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Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature

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There is considerable evidence for solar influence on the Earth's pre-industrial climate and the Sun may well have been a factor in post-industrial climate change in the first half of the last century. Here we show that over the past 20 years, all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global mean temperatures.

Keywords: solar variability and climate; solar–terrestrial physics; anthropogenic climate change

1. Introduction

A number of studies have indicated that solar variations had an effect on pre-industrial climate throughout the Holocene. These studies have been made in many parts of the world and employ a wide variety of palaeoclimate data (Davis & Shafer 1992; Jirikowic *et al.* 1993; Davis 1994; van Geel *et al.* 1998; Yu & Ito 1999; Bond *et al.* 2001; Neff *et al.* 2001; Hu *et al.* 2003; Sarnthein *et al.* 2003; Christla *et al.* 2004; Prasad *et al.* 2004; Wei & Wang 2004; Maasch *et al.* 2005; Mayewski *et al.* 2005; Wang *et al.* 2005*a*; Bard & Frank 2006; Polissar *et al.* 2006). Some of the most interesting of these studies used data that are indicators of more than just local climatic conditions. For example, Bond *et al.* (2001) studied the average abundance of ice-rafted debris (IRD), as measured in the cores of ocean bed sediment throughout the middle and North Atlantic. IRD are glasses, grains and crystals that are gouged out by known glaciers, which are then carved off in icebergs and deposited in the sediment when and where the icebergs melt. The sediment is dated using microfossils found at the same level in the core. The abundances of this IRD are very sensitive indicators of currents, winds and temperatures throughout the North Atlantic and reveal high, and highly significant, correlations with both the ^{10}Be and ^{14}C cosmogenic isotopes. A second example has been obtained from

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the deviation of the oxygen isotope ratio from a reference standard variation, $\delta^{18}O$, as measured in stalagmites in Oman and China in two separate studies (Neff *et al.* 2001; Wang *et al.* 2005*a*). These studies reveal an exceptional correspondence with the cosmogenic isotopes on all time scales between decades and several thousand years. The $\delta^{18}O$ is, in each case, a proxy for local rainfall and reveals enhanced precipitation caused by small north–south migrations of the intertropical convergence zone. Large effects are seen because the latitudinal gradients around the sites are large. The fact that the effect is seen at widely spaced locations is evidence for coherent shifts in the latitude of the monsoon belt.

These correlations of palaeoclimate indicators are found for both the ^{14}C and ^{10}Be cosmogenic isotopes. The ^{10}Be is a spallation product of galactic cosmic rays hitting atmospheric O, N and Ar atoms; the ^{14}C is produced by thermal neutrons, generated by cosmic rays, interacting with N. However, their transport and deposition into the reservoirs where they are detected (for example, ancient tree trunks for ^{14}C and ice sheets or ocean sediments in the case of ^{10}Be) are vastly different in the two cases. As a result, we can discount the possibility that the isotope abundances in their respective reservoirs are similarly influenced by climate during their terrestrial life history because the transport and deposition of each is so different. Thus, it is concluded that the correlations are found for both isotopes owing to the one common denominator in their production, namely the incident cosmic ray flux. On the time scales of the variations seen (decades to several thousand years), the dominant cause of variation in cosmic ray fluxes is the Sun (Beer *et al.* 2006). Hence, these studies are strong indicators of an influence of solar variability on pre-industrial climate.

The research discussed previously studied variations of pre-industrial climate on a huge range of timescales between 10^2 and 10^8 years. Recently, solar effects on climate on time scales of 100 years and less have also been detected, even extending into the era of fossil fuel burning. Both observations and general circulation models (GCMs) of the coupled ocean–atmosphere climate system have improved our understanding of the coupling mechanisms and the natural internal variability of the climate system, such that it is now becoming feasible to detect genuine solar forcing in climate records (Haigh 2003). The thermal capacity of the Earth's oceans is large and this will tend to smooth out decadal-scale (and hence solar cycle) variations in global temperatures, but this is not true of centennial variations (Wigley & Raper 1990). There is considerable evidence for century-scale drifts in various solar outputs, in addition to the solar cycle variations (Lean *et al.* 1995; Lockwood *et al.* 1999; Solanki *et al.* 2001, 2004; Lockwood 2004, 2006; Beer *et al.* 2006; Rouillard *et al.* 2007). In order to evaluate the relative contribution of solar variability and anthropogenic greenhouse effects to climate change (and other important factors such as volcanoes and sulphate aerosol pollution), GCMs have become increasingly important. Detection–attribution techniques (see the review by Ingram (2006)) use regression of the observed global spatial patterns of surface temperature change with those obtained from a GCM in response to various forcing inputs. These studies have detected a solar contribution to global temperature rise in the first half of the twentieth century: a contribution that implies some form of amplification of the solar radiative forcing variation (Cubasch *et al.* 1997; Stott *et al.* 2000, 2003; North & Wu 2001; Douglass & Clader 2002; Meehl *et al.* 2003; Ingram 2006).

Three main mechanisms for centennial-scale solar effects on climate have been proposed. The first is via variations in the total solar irradiance (TSI) which would undoubtedly cause changes in climate if they are of sufficient amplitude. We have no direct measure of TSI variations on century time scales, but reconstructions do vary with the cosmogenic isotope production rate and so this effect has the potential to explain the palaeoclimate correlations (Lockwood 2006). However, the inferred changes in TSI are much smaller than required to cause significant climate change (Foukal *et al.* 2006; Lockwood 2006). The second mechanism invokes variations in the solar UV irradiance, which are larger than those in TSI, and mechanisms have been proposed whereby despite the low power in this part of the solar spectrum, they influence the troposphere via the overlying stratosphere (Haigh 2001). The third proposed mechanism is considerably different from the other two—it has been suggested that air ions generated by cosmic rays modulate the production of clouds (Svensmark 2007). This mechanism (Carslaw *et al.* 2002) has been highly controversial and the data series have generally been too short (and of inadequate homogeneity) to detect solar cycle variations in cloud cover; however, recent observations of short-lived (lasting of the order of 1 day) transient events indicate there may indeed be an effect on clean, maritime air (Harrison & Stephenson 2006).

These three proposed mechanisms are linked by a common element, namely the magnetic field that emerges from the Sun. The field threading the solar surface modulates the TSI and UV irradiance and our understanding of these effects has advanced dramatically in recent years (Krivova *et al.* 2003; Solanki & Krivova 2006). A small fraction of this photospheric field passes through the solar atmosphere and is dragged out into the heliosphere by the solar wind. This open solar flux has been shown to vary greatly on centennial time scales (Lockwood *et al.* 1999; Rouillard *et al.* 2007) and models that reproduce these variations predict that the total photospheric field (and TSI) will also have varied to some extent (Solanki *et al.* 2001; Wang *et al.* 2005*b*). The open magnetic field has also been shown to be a key part of the shield that protects the Earth from cosmic rays and to anti-correlate very highly with cosmic ray fluxes (Lockwood 2001; Rouillard & Lockwood 2004). Hence, TSI, UV and direct cosmic ray effects vary together and cannot be distinguished by correlative methods alone (Lockwood 2006).

One fact that could help distinguish between the effects of changes in solar irradiance and galactic cosmic rays is that the former effect is not influenced by changes in the Earth's magnetic field, whereas any latter effect would be. In this respect, recent reports of associations between geomagnetic and climatic changes (Gallet *et al.* 2005, 2006; Courtillot *et al.* 2007) would be very significant, if confirmed. These changes have been linked to latitudinal motions of the intertropical convergence zone (Haug *et al.* 2001) and effects on civilizations that had a critical dependence on rainfall (Hodell *et al.* 1995; Curtis *et al.* 1996; deMenocal 2001; Haug *et al.* 2003; Gallet & Genevey 2007).

Lastly, we note that transient bursts of solar energetic particles, often associated with very large solar flares, have been observed to have effects on the Earth's middle and lower atmosphere, including the large-scale destruction of polar stratospheric and tropospheric ozone (Jackman *et al.* 1993, 2001; Seppälä *et al.* 2004). However, we do not explicitly consider these events further here, beyond their general correlation with sunspot number and open solar flux. This is for a number of following reasons: (i) the events that cause significant effects are

Figure 1. (*Opposite.*) Solar and heliospheric observations for recent decades compared with global mean temperature data. (*a*) The international sunspot number, R, compiled by the World Data Centre (WDC) for the Sunspot Index, Brussels, Belgium. (*b*) The open solar flux F_S derived from the radial component of the interplanetary magnetic field, taken from the OMNI2 composite dataset compiled by NASA's Goddard Space Flight Centre (GSFC), USA. (*c*) The neutron count rate C due to cosmic rays of rigidity of above 3 GV, recorded by the Climax neutron monitor and distributed via WDC-A, Boulder, USA. (*d*) The TSI composite compiled by the World Radiation Centre, PMOD Davos, Switzerland. (*e*) The GISS analysis of the global mean surface air temperature anomaly ΔT (with respect to the mean for 1951–1980), compiled by GSFC, primarily from meteorological station data. The black lines are monthly means and in (*d*) daily values are also shown in grey. A thin horizontal line at TSI of 1365.3 W m^{-2} has been drawn in (*d*) to highlight that values in the recent solar minimum have fallen below the minima of near 1365.5 W m^{-2} seen during both the previous two solar minima.

sufficiently rare that detecting a long-term trend in their occurrence is very difficult with the limited data available with us, (ii) observations and models show that the ozone can take up to two months to recover, but that after that there is no apparent longer-lived change induced by the transient, and (iii) links between the polar middle atmospheric ozone depletion and the global surface air temperature variation are not clear.

It is not the purpose of this paper to investigate further the proposed mechanisms discussed in this introduction nor, indeed, to evaluate the reported connections between solar variability and changes in climate on millennial or centennial timescales. Rather, the aim of the present paper is to study data from the last 40 years in some detail in order to see if solar variations could have played any role in observed present-day global warming.

2. Observations

Figure 1 shows monthly means of observations of various solar parameters taken since 1975 and compares them with the GISS reconstruction of global mean air surface temperature, based primarily on meteorological station measurements (Hansen *et al.* 1999). The international sunspot number R (figure 1*a*) reveals the decadal-scale solar activity cycle that also dominates the variation in the other solar parameters: the open solar flux F_S (figure 1*b*), derived from the observed radial component of the interplanetary magnetic field (Lockwood *et al.* 1999); the counts C of neutrons generated by cosmic rays incident on the Earth's atmosphere, as observed at Climax (figure 1*c*); and the TSI (figure 1*d*). The TSI data are from various space-based radiometers. Here we use the Physikalisch-Meteorologisches Observatorium (PMOD) TSI data composite (Fröhlich & Lean 2004) that does differ from others (Willson & Mordvinov 2003) but has the most rigorous set of time-dependent intercalibrations between the radiometers that account for both instrument degradations and pointing 'glitches' (Fröhlich 2006).

3. Trends on time scales greater than the solar cycle length

The Earth's surface air temperature (figure 1*e*) does not respond to the solar cycle. Even a large amplitude modulation would be heavily damped in the global mean temperature record by the long thermal time constants associated with parts of

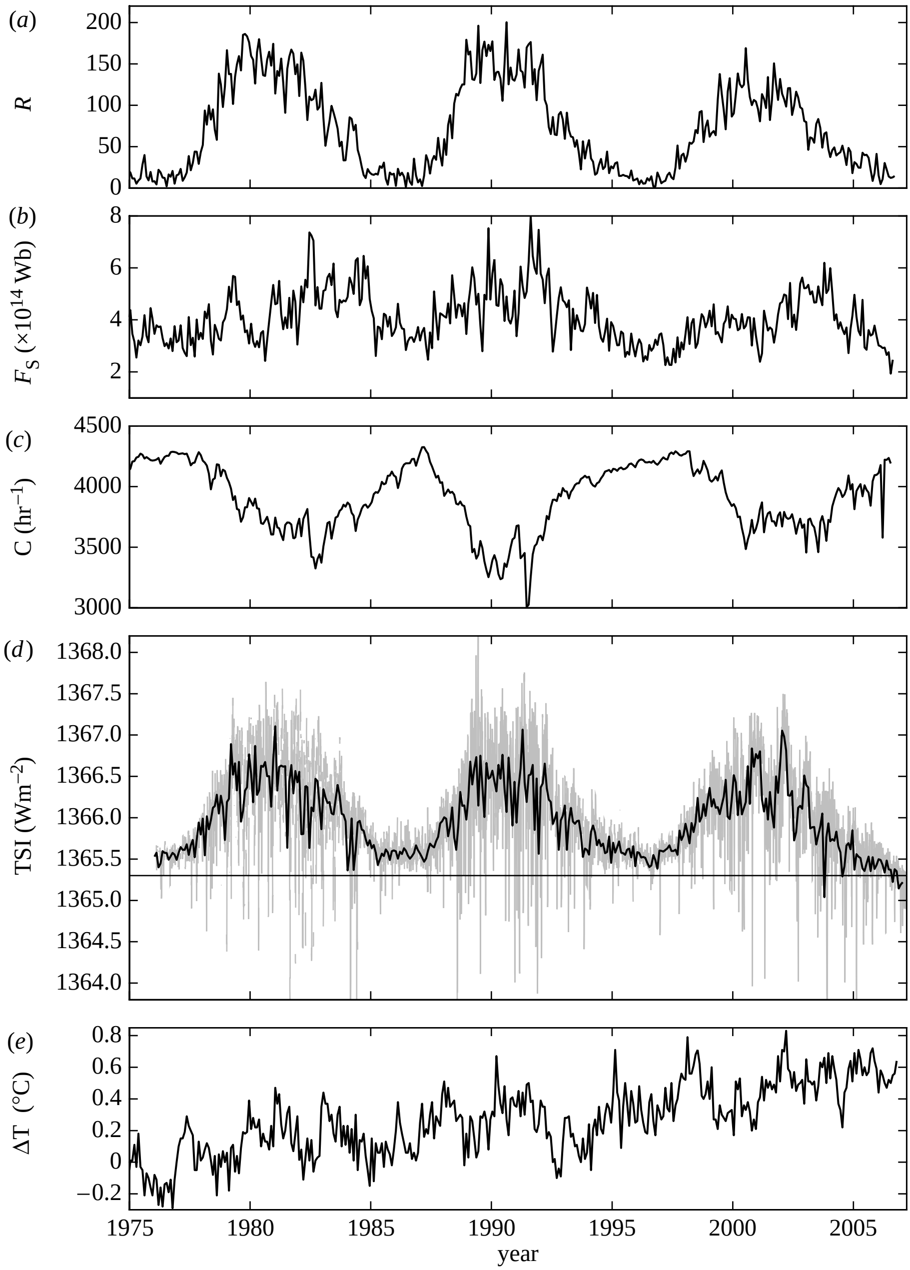

Figure 1. (*Caption opposite.*)

the climate system, in particular the oceans (Wigley & Raper 1990). However, solar variations on time scales greater than a decade will not be smoothed to such an extent and if, via any of the proposed mechanisms discussed above, they give a sufficiently large amplitude modulation of the Earth's radiation budget, then they would leave a signature in the Earth's surface temperature record.

Hence, we need to smooth out the solar cycle variations in figure 1 to reveal any longer-term trends. Figures 2 and 3 demonstrate the simple method we use to

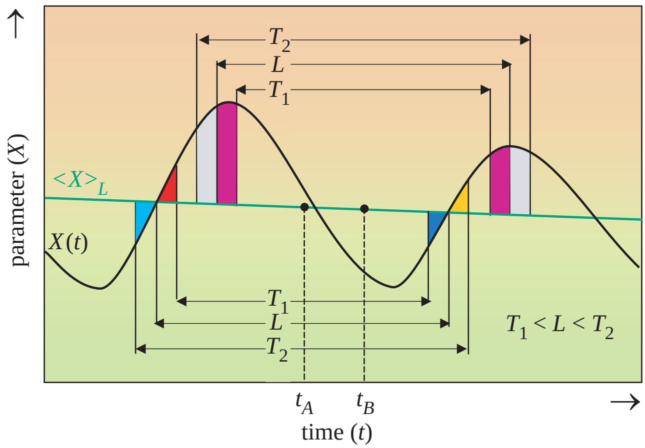

Figure 2. Schematic illustration of running means of a periodic parameter $X(t)$, over intervals T_1, L and T_2 where L is the cycle length. The intervals centred on the time t_B run from peak to peak and use of $T_1 < L$ results in the omission from the running mean of two intervals (shaded mauve) for which X exceeds the true cycle-averaged mean, $\langle X\rangle_L$; thus the mean of X over the interval T_1, $\langle X\rangle_{T_1}$, is less than that for the interval L, $\langle X\rangle_L$. Correspondingly, the interval $T_2 > L$ includes two additional intervals (shaded grey) when X exceeds the true cycle-averaged mean, $\langle X\rangle_L$, so $\langle X\rangle_{T_2}$ exceeds $\langle X\rangle_L$. Conversely, for intervals that run from minimum to minimum (not shown), $\langle X\rangle_{T_1} > \langle X\rangle_L$ and $\langle X\rangle_{T_2} < \langle X\rangle_L$. On the other hand, the intervals centred on time t_A run between points of peak gradient in X. In this case, $T_1 < L$ results in the omission of one interval when $X > \langle X\rangle_L$ (in red) but also of an interval when $X < \langle X\rangle_L$ (in blue). There is a t_A for which these two have equal and opposite effects such that $\langle X\rangle_{T_1} = \langle X\rangle_L$. Similarly for $T_2 > L$, because X is nearly linear around peak gradient, the added regions (shaded light blue and orange) would cancel and so $\langle X\rangle_{T_2} \approx \langle X\rangle_L$. The time t_A is a 'node' of the variations shown in figure 3.

achieve this. The solar cycle length, L, varies around 11 years. We here take running means of the data series shown in figure 1 over intervals of length T, which we vary between 9 and 13 years in steps of 0.25 years. The mean is then ascribed to the centre of each interval. Figure 3a shows the results for the sunspot number, R. The orange curve is $\langle R\rangle_T$ for $T=13$ years and the blue is for $T=9$ years and the colour of the line is graduated between the two according to the T used. Twice during each solar cycle are points ('nodes', marked by vertical dashed lines) where the value of T used has almost no effect on the running mean obtained and so the average over the solar cycle $\langle R\rangle_L$ is well defined. Figure 2 demonstrates why these nodes occur. To derive $\langle R\rangle_L$ between the nodes, the cycle length L is taken to be the temporal separation of every

Figure 3. (*Opposite.*) Running means of the parameters shown in figure 1. (a) The sunspot number, R; (c) the open solar flux F_S from the radial component of the interplanetary magnetic field; (d) the Climax cosmic ray neutron counts C; (e) the total solar irradiance, TSI; and (f) the global mean surface air temperature anomaly ΔT. In each case, the blue to orange lines show running means over intervals $T=[9.00{:}0.25{:}13.00]$. The red line gives averages over the interpolated solar cycle length L shown by the grey-shaded area in (b). The black dots in (b) show the cycle length derived from the node locations given by the vertical dashed lines in (a). In addition to showing the temperature anomaly from the GISS reconstruction (for which the mean $\Delta T=0$ for an interval centred on 1966), part (f) also shows that from the HadCRUT3 (Brohan *et al.* 2006) reconstruction (with mean $\Delta T=0$ for an interval centred on 1981: the different reference date giving an offset between the curves for clarity).

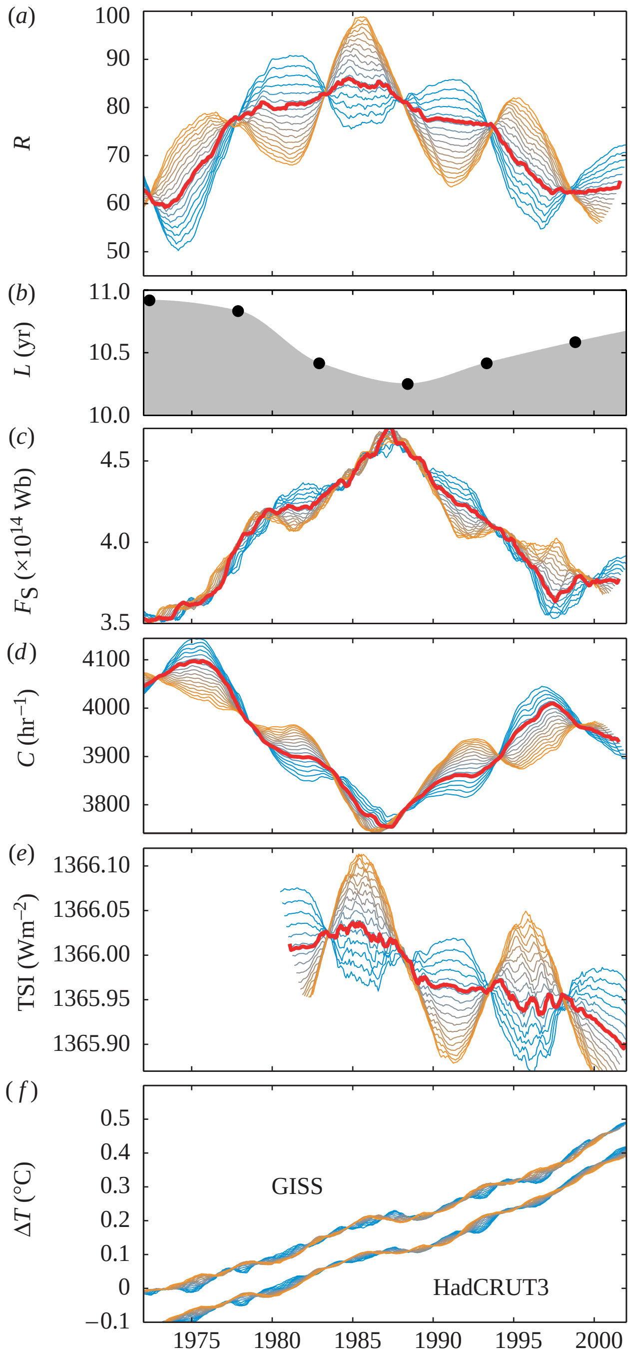

Figure 3. (*Caption opposite.*)

other node (giving the black dots in figure 3*b*). Values of L are then interpolated using a cubic fit (shown by the grey-shaded area in figure 3*b*). The red line in figure 3*a* shows the means of R over the interpolated cycle length L, $\langle R\rangle_L$, giving the trend in the sunspot number with the solar cycle oscillation removed.

Figure 4. (*Opposite.*) Centennial variations revealed by running means over the solar cycle length L since 1890 of (*a*) the sunspot number, R; (*c*) the open solar flux F_S from geomagnetic activity data (available from WDC-C1, Chilton, UK); (*d*) the abundance of the ^{10}Be cosmogenic isotope, [^{10}Be]; and (*e*) the global mean surface air temperature anomaly ΔT. The solar cycle length L is shown in (*b*) using the same format as figure 3*b*. The thin line in (*b*) shows L determined using a sliding window autocorrelation technique and the grey line in (*d*) is a regression fit to [^{10}Be] from early neutron monitor and ionization chamber data before 1955 and to the Climax cosmic ray counts after 1955.

The variation of $\langle R\rangle_L$ for 1890–2000 is shown in figure 4*a* (the values for after 1975 being the same as the red line in figure 3*a*) and the L estimates for the same interval are given in figure 4*b*, using the same procedure and plot format as in figure 3*b*. Also shown in figure 4*b* (as a thin line) are the L estimates made using a sliding window auto-correlation technique (Lockwood 2001). It can be seen that the results are very similar, giving confidence that the values of L, and hence the interpolations based on L between the nodes, are correct.

Figure 4 compares the centennial variations in $\langle R\rangle_L$ and L with the correspondingly smoothed variations in the open solar flux, cosmic ray intensity and global surface air temperature. The open solar flux on these longer time scales is determined from geomagnetic activity data (Lockwood *et al.* 1999; Rouillard *et al.* 2007). The cosmic ray records shown by the thick line in figure 4*d* are the abundance of the cosmogenic ^{10}Be isotope, [^{10}Be], from the Dye-3 Greenland ice core (Beer *et al.* 1998, 2006); in addition, a composite of cosmic ray observations (by Forbush, Neher and the Climax neutron monitor) have been scaled by regression to the [^{10}Be] data (Rouillard & Lockwood in press) and are shown by the grey line. The century-scale solar variations show some consistent features. Around 1900, the smoothed sunspot number $\langle R\rangle_L$ and open solar flux $\langle F_S\rangle_L$ were minima, whereas the solar cycle length L and $\langle[^{10}\text{Be}]\rangle_L$ were maxima. The general anti-correlation of $\langle R\rangle_L$ and L is well known and the anticorrelation of F_S and cosmic ray fluxes at the Earth has also emerged in several recent studies (Cane *et al.* 1999; Rouillard & Lockwood 2004) and is expected because F_S quantifies the total magnetic field in the heliosphere, which is a key element of the cosmic ray shield.

4. Recent solar trends and their implications

All the solar parameters show significant change over the twentieth century and it has been suggested that this is, at least, part of the cause of the global mean temperature rise seen in figure 4*e*, although it has previously been noted that recent solar and climate data reveal diverging trends (Solanki & Krivova 2003; Stott *et al.* 2003; Lockwood 2004). It should be noted that the solar cycle length L presented here does not appear as similar to the inverse of the global temperature anomaly as has been reported elsewhere (Friis-Christensen & Lassen 1991). This is because it has not been smoothed with the long time-scale filter used in those studies. As discussed in §1, two classes of mechanisms have been proposed whereby the solar changes shown in figure 4 could have influenced the temperature of the Earth. The first is that the total (or spectral UV) solar irradiance has varied on centennial time scales; the second is that cosmic rays modulate the formation of

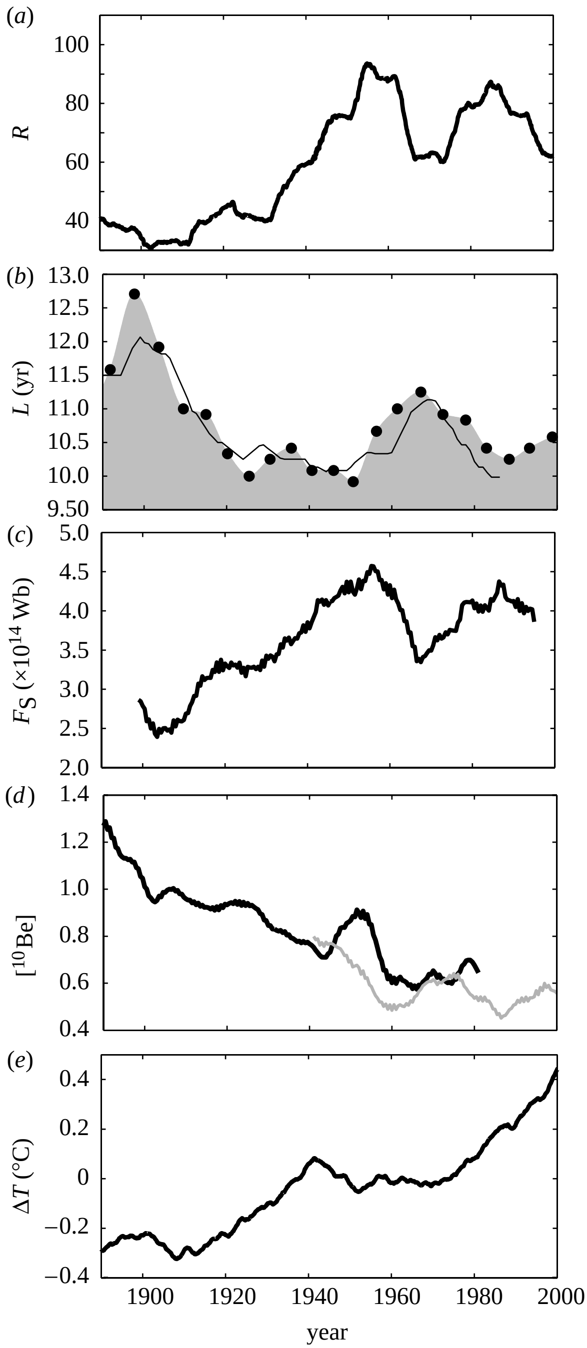

Figure 4. (*Caption opposite.*)

clouds. Both of these would influence the terrestrial radiation budget. For the cosmic ray mechanism, it has been proposed that the long-term decline in cosmic rays over much of the twentieth century (seen in figure 4*d* and caused by the rise in open solar flux seen in figure 4*c*) would cause a decline in global cover of low-altitude clouds, for which the radiative forcing caused by the albedo decrease outweighs that of the trapping effect on the outgoing thermal long-wave radiation. We here do not discuss these mechanisms in any detail. Rather, we look at the solar changes over the last three decades, in the context of the changes that took place over the most of the twentieth century.

Figure 3 shows the variations since 1970 of the solar cycle means of the sunspot number $\langle R \rangle_L$, the open solar flux $\langle F_S \rangle_L$, the climax cosmic ray neutron counts $\langle C \rangle_L$ and the solar cycle length L. In each case, the solar cycle variation has been smoothed to give the red line, using exactly the same procedure as described in §3 for figure 3*a*. Figure 3 shows that the smoothed sunspot number $\langle R \rangle_L$ clearly peaked around 1985 and has declined since and the anticorrelation with L seen in figure 4 has persisted. The open solar flux peaked around 1987, the 2-year lag after $\langle R \rangle_L$ being consistent with the time constant from models of its long-term variation (Solanki *et al.* 2000, 2001; Wang *et al.* 2005*b*). The anti-correlation between cosmic ray fluxes and the open solar flux, observed on both annual and decadal time scales (Rouillard & Lockwood 2004), is here shown to also apply to the trends revealed when the solar cycle is averaged out. $\langle \mathrm{TSI} \rangle_L$ has fallen since the peak $\langle R \rangle_L$ in 1985 and this is reflected in the significantly lower peak seen at the current solar minimum than during the previous two solar minima (see figure 1*d*). The relationship between $\langle R \rangle_L$ and $\langle \mathrm{TSI} \rangle_L$ is expected from recent studies of the effect of photospheric magnetic fields (Krivova *et al.* 2003; Solanki & Krivova 2006). Note that the trends shown by the red lines in figure 3 are confirmed by the nodes which do not depend on the L estimates.

The downward trend in TSI after 1985 contrasts with the inferred rise in the various TSI reconstructions before 1976 (Lean *et al.* 1995; Lockwood & Stamper 1999; Foster 2004; Foukal *et al.* 2004; Lockwood 2006). Hence, all solar trends since 1987 have been in the opposite direction to those seen or inferred in the majority of the twentieth century—particularly in the first half of that century (figure 4) when detection–attribution techniques using GCMs detected some solar influence on climate. This should be contrasted with the correspondingly smoothed global surface air temperature anomaly $\langle \Delta T \rangle_L$ shown in figures 3*f* and 4*e* for which the trend is upward (global warming) both before and after 1985. This trend is seen to be almost identical in the GISS (Hansen *et al.* 1999) and the HadCRUT3 (Brohan *et al.* 2006) reconstructions.

Figure 3 provides an indication of long-term TSI variations, as implied by the various reconstructions but the amplitude of which has been the subject of recent debate (Foukal *et al.* 2006). The variation of TSI with the open solar flux is not as great as for the solar cycle variations (Lockwood & Stamper 1999) but is consistent with recent analysis of the connection between TSI and cosmogenic isotopes (Lockwood 2006). The trend in average TSI revealed in figure 3 is highly significant in this respect.

Figure 1*d* shows that recent values of TSI have fallen below the minima of approximately 1365.5 W m^{-2} seen during both of the previous two solar minima. Values for 2007 have fallen below 1365.3 W m^{-2} (marked by the horizontal thin line) and although they are provisional at the time of writing, the recent solar minimum is showing lower TSI values than the two previous minima. The sunspot numbers are similar in all three cycles, indicating that the brightening effect of small-scale magnetic flux tubes (faculae and network) must have been smaller during the recent minimum. Thus, we are beginning to acquire the data needed to quantify the magnitude of the long-term drift of TSI (Foukal *et al.* 2006; Lockwood 2004, 2006).

Finally, we note that the cosmogenic isotope record shows that a number of century-scale decreases and increases in cosmic ray fluxes have taken place over the past few millennia. The minima appear to be examples of grand maxima in solar activity of the type seen in recent decades. Extrapolations of solar activity trends into the future are notoriously unreliable. (For example, one might have expected the fall in solar activity seen around 1960 to continue; however, figure 4 shows that in reality it rose again to a peak near 1985.) Nevertheless, it is possible that the decline seen since 1985 marks the beginning of the end of the recent grand maximum in solar activity and the cosmogenic isotope record suggests that even if the present decline is interrupted in the near future, mean values will decline over the next century. This would reduce the solar forcing of climate, but to what extent this might counteract the effect of anthropogenic warming, if at all, is certainly not yet known. For this reason, studies of putative amplification of solar forcing over the past 150 years (Stott *et al.* 2003) are likely to be important for understanding future changes.

5. Conclusions

There are many interesting palaeoclimate studies that suggest that solar variability had an influence on pre-industrial climate. There are also some detection–attribution studies using global climate models that suggest there was a detectable influence of solar variability in the first half of the twentieth century and that the solar radiative forcing variations were amplified by some mechanism that is, as yet, unknown. However, these findings are not relevant to any debates about modern climate change. Our results show that the observed rapid rise in global mean temperatures seen after 1985 cannot be ascribed to solar variability, whichever of the mechanisms is invoked and no matter how much the solar variation is amplified.

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