

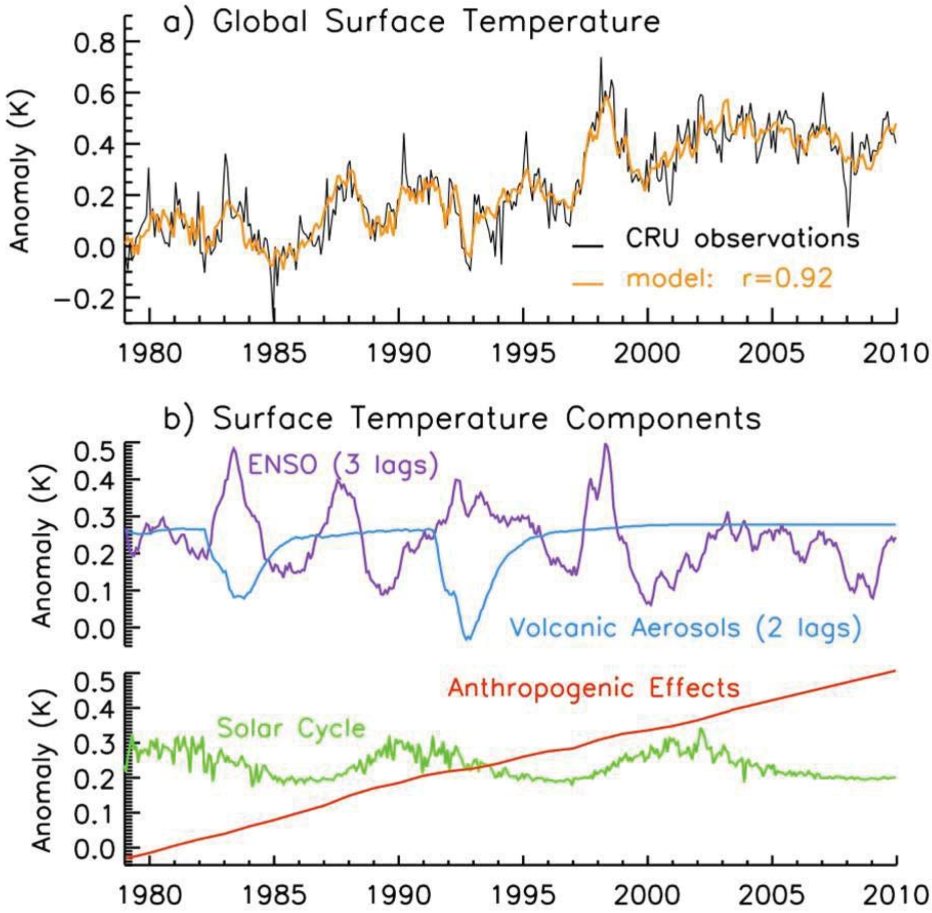

FIGURE 2.1 Global temperature and surface temperature components of Earth's climate. Combined El Niño-Southern Oscillation (ENSO), volcanic aerosols, solar activity, and anthropogenic effects explain 85 percent of observed temperature variance. SOURCE: G. Kopp and J.L. Lean, A new, lower value of total solar irradiance: Evidence and climate significance, *Geophysical Research Letters* 38:L01706, 2011; Copyright 2011 American Geophysical Union, reproduced by permission of American Geophysical Union.

The Sun may vary by as much as 0.1 percent over the 11-year solar cycle and perhaps by 0.05 to 0.3 percent over centennial timescales. Uncertainty in the long-term variability is limited by the proxy models used to derive irradiance backward in time, before the measurement record began. Kopp used an estimate of how the Sun might have varied coming out of the Maunder Minimum, by approximately 0.1 percent over 80 years, to derive accuracy and stability requirements for measuring TSI. Although change of that magnitude may be easy to measure over a solar rotation or over a maximum-to-minimum half solar cycle, it is a considerable challenge to derive a change that small over a century. This derivation requires a stability of 10 parts per million (which is at the frontier of the possible with the best instruments today), and it requires substantial periods of overlap between those measurements with different instruments and a long-term accuracy of 100 parts per million. These tight demands make it difficult to obtain such measurements needed for climate science. To resolve the offsets among the various measurements of TSI that make up the 33-year record, Kopp and his colleagues established a test facility using a calibrated cryogenic radiometer and a laser source at solar power levels to provide the first-ever end-to-end validation of active cavity solar irradiance instruments. This facility also helped resolve the source of the offsets among the various TSI instruments. For the Solar Radiation and Climate Experiment (SORCE) Total Irradiance Monitor (TIM) the precision aperture is at the front of the instrument. All of the other sensors use view-limiting apertures in front of the precision aperture. By overfilling and underfilling that aperture, Kopp determined that scattered light was the source of a large fraction of the offsets between those instruments and SORCE TIM, which measures a TSI of approximately 1361 W m^{-2}, the lowest among the group (see Figure 1.1 in Chapter 1). The scattering-corrected Active Cavity Radiometer Irradiance Monitor (ACRIM) measurements are now very close to this value, as are those from Precision Monitoring Sensor (PREMOS). A large scattering correction was derived for the Variability of Solar Irradiance and Gravity Oscillations (VIRGO) instrument, but it has yet to be applied.

Although the general agreement among the ACRIM, PREMOS, and TIM instruments has improved since the discovery of scattered light in the ACRIM and PREMOS sensors, Kopp showed that only the TIM is accurate (100 ppm) and stable (10 ppm per year) enough to monitor the long-term changes of the Sun at climate-quality levels on timescales of years to decades. Without this level of stability it is difficult to distinguish real solar change (for example, between successive solar minima) over instrument drift. Thus, Kopp concluded, it is crucial that the TSI record from TIM remains unbroken, a proposition growing riskier with time since the failure of the Glory launch in 2011, and one that now must rely on overlap between SORCE and the Total Solar Irradiance Sensor.

Assessing Solar and Solar-Terrestrial Influences as a Component of Earth's Climate Change Picture

Daniel N. Baker, University of Colorado, Boulder

Given the previous discussion there are then two challenges: understanding the variation in TSI in the modern era and extrapolating back in time on the order of tens of millennia to understand the variation in TSI through the use of proxies. Baker pointed out that measurements of total solar irradiance vary widely, and the normalization of the values could possibly obscure small trends—a problem he feels should be addressed. Historical TSI reconstruction connects these contemporary TSI measurements via an index that requires extrapolating the TSI back in time—with the attendant uncertainties. As Baker summarized, the connection between TSI and various proxies is that the size of the heliosphere controls the number of galactic cosmic rays (GCRs) that reach Earth: the GCR flux is higher at solar minimum. Isotopic abundances in the atmosphere are altered by GCR flux, generating increased ^{14}C and ^{10}Be, and this isotopic evidence is found in tree rings and ice cores.

Baker also noted that GCRs reach into the stratosphere and troposphere, and are an important "top-down" mechanism for coupling the Sun to climate. For example, Lockwood et al. found a correlation between GCR and TSI,[6] and Russell et al. presented a discussion of the link between the modulated energetic particle flux and nitrogen oxide production in the stratosphere showing a link to ozone.[7] The destruction of ozone changes the energy balance in the atmosphere because ozone absorbs solar radiation. Baker discussed how Randall et al. quantified this in terms of the trend in ozone using the WACCM general circulation model that includes the upper-atmosphere dynamics and chemistry.[8] The high-latitude case shows a depletion of stratospheric ozone due to increases in nitrogen oxides from energetic particles that then is reflected in a lower-atmosphere increase in ozone due to destruction of chlorine oxide through reactions with nitrogen oxides. Baker concluded, however, that all of these processes appear to have a minimal effect on surface temperatures.

Behavior of Quiet Sun Contributions to Solar Irradiance

Peter Foukal, Heliophysics, Inc.

The main aim of Peter Foukal's presentation was to consider whether the Sun dimmed enough during the 17th century Maunder Minimum of solar activity to influence climate. He argued that the simplest way to achieve sufficient dimming is through a decline in the area coverage of small flux tubes in the quiet magnetic network and internetwork (Figure 2.2).

The fractional decline required may be less than the complete disappearance required by earlier irradiance models, judging by recent findings from solar photometry. These findings[9] indicate that the excess radiative flux/unit area of faculae increases with their decreasing cross section. This relationship suggests that climatically significant variations in TSI might be achieved without the need for the complete disappearance of photospheric magnetism. Foukal noted that this relationship is important because ^{10}Be proxy record studies indicate persistence of a residual 11-year solar cycle through the Maunder Minimum.

Foukal then pointed out that present estimates of the quiet network's contribution to total irradiance (Figure 2.3) are uncertain because of limitations on angular resolution, angular coverage, or wavelength coverage. He described how, ideally, the measurement should be carried out with the Solar Bolometric Imager, which has been flown by the Johns Hopkins University Applied Physics Laboratory on NASA balloons,[10] but modified for larger image scale and higher angular resolution.

If the contribution of the quiet network to TSI is significant, it is still necessary to know whether the network's area decayed. This decay is controversial,[11] but the most reproducible indices of network area (such as MgII) did indicate a decline by 5-10 percent below the average of previous minimum values, during the most recent 2008-2009 activity minimum.[12] This amount of decline during a minimum that was only about 1 year longer than normal suggests an even greater decline during a Maunder

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[6] M. Lockwood, What do cosmogenic isotopes tell us about past solar forcing of climate? *Space Science Review* 125:95-109, 2005.

[7] J.M. Russell, S. Solomon, L.L. Gordley, E.E. Remsberg, and L.B. Callis, The variability of stratospheric and mesospheric NO_2 in the polar winter night observed by LIMS, *Journal of Geophysical Research* 89:7267-7275, 1984.

[8] C. Randall, E.D. Peck, L.A. Holt, V. Harvey, D.R. Marsh, X. Fang, C.H. Jackman, M.J. Mills, and S.M. Bailey, Atmospheric coupling via energetic particle precipitation, paper presented at the American Geophysical Union Fall Meeting, December 13-17, 2010, San Francisco, Calif., 2010.

[9] P. Foukal, A. Ortiz, and R. Schnerr, Dimming of the 17th Century Sun, *The Astrophysical Journal Letters* 733:L38, 2011.

[10] P. Bernasconi, H.A.C. Eaton, P. Foukal, and D.M. Rust, The solar bolometric imager, *Advances in Space Research* 33:1746-1754, 2004.

[11] C.J. Schrijver, W.C. Livingston, T.N. Woods, and R.A. Mewaldt, The minimal solar activity in 2008-2009 and its implications for long-term climate modeling, *Geophysical Research Letters* 38: L06701, 2011.

[12] C. Frölich, Evidence of a long-term trend in total solar irradiance, *Astronomy and Astrophysics* 501: L27-L30, 2009.

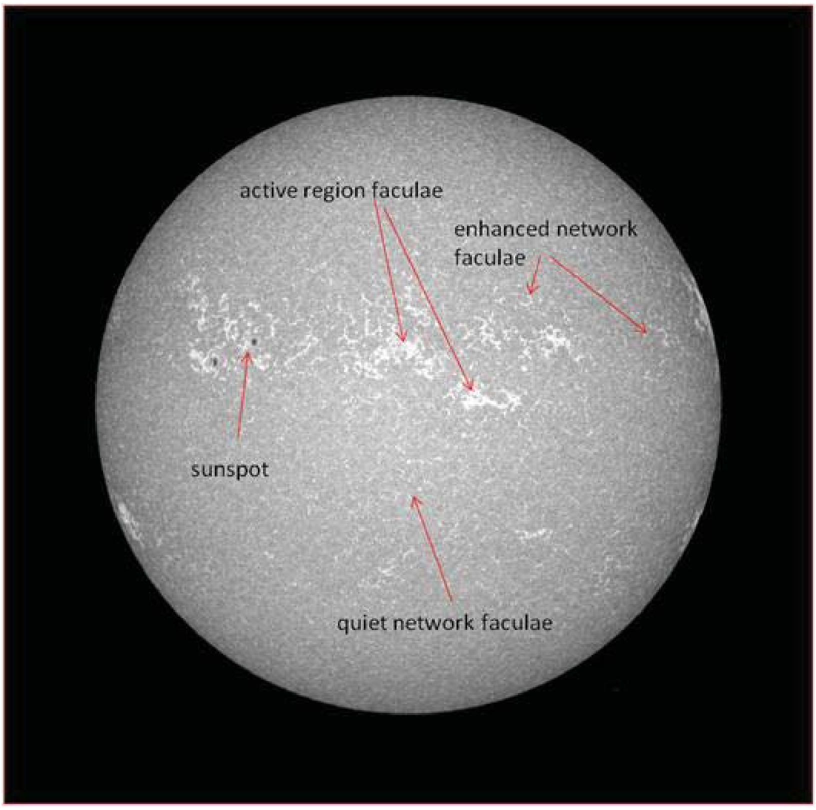

FIGURE 2.2 Image of the Sun's upper photosphere in the 170 nm continuum showing the magnetic structures responsible variation in for total solar irradiance and in 130-240 nm ultraviolet irradiance. SOURCE: Courtesy of P. Foukal, Heliophysics, Inc.

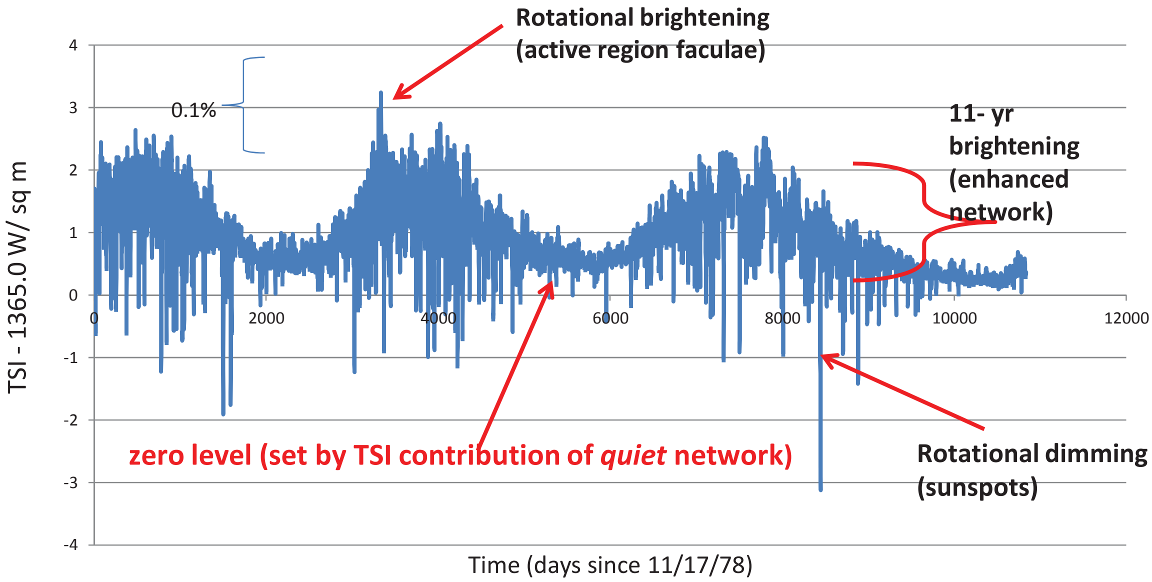

FIGURE 2.3 Variation in total solar irradiance (TSI) measured radiometrically (Physikalisch-Meteorologisches Observatorium Davos composite) between 1978 and the present, identifying the magnetic structures responsible for variation in TSI and the 130-240 nm ultraviolet irradiance. SOURCE: Courtesy of P. Foukal, Heliophysics, Inc.

Minimum-like episode lasting 70 years. Foukal asserted that further work is required on this network-area behavior during extended activity minima.

Foukal stressed that there is no evidence for the large (~0.3 percent) increase in TSI during the early 20th century reported in a recent, widely quoted, study based on ^{10}Be.[13] That level of increase in TSI would require the complete disappearance of the quiet network and internetwork going back in time to 1900. This requirement contradicts the presence of a fully developed network on Ca K spectroheliograms available since the 1890s.[14] Foukal asserted that this model, which also predicts strong TSI driving of climate throughout the Holocene, cannot be correct.

Heliospheric Phenomena Responsible for Cosmic Ray Modulation at the Earth
Joe Giacalone, University of Arizona

Galactic cosmic rays are expected to be essentially isotropic in the space immediately outside the heliosphere and penetrate the solar system with nearly equal probability from all directions. As GCRs enter the solar system, they undergo both energetic and intensity variations resulting from their interaction with the solar wind, interplanetary magnetic field, and the heliosphere (Figure 2.4). As Joe Giacalone discussed, GCRs interact with atomic nuclei in Earth's atmosphere, creating a secondary cosmic ray (neutron) that can interact with a background very abundant in oxygen and nitrogen to form ^{14}C or ^{10}Be, among other nuclei. The GCR intensity at the top of Earth's atmosphere is anti-correlated with the number of sunspots—GCR intensity is higher when there are fewer sunspots. This anti-correlation is the basis for using ^{14}C and ^{10}Be deposited in tree rings and ice cores as a proxy measure of solar activity dating back thousands of years. In addition to the 11-year GCR cycle, there is also a 22-year variation related to the polarity of the solar magnetic field. These variations can be understood through the physics of charged-particle motion in turbulent electric and magnetic fields associated with the solar wind plasma. Even during the Maunder Minimum when sunspots were scarce, there were still polarity reversals, and there were still enhancements of GCRs in the 11-year cycle such that a stronger magnetic field yielded smaller GCR flux. The highest flux of GCRs on record occurred during the most recent solar minimum.

The radioisotope record in ^{14}C and ^{10}Be provides information on the varying concentration of these isotopes in the biosphere over past millennia. This information can be translated into a time series showing the variation in flux of the GCRs mainly responsible for the formation of these isotopes. The resulting GCR flux variation has been used in Sun-climate studies in two separate ways. It can be used directly to study the possible effect of GCR variation on atmospheric electrification and cloud formation. As pointed out in the presentation by Giacalone, recent findings from laboratory measurements at CERN have brought more attention to studies of cosmic ray effects. He also described the various influences causing GCR flux variation on timescales from days to millennia. Sudden changes in the solar magnetic field or in the resulting heliospheric structures account for the rapid changes. The 11- and 22-year cycles are caused by more gradual variation of the heliospheric field strength and complexity, and in the number of solar eruptive events over the sunspot cycle. Supernova eruptions and other changes in the interstellar medium play a role on millennial timescales because of the large distances between stars and the diffusive transport of the GCR population. Nearby supernovae can create short-lived pulses, but these are exceptionally rare.

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[13] A. Shapiro, W. Schmutz, E. Rozanov, M. Schoell, M. Haberreiter, A.V. Shapiro, and S. Nyeki, A new approach to the long-term reconstruction of the solar irradiance leads to large historical solar forcing. *Astronomy and Astrophysics* 529:67, 2011.

[14] P. Foukal, A new look at solar irradiance variation, *Solar Physics* 279:365-381, 2012.

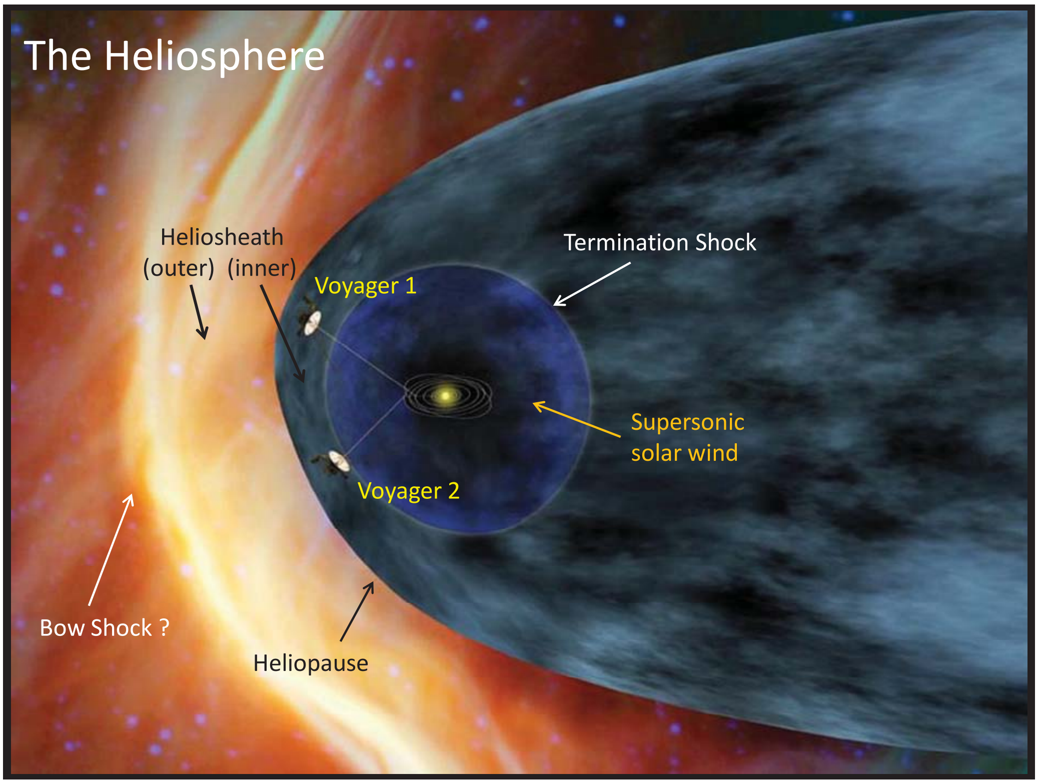

FIGURE 2.4 Diagram of the heliosphere. SOURCE: Courtesy of J. Giacalone, University of Arizona, modified from NASA image available at http://www.nasa.gov/mission_pages/sunearth/multimedia/Heliosphere.html, courtesy of NASA/Goddard/Walt Feimer.

Giacalone also pointed out that, although the four basic processes of particle diffusion, convection, drifts, and energy changes have been known for 50 years, the transport coefficients needed to calculate their effects are still poorly known. However, it is now accepted that none of the processes included in the classic Parker transport equation can be neglected; it is a complex system. This complexity limits the accuracy of attempts to use the isotope record to derive the record of solar irradiance. The solar modulation of cosmic rays is caused by both the relatively gradual evolution in the background solar wind and by the pulses associated with coronal eruptions, through the complex processes referred to. Much of the variation in irradiance (at least the 11-year variation) originates from the emission from plasma heated by the dynamics of the near-surface magnetic field with contributions from both the open and closed field components both during quiescence and during flarings. This differential behavior makes it difficult to use radioisotopes to generate more than a rough estimate of variation in TSI and ultraviolet flux, such as those shown by workshop presenter Raimund Muscheler.

Giacalone showed the evidence for a low-level 11-year cycle in radioisotopes during the extended Maunder Minimum of solar activity during the 17th century. Such isotopic evidence currently provides the best chance of determining how much the solar magnetic field decreased during that period and therefore how much the Sun dimmed. He discussed how the differences between galactic cosmic rays and anomalous cosmic rays (ACRs) could be seen during the most recent solar minimum. The GCR intensity was the highest measured by spacecraft, but ACRs had a lower intensity compared to previous solar minima. He suggested one possible interpretation was that fewer ACRs were being produced at the termination shock of the heliosphere. This difference is useful for determining the physics of cosmic ray transport in the heliosphere.

The Record of Solar Forcing in Cosmogenic Isotope Data
Raimund Muscheler, Lund University, Sweden

Muscheler discussed how information can be recovered about the Sun's activity in the past from studies of cosmogenic isotope data. The most common isotopes used in these studies are ^{10}Be in ice cores and ^{14}C in tree rings, and they can be used together to separate changes in solar activity from differences in climate. He noted that responses in the data are seen not only for solar modulation but also for variations in Earth's geomagnetic field on timescales longer than 500 years. The challenge is to detect reliable signals from these data sets for a particular time period. TSI can be considered to be more closely tied to the closed flux (which is larger than the open-field fraction) and magnetic features on the Sun compared to the modulation of the GCRs in the heliosphere by the Sun's open flux. He noted that when talking about the cosmic-ray flux at Earth, Earth's magnetic field determines where and how much of the cosmic -ray flux makes it into Earth's atmosphere. An estimate of the geomagnetic field intensity is necessary along with isotope measurements to determine the solar modulation. In the atmosphere itself, circulation and climate also affect the deposition of the isotopes.

^{14}C's response to variations in the solar cycle is affected by the fact that the ^{14}C is taken up in CO_2. Muscheler explained that CO_2 remains in the atmosphere for approximately 7-8 years and then has a long residence time in the large reservoir of the ocean where it can continue to exchange with the atmosphere and the biosphere before being trapped in tree rings. This leads to a dampening of the smaller-scale variations. Because of this residence time in a large reservoir, ^{14}C is a less direct proxy for cosmic rays, but it does have the advantage of being less subject to concerns about geographic influences than is ^{10}Be. ^{14}C records a more global signal on 11-year-cycle timescales or longer. Muscheler stated that even if changes in climate cause changes in the carbon cycles of the biosphere and the ocean, the ^{14}C in the atmosphere changes at the same rate and so does not obscure a solar signal. Even though climate influence is unlikely to be a major influence, a model of the carbon cycle is needed to calculate ^{14}C production rates to make an assumption about the carbon cycle. Variations in ^{14}C in the atmosphere alone do not provide a signal of the production of ^{14}C.

Muscheler discussed how ^{10}Be is produced by spallation processes in the atmosphere through reactions with nitrogen and oxygen. These reactions require high-energy particles. Normally energies at these levels are seen only in GCRs and in the relatively rare solar proton events (SPEs). These SPE contributions are relatively short-lived and are generally believed to be undetectable in the climatological record because they are obscured by other short cycles, such as the changes in ^{18}O caused by yearly temperature changes.

Muscheler continued by explaining how ^{10}Be is produced in the stratosphere, becomes attached to aerosols, and is then sensitive to stratosphere-troposphere exchange processes before being deposited and trapped in ice cores. ^{10}Be is further complicated by the geomagnetic field configuration characteristic of the location. High-latitude locations such as Greenland or Antarctica have little shielding, and so the solar signal is relatively strong. At low latitudes there is little variation with solar cycle due to the stronger geomagnetic shielding. A still unresolved issue is how to go from a local measurement with some random variability to a globally representative value. Muscheler summarized ^{10}Be as a relatively direct proxy for cosmic rays with significant noise associated with location and climate influences.

Muscheler discussed two commonly used data sets from the past 1,000 years for ^{10}Be. Both sets of data show a largely consistent picture with the Maunder and Spörer Minima from activity indices seen in the ^{10}Be record. There is a disagreement between researchers when looking at the records from the past 50 years. On the basis of one data set, it can be argued that today's base solar activity is high, but that it is not unprecedented. Others claim that their reconstruction indicates a period of high solar activity in the past 60 years that is unique in the past 1,150 years. Muscheler suggested that the difference between the recent records is caused by one of them having been influenced by non-solar-related climate change. Muscheler discussed evidence of long-term changes in solar activity over the past 10,000 years. There are, however, uncertainties engendered by the comparison of the ^{10}Be to the ^{14}C record. These differences may be due to changes in ^{10}Be transport, snow accumulation rates, carbon cycle uncertainties, or geomagnetic field uncertainties. Muscheler stated that further research would be required to understand these differences.

Muscheler pointed out that there is good agreement between ^{10}Be and ^{14}C on the scale of the 11-, 88-, and 207-year solar cycles and that those signals can be clearly seen. On the other hand, there is no evidence of sustained periods on the order of 1,000 years of low solar activity in either the ^{10}Be or the ^{14}C record. This can be said with some confidence for the records going back over the past 10,000 years; however, characterization any farther back than that is more complicated because of the influence of climate change during the last ice age on the ^{10}Be record.

In response to a question from the audience on the "climate/cosmic ray hypothesis" (i.e., that cosmic rays decreased over the last half of the 20th century and that this decrease is linked to the climate change of the past 30 years), Muscheler stated that proxy data indicate that the cosmic-ray flux actually decreased early in the 20th century, but recently the level has been steady and high. Based on the proposed link between increased GCR flux and cloudiness, one might have expected that the late 20th century would be cooler than the early 20th century—a state that was not observed.

Another audience member pointed out that it is necessary to be careful about the scale of the solar activity minima; minima on the scale of the heliosphere are not appropriately grouped with those on the scale of a hundred kilometers. The relationship between the large- and the small-scale field of the Sun is not known. Muscheler agreed that in his radionuclide data, only the solar modulation of GCRs can be clearly seen.

Solar Grand Minima Inferred from Observations of Sun-like Stars

Dan Lubin, Scripps Institution of Oceanography, University of California, San Diego

Dan Lubin discussed how the behavior of Sun-like stars can provide insight into the Sun's activity and how solar forcing may change in the future. The frequency of grand minima (Maunder Minimum-like occurrences) is difficult to extract from the geophysical proxy record. In a sample of solar-type stars, the fraction of very inactive stars is analogous to the fraction of the Sun's lifetime spent in a Maunder Minimum-like state. Early estimates of grand minimum frequency in solar-type stars ranged from 10 to 30 percent,[15] implying that the Sun's influence could be overpowering. It was later determined using much more accurate distance data from the European Space Agency's Hipparcos Space Astrometry mission that these studies included many stars that evolved off the main sequence and are no longer burning hydrogen like the Sun.[16,17] More recent studies, using the Hipparchos data and accounting for the metallicity of the star, place the estimate in the range of less than 3 percent for the fraction of the Sun's lifetime spent in a Maunder Minimum-like state of low activity.[18] The deduced frequency of occurrence of a Maunder Minimum state is sensitive to the choice of metallicity threshold and the definition of level corresponding to "inactive."

Lubin pointed out that the early pre-Hipparcos estimates of Maunder Minimum analog frequency gave estimates that are too large. Instantaneous activity measurements of the hydrogen and potassium spectral lines (HK) are suggestive but not conclusive for identifying Maunder Minimum analog candidates; the result depends strongly on the chosen inactive threshold. Very low activity may be seen with an old star nearing the end of its main sequence lifetime. However, the historical Maunder Minimum most likely did involve very low HK activity and weak cycling compared with the present-day Sun.

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[15] S. Baliunas, and R. Jastrow, Evidence for long-term brightness changes of solar-type stars, *Nature* 348:520-523, 1990.

[16] J.T. Wright, Do we know of any Maunder Minimum stars? *The Astrophysics, Journal* 128:1273, 2004.

[17] P.G. Judge, and S.H. Saar, The outer solar atmosphere during the Maunder Minimum: A stellar perspective, *The Astrophysics Journal* 663:643, 2007.

[18] D. Lubin, D. Tytler, and D. Kirkman, Frequency of Maunder minimum events in solar-type stars inferred from activity and metallicity observations, *The Astrophysical Journal Letters* 747: L32, 2012.

EVIDENCE OF SUN-CLIMATE CONNECTIONS ON DIFFERENT TIMESCALES

Instrument meteorological records rarely extend back more than 200 years; therefore, a long-term perspective on solar forcing must rely on the records provided by paleoclimate archives—principally, ice cores, lake and marine sediments, stalagmites, corals, and tree rings. Within each of these natural archives, a number of parameters can be measured and their relationship to climate assessed through calibrations with overlapping instrument data. In this way, paleoclimate proxies extend the record of past climate over past millennia.

Workshop presentations on this topic included discussions of detection of solar signals from paleorecords and temperature proxies as well as the role of cyclic and secular forcing at Earth's surface and the corresponding climate response.

Detection of the Solar Signal in Climate from Paleorecords

Raymond S. Bradley, University of Massachusetts

Paleoclimate archives also provide an index of past solar activity, through the record of changes in cosmogenic isotopes recorded in tree rings and ice cores. In particular, variations in the cosmogenic isotopes ^{10}Be and ^{14}C indicate changes in the production rate of these isotopes. Raymond Bradley described how, over the past 12,000 years, these variations have been controlled mainly by changes in Earth's magnetic field, and the field was weaker than today's for much of that period (only ~40% of the present day value at 7000 years before present). Thus, isolating solar magnetic effects on the production rate of ^{10}Be and ^{14}C requires that changes in the geomagnetic field strength be removed, leaving the heliomagnetic signal as a residual. Unfortunately, past changes in Earth's magnetic field are not well constrained, and Bradley indicated that further research on this topic is needed to refine the signal of whatever residual solar signal may be present. Furthermore, although attempts have been made to calibrate changes in ^{10}Be in terms of variations in total solar irradiance,[19] it is still debatable how variations in cosmogenic isotope production relate to changes in total or spectrally distributed irradiance.

Bradley noted that, despite these limitations, paleoclimatologists have generally accepted that the record of ^{10}Be or ^{14}C anomalies provides an index of changes in TSI, and have often sought to correlate paleoclimatic records with these data. The results have been mixed. In the case of the high-resolution Belukha glacier ice core data (from the Siberian Altai), a well-defined correlation between δ^{18}O (a proxy for March-November mean temperature) and ^{10}Be was found, with the strongest correlation associated with a 20-year lag in the temperature response.[20] Furthermore, spectral analysis of the δ^{18}O record revealed statistically significant variance at 10.8, 86, and 205 years, frequencies known to be prominent in the ^{14}C anomaly record. However, when other nearby proxy records were examined, there was no evidence for a similar relationship to solar forcing, leaving open the question of whether the Belukha record is superior to the others, or whether the observed relationship is only of local significance.

Bradley discussed how a number of high-resolution ice core records have noted a strong relationship between ^{14}C anomalies and changes in oxygen isotopes in the stalagmite carbonate. For example, Neff et al. noted a high correlation between δ^{18}O in a stalagmite from Oman, and ^{14}C, which they suggest is related to solar influences on monsoon-derived rainfall.[21] Similarly, Wang et al. examine

[19] See, for example, F. Steinhilber, J. Beer, and C. Fröhlich, Total solar irradiance during the Holocene, *Geophysical Research Letters* 36:L19704, 2009.

[20] A. Eichler, S. Olivier, K. Henderson, A. Laube, J. Beer, T. Papina, H.W. Gäggeler, and M. Schwikowski, Temperature response in the Altai region lags solar forcing, *Geophysical, Research, Letters* 36: L01808, 2009.

[21] U. Neff, S.J. Burns, A. Mangini, M. Mudelsee, D. Fleitmann, and A. Matter, Strong coherence between solar variability and the monsoon in Oman between 0 and 6 kyr ago, *Nature* 411:290-293, 2001.

$\delta^{18}O$ in a well-dated monsoon-derived stalagmite from southern China and found a highly statistically significant relationship with ^{14}C anomalies over the past ~9,000 years.[22]

Bradley asserted that it is noteworthy that all these studies focus on changes in the hydrological cycle of each region, rather than changes in temperature. This points to the possibility that if there is a solar effect on climate, it is manifested in terms of changes in the general circulation, rather than in a direct temperature signal. Bradley noted that in fact, despite the serious limitations in terms of statistical significance of most of the published paleoclimate studies that claim to find a solar signal in the records, there is nevertheless a clear geographical pattern in the overall signal that emerges when all records are mapped out. Specifically, periods of high cosmogenic isotope production (which might be related to reduced irradiance) appear to be associated with weaker monsoon rainfall in Oman, India, and southern China. There is also evidence for colder conditions at high latitudes, more extensive sea-ice in the North Atlantic, and wetter and colder conditions in western Europe, suggesting a general expansion of the polar vortex and a southward displacement of the westerlies when solar activity is low. There is a corresponding displacement, or seasonal shift in the intertropical convergence zone, affecting rainfall distribution in Central and South America and equatorial Africa.[23,24,25] Meehl et al. suggested that this pattern results from regional differences in radiation receipts, with cloud-free zones differentially warming more than cloudy regions during periods of higher TSI, leading to changes in circulation patterns.[26] Others have related solar-driven changes in stratospheric heating to changes in tropospheric circulation.[27] Bradley concluded that either top-down or bottom-up effects (or both) may be relevant in explaining the pattern of hydrological changes that appear to be present in the paleoclimatic records. However, he asserted that it is clear that the current evidence for solar forcing from paleoclimate is very limited, and most records do not provide the necessary resolution or signal strength to detect a solar signal if it is present. Bradley suggested that further studies could be designed to address this question in a more rigorous and systematic manner.

Detecting the Solar Cycle Via Temperature Proxies Back to the Maunder Minimum

Gerald R. North, Texas A&M University

Gerald North described an approach to detection of a solar signal in ^{18}O climate records thought to record air temperature at the time of deposition on snow/ice fields. Some of these records are claimed to resolve timescales fine enough to spectrally resolve signals at the 11-year-cycle period. North described efforts to do this in oxygen isotope data from the Dye-3 core from Greenland and the Taylor Dome cores from Antarctica, both of which revealed a weak 11-year signal. He described how further research, involving additional well-dated records and band pass filtering, may further elucidate the temporal evolution of such signals in relation to the long-term record of solar forcing.

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[22] Y. Wang, H. Cheng, R.L. Edwards, Y. He, X. Kong, Z. An, J. Wu, M.J. Kelly, C. A. Dykoski, and X. Li, The Holocene Asian Monsoon: Links to solar changes and North Atlantic climate, *Science* 308:854-857, 2005.

[23] D.E. Black, L.C. Peterson, J.T. Overpeck, A. Kaplan, M.N. Evans, and M. Kashgarian, Eight centuries of North Atlantic ocean atmosphere variability, *Science* 286:1709-1713, 1999.

[24] D.E. Black, R.C. Thunell, L.C. Peterson, A. Kaplan, and E.J. Tappa, A 2000-year record of tropical North Atlantic hydrographic variability, *Paleoceanography* 19:PA2022, 2004.

[25] J.C. Stager, D. Ryves, B.F. Cumming, L.D. Meeker, and J. Beer, Solar variability and the levels of Lake Victoria, East Africa, during the last millennium, *Journal of Palelimnology* 33:243-251, 2005.

[26] G.A. Meehl, and C. Tebaldi, More intense, more frequent, and longer lasting heat waves in the 21st century, *Science* 305:994-997, 2004.

[27] See, for example, D.T. Shindell, G. Faluvegi, and N. Bell, Preindustrial-to-present-day radiative forcing by tropospheric ozone from improved simulations with the GISS chemistry-climate GCM, *Atmospheric Chemistry and Physics* 3:1675-1702, 2003.

Climate Response at Earth's Surface to Cyclic and Secular Solar Forcing
Ka-Kit Tung, University of Washington

One overriding problem in all studies that attempt to relate past changes in climate to solar forcing involves the complications of other forcing factors operating on similar timescales. Volcanic forcing is of particular significance, especially during recent centuries (including the Maunder and Dalton Minima) when explosive eruptions were common (Figure 2.5). In addition, internal modes of circulation, such as the Atlantic Multidecadal Oscillation (AMO), further complicate signal detection at certain frequencies. Ka-Kit Tung examined this matter by focusing on the longest instrumental temperature record, from central England, which extends back over 350 years, as well as estimates of the global surface temperature instrument record since 1850 to help define a component of these records due to unforced internal variability likely associated with the AMO. This analysis suggests that >90 percent of the variance in temperatures can be accounted for by non-solar forcing factors and internal modes of variability.

Using the central England temperature record to help define AMO cycles in earlier centuries, Tung also estimated that roughly half of the warming at the end of the Maunder Minimum period could be due to AMO variability and that, more generally, internal variability combined with volcanic forcing can explain a significant part of the variability commonly attributed to solar variations.

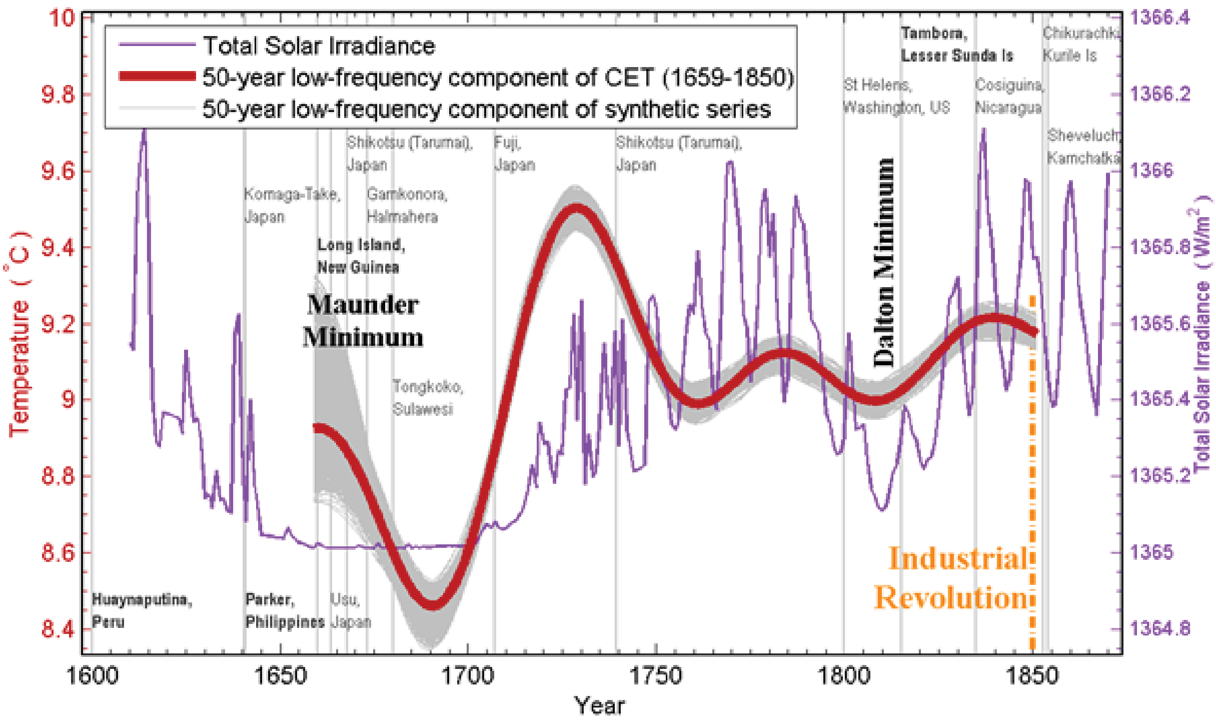

FIGURE 2.5 The low-frequency portion of the Central England temperature record, which could represent the Northern Hemisphere mean, is plotted along with the solar total solar irradiance (TSI) index and the occurrence of known large volcanic explosions. The figure indicates that the warming at the end of the Maunder Minimum around 1700 leads the increase in TSI by about 20-30 years and suggests that the warming may instead be a recovery from the cooling produced by the aerosols from a series of large volcanic eruptions between 1660 and 1680. SOURCE: Courtesy of K.K. Tung and J. Zhou, University of Washington, "Climate Response at Earth's Surface to Cyclic and Secular Forcing," presentation to the Workshop on the Effects of Solar Variability on Earth's Climate, September 9, 2011.

MECHANISMS FOR SUN-CLIMATE CONNECTIONS

Mechanisms proposed to explain Earth's climate response to solar variability can be grouped into three broad categories involving the response to variations in total solar irradiance, ultraviolet irradiance, and corpuscular radiation. The following talks at the workshop outlined the current rationale for considering how these stimuli might lead to significant responses by the climate system.

Issues in Climate Science Underlying Sun/Climate Research

Isaac M. Held, National Oceanic and Atmospheric Administration
Geophysical Fluid Dynamics Laboratory

In his presentation Isaac Held asserted that the response of the climate to radiative heating—whether it comes from greenhouse gases trapping heat, stratospheric aerosols from volcanic eruptions or aerosols of various origin reflecting sunlight back to space, or finally variable TSI heating—involves both the troposphere and the ocean. The surface and the troposphere are intimately coupled through fast radiative-convective adjustments so that they respond as a whole, with part of the heat input going into the ocean. The ocean heat uptake and later slow release back to the atmosphere are the factors responsible for the difference between the transient response of the climate to radiative forcing as compared to the equilibrium climate (some 40-70 percent of the adjustment is achieved on a timescale on the order of 4 years, whereas equilibration takes centuries). This transient behavior can be demonstrated using a simple two-box model of the mixed layer and deep ocean, and it applies to all radiative forcings, such as to the Mount Pinatubo volcanic aerosols, as well as for the response to the 11-year solar cycle. On stratosphere-troposphere coupling, there is recent observational evidence that in the Southern Hemisphere the surface westerlies (and the storm track) have shifted poleward by a few degrees due possibly to the ozone hole over the South Pole in the stratosphere.

Held summarized work on this issue, focusing on a potential mechanism that employs the fact that cooling in the polar stratosphere associated with the loss of ozone increases the horizontal temperature gradient near the tropopause. Strengthening the horizontal temperature gradient alters in turn the fluxes of angular momentum by midlatitude eddies. The angular momentum budget of the troposphere controls the surface westerlies. This mechanism could work with volcanic aerosol warming or greenhouse gas cooling of the stratosphere, as well as for the solar warming of the lower stratosphere through ultraviolet absorption by ozone. Held noted that it is more difficult for perturbations to the middle stratosphere to engage this kind of mechanism. Other dynamics would be needed to communicate signals from the middle to the lower stratospheric regions capable of influencing Earth's angular momentum budget significantly.

Indirect Climate Effects of the Sun Through Modulation of the Mean Circulation Structure

Caspar Ammann, National Center for Atmospheric Research

Caspar Amman emphasized the indirect climate effects of the Sun. He suggested that solar heating appears to be plausible as a radiative driver for the medieval warm period (approximately A.D. 900-1250) (Figure 2.6). When Earth's radiative balance is altered, as in the case of a change in the solar-cycle forcing, not all locations are affected equally. He argued that although the global mean temperature change may be small, regional signatures in moisture, pressure, and temperature offer a consistent picture as revealed by proxy records. The equatorial central Pacific is generally colder, the runoff from rivers in Peru is reduced, and drier conditions affect the western United States. The western tropical Pacific is warmer, with a high-pressure system in the northwestern Pacific steering storm tracks further north, bringing moisture to Alaska and warming the interior of northern continents. The storm tracks drift to northern Europe, with moisture deposited in the northern part of Scandinavia although the Mediterranean

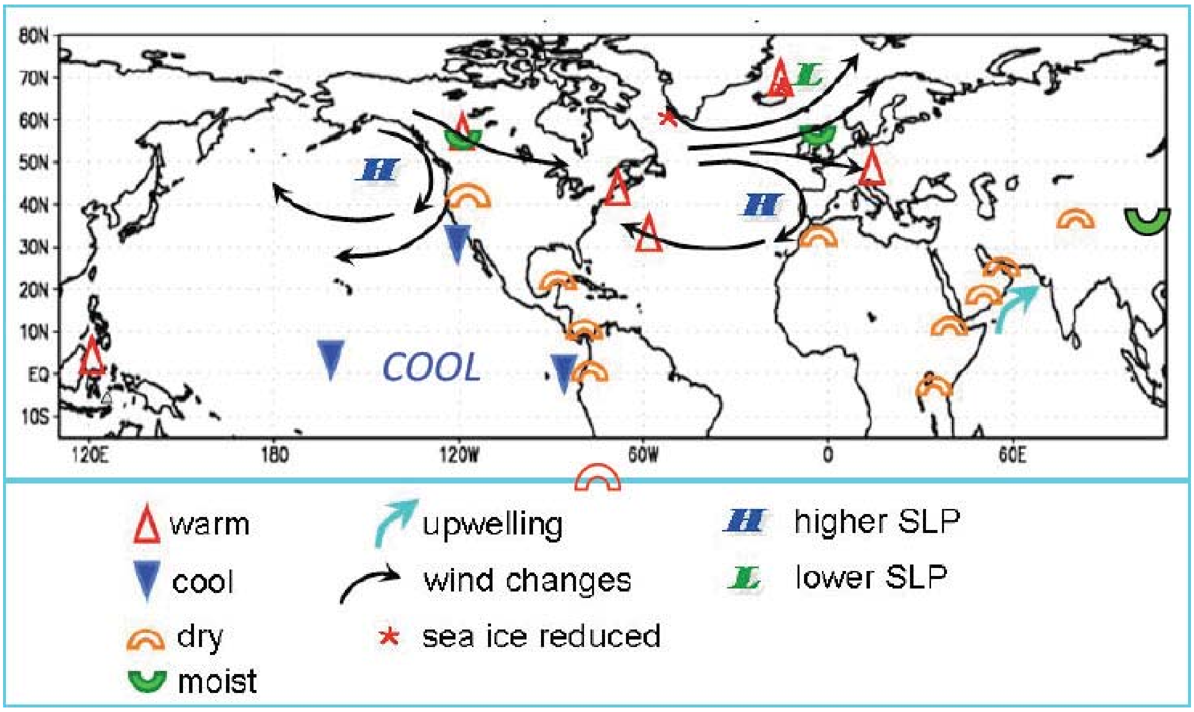

FIGURE 2.6 Dynamical mapping of persistent medieval anomalies in the Northern Hemisphere winter. SOURCE: N.E. Graham, C.M. Ammann, D. Fleitmann, K.M. Cobb, and J. Luterbacher, Support for global climate reorganization during the Medieval Climate Anomaly, *Climate Dynamics* 37:1217-1245, 2011.

remains dry. Global climate models (GCMs) currently do not reproduce the tropical features seen in proxy records, giving instead a more uniform warming. One model was able to present an improved spatial structure of response to medieval solar forcing when the solar flux into the Indian Ocean was artificially enhanced, producing a small expansion of the zonal overturning circulation of the atmosphere over the tropical Pacific Ocean (Walker cell) and inducing circumhemispheric circulations. The mechanisms involved are complex, and it is possible that both stratospheric-tropospheric dynamical coupling and coupled atmosphere-ocean dynamics are involved.

Climate Response to the Solar Cycle as Observed in the Stratosphere

Lon Hood, University of Arizona

Lon Hood's presentation at the workshop covered the decadal signal in measurements of ozone mixing ratio in the upper stratosphere. These satellite measurements correlate with the ultraviolet variation associated with the 11-year solar cycle. The cyclic response of ozone in the middle stratosphere is rather weak, but larger again in the lower stratosphere. The WACCM3 climate model (which extends above the stratosphere) is able to simulate the upper- and middle-stratosphere signals but not the lower-stratosphere ones. Hood noted that it is possible that there is a change in the meridional circulation in the stratosphere, through the interaction with planetary waves, that could bring ozone from above to the lower stratosphere. The question is what could have produced the decadal variation in the planetary wave driving. There are both top-down and bottom-up potential mechanisms. The top-down (actually upper to lower stratosphere) mechanism involves the direct solar heating of the upper stratosphere, altering the circulation in such a way as to modify the planetary propagation. The bottom-up mechanism has the TSI radiative heating modifying the planetary wave amplitudes near the surface, which then propagate upward into the stratosphere. The La Niña type of response during solar peak years proposed by Gerald Meehl and Harry van Loon could affect the production of planetary waves. However, Hood contended that regression analysis of sea surface temperature data does not show this pattern.

Solar Effects Transmitted by Stratosphere-Troposphere Coupling

Joanna D. Haigh, Imperial College, London

Joanna Haigh focused on the solar effects transmitted from the stratosphere to the troposphere through a dynamical coupling between the two layers. Solar-cycle signals in observational zonal mean temperature data show that when the Sun is more active, warming occurs in the tropical lower stratosphere and in vertical bands passing through the midlatitude troposphere (Figure 2.7). Consistent with this observation is an increase in the extent of the major meridional overturning (Hadley) cells of the tropical atmosphere and a slight shift toward the poles of the midlatitude jets. Surface air temperatures show a pattern in the North Atlantic consistent with the positive phase of the North Atlantic Oscillation. GCMs simulating solar influence with enhanced ultraviolet radiation show similar patterns of response, although the magnitude depends on the changes in solar spectrum (and implied influence on stratospheric ozone). Haigh claimed that studies with simpler models show that this pattern of response can be produced through the effects on wave momentum and heat fluxes of changing the thermal structure around the tropopause, and through a feedback on the mean state. She noted that recent measurements of the solar spectrum from the SORCE satellite imply large changes in ultraviolet that would reinforce these mechanisms.

Direct Solar Forcing of the Lower Atmosphere and Ocean

Gerald A. Meehl, National Center for Atmospheric Research

Gerald Meehl showed evidence that when observed sea surface temperature data are composited using only sunspot peak years, the tropical Pacific shows a pronounced La Niña-like pattern, with a cooling of almost 1°C in the equatorial eastern Pacific. This result has been seen in simulations using global coupled climate models. Diagnosis of the model results show that both bottom-up (related to air-sea coupling) and top-down (related to stratospheric ozone) mechanisms are needed to give the correct amplitude of the observed response (Figure 2.8). According to Meehl, the bottom-up mechanism involves greater solar heating of the tropical and subtropical ocean in the eastern Pacific for solar maximum, where there are relatively cloud-free conditions. The evaporated water vapor is transported to the western Pacific by the trade winds, enhancing the convection there and thereby increasing the strength of the Walker circulation. The enhanced surface easterlies drive a La Niña-like cold tongue in the eastern equatorial Pacific from the increased upwelling from the cold water below the thermocline. The signal appears in the sunspot peak years with dynamical coupled processes working on the timescale of El Niño-Southern Oscillation (ENSO), and those coupled dynamics then transition the tropical Pacific to a more El Niño-like pattern in the several years following the peak solar years. This La Niña-like pattern appears shortly after the rapid increase in solar activity from solar minimum to solar maximum, and is usually in evidence early in the broader solar maximum that lasts for several years. Thus, averaged over the several years of solar maximum, the initial La Niña-like pattern is not seen as strongly, and the El Niño-like pattern is more evident. The top-down mechanism related to stratospheric ozone also ends up strengthening tropical convection and precipitation, with the result that the same coupled air-sea dynamics produce responses similar to that for the bottom-up mechanism. Therefore, Meehl concluded, in the models the top-down and bottom-up mechanisms reinforce each other and work in the same sense to give measurable signals in sea surface temperature and precipitation in the tropics, with connections to midlatitude circulation (i.e., an anomalous high-pressure region in the North Pacific that extends to parts of North America).

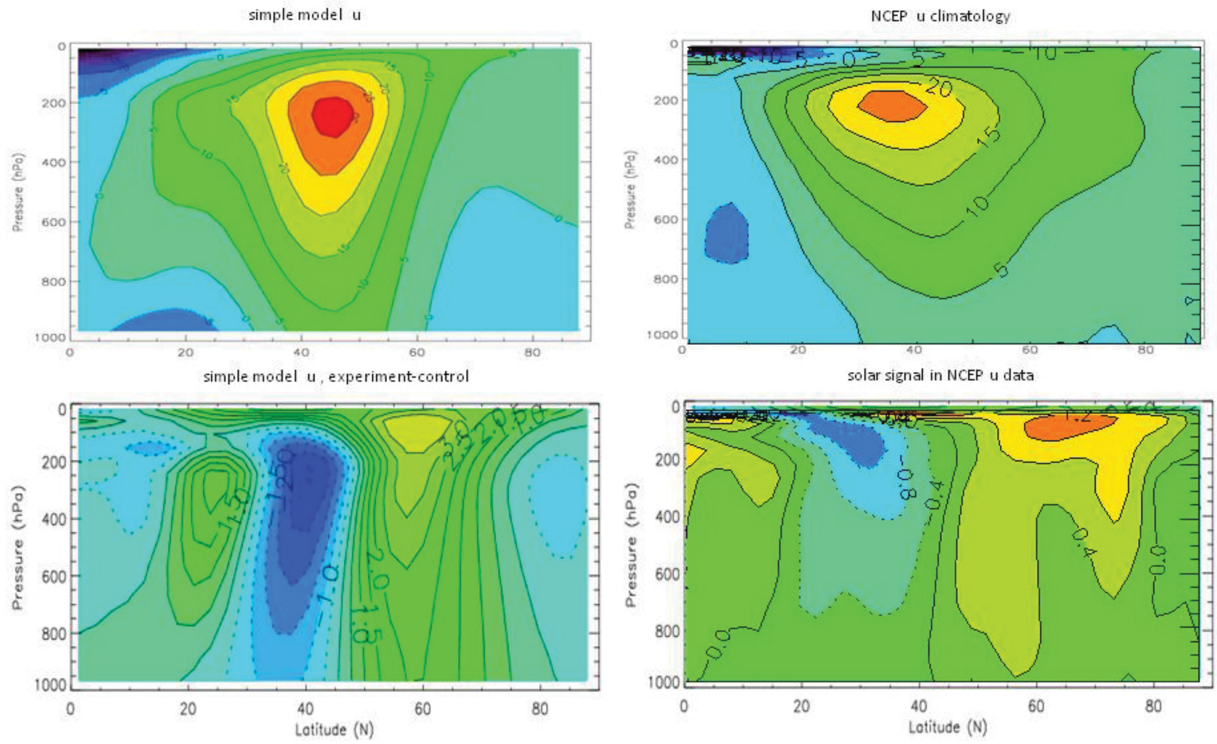

FIGURE 2.7 Northern hemisphere zonal and annual mean zonal wind (m/s) as a function of latitude and atmospheric pressure. *Top row, right:* climatology from National Centers for Environmental Prediction (NCEP) Reanalysis data set; *left:* climatology from a simplified climate model. *Bottom row, right:* solar 11-year-cycle signal from a multiple regression analysis of NCEP data; *left:* response in a simple model to heating applied (only) in the tropical lower stratosphere. Both sets of panels show a weakening and poleward shift in the westerly jet. This figure does not present a model simulation of solar effects but demonstrates that a thermal perturbation to the stratosphere can produce similar patterns in tropospheric response, giving indications as to potential mechanisms for a solar influence on climate. SOURCE: J. Haigh, M. Blackburn, and R. Day, The response of tropospheric circulation to perturbations in lower-stratospheric temperature, *Journal of Climate* 18:3672-3685, 2005; © Copyright 2005 American Meterological Society (AMS).

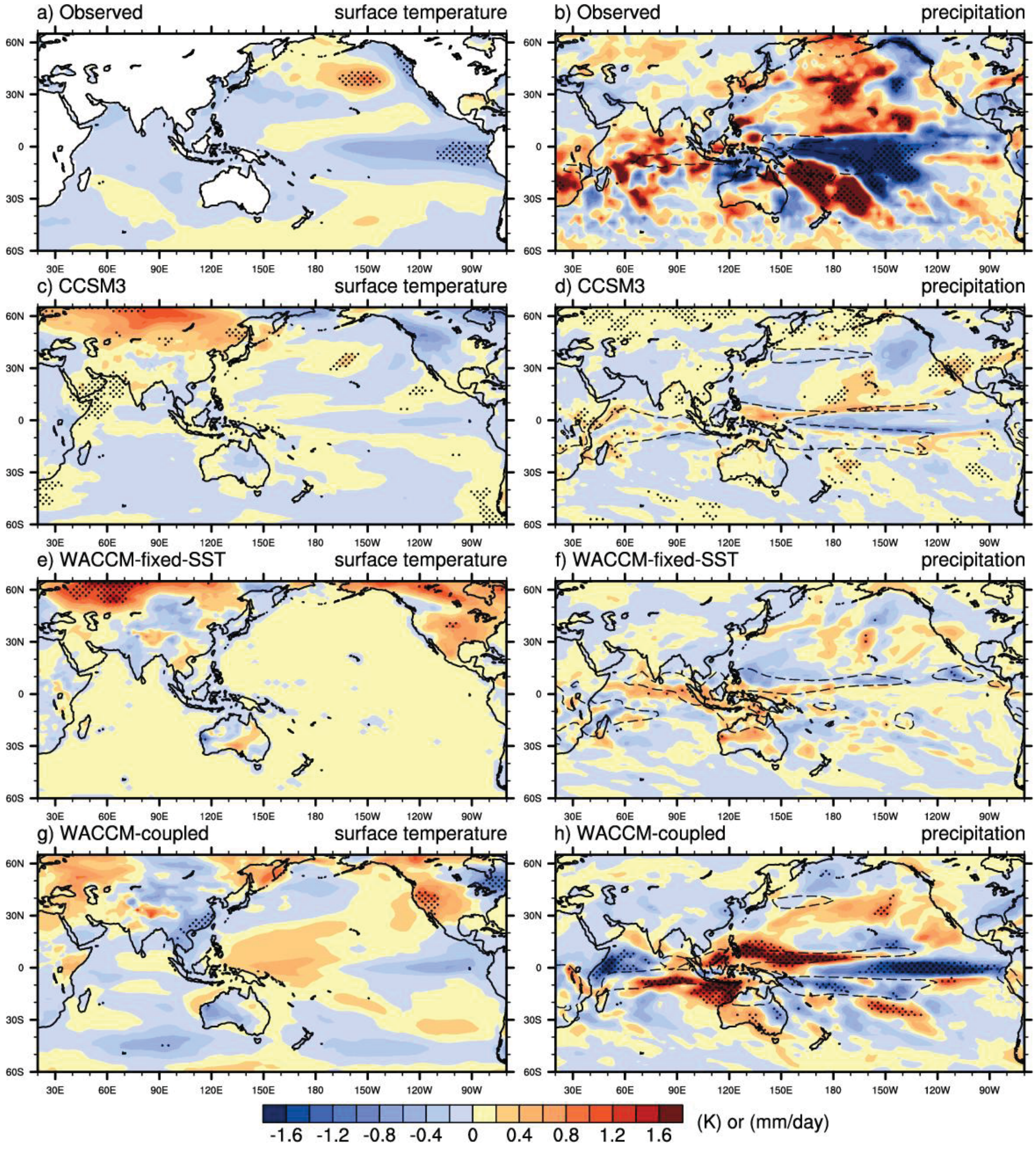

FIGURE 2.8 Composite averages for December-January-February for peak solar years (a,b). Observed, bottom-up coupled air-sea mechanism only (c,d); top-down stratospheric-ozone mechanism only (e,f); and both bottom-up and top-down mechanism (g,h). SOURCE: G.A. Meehl, J.M. Arblaster, K. Matthes, F. Sassi, and H. van Loon, Amplifying the Pacific climate system response to a small 11 year solar cycle forcing, *Science* 325:1114-1118, 2009; reprinted with permission from AAAS.

The Impact of Energetic Particle Precipitation on the Atmosphere
Charles Jackman, NASA Goddard Space Flight Center

Charles Jackman reported on solar energetic precipitating particles (EPPs), which are electrons and protons generated by solar flares, coronal mass ejections, and geomagnetic storms. They precipitate in Earth's polar regions, where they enhance the production of HO_x and NO_x that destroy ozone in the mesosphere and upper stratosphere (Figure 2.9). Because of the relatively short lifetime of HO_x constituents, most of the atmospheric and climate-relevant EPP focus is on NO_x. Solar protons and electrons have episodic seasonal and solar cycle influence on the polar mesosphere. Measurements and models show that in years when significant winter-time meteorological events occur, EPP-enhanced NO_x is transported from the upper mesosphere and lower thermosphere to lower altitudes where their impact may last several months, decreasing ozone by a few percent. There may even be a top-down effect where by EPP-NO_x induced ozone destruction leads to changes in surface air temperature. Jackman noted that there may be a coupling between electron impact and climate,[28,29] but that these findings need further work and affirmation. Jackman stated that GCRs (primarily protons and alpha particles) also create NO_x and HO_x but at lower altitudes due to their higher energy compared to solar particles. Because the incidence of GCRs varies inversely with solar activity, their effects on stratospheric chemistry tend to be out of phase with those of EPPs. Including GCRs in models results in an increase (relative to no GCRs) in NO_y of 10-20 percent in the lower stratosphere, with the greatest effects at high latitudes, and a decrease is stratospheric ozone by around 1 percent. However, a GCR-driven solar-cycle variation in polar NO_y is less than about 5 percent (greater at solar minimum than at solar maximum), resulting in annually averaged variations in polar ozone of less than 0.06 percent.

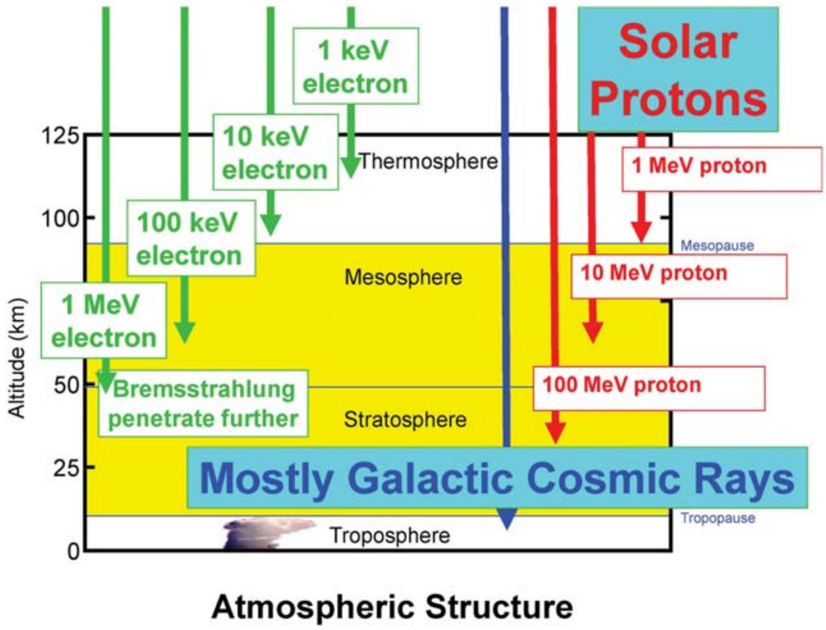

FIGURE 2.9 The atmospheric structure with incoming galactic cosmic rays and solar protons. SOURCE: C. Jackman, NASA Goddard Space Flight Center, "The Impact of Energetic Particle Precipitation on the Atmosphere," presentation to the Workshop on the Effects of Solar Variability on Earth's Climate, September 9, 2011.

[28] E. Rozanov, L. Callis, M. Schlesinger, F. Yang, N. Andronova, and V. Zubov, Atmospheric response to NO_y source due to energetic electron precipitation, *Geophysical Research Letters* 32:L14811, 2005.

[29] A. Seppälä, C.E. Randall, M.A. Clilverd, E. Rozanov, and C.J. Rodger, Geomagnetic activity and polar surface air temperature variability, *Journal of Geophysical Research* 114:A10312, 2009.

Cosmic Rays and Cloud Nucleation

Jeffrey Pierce, Dalhousie University, Halifax, Nova Scotia

Evidence of a correlation between GCRs and climate via their influence on cloud cover has been debated, but insight into potential underlying physical mechanisms is providing a better understanding of the types of studies required to better quantify any impact. According to Jeffrey Pierce, there are two potential GCR-cloud-climate pathways:

1. GCRs enhance aerosol nucleation rates and cloud condensation nuclei concentrations through ionization of gases. These changes modify cloud formation, cloud amount, and subsequently, the shortwave radiation reaching the surface.
2. GCRs impact precipitation through the modification of near-cloud electrification with subsequent impact on the freezing of supercooled liquid droplets. Processes in this category could alter the global electrical circuit with potential but as yet unknown mechanisms.

Pierce noted that the first mechanism has been studied in far greater detail. International Satellite Cloud Climatology Project cloud analysis has suggested a 2 percent absolute change in cloud amount over the solar cycle, which corresponds to a 6 percent relative change.[30] Although there is a 5-20 percent change in GCR-induced ionization in the troposphere over the solar cycle, this results (due to a number of dampening factors) in a smaller increase in nucleation rates, an even smaller increase in cloud condensation nuclei, and finally, a still smaller change in cloud amount. Thus it appears that the ion-aerosol clear-sky mechanism is too weak to explain the observed cloud changes, even with favorable assumptions for model inputs. Pierce asserted that a number of controlled experiments are necessary to better assess both the ion-aerosol hypothesis and the near-cloud hypothesis.[31]

[30] K.S. Carslaw, R.G. Harrison, and J. Kirkby, Cosmic rays, clouds and climate, *Science* 298:1732-1737, 2002.
[31] See also discussion by Daniel Baker, above.

3
Panel Discussion

The final workshop session was a discussion led by chairs of the sessions, and all participants were encouraged to share their thoughts on the open research questions in these fields. The principal topics for discussion were as follows:

- *Solar irradiance variability (total solar irradiance [TSI] and spectral).* What do we know about TSI variability now and in the past?
- *Sun-climate connections on different timescales.* What do we know about the variability of climate on global and regional spatial scales on timescales of years, decades, and longer?
- *Mechanisms for Sun-climate connections.* Do we understand and have we correctly modeled the top-down, bottom-up, galactic cosmic ray forcings and chemical couplings that determine the system response?

The discussion was led by Joanna Haigh; Daniel Baker was the facilitator. The panel members—Joe Giacalone, Ka-Kit Tung, Isaac Held, and Peter Pilewskie—were the chairs of the four workshop sessions (with the exception of Joe Giacalone, who stood in for Peter Foukal).

The basic question in understanding the Sun's role in climate change is a compelling one: How well is past and present total solar irradiance known and understood? As Haigh pointed out, it is certainly an issue of concern that the existing TSI database has been derived from measurements that could not be intercalibrated to the degree of accuracy necessary for climate studies.

Giacalone led off the panel discussion by providing an overview of what he felt were the key issues, stating that understanding the Sun's role in climate is an important and compelling issue. The research community has to understand the Sun's variability and how it can be tied to proxy measurements, and with what degree of accuracy. Greg Kopp pointed out that understanding the Sun, its output, and the various proxies used to infer its output may inform the ability to specify the accuracy of back-projections of paleo-TSI based on various proxies (including sunspot number). Mark Rast pointed out the difficulty of the issue, given that simplifying assumptions are currently made about the relationship between sunspots, faculae, and TSI when in fact modern observations have indicated that the situation is really quite complex.

Baker questioned the audience for key steps that NASA and the National Science Foundation (NSF) can pursue to address these questions. Rast responded that radiometric imaging of the Sun is important not only to extrapolate irradiance, but also to understand the substructure of the magnetic field and its relationship to spectral irradiance. Giacalone and others also pointed out as a research area that needs to be more fully understood the relationship between the galactic cosmic-ray flux and details of the interaction with the variable solar wind and magnetic field configuration. He and other audience members noted that now, as the extended solar minimum ends, would be an excellent time to study this phenomenon. Philip Judge suggested that, at the moment, the research is limited by time series length and that it will be necessary to continue with accurate measurements in the future. Giacalone posed the question of whether other potential proxy records exist, for example from Mars or a meteorite.

Tung led a discussion that reflected the talks and comments from the audience on the issues surrounding the modeling of past climate events. He noted that, when viewed from the perspective of the global response, there is a coherent structure of predictable patterns in latitude, longitude, height, and three-dimensional spatial domains that may change with changing external or internal forcing terms. Much of the emphasis in climate and especially paleoclimate studies has been on the global mean response. There will, however, be significant changes as a function of height, local time, latitude, longitude, and season. The troposphere tends to respond as a whole to changes in radiative forcing owing to the action of moist convection, and there are coherent patterns to high-latitude response (warming) to the movement of storm tracks and to precipitation patterns.

Tung also noted that workshop participant Gerald Meehl had shown that there is a huge response in the equatorial Pacific to variations in solar-cycle flux, cooling of almost 1 degree, which is 10 times what might be expected from solar heating, at the solar peak years, relative to the average climatology, and that Meehl could reproduce this finding in global climate models with the mechanism of positive feedback using clouds. Held pointed out that one of the fundamental questions is whether the Pacific climate system plays a role in amplifying the response of Earth's climate system to changes in the solar signal. He expressed his doubts that the Pacific Ocean El Niño-Southern Oscillation-like dynamic is strongly involved in the response to the solar cycle. Tung summarized another mechanism discussed in Meehl's presentation, the top-down stratosphere ozone mechanism, in which increased levels of radiation lead to increased ozone heating and ozone production, which modifies the temperature and zonal wind in the stratosphere, which in turn alters wave propagation. In addition, warming in the tropical lower stratosphere changes vertical convection in the tropics, and can shift the Hadley circulation and storm tracks. Some members of the audience and panel felt that answering the question about the effects on the Pacific climate system may require spectrally resolved measurements of the solar irradiance rather than just of the TSI. The role of top-down forcing is an evolving research question. Pilewskie proposed that since this is a multidisciplinary problem, it would be beneficial to establish a cooperative program between NASA and NSF as has been done previously for specific problems. In addition, he suggested a standardization of data used for models as well as wide availability of data to the public. Other participants voiced support for this suggestion as well.

A discussion of the nature of the comparison of model predictions evolved from the review of the results of the talks. The principal issue is that when model results and observations are compared, three effects have to be clearly delineated: (1) variation in the TSI, (2) variation in the shape and magnitude of the spectral distribution of the solar flux, and (3) the time-dependent behavior of changes caused by aerosol events (e.g., eruptions of volcanoes). The need for coherent and well-defined model intercomparisons was also stressed.

Held then reviewed the results of session 2 of the workshop, summarizing four themes that he saw as emerging from the talks: (1) there is a spatially coherent picture of past climate emerging from the proxy-based studies; (2) there should be a broad-based study of the available proxy data to look at the amplitude and phase of the deduced solar flux variation; (3) trying in historical studies to separate the effects of changes in TSI from the effects of volcanoes and greenhouse gases in historical studies is fraught with difficulty, and the community needs to be very careful in understanding the error budget associated with this process; and (4) modeling studies are needed of the stratospheric response, the ozone response to the solar cycle, and how those responses penetrate into the troposphere.

With respect to point 1 the spatially coherent picture emerging from proxy studies was one of cooler temperatures at high northern latitudes, weaker monsoons, and reduced seasonal movement of the intertropical convergence zones. Caspar Ammann felt that, when considering the correlation of the response of different regions to changes in TSI, if the community is interested in looking at a solar response in the system, the general response of the internal variability must be considered: What is systematic in how the internal variability might be modulated, either in phase or in amplitude, or even in some of its spatial expression, through the solar cycle?

Pilewskie summarized the fourth session as consisting of an investigation of the role of energetic particles of both solar and extrasolar origin, with a contribution from Dan Lubin on the need for understanding solar spectral variability through observations of other Sun-like stars. In his presentation, Charles Jackman had focused mostly on solar particles and their influences on the middle atmosphere and potentially on climate, and Jeffrey Pierce's talk described the influence of galactic cosmic rays on clouds via two mechanisms—nucleation impacts and changes in the fair weather electric circuit of the atmosphere. A central question is then, Where does the role of energetic particles fit in the effort to understand the influence of the Sun on climate? The discussion among several workshop participants indicated that although TSI is the main driver of response, there is the question of whether smaller (in terms of energy) perturbations can have a tangible effect on climate and by what mechanisms, and whether that impact might show a significant location dependence.

The panel discussion concluded with a general discussion of whether the workshop had addressed the issues raised by NASA and NSF—what is known about the role of the Sun in determining climate, and what are the future research directions? During the discussion period, several workshop participants stated that many of the major issues had been aired in the workshop but that significant and important work remained. In addition, participants discussed what sorts of investments agencies could make now with available resources in, for example, improving existing data sets, versus continuing measurements or starting new measurements or new observations, or making new investments in modeling efforts to address these open issues. Suggestions included looking at model studies in a systematic way; examining the paleoclimate record to see whether there were natural oscillations in the system that could result in the system transitioning from one mode to another; developing an understanding of the inherent timescales in the system and the feedbacks that might amplify effects; determining through model or data studies if there are certain regions that are more susceptible to solar influence on climate; evaluating the quality of the past record of environmental response to establish a better chronology; or developing a better understanding of the issues associated with some of the proxies used in studying the Sun-climate linkage.

At the end of the panel discussion Gerald North summarized the issues that were developed during the workshop. He made three principal points:

1. NASA has led the way in providing a model for ready access to data from many sources—the challenge is to provide better access to paleoclimate data while recognizing the effort it takes to acquire and archive those data in a form accessible to the community.
2. Coupled models, with their inherent complexity, are the future and need to be used more widely for well-designed studies. It is fortunate that climate modeling has advanced to the point that such projects can be undertaken with some confidence.
3. The directly measured record is limited and not without its issues, and so the challenge is to make sure that a means is developed to infer the time history of TSI variability and the limitations on the ability to specify that past behavior.

North also summarized other issues that he felt had been addressed during the workshop and that were particularly noteworthy. Those issues included, among others, the need to be careful in making inferences from the isotope record, which may reflect influences of atmospheric circulation; the need to understand the role galactic cosmic rays may play in cloud nucleation; and the influence of variations in geomagnetic field on the paleo-climate record. North noted that Peter Foukal's discussion of the Sun was particularly interesting because of the unresolved issues with understanding variability and the sources of variability in TSI arising from the details of the quiet network. Also, a better understanding is needed of how solar brightness, TSI, and the spectral and spatial distribution of energy are affected by the faculae and the dynamics of the Sun.

Appendixes

A
Statement of Task and Preliminary Workplan

STATEMENT OF TASK

An ad hoc committee will plan and conduct a public workshop that will examine the state of knowledge regarding the climate response to solar variability and will explore some of the outstanding scientific issues that might guide future research thrusts.

The committee will hold a data-gathering meeting in the process of developing the agenda for the workshop and defining the specific topics for invited presentations and discussions. The committee will subsequently select and invite speakers and other participants and moderate the discussions at the event. The committee will prepare a workshop report that will summarize what transpired at the event but will not contain any findings or recommendations.

PRELIMINARY WORKPLAN

The committee will consist of 10-14 people who will meet once in person in early summer 2010 to plan the workshop, which will be open to the public. The workshop itself will be held in late fall 2010 over 3.5 days and will include approximately 25 invited participants. After the workshop, a short summary report without findings or recommendations will be produced.

Prior to its first meeting, the organizing meeting will review with the study sponsors and with the director of the Board on Atmospheric Sciences and Climate potential topics for discussion at the workshop. Based on discussions to date with NASA, the following is a tentative list of questions to be addressed at the workshop:

- What part of observed atmospheric variability is in response to solar forcing, particularly in the lower atmosphere? Are attributed signals consistent over different timescales?
- What are the associations between sunspots or cosmogenic isotopes and the magnitude of solar irradiance changes in the past?
- If long-term solar irradiance variations are insufficient to impact climate, were other solar-modulated parameters, such as galactic cosmic-ray flux, responsible for the reported paleo Sun-climate connections?
- Is empirical evidence sufficient to conclude that the spatial response in climate models is consistent or not? What does the evidence imply about the relative roles of the Sun and greenhouse gases (GHGs) in past, present, and future climate change, and what does this mean for projections of regional climate response to other radiative forcings, such as GHGs?
- What are the research directions and model extensions necessary to improve the models, using solar forcings and observed climate responses to test their fidelity?
- Are the long-standing concepts of radiative forcings and responses that are the basis for the models adequate to accommodate the actual physical processes?
- What are the research needs in the near term to inform the next Intergovernmental Panel Climate Change assessment?

B
Workshop Agenda and Participants

AGENDA

September 8, 2011

8:45 a.m. Welcome — *Gerald R. North, Texas A&M University*

Session 1

9:00 Overview and Advances in Radiometry for Solar Observations
Greg Kopp, University of Colorado, Boulder

10:00 Assessing Solar and Solar-Terrestrial Influences as a Component of Earth's Climate Change Picture
Daniel N. Baker, University of Colorado, Boulder

11:00 Heliospheric Phenomena Responsible for Cosmic Ray Modulation at the Earth
Joe Giacalone, University of Arizona

11:45 Behavior of Quiet Sun Contributions to Solar Irradiance
Peter Foukal, Heliophysics, Inc. (by WebEx), Session Chair

12:30 p.m. Lunch

1:15 The Record of Solar Forcing in Cosmogenic Isotope Data
Raimund Muscheler, Lund University, Sweden

Session 2

2:00 Issues in Climate Science Underlying Sun/Climate Research
Isaac M. Held, NOAA GFDL, Session Chair

3:00 Indirect Climate Effects of the Sun Through Modulation of the Mean Circulation Structure
Caspar Ammann, National Center for Atmospheric Research

4:00	Climate Response to the Solar Cycle as Observed in the Stratosphere	*Lon Hood, University of Arizona*
4:45	Direct Solar Forcing of the Lower Atmosphere and Ocean	*Gerald A. Meehl, National Center for Atmospheric Research*
5:30	Adjourn for the day	

September 9, 2011

Session 3

9:00 a.m.	Detection of the Solar Signal in Climate from Paleorecords	*Raymond S. Bradley, University of Massachusetts*
9:45	Detecting the Solar Cycle Via Temperature Proxies Back to the Maunder Minimum	*Gerald North, Texas A&M University*
10:45	Climate Response at Earth's Surface to Cyclic and Secular Solar Forcing	*Ka-Kit Tung, University of Washington, Session Chair*
11:40	Solar Effects Transmitted by Stratosphere-Troposphere Coupling	*Joanna D. Haigh, Imperial College, London*
12:25 p.m.	Lunch	

Session 4

1:30	The Impact of Energetic Particle Precipitation on the Atmosphere	*Charles Jackman, NASA Goddard Space Flight Center*
2:15	Cosmic Rays and Cloud Nucleation	*Jeffrey Pierce, Dalhousie University*
3:00	Solar Grand Minima Inferred from Observations of Sun-like Stars	*Dan Lubin, Scripps Institution of Oceanography, University of California, San Diego*

Panel Discussion

3:45	Panel Discussion led by Joanna Haigh and Daniel Baker

1. What is the most recent and/or most compelling evidence of the impact of solar variability on climate, particularly in the lower atmosphere, over decadal timescales?
2. What can we learn of the variability of solar irradiance using paleoclimate records?
3. What can we learn of climate responses to solar variability using paleoclimate records?
4. Are there any significant climate impacts of solar variability on regional scales?
5. What are the research directions, additional observations, and/or model improvements necessary to improve understanding and forecast ability regarding solar variability and climate, particularly over the solar cycle timescale?

5:00	Closing Remarks	*Gerald North, Texas A&M University*
5:30	Workshop adjourns	

PARTICIPANTS

Caspar Ammann, National Center for Atmospheric Research
Susanne Benze, University of Colorado, Boulder
Blair Bowers, Caset Associates, Ltd.
Matthias Brakesusch, University of Colorado, Boulder
Gabriel Chiodo, Universidad Complutense de Madrid
Odele Coddinggon, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder
Guiliana de Toma, High Altitude Observatory, National Center for Atmospheric Research
Ells Dutton, Global Monitoring Division, National Oceanic and Atmospheric Administration
Juan Fontenla, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder
Joe Giacalone, University of Arizona
Sarah Gibson, High Altitude Observatory, National Center for Atmospheric Research
Douglas Gough, JILA, University of Colorado, Boulder
Madhulika Guhathakurta, Living With a Star, National Aeronautics and Space Administration
Jerald Harder, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder
V. Lynn Harvey, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder
Lon Hood, University of Arizona
Charles Jackman, NASA Goddard Space Flight Center
Philip Judge, High Altitude Observatory, National Center for Atmospheric Research
Farzad Kamalabadi, University of Illinois at Urbana-Champaign
Peter Kiedron, Earth System Research Laboratory, National Oceanic and Atmospheric Administration
Hyosub Kil, Applied Physics Laboratory, Johns Hopkins University
Greg Kopp, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder
Andrew Kren, University of Colorado, Boulder
Hanli Liu, High Altitude Observatory, National Center for Atmospheric Research
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Abigail Sheffer, Space Studies Board
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Amanda Thibault, Aeronautics and Space Engineering Board
Terri Baker, Space Studies Board

C
Abstracts Prepared by Workshop Speakers

Overview and Advances in Solar Radiometry for Climate Studies

Greg Kopp, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder

The Sun provides nearly all the energy driving Earth's climate system. Even typical short-term variations of 0.1 percent in this incident irradiance exceed all other energy sources combined. The 33-year space-borne total solar irradiance (TSI) measurement record, shown in Figure C.1, enables estimates of the portion of climate change due to solar variability on global and regional scales. Extensions of this modern record via proxies provide historical estimates of long-term solar variability and the corresponding climate effects. Daily spectral solar irradiance (SSI) measurements over the majority of the solar spectrum commenced a few years ago and show promise for helping researchers understand heating, circulation, and chemistry effects in Earth's atmosphere.

To discern natural and anthropogenic effects, climate studies require long-term records of incident solar irradiances. For TSI, the net radiative energy driving Earth's climate system, these are based on the space-borne measurements shown in Figure C.1. The offsets between these measurements, which are as large as 0.34 percent currently, are due to instrument calibration differences. Recent laboratory tests by the international teams involved in these measurements have identified the primary cause of these measurement offsets, helping improve the existing record retroactively. Such offsets, along with differing instrument drifts, must be corrected to create a composite TSI record having the accuracy and stability needed for reliable climate studies and estimates of Earth's radiative energy balance.

I will give an overview of solar irradiance measurements and recent progress to improve this record's accuracy. Using estimates of solar variability over long-term timescales relevant for climate studies, I will derive the record's accuracy and stability requirements and assess the current status for achieving these requirements, comparing to recent solar minima as examples. By extending the record via proxies to paleo timescales, I will discuss estimates of climate sensitivity to solar forcing over recent and historical times. I will also present the current state of the instruments acquiring these measurements and the planned future means of continuing the TSI record as well as the newer SSI measurements.

Assessing Solar and Solar-Terrestrial Influences as a Component of Earth's Climate Change Picture

Daniel N. Baker, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder

Researchers have long been intrigued by questions about how solar variability and related solar-terrestrial influences can affect Earth's middle and lower atmosphere. A goal of basic research programs has been to establish a comprehensive intellectual foundation for the investigation of the effect of solar variability on climate. It is clear that conclusive observations of cause-effect relationships (at the requisite level of confidence) are a very large challenge. Satisfactory work in this arena requires close collaboration between solar, magnetospheric, and atmospheric scientists. It is important to note that new generations of atmospheric models now are able to couple together all the layers of Earth's extended atmosphere. Through such models, and with increasingly complete observations, we are in a steadily

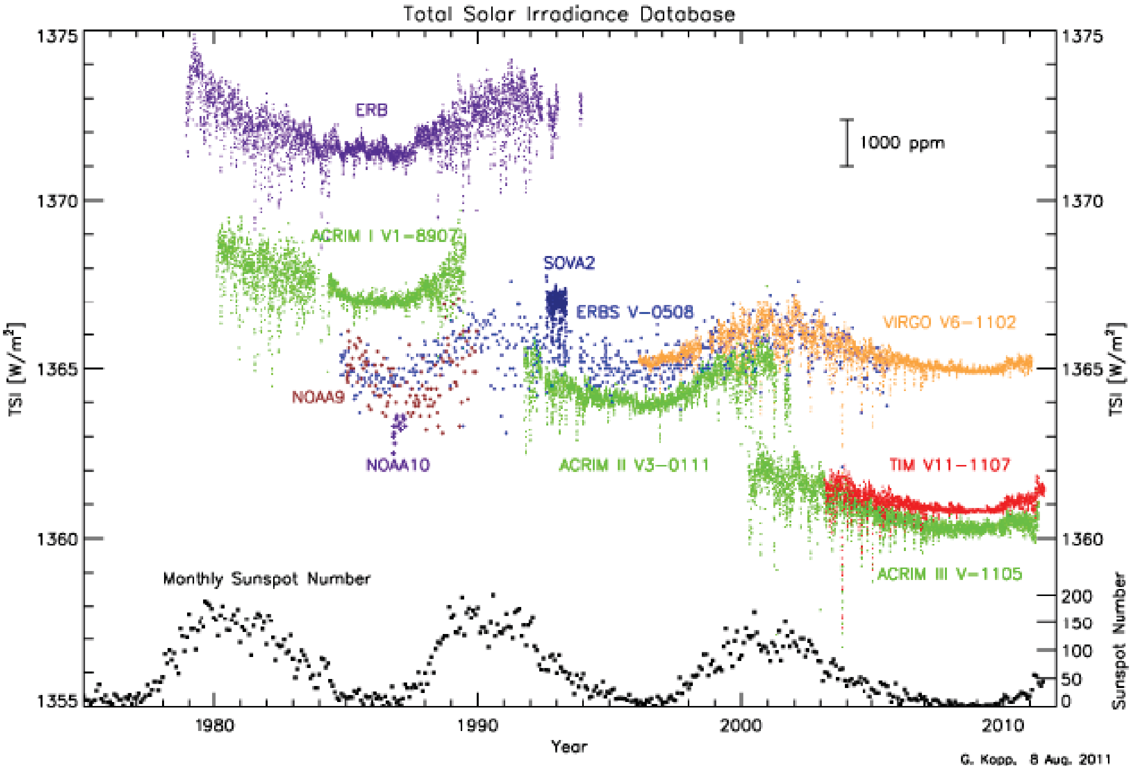

FIGURE C.1 The 33-year total solar irradiance (TSI) record is the result of measurements made by several instruments. Measurement overlap helps correct for the majority of the differences between instruments, but improved instrument calibrations are needed to provide the required accuracies and stabilities in this solar climate data record for reliable climate studies. SOURCE: Courtesy of G. Kopp, University of Colorado.

improving position to understand the complex (and often subtle) ways that solar influences at high altitudes affect the lower atmosphere. This talk will discuss long-standing questions and recent progress in understanding this crucial aspect of the Sun-Earth connection.

Heliospheric Phenomena Responsible for Cosmic Ray Modulation at the Earth

Joe Giacalone, Department of Planetary Sciences, University of Arizona, Tucson

Galactic cosmic rays (GCRs) are essentially uniform in the space immediately outside Earth's heliosphere and penetrate the solar system with very nearly equal probability from all directions. The GCR spectrum there is a smooth power law in energy over several decades. As they enter the solar system, GCRs suffer both spectral and intensity variations resulting from their interaction with the solar wind, interplanetary magnetic field, and heliosphere. The GCR intensity is known to anti-correlate with the number of sunspots on the Sun—having a higher intensity when there are few sunspots. This anti-correlation is the basis for using cosmogenic nuclei deposited in tree rings and ice cores as a proxy measure of solar activity dating back thousands of years.

In addition to the well-known 11-year cosmic-ray cycle, there is also a 22-year variation related to the polarity of the solar magnetic field. These variations can be interstood using the physics of charged-particle motion in turbulent electric and magnetic fields associated with the solar wind plasma. This talk will review the understanding of the physics of cosmic-ray transport, focusing primarily on the causes of the modulation of GCRs in the solar system. It will also discuss observations of cosmic rays from the recent long and deep sunspot minimum.

Recent Findings on Dimming of the 17th Century Sun

Peter Foukal, Heliophysics, Inc.

Sunspots and faculae modulate solar convective heat flow and total solar irradiance over the 11-year activity cycle. The amplitude of this modulation attains 0.09 percent in annual means during the largest recorded solar cycle that peaked around 1957. The rising envelope of this modulation, caused by the increase in spots and faculae observed since the beginning of regular collection of sunspot data around 1700, sets a lower limit of about 0.04 percent to the 11-year smoothed TSI increase over the intervening 2.5 centuries.

Additional solar dimming might have occurred during the 17th century if the area covered by the small-diameter, bright photospheric magnetic flux tubes of the quiet Sun decreased during the extended Maunder Minimum of solar activity between about 1645 and 1715. Their contribution sets the zero level of TSI at activity minima. Evidence for their disappearance and for a resulting additional 0.2 percent dimming during the Maunder Minimum was put forward, based on stellar photometry.[1] That stellar photometry evidence was retracted in 2002, but this does not necessarily mean that the dimming did not occur.

New findings from solar photometry indicate that the TSI-effectiveness per unit area of these small flux tubes increases with decreasing cross sectional area. So the progressive removal of ever-smaller flux tubes with declining solar activity during an extended minimum would dim the Sun more than expected from standard irradiance models. Such models linearly extrapolate the irradiance contribution of larger active region faculae, to the smaller flux tubes of the quiet Sun.

These findings[2] make it more likely that the 17th century Sun might have dimmed by a climatologically significant (~ 0.2 percent) amount without requiring complete disappearance of photospheric magnetism. Such partial disappearance would agree better with radioisotope evidence that a weakened 11-year cycle persisted throughout the Maunder Minimum. Improved observations are under way to accurately measure the uncertain TSI contribution of the quiet Sun flux tubes down to sizes barely resolvable with the largest solar telescopes.[3]

Also, it remains to be seen whether 17th century photospheric magnetism weakened below the level observed during normal 11-year activity minima.[4] During the extended activity minimum of 2008-2009, the main indices such as F10.7 and Mg II dipped several percent below their preceding 11-year minima. These anomalous dips during a minimum only about 1 year longer than normal, suggest that magnetism during a minimum extending for 70 years would have decayed well below quiet Sun levels. However, examination of this important conclusion using, for example, improved ^{10}Be radioisotope evidence is desirable.

This work has been supported by NASA Living With a Star grants NNX09AP96G and NNX10AC09G.

[1] J. Lean, A. Skumanich, and O. White, Estimating the Sun's radiative output during the Maunder Minimum, *Geophysical Research Letters* 19(15):1591, 1992.

[2] P. Foukal, A. Ortiz, and R. Schnerr, Dimming of the 17th Century Sun, *The Astrophysical Journal Letters* 733:L38, 2011.

[3] R. Schnerr and H. Spruit, The brightness of magnetic field concentrations in the quiet Sun, *Astronomy and Astrophysics* 532:A136, 2011.

[4] C. Schrijver, W. Livingston, T. Woods, and R. Mewaldt, The minimal solar activity in 2008-2009 and its implications for long-term climate modeling, *Geophysical Research Letters* 38: L06701, 2011.

The Record of Solar Forcing in Cosmogenic Isotope Data

Raimund Muscheler, Department of Earth and Ecosystem Sciences, Division of Geology, Lund University, Sweden

Cosmogenic radionuclides are the most reliable proxies for reconstructing solar activity variations thousands of years back into the past. Several characteristics of solar activity variations have been identified in these records. These range from longer-term solar cycles (e.g., the 207-year cycle), the bundling of solar minimum periods and possible longer-term changes in solar activity. Recently an increasing number of studies have attempted quantitative reconstructions of solar activity changes based on radionuclide records.[5,6,7,8]

Disagreements between some of the results illustrate the difficulties in isolating the solar signal from ice core ^{10}Be and tree-ring ^{14}C records. The challenges consist in identifying influences of weather and climate on cosmogenic radionuclide records. Failure to correctly identify a climate impact in cosmogenic radionuclide records could lead directly to an erroneous inference of a solar influence on climate. Moreover, the geomagnetic influence has to be corrected for. For quantitative estimates of absolute solar activity levels one has to correctly normalize the records and, in addition, there are different estimates of the intergalactic cosmic ray spectrum. Depending on the applied spectrum one can obtain different results.

Figure C.2 illustrates the potential and the problems of cosmogenic radionuclide-based reconstructions of solar activity changes. It shows a reconstruction of the solar modulation function based on ^{10}Be and ^{14}C together with the group sunspot number reconstruction. The calculations are based on the production results from Masarik and Beer,[9] and the data are corrected for the geomagnetic dipole field intensity variations.[10] Figure C.2 shows that especially long-term changes in solar activity or absolute levels of solar activity are uncertain. Depending on the geomagnetic field correction and the interpretation of the radionuclide records one can get significant differences in the results. The same applies to the past 100 years, which is a crucial period for connecting the radionuclide records to observational data. For this period the ^{14}C record includes the difficulty of an anthropogenic influence due to fossil fuel burning[11] and nuclear weapon tests. ^{10}Be records for the last century show differences between Greenland and Antarctica that add to the normalization uncertainty.[12]

Nevertheless, there is an agreement between different radionuclide records for the majority of the supposed solar minimum periods during the past 10,000 years (see Figure C.2) and there is good qualitative agreement with the sunspot record. Improvement in geomagnetic field reconstructions, new knowledge about the intergalactic cosmic-ray spectrum, additional radionuclide records, and improved knowledge about the geochemical behavior of ^{14}C and ^{10}Be can reduce the

[5] R. Muscheler, F. Joos, J. Beer, S.A. Mueller, M. Vonmoos, and I. Snowball, Solar activity during the last 1000 yr inferred from radionuclide records, *Quaternary Science Reviews* 26(1-2):82-97, 2007.

[6] S.K. Solanki, I.G. Usoskin, B. Kromer, M. Schüssler, and J. Beer, Unusual activity of the Sun during recent decades compared to the previous 11,000 years, *Nature* 431:1084-1087, 2004.

[7] F. Steinhilber, J.A. Abreu, and J. Beer, Solar modulation during the Holocene, *Astrophysics Space Science Transactions*, 4:1-6, 2008.

[8] M. Vonmoos, J. Beer, and R. Muscheler, Large variations in Holocene solar activity: Constraints from ^{10}Be in the Greenland Ice Core Project ice core, *Journal of Geophysical Research* 111:A10105, 2006.

[9] J. Masarik, J. Beer, Simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere, *Journal of Geophysical Research* 104(D10):12099-12111, 1999.

[10] S. Yang, H. Odah, and J. Shaw, Variations in the geomagnetic dipole moment over the last 12000 years, *Geophysical Journal International* 140:158-162, 2000.

[11] H.E. Suess, Natural radiocarbon and the rate of exchange of carbon dioxide between the atmosphere and the sea pp. 52-56 in *Proceedings of the Conference on Nuclear Processes in Geological Settings*, (National Research Council Committee on Nuclear Science, ed.), University of Chicago Press, Chicago, Ill., 1953.

[12] G.M. Raisbeck, and F. Yiou, Comment on "Millennium scale sunspot number reconstruction: Evidence for an unusually active Sun since the 1940s", *Physical Review Letters* 92(19):199001, 2004.

uncertainties in radionuclide-based solar activity reconstructions. With new high-resolution ^{10}Be and ^{14}C records there is the potential to track solar activity variations including the solar 11-year cycle more than 10,000 years back in time. In addition, there is the prospect that one can reliably reconstruct sustained levels of high or low solar activity. Cyclic variations in cosmogenic radionuclide records might allow researchers to estimate likely levels of future solar activity. For example, the suggestions of the dawn of a new Maunder Minimum-type solar minimum are based largely on extrapolation of the cyclic behavior visible in radionuclide records. However, without a better understanding of the solar dynamo these predictions seem rather speculative at the moment.

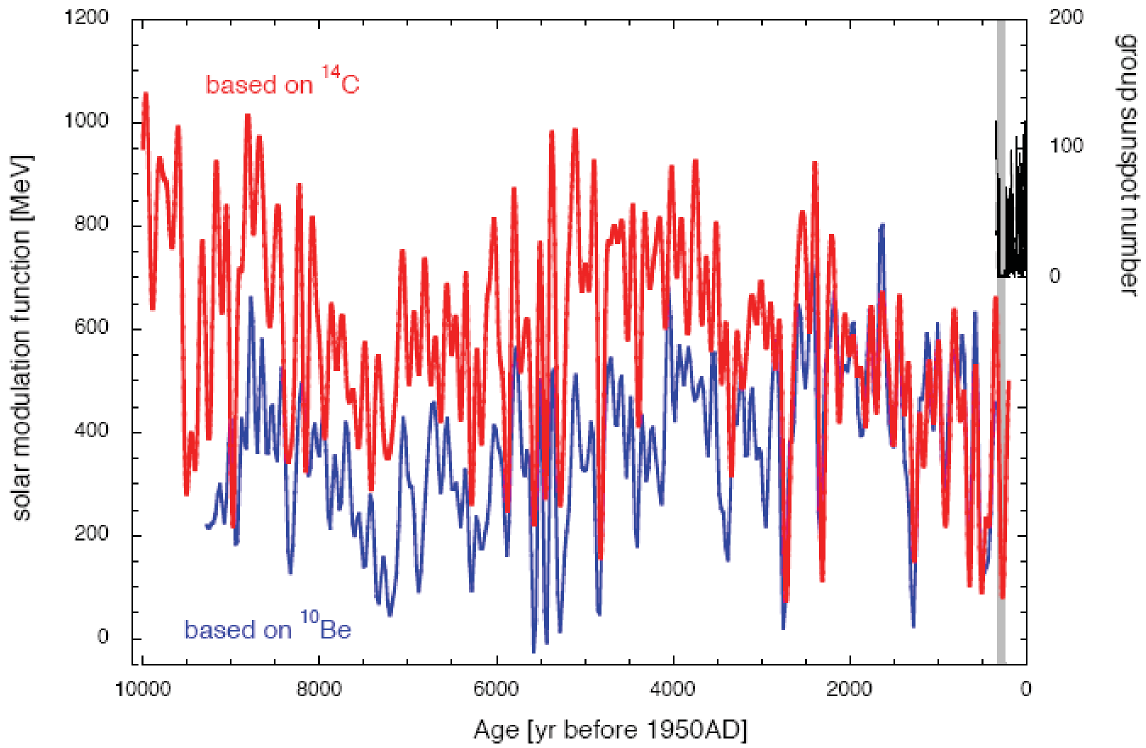

FIGURE C.2 Two estimates of variations in the solar modulation function inferred from an ice core ^{10}Be record (Vonmoos et al., 2006) and a tree-ring-based ^{14}C production record (Muscheler et al., 2004) together with the group sunspot number record for the past 400 years (Hoyt and Schatten, 1998). The so-called Maunder Minimum, which is characterized by an almost complete lack of sunspots, is highlighted with the grey shading. Both radionuclide-based records are low-pass filtered with a cut-off frequency of 1/100 yr-1. See M. Vonmoos, J. Beer, and R. Muscheler, Large variations in Holocene solar activity: Constraints from ^{10}Be in the Greenland Ice Core Project ice core, *Journal of Geophysical Research* 111:A10105, 2006; R. Muscheler, J. Beer, G. Wagner, C. Laj, C. Kissel, G.M. Raisbeck, F. Yiou, and P.W. Kubik, Changes in the carbon cycle during the last deglaciation as indicated by the comparison of ^{10}Be and ^{14}C records, *Earth Planet Science Letters* 219(3-4):325-340, 2004; and D.V. Hoyt, and K.H. Schatten, Group sunspot numbers: a new solar activity reconstruction, *Solar Physics* 179(1):189-219, 1998.
SOURCE: Raimund Muscheler, Lund University, “The Record of Solar Forcing in Cosmogenic Isotope Data,” presentation to the Committee on the Effects of Solar Variability on Earth’s Climate, September 8, 2011.

Issues in Climate Science Underlying Sun/Climate Research

Isaac Held, National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory

In this talk I will discuss some aspects of climate research that provide a wider context for analyses of the climatic effects of solar variability. I divide this discussion into three parts: bottom-up effects related to the energy balance of the troposphere; top-down effects related to effects on the troposphere of the state of the stratosphere; and the possibility of solar-modulated cosmic ray-induced nucleation on cloud cover.

I will first discuss the proposition that the troposphere acts as a strongly coupled system as it responds to changes in its energy balance, insensitive to the details of the spatial distribution of the forcing—especially in the vertical, and to a more limited extent, horizontally. This coupling underlies the utility of the concept of “radiative forcing.” I’ll discuss the standard conversion factor (doubling CO_2 ⇔ 2 percent change in insolation) that is a simple consequence of CO_2 radiative forcing estimates, and the classic experiments at the dawn of research on climate change with global climate models that showed very similar tropospheric responses to changes in the total solar irradiance and to changes in CO_2. The importance of the frequency-dependence of climate responses in relating greenhouse gas, volcanic, and solar cycle responses will be mentioned. Hydrological responses provide the most likely route through which to break away from a universal relationship between radiative forcing and response, and some geoengineering literature will be introduced in this context.

Stratospheric influences on the troposphere have been discussed in the context of research on the response to volcanoes, solar cycle ultraviolet forcing, the quasi-biennial oscillation, and, especially, the ozone hole—as well as in the long-range weather prediction context. I will describe an emerging picture of the mechanisms responsible for this coupling, especially in regard to coupling to the tropospheric annular modes and the central role played by meridional temperature gradients at the tropopause/lower stratosphere. I will argue that the ozone hole plus observed trends in Southern Hemisphere winds provides a useful quantitative check on models of this coupling, indicating in particular how large the perturbation to lower stratospheric temperature gradients needs to be to generate an observable effect.

Finally, I will briefly mention research on the indirect aerosol effects through which particles affect climate not by direct alternation of solar fluxes but by modifying cloud condensation nuclei. Observational and modeling studies of the susceptibility of cloud radiative properties to changes in cloud condensation nuclei are especially relevant as background for any discussions of conceivable solar activity-modulated cosmic ray ionization effects on cloud condensation nuclei and climate.

Indirect Climate Effects of the Sun Through Modulation of the Mean Circulation Structure

Caspar Ammann, National Center for Atmospheric Research

Solar irradiance changes have now been monitored from space for several decades. Based on the collected data, there are no clear indications that the total irradiance changes might have varied substantially more than the range directly observed. In fact, climate reconstructions would suggest that larger irradiance changes are not necessary to explain the mean temperature fluctuations of past centuries and millennia. There is good confidence in this interpretation because the global/hemispheric mean temperature of the globe is tightly linked to the radiative balance of the planet, actually remarkably so, despite the often stated low level of understanding of solar radiative forcing. Therefore, direct irradiance changes most likely have left relatively small, albeit discernible, imprints in large-scale mean temperatures.

However, two other issues can be raised that, in combination, might offer a suggestion for an indirect pathway for the Sun to affect the climate system.

Most recently, the observations by the Solar Radiation and Climate Experiment (SORCE) spectral irradiance monitor have highlighted large variability in the higher-frequency component of the solar spectrum, even higher than previously acknowledged. Independent of how exactly the variations are distributed across the wavelength, a strong shift in its distribution will have effects on the vertical temperature profile of Earth's atmosphere, and therefore on various important properties, such as the chemical composition, temperature gradients, and steering of waves through refraction or reflection. Strong spectral changes in solar output might therefore be a possible cause of mean circulation changes. The strongest effects would be expected above the lower atmosphere, but because of vertical coupling, some effects down toward the surface are possible.

This is where the second factor potentially could be helping to substantiate such a solar modulation of the climate system. Paleoclimate records have long been used to suggest a solar influence on climate. The problem generally has been that a unifying framework was lacking as to how to interpret that influence. Very often, the interpretation of a solar influence in the paleoclimate archives was simply based on statistical analyses, most commonly through quasi-identification of certain frequencies of variability close to "known solar bands." Criticism of picking and choosing of records, as well as the lack of process understanding that would have helped explain mechanistically a solar influence on the records, separated the paleo community on the Sun-climate connection question. However, as researchers gain more insight into the various paleoclimate records, it becomes possible to interpret the various time series within a quantitative geophysical framework, a framework held together by dynamical processes, not mere correlations. With this approach, new ways to reconstruct multivariate climate fields have emerged. These approaches allow for a more flexible and comprehensive inclusion of different climate signals that include seasonally dependent temperature, and moisture, as well as links to regional or large-scale dynamics such as atmospheric wave structure, coastal upwelling, and even ocean overturning.

Based on such a system-level interpretation of past climate, it becomes possible to analyze both temporal and spatial changes in light of different climate drivers. This topic offers a fruitful environment for scientific investigations across the solar physics, climate dynamics, paleoclimate, and climate modeling disciplines. Although not conclusive, a solar influence on climate can be postulated more robustly in the arena of indirect effects on large-scale circulation rather than through direct irradiance alone. At the same time, such a multiscale approach might offer an important evaluation of climate models in their ability to reproduce changes in variability that are ultimately going to be responsible for regional climate, just as they have in the past.

Climate Response to the Solar Cycle as Observed in the Stratosphere

Lon L. Hood, Lunar and Planetary Laboratory, University of Arizona

Multiple linear regression analyses of satellite-derived stratospheric ozone and temperature records indicate the existence of significant responses to 11-year solar forcing primarily at tropical and subtropical latitudes. The observed 11-year variation of ozone and temperature in the tropical upper stratosphere is attributable to direct photochemical and radiative forcing by solar irradiance at ultraviolet wavelengths, which is mainly responsible for the production of ozone in the stratosphere. In addition, a significant 11-year variation of ozone and temperature is observed in the tropical and subtropical lower stratosphere that has a dominantly dynamical origin and is currently not well understood. The lower stratospheric ozone variation is the principal contributor to the solar-cycle variation of total (column) ozone. At higher latitudes in the polar upper stratosphere and lower mesosphere, solar and magnetospheric energetic particle precipitation produces detectable interannual and decadal changes in ozone, especially in the Southern Hemisphere. Finally, in the polar lower stratosphere, a nonlinear response to 11-year solar forcing of temperature and geopotential height is observed with a sign that depends on the phase of the equatorial quasi-biennial wind oscillation (QBO).

The origin of the observed tropical and subtropical lower stratospheric response to 11-year solar forcing is a topic of current research and has implications for understanding of solar-induced climate change in the troposphere. Two end-member mechanisms can be identified. First, it is possible that direct solar (mainly ultraviolet) forcing in the upper stratosphere perturbs stratospheric circulation in such a way as to modify planetary wave propagation and decelerate the mean meridional (Brewer-Dobson) circulation (BDC) near solar maxima. This "top-down" mechanism would then result in an 11-year variation of the tropical upwelling rate, which would in turn advectively modulate ozone concentrations in the lower stratosphere, consistent with observations. Second, it is possible that there is a significant troposphere-ocean response to solar variability that is driven mainly by direct changes in total solar irradiance. This "bottom-up" mechanism would then reduce planetary wave amplitudes in the troposphere near solar maxima, which would also modulate the BDC, the tropical upwelling rate, and ozone concentrations in the lower stratosphere, as is observed. These mechanisms are not mutually exclusive and both may be important. For example, top-down forcing from the upper stratospheric response may, in principle, produce significant indirect effects on surface climate, which would then have dynamical feedbacks on the stratosphere. However, if it is found that top-down ultraviolet forcing mainly produces the lower stratospheric response, then support would be obtained for the view that top-down solar ultraviolet forcing is the primary driver of solar-induced tropospheric climate change. If, on the other hand, the observed lower stratospheric response is primarily a consequence of bottom-up dynamical feedbacks from a troposphere-ocean response that is driven mainly by changes in TSI, then it would follow that direct TSI forcing of near-surface climate is the main driver of solar-induced climate change.

Current work focuses mainly on investigation of the bottom-up mechanism for producing the lower stratospheric response to 11-year solar forcing at low latitudes. Specifically, we are investigating whether a statistically significant solar cycle response of the troposphere-ocean system exists that has characteristics consistent with producing the observed lower stratospheric response through a modification of planetary wave amplitudes. To characterize the troposphere-ocean response, a multiple linear regression statistical model is applied to Hadley Centre sea level pressure (SLP) and sea surface temperature (SST) data, which are available back to ~1870. In agreement with previous authors, the most statistically significant positive response is obtained for SLP in the North Pacific during northern winter, consisting of a weakening and westward shift of the Aleutian low near solar maxima relative to solar minima. This response is similar to that which occurs during the cold (La Niña) phase of the El Niño-Southern Oscillation. To test whether the response is indeed solar (rather than a consequence of aliasing from a few strong El Niño-Southern Oscillation events), the analysis is repeated for two separate time periods (1880-1945 and 1946-2009). It is found that the North Pacific SLP response to 11-year solar forcing is approximately repeatable during the two time periods, supporting the reality of the solar response. An associated response of North Pacific wintertime SST is also obtained but is less repeatable for separate time periods. In addition, a marginally significant SLP decrease over eastern Europe is obtained near solar maxima relative to solar minima.

The "La Niña-like" character of the North Pacific SLP response is in agreement with previous analyses using compositing methods[13] and with some climate model studies.[14] It also agrees with some paleoclimate studies, which have found evidence for La Niña-like conditions in the Pacific region during periods of prolonged solar activity increases, such as the "medieval climate anomaly."[15] Both the positive North Pacific SLP response and the negative eastern European SLP response under solar maximum conditions correspond to regions of known tropospheric precursors of anomalous stratospheric circulation changes.[16] Increases in North Pacific SLP tend to weaken and shift westward the Aleutian low, while decreases in eastern European SLP tend to weaken and shift eastward the Siberian high. To first order, this weakens the wave one quasi-stationary Rossby wave forcing at northern middle to high latitudes,

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[13] See, for example, H. van Loon, G. Meehl, and D. Shea, Coupled air-sea response to solar forcing in the Pacific region during northern winter, *Journal of Geophysical Research* 112:D02108, 2007.

[14] See, for example, G. Meehl, J. Arblaster, K Matthes, F. Sassi, and H. van Loon, Amplifying the Pacific Climate System response to a small 11-year solar cycle forcing, *Science* 325(5944):1114-1118, 2009.

[15] See, for example, M. Mann, Z. Zhang, S. Rutherford, R. Bradley, M. Hughes, D. Shindell, C. Ammann, G. Faluvegi, and F. Ni, Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, *Science* 326(5957):1256-1260, 2009.

[16] See, for example, C. Garfinkel, D. Hartmann, and F. Sassi, Tropospheric precursors of anomalous Northern Hemisphere stratospheric polar vortices, *Journal of Climate* 23:3282-3299, 2010.

which allows a strengthening of the polar vortex and a deceleration of the BDC. The observed SLP response is therefore most consistent with a bottom-up mechanism for driving the tropical lower stratospheric response. A simplified analytic model suggests that much of the observed tropical lower stratospheric response, including the solar cycle variation of total ozone, can be explained by this mechanism.

However, these results are preliminary, and more work is needed to establish the relative importance of the bottom-up and top-down mechanisms for producing the lower stratospheric response. More detailed comparisons with global climate model simulations with and without a coupled troposphere and ocean, with and without a simulated QBO, with TSI changes alone, and with various possible solar spectral irradiance changes would assist in identifying the dominant physical mechanisms.

Amplifying the Pacific Climate System Response to a Small 11-Year Solar Cycle Forcing

Gerald A. Meehl, Julie M. Arblaster, Katja Matthes, Fabrizio Sassi, and Harry van Loon, National Center for Atmospheric Research

One of the mysteries regarding Earth's climate system response to variations in solar output is how the relatively small fluctuations of the 11-year solar cycle can produce the magnitude of the observed climate signals in the tropical Pacific associated with such solar fluctuations. These observations include, for peaks in the 11-year sunspot cycle, below-normal sea surface temperatures in the equatorial eastern Pacific, enhanced precipitation in the Pacific intertropical convergence zone and South Pacific convergence zone, and above-normal sea level pressure in the midlatitude North and South Pacific. To investigate what could be producing these signals in observations, two mechanisms, the top-down stratospheric response of ozone to fluctuations of shortwave solar forcing, and the bottom-up coupled ocean-atmosphere surface response, are included in versions of three global climate models with either mechanism acting alone or both together. We show that the two mechanisms act together to enhance the climatological off-equatorial tropical precipitation maxima in the Pacific, lower the eastern equatorial Pacific sea surface temperatures during peaks in the 11-year solar cycle, and reduce low-latitude clouds to amplify the solar forcing at the surface.

Detection of the Solar Signal in Climate from Paleorecords

Raymond S. Bradley, Climate System Research Center, University of Massachusetts

All paleoclimatic studies of solar forcing rely on the record of ^{14}C or ^{10}Be anomalies from tree rings or ice cores as a proxy for changes in irradiance, even though the relationship between variations in these cosmogenic isotopes and total (or ultraviolet) solar irradiance remains enigmatic. Furthermore, the record of anomalies that is generally used is derived by first removing the (large) geomagnetic signal in some way, adding uncertainty to the resulting anomaly series. But this is generally the starting point for paleoclimatic studies that involve solar forcing. Although many paleoclimate studies claim that there is a record of solar forcing in proxy records, very few of these demonstrate a convincing, statistically significant relationship. Often, the argument rests on nothing more than a crude similarity between a time series of the proxy and the cosmogenic isotope anomaly series. In other cases, the claim may be based on spectral power in the proxy record at the approximate frequencies known to be present in the cosmogenic isotope series. Proxies may be temperature-related, or hydrological indicators. In short, although there is a lot of literature on this topic, very little of it stands up to scrutiny. Nevertheless, rather surprisingly, if the individual series (with their inherent limitations) are accepted, and the implied relationships are mapped out, a fairly coherent pattern emerges, providing an intriguing hint that some of the recognized climate changes during the Holocene may indeed have been driven by solar activity changes. Notably, periods of low solar activity are generally associated with lower temperatures at mid- to high-latitude sites, and with weaker monsoon activity in the tropics. However, most published paleoclimate studies do *not* recognize any link with solar forcing, and so there is a danger of the "reinforcement syndrome," whereby only a very small number of well-publicized studies establish a paradigm that may not be supported by most records.

General circulation models (with a well-developed stratospheric chemistry component) could be used to assess the possible effects of solar irradiance changes (total and ultraviolet) on global and regional climate and thereby guide a paleoclimate research strategy. Current models suggest that climate effects are possible, even with relatively small changes in total irradiance (though most models have used larger changes in TSI than current research suggests is likely). Importantly, they indicate that there may have been distinct changes in atmospheric circulation, resulting in regional patterns of climate change, rather than simply overall warming or cooling.

This field cries out for a more systematic and rigorous approach to determine whether solar forcing has played an important role in past climate changes. A well-designed and statistically rigorous strategy, using a network of well-dated high-resolution proxies, in association with general circulation modeling studies, is needed.

Detecting the Solar Cycle via Temperature Proxies Back to the Maunder Minimum

Gerald R. North, Department of Atmospheric Sciences, Texas A&M University

This talk focuses on the very faint (a few hundredths of a degree centigrade) temperature signature associated with the 11-year solar cycle. If solar TSI changes were the only cause of the response, a simple climate model could be used to map the amplitude and phase lag of the response over the planet. One can use regression/detection methods to estimate the strength of the signal simultaneously with the volcanic, greenhouse, and aerosol signals. The signal strength is consistent with this kind of forcing and response. Data from ice cores can also be used to detect the 11-year response through the ^{18}O isotope record. Such a peak in the spectra is indeed present in several cores from Greenland and Antarctica. Data from the core taken from Taylor Dome in Antarctica have a high enough signal-to-noise ratio that one can reconstruct the time series in a narrow band about the 11-year peak by band-pass filtering. The reconstruction clearly shows the Maunder Minimum at its correct time. The Dye-3 core from southern Greenland shows some indications of the same, but the signal-to-noise ratio is less favorable. This research represents an independent indicator, based on temperature response, of past solar influences in forcing climate change at the decadal timescale.

Climate Response at Earth's Surface to Cyclic and Secular Solar Forcing

Ka-Kit Tung, University of Washington

I will review recent results on responses at the surface to the 11-year solar cycle and to the longer-term secular trend in the longest global temperature dataset. Finally I will discuss some new results on analyzing the 350-year Central England temperature record back to the Maunder Minimum, to see if there is a larger solar signature.

Solar Effects Transmitted by Stratosphere-Troposphere Coupling

Joanna Haigh, Imperial College, London

Data from satellite-borne radiometers indicate that total solar irradiance is greater when the Sun is more active, by about 0.1 percent at the maximum relative to the minimum of the 11-year cycle. Based on simple energy balance arguments, and a standard estimate of climate sensitivity to radiative forcing, this translates into a variation in the global mean surface temperature of around 0.1 K over the solar cycle. Analysis of observational records concurs with this, but the distribution of the solar signal is decidedly non-uniform. Within the troposphere the largest response occurs in midlatitudes with bands of warming (of approximately 0.5 K) extending from the surface to the tropopause. Above this, in the lower stratosphere, greatest warming appears in the tropics. Zonal winds in the lower atmosphere show a solar cycle response in which the midlatitude jet-streams (and associated storm tracks) move slightly poleward when the Sun is more active.

The observed patterns in zonal mean temperature and wind can be reproduced qualitatively in experiments with climate models in which solar ultraviolet is increased but with surface temperatures fixed. The amplitude of the signal is found to be enhanced if ozone concentrations in the stratosphere are allowed to respond to the increased solar ultraviolet. The magnitude of the modeled response, however, is smaller than the observed response. From this we conclude that ultraviolet heating of the stratosphere may make a contribution to the solar effect on surface climate, and that the magnitude of the ultraviolet change and, importantly, its effect on ozone, are significant in determining the magnitude.

Experiments with simplified global climate models have provided indications of the mechanisms whereby changes in the thermal structure of the lower stratosphere may influence the atmosphere below. The deposition of zonal momentum near the tropopause by upward-propagating synoptic-scale waves is affected by the change in local temperature structure producing zonal accelerations and changes to the mean meridional circulation of the troposphere. These affect the zonal wind at lower levels and thus the background flow upon which subsequent wave propagation takes place. This provides a feedback between the waves and mean flow anomalies that serves to reinforce the initial changes. These results have a wider application in understanding the climate effects of other stratospheric perturbations (such as chemical ozone depletion or the injection of volcanic aerosol) and could be important in terms of assessing the role of human activity in past and future climate, as well as providing a good testbed for current understanding of atmospheric dynamics.

Over the past few years the Sun has been in a state of very low activity, and measurements from the SORCE satellite are suggesting that the solar spectrum has been behaving in an unexpected fashion. In particular, daily measurements by the Spectral Irradiance Monitor (SIM) show a much larger (factor of four to six) decay at near- ultraviolet wavelengths over the latter part of the most recent solar cycle than previously understood. If, as suggested above, ultraviolet heating of the stratosphere makes a contribution to the solar effect on surface climate, then the larger ultraviolet changes shown by SIM would imply a larger role for the stratosphere in determining the tropospheric response to solar variability.

The Impact of Energetic Particle Precipitation on the Atmosphere

Charles H. Jackman, National Aeronautics and Space Agency Goddard Space Flight Center

Energetic precipitating particles (EPPs) include both solar particles and galactic cosmic rays, which can influence the atmosphere. Solar particles cause impacts in the polar middle atmosphere, and galactic cosmic rays create impacts in the lower stratosphere and troposphere.

The solar particles can cause significant constituent changes in the polar mesosphere and stratosphere (middle atmosphere) during certain periods. Both solar protons and electrons can influence the polar middle atmosphere through ionization and dissociation processes. Solar EPPs can enhance HO_x (H, OH, HO_2) through the formation of positive ions followed by complex ion chemistry and NO_x (N, NO, NO_2) through the dissociation of molecular nitrogen.

The solar EPP-created HO_x increases can lead to ozone destruction in the mesosphere and upper stratosphere via several catalytic loss cycles. Such middle atmospheric HO_x-caused ozone loss is rather short-lived due to the relatively short lifetime (hours) of the HO_x constituents. The HO_x-caused ozone depletion of greater than 30 percent has been observed during several large solar proton events (SPEs) in the past 40 years. HO_x enhancements due to SPEs were confirmed by observations in the past solar cycle. A number of modeling studies have been undertaken over this time period that show predictions of enhanced HO_x accompanied by decreased ozone due to energetic particles.

The solar EPP-created NO_x family has a longer lifetime than the HO_x family and can also lead to catalytic ozone destruction. EPP-caused enhancements of the NO_x family can affect ozone promptly, if produced in the stratosphere, or subsequently, if produced in the lower thermosphere or mesosphere and transported to the stratosphere. NO_x enhancements due to auroral electrons, medium- and high-energy electrons, relativistic electron precipitation events, and SPEs have been measured and/or modeled for decades. Model predictions and measurements show that certain years have significant wintertime meteorological events, which result in the transport of EPP-caused NO_x enhancements in the upper mesosphere and lower thermosphere to lower altitudes.

The NO_x-caused ozone depletion has also been observed during several solar proton events in the past 40 years. Model predictions indicate that the longer-lived SPE-caused polar stratospheric ozone decrease was statistically significant, but less than 5 percent, in the Northern Hemisphere for the extremely active 5-year time period average (2000-2004). Computations of total ozone do not indicate any long-term SPE total ozone impact over the 1965-2004 period.

Galactic cosmic rays also create NO_x and HO_x constituents, but at lower altitudes since these particles have much higher energies. The inclusion of galactic cosmic ray-created NO_x constituents can increase the odd nitrogen or NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, $ClONO_2$, $BrONO_2$) family in the lower stratosphere by up to about 20 percent, with small associated ozone decreases of <2 percent. However, the variation in the GCR-driven change in NO_y from solar maximum to solar minimum is less than about 5 percent, which results in annually averaged total ozone variations of <0.06 percent.

This talk will provide an overview of several of the EPP-related important processes and their impacts on the atmosphere.

Cosmic Rays, Aerosols and Clouds

Jeffrey Pierce, Dalhousie University, Halifax, Nova Scotia

Cloud cover has been reported to correlate with the flux of galactic cosmic rays to the troposphere, although these correlations are still controversial. Because the tropospheric galactic cosmic ray flux is affected by solar activity, this GCR/cloud connection could be an important pathway for the Sun to influence climate. However, we are just beginning to understand the physical pathways connecting GCRs and clouds. The proposed pathways include (1) the *ion-aerosol clear-sky hypothesis* whereby GCRs ionize gases and thus may enhance aerosol nucleation rates and cloud condensation nuclei concentrations, and (2) the *ion-aerosol near-cloud hypothesis* whereby GCRs affect the charge distribution near clouds and thus may affect the freezing of supercooled drops, which will affect precipitation. In this talk, I will review the reported observations of GCR/aerosol/cloud correlations, discuss the proposed physical pathways of GCRs affecting clouds, and present research evaluating the strength of the ion-aerosol clear-sky hypothesis. I will conclude with thoughts on the next steps in GCR/aerosol/cloud research.

The Frequency of Solar Grand Minima Estimated from Studies of Solar-Type Stars

Dan Lubin, Scripps Institution of Oceanography, University of California, San Diego

The Maunder Minimum is a key event in climate change research (1) from the vantage point as a natural control experiment in which greenhouse gas (GHG) abundances were at a pre-industrial constant while solar forcing changed by a magnitude comparable to recent GHG increases, and (2) given recent interest and speculation that a similar grand minimum might occur later this century. To date, periodicity in solar grand minima has been difficult to detect in geophysical proxy data, and an alternative approach involves estimating the frequency of the Sun's lifetime spent in a grand minimum state by searching for evidence of grand minima in solar-type stars. Most often this is done by measuring calcium (Ca), hydrogen (H), and potassium (K) flux as an indicator of chromospheric activity, or by photometric observations of solar cycles on decadal timescales. Early estimates of grand minimum frequency in solar-type stars ranged from 10 to 30 percent. However, these early studies inadvertently included many stars that have evolved off the main sequence. More recently, Hipparcos parallax measurements have yielded reliable differentiation between true main sequence stars and slightly evolved stars. In addition, measurements of stellar lithium abundance, and spectroscopically derived metallicity, can provide additional constraints on age and help refine detections of grand minimum analogs in solar-type stars. At the same time, some evidence suggests that instantaneous Ca, H, and K flux measurements alone may be unsuitable for detecting grand minimum analog candidates: at least one plausible candidate has been identified in time series data including a flat activity cycle but with chromospheric activity greater than present-day solar activity. Based on the most recent studies, an estimate emerges in the range of 5 to 6 percent for the fraction of the Sun's lifetime spent in a low-activity and reduced-luminosity state analogous to the Maunder Minimum.

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Biographies of Committee Members and Staff

GERALD R. NORTH, *Chair,* is a Distinguished Professor of Atmospheric Sciences and Oceanography (1986-present), served as head of the Department of Atmospheric Sciences (1995-2003), and held the Harold J. Haynes Endowed Chair in Geosciences from 2004 to 2009 at Texas A&M University. Previously Dr. North worked as a senior research scientist at the NASA/Goddard Space Flight Center (1978-1986). His professional interests include climate analysis, climate and hydrological modeling, satellite remote sensing and mission planning, and statistical methods in atmospheric science. Dr. North and his research group are interested in climate change and the determination of its origins. They work with simplified climate models that lend themselves to analytical study, estimation theory as applied to observing systems, and the testing of all climate models through statistical approaches. Dr. North is a fellow of the American Association for the Advancement of Science (AAAS), the American Meteorological Society, and the American Geophysical Union (AGU). He is former editor-in-chief of *Reviews of Geophysics* and is currently editor in chief of the *Encyclopedia of the Atmospheric Sciences,* Second Edition. Dr. North received his Ph.D. in physics from the University of Wisconsin (1966). He has served as a member of the National Research Council's (NRC's) Board of Atmospheric Sciences and Climate and as chair of the Committee on Surface Temperature Reconstructions for the Last 2,000 Years (2006).

DANIEL N. BAKER is director of the Laboratory for Atmospheric and Space Physics at the University of Colorado, Boulder, where he also holds appointments as professor of astrophysical and planetary sciences and as a professor of physics. His primary research interest is the study of plasma physical and energetic particle phenomena in planetary magnetospheres and in the Earth's vicinity. He conducts research in space instrument design, space physics data analysis, and magnetospheric modeling. He currently is an investigator on several NASA space missions including the MESSENGER mission to Mercury, the Magnetospheric MultiScale mission, the Radiation Belt Storm Probes mission, and the Canadian ORBITALS mission. Dr. Baker has published more than 700 papers in the refereed literature and has edited six books on topics in space physics. He earned his Ph.D. in physics from the University of Iowa. In 2010, Dr. Baker was elected to the National Academy of Engineering for leadership in studies, measurements, and predictive tools for the Earth's radiation environment and its impact on U.S. security. He is a fellow of the AGU, the International Academy of Astronautics, and the American Association for the Advancement of Science. Among his other awards are the 2007 University of Colorado's Robert L. Stearns Award for outstanding research, service, and teaching; the 2010 American Institute of Aeronautics and Astronautics' James A. Van Allen Space Environments Award for excellence and leadership in space research; and his selection in 2004 as a National Associate of the National Academy of Sciences. Dr. Baker served as president of the Space Physics and Aeronomy section of AGU (2002-2004), and he presently serves on advisory panels of the U.S. Air Force and the National Science Foundation (NSF). He is a member of the NRC's Committee on the Effects of Solar Variability on Earth's Climate: A Workshop and has served as a member of the Space Studies Board and several NRC committees, including the Committee on Solar and Space Physics (chair), the Committee on Assessment of Interagency Cooperation on Space and Earth Science Missions (co-chair), the steering committee for the NRC's 2003 decadal survey in solar and space physics, the 2006 Decadal Review of the U.S. National

Space Weather Program, and the 2006 Committee on an Assessment of Balance in NASA's Science Programs.

RAYMOND S. BRADLEY is a University Distinguished Professor of Geosciences and director of the Climate Systems Research Center at the University of Massachusetts. Dr. Bradley's research interests are in climatology and paleoclimatology, with a particular focus on the postglacial period (the past 12,000 years). Dr. Bradley has written or edited 12 books on these subjects, including *Paleoclimatology: Reconstructing Climates of the Quaternary and Climate Change and Society* (with N.E. Law). He has been an advisor to various government and international agencies, including those in the United States, Switzerland, Sweden, and the United Kingdom, and in particular for NSF, National Oceanic and Atmospheric Adminiatration (NOAA), Intergovernmental Panel on Climate Change (IPCC), and the U.S.-Russia Working Group on Environmental Protection, and the International Geosphere-Biosphere Program, Stockholm, Sweden. He is a fellow of the AGU, the Arctic Institute of North America, and the AAAS. He received an honorary doctorate from Lancaster University, England, for his contributions to paleoclimatology. He was also awarded the Oeschger Medal of the European Geosciences Union. Dr. Bradley earned his Ph.D. at the University of Colorado, Boulder. He served previously on the NRC's Panel on Climate Variability on Decade-to-Century Time Scales, the Grasslands Study Panel, and the Committee on Monitoring and Trend Assessment in Acid Deposition.

PETER FOUKAL is the president of Heliophysics, Inc., and the founder and past-president of Cambridge Research and Instrumentation, Inc., a high-tech firm specializing in electro-optics. His experience includes research and teaching positions at the California Institute of Technology and Harvard University and a position as vice president of AER, Inc. He was awarded a NATO senior fellowship at Nice Observatory, France, and has served as a member or as chair of numerous panels and advisory boards of NSF and NASA. He is past-president of Division II of the International Astronomical Union (IAU), a past member of the editorial board of *Solar Physics Journal*, and at present a member of the Corporation of Wheelock College. Besides the IAU, his professional affiliations include memberships in the American Astronomical Society and the AGU. He is author or co-author of more than 120 publications in scientific journals and author of the widely used text *Solar Astrophysics*. Dr. Foukal earned his Ph.D. in astrophysics from Manchester University, United Kingdom. His previous NRC experience includes serving on the Board of Atmospheric Sciences and Climate's Committee on Solar and Terrestrial Research and the Associateship and Fellowship Programs Advisory Committee's Panel on Space Sciences.

JOANNA D. HAIGH is professor and head of the Department of Atmospheric Physics at Imperial College, London. Prior to joining Imperial College as a lecturer, she was a research associate at Oxford University. Dr. Haigh's research interests are in the area of radiative transfer in the atmosphere, climate modeling, radiative forcing of climate change, and the influence of solar irradiance variability on climate. She has been vice president of the Royal Meteorological Society, editor of *Quarterly Journal of the Royal Meteorological Society*, and a lead author of the IPCC Third Assessment, and she has acted on many U.K. and international panels. Currently she is the U.K. representative to the International Association of Meteorology and Atmospheric Sciences, editor of the *Journal of the Atmospheric Sciences*, and a member of the Royal Society's Climate Change Advisory Group. She is a fellow of the Institute of Physics and of the Royal Meteorological Society, and she has received the 2004 Charles Chree Medal of the Institute of Physics and the 2010 Adrian Gill Prize of the Royal Meteorological Society for her work on solar influences on climate. She earned her D.Phil. from the University of Oxford.

ISAAC M. HELD is a senior research scientist at NOAA's Geophysical Fluid Dynamics Laboratory, where he has spent most of his career. He is a lecturer with the rank of professor at Princeton University in its Atmospheric and Oceanic Sciences Program and is an associate faculty member in Princeton's Applied and Computational Mathematics Program and in the Princeton Environmental Institute. Dr.

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ABIGAIL A. SHEFFER, *Study Director,* joined the Space Studies Board (SSB) in Fall 2009 as a Christine Mirzayan Science and Technology Policy Graduate Fellow to work on the report *Visions and Voyages for Planetary Science in the Decade 2013-2022*. She went on to become an associate program officer for SSB. Dr. Sheffer earned her Ph.D. in planetary science from the University of Arizona and her A.B. in geosciences from Princeton University. Since coming to the SSB, she has worked on several additional studies, including *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*, *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*, and *Solar and Space Physics: A Science for a Technological Society.*

ARTHUR A. CHARO joined the SSB in 1995 as a senior program officer. He has directed studies that have resulted in some 33 reports, notably the first NRC decadal survey in solar and space physics (2003) and in Earth science and applications from space (2007). Dr. Charo received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. He then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a research fellow from 1985 to 1988. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was also the 1988-1989 American Institute of Physics AAAS Congressional Science Fellow. In addition to NRC reports, he is the author of research papers in molecular spectroscopy, reports on arms control and space policy, and the monograph "Continental Air Defense: A Neglected Dimension of Strategic Defense" (University Press of America, 1990).

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MICHAEL BARTON, an SSB Lloyd V. Berkner space policy intern, recently graduated from Mississippi State University with a B.S. in aerospace engineering with a concentration in astronautics and a minor in leadership studies. He spent last summer in the NASA Academy for Space Exploration at NASA Glenn Research Center, where he worked on research projects in computational fluid dynamics and microgravity test beds. As part of the NASA Academy, Mr. Barton was able to tour other NASA centers and commercial space operations, as well as meet many engineers and managers across the workforce. Previous to that, he was a co-op engineer in space shuttle guidance and navigation during the waning years of the Space Shuttle Program at NASA Kennedy Space Center. These experiences have given him insight into the culture and operational processes of NASA. At Mississippi State, Mr. Barton has served as president or vice president of several engineering student organizations and honor societies, and he has worked as an undergraduate teaching assistant and researcher in computational fluid dynamics. Mr. Barton plans to pursue a master's degree in aerospace engineering next fall.

MICHAEL H. MOLONEY is the director of the SSB and the ASEB at the NRC. Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Before joining the SSB and ASEB in April 2010, he was associate director of the BPA and study director for the Astro2010 decadal survey for astronomy and astrophysics. In addition to his professional experience at the NRC, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government and served in that capacity at the Embassy of Ireland in Washington, D.C., the Mission of Ireland to the United Nations in New York, and the Department of Foreign Affairs in Dublin, Ireland. A physicist, Dr. Moloney did his graduate Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

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Acronyms and Terms

ACR	Anomalous Cosmic Ray
ACRIM	Active Cavity Radiometer Irradiance Monitor
AMO	Atlantic Multidecadal Oscillation
CERN	European Organization for Nuclear Research
CME	Coronal mass ejection
cosmic ray	Highly energetic atomic nucleus that travels through space at nearly the speed of light
Dalton Minima	A period of low solar activity lasting from 1790 to 1830 and named after John Dalton
ENSO	El Niño-Southern Oscillation
EPP	Energizing precipitating particle
Forcing	An externally imposed perturbation in the radiative energy budget of Earth's climate system. Also called radiative forcing.
GCM	Global climate model
GCR	Galactic cosmic ray
Hadley cell	Atmospheric circulation with rising motion near the equator, poleward flow, and sinking motion in the subtropics
Little Ice Age	A cooling period from 1550 to 1850
Maunder Minimum	A period of low solar activity lasting from 1645 to 1715 and named after Edward W. Maunder
Milankovitch cycle	Long-term changes in Earth's orbit that in turn affect its climate over long periods of time
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NSF	National Science Foundation
Photosphere	Visible surface of the Sun
PREMOS	Precision Monitoring Sensor experiment onboard the PICARD French microsatellite mission
QBO	Quasi-biennial oscillation

SBUV	Solar backscatter ultraviolet
SEP	Solar energetic particle
SIM	Spectral Irradiance Monitor
SOLSTICE	Solar Stellar Intercomparison Experiment
SORCE	Solar Radiation and Climate Experiment
SPE	Solar proton event
Spörer minimum	A period of low solar activity lasting from 1460 to 1550 and named after Gustav Spörer
SSI	Solar spectral irradiance
SST	Sea surface temperature
TIM	Total Irradiance Monitor
TSI	Total solar irradiance