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REVIEWS

Variations in solar luminosity and their effect on the Earth's climate

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Variations in the Sun's total energy output (luminosity) are caused by changing dark (sunspot) and bright structures on the solar disk during the 11-year sunspot cycle. The variations measured from spacecraft since 1978 are too small to have contributed appreciably to accelerated global warming over the past 30 years. In this Review, we show that detailed analysis of these small output variations has greatly advanced our understanding of solar luminosity change, and this new understanding indicates that brightening of the Sun is unlikely to have had a significant influence on global warming since the seventeenth century. Additional climate forcing by changes in the Sun's output of ultraviolet light, and of magnetized plasmas, cannot be ruled out. The suggested mechanisms are, however, too complex to evaluate meaningfully at present.

The possible effect on climate of variations in the Sun's total power output, or luminosity, has interested the scientific and financial communities since at least William Herschel's eighteenth-century study of correlations between sunspots and British grain prices. A proper measure for the Sun's output in this context is the wavelength-integrated radiation flux illuminating the Earth at its average distance from the Sun, called the total solar irradiance (TSI). Uncertainties imposed by the Earth's atmosphere delayed precise determination of variations in TSI until satellite-borne radiometry became available about a quarter of a century ago. Although the TSI fluctuations discovered so far through these measurements are too small to have a significant effect on climate[1], their analysis has now led to a robust understanding of solar luminosity variations, and new insights into the influence of magnetic fields on stellar convection. This advance in understanding is important, because it allows us to use the relatively short time series of space-borne measurements, along with other kinds of solar observations, to draw conclusions about the probable behaviour of TSI over past centuries and millennia, the timescales of more direct interest to climate studies.

From the theory of stellar evolution, we know that the Sun has gradually brightened by about 30% since it settled down to steady nuclear burning of hydrogen roughly 4.5 billion years ago. In spite of this reduced luminosity, the early Earth avoided completely freezing over, most probably because of much higher concentrations of greenhouse gases, such as methane or carbon dioxide (CO_2) (ref. 2). The more recent glacial/interglacial cycles provide us with an example of climate response over the shorter timescales of tens of thousands to millions—rather than billions—of years. The driving force here appears to be mainly variations in insolation, that is, the latitudinal and seasonal distribution of solar energy incident on the Earth, rather than in TSI itself. Such variations are thought to be caused by cyclic and predictable changes in the Earth's orbital parameters, the primary forcing effect being amplified by feedbacks involving CO_2 (ref. 3).

Here we review recent advances in our understanding of variations in TSI itself, which affect the planet's energy balance directly. This driving is relatively straightforward compared to possible climate driving due to the variable solar output of ultraviolet light, and of magnetized plasmas in the solar wind. These more speculative possibilities are difficult to assess at present.

Sunspots and bright faculae cause TSI variations

The first convincing evidence of TSI variation was obtained by ACRIM (Active Cavity Radiometer Irradiance Monitor), an electrical substitution radiometer flown on the Solar Maximum Mission (SMM) satellite in 1980 (ref. 4). The data showed clearly how TSI decreases from day to day as a dark sunspot forms or rotates onto the solar disk, then recovers as the spot's projected area declines. Those first historic measurements from ACRIM, and also from the somewhat less precise Nimbus 7 radiometry beginning in late 1978, initiated a continuous record of TSI compiled from several spacecraft[5].

This record (Fig. 1) shows a day-to-day variation of about 0.3% peak-to-peak amplitude most evident near maxima of the solar activity cycle. The high-frequency signal is superposed on an 11-year variation, of approximately 0.05–0.07% amplitude, which peaks around maxima of sunspot number. Brightening of the Sun with increasing sunspot number would be difficult to explain if dark magnetic sunspots were the only structures visible on the solar disk. In fact, as seen in Fig. 2, the Sun's photosphere (the atmospheric layer we see in broad-band visible light) is also flecked with many bright magnetic areas called faculae. They are immediately apparent where concentrated in bright clumps around sunspot groups. In a less conspicuous way, they are widespread also in the so-called magnetic network, which covers most of the solar surface (see, for example, ref. 6). We refer below to the bright clumps and the magnetic network collectively as the bright component of the surface magnetic field, or as 'magnetic brightenings'.

Each such dark or bright structure contributes a TSI variation equal to the product of its projected area and its photometric contrast relative to the adjacent, undisturbed photospheric disk. Empirical models reconstruct a TSI variation by adding up these contributions using records of the changing areas of the spots and magnetic brightenings. These models can account for over 80% of the variance in the irradiance time series[7–11] (Fig. 3). This shows that additional

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contributions to the TSI variation from photospheric temperature variations outside spots and magnetic brightenings must be small. Apparently, neither the darkness of spots nor the increased flux from the bright component is cancelled by compensating variations in solar brightness elsewhere on the disk. This has historically caused significant debate in the literature, because the photometric accuracy of solar images is insufficient to detect such cancelling contributions if they are spread over large areas. Their possible presence is thus hard to disprove by more direct means.

Physical mechanisms of luminosity variation

The observations show that magnetic structures reduce or increase the local radiation flux for as long as they exist at the surface. They present (in the case of sunspots, for example) a local magnetic obstruction to the flow of heat through the Sun. One may ask why such a disturbance in the heat flow does not simply readjust ('shunt') around the obstacle. If this were the case, it would not cause a TSI variation at all. Several mechanisms that might store (for spots) or release (for the bright component) the energy involved in irradiance variations have been suggested in response to this conceptual problem. For instance, the 'missing' radiative flux of a spot might, in principle, be stored in intensifying its strong magnetic field[12]. But this storage would only occur while the spot's magnetic energy is increasing, whereas the amplitude of sunspot-induced dips in TSI depends only on changes of the spot's projected area, not on whether its true area is growing or decaying, or on the magnetic field strength[13]. More broadly, this observational constraint seems to disqualify any mechanisms that depend on plasma flows[14] or other phenomena associated with growth of a spot. Magnetic 'stirring', a proposed enhanced entrainment of heat associated with rising magnetic flux tubes[15], seems to play little part, given the close amplitude match between measured and reconstructed TSI variations.

Modelling of sunspots using current magnetohydrodynamic codes[16] confirms that their darkness can be understood as thermal 'plugs' in which intense vertical magnetic fields divert heat flow from deeper layers[17,18]. Magnetic brightenings act in the opposite sense, as local thermal 'leaks'[19,20]. They are bright because the effect of their smaller-scale magnetic field is to form small depressions in the photospheric surface, enabling radiation from lower and hotter atmospheric layers to escape more easily[19,21]. These depressions have now been imaged directly in the highest-resolution pictures of the photosphere[22] (Fig. 2), and are reproduced in detail by realistic three-dimensional radiative magnetohydrodynamic simulations of these small magnetic structures[23].

Calculations with such a thermal impedance model of solar luminosity variation (Fig. 4) show that the heat flux diverted by a spot is not merely shunted aside to reappear nearby. Instead, the thermal perturbation spreads horizontally and back down into the Sun, much more quickly than it can be radiated from the photosphere. As a consequence, the 'blocked heat flux' effectively remains stored in the Sun for hundreds of millennia instead of appearing elsewhere on the surface, in agreement with the observation that 'bright rings' around spots are weak or absent[24,25]. This rapid redistribution is also in agreement with the absence of 'thermal shadows' preceding spot emergence[26], and the absence of phase differences between the irradiance dip and the appearance of a spot's magnetic field at the photosphere[18]. The thermal plug model predicts that the Sun's luminosity immediately drops by a factor equal to the product of the spot's cross-sectional area and its brightness deficit, as observed. This factor is independent of the spot's growth or decay rate, also in agreement with observations[13]. The heat missing from the spot is stored as slightly increased internal and potential energy of the entire solar convective envelope. The predicted changes in solar radius accompanying changes in spot area are unobservably small[27]. This is consistent with the increasingly tight upper limits on measured radius variations discussed below.

The Sun's remarkable ability to store, rather than quickly re-radiate, fluctuations in heat flow to the photosphere can be understood in terms of a simple illustration. Consider a satellite in temperature equilibrium with its surroundings in space. Then imagine that current flow through a resistor on the satellite is briefly turned on, sending a heat pulse spreading rapidly through the satellite at a rate determined by the thermal diffusivity of aluminium, its main constituent. New isotherms describing the somewhat warmer temperature distribution within the satellite will be relatively quickly established over this diffusive timescale. But the satellite is

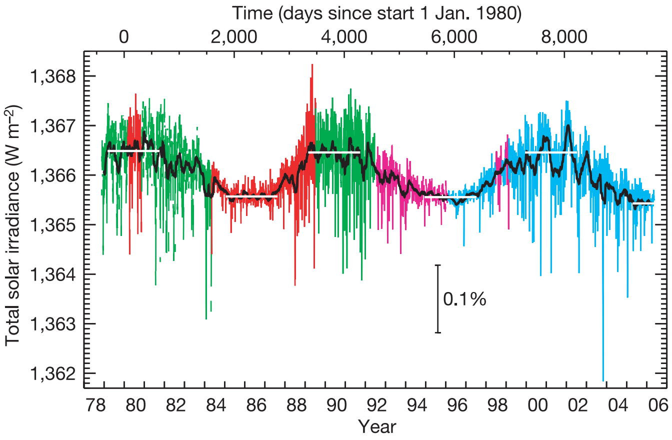

Figure 1 | Temporal variation of total solar irradiance, as measured by radiometers on several spacecraft since 1978. Daily measurements are shown with a 81-day running average. The TSI increases around the maxima of sunspot number that occurred near 1980, 1990 and 2001. The high-frequency variation is caused by the changing projected areas of spots and faculae on the solar disk as the Sun rotates on its axis in approximately 27 days. The TSI variation amplitudes of the three sunspot cycles shown (horizontal lines) are 0.92, 0.89 and 0.90 $\mathrm{W\,m^{-2}}$, respectively, with an average minimum of 1,365.52 ± 0.009 $\mathrm{W\,m^{-2}}$ and differences of the minima from this average of +0.051, +0.037 and −0.089 $\mathrm{W\,m^{-2}}$.

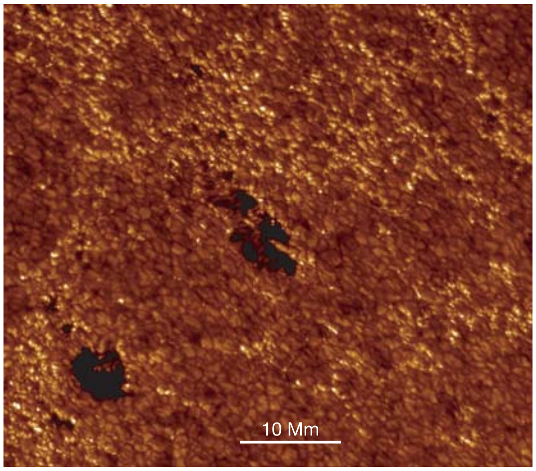

Figure 2 | An image of the solar photosphere (the surface of the solar disk seen in visible light), showing the structures responsible for the TSI variations. The granules, covering most of the area, are the convective flows carrying energy from the interior. They contribute the steady component of the irradiance received by the Earth. Magnetic structures are dark (sunspots) or bright (the small bright points called faculae) and contribute a component that varies with the sunspot cycle. Faculae show up especially towards the limb of the solar disk. Their contribution dominates over the dark spots, so that the Sun is slightly brighter at sunspot maximum. Scale bar, ten megametres. (Image taken with the Swedish 1-m Solar Telescope by B. De Pontieu on 16 June 2003.)

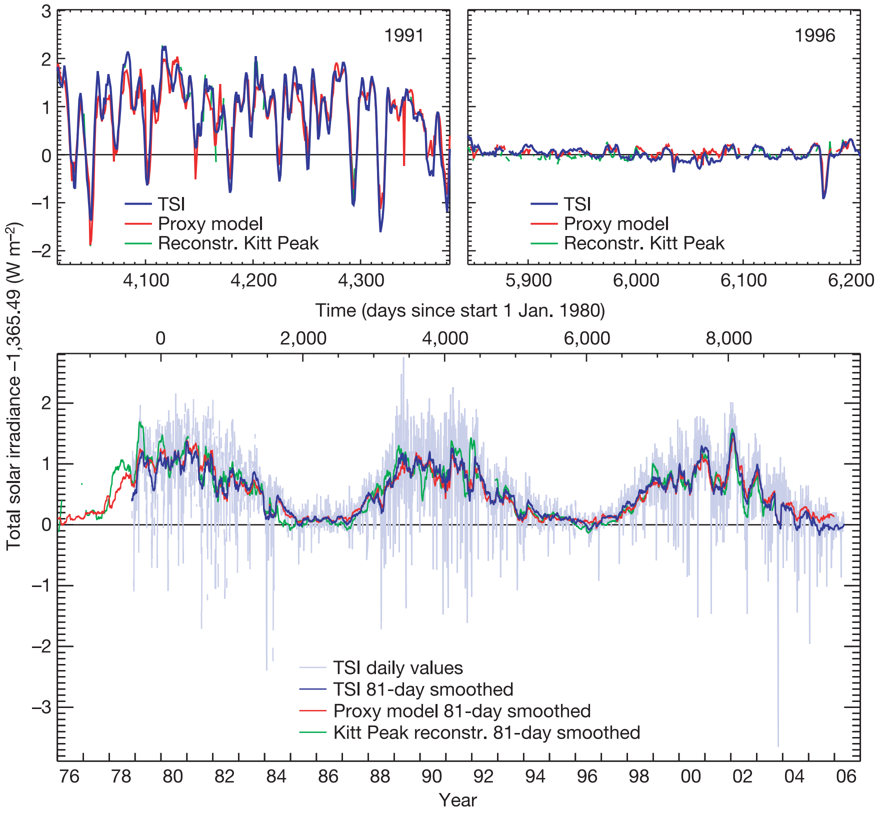

Figure 3 | Variations in total solar irradiance. Lower panel, a comparison of radiometrically measured TSI variation[5] as daily values (light blue) and as 81-day smoothed curve (dark blue). Also plotted are TSI reconstructed from contributions of sunspots, faculae and network[10] (red curve) and from Kitt Peak magnetograms[11]. Differences between the red and green curves illustrate remaining uncertainties in the reconstruction of TSI variation over the 11-year cycle. The upper panels illustrate fluctuations due to spots and magnetic brightenings moving across the solar disk on the 27-day solar rotational timescale, with daily TSI values on an expanded timescale during a solar maximum (1991) and minimum (1996). Again, the reconstructions are also plotted for comparison.

now warmer than before, and must eventually return to equilibrium with its space surroundings by radiating the heat liberated by the resistor. For a satellite, this timescale for radiative equilibration is about two orders of magnitude longer than the diffusive timescale, and until it is achieved, the resistor's heat pulse is stored in the satellite.

The solar equivalent of the thermal diffusion in a metal is thermal exchange by convective flows. The radiative equilibration timescale of the Sun's convection zone, about 100,000 years, is about six orders of magnitude longer than this exchange timescale, and storage of thermal disturbances is much more efficient than in the metal analogy. As a consequence, neither the excess emission in the bright magnetic component nor the darkness of spots is expected to be compensated by measurable changes in photospheric temperature elsewhere on the disk.

These findings were originally obtained from calculations in which convection was approximated by turbulent diffusion. Recent three-dimensional hydrodynamical simulations, which accurately reproduce observation of solar convection near the photosphere[28], confirm the picture sketched above, of the Sun's convective envelope as a 'thermal superconductor' with a huge thermal inertia[27]. We note that this thermal inertia explains not only why 'superficial' photospheric magnetic structures can cause net irradiance fluctuations, but also explains why additional variations with 'deeper' origins in the Sun have not been observed so far.

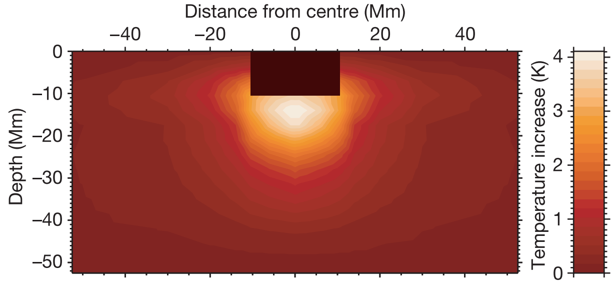

Figure 4 | Thermal disturbance caused by a sunspot, computed as a function of distance from it and depth into the Sun[18]. Brightness represents temperature difference compared with an unspotted model of the Sun. At the surface the increase almost vanishes: there is no 'bright ring' around the spot. Instead of reappearing at the surface, the thermal energy blocked by the dark spot remains stored in the solar interior[17,18].

Variation in irradiance by other mechanisms

A number of observational techniques have been used to search for other, possibly quite different, modes of solar luminosity variation. For example, variations in global heat flux carried by large convective cells are predicted by certain idealized models. Neither these cells, nor other evidence for global temperature variations, have been found in precise photometric mapping of the photosphere[29,30]. Gradients of photospheric heat flux in heliographic latitude have been reported, but further analysis indicates that these arise from inhomogeneities in the distribution of the network[31], rather than from deeper-lying convective patterns, as originally believed. A slow increase of photospheric effective temperature outside magnetic structures has been reported from measurements of certain temperature-sensitive photospheric spectral lines since 1978, but the amplitude is very small—roughly equivalent to a TSI variation of 0.01% per decade (ref. 32).

Measurements of the solar diameter originally attracted attention because they seemed to offer a unique diagnostic of otherwise unobservable internal temperature variations. However, the amplitude of reported diameter variations has decreased with improved measurement techniques. Separate analyses of the data from the Michelson Doppler Imager (MDI) instrument on the SOHO spacecraft, using both heliometric and helioseismic techniques, show no evidence of secular trends in diameter, or variations attributable to the 11-year cycle, at the level of a few milliarcseconds (a few kilometers on the Sun[33,34]). This is consistent with, but ten times better than, upper limits from the best ground-based measurements of the Sun's diameter[35]. Conflicting detections nearly two orders of magnitude larger continue to be cited, however[36–38]. If diameter variations were detected within the tight upper limits they would be quite small relative to variations in TSI, indicating an origin in layers close below the surface[27,39]. Thus, it is unlikely that diameter measurements can reveal deeper-lying sources of solar irradiance variation, as was originally hoped. In fact, they put strict limits on the presence of such sources. Their small amplitude also implies that changes in the size of the solar disk contribute negligibly to the TSI.

Part of the increased irradiance measured around sunspot maxima has been interpreted in some studies as evidence for enhanced temperatures extending deep inside the convective envelope[40]. The resulting expansion of the envelope, however, would cause the frequencies of global sound wave oscillations to decrease[41], whereas helioseismic observations show an increase at activity maximum[42]. Moreover, the frequency and wavenumber dependence of this effect show that it is not due to a change in the solar radius. Most of it is explained by the increased 'stiffness' of the solar atmosphere due to magnetic fields[43]. A remaining small cooling seems consistent with the enhanced radiative losses from the surface due to the bright component[44], rather than with heating from below.

Overall, no significant evidence can be claimed at present for modes of irradiance variation other than the surface spottiness caused by magnetic fields. Studies of other stars support this conclusion, as the reported photometric variability of Sun-like stars always correlates with magnetic activity level[45]. So far, no cases have been reported of significant luminosity variations caused, for instance, by the random variations that one might expect from fluctuations of stellar convective efficiency.

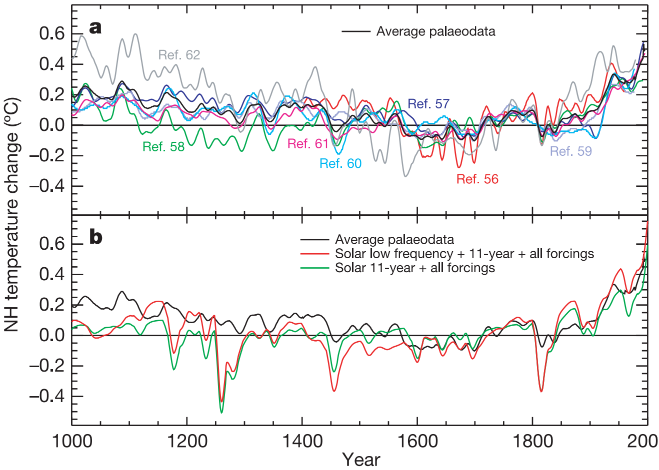

Figure 5 | Northern Hemisphere temperatures compared to model results. **a**, Variations of Northern Hemisphere (NH) mean temperature over the past millennium as reconstructed in seven recent studies[56–62]. The plots were constructed from the original data, low-pass-filtered with a 30-year, 19-term gaussian filter. The black line shows the unweighted mean of the individual smoothed curves. All data are zeroed over 1601–1900. **b**, Comparison of the reconstructed Northern Hemisphere temperature for the past millennium with the modelled temperature changes including volcanic[68] and anthropogenic forcing[64], with TSI forcing by solar cycle amplitude (green curve) and with additional low-frequency variations (red curve); TSI data are from ref. 69, extended using ^{10}Be (ref. 70). The climate sensitivity assumed is a central value of 2.6 °C equilibrium warming for a CO_2 doubling. The filtering and zeroing of the model results is the same as used for the temperature reconstructions.

This absence of other solar luminosity variation modes may seem remarkable. For example, the power required to drive the Sun's 11-year magnetic oscillation must ultimately be drawn from solar heat flow. Attempts to model such 'structural' luminosity variations[37] confirm the earlier finding that 11-year output variations can be produced provided that a perturbation is introduced in relatively shallow layers (a few per cent of the solar radius), where the thermal timescale is short[27,39]. There is, however, no evidence at the observed surface itself of the kinds of magnetic fields that are assumed to exist just below it in these models. In addition, most dynamo models place the field generation deep inside or even below the convection zone, where thermal perturbations are severely attenuated because of the 100,000-year radiative relaxation time of these more massive layers. Such structural luminosity variations are thus unlikely to play a role on decadal or even centennial timescales.

Multi-decadal to millennial variations of TSI

If only photospheric magnetic structures influence TSI, what range of TSI variation might be expected from the behaviour of solar activity over recent centuries? One influential study[46] extrapolated this relationship between activity and TSI to activity levels lower than any directly observed on the Sun—levels where any vestige of even the weakest photospheric magnetic structures is removed. At the time, it was believed that such ultra-quiet behaviour had been observed in certain Sun-like stars. This extrapolation introduced an additional, low-frequency TSI variation having an amplitude about three times larger than the present 11-year variation expected from spots and the bright magnetic component.

The apparent success of this model in driving climate variations that appeared to match observed variations attracted wide attention. However, this study has since been retracted[47], partly because the stars it was based on have since been shown to be less Sun-like than was originally believed[48], and also because it implied that the magnetic network must have been absent before the beginning of the twentieth century. This disagrees with archival solar images[49]. Observables invoked in other reconstructions—for example, sunspot cycle length[50,51], the smoothed activity level[46,51], or geomagnetic indices[52]—lack a demonstrated connection to TSI variation, and such models remain speculative.

The possibility of larger irradiance variations generated by higher past solar activity levels has received less attention. In the present Sun, the photometric effects of the bright and dark magnetic components partially cancel, so higher levels of irradiance variation could result if this balance were to change[53]. In fact, the ratio of sunspot to facular area is observed to increase at the highest solar activity, such as during cycle 19 peaking around 1957. Such spot dominance also seems required to explain the photometric variability on younger and more active stars that are otherwise similar to the Sun[45]. Recent reconstructions from ^{14}C records disagree on whether the Sun might have experienced extended episodes of very high activity in the past 10,000 years, much above that encountered in the recent past[54,55]. The intriguing possibility of larger luminosity variations by such a 'hyperactive' Sun deserves closer attention.

The climate record and possible TSI variations

Additional evidence on past TSI variations might, in principle, be gleaned from reconstructions of the Earth's climate record. But the relationship between TSI variations and climate is complex, being significantly affected by uncertainties in the climate sensitivity, the large thermal inertia of the oceans, and the effects of non-solar forcings such as volcanism and human-induced factors.

Figure 5a shows seven reconstructions of Northern Hemisphere temperature for the past millennium[56–62], smoothed with a 30-year low-pass filter, and their unweighted mean. The mean curve shows a gradual cooling to around 1700, followed by a warming that has accelerated in the twentieth century, resulting in a shape widely described as a 'hockey stick'. Figure 5b compares the average temperature curve with climate model simulations of Northern Hemisphere temperature. We use the upwelling-diffusion energy balance climate model used by IPCC[63–67] for these model simulations. In the present context, models of this type have advantages over more complex atmosphere–ocean general circulation models (see, for example, ref. 67), not least because the climate sensitivity can be specified by the user.

The present simulations consider TSI forcing combined with volcanic[68] and anthropogenic contributions[63,64]. We consider that TSI variations are produced only by the net effect of dark and bright magnetic contributions (from ref. 69). As explained in previous sections, this is the only physically defensible TSI forcing at present. The TSI data were extended to 1000 AD using the ^{10}Be isotope record[70].

It can be seen from Fig. 5b that the observed cooling towards a minimum around the seventeenth century is hardly significant in the modelled temperatures using this small but realistic TSI variation (green curve). We also considered the case where the forcing by the dark and bright magnetic components was modified by adding a low-frequency component[69], amplifying the solar forcing range by 3 to 4 over this time period. In this case (red curve), the model cooling trend is closer to the reconstructed palaeotemperature trend. Further simulations with solar forcing alone show that the solar contribution to warming over the past 30 years is negligible[48]. These results indicate that a TSI variation at least three times larger than is justified from present evidence is required to produce a climate variation of the amplitude suggested by the seventeenth-century cooling. A more detailed statistical comparison between the modelled and reconstructed curves is problematic because of uncertainties in the palaeotemperature reconstruction, in the TSI proxies used, and in the modelling of, for example, the volcanic contribution.

The use of the sunspot number and of radioisotopes as proxies of TSI variation deserves some comment. As pointed out above, the only defensible TSI variation at present arises from the net contribution of bright and dark photospheric magnetic structures. The areas of such structures are available from measurements dating back only to the beginning of the twentieth century. For the earlier period dating back to the beginning of telescope observations of the solar disk in the early seventeenth century, the rough level of solar activity is commonly measured using a somewhat arbitrary statistic based on the daily number of sunspots visible through a small telescope. This sunspot number, R, gives a fair estimate of TSI decrease due to spots. On average, it also estimates the TSI increase due to the bright component, as this tends to vary in rough proportion to the sunspot dimming. However, the relative contributions to TSI of the dark and bright components vary significantly between sunspot cycles, so the estimate of TSI obtained from use of R in any given cycle can be in error by as much as 30%. Nevertheless, the behaviour of R does provide very interesting information on the variation of TSI over centennial timescales back to the early seventeenth century.

Use of a radio-isotope as a proxy for TSI variation introduces additional uncertainties. The radio-isotopes are not produced in the Earth's atmosphere directly by the Sun's flux of energetic particles. For recent levels of solar activity, they are produced mainly by high-energy galactic cosmic rays, from outside the Solar System. Their modulation with the solar cycle is due to changes in shielding of these cosmic rays by the heliosphere (the solar wind). The efficiency of this shielding depends on solar plasma outflows from open magnetic fields in quiet regions and individual events such as flares and coronal mass ejections[71]. Although this shielding increases roughly with the general level of solar activity, it is only very loosely proportional to the areas of the dark and bright magnetic structures that drive TSI. In view of this, it is unrealistic to expect a fixed relation between variations in ^{10}Be production rate and TSI over the past millennium. The relation is complicated further by possible climate influences on the ^{10}Be deposition rate[72], causing errors in the inferred ^{10}Be formation rate.

Evidence for the influence of the Sun on climate has recently been extended by a millennial-scale correlation found between North Atlantic climate (inferred from the properties of deep sea sediments) and solar activity (inferred from ^{10}Be and ^{14}C), extending back about 10,000 years (ref. 73). It remains to be seen whether the correlation is confined to the North Atlantic, or is global[74]. No specific mechanism has been identified so far to generate millennial-scale solar irradiance variations.

Overall, we can find no evidence for solar luminosity variations of sufficient amplitude to drive significant climate variations on centennial, millennial and even million-year timescales. Better reconstructions of global temperature and solar activity will be required to investigate further the apparent relationships between climate and solar activity seen over the past millennium and through the Holocene, particularly if the signature of any solar influence is spatially restricted[75].

Less direct Sun–climate couplings driven by the Sun's well-known variability in ultraviolet flux and in outputs of magnetized plasma might yet account for Sun–climate correlations that defy explanation by the direct influence of TSI variation considered here. The proposed indirect mechanisms[76,77] are, however, complex, and involve subtle interactions between the troposphere, stratosphere and even higher layers of the Earth's atmosphere that are much less well understood than the direct radiative forcing effect. Modelling of such interactions is proceeding rapidly, but incisive tests of the models will be required to achieve certainty. For instance, a recent reconstruction[78] shows that the time series of solar ultraviolet flux since 1915 differs substantially from the behaviour of TSI and exhibits a surprisingly poor correlation with global temperature. Clearly, more needs to be done on such reconstructions to help guide future modelling.

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