The Sun and Climate

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Of the many objects in the universe, only two are essential for life as we know it: the Earth itself, and the Sun: the star around which it circles, year after year. Burning steadily in stable, middle age, the Sun--now about five billion years old--provides an unfailing source of light and energy. The Sun's heat is so intense that at a distance of 93 million miles it warms the surface of the otherwise cold and lifeless Earth some 250° Centigrade, to -18° C (0° Fahrenheit). Thus warmed, the solid Earth releases a portion of its heat in the form of infrared radiation, which is trapped by atmospheric greenhouse gases, further raising the surface temperature to a more comfortable 15° C (59° F). In this way, the Sun's radiation and the Earth's blanket of greenhouse gases sustain the mean global temperature at a level supportive of life. Sunlight also powers photosynthesis, and provides energy for the atmospheric and oceanic circulations that profoundly affect all living things.

Like other stars of similar age, size, and composition, the Sun shows many signs of variability. Most pronounced and by far the most familiar is a cycle of about eleven years in the number of dark spots on its glowing surface (Fig. 1). But although the Sun is known to be a variable star, its total output of radiation is often assumed to be so stable that we can neglect any possible impacts on climate. Testimony to this assumption is the term that has been employed for more than a century to describe the radiation in all wavelengths received from the Sun: the so-called "solar constant," whose value at the mean Sun-Earth distance is a little over 1 1/3 kilowatts per square meter of surface.

In truth, the solar "constant" varies. Historical attempts to detect possible changes from the ground were thwarted by variable absorption in the air overhead. Measurements from spacecraft avoid this problem, and the most precise of these, made continuously since 1979 (Fig. 2a, b), have revealed changes on all time scales--from minutes to decades--including a pronounced cycle of roughly eleven years. Sunspots and other forms of *solar activity* are produced by magnetic fields, whose changes also affect the radiation that the Sun emits, including its distribution among shorter and longer wavelengths. The most highly variable parts of the Sun's spectrum of radiation are found at the very shortest wavelengths--the ultraviolet (UV) and X-ray region--and in the very longest and far less energetic band of radio waves.

New insights into the variable nature of the Sun have almost always been followed by efforts to find possible impacts on the Earth--chiefly through comparisons with weather and climate records. Initially the quest was not so much a detached inquiry as a determined effort to demonstrate a long-sought hope: that keys found in the cyclic nature of solar behavior might open the doors of down-to-Earth predictions.

In the latter part of the 19th century, there were many claims of new-found connections between sunspots and climate. It began with the announcement by the amateur astronomer Heinrich Schwabe, in 1843, that sunspots come and go in an apparently regular eleven-year cycle. What followed was a flood of reported correlations, not only with local and regional weather but with crop yields, human health, and economic trends. These purported connections-- that frequently broke down under closer statistical scrutiny--lacked the buttress of physical explanation and were in time forgotten or abandoned.

After more than a century of controversy, the debate as to whether solar variability has any significant effect on the climate of the Earth remains to be settled, one way or the other. This long unanswered question has of late emerged anew, and with some urgency--in the context of widespread concerns of impending global greenhouse warming. For in order to gauge the possible impacts of anthropogenic greenhouse gases on the present or future climate, we must first know the natural variations on which our own activities are imposed.

THE MANY CAUSES OF CLIMATIC CHANGE

Between 1850 and 1990 the global-mean temperature at the surface of the Earth warmed by approximately 0.5° C (about 1° F). During the same period, the amount of carbon dioxide measured in the Earth's atmosphere increased by about 25 percent, as a consequence of our ever- increasing use of fossil fuels (Fig. 3c). This raises the possibility that the two trends are directly connected, and that the century-long warming is a long- anticipated sign of the climate system's response to human activities.

Still, more factors were obviously perturbing the climate system than the lone hand of greenhouse gases. The global-mean temperature did not rise steadily: statistical analyses of the temperature record since 1850 reveal significant year-to-year and decade-to-decade variability. Moreover, what is known of the longer climatic record suggests that surface temperatures may have been systematically increasing since the late 17th century (Figure 3d), well before the onset of the Industrial Revolution, when greenhouse gas concentrations first began their upward climb.

Other natural perturbations, which have also varied during the past few centuries, might help explain the difference between the change expected from a simple increase in greenhouse gases and what has been observed.

Like the concentrations of greenhouse gases, solar activity has risen systematically through the past 100 years, as recorded in the number of sunspots (Fig. 1). An upward trend is also found in the number of solid particles, or *aerosols*, in the lower atmosphere. The burning of fossil fuels that has led to an increase in greenhouse gases has introduced as well an ever-increasing load of sulfur-bearing or sulfate aerosols, which also affect the temperature at the surface of the Earth. In contrast, the aerosols ejected into the atmosphere by volcanic eruptions decreased markedly during most of the twentieth century, compared to conditions in the century preceding (Fig. 3b), as a result of a presumably random drop in the long-term average of volcanic activity. Other potential causes of climate change include the depletion of stratospheric ozone in recent decades, again through human activities, and global changes in the surface reflectivity--or *albedo* --of the planet, as we modify the patterns of vegetation that cover the land. In conjunction with possible internal system changes such as variations in ocean circulation, these influences define the most likely causes of climatic change in the recent era.

Different influences on climate affect the system in ways that in principle can be distinguished on the basis of geography, altitude, and time history. More often, however, the impacts of multiple influences are mixed together, and further confused by imperfect knowledge of how each of them has changed, and uncertainties in how climate itself has varied.

In global average, increases in greenhouse gas concentrations or in solar radiation bring warmer surface temperatures since they add energy to the climate system. In contrast, increased industrial and volcanic aerosols restrict the penetration of solar radiation to the Earth's surface and lead to surface cooling. A drop in the concentration of ozone in the lower stratosphere should also produce a net cooling at the surface. Changes in albedo that increase the planet's reflectivity will lead to cooling, and those that make it less reflective and more absorbing, to a temperature rise.

SOLAR INPUTS TO THE EARTH

The Sun's radiation

The Sun, like other stars, is a burning ball of mostly gaseous hydrogen, large enough to hold a million Earths. The temperature of its surface is about 6000° C-- as hot as a welder's flame--and the radiation that it emits peaks in a band of wavelengths called the "visible spectrum." It is all that our eyes can see, yet less than half of the solar radiation that reaches the Earth lies within this thin, central slice of a much wider spectrum of wavelengths. Our skin can feel as heat a part of the rest--the infrared--and is also acutely sensitive to another part: the unfelt but more energetic and potentially damaging ultraviolet. Solar X-rays, gamma rays, and radio waves make up the remainder, which constitutes less than 0.1 percent of the solar energy received at the Earth.

The Earth's response

The air above us is relatively transparent to visible radiation, allowing the bulk of the Sun's energy to reach the Earth's lower atmosphere and surface. Fortunately, the atmosphere is opaque to almost all solar radiation in the UV, shielding the biosphere from these potentially harmful rays.

The Earth receives most of its direct heat from the visible and near- infrared spectrum of sunlight, retaining about 70 percent of what pours down on its day-lit hemisphere. The rest is returned, by reflection, back into the cold of space. A part of what the ground and oceans and lower atmosphere absorb also leaks outward through the atmosphere in the form of infrared radiation. The remaining fraction--trapped in part by greenhouse gases--sustains the habitable environment to which we are accustomed. Any variation in total radiation from the Sun will force an accompanying change in mean-surface temperature.

Solar UV radiation, unlike that in the visible and infrared spectrum, seldom reaches the surface of the Earth since it is absorbed by the atmosphere. In addition, a steady stream of energetic particles and magnetic fields (the *solar wind*) flow continuously outward from the Sun, impacting and deforming the Earth's extended magnetic field. These upper reaches of the atmosphere are influenced strongly by the flow of particles and solar UV radiation. The changes that they feel can potentially affect the climate, through various connections to the lower atmosphere and surface of the Earth. As an example, variations in the flow of both UV radiation and atomic particles that accompany changes in overall solar activity alter the amount of ozone in the stratosphere. Since ozone in turn affects the lower atmosphere and biosphere, it provides another possible connection between solar variability and the climate system.

How the Earth's surface temperature adjusts to a given change in solar radiation depends on the processes by which the climate system responds to variations in the energy it receives. Some of these so-called *feedbacks* amplify the effects of changes that are imposed; others reduce them. Lumped together, they make up what is called the *sensitivity* of the climate system: the number of degrees that the mean-surface temperature will be raised or lowered in response to a given change, up or down, in solar radiation or any other climate driver. To understand the impacts of solar variations on climate we need to know how much the solar inputs vary, and how the climate system responds to these changes.

CHANGES IN SOLAR RADIATION

We need answers to a number of questions about the Sun itself in order to predict how solar radiation will change.

How much does the Sun's radiation vary?

Observations from space reveal that the total radiation from the Sun is continually changing--with variations of up to 0.2 percent from one month to the next. The timing and nature of these shorter-term fluctuations are consistent with the Sun's 27-day period of rotation, and occur because persisting darker--or brighter--areas on the solar surface alter the amount of sunlight received at the Earth.

This "rotational modulation" of solar total radiation (Fig. 2a) is superimposed on a much-longer cycle of about eleven-years (called the Schwabe cycle, after the discoverer of the sunspot cycle) which had an amplitude of about 0.1 percent in the two most recent cycles (Fig. 2b). The enhanced solar activity that characterized the Sun at the peak of the last two cycles, in 1979- 1981 and again in 1989-1991, increased both the overall brightness and the amplitude of the rotational modulation. The nature of these dark and bright structures, and the reason why the Sun is slightly brighter when there are more sunspots, are explained below.

Still, since we have been able to monitor solar total radiation for only about fifteen years, knowledge of the Schwabe radiation cycle is less than complete. Experimental uncertainties in the spaceborne measurements allow an amplitude as high as 0.15 percent for the Schwabe cycle. Moreover, other cycles may be quite different, as a result of longer-term changes on the Sun. One and a half decades of solar monitoring is simply not long enough to detect other possible cycles of longer period--and perhaps higher amplitude--that may well be fundamental features of the Sun.

How do changes in solar activity affect different parts of the spectrum?

As the sunspot number rises or falls, the distribution of energy within the spectrum of sunlight also changes. High levels of solar activity enhance radiation in UV and X-ray wavelengths, and in radio wavelengths, far more than in the visible portion of the spectrum. At peaks of the eleven-year cycle, radiation at longer UV wavelengths, for example, increases by a few percent, compared with an increase of but 0.1 percent in the total radiation. Still larger changes--of factors of two or more--are found in extremely short UV and X-ray wavelengths.

Through what extremes has solar radiation changed in the past?

There are no direct measurements of solar radiation on climatological time scales, but a variety of circumstantial evidence suggests that longer- term variations do occur, perhaps with larger amplitudes than those found in the two most recent eleven-year Schwabe cycles.

We know that there are significant changes of much longer term in the overall level of solar activity. Sunspots have been observed and recorded by astronomers since the early 1600s, and long-term changes in their number are clearly evident. Much longer records of solar behavior come from atomic *isotopes* that are produced in our atmosphere by the impact of galactic cosmic rays, whose rate of incidence at the Earth is affected by conditions on the Sun. When the Sun is more active, its own magnetic fields deflect some of the cosmic rays that would otherwise reach the Earth. When it is less active, we receive more of them.

Isotopes of chemical elements are distinguished by different atomic weights. The most valuable for what they tell of the Sun are carbon of atomic weight 14 (^{14}C, or "radiocarbon"), found in tree-rings, and beryllium of weight 10 (^{10}Be) that is naturally sequestered in polar ice deposits. Well-dated records of both of these indirect indicators of solar activity reach back many thousands of years and exhibit cyclic variations of about 2300, 210 and 88 years, as well as 11 years, all of which are ascribed to the Sun.

Quite evident in the most recent several hundred years of the isotopic records is a seventy-year period of very low solar activity in the 17th and early 18th centuries--known as the Maunder Minimum--and following it, an unsteady, long-term rise to the present-day era of high sunspot numbers, called the Modern Maximum (Fig. 2 c, d). By applying what has been learned about solar radiation changes from the recent measurements from space, we can infer that this gradual build-up in solar activity over several hundred years may have been accompanied by a parallel increase in the radiation received from the Sun.

Adding to the case is a finding from nighttime astronomy that the present level of activity on the Sun is higher than the average found in a selection of other stars of similar mass, age, and chemical composition. This comparison suggests that solar activity can drop for periods of many decades, to levels that are lower than the minima of today's eleven-year cycle. At such times, the accompanying drop in solar total and UV radiation could fall outside the bounds of the variations that have been observed from space since 1979. This may well have been the case during the Maunder Minimum.

A recent reconstruction of the solar total radiation since the 17th century that is consistent with both stellar and isotopic findings suggests an increase in solar total radiation of roughly 0.25 percent over the past three hundred years (Fig. 2c). Other studies also point to reductions in solar radiation during the Maunder Minimum in the range of 0.1 to 0.6 percent.

Why do changes in solar radiation occur?

Changes in the Sun's total radiation and how it is distributed in wavelength occur primarily because solar activity produces two different phenomena that alter the surface brightness, and hence modulate the outward flow of radiated energy. The first of these are the dark spots that appear in great number during times of high solar activity. Cooler than surrounding regions, sunspots "block" for a time some of the radiation that the Sun would otherwise emit. The second are known collectively as *faculae* . They are brighter than the surrounding surface, and add to the overall radiation from the Sun. The radiation that is emitted from the Sun varies continually in response to the push and pull of these two competing and constantly changing features. In years of maximum solar activity, it is the bright faculae that prevail, raising the levels of both total and UV radiation.

Can we predict future long-term changes in solar radiation?

Speculation regarding past or future changes in solar radiation is based on what we can infer, indirectly, from past observations of solar activity--particularly bright faculae--since direct measurements of radiation exist for only the last fifteen years. One explanation for the postulated reduction in solar radiation during the 17th century Maunder Minimum is that the Sun's surface was not only largely devoid of spots and faculae, but also less bright, overall. Numerical estimates based on observations of Sun-like stars suggest that were the entire solar surface dimmed to a level seen today on but about a seventh of the Sun's undisturbed surface, the total radiation would drop by 0.25 percent. What we know of the connection between solar activity and radiation, coupled with high abundances of isotopes in tree-rings and ice-cores (Fig. 2d), supports the likely case that during the Maunder Minimum solar activity remained for over half a century at very low levels.

The present production of terrestrial ^{14}C and ^{10}Be appears to be near historically-low levels, due to persistently high solar activity that inhibits the rate at which these isotopes are produced. The same isotopic records show that the Sun seems to have been building up over the last several hundred years to a state of enhanced activity that is the opposite of the suppressed levels of the 17th century Maunder Minimum. From this we might expect that solar radiation is also approaching levels last seen in the 12th century Medieval Maximum. Still, any extrapolation of future changes in the long-term behavior of the Sun is highly uncertain, since we are as yet unable to make accurate predictions of the level of solar activity in even the next eleven-year cycle, which will reach a maximum in about the year 2000. Whether solar activity will remain in coming decades at its present high level- -as is sometimes inferred from statistical projections of the isotope records--or decline toward another Maunder-like minimum is simply not known. Moreover, other mechanisms may be at work to modulate the energy that escapes from the Sun.

RESPONSE OF CLIMATE TO CHANGING SOLAR RADIATION

A number of questions need to be answered if we are to understand the impact of solar changes on the climate system.

How sensitive is the Earth's climate to changes in solar radiation?

The sensitivity of climate to solar radiation changes, as defined earlier, is not well known. A conservative estimate is that a 0.1 percent change in solar total radiation will bring about a temperature response of 0.06 to 0.2° C, providing the change persists long enough for the climate system to adjust. This could take ten to 100 years.

Changes in visible and infrared solar radiation alter the surface temperature by simple heating; other parts of the spectrum can also affect climate, through paths that are less direct. We know, for example, that the enhanced UV radiation that pours outward from the Sun at times of high solar activity increases the amount of ozone in the stratosphere. At times of minima in the eleven-year cycle, less ozone is found. One consequence of these solar perturbations is to complicate the detection of human-induced depletion of the protective ozone layer; another may be to perturb the temperature at the Earth's surface, through connections that link the upper and lower parts of the atmosphere.

How does solar forcing compare to that from other sources?

The most likely cause of climate change in the period since about 1850, based on estimated magnitudes of known perturbations (Fig. 4), is the growing concentration of greenhouse gases: in particular carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and the commercially-made compounds of chlorine, fluorine, and carbon called *halocarbons* . Other causes, including solar radiative output variations, are thought to be less important, but they are also far less certain. Most poorly known is the magnitude of the potentially-large cooling effect of atmospheric aerosols.

A comparison of significant climate perturbations for the period from 1850 through 1990 is shown in Fig. 4, in terms of the estimated energy that each has added to or subtracted from a stable climate system. Some, like the increasing radiation from the Sun, have added energy; others, like atmospheric aerosols or stratospheric ozone, have taken it away. The net result is an addition of 1.2 watts per square meter. The Sun accounts for about a quarter of the net amount, even though it contributes but 10 percent of the total on the positive, warming side of the balance sheet. Most of the change is attributed to the push and pull of the other, much larger perturbations--which are predominantly of human origin.

If we assume that the climate is equally sensitive to radiative forcing from each of these causes, the net increase of 1.2 watts should have brought about an increase in global mean temperature of 0.3 to 1.1° C, depending on the climate sensitivity that is assumed. The documented rise of about 0.5° C in the same period falls at the low end of this range. It may be premature to make such a comparison, however, since it is uncertain when all of the warming would be felt, given the lag times of up to a century that are imposed on the climate system by the thermal inertia of the oceans.

What can we learn from climate changes in the pre-industrial era?

What is known of climate change prior to the Industrial Revolution affords additional insight. The well-documented surface temperature rise since 1850 can be viewed as but the most recent 60 percent of a warming of about 0.8° C since the 17th century (Fig. 3d), interrupted periodically by volcanic effects. Estimates of Northern hemisphere surface temperatures from 1610 to 1800--during part of the so-called Little Ice Age--correlate well with a reconstruction of changes in solar total radiation--around the time of the Maunder Minimum (Fig. 2c). This suggests, without proving, a predominant solar influence on climate throughout this 200 year, pre-industrial epoch. The reconstructions of solar radiation and surface temperature shown for these years in Figures 3a and 3d tell of an increase in solar radiation of 0.14 percent and a coincident warming of 0.28° C. If we apply the same implied sensitivity to the period since 1850, the 0.13 percent increase in solar radiation in the last 140 years should have produced a warming of 0.26° C, or about half of that observed. If we apply the same relationship to the last 25 years, solar changes can account for less than a third of the warming observed (Fig. 5).

In summary, extending the relationship between surface warming and solar change from the Maunder Minimum to the present era implies that while the Sun could account for almost all of the temperature change from 1600 to 1800, it can explain at most a half of the warming from 1600 to the present. When effects of dust from known volcanic eruptions in the early 19th century are also included, solar and volcanic effects can satisfactorily explain much that is known of climate change from 1600 to beginning of the industrial epoch, around 1850.

How might solar variations affect projections of global greenhouse warming?

What has happened in the past can help us assess the relative importance of solar and anthropogenic changes in the climate of the future.

It seems likely that changes in solar radiation, linked to long-term variations in solar activity, may have been the dominant climate driver in the period between about AD 1600 and 1850. As discussed earlier, the explanation of trends in global surface temperature since that time is not as simple, when both the positive and negative impacts of fossil fuel consumption are added to the picture.

Since 1850, variations in global surface temperature appear to track changes in the level of solar activity at least as well as they track increasing greenhouse gas concentrations. At the same time, when probable energy inputs are taken into account (as in Fig. 4), solar effects can account for only a fourth of the net change in climate forcing in this 140 year period. It could be that the climate system is more sensitive than we think to changes in solar energy, as opposed to greenhouse gas increases. There could also be errors in our estimates of the magnitudes of other climate forcing terms-- especially aerosol cooling--or, as mentioned earlier, time lags in how the climate system responds.

On the basis of what we now know, solar changes might account for a rise of about 0.5° C since the 17th century, perhaps half of the warming since 1850, and less than a third of the warming in the last twenty- five years. The possibility of solar-induced changes of these magnitudes complicates the unambiguous detection of a possible greenhouse warming signal in climate records of the last 100 years or so. We need remember, however, that to ascribe any significant fraction of the documented warming since 1850 to the Sun requires high estimates of climate sensitivity. It also requires the added assumption that long-term changes in solar total radiation can exceed by two and a half times what has been observed in recent measurements from space.

Looking ahead, were solar changes limited to what has been measured in the last fifteen years, future changes in the Sun's total radiation would have only a negligible effect on the temperature increases of 1 to 3° C that are now projected in IPCC models for the end of the next century. If greater changes in solar radiation occur--as seems probable based on what is known of climate and solar activity in the past--the Sun needs to be considered in long-term climate projections. The present high levels of solar activity may be approaching all that the Sun can deliver, in terms of total radiation. But, were the Sun's activity and total radiation to drop in the coming century to levels of the Maunder Minimum, solar effects might reduce the expected surface temperature effects of enhanced greenhouse warming--by at most about 0.5° C.

Does the Sun affect climate on time scales of 11 years or less?

Assessments of climate change that consider possible effects of the Sun presently focus on multi-decadal and centennial time scales, assuming that the Schwabe radiation cycle is too short and its amplitude too small to have any significant effect on the climate system. Yet an assortment of recent and historical data, including those from ice-cores, corals, and the instrumental weather record, do reveal climatic variations with periods of about eleven years.

Since the observed Schwabe cycle variations are small, eleven-year periods frequently found in climate data are often ascribed instead to hypothesized oscillations in the atmosphere or oceans, internal to the climate system. A possible solar connection is also often discounted on the basis that climatic events of ten to twelve years duration are neither globally distributed nor always in phase with the ups and downs of the solar cycle. Numerical simulations of the surface-temperature response to a reduction of 0.25 percent in solar total radiation caution against these simplified assumptions. They indicate that some regions of the Earth's surface may cool, and others warm, by amplitudes larger than the net global response, as a result of differences in solar heating of land and ocean surfaces.

More subtle solar influences may also be occurring. An apparent correlation between weather patterns and the phase of the Schwabe cycle has been found when the direction of winds in the tropical lower stratosphere is taken into account. These systematic winds oscillate from easterly to westerly with a period slightly greater than two years. Model simulations using solar-cycle forcing slightly larger than was seen during the last decade suggest that the associated solar UV radiation variations could be modifying the Earth's weather by altering the wind and temperature patterns in the stratosphere, both directly and through their effect on ozone concentrations.

Are the Ice Ages linked to changes in solar radiation?

Solar radiation received at the Earth can vary by means that are unrelated to any changes on the Sun itself. The best studied of these are very long-term changes in the Earth's orbit around the Sun, which alter the distribution of sunlight both geographically and seasonally. They are now believed to trigger the coming and going of the major Ice Ages. As such, they may provide a powerful demonstration of the impacts of changes in solar radiation on the climate system.

The changes involved arise from gradual shifts in the shape and orientation of the Earth's orbit around the Sun, and in the present 23 1/2° tilt of the Earth's axis of rotation. These cyclic changes, brought about by the changing gravitational pull of the other planets and the Moon, introduce periods of about 19, 23, 41, and 100 thousand years in the distribution of sunlight over the globe. The total annual dosage, averaged over the entire surface, varies by up to 0.1 percent, while more specific, seasonal changes at any place can reach a few percent. Such changes are apparently sufficient to trigger major changes in climate--implying that the Earth's climate system may be more sensitive to small solar radiative perturbations than one might think.

Climate simulations are as yet unable to account for the unexpectedly prominent 100 thousand year periodicity in the record of past climate. This long period is associated with the eccentricity of the Earth's orbit, which oscillates between circular and slightly elliptical. Accompanying changes in the Sun-Earth distance directly affect the amount of solar radiation incident in on the Earth in different parts of the year. Changes in activity on the Sun itself could exert a similar effect.

CONCLUSIONS

That the Sun plays a critical part in the Earth's climate system is indisputable; moreover, both the Sun and the climate change continually, over all time scales. Yet the physical connections that might link the variations seen on one with the variability presently occurring in the other are but poorly known. One and a half decades of continuous monitoring of direct solar radiation have provided long-needed information, but this short period of time is but a wink of an eye in the life of the Sun, and a woefully inadequate sample of the full range of its possible behavior.

We now know--thanks to recent spaceborne monitoring--that sunlight received at the Earth follows the drum beat of the eleven-year sunspot cycle, with both the total and short wavelength emissions varying in phase with solar activity. At the peaks of recent eleven-year cycles the total energy from the Sun increased by about 0.1 percent, and the UV portion by several percent or more. In years of the cycle when sunspots are few--as is presently the case--both total and UV radiation are diminished.

We also know from isotopic archives of solar activity that the Sun exhibits greater variability on time scales that exceed the eleven-year cycle. Detecting and confirming larger-amplitude, longer-period cycles in solar radiation--if they indeed exist--will require reliable continuous solar monitoring, well into the next century. NASA's Office of Mission to Planet Earth and the European Space Agency are presently conducting these measurements on, respectively, the Upper Atmosphere Research Satellite and the Solar Heliospheric Observatory. Future solar radiation monitoring is planned for NASA's Earth Observing System and the NOAA/DoD National Polar- Orbiting Operational Environmental Satellite System, although in the latter case not at UV wavelengths. Redundancy afforded by multiple space-based instruments is critical for separating solar and instrumental effects in these difficult radiometric measurements, and to ensure overlap so that the long- term database is not broken. Supporting observations from the ground are also necessary in order to interpret the causes of measured variations. Present lack of access to space, the overall low priority of solar influences in global change research, and continued reductions of Earth environmental monitoring threaten the accomplishment of this task.

Climate model simulations indicate that changes in solar radiation a few times larger than those confirmed in the eleven-year cycle, and persisting over multi-decadal time scales, would directly affect the surface temperature. Since such models cannot account for the climate system's apparent sensitivity to small perturbations in solar energy apparently brought about by the very long term changes in the Earth's orbit about the Sun, they may also underestimate climate sensitivity to energy output fluctuations caused by solar activity, even during the eleven-year Schwabe cycle. Nor do these simulations yet include potential effects of changes in the solar spectrum, including the more variable UV.

The unsolved puzzle of how subtle variations driven by Earth-orbit changes can affect the climate suggests a closer look at feedback processes, including other pathways than direct solar radiative forcing. These should include known changes in solar energy inputs across the entire spectrum and possible connections that might amplify small changes in radiation, not only at the Earth's surface but from the top to the bottom of the atmosphere. Such studies of solar perturbations can serve the broader cause as diagnostic probes of the atmosphere and climate system.

Ambiguities regarding projected greenhouse warming call in much the same way for clearer information regarding the role of the Sun, as a possibly important contributor to the current warming trend. Climate simulations using only greenhouse gas changes predict a warming that exceeds the 0.5°C that is documented in the instrumental record of the past 140 years. To reconcile the difference between the observed and the predicted values, either the models are wrong or other, natural and anthropogenic forcings must be properly factored in.

If variations in the output of the Sun are indeed limited to the tenth of a percent that is recorded in direct measurements, future solar changes will likely have but a small effect, one way or the other, on the surface warming of a few degrees that is expected to result from doubled concentrations of greenhouse gases. If we include reasoned deductions from what we know of the Sun and climate in the past, we must allow that solar changes could potentially alter the anticipated effects of carbon dioxide and other greenhouse gases on the surface temperature of the Earth.

In this case the Sun could make a difference of about 0.5° C in the surface temperatures now projected by consensus climate models for doubled concentrations of CO_2. A fortuitous future cooling of this amount, due to the Sun, would not fully compensate for the effects of increases in greenhouse gases, which are projected to warm the Earth by 1 to 3°. Furthermore, the overall, long-term level of solar activity would have to fall steadily and systematically over the next few hundred years from the current, high sunspot numbers that have characterized the greater part of the 20th century. Were that to happen, the principal impacts would be to cloud for a time the unambiguous detection of enhanced greenhouse warming and to soften, by at most about a half, its projected impact on the temperature of the planet. The rapid warming since 1970 is several times larger than that expected from any known or suspected effects of the Sun, and may already indicate the growing influence of atmospheric greenhouse gases on the Earth's climate.

For Further Reading

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Scientific reviewers provide technical advice to the authors and Editor, who bear ultimate responsibility for the accuracy and balance of any opinions that are expressed.

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The Sun doesnâ€™t always shine at perpetually the same level of brightness; it brightens and dims slightly, taking 11 years to complete one solar cycle. During each cycle, the Sun undergoes various changes in its activity and appearance.Â What Effect Do Solar Cycles Have on Earthâ€™s Climate? According to the United Nationsâ€™ Intergovernmental Panel on Climate Change (IPCC), the current scientific consensus is that long and short-term variations in solar activity play only a very small role in Earthâ€™s climate. Warming from increased levels of human-produced greenhouse gases is actually many times stronger than any effects due to recent variations in solar activity.