

Living with a Star:
NEW OPPORTUNITIES
IN SUN-CLIMATE RESEARCH

Report of the NASA LWS Sun-Climate Task Group

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I. BACKGROUND

How constant is the Sun? To what extent do known solar variations affect the short-term weather and long-term climate on the Earth? Has the Sun played any part in the documented warming of the past one hundred years? What climatic changes of the past thousand, tens of thousands or hundreds of thousands of years have been driven by solar variations, and through what mechanisms? How well and how far into the future can we predict how the outputs from the Sun will vary?

These questions, so often asked today, have been around in one form or another for a long, long time. For at least 200 years, natural philosophers and astronomers, then solar physicists and meteorologists, and now climatologists and paleoclimatologists and oceanographers have tried to find the answers, in the hope of achieving practical weather and climate prediction.

In truth, concerns about the Sun's constancy are common in early religions and are probably as old as human thought. Almost as old, we may presume, are the common intuitive feelings that since the Sun is the obvious source of heat and light and day and night, might it not also alter the course of weather and climate, through variations in the amount of energy that it delivers to the Earth?

It has been known for a long time that the Sun varies. More than 2000 years ago court astronomers in China were observing, describing and astrologically interpreting dark spots on the face of the Sun that were large enough to be seen with the naked eye: some larger and more auspicious than others, although often none at all. When the first telescopes were pointed at the Sun, more than sixteen centuries later, by Galileo Galilei and other European astronomers, the same transitory markings were readily found, clearly identified as solar features (not planets), and more closely observed and followed from day to day. Brighter areas surrounding sunspots were also noted and recorded and found to be equally transitory and variable. Solar opposites. In Latin: *maculae* and *faculae*—the yin and yang of the solar surface that were indeed competing, each day, then as now, to modulate the outward flow of radiation from the visible surface of the star.

The notion that conditions on the Earth might be affected by these ever-changing features on the face of the Sun, though ninety-three million miles away, was an

obvious conclusion. And an old one in 1726, when Jonathan Swift wove this common presumption into *Gulliver's Travels*. There he tells of the floating island of Laputa—a mythical land of philosophers and astronomers who were obsessed with the sky. And they were not a happy lot. Among their many apprehensions was that the face of the Sun would by degrees be so covered by spots that it would no longer give sufficient heat and light to the world. When the Laputians met an acquaintance early in the day their first question was not the usual “How are you?” but “How did the *Sun* look this morning?”

Real astronomers who looked at the real Sun in the real world were also intrigued in the seventeenth and eighteenth centuries by the possibility of a connection. Obvious to any of them was the enormous practical benefit to society—in an age when the prediction of weather was based almost entirely on accumulated lore and seasonal expectations—were a clear connection to be found linking the presence or absence of easily observed spots or other features on the Sun to local or regional conditions.

Many claimed to have found it, including Sir William Herschel, the renowned astronomer and telescope maker, whose paper published in 1801 in the *Philosophical Transactions of the Royal Society* reported his discovery of a persistent relationship between sunspots and the price of a bushel of wheat on the London market. Based on his own and earlier observations of the Sun since about 1650, he found that during protracted periods when sunspots were scarce, the price of wheat was always higher. Herschel reasoned that fewer spots on the Sun denoted abnormality and an accompanying deficiency in the radiation that was emitted, leading to poorer growing conditions, diminished agricultural production, and through the inexorable law of supply and demand, higher commodity prices.

When Herschel published his paper, the cyclic eleven-year rise and fall in the number of sunspots was not yet known, and wouldn't be for nearly half a century. The belated discovery of this strongly periodic feature in the annually-averaged numbers of spots on the visible surface of the Sun was announced by Hofrath Schwabe, a German pharmacist and amateur astronomer, in 1843. In time it proved to be a seminal revelation into the physical nature of solar activity and variability. In the mid-nineteenth century, however, the principal effect on scientists and many other people was a rush to find statistical evidence of meaningful connections with other phenomena—and particularly the weather, in the hope of finding keys to practical weather prediction. Schwabe's announcement triggered an avalanche of papers that continued for years,

purporting to have found correlations between the sunspot cycle and a host of things meteorological, hydrological, oceanographic, physiological, behavioral, and economic.

Sir Norman Lockyer, the Victorian solar physicist who founded and for fifty years edited the journal *Nature* was an early champion of these searches, counseling in 1873 that "...in Meteorology, as in Astronomy, the thing to hunt down is a cycle." He had found one, himself, the previous year, in records of the intensity of monsoon rains in Ceylon that were clearly linked, he said, to the ups and downs of the eleven-year sunspot cycle; adding, with characteristic modesty, that based on his discovery, "...the riddle of the probable times of occurrence of Indian Famines has now been read."

Indeed, until relatively late in the 20th century almost the only tool available for the investigation of possible influences of solar variability on weather and climate was the statistical comparison of indices of solar activity with contemporary meteorological records. And while some of these searches proved valuable as probes and tests of a complex system, most of what was found seemed soon to go away, and few of the correlations that were claimed stood up to rigorous statistical tests. Without the buttress of a solid physical explanation, none proved to be of any significant value in practical weather or climate prediction. The required leap of faith between what was seen on the Sun and what was felt at the bottom of an ocean of air on the Earth was simply too great, in the absence of a fuller knowledge of what happens in between.

Beginning in the 1870s, heroic efforts were made by Samuel Pierpont Langley and others to put the question on a more solid basis by attempting direct measurements of the Sun's radiation from the top of Mt. Whitney and Pike's Peak and other high-altitude stations. Through the persistence of Langley's assistant and successor, Charles Greeley Abbot, attempts to identify possible changes in solar irradiance from the surface of the Earth were continued at different stations around the world through the first half of the ensuing century: but to little avail, due to difficulties in calibration and even larger uncertainties in compensating for the variable absorption and scattering in the intervening atmosphere.

Missing but sorely needed in all the early attempts to find answers to the Sun-Climate question was a deeper understanding of the nature of solar variability and its effects on the energy released in all forms from the surface of the Sun; a more complete understanding of the chemistry and dynamics of the Earth's

atmosphere, and of the coupled atmosphere-ocean-earth climate system; the availability of analytical models and other techniques to test and evaluate proposed forcings, feedbacks, and responses in a system that was inherently interactive and complex; a consistent documentation of global climatic changes on all time scales; a fuller appreciation of the possible processes that couple the upper, middle and lower atmosphere with the land surface and oceans; and perhaps most important; ongoing measurements of the total and spectral irradiance from the Sun as a star.

II. SUN-CLIMATE SCIENCE TODAY

Enormous advances have been made in the last quarter century in all of these needed areas, covering the two essential halves of the Sun-Climate question: in what we know of solar variations and, equally important, in what we know of the climate system and of climatic changes. These research achievements allow us to examine all aspects of the question more directly and quantitatively than was ever possible before, and in the brighter light and more objective context of other known or suspected climate change mechanisms, including human-induced global greenhouse warming.

Brief summaries of present status and current understanding are given below for nine facets of Sun-Climate science in which major progress has been made in recent years. At the same time it will be seen that in every instance, significant elements of uncertainty still remain. Some of the most important of these unanswered questions are considered later, in Section IV.

Measurements of Total Solar Irradiance and their Interpretation

Many of the advances of the past twenty-five years are the products and by-products of continuous monitoring from space of what was once the primary missing link in the Sun-Climate problem: direct measurements of the flow of radiative energy from the surface of the Sun. As a result, we now have a continuous hour-to-hour and day-to-day record of this fundamental input to the climate system, as received at the top of the Earth's atmosphere: truly, where the rubber meets the road. These seminal measurements of total solar irradiance (TSI)—initiated in 1978 and continuing today—give needed substance to modern investigations of the Sun and Climate, while providing answers to the oldest of all solar questions: How constant is the Sun? By how much does its radiative output vary, and on what time scales?

We now know that the total solar irradiance varies from minute to minute, reflecting activity-driven changes on the face of the Sun; from day to day in step with solar rotation and the evolution of solar active regions, with amplitudes of up to about 0.3%; and more important in terms of climate, from year to year with a peak-to-peak rms amplitude of about 0.1%, in phase with Hofrath Schwabe's 11-year sunspot cycle¹. In years when the Sun is more active, and more spots are

seen, more radiative energy is delivered to the Earth—just as Herschel had surmised.

The impact of radiative variations of this amplitude on surface temperature depends on the persistence of an increase or decrease, and the sensitivity of the climate system to solar forcing. In theory, and were nothing else at work, a long-term, sustained increase of 0.1% in TSI can be expected to warm the surface temperature of the Earth by about 0.05° C. And indeed, changes of this amount have since been found in 20th century records of averaged air temperature^{2,3} and in the surface and subsurface temperature of the oceans.^{4,5} These could easily be attributed to changes in TSI, for the amplitudes and phase of the temperature anomalies are consistent with the eleven-year variation that is found in the measured output of the Sun. Changes in solar irradiance are also the most likely solar explanation of these atmospheric and oceanic signals, on the basis of the relative energies that are involved.

But the close agreement with the ocean data, in particular, is in some ways enigmatic, for the thermal inertia of the oceans should more heavily damp the climate system's response to rapid fluctuations in external forcing of this kind. The e-folding time of the mixed layer of the ocean is about three years, and the Sun's eleven-year cyclic forcing persists in one direction for not much longer than that before reversing itself. The result should be a reduction of a factor of two or more in climate sensitivity to solar forcing at this frequency, and not the full amount that is observed. What seems likely is that other climatic processes are indeed at work, including possible nonlinear feedbacks that enhance, in effect, the response of the climate system to subtle solar irradiance forcing.

We cannot forget, however, that there are eleven-year variations in other non-radiative outputs of the Sun—in the flow of charged particles, for example—which could in some way be responsible for all or part of these apparent cyclic responses of the atmosphere to varying solar activity.

Other questions also remain. Is the 0.1% eleven-year modulation the only significant variation in the radiative output of the Sun? Or is it the only one that we could expect to detect in so short a sampled span? The period for which we have direct measurements of TSI has not sampled the full range of solar variability, including recurrent 50 to 100-year episodes of severely suppressed activity, like the Maunder Minimum of 1645-1715, that are prominent features of all longer solar records, or times of gradual rise in the overall level of solar activity, as was the case during the first half of the 20th century.

Could there be other, deeper-lying causes of change in solar irradiance--periodic or aperiodic, related or unrelated to solar activity—that operate more slowly and on longer scales of time?

At this time we simply do not know whether longer-term climatically-significant variations in solar irradiance exist or don't exist. Nor do we know the magnitude of these conceivable changes.

A number of studies have postulated the existence of solar irradiance changes, acting over time scales of decades, which are from two to four times greater in amplitude than the 0.1% eleven-year change that has thus far been observed⁶. An initial reason for suspecting that such variations might exist came from early interpretations of observations of a limited number of Sun-like stars⁷. But as explained in Section IV, the reality of this initial interpretation has since been called in question by other and more extensive stellar data.

Other reasons for suspecting the existence of possible larger-amplitude, longer-term activity-related changes in TSI include an apparent correlation between the Spörer and Maunder minima of solar activity in the 15th through the early 18th centuries and particularly cold epochs of the contemporaneous Little Ice Age, and the close correspondence between features in the paleoclimate record of the Holocene with what is known of the behavior of solar activity from proxy data during the same epochs⁸. But these apparent associations are with indices of solar *activity* and not necessarily solar *irradiance*. While irradiance changes are arguably the most likely solar cause, they are but one of several activity-related variations in the output of the star.

The Causes of Observed Changes in TSI

Sun-Climate research has been aided considerably by remarkable analytical success in identifying the magnetic structures on the surface of the Sun that explain both the day-to-day, short-term fluctuations and the year-to-year, solar-cycle-related changes that are found in the TSI record. Sunspots inhibit the upward convective transport of energy to the photosphere and *diminish* the emergent radiation in proportion to their total projected area as seen from the Earth. The effects of the bright facular areas that surround sunspots and the bright boundaries of the tops of convective solar granules act in the opposite direction to *increase* the TSI. The net effect, as noted earlier, is a constant push

and pull among these competing forces, and in annual average the brighter elements prevail. This accounts for the observed rise in measured TSI at the times of maxima in the eleven-year solar activity cycle, and the ensuing fall as solar activity and sunspot numbers decline.

These clear and undeniable associations between observed solar activity and measured solar irradiance have been applied as a template for interpreting earlier observations made of the disk of the Sun in terms of prior changes in total or spectral irradiance^{6,9-11}.

The period for which these after-the-fact reconstructions are inherently most accurate begins in the second half of the 19th century. It was then, in response to widespread interest in the terrestrial effects of the sunspot cycle, that the daily photographic patrol of the white-light solar disk which continues to this day was first begun: initially in 1858, at London's Kew Observatory; then, not long after, at the Royal Greenwich Observatory; and in due course at other stations in other countries around the world. A corresponding set of continuous photographic images of the solar chromosphere is available from at least 1905 onward. For this period of time—and certainly from perhaps 1880 through 1978—the changes in TSI that are related to the eleven-year solar cycle can be reconstructed with some confidence. What they cannot tell with any assurance, however, is whether slower changes in solar irradiance were also at work during this time, or their likely amplitudes.

The reconstructions of TSI derived from historical sunspot records look a lot like the trends and excursions in the mean global surface temperature record for the same period. Moreover, when the effect of postulated, slower and somewhat greater changes in TSI are also included—keyed to drifts of longer-than-decadal duration in the overall level of solar activity—the fit with the surface temperature record of the last 100 years is remarkably good^{6,11,12}. Based on this assumption of an increase in the amplitude of irradiance variations that accompany slower changes in solar activity, about half of the documented rise in global surface temperature in the period from about 1900 to 1940 can be ascribed to solar changes. In the remaining years of the century the fraction falls to about one fourth of the total rise in temperature, with the remainder attributed to ever increasing greenhouse warming¹³. But it must be emphasized, once again, that the larger-amplitude, slower changes in solar irradiance on which these deductions are founded have yet to be observed.

How much farther back in time can we hope to reconstruct activity-related changes in solar irradiance? Detailed drawings of the disk of the Sun, and written records of sunspots and faculae obtained from similar telescopic observations, are available for the last several hundred years. From these, one can construct representative annual averages of solar activity for use in reconstructing eleven-year, activity-related changes in irradiance. But the utility of these earlier historic records begins to fade when there are fewer than 365 sampled dates in any year. By this criterion the quality of the historical record of annually-averaged sunspot activity (and by association, of reconstructed changes in solar irradiance) degrades from *excellent* in the period since 1850, to *fair* from that date to about 1818, and successively *poorer* before that time.

Nonetheless, the pieced-together accounts of the telescopic appearance of the surface of the Sun, starting in the early 17th century and continuing to this day, probably comprise the longest continuing diary of anything in all of science. With diminishing certainty the nearly 400-year record of archived observations of the disk of the Sun—reaching back to Galileo’s first drawings of the projected solar disk—can now be read as an indicator of likely *eleven-year solar-activity-related* variations in the Sun’s radiative input to the Earth. As noted above, this is not the whole story, were slower changes in TSI also present.

Interpreting the far longer *proxy* records of solar activity derived from the carbon and beryllium isotopes ¹⁴C and ¹⁰Be in terms of past changes in solar total or spectral irradiance is an even riskier step, and another leading challenge for future research.

Measurements and Modeled Reconstructions of Solar Spectral Irradiance

The bulk of the radiation from the Sun, in the visible and near-infrared, is emitted from the roughly 6000° K white-light surface of the photosphere. Radiation in both shorter and longer wavelengths originates at higher levels and in quite different physical regimes in the hotter chromosphere and corona. As a result, activity-related changes in solar spectral irradiance are not the same in different regions of the spectrum, increasing by orders of magnitude from the visible to the far ultraviolet, and from the near infrared to wavelengths of radio emission^{9,12,14}.

Of particular interest in Sun-Climate studies are the regions of the more variable far- and middle-ultraviolet spectrum that control the chemical composition and

photochemistry of the middle atmosphere, including the stratospheric ozone layer^{15,16}. The extent to which eleven-year cyclic variations in solar ultraviolet radiation affect the amount of ozone in the upper stratosphere is reasonably well established, although the ozone measurements on which the relationship is based—taken during the last two solar cycles—are clouded to some extent by the competing effects of the 1982 El Chichón and 1991 Mt. Pinatubo volcanic eruptions that occurred during the same period. Several studies have also suggested possible linkages between stratospheric ozone and circulation in the troposphere¹⁷.

The chain of physical and chemical processes that link solar activity to solar ultraviolet radiation to stratospheric ozone and then, possibly, to radiative or dynamical coupling between the stratosphere and troposphere is one of the two most likely mechanisms—on the basis of available energy—to account for apparent connections between solar activity and climate¹⁶. The other is direct solar heating through changes in TSI. The effects of either of them could be either damped or amplified by possible feedback mechanisms within the internal climate system.

Direct measurements from space of the spectral irradiance from the Sun as a star have been recorded in regions of the ultraviolet spectrum for a good many years on isolated rocket flights and on earlier spacecraft missions, though never for as long or continuous a span as the TSI. These data have been of considerable value in both solar and solar-terrestrial physics.

Past changes in the Sun's ultraviolet spectral irradiance can also be reconstructed from observations of the solar disk, from models, and from existing solar data taken in visible wavelengths, as in the central portion of strong Fraunhofer lines that originate at the same level in the Sun as does much of the ultraviolet radiation⁹. A recent proxy reconstruction made in this way of archived spectrograms of the Sun made in the core of the Calcium K line, has helped clarify the limits of likely changes in solar total irradiance during the reduced levels of solar activity that characterized solar behavior in the period from about 1900 through 1930¹⁸. A similar study has also shown—somewhat surprisingly—that variations in the ultraviolet spectral irradiance may not be as closely correlated with surface temperatures as those in total irradiance¹⁹. This may have much to say about differences in the climatic roles of variations in solar ultraviolet emission and in total irradiance.

With the launch and successful operation of the NASA Solar Radiation and Climate Experiment (SORCE) in 2003 these equally important precision radiometric measurements, spanning the solar spectrum with high spectral resolution from the far ultraviolet through the near infrared, are now being accumulated on a continuous, ongoing basis. Findings from SORCE, which also carries a TSI radiometer, should allow investigators to deconvolve observed changes in the TSI in terms of the relative contributions to the total integral from different spectral regions and emission lines.

Clarifying the Sensitivity of Climate to Changes in Solar Activity

The expected response of the mean temperature of the Earth's surface to a change of a given amount in solar irradiance is a fundamental parameter in numerical models of the climate system, and a particularly important element in any assessment of the role of solar variability in relation to other climate forcing mechanisms. In climate models, the relationship between a change in forcing ΔF and a resultant change in temperature ΔT is expressed most simply as

$$\Delta T = \lambda \Delta F$$

where the constant of proportionality λ is the climate *sensitivity*.

For a system in thermal equilibrium, the theoretical sensitivity of the mean temperature of the surface of the Earth to direct *solar irradiance forcing* can be approximated using a simple Stefan-Boltzmann radiation model. On this basis, and in the absence of any feedbacks, a 0.1% increase in TSI (the measured peak-to-peak change over an eleven-year solar cycle) would be expected to raise the mean surface temperature of the Earth by about 0.05°C.

It is of course more meaningful to determine the parameter empirically, as has recently been done, using sophisticated analyses of globally-complete meteorological data sets for the twenty-five year period for which direct measurements of TSI are available²⁰. When the known effects of the other dominant forcing mechanisms are subtracted—including El Niño/La Niña, volcanic eruptions, and the documented increases in greenhouse gases and atmospheric aerosols—a clear eleven-year modulation remains, in phase with the solar activity cycle. If one assumes that variations in solar irradiance are the cause, the amplitude of the apparently solar-driven modulation in surface temperature is about two times greater, as noted earlier, than simple theory would predict.

The discrepancy of a factor of two is in apparent agreement with a similar eleven-year response found in ocean temperature data sets, and with what might be implied, by extension to longer-term solar changes, in the case of the remarkable correspondence between features found in paleoclimatic data for the Holocene and proxy records of solar activity variations in the same period. A likely explanation of the apparent discrepancy, as noted earlier, is a non-linear feedback in the climate-system that amplifies the direct impacts of rather small changes in solar irradiance.

A recent investigation of climate attribution and climate sensitivity utilized ensemble experiments with a global coupled climate model to replicate global surface temperature data for the entire 20th century, and came to the same conclusion¹³. In common with other similar studies it was found necessary to combine solar and anthropogenic forcing (in the ratio of about 1:1) to explain the documented warming of the Earth in the first half of the century, while radiative forcing (by ever-increasing greenhouse gases and aerosols) dominated (overall by about 4:1) in the period from about 1940 onward. More significant in terms of climate sensitivity, was the model's *amplification* of the effects of changes in solar irradiance when these act in combination with anthropogenic forcing. The difference was traced to the fact that solar irradiative forcing, unlike greenhouse warming, is spatially heterogeneous and hence subject to regional feedbacks that involve temperature gradients and global circulation regimes such as Hadley and Walker circulations.

These and other results suggest that the effect of solar irradiance variability on climate depends to some degree on pre-existing conditions and on what else is at work at the time, and where, in the coupled climate system. If so, it may help explain the will o' the wisp nature of so many of the here-today, gone-tomorrow correlations that have been claimed through the years linking climate parameters with the sunspot cycle—including, among others, Norman Lockyer's purported discovery of an eleven-year monsoon cycle in British India in 1872 .

Evidence for Eleven-Year Solar Forcing in the Lower Atmosphere

It has been known for many years that the upper atmosphere of the Earth (at altitudes above about fifty kilometers) reacts emphatically and unequivocally to variations in both solar activity and solar irradiance, with dramatic changes, for example, in the electron density of the ionosphere and the temperature structure of the thermosphere and mesosphere¹⁴. Changes that are clearly related to the

eleven-year solar cycle have also be noted in the (density-related) heights of constant pressure levels in the lower half of the stratosphere²¹.

All of these more rarefied regions of the Earth's atmosphere are more directly exposed and in many ways more vulnerable to solar disturbances and solar variations, but they are but weakly linked—by virtue of enormous differences in density—to the realm of weather and climate in the underlying troposphere. While apparent solar-driven eleven-year effects have been noted through the years in limited regional weather records, it is only recently that climatically-significant signals of this sort have been found in *hemispheric* or *globally-averaged* tropospheric data sets of the type that are employed today for global climate change attribution.

One of these recent studies² was based on the analysis of radiosonde measurements of air temperature as a function of height from the surface of the Earth to the top of the troposphere, taken at weather stations around the world from pole to pole in the forty-year period from 1958 through 1999. When summertime measurements from heights of about 3 km to 12 km were averaged over the Northern Hemisphere, a clear eleven-year signal emerged, in phase with the solar activity cycle. Higher temperatures were found, as expected, in years of maximum solar activity. Further investigation of the entire global data set revealed patterns of systematic differences in the temperature response, in both sign and amplitude, as a function of both latitude and height above the surface. The nature of the differences suggests that the solar signal observed is imposed from the stratosphere, as a result of dynamical motions in the atmosphere.

A second and more recent study³, based on meteorological data for the entire globe for roughly the same period, from 1958 through 2001, found strong evidence in the included span of four solar cycles for a significant response to eleven-year solar forcing in all major meteorological observables throughout the troposphere in low and mid-latitudes, when signals due to other known sources of climate forcing were removed from the data. Corrections of this sort were made for El Niño/La Niña (ENSO) effects, volcanic eruptions, changes in atmospheric aerosols, and a linear trend attributed to global greenhouse gases. The meteorological parameters that were found to be strongly associated with solar forcing included the vertical (geopotential) density structure of the troposphere; zonally-averaged temperatures; zonally-averaged specific humidity; and averaged vertical velocity in the troposphere. Moreover, the patterns of geographic and altitude differences found in the responses of all of these parameters are consistent with the notion of an atmospheric response to

forcing by eleven-year, cyclic changes in solar irradiation that involves global-scale circulation processes, including the modification of the Hadley and Walker cell circulation systems that carry heat from equatorial to polar regions.

Evidence for Eleven-Year Solar Forcing in the Upper Ocean

Investigations into the role of the oceans as agents of climate change in the last several decades have focused on ocean-atmosphere interactions and affiliated internal modes of climate variability such as ENSO and the North Atlantic Oscillation; on subsurface heat storage in ocean basins; and on the causes and consequences of changes in the thermohaline circulation of the deep oceans.

Variations in solar irradiance are a potential forcing factor in each of these. In two recent studies involving different aspects of the oceans, the signatures of solar variability have been found, consistent in one case with the expected surface and subsurface responses from measured eleven-year cyclic solar irradiance variations. In the other, the apparent agreement is with the long and distinctive pattern of recurrent periods of prolonged suppression of solar activity identified in the tree-ring radiocarbon record.

The first of these^{4,5}, an extensive analysis of surface and subsurface temperature data for the Atlantic, Indian, Pacific, and global-averaged Oceans, spanning conditions from 20° to 60° N through the last 42 years, confirmed a more limited finding made in 1991 that varying solar forcing is a readily apparent feature in ocean surface temperature records²². The later investigation finds systematic decadal and interdecadal changes in ocean temperatures that are in phase with the eleven-year solar activity cycle. As such they are consistent with the forcing expected from now-documented changes in total solar irradiance, including the response of temperature as a function of depth in the upper layer of the ocean to depths of 80 to 160 meters.

These documented changes suggest that natural modes of the global climate system are phase-locked to the eleven-year solar activity cycle, although important questions remain. As noted earlier, if irradiance changes are the cause, the amplitudes of this apparent response of surface and subsurface ocean temperatures to solar forcing exceeds what is expected, based on conventional estimates of climate sensitivity and the damping effects of the thermal inertia of the oceans. The apparent enigma—here as in other recent examples of purported Sun-Climate connections—underlines our imperfect knowledge of the sensitivity

of various climate-related parameters to changes in solar forcing, as well as the likelihood that the different forcing factors and other sources of variability within the climate system are inevitably entwined and interrelated.

That subtle changes in solar irradiation might serve as a phase-locking device is in some ways similar to our present interpretation of the glacial-interglacial cycles of the Pleistocene in which the effects of relatively small changes in the distribution of solar insolation over the globe, arising from changes in the orbit of the Earth and the inclination of its axis of rotation, may have served as the pace-maker for the coming and going of the major glaciations.

Evidence of Past Solar Variability in Cosmogenic Nuclides

^{14}C and ^{10}Be are naturally-sequestered cosmogenic nuclides that serve as indirect, or *proxy* indicators of past changes in solar activity—and potentially, although not directly, of related changes in solar irradiance. Their recovery and analysis has confirmed the existence of prolonged episodes of major depression in the overall level of solar activity, such as the Maunder Minimum, and very much extended the span of retrievable solar history.

Cosmogenic nuclides are produced in the rarefied air of the middle atmosphere when high-energy particles of cosmic origin impinge on neutral atoms of nitrogen and oxygen. Each atom of ^{14}C that is created is the product of a direct hit by an incoming neutron on the nucleus of the most abundant isotope in the atmosphere, ^{14}N . In the process a proton is expelled, leaving behind a non-stable isotope of carbon of weight 14: the most abundant cosmogenic nuclide. The second most abundant, ^{10}Be , is produced by nuclear spallation when incoming, high-energy protons bombard and break apart neutral atoms of either oxygen or nitrogen.

The number of cosmic ray particles that reach the Earth to do this work is modulated by slow trends in the strength of the Earth's dipole moment, and also by a spectrum of shorter changes in solar activity, chiefly through scattering and deflection of these particles in their passage through the heliosphere. Fewer cosmic particles arrive to enter the Earth's atmosphere when the Sun is more active; more when it is less so. As a result the production rates of ^{14}C and ^{10}Be are strongly anti-correlated with solar activity, as confirmed by more than half a century of direct observation with neutron monitors at mountain top stations²³.

The radiocarbon that is produced in the mesosphere and stratosphere quickly combines with oxygen to form carbon dioxide, a part of which, in time, is ingested into the leaves of trees. There, through photosynthesis, CO₂ combines with hydrogen to form cellulose, and in this form the isotopic carbon of weight 14 is at last entrapped in annual rings of springtime growth. The ratio of ¹⁴C to ¹²C in a tree-ring reflects the average rate of production of radiocarbon in the atmosphere (and from this, the average flux of high-energy cosmic rays at the Earth; and from this, the average level of solar activity) during the several years that a molecule of carbon dioxide spends, on average, cycling among the atmosphere, biosphere, and ocean mixed layer.

Precision measurements of ¹⁴C/¹²C ratios in annual rings of the long-lived bristlecone pine have provided a continuous, proxy record of long-term changes in the level of solar activity through the last 11,000 years: since the end of the last Ice Age²⁴. As such, these data now extend the length of the historical, written record of solar activity by a factor of about thirty: and the eleven-year signal, though severely attenuated by smoothing in the exchange processes of the terrestrial carbon cycle, can be detected, albeit with difficulty, throughout. A more obvious and climatically more significant feature of the long record is the recurrence of repeated Maunder Minimum-like depressions in the overall level of solar activity, each persisting for thirty to about 100 years.

An independent verification of these insights into solar history has come from the analysis of ¹⁰Be in polar ice and deep-sea cores^{4,25,26}. Since the ¹⁰Be and ¹⁴C records are subject to quite different types of internal modulations, we can at first assume that features common to both of them point to the Sun as the most likely cause.

Cosmogenic ¹⁰Be is like ¹⁴C in that it accumulates in the lower stratosphere for a year or more before entering the troposphere. But unlike radiocarbon, it is deposited to the Earth's surface more promptly, through either precipitation or dry deposition, and is not biogeochemically recycled. The beryllium that reaches the surface in polar regions is entrapped in annual layers of fallen snow which are in time compressed and preserved as annual layers of hardened ice which are initially separated by lines of superficial thawing and refreezing. Since ¹⁰Be is rapidly scavenged by precipitation, its abundance in the atmosphere varies greatly on all time scales. Because of this, changes in the ice-core record of ¹⁰Be can be due to non-local shifts in meteorology and precipitation patterns.

Unlike ^{14}C , which in the form of CO_2 is well mixed throughout the global atmosphere, the amount of ^{10}Be that accumulates on the surface of the Earth varies considerably from place to place, as it is very much a function of the amount of rain or snow that has fallen there, and hence of local and regional weather patterns. Variations found in layers of snow and ice at any site can be corrected for local precipitation effects, but corrections for non-local meteorological variations in the delivery of ^{10}Be to the ice caps is not possible.

Nevertheless, sequestered in a much older repository, and with a half life of 1.5 million years (compared to 5730 for ^{14}C) ^{10}Be in ice offers the potential of extending the reach of recorded solar history in the deepest, Greenland cores more than 200,000 years into the past, and potentially, in the deepest Antarctic cores, to as much as 400,000 years, through a number of glacial-interglacial cycles: in all, a span of time that represents the best documented and most intensively studied period of the climate history of the Earth.

Since the ^{10}Be record is capable of much higher temporal resolution than ^{14}C , what may be more valuable is the prospect of high resolution year-by-year information on changes in solar activity through the last several thousand years, derived from analyses of ice nearer the surface, where annual layers of ice are more clearly preserved. In either case, what these proxy indicators tell us directly about the Sun is of apparent changes in solar magnetic activity, which is a big step removed from what climatologists would most like to know.

Solar Influence on North Atlantic Climate during the Holocene

A more recent oceanographic study, based on reconstructions of the North Atlantic climate during the Holocene epoch, has found what may be the most compelling link between climate and the changing Sun: in this case an apparent regional climatic response to a series of prolonged episodes of suppressed solar activity, like the Maunder Minimum, each lasting from 50 to 150 years⁸.

The paleoclimatic data, covering the full span of the present interglacial epoch, are a record of the concentration of identifiable mineral tracers in layered sediments on the sea floor of the northern North Atlantic Ocean. The tracers originate on the land and are carried out to sea in drift ice. Their presence in sea-floor samples at different locations in the surrounding ocean reflects the southward expansion of cooler, ice-bearing water: thus serving as indicators of changing climatic conditions at high Northern latitudes. The study demonstrates

that the sub-polar North Atlantic Ocean has experienced nine distinctive expansions of cooler water in the past 11,000 years, occurring roughly every 1000 to 2000 years, with a mean spacing of about 1350 years.

Each of these cooling events coincides in time with strong, distinctive minima in solar activity, based on contemporaneous records of the production of ^{14}C from tree-ring records and ^{10}Be from deep-sea cores. For reasons cited above, these features, found in both ^{14}C and ^{10}Be records, are of likely solar origin, since the two records are subject to quite different non-solar internal sources of variability. The North Atlantic finding suggests that solar variability exerts a strong effect on climate on centennial to millennial time scales, perhaps through changes in ocean thermohaline circulation that in turn amplify the direct effects of smaller variations in solar irradiance.

This striking correspondence between North Atlantic climate and periods of suppressed solar activity during the Holocene has not surprisingly been interpreted as evidence of a dominant Sun-Climate connection. If so, it may (or may not) be driven by slow and as yet unobserved changes in solar irradiance. But to produce so strong and unflinching a response, the solar driving forces—whatever their origin—would probably need some assistance, if what we now know of the bounds of solar variations of any kind applies on these longer time scales. The most likely accomplice seems at this time to be often-invoked positive feedbacks of one kind or another in the climate system itself.

There is still a nagging question, in some minds, as to whether major shifts in climate might on their own produce the well-correlated fluctuations seen in records of ^{14}C and ^{10}Be . For reasons noted earlier, were this the case, this trick of Nature would have to be accomplished through two quite different processes: one through climate-dependent shifts in the operation of the terrestrial carbon cycle, and the other through climate-related shifts in the large-scale circulation of the atmosphere and their effects on precipitation in polar regions. Were this the case, however, it could more simply explain the lock-step correlations in Holocene records that link surface temperature, ^{14}C , and ^{10}Be —and with no need for the Sun at all. What it would not explain is the close correspondence between historical observations of solar activity and contemporaneous records of ^{14}C and ^{10}Be . These as yet unresolved issues are at the forefront of Sun-Climate research today.

Clearer Pictures of Climate History and the Climate System

While some facts were known about the surface of the Sun, two hundred years ago when Sir William Herschel proposed a causal connection between sunspots and the price of wheat, next to nothing was known about what we now call climate, as opposed to short-term weather: how constant or inconstant it is or has been, regionally or globally; how the climate system works; and what can trigger lasting changes. The same was true almost a century later when Sir Norman Lockyer laid his claim to having unlocked the secrets of the Indian monsoon.

That is no longer the case, due to our present ability to observe and study global phenomena from the vantage point of space; a very much increased emphasis on the study of climate and paleoclimate within the atmospheric science community; technological and analytical advances that allow more detailed and comprehensive reconstructions of past climate; the availability of readily accessible climate data and paleoclimate records in digital form; and the impetus of world concerns regarding impending global climate change. Important among these advances were:

- the evolution of numerical models of global atmospheric circulation;
- oceanographic, hydrological, and biological studies that led to the concept of an interactive climate system and ultimately, the development of models of the coupled climate system;
- extensive, contemporaneous global records of essential climatic parameters, such as cloud cover, sea ice, ocean conditions, land use, and other tropospheric and stratospheric data to constrain and improve the models to reveal climate forcing, feedbacks, and responses;
- advances in geochemistry that allow paleoclimatologists to read the climatic information preserved in datable natural diaries, including tree-rings, ice and deep-sea cores, coral deposits and lake sediments, and the technological advances and commitments that have allowed the recovery of these invaluable records; and
- the unprecedented, internationally-mobilized efforts in this and the last decade of the Intergovernmental Panel on Climate Change²⁷ to advance our understanding of past climate and the global climate system and in response to societal needs to predict the future course of climate, including the impacts of solar variations.

The products of these developments in modern climatology that are of particular value to Sun-Climate science are

- a vast extension in both time and space of what is known of past climatic changes, in both the recent, historical past and the Holocene and Pleistocene epochs;
- analytical models of the coupled climate system to test proposed mechanisms of Sun-Climate connections in a detached and wholly objective way; to explore the sensitivity of various climate parameters to solar perturbations of various kinds; and for climate attribution studies; and
- impetus and support for the continued development of fully coupled physical and chemical models of the entire atmosphere, from top to bottom, to test a variety of proposed mechanisms that might link solar-induced variations in the upper atmosphere to conditions in the troposphere.

III. SUN-CLIMATE RESEARCH IN THE NASA *LIVING WITH A STAR* PROGRAM

The Sun is the only star in the sky on which we completely and utterly depend. It is also inconstant. We who are fortunate enough to live on the only habitable planet in the realm of the star can at least try to understand it, including the nature and extent of its variations, and all the risks involved.

Living With a Star is a NASA initiative employing the combination of dedicated spacecraft with targeted research and modeling efforts to improve what we know of solar effects of all kinds on the Earth and its surrounding space environment, with particular emphasis on those that have significant practical impacts on life and society. The highest priority among these concerns is the subject of this report: the potential effects of solar variability on regional and global climate, including the extent to which solar variability has contributed to the well-documented warming of the Earth in the last 100 years.

Understanding how the climate system reacts to external forcing from the Sun will also greatly improve our knowledge of how climate will respond to other climate drivers, including those of anthropogenic origin.

A parallel element of the LWS program addresses solar effects on “space weather”: the impulsive emissions of charged particles, short-wave electromagnetic radiation and magnetic disturbances in the upper atmosphere and near-Earth environment that also affect life and society. These include a wide variety of solar impacts on aeronautics, astronautics, electric power transmission, and national defense. Specific examples are (1) the impacts of potentially-damaging high energy radiation and atomic particles of solar origin on satellites and satellite operations, spacecraft electronics systems and components, electronic communications, electric power distribution grids, navigational and GPS systems, and high altitude aircraft; and (2) the threat of sporadic, high-energy solar radiation to astronauts and high altitude aircraft passengers and crews.

Elements of the LWS program include an array of dedicated spacecraft in near-Earth and near-Sun orbits that will closely study and observe both the Sun itself and the impacts of its variations on the Earth’s radiation belts and magnetosphere, the upper atmosphere, and ionosphere. These spacecraft,

positioned to study and monitor changing conditions in the Sun-Earth neighborhood, will also serve as sentinels of solar storms and impulsive events.

The program also supports targeted scientific and technological research that addresses specific questions and challenges in both Sun-Climate and Space Weather. More information can be found at <http://lws.gsfc.nasa.gov>

The LWS program is a part of the Sun-Earth Connection (SEC) theme within the NASA Office of Space Science. Earlier and ongoing measurements from space (of total solar irradiance, whole-Sun spectral irradiance and the dynamics and chemistry of the upper and middle atmosphere) that have given new meaning and impetus to the study of solar influences on weather and climate have been supported by other missions and themes within the complementary NASA Office of Earth Science, and by other federal agencies.

A Rationale for Research Priorities

The primary research emphasis in this report is on longer-term (i.e., decadal to millennial) solar and climatic changes as opposed to the shorter-term events that are triggered in the outer atmosphere by solar flares and coronal mass ejections or by variations in the solar wind, including the passage of solar sector boundaries. Systematic changes in some of these faster and more impulsive events may indeed perturb short-term weather and longer-term climate. Moreover, investigations of shorter-term impacts of solar variability can also serve a more general need of probing the response of the atmosphere to different kinds of solar stimuli.

The explicit emphasis of the *Living With a Star* program is on those effects of solar variability that have significant practical impacts on life and society. The consequences of changes in the climate, and the societal benefits of understanding and foreseeing the future course of pervasive climatic changes is in our view a compelling reason to focus Sun-Climate research in the LWS Program on the effects of solar changes that operate on time scales of years to decades and longer: the timescales for which persistent external forcing of the climate system is most likely to exert a significant effect. The response of the weather and climate system to external forcing is much a function of duration and persistence, due to the thermal inertia of the atmosphere and land and ice and particularly the oceans, and the time-scales of many atmospheric and oceanic processes

Equally important in our view is an initial primary emphasis on the climatic effects of variations in the *electromagnetic radiation* from the Sun, as opposed to possible but less direct effects of incoming *solar particles and fields*. We also recommend an added emphasis on two radiative processes: direct heating by visible and infrared irradiation; and the less direct effects of varying near-ultraviolet radiation (and possibly, from changes in the flux of incoming energetic electrons from the Sun) on stratospheric ozone.

Changes in these forcing factors are not the only external impulses that the climate system senses from the Sun. Nor are they the most highly variable. But unlike the effects of solar particles and fields, whose impacts are largely spent on the upper atmosphere, changes in irradiance reach the lower atmosphere directly. The radiative changes are also the most energetic, and by orders of magnitude, as is evident in the table below.

This is not meant to discourage the careful investigation of any other probable Sun-Climate mechanism—such as the possible effects of solar particles or cosmic rays on high-level cloud nucleation²⁸ or on the scavenging of aerosols²⁹, for example—for these may prove important.

In truth, beyond the long-established connections that link changes in solar ultraviolet radiation to atmospheric ozone, we do not know which of the Sun's ever changing outputs is responsible for any apparent climatic response to eleven-year and longer solar variability. Nor do we know with any certainty the chain of possibly nonlinear processes through which these changes may ultimately perturb the climate system. But faced with these uncertainties we think it prudent to examine first and thoroughly the most likely solar suspects, and those that are most capable—by virtue of the relative energies that are involved—of direct effects on the climate system.

Table 1. Examples of the magnitude and variability of solar energy inputs to the Earth (based on reference 14)

Source	Total Energy (W m ⁻²)	Solar Cycle Change (W m ⁻²)	Solar Cycle Change (percent)	Level of Deposition in the Earth's Atmosphere
SOLAR RADIATION				
Total irradiance	1366.	1.3	0.1	Surface and throughout atmosphere
Visible and near-Infrared 300-1200 nm	1090.	1.1	0.1	Surface and Troposphere
Near ultraviolet 200-300 nm	15.4	.16	1.0	10-50 km
X-Ray and UV 0-200 nm	0.1	.02	20.	50-500 km
ENERGETIC PARTICLES				
Solar protons	0.002			30-90 km
Galactic cosmic rays	0.000007			0-90 km
SOLAR WIND				
	0.0003			Above 500 km

Particular attention in the *Living With a Star* program should be given to the underlying question of the relative role of the Sun in the context of other sources of climate forcing, including especially those of anthropogenic origin. Toward this end the program should focus on those research questions that most limit our ability to make this important assessment.

The greatest potential benefit to life and society will come with a realization of the ultimate end-product of Sun-Climate research, which is the ability to predict the course of solar variability and its likely effects on global and regional climate decades in advance. This can only come from a more complete understanding of the mechanisms within the Sun that produce long-term changes in solar activity

and irradiation and a fuller knowledge of the impacts of solar variations of all kinds on regional and global climate.

**THE IMMEDIATE GOAL OF SUN-CLIMATE RESEARCH
IN THE LWS PROGRAM**

To identify clear mechanistic pathways
relating solar variability to climate change;
to quantify the processes involved; and
to determine their impacts
in the context of other climate change mechanisms

THE LONG-TERM CHALLENGE

To develop the capability of predicting the effects of solar variations on climate
decades in advance

IV. UNANSWERED QUESTIONS

In what follows we assign high priority to four basic questions in modern Sun-Climate research that currently limit more definitive assessments of the role of solar variability as an agent of climatic change. These are followed by an accompanying set of related issues which are defined in more detail.

The first two of the high priority set address the basic question of the sensitivity of climate to solar forcing, in the context of other contributing agents and within a system that depends to some degree on existing conditions and the interplay of multiple climate forcing factors.

The third—which is specifically relevant to remaining uncertainties in the issue of global greenhouse warming—is the question of whether the solar irradiance exhibits slower variations of longer-term that may surpass the 0.1% rms amplitude that has been found to accompany the eleven-year activity cycle. A clearer specification of the impact of solar variability on the documented global warming of the last 100 years hinges at present on a reliable answer to this one pragmatic question.

The fourth question addresses the issue of climate attribution, in calling for new analyses of historical and paleoclimatic data to examine the impacts of established variations in solar activity on regional and global climate. These re-examinations of the cold case files of solar and climate variations would address three overlapping eras of varying data quality. The most reliable is of course the twenty-five-year span of continuous measurements of the TSI, from late 1978 to the present day. The second is the overlapping, roughly 150-year modern era of instrumented weather and climate records which is as well the period of the most complete records of solar surface activity. The third is the full span of the present interglacial epoch, to about 10,000 years ago: a period of time that includes repeated instances, like the Maunder Minimum, of prolonged episodes of suppressed solar activity. These priority periods, and a general strategy for addressing them, are described in more detail in Section VI.

Four High-Priority Questions In Sun-Climate Research

- The paradox of greater-than-expected climatic sensitivity: why is the surface temperature of the Earth, in both the air and the oceans, more sensitive to eleven-year, cyclic changes in solar activity than simple radiative theory would predict? What other climatic feedbacks or solar variations are involved?
- Which solar forcing mechanisms, radiative or non-radiative, are climatically significant, when the causal chain of each of them is quantified and tested? How do they interact in conjunction with other climate forcing factors such as global greenhouse warming, or with internal variability processes such as NSO, NAO, or with changes in the thermohaline circulation in the oceans?
- Are there longer-term, climatically-significant variations in solar irradiance in addition to the 0.1% surface-activity-related modulation that accompanies the eleven-year solar cycle? What are the sources of any of these purported, slower changes?
- What were the effects of solar variability on climate during:
 - o the last 25 years (the period of continuous direct measurement of the total solar irradiance)?
 - o the last 150 years (the era of modern instrumented weather records and synoptic photographic coverage of the solar disk)?
 - o the last 10,000 years (the Holocene interglacial epoch that includes the Maunder Minimum and twelve similar episodes of suppressed solar activity)?

Answers to these and other questions of current interest in Sun-Climate research will obviously depend on a deeper understanding in a number of related issues, some of which are stated and described in more detail below. Progress will also require continued synoptic monitoring of a critical set of essential Sun-Climate parameters and a number of focused Sun-Climate studies and other auxiliary activities, which are described in tabular form in Section V.

Some Important Related Issues

1. What do proxy indicators of long-term solar activity tell us about changes in the solar total or spectral irradiance? Or of climatically-significant changes in other variable outputs of the Sun?

Most of what we know about solar variations of longer term (and practically all that is known of solar variations before the era of the astronomical telescope) has been learned from the interpretation of ^{14}C and ^{10}Be in dated tree-rings and in ice and deep-sea cores. What these records tell us about the Sun, however, deals only with changes in solar magnetic activity. What we know best in the deductive chain through which these proxy data are interpreted is the long-established connection linking the atmospheric production rate of these cosmogenic nuclides to solar surface activity, expressed in terms of conventional solar activity indices²³. From the analysis of spacecraft measurements and other solar observations we also know the expected *effects* of eleven-year variations in solar activity on the solar radiation received at the Earth, as documented during the last twenty-five years. By combining these two findings, researchers have also endeavored to extend the interpretation of the cosmogenic nuclide records in terms of probable past changes in solar irradiation^{6,9,11,12,22}.

The important distinctions between changes in solar *activity* and changes in solar *irradiance*, and between *observed* irradiance changes and those that are theoretically *derived*, can all too easily be “lost in translation” — and sometimes are — when these arcane data sets from solar physics are employed in climate studies and climate models.

For these and more fundamental reasons it would be of immense value were we to find a way to interpret the cosmogenic, proxy indicators of solar

activity in terms of past changes in solar irradiance, more directly and with fewer assumptions.

To do this, we need first a better understanding of the processes through which fluxes of incoming high-energy cosmic rays are modulated in the heliosphere by changing solar magnetic activity. We need next a more complete picture, or whole-Sun model, of the solar magnetic fields that (1) on the surface of the Sun modulate solar irradiance, and (2) by their extension through the corona and into the heliosphere modulate at the same time the flux of high energy galactic cosmic rays. We also need to establish the impacts on all solar outputs—including total and spectral irradiance—of long-term changes in solar activity such as the Maunder Minimum; and whether the amplitude of irradiance changes associated with these episodes falls within the bounds of the eleven-year, 0.1% peak-to-peak changes that have been found to accompany the eleven-year solar activity cycle.

2. Are there other natural archives that contain useful information regarding past changes in solar activity and solar radiation?

^{14}C and ^{10}Be are the two most abundant of a number of cosmogenic nuclides whose production in the upper atmosphere is modulated by solar activity. The paths and processes through which each of them is eventually sequestered at the surface of the Earth are quite different, as are their half lives, and they are more valuable as solar tracers because of these differences.

What is clear is that two sources of evidence are better than one. And that more would be helpful, including perhaps, the recovery and interpretation of other, albeit less prevalent cosmogenic isotopes or other geochemical tracers. For example, there may be additional information, as yet unread, in the cellular structure or chemical make-up of the cells that comprise dated growth rings in trees.

Most valuable for studies of the Sun and climate would be natural tracers that tell not of solar activity but directly of solar irradiance, total or ultraviolet, or changes in atmospheric ozone. Some of these may indeed exist. Coral deposits grow, like trees, in annual surges, as do the shells of many mollusks. These bands or “annulations” result from seasonal changes in the temperature of ocean water near the surface that affect the production of calcium carbonate. Tropical coral deposits are cored, like ice, to recover

climatic information of this kind which can be read in terms of annual changes in the combined effects of solar radiation, meteorological conditions (particularly those associated with ocean salinity changes, precipitation and evaporation), and the depth and temperature of the ocean where corals grow.

3. What are the direct or indirect roles of solar near-ultraviolet, visible, and infrared radiation in heating the troposphere, the land surface, and the oceans?

Climate models that include external solar forcing are generally cast in terms of the total energy received from the Sun in all wavelengths: i.e., the total solar irradiance (TSI) incident on the top of the Earth's atmosphere, and the relative changes in that quantity. Some of these, as well as models of the middle and upper atmosphere, employ changes in solar spectral irradiance.

The climate system is driven by photochemical and radiative transfer processes that are highly spectrally-sensitive and that bear little resemblance to a black body cavity with a little hole in the front. As an example, the visible and near infrared portions of the solar spectrum account for about 80% of the TSI. If the activity-related variation in that 80% is mainly in the visible portion (which is largely absorbed at the solid and liquid surface of the Earth) it will have quite different impacts on climate than were it chiefly in the infrared, which is absorbed in the free atmosphere.

Other equally-important distinctions include the spectrally-specific responses of the photochemistry in the stratosphere involving the more variable solar ultraviolet; the equally-selective response of greenhouse gases to radiation in different spectral bands in the ultraviolet and infra-red; the wavelength-dependent absorption and scattering in the photoptic zone of the upper ocean; and the wavelength dependence of the albedo of the Earth surface, due to differences in the reflective properties of vegetation and soils, and the marks of man.

The wavelength-dependence of solar variability and terrestrial response are intrinsic elements in estimates of climate sensitivity to solar forcing. Differences in the amplitudes of different spectral responses may well be involved in the apparent mismatch between the expected effects of changes in TSI based on simple heating and the larger apparent responses that are found in certain climate data sets.

The blackened cavities of solar radiometers that entrap and measure TSI are by design blind to wavelength and sense only the integral of all changes in the spectrum of solar radiation, yet different spectral components change in different ways. The solar output in the visible and near infrared varies only slightly with solar activity and solar rotation, while the shortest wavelengths, which originate at hotter and higher levels in the solar atmosphere, change by orders of magnitude. It is for this reason somewhat surprising that reconstructed, year-by-year variations in UV spectral irradiance for the last 100 years appear to be less well correlated with the global mean surface temperature record than are those in reconstructed solar irradiance¹⁹.

Considerable data already exist regarding past changes in UV spectral irradiance, as well as models of expected changes in whole-Sun spectral emission in the UV, visible and infrared, as a function of changing solar activity⁹. Much could be done with these existing resources and tools to examine more closely the effects of the spectral components of changing irradiance on climate.

With more extensive and continuous data from the SORCE mission there will be additional opportunities to examine the effects on climate of variations in the different spectral components that make up the TSI.

4. Through what mechanisms do changes in solar activity, and solar-induced changes in stratospheric ozone, excite or affect internal variability modes in the atmosphere, such as ENSO and the North Atlantic Oscillation?

Quasi-periodic modes of internal variability in the coupled oceans and atmosphere are now thought to dominate short-term climatic changes on time scales of one to five years or more. Best known and most thoroughly studied are the phenomena known as El Niño and La Niña: persistent warming or cooling of the surface waters of the tropical eastern Pacific Ocean that can perturb the climate of much of the Earth for several years at a time. They are closely linked to a large scale, see-saw in sea-level air pressure between areas of the western and eastern Pacific Ocean known as the Southern Oscillation. A similar phenomenon of comparable importance to global climate is the North Atlantic Oscillation, or NAO: a corresponding see-saw in air pressure between regions of the North Atlantic Ocean.

Some studies of climate suggest that the amplitude and other characteristics of ENSO, for example, may be very much altered by other climate drivers, such as global greenhouse warming. Persistent changes in solar heating, through changes in total or spectral irradiance, or through less direct solar forcing, may also provoke or amplify internal oscillations of this kind, particularly when geographic differences in insolation are also taken into account.

Solar-induced changes in stratospheric ozone could as well affect these modes of internal variability. For example, changes in stratospheric ozone may change zonal-mean temperature gradients and thus zonal-mean winds. These induced changes, if sufficiently large, can enhance the frequency of stratospheric sudden warmings, whose effects are communicated to the troposphere where they can influence the behavior of internal variability.

5. Through what mechanisms do changes in solar activity and irradiance alter the thermohaline circulation of the ocean?

The oceans, by virtue of their extent, circulation, and enormous thermal capacity, are of obvious importance as an agent of both climate stability and climate change. They are also the source of much of what is known of the climate of the past.

The climate of the recent Pleistocene epoch, from about 60,000 to 10,000 years BP is now known to have undergone a long series of rapid warming events, with abrupt jumps in air temperature of 6° to 10° C that took place in the span of a few years to at most a few decades. Evidence for these rapid “flickerings” of the Ice Age climate, persisting for a few hundred to a few thousand years, came first from the Greenland ice cores³⁰. Precisely the same pattern was later found as well and as clearly in planktonic evidence from deep sea cores from the Caribbean and the coast of California, confirming the hemispheric and possible global nature of these events.

Changes in the global circulation of the deep ocean, in particular, are believed to have played an important role in these abrupt climatic changes of the past. The three-dimensional, thermohaline circulation of the global ocean is driven by differences in the density of sea water in adjoining ocean basins. Denser water in colder oceans subsides, and is driven horizontally along the ocean bottom to warmer basins where the water is less dense. Surface evaporation

increases the salinity and also the density of sea water with similar effects on vertical and horizontal circulation.

Irradiance changes due to solar variability can be expected to alter ocean surface temperatures as well as surface evaporation and hence salinity. These effects, coupled with geographic differences in land forms and the inevitable heterogeneity in the distribution of solar irradiation, can alter to some degree the regional and global patterns of thermohaline circulation. One interpretation of recent findings of a strong solar signal in paleoclimate records from the sub-polar North Atlantic is the possible amplification of thermohaline circulation patterns by relatively small changes in solar irradiance at high latitudes⁸.

6. What can be learned of longer-term variations in solar activity and irradiance from studies of Sun-like stars?

There are an untold number of stars in the sky that are much like the Sun in terms of evolutionary age and mass and diameter. While they are too distant to be optically resolved, many examples now exist of stars that exhibit cyclic activity, like the Sun, but over a wider range of variation. Some give evidence of Maunder-Minimum-like episodes of suppressed magnetic activity. In the last few decades, a number of observing programs have been devoted to monitoring and interpreting different samples of Sun-like stars, through ongoing spectral and photometric observations—with the aim, in part, of extending what we know about the Sun itself.

As noted earlier, an early interpretation of some of these data⁷ seemed to substantiate, by extension to the Sun, the possibility of slow variations in solar irradiance, accompanying decades-long epochs of suppressed magnetic activity, with amplitudes several times larger than the rms amplitude of eleven-year variations that was then evident in the relatively short span of existing measurements of the TSI. On this basis of presumed stellar analogues, longer-term changes such as the Maunder Minimum—evident in the direct and proxy records of solar activity—were conditionally interpreted in terms of slow changes of 0.2% to 0.5% in total solar irradiance. Estimates in this range were then applied to the historical record of sunspot activity to reconstruct likely changes in total solar irradiance through last several hundred years⁶.

These qualified reconstructions of past changes in solar irradiance, which were based quite explicitly on assumed long-term changes that have yet to be observed, have been subsequently adopted in a growing number of climate models and climate attribution studies¹³. They were also initially interpreted as evidence that much if not all of the global warming of the last 100 years could be attributed to natural as opposed to anthropogenic causes³¹.

Subsequent studies of Sun-like stars and of the documented behavior of the Sun itself during an early 20th century minimum in solar activity have called the original interpretation of the stellar data into question³². What seems more likely today is that the unusually inactive stars that were originally sampled were not the same but somewhat different from the Sun, rather than “solar analogs caught passing through a Maunder Minimum phase.” This revised interpretation obviously affects at least some of the conclusions drawn in climate model studies that utilized reconstructed values of solar irradiance. Further resolution of these uncertainties is obviously very important in Sun-Climate research.

V. REQUISITES FOR PROGRESS IN SUN-CLIMATE RESEARCH

Our perception of the most likely current needs in Sun-Climate research is summarized below, in three categories. The first and highest priority overall is our assessment of the essential parameters that need to be monitored on a long-term, daily basis. The second lists needed modeling and process studies, in approximate order of priority. The third category includes related studies that can contribute to the overall understanding of Sun-Climate processes and to the ultimate, longer-term goal of predicting climatically significant solar variations, years or decades in advance.

The scientific rationale for including each item is also briefly stated.

A. Long-Term Synoptic Monitoring of Essential Sun-Climate Parameters

Need	Scientific Driver
Total solar irradiance (TSI) from an overlapping sequence of intercalibrated spacecraft missions, to extend the present record for at least another fifty years	Needed (1) to document possible changes of decadal and longer scale; (2) to determine climate sensitivity; (3) for climate-change attribution for the period (1978 to the present) in which these direct measurements are available; and (4) to aid the development of analytical models of both the Sun itself and the physical connections linking the production of cosmogenic nuclides, solar magnetic activity, and changes in TSI, in order to advance the interpretation of the ¹⁴ C and ¹⁰ Be proxy data

<p>Whole Disk Spectral irradiance from a series of overlapping intercalibrated instruments, including those aboard the presently operational UARS, TIMED and SORCE missions, in wavelengths from at least 120 to ideally 2000 nm</p>	<p>Needed (1) to specify the relative contributions of irradiance changes in different spectral regions to observed changes in TSI; (2) to explore the direct impacts of these changes on various climatic parameters; (3) to refine our understanding of the climatic impacts of solar-induced changes in stratospheric ozone; (4) to improve modeled simulations of mesosphere-stratosphere-troposphere interactions; (5) for inputs to GCMs that include interactive photochemistry and the effects of changing solar UV radiation on ozone, temperature and circulation; and (6) for studies of the penetration and impacts of solar irradiance of different wavelengths in the surface layers of the ocean</p>
<p>Atmospheric parameters such as tropospheric, stratospheric and mesospheric temperature; geopotential structure, relative humidity and vertical velocities throughout the troposphere; and ozone at all levels in the atmosphere</p>	<p>Needed for climate monitoring, process studies, and climate model validation</p>
<p>Fluxes of solar protons, electrons and other precipitating energetic particles</p>	<p>Needed to further the investigation of the influence of these high energy particles on the production of nitric oxide (NO) in the lower thermosphere, mesosphere and upper stratosphere; the subsequent downward transport of NO into the middle and lower stratosphere; and the catalytic effect of NO on the ozone abundance in all these regions</p>

B. Focused Sun-Climate Studies

Need	Scientific Driver
<p>Clarification of (1) the processes through which changes in solar magnetic activity modulate the Earth's receipt of high energy cosmic rays, and (2) the association of these processes with the flow of radiative energy from the solar surface</p>	<p>Needed to establish whether and how solar irradiance variations can be deduced from ^{14}C and ^{10}Be proxy records of solar activity, and the sources and extent of the uncertainties that are involved in these deductions</p>
<p>Comparisons of ^{14}C and ^{10}Be data, and of cosmic ray (neutron monitor) and ^{10}Be data using atmospheric models of ^{10}Be for periods of time in which these pairs of data overlap</p>	<p>Needed to improve our understanding of the reliability and limitations of these proxy indicators of solar activity</p>
<p>Tests of the reliability and validity of reconstructions of past changes in solar and spectral irradiance based on records of solar surface activity</p>	<p>Needed to clarify the feasibility and limitations of recovering past changes in solar irradiance and to explore ways of improving techniques for achieving this end</p>
<p>Utilization of suites of specific meteorological and oceanographic observations selected to test and clarify specific Sun-Climate connections, such as the eleven-year cycle often seen in $^{18}\text{O}/^{16}\text{O}$ data in polar ice cores and the larger than expected eleven-year signals found in tropospheric parameters and in ocean surface and subsurface temperatures; and to identify possible dynamical or other feedbacks that may amplify the effects of solar variability</p>	<p>Needed to investigate the nature of suspected Sun-Climate connections and to identify the physical and chemical processes involved</p>

<p>Investigation of the climatic consequences of geographic differences in the effects of varying solar total and spectral irradiation at the Earth's surface, including effects on Hadley and Walker cell circulation, on internal variability modes, and on the thermohaline circulation of the oceans</p>	<p>Needed to explore the likely feedback processes that may enhance the sensitivity of climate to changes in solar irradiation</p>
<p>Examination of the direct effects of solar near-UV, visible and infrared heating on the troposphere and the stratosphere</p>	<p>Needed (1) to specify more accurately the solar inputs to GCMs and global climate models; (2) for improving estimates of the sensitivity of climate to solar radiative forcing; and (3) for climate change attribution</p>
<p>Investigation of the possible excitation and amplification of internal variability modes in the atmosphere (such as ENSO and NAO) by solar activity-related changes, including solar-induced changes in stratospheric ozone</p>	<p>Needed to specify more accurately the solar inputs to GCMs and global climate models; for improving estimates of the sensitivity of climate to solar radiative forcing; and for climate change attribution</p>
<p>Examination of the effects of changes in near-UV, visible, infrared and total solar irradiance on the thermohaline circulation of the oceans</p>	<p>Needed to explore and specify the role of solar variations in long-term climatic changes that are driven by changes in the circulation of the deep oceans</p>
<p>Investigations of radiative and dynamical coupling between the stratosphere and troposphere</p>	<p>Needed to further our knowledge of the mechanisms through which solar-induced changes in stratospheric ozone can affect regional and global climate</p>

C. Needs for Improved Understanding

Need	Scientific Driver
<p>Development and testing of comprehensive physical models of the solar dynamo and the entire Sun, capable of replicating the eleven and twenty-two year solar cycles and also longer-term changes in the overall level of solar activity, such as the Maunder Minimum; and capable of predicting year-to-year and decadal changes in any solar output that can affect climate</p>	<p>Needed (1) for climate-change attribution and prediction; and (2) to enhance our ability to interpret past changes in solar activity in terms of their climatic effects</p>
<p>Studies of extant observations of the strength, polarity and topology of solar magnetic fields from the photosphere through the heliosphere to the orbit of the Earth, including vector magnetograms of the visible hemisphere of the Sun and direct measurements of the magnetic field in the solar polar regions</p>	<p>Needed (1) to understand, model and predict eleven-year and longer-term changes in solar activity; and (2) to improve our understanding of the mechanisms through which the extended magnetic field of the Sun modulates the flux of high energy galactic cosmic rays at the Earth and hence the production of the cosmogenic nuclides that serve as proxy measures of past solar activity</p>
<p>Investigation and definition of solar subsurface structures related to active regions, obtained through high spatial resolution helioseismology from space</p>	<p>Needed to advance our understanding of the solar dynamo and the origins of variations in solar total and spectral irradiance on all time scales</p>

<p>Continued measurements of the fluxes of high-energy cosmic rays, ideally from monitors in near-Earth orbit</p>	<p>Needed (1) to study the effects of changing solar activity on the real-time production of ^{14}C, ^{10}Be and other cosmogenic nuclides, in order to advance our understanding of the uses and limitations of these sources of proxy data; and (2) to help resolve the question of whether cosmic rays exert a climatically-significant effect on cloud nucleation, and hence on the receipt of solar irradiance at the surface of the Earth</p>
<p>Photometric monitoring and spectroscopy of Sun-like stars, to extend what is known of the expected bounds of solar variability</p>	<p>Needed (1) as a way of testing and adding information to our present understanding of long-term solar behavior, and particularly the reality and expected recurrence of periods of distinctly different solar behavior such as the Maunder Minimum; (2) to improve our present estimates of the expected range through which solar activity and solar radiation may vary, on all time scales; and (3) to aid the development and testing of models of solar variability</p>
<p>Studies of extant data describing the composition, speed, turbulence and polarity of the solar wind, from the inner corona to the orbit of the Earth</p>	<p>Needed to explore the role of charged particles of solar origin in modulating the flux of high energy galactic cosmic rays at the Earth</p>

VI. PRIORITIES AND ESSENTIAL ELEMENTS FOR A VIABLE SUN-CLIMATE RESEARCH EFFORT

Slices of Time that Warrant Particular Study

Closer and more organized examinations of available climate and solar data from specific periods in the past can advance our understanding of the sensitivity of climate to solar forcing under various conditions, including the pre-existing state of the climate system, and help identify possible Sun-Climate processes. They can also illuminate areas where additional data, now unavailable, are needed.

The three periods which are summarized below are those cited in Section III for emphasis in the *Living With a Star* Program.

An obvious first choice for intensive study (sample “A”) is the last twenty-five years, the period for which the most complete and reliable data, both solar and climatic, are available and readily accessible. These include the only direct, continuous measurements of TSI; extensive observations of near-Earth space, including the fluxes of charged particles of solar origin; the most continuous and comprehensive records of temperatures in the upper oceans; and modern, extensive meteorological and stratospheric data, from surface stations and from space, covering most of the globe.

These diverse data sets, which already exist, can be put together and carefully analyzed in a systematic way, with the goal of examining direct and indirect effects of known solar forcing, including possible nonlinear interactions between different forcing mechanisms in the climate system. An organized campaign of this nature—based not so much on *data taking* as on what might be called *data mining*—could prove of inestimable value in clarifying the role of solar variability in the coupled climate system, with special attention to forcings, feedbacks, and responses.

A second choice for priority emphasis (sample “B”) expands the temporal span to include the wider range of solar variability in the most recent century and a half: the period since about 1850. As noted earlier it includes (1) the full period of synoptic, instrumented weather records with global coverage; (2) the complete span of daily photographic images of the disk of the Sun; and (3) a thirty-year

period of depressed solar activity (1880-1910), followed by a gradual rise through the next forty or fifty years. In terms of climate attribution and interactions it includes as well (a) distinct periods of both few and some of the most explosive volcanic eruptions of historic time, including Krakatoa (1883), Pelée (1902), Colima (1903) and (Katmai 1912); (b) the onset of the exponential rise in anthropogenic CO₂ and CH₄ in the atmosphere; and (c) the well-documented global warming of the past 100 years.

A third priority slice of time, “C,” covering the last 11,000 years of Earth history, covers the full expanse of the Holocene epoch, and a long series of apparently similar secular excursions in the overall level of solar activity.

Ways in which the LWS Program can Foster Needed Research

Among the challenges that face Sun-Climate research today is a paucity of human resources: there are very few scientists in the world who devote all or most of their efforts to the investigation of the effects of solar variability on climate. Through the years the U.S. National Research Council has commissioned reviews of the subject, and in recent years there are more sessions at professional meetings, and more workshops of one kind or another devoted to all or parts of the subject. But in the absence of an identifiable, critical mass of dedicated practitioners there are no societies, sections of societies, advanced degrees or journals that are wholly devoted to the subject, and little else to provide a home or common meeting ground.

Above all, there needs to be more active and frequent contact between scientists in different disciplines, for the Sun-Climate question is by nature interdisciplinary, and becoming more so with the fuller understanding of a climate system that involves much more than the Sun and the atmosphere. What was once a riddle in old-time solar astronomy is today a high-visibility research topic that reaches far beyond the bounds of solar physics to include atmospheric physics and chemistry, physical oceanography, paleoclimatology, stellar astrophysics, and geochemistry. As with most scientific problems that call for collaboration among different disciplines, the common language and the glue that will most likely bond the needed efforts together are analytical models and the data and codes and insights that modelers need.

As a first step, the solar physics and climate-science communities—which have historically approached the Sun-Climate question in different cultural ways and

from opposite ends of a one-way causal chain—clearly need to be brought and kept in closer working contact, to exchange ideas and data and information, and to work together in perfecting models of Sun-Climate effects.

A Series of Interdisciplinary Sun-Climate Institutes

A proven mechanism for bringing research scientists from different fields together in close working contact are what might be called mini-institutes: informal focused workshops that are first and foremost interdisciplinary. Ideally these would last a full week or more in a retreat setting in which new acquaintances are made and ideas and information are shared and seeds are planted for subsequent scientific exchange and collaboration. The underlying goal would be to advance research and understanding in specific, targeted areas of Sun-Climate research that are of particular need and importance. A suggested list of ten such topics (reflecting problems that were singled out in this report) is given below.

RECOMMENDED TOPICS FOR EMPHASIS IN A SERIES OF INFORMAL SUN-CLIMATE INSTITUTES

- Influence of solar variability on the oceans and ocean circulation
- Influence of solar variability on the dynamics of the lower atmosphere, including possible effects on Hadley cell and Walker cell circulation
- Interpreting cosmic nuclide data in terms of solar activity and irradiance
- Solar-driven changes in stratospheric ozone and their climatic impacts
- Solar influence on internal variability modes in the atmosphere, such as ENSO, NAO and the Pacific Decadal Oscillation
- Comparisons of solar variability, stratospheric ozone variations, and climate in the 25-year period for which direct solar measurements are available

- Comparison of solar variability and climate in the 150-year period of instrumented weather and climate records
- Characteristics of global and regional climate during such episodes as the Maunder (1645-1715), Dalton (1790-1820), and Modern Minima (1880-1910) of solar activity, and their counterparts throughout the Holocene
- Climate impacts of solar forcing in conjunction with other natural and anthropogenic climate drivers
- Numerical models of solar variability, including scenarios for long-term evolution and change
- Cyclic and secular changes in Sun-like stars: implications for solar irradiance variability

Participation at each Sun-Climate Institute might be limited to no more than about twenty recognized specialists from this country and abroad, largely by invitation and including several graduate students, with limited repeat attendance. The proceedings and conclusions of each Institute, which should include a number of informal, introductory review papers, prepared in advance, and other summarized findings and recommendations, can be made available on the web to share the benefits of the Institute with a much wider audience.

END

Appendix A

NASA LWS Sun-Climate Task Group

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Appendix B

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