REVIEW ARTICLE

Changes in the solar constant and climatic effects

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Spacecraft measurements have established that the total radiative output of the Sun varies at the 0.1–0.3% level. The observed fluctuations are well modelled as radiative deficits proportional to the area of the solar disk covered by sunspots. Historical records of projected sunspot areas allow an accurate reconstruction of these short-term fluctuations over the past century. Such changes can be expected to perturb the terrestrial surface temperature by a fraction of a degree centigrade and probable evidence of this solar-induced signal has been found. The effect, though important in terms of understanding the climate system, is too small to be significant in practical weather or climate predictions.

RADIATION from the Sun is the dominant source of energy input to the Earth's atmosphere. Solar energy, coupled with the rotational inertia of the spinning planet, drive the circulation patterns of oceans and air that are the basis for all the phenomena known as weather and climate. Regional weather patterns may result from local perturbations of geographical, orographic, or other origins, including anthropogenic ones, but all of these processes depend on a fundamental flux of solar energy. The equilibrium temperature of the Earth's surface and seas is ultimately determined by a balance between solar radiation absorbed by the Earth, primarily at visible and near IR wavelengths, and long-wave radiation that is re-emitted to space. Should the total solar input vary as a persistent trend, the surface temperature of the Earth will in time respond in a direct and predictable fashion: global cooling in response to decreased solar radiation, and warming following an increase. The diurnal variation of cold nights and warmer days, and seasonal patterns from winter to summer attest to the role of insolation as the principal temperature control.

Such reasoning has prompted innumerable attempts at identifying the signature of solar variability in climate records. What is surprising is how difficult it has been to find any unequivocal evidence of any significant forcing by known solar variability[1,2]. Meadows[3] has traced the spotted and often confused history of such attempts, most of which were statistical tests of supposed connections between observed solar activity and various meteorological parameters. He adopted an earlier estimate[4] that "Solar activity does not produce a significant variation [upper limit of 0.1%] in the value of the solar constant". With this exclusion, any significant Sun–weather effects depended on indirect or 'trigger' mechanisms, which might result, for example, from perturbations in the energetically weak solar wind on the Earth's upper atmosphere and possible subsequent tropospheric response. Meadows concluded that: "If [an acceptable mechanism] could only be defined, the whole controversial field might be rapidly translated into the realms of high respectability".

We discuss here recent evidence for measured variations in the solar luminosity which provide a direct and simple mechanism for associated climatic change. Such variations, though small in amplitude, constitute a significant breakthrough in solar–terrestrial physics: for the first time a form of solar variability has been identified that is sufficiently energetic to alter directly the basic radiation balance of the lower atmosphere. Moreover, a wholly consistent response in surface temperature has already been (independently) identified[5], lending credence to the reality of the connection. The resultant changes in surface temperature are very small—no more than a few tenths of 1 °C. But the existence of a probable response opens the door to the possibility of larger effects, due to longer and more important changes in the bulk radiative output of the Sun.

Observational evidence for solar constant changes

Precision measurements of the total solar flux, or 'solar constant', S, have long been desired; they have become possible on a continuous basis only in the present decade with sophisticated radiometers in Earth orbit. Langley had foreseen the need to rise above the atmosphere 80 yr ago when he called for the establishment of an elevated solar observatory[6]: "The Earth's temperature and the life of its inhabitants, both animal and vegetable, depend on the solar radiation. Yet we confess that even at this late day we do not know, with any certainty, what the total amount of solar radiation is, whether it is constant or variable, or what effect upon terrestrial life and temperature a given change in it would produce. Our ignorance of these fundamental things is largely, though not wholly, due to the variability of our own atmosphere, which prevents us from studying that of the Sun".

In 1881, Langley had attempted a precision measurement of the solar constant from the top of Mt Whitney, 14,495 ft. elevation. Subsequently, he and Abbot for many years tried to measure the solar constant from mountain tops but their measurements were still limited by uncertainties in atmospheric transmission to about ±1% [7]. In 1980, near the peak of the

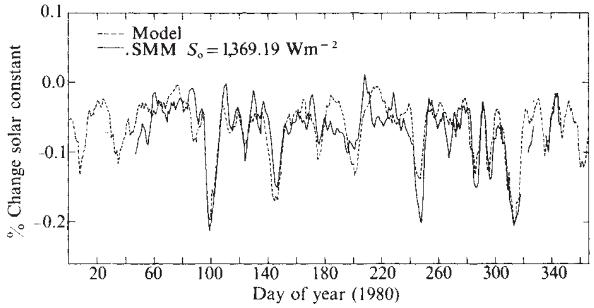

Fig. 1 Comparison of the model results to the SMM measurements for 1980. A quiet Sun solar irradiance of 1,369.2 W m^{-2} is assumed for the SMM measurements and per cent deviations are from this value. Most of the differences between the model and measurements can be attributed to random errors in the measured sunspot areas.

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solar activity cycle, the SMM spacecraft succeeded in accumulating nine months of continuous measurements of the solar constant with an unprecedented internal precision of 0.01%[8]. In these data was clear evidence of changes at the level of 0.1–0.3%, about an order of magnitude lower than the threshold of previous, ground-based measurements. A similar radiometer on the Nimbus 7 spacecraft[9,10] confirmed that these excursions, lasting 1 to 2 weeks, were depletions in the total output of the Sun. With these data the possibility of a rigorously constant S was unambiguously disproven for the first time.

Theoretical understanding of solar constant changes

The continuous solar constant measurements accumulated by the SMM in 1980 are shown in Fig. 1, as daily averages. Error bars are approximately the width of the line used to trace the record. It is obvious that the variations of S seen by the SMM are not those of a white noise spectrum, but are well approximated by a steady background with minor rises and major, superposed dips of varying amplitude. The time series of Fig. 1 suggests a process by which S is depleted over time scales of days to weeks without a compensating emission process. Moreover, initial analysis of the SMM data established the fact that the major dips were always coincident with the passage of large sunspot groups across the solar disk.

Sunspots are localized regions on the solar surface which appear dark in relation to the background solar photosphere (Fig. 2). The umbra, or dark central region of a sunspot, has a temperature of about 4,000 K, some 1,800 K or 30% cooler than the adjacent photosphere. A sunspot penumbra has a typical temperature of about 5,400 K.

Sunspots are regions of intense, concentrated magnetic field. These strong magnetic fields inhibit the local, vertical, convective transport of energy, leading to a lower, local radiative flux and a corresponding reduction in local temperature. It has long been suspected that the presence of sunspots, which are known to follow an 11-yr recurrence cycle, could modulate the Sun's total radiative output. In serious question, however, has been whether solar activity would decrease[11] or increase[12,13] the total solar flux, because dark sunspots are always accompanied by bright (hotter) facular regions in the photosphere and chromosphere. A third and equally tenable hypothesis was that a detailed balance in S would ensue between sunspot depletion and facular emission, resulting in a rigorously invariant solar constant. The SMM and Nimbus measurements establish that only a small fraction of the energy blocked by sunspots is balanced by immediate enhanced emission from bright features such as faculae and plages[8,14–16]. On time scales of months or years, there is no detailed balance. As we shall see, this fact has practical consequences for the effect of solar variability on the Earth's temperature.

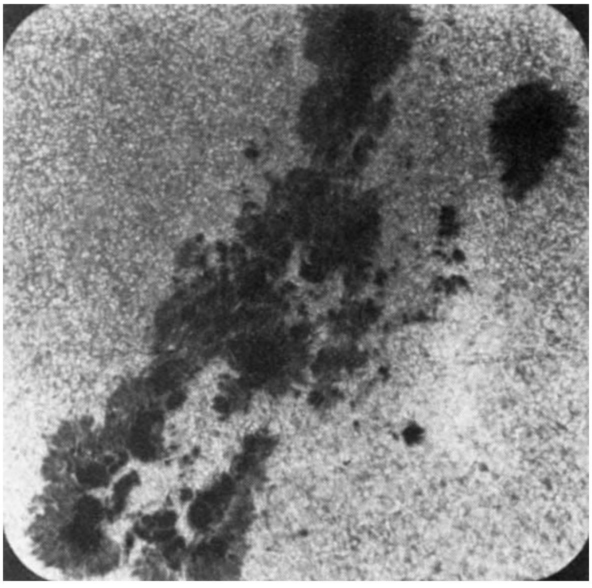

Fig. 2 A large sunspot group showing dark umbral and intermediate penumbral regions contrasted against the brighter surrounding photosphere. (Sacramento Peak Observatory, Association of Universities for Research in Astronomy, Inc.)

The basis for these important conclusions is the success of simple, blocking models in replicating the observed pattern of fluctuations in S that were observed with the SMM and Nimbus spacecraft (Fig. 1) using daily, observed values of projected areas and positions of sunspots made by ground stations. The symmetric, gaussian shapes of the major dips are readily explained as the result of spherical projection: a sunspot of fixed size will block more of the apparent area of the solar disk as solar rotation carries it towards the Sun's central meridian. Furthermore, the magnitude of the observed depletions in S are well duplicated by measured sunspot areas and canonical values of umbral and penumbral contrasts.

Schatten *et al.*[17,18] have endeavoured to attribute considerably more of the observed fluctuations in S as due to facular brightening, thereby implying a detailed balance in the total solar flux. This divergent interpretation is challenged by other, independent studies of the same spacecraft data[8,14,15,16,19–21]. As explained elsewhere[22,23], the discrepancy may be due to the failure of studies implying detailed balance to make use of actual, daily observations of sunspot and facular areas or to utilize the full SMM solar constant record. When this is done a better fit and a more accurate interpretation is obtained. The difference in terms of the storage of radiative flux within the Sun and in terms of potential climate effects is fundamental.

The model for sunspot blocking used in Fig. 1 is based on daily measured positions and areas of sunspots and on standard umbral, penumbral and facular contrasts of −0.75, −0.25 and +0.03 respectively[14]. Also included is the well-known effect of limb-darkening. The brightness of the apparent disk of the Sun decreases towards the edge, or limb; as a consequence sunspots near the limb have lower contrast relative to the background Sun than they do near the centre of the disk. The amount of irradiance blocked by a sunspot therefore decreases as it moves away from the apparent centre line, seen from the Earth, due to a combination of geometrical foreshortening and limb darkening. The model used in Fig. 1 also assumes that the blocked radiation is never released. In time it must be, but with the data now available it is possible only to conclude that the blocked energy does not reappear in recognized form for time scales of at least months, and probably a year. Continued measurements should help to refine the estimate of effective storage time. The notion of a frustrated Sun, with stored, and gradually released energy from remembered sunspots is not an altogether unreasonable one. Blocked, radiative energy can be stored in mechanical form in the lower convection zone with a relaxation time of up to 10^5 yr, (refs 24–26) during which time it will only slowly seep out. For purposes of comparisons with SMM or Nimbus data a storage time of this length is almost infinity.

The remarkable fit of SMM observations with simple, sunspot blocking models allows us to take two further steps. We can now predict the short-term excursions in S (should climatologists want them) a few days in advance, based on easily obtained measurements of sunspot areas and positions and the known rotational properties of the Sun. By the same technique we can also reconstruct the past history of daily fluctuations in S from archived sunspot data. Precise records of sunspot areas and positions exist for more than 100 yr. Figure 3 shows reconstructed, daily records of S for four sample years as they were generated from historical sunspot records[14]. The 108-yr reconstruction shows the expected signature of the 11-yr sunspot cycle, with greater accumulated depletion during years of enhanced sunspot numbers.

These predictions and reconstructions tell all we know with certainty of solar constant excursions. But there may well be more to the story in the form of longer, possibly independent

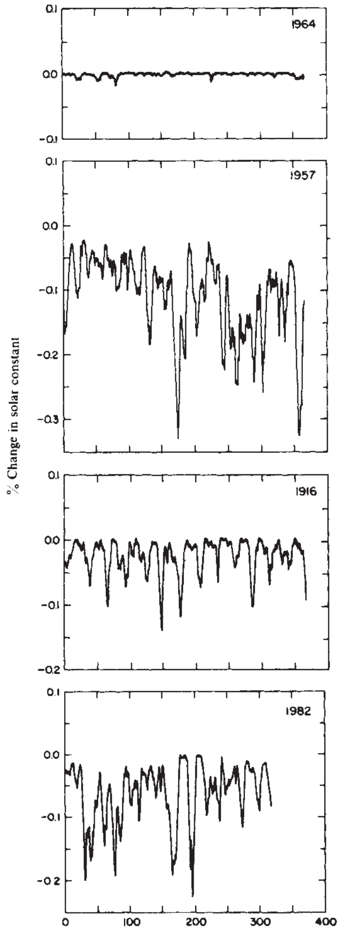

Fig. 3 Daily solar constant values reconstructed from sunspot and facular area records for sample years of low activity, high activity and recurrent, moderate activity with a similar reconstruction for 1982, to 14 November.

trends. Such trends, if they exist, could be of greater climatic impact, through persistence, than the short-term sunspot blocking effects noted above. The existence of one such possible trend, an apparent decrease in S of ~0.02–0.04% yr^{-1}, has already been noted in the Nimbus[27] and SMM[28] records. The model shown in Fig. 1 would predict a downward trend of about this amount in the 1979–82 period due to an averaged increase in sunspot areas during this time, even though sunspot numbers were simultaneously decreasing. It is probably too early, however, to determine whether the measured trend is real, and, if real, how much of it is due to accumulated sunspot blocking or some other effect.

We may sum up the recent discoveries concerning the solar constant as follows:

(1) The solar constant varies.

(2) The fluctuations are almost wholly explained by the simple mechanism of sunspot blocking, by which S is reduced in direct proportion to the fraction of the apparent solar disk that is covered by sunspots.

(3) Excursions in S during high solar activity are at most 0.5%, and more generally 0.1% or less, maximizing in each case when large sunspot groups are near the central meridian.

(4) Excursions of this nature persist throughout the period of visibility of the spot—for 14 days or less.

(5) The radiation blocked by sunspots does not immediately reappear where it can be seen or sensed; it is in some way stored within the Sun, to seep out much more slowly as an integrated increase in radiative flux.

(6) Photospheric and chromospheric faculae (surface regions brighter than the background disk) play at most a minor role in modulating the instantaneous value of S.

Evidence for a solar cycle effect in temperatures

A possible, 11-yr signal due to sunspot effects has long been sought in both regional and globally-averaged surface temperature records[29–34]—a search that has origins in ancient weather lore[35] and in literature[36,37]. The lack of any clear success in these attempts almost certainly implies that any globally distributed, coherent variation due to sunspot-cycle forcing must have a small amplitude. Still possible, however, are enhanced, regional or seasonal responses in areas of extended land mass and lower thermal inertia. Currie[5] has found statistically significant evidence for such a variation of annual-averaged surface temperature in 53 stations in the northeastern sector of North America, based on recent analyses of 80 yr of surface data. The varation found by Currie has a mean amplitude of about 0.18 °C; it was absent or undetectable in other regions of North America for which extended records exist. The mean period of the temperature variation was 10.5–10.7 yr, which may be compared with the mean sunspot blocking period shown in Fig. 4 of ~10.6 yr. Currie found that the air temperature lagged sunspot numbers by 5.7±0.7 yr in the sense that temperatures tended to be lower at maxima in the 11-yr sunspot cycle; this is almost precisely what would be expected were the temperature effect due to sunspot blocking, with a reduced solar constant at times of high sunspot numbers. The apparent confirmation of a suspected regional, solar–climate effect is intriguing; before it can be accepted, however, it should be tested on other continents and with realistic climate models. But a small solar constant signal, restricted to an inland region geographically removed from the thermal inertia of the oceans and downwind of a major mountain chain is not unreasonable.

We have found further possible evidence in the same geographical region by examining the occurrence of temperature extrema in a data set[38] of mean monthly temperatures for the 48 contiguous US states over the time span 1900–80. The occurrence of a monthly high temperature record was a factor of 3 more frequent during the three years of minimal sunspot blocking than during the three years of maximum sunspot blocking. The same effect is found in the remaining regions of the continental US although with a slightly weaker signal. This factor of three greater probability of finding temperature maxima at minimum solar activity is a statistically significant result, with only a 1% probability of occurring by chance. The corresponding occurrence of record low temperatures during maximum sunspot blocking has a much weaker mirror relationship: record low temperatures were 30% more frequent in maximum than in minimum sunspot blocking years, although there is a 20% probability of this having occurred by chance.

Theoretically expected temperature response

What global surface temperature response should we expect from the reconstructed solar constant forcing? A reasonable answer is shown in Fig. 4, from a simple global climate model that assumes energy balance between incoming solar radiation and outgoing IR[39,40]. The model includes terms for the thermal inertia of the oceans: a mixing layer (upper level equivalent 87 m of water) with a thermal response scale of 5–10 yr, and a deep ocean with a volume 20 times larger. The effect of a

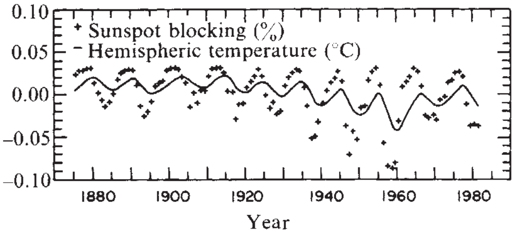

Fig. 4 The yearly mean deviations in solar irradiance indicated by the sunspot blocking model for 1874–1981 with expected hemispheric temperature variations as calculated using a simple energy balance climate model.

short-term change in insolation will be moderated by the large thermal inertia of the strongly-interacting surface regions (atmosphere, land surface and ocean mixed layer) of the Earth. The degree of attenuation will depend on the frequency and persistence of the forcing signal. A cyclic perturbation in insolation with a period of 11 yr will induce a surface temperature response that is a factor of 2–3 smaller than the equilibrium response to the same forcing. The equilibrium response of surface temperature to solar constant changes is generally estimated at 0.1 °C for a 0.1% radiative perturbation[41]. Peak-to-peak variations in solar forcing of 0.12% on an 11-yr cycle derived from extrapolated sunspot blocking models will lead to a similar cycle in mean global temperature with an amplitude of only 0.06 °C. Possible feedback mechanisms make this estimate uncertain by a factor of at least 2, but more detailed calculations of atmospheric circulation tend to support the energy balance arguments given above.

The atmosphere itself has a thermal inertia time scale far shorter than 1 yr (as evidenced by diurnal and seasonal variations). Therefore an inland region that is isolated from ocean temperature moderation can react to solar forcing in a manner more nearly that of the theoretical equilibrium response. Regions at high latitude will also experience larger responses due to the positive feedback of snow-albedo in which decreased solar radiation leads to greater snow cover, hence higher albedo and an even lower surface temperature. Currie's finding[5] of a weak, 11-yr cycle in inland North American air temperatures is therefore consistent in period, phase and amplitude with that expected theoretically from reconstructed sunspot blocking[14].

One can also test the compiled record of annual mean Northern Hemisphere temperature[42] for evidence of the same effect. We have done so and find that the mean hemispheric temperature during 1881–1981 was on average 0.036 °C cooler in the 3 yr of peak sunspot blocking as compared with the adjacent 3 yr of minimum solar activity. The reconstructed solar constant for the same period exhibits mean peak-to-peak variations of 0.06%; hence the observed temperature change is almost exactly what one should expect for a hemispheric average, based on simple climate models. Unfortunately, as is so often the case in solar–climate studies, the finding just cited is not statistically significant—about 50% of the time, given the statistics of the population sample, the same correspondence could occur from mere chance.

The response of surface temperature to forcing by sunspot blocking can be summarized as follows:

(1) On a hemispheric or global scale surface temperature responds to the 11-yr sunspot cycle, with an amplitude of 0.036 °C. However, this variation, although in accord with predictions of simple climate models, is not statistically significant.

(2) Station records for the past 80 yr in the north-east sector of the US establish that the mean surface temperature responds to solar, 11-yr forcing with an amplitude of a few tenths of 1 °C.

(3) A significant variation in the temporal distribution of record high monthly mean temperatures occurs in the same geographical region cited above, in response to solar forcing. The number of record low monthly mean temperatures also responds in a manner consistent with solar forcing, but not in a statistically significant way.

The phase of the relationship between sunspots and the solar constant, described above, is precisely opposite that which has been proposed to link longer-term changes in the envelope of solar activity with century-scale changes in climate[43]. The possible association of the Maunder and Sporer minima of solar activity, lasting 70 and 130 yr, with coincident cold periods of the Little Ice Age has been interpreted, for example, as the result of a postulated drop of about 1% in the solar constant[44]. The simple extrapolation of the mechanism of sunspot blocking to century-scale changes in the envelope of the activity cycle would induce an apparent secular modulation of at most 0.1%, with an increased solar constant at times of suppressed activity, such as the Maunder Minimum. Whether such an extrapolation is justified is another question. It is altogether possible that solar processes other than accumulated sunspot blocking act to modulate the solar constant in the longer term, and that such processes could oppose, in sense, the higher frequency modulation due to the 11-yr sunspot cycle. Such long-term changes are, of course, wholly speculative, since precision measurements of the solar constant span no more than 4 yr.

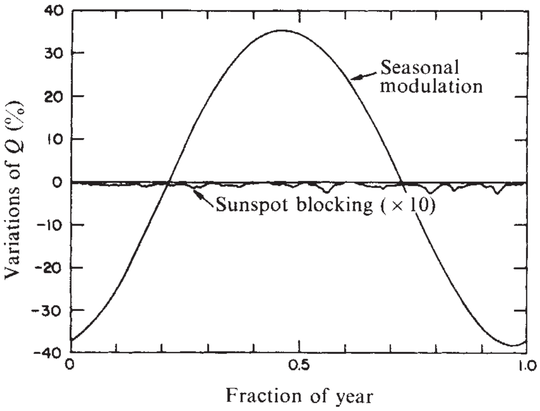

Fig. 5 Variation of daily solar irradiance (represented by Q) about the yearly mean due to seasonal effects in per cent deviation from a hemispheric average. The solar constant reconstruction for 1981 is shown multiplied by a factor of 10 for comparison.

Importance of climatic response

As shown above, both observation and theory seem to support the case for a small but direct surface air temperature response to measured and extrapolated solar constant fluctuations that is within a factor of 2 of the expected change in the solar luminosity.

These conclusions suggest several practical queations: (1) Is the apparent temperature response detectable as a perceptible weather effect? That is, can the average person sense a solar constant perturbation? (2) Will the anticipated climatic change be significant in practical or economic terms? (3) Can identifying the cause of climatic change at this level lead to better weather prediction?

Considering that the amplitude of the solar-induced mean temperature signal is but a few tenths of 1 °C, the answer to all of the above questions must surely be negative. A surface temperature effect of this magnitude is truly insignificant and for practical purposes imperceptible in the presence of typical diurnal extremes of 10° and a seasonal range of at least 30°. It is hard to see how a cyclic variation of a few tenths of a degree in the mean could have either predictive or economic import.

However, a factor of 3 enhancement in the frequency of temperature maxima occurring over a sunspot cycle could yield a marginally positive answer to all three of our pragmatic questions. People are much more likely to notice and remember unusual climate extremes. In economic terms it is again the extremes which cause dislocations. A factor of 3 change in the probability of occurrence of extrema in temperature is also of possible though limited predictive power.

Another way of gauging the climatic importance of a small perturbation to the solar constant is to compare it with the seasonal cycle of insolation. In Fig. 5 we compare the intra-annual variation of daily sunlight received over the Northern Hemisphere with the variation of S as reconstructed from sunspot blocking for 1981 (the latter is multiplied by 10 to make it visible). As one can see the interannual variation due to seasonal effects easily overwhelms that due to sunspot blocking. As another test, if we define the onset of spring to be 21 March in a year with 'normal' solar irradiance, how much will anticipated insolation changes due to sunspot blocking shift the effective first day of spring? In a year with high sunspot blocking (such as 1981 or 1982) the integrated irradiation reaches that of a normal spring about 0.2 days late. One effect of a sunspot-blocked solar constant could thus be the delay of the onset of spring by a few hours. By comparison, the meteorologically defined onset of spring, the date of last severe frost, has a typical variation of about 21 days and extreme differences of about 90 days in mid-latitude regions. Hence any shift due to the solar constant sunspot blocking is unimportant compared with typical variations, just as any induced change of mean surface temperature is also small compared with typical variations. This could be qualified, perhaps, by the fact that the mean sunspot blocking effect extends over a few years, thus allowing seasonal variations to be averaged over, making it slightly easier to detect the small effect.

Discussion

Solar constant variations of at most 0.5% for a few days and ~0.1% for a few years are now known to exist, but their expected effects on surface temperature are by any measure minor. Modelled or measured climate responses are insignificant compared with normally occurring changes and to apparently random variations in temperature. Thus it seems wholly unjustified to attribute the coincidence of a harsh winter such as that of the past year in some regions to a direct effect of a coincident solar constant deficit[28].

On the other hand, the importance of climate responses which might result from solar constant variations should not be dismissed. The identification of a simple, external forcing function such as a variable solar constant, which induces detectable changes of mean temperature, however slight, may provide a practical test of climate sensitivity on regional scales. Climate sensitivity verification is crucial to understanding such problems as the impact of anthropogenic carbon dioxide increases and land use changes. In a world where the demand for food is ever closer to the available supply, it may be true that any predictable fluctuation in climate will in time become important.

Perhaps the most important conclusion of the variations now established in the solar constant is that the Sun is indeed variable in its most fundamental output and that plausible responses of surface temperature have now been at least tentatively identified. Thus to increase our understanding of solar variability, we must continue the precision monitoring of the outputs of the Sun.

The demonstrated connection between changes in the solar constant and surface temperature exemplifies the kind of effort needed to redirect the study of solar–terrestrial relationships. Precision, spaceborne measurements of the solar output have enabled us to identify, and delimit, at least on time scales of days to years, a real climatic effect. Important questions remain unanswered. What are the detectable impacts of measured changes in solar short-wave radiation, or in the variable, particle inputs to the upper atmosphere? Do 'trigger' mechanisms have a role in amplifying the effects of variations in S or in other, weaker outputs of the Sun? Is the solar constant variable, perhaps in different or opposing ways, on longer time scales? New attempts at answering these and other such questions must surely focus not on statistical correlations but on mechanisms, modelling, and above all, measurements. Until we know how and in what ways the Sun varies we can only guess the possible terrestrial consequences.

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ARTICLES

The 5-min oscillations of the Sun are incompatible with a rapidly-rotating core

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Hill's suggestion that Einstein's general relativity may be invalid requires a rapidly spinning solar core. The triplet structure observed in the solar 5-minute power spectrum seems incompatible with this rotating core. But the triplet structure can be accounted for as the effect of a magnetically distorted core rotating with a ~12.5-day period.

FROM a study of the fine structure of solar oscillations Hill[1,2] has concluded that the Sun's core is rotating with a period of ~4 days. From a consideration of the effect of the resulting J_2 on Mercury's motion he concludes that Einstein's general relativity may be invalid[1]. From the same data Gough[3] agrees that the Sun contains a rapidly rotating core, but he disagrees with the implication *vis-à-vis* Einstein's theory.

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