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The effects of solar variability on the Earth's climate

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The absolute value of total solar irradiance is not known to better than *ca.* 0.3% but measurements from satellite instruments over the past two solar cycles have shown that it varies by *ca.* 0.1% on this time-scale. Over longer periods its value has been reconstructed using proxy measures of solar activity, and these suggest that during the Maunder minimum in solar activity of the late 17th century it was 3–4 W m^{-2} lower than at present. Observational data suggest that the Sun has influenced temperatures on decadal, centennial and millennial time-scales, but radiative forcing considerations and the results of energy-balance models and general circulation models suggest that the warming during the latter part of the 20th century cannot be ascribed entirely to solar effects. However, chemical and dynamical processes in the middle atmosphere may act to amplify the solar impact. An analysis of zonal mean temperature data shows that solar effects may be differentiated from those associated with other factors such as volcanic eruptions and the El Niño Southern Oscillation.

Keywords: solar irradiance; solar ultraviolet radiation; climate change; radiative forcing; stratospheric ozone

1. Introduction

The extent to which changes in solar activity affect climate has been the subject of considerable investigation over many years and has often been the cause of speculation and controversy. As observational and modelling techniques improve, and our understanding of the natural internal variability of the climate system advances, it is becoming more feasible both to detect solar signals in climate records and to investigate the mechanisms whereby the solar influence acts. This subject is an interesting and complex scientific area to study, but it is now also of considerable practical importance in terms of differentiating natural and anthropogenic causes of climate change so that more reliable estimates can be made of the potential future impacts of human activities on climate.

This paper will review current knowledge concerning the variability of total solar irradiance (TSI), how this relates to other measure of solar activity and what it implies for the solar radiative forcing of climate change. Some studies relating meteorological measurements to solar activity will be discussed, and a new analysis of

One contribution of 25 to a Theme 'Science and applications of the space environment: new results and interdisciplinary connections'.

solar, and other, signals in zonal mean temperature is presented. The success of general circulation models in reproducing the observed signals is assessed, and the potential for chemical and dynamical processes in the middle atmosphere to amplify the solar impact is discussed.

2. Solar variability

(a) *Observations of solar variability*

TSI measurements have been made from satellites since 1979. The calibration of the instruments limits the absolute accuracy of the measurements to a few W m^{-2}, but the precision of the records from individual instruments shows a consistent picture of variation of *ca.* 1.4 W m^{-2}, or *ca.* 0.1%, from minimum to maximum of the *ca.* 11-year activity solar cycle. Although individual instrument records last for a number of years, each sensor suffers degradation in orbit, so construction of a composite series (or best estimate) of TSI from overlapping records becomes a complex task. Willson (1997) deduced that TSI was 0.5 W m^{-2} higher during the solar minimum of 1996 than during the solar minimum of 1986. C. Fröhlich *et al*. (2002, unpublished research), however, show almost identical values in 1986 and 1996.† The difference between these two assessments depends critically on the corrections necessary to compensate for problems of unexplained drift and uncalibrated degradation in the time-series. Thus, longer-term and more accurate measurements are required before trends in TSI can be monitored to sufficient accuracy for direct application in studies of climate change.

Other indicators of solar activity have been observed over longer periods; these include sunspot numbers, solar diameter, solar radio flux at 10.7 cm and the *aa* index, which gives a measure of the magnitude of the solar magnetic field at the Earth. As indicators of solar activity, these parameters vary markedly. For example, over the last century, sunspot number and 10.7 cm flux showed their highest values at the solar maximum of 1958, whereas the *aa* index peaked during 1990. This is because sunspot numbers return to essentially zero at each solar minimum, whereas the *aa* index shows 11-year cycles imposed on a longer-term modulation (Lean & Rind 1998). Changes in the heliosphere arising from fluctuations in the Sun's magnetic field mean that galactic cosmic rays (GCRs) are less able to reach the Earth when the Sun is more active, so the cosmic-ray flux is inversely related to solar activity, although, again, there are subtle differences between this and radiometric indices. Measurements of GCRs have been made at surface stations, and cosmogenic isotopes in tree-rings and ice-cores provide evidence of longer term variations.

(b) *Reconstructions of past TSI*

As direct measurements of TSI were only available over the last two decades, it is necessary to use other proxy measures of solar output to deduce variations at earlier dates. However, as noted above, the solar proxies vary widely, and it is not clear which, if any, can be used to indicate past values of TSI satisfactorily.

One physical approach is based on the premise that solar radiative output is determined by a balance between increases due to the development of faculae (bright

† See http://www.pmodwrc.ch/solar_const/solar_const.html for details.

patches on the Sun's surface) and decreases due to the presence of sunspots. Longer-term changes are also speculated to be occurring in the quiet Sun, against which these variable active regions are set. The sunspot darkening depends on the area of the solar disc covered by the sunspots, while the facular brightening has been related to a variety of indices. These include sunspot number (Lean *et al*. 1995), emission of singly ionized calcium (Ca II at 393.4 nm) (Lean *et al*. 1992), solar-cycle length, solar-cycle decay rate, solar rotation rate and various empirical combinations of all of these (Hoyt & Schatten 1993; Solanki & Fligge 1998).

Figure 1 shows group sunspot numbers from 1610 to 1996 (Hoyt & Schatten 1998, henceforth denoted by 'HS'), together with five TSI reconstructions. The sunspot numbers (in green, scaled to correspond to Nimbus-7 TSI observations for 1979–1993) show little long-term trend. Lean *et al*. (1995, 'LBB') (red curve) determine long-term variability from the sunspot cycle amplitude, while Hoyt & Schatten (1993) (violet curve) use mainly its length. The two Solanki & Fligge (1998) curves (cyan and blue) are similar in derivation to the Lean *et al*. and Hoyt & Schatten methods but make an additional assumption concerning the long-term contribution of the 'quiet Sun' based on observations of the behaviour of Sun-like stars (Baliunas & Jastrow 1990) and the assumption that during the Maunder minimum (an extended period during the late 17th century, during which no sunspots were observed) the Sun was in a non-cycling state. Lockwood & Stamper (1999) (yellow curve) use an entirely different approach, based not on sunspot numbers but on the *aa* geomagnetic index, and predict somewhat larger variation over individual cycles but less over the longer term. Clearly, even disregarding the shifts due to absolute scaling, there are large differences between the TSI reconstructions.

(*c*) *Radiative forcing of climate change*

The TSI reconstructions shown in figure 1 suggest a maximum increase in TSI of *ca.* 3.9 $\mathrm{W\,m^{-2}}$ since the Maunder minimum. This corresponds to a radiative forcing of the order of 0.7 $\mathrm{W\,m^{-2}}$,† which, using a climate-forcing parameter‡ of 0.5 $\mathrm{K\,W^{-1}\,m^{2}}$ (IPCC 2001), would suggest a solar-induced warming in global average surface temperature of *ca.* 0.35 K since that time. Similarly the variation of 1.4 $\mathrm{W\,m^{-2}}$ observed between the 11-year cycle minimum in 1986 and maximum in 1991 could be deduced potentially to cause a mean increase in global average surface temperature of *ca.* 0.12 K if the ocean–atmosphere system responded without lag/inertia. If the difference in TSI of 0.5 $\mathrm{W\,m^{-2}}$ deduced by Willson (1997) to have taken place between the solar minima in 1986 and 1996 reflects an underlying trend in solar irradiance, it would represent a radiative forcing of 0.09 $\mathrm{W\,m^{-2}}$ that can be compared with *ca.* 0.3 $\mathrm{W\,m^{-2}}$ due to well-mixed GHGs over the same period.

† Geometric factors affect the conversion from change in TSI to radiative forcing: it is necessary to divide by a factor of four, representing the ratio of the area of the Earth's disc projected towards the Sun to the total surface area of the Earth, and to multiply by a factor of 0.7, to take account of the Earth's albedo of 30%. Thus, a variation of 1 $\mathrm{W\,m^{-2}}$ in TSI represents a variation in global average instantaneous radiative forcing of *ca.* 0.175 $\mathrm{W\,m^{-2}}$. Here radiative forcing has been defined as the change in net downward radiative flux at the top of the atmosphere; this is not the complete definition of IPCC (2001), which uses the value at the tropopause allowing for adjustment of stratospheric (but not tropospheric) temperatures. Further discussion of the adjusted radiative forcing can be found in § 5 *a*.

‡ Coupled atmosphere–ocean general-circulation models show that the global average surface-temperature response is approximately proportional to the global-mean adjusted radiative forcing. The constant of proportionality is referred to as the climate-forcing parameter.

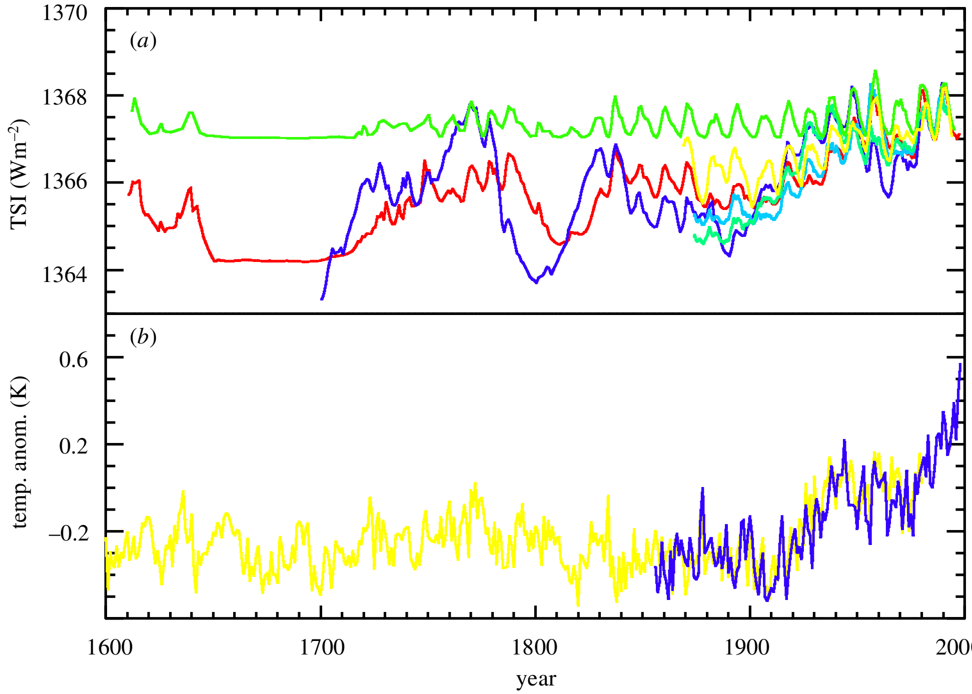

Figure 1. (a) Reconstructions of total solar irradiance from group sunspot numbers, scaled to Nimbus-7 measurements 1979–1993, green line; Lean *et al.* (1995), red line; Hoyt & Schatten (1993), violet line; Solanki & Fligge (1998), cyan and blue lines; Lockwood & Stamper (1999), yellow line. (b) Reconstructions of surface temperature: global average anomalies relative to 1961–1990 average (Jones *et al.* 1999), violet line; Northern Hemisphere average (Mann *et al.* 1998), shifted to match Jones *et al.*'s record in overlapping period, yellow line. Adapted from figure 2 of Haigh (2000) with permission from the Royal Meteorological Society.

3. Solar signals in meteorological observations

(a) *Correlations*

In order to extract a measure of the influence of the Sun on climate, many studies have sought to find correlations between indices of solar activity and meteorological parameters. Hoyt & Schatten (1997) present a good review. Many of the results claimed are statistically questionable, sometimes because the data series used are not sufficiently long or because other factors, such as El Niño or volcanic eruptions, which might have contributed to climate variability, have been ignored.

Nevertheless, some recent studies have been able to demonstrate a fairly robust response. White *et al.* (1997) analysed records of upper-ocean temperatures using both surface marine weather observations (1900–1991) and upper-ocean bathythermograph temperature profiles (1955–1994). They band-passed basin average temperatures, finding each frequency component in phase across the Indian, Pacific and Atlantic Oceans, yielding global average records with maximum changes of 0.08 ± 0.02 K on decadal (*ca.* 11-year period) scales and 0.14 ± 0.02 K on interdecadal (*ca.* 22-year period) scales. These showed the highest correlation with solar irradiance at phase lags of 1–2 yr. The profile data also indicated that the signals are confined

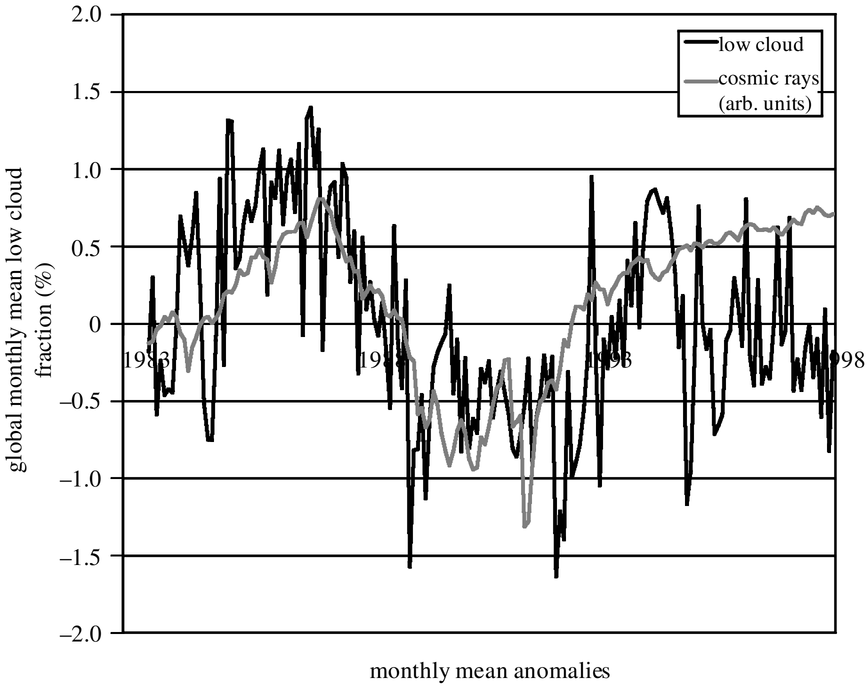

Figure 2. Black curve, global mean low cloud amount from the International Satellite Cloud Climatology Project (ISCCP) D2 dataset; grey curve, cosmic rays measured at Climax, CO, USA. A 12-month running mean has been applied to both datasets.

to the upper *ca.* 100 m of the oceans. The amplitude deduced for the 11-year cycle is similar to that implied from the radiative forcing considerations discussed in § 2 *c*.

Labitzke & van Loon (1997) used the Free University of Berlin daily stratospheric maps of the Northern Hemisphere to show high correlation between 30 hPa geopotential height and the 10.7 cm solar index over nearly four solar cycles between 1958 and 1996. The correlation pattern has largest values in the subtropics and holds at all times of year but is strongest in summer. They suggested that the largest effect is seen in the subtropics because of enhanced circulation in the Hadley cells at time of higher solar activity. Labitzke *et al.* (2002) have performed a similar analysis using geopotential height and temperature data from the NCEP/NCAR reanalysis. The Northern Hemisphere results confirmed the previous work and show a similar pattern of correlation in the Southern Hemisphere.

Marsh & Svensmark (2000) demonstrated a high degree of correlation between low cloud cover, from the ISCCP satellite D2 dataset, and solar activity between 1984 and 1994. They show that the correlation with GCRs was higher than the anticorrelation with the solar 10.7 cm index, suggesting that mechanisms that involve GCRs in amplifying the solar influence are more probable than those involving irradiance. However, Lockwood (2002) shows that the anticorrelation with TSI is equally high. Furthermore, an update to these records (figure 2) shows that, since that time, the two time-series have diverged so that it remains to be seen whether the correlation between low cloud and solar activity will hold over a longer period.

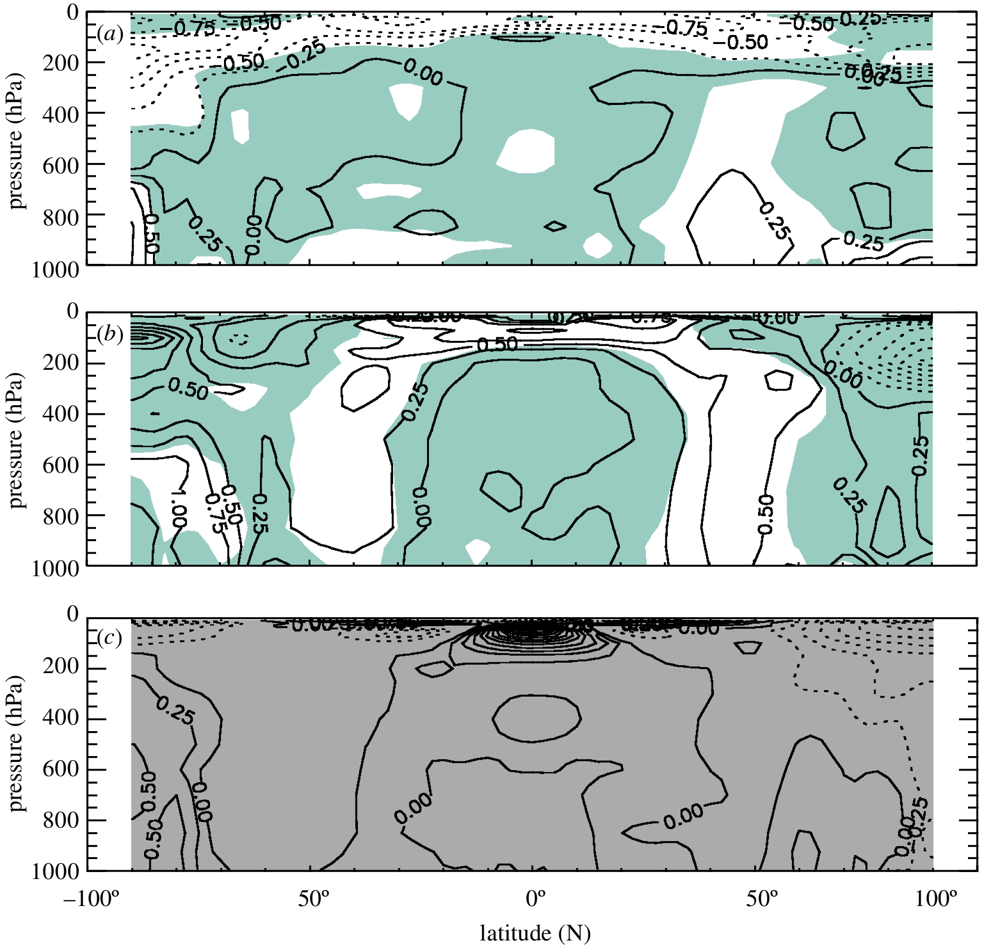

Figure 3. Amplitudes of the components of variability in zonal mean temperature due to (*a*) trend; (*b*) solar; (*c*) QBO. The units are kelvin per decade for the trend, otherwise maximum variation (K) over the data period. Shaded areas are not statistically significant at the 95% level using a student's t-test.

On longer time-scales, HS found correlation dating back to 1700 between their reconstructed TSI series and temperature data from Groveman & Landsberg (1979, hereafter 'GL') for 1579–1880 and Jones (1988) for the more recent period. Lassen & Friis-Christensen (2000, 'LFC') found a high correlation from 1550 to 1980 between a smoothed series of the length of the solar cycle and Northern Hemisphere land-surface temperatures as compiled by Mann *et al.* (1998, 'MBH'). LBB compared their TSI series with the Bradley & Jones (1993, 'BJ') and IPCC (1992) temperature records and found close agreement prior to 1900. However, the correlation was not as high during 1930–1950, as was found by LFC or HS using indices based on solar-cycle length rather than sunspot numbers. LBB estimated that solar effects could account for less than one-third of the warming observed since 1970. Subsequent assessment of

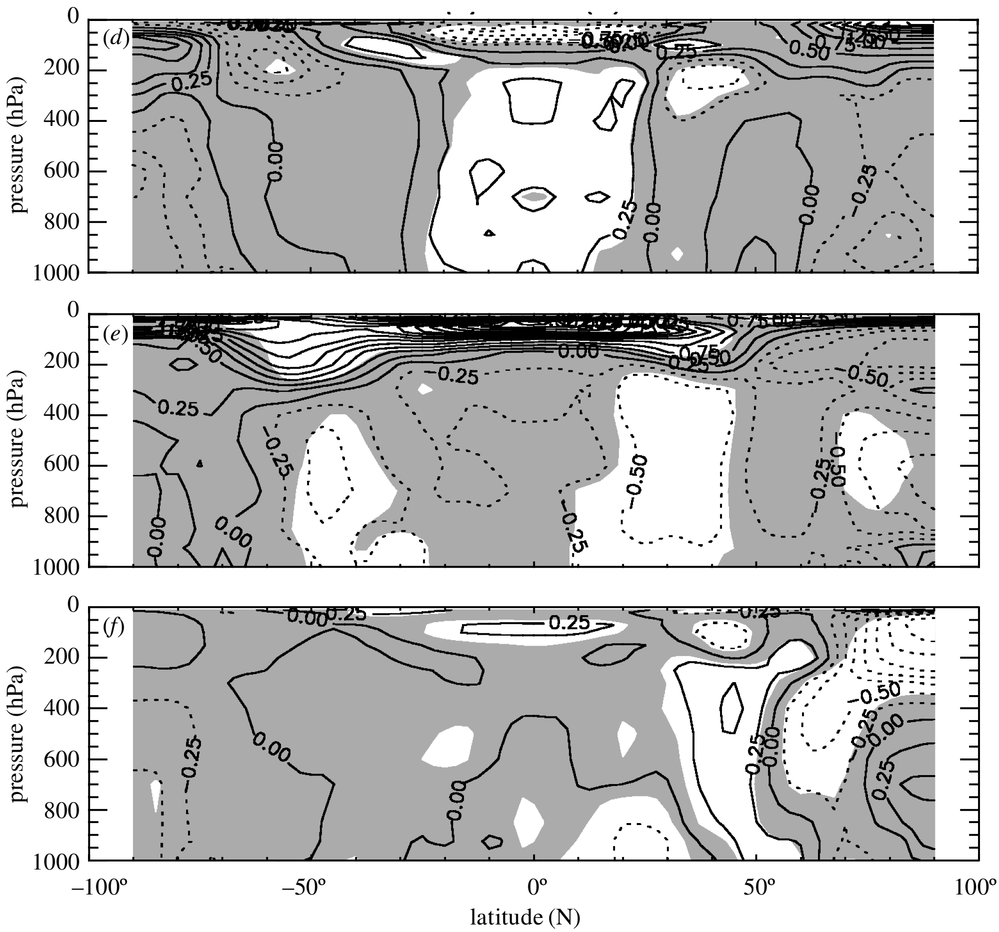

Figure 3. (*Cont.*) Amplitudes of the components of variability in zonal mean temperature due to (*d*) ENSO (K); (*e*) volcanoes (K); (*f*) NAO (K).

the LFC analysis by Laut & Gunderman (2000) suggests that non-uniform weighting given to the data points in that study resulted in an artificial enhancement of the late-20th century increase.

Bond *et al.* (2001) investigate the influence of the Sun on the climate of the North Atlantic region over the entire Holocene (i.e. from *ca.* 11 000 years ago to the present) using data extracted from deep-sea-sediment cores. The level of solar activity is estimated from the concentrations of ^{14}C and ^{10}Be isotopes, produced by the action of GCRs. The climate is indicated by the concentrations of mineral tracers which were deposited from drift ice circulating in the sub-polar North Atlantic, increases in the tracers indicating a southward expansion of cooler, ice-bearing water. They show that every multi-centennial expansion of cooler water was associated with a strong minimum in solar activity. This is a remarkable result and provides strong evidence that solar activity does indeed modulate climate on centennial–millennial time-scales. The authors suggest that changes in ocean thermohaline overturning, associated with the supply of fresh (low-density) water from the drift ice, and coupled to atmospheric circulations, may act to amplify the direct effects of small variations in solar irradiance.

(*b*) *Regressions*

The correlation studies suggest that climate responds to solar activity but cannot give reliable quantitative estimates of the response because other factors may be contributing to the climate variability. For example, major volcanic eruptions took place in 1991 and 1982, coincidentally both soon after solar maxima, so that any volcanic signal in climate records spanning only a few decades over this period might be aliased onto a solar signal in a simple correlation. One way to separate the effects is to use models to seek an understanding of the underlying physical mechanisms involved (see § 4), but analysis of the observational data using multiple regression techniques also has the potential to differentiate the signals.

The lower panel of figure 1 shows (in violet) the Jones *et al.* (1999) observational record of global mean surface temperature and (in yellow) the MBH Northern Hemisphere surface-temperature reconstruction. From this it appears that the observed warming since the late 17th century is larger than can be explained by the solar radiative forcing estimates of § 2 *c*.

Regression of solar indices onto such climate records provides an approach to assessing the magnitude of any solar influence. Wigley *et al.* (1997) attempted to quantify the solar effect by regressing the surface-temperature series onto greenhouse-gas (GHG), tropospheric aerosol and solar indices and finding the combination of forcings that best matched the data. They found that inclusion of solar effects improved representation of the warming in the period 1900–1940.

Figure 3 presents the results of a multiple regression analysis of zonal mean-temperature data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset. The analysis incorporated an autoregressive noise model of order one and eleven indices: a constant, a linear trend, the solar 10.7 cm flux, the quasi-biennial oscillation (QBO), the El Niño Southern Oscillation (ENSO), stratospheric aerosol loading (related to volcanic eruptions (Sato *et al.* 1993)), North Atlantic Oscillation (NAO) and four indices representing the amplitude and phase of the annual and semi-annual cycles. Figure 3*a* shows a strong cooling trend in the stratosphere and warming in the troposphere in mid-latitudes. The solar signal is presented in figure 3*b*, with warming in the tropical lower stratosphere at higher levels of solar activity extending in vertical bands into the troposphere in both hemispheres at latitudes 20–60°. The effects of the QBO (figure 3*c*) are largely confined to the tropical lower stratosphere, while the ENSO signal (figure 3*d*) is seen clearly throughout the tropics. Volcanic eruptions cause the stratosphere to warm and the troposphere to cool (figure 3*e*), while the NAO signal (figure 3*f*) is mainly confined to mid-latitudes of the Northern Hemisphere.

Only data since January 1979 were employed in the calculations described above, because of systematic differences between the data before and after that date due to the inclusion of measurements from satellites. Figure 4*d* shows this discontinuity, in temperature at 35° S, 200 hPa, very clearly. Figure 4*a* shows the components of the

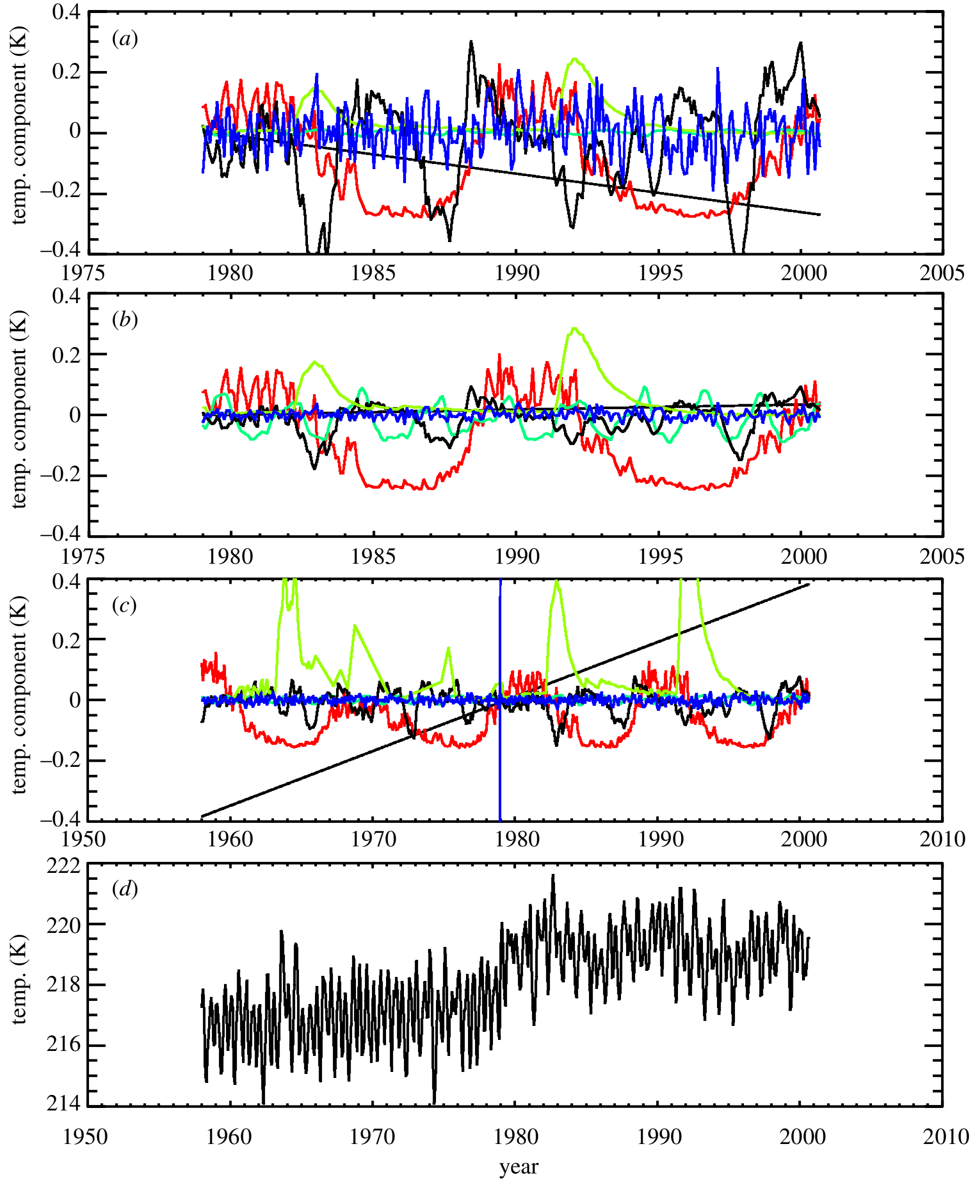

Figure 4. (*a*) Components of zonal mean temperature anomaly from multiple regression analysis of 1979–2000 data deduced to be due to trend (straight black line), solar variability (red line), volcanic aerosol (green line), QBO (cyan line), NAO (blue line) and ENSO (black line) at (*a*) 35° N, 200 hPa; (*b*) 35° S, 200 hPa. (*c*) As in (*b*) using 1958–2000 data. (*d*) Raw data at 35° S, 200 hPa.

regression at two points using just the post-1978 data. Note that these values need to be added to the mean value and the annual and semi-annual cycles to reconstruct the data series. At 35° N there is a significant ENSO component and plenty of variability due to the NAO but also a clear solar contribution. At 35° S the ENSO and NAO contributions are much smaller, and the variation is dominated by solar and volcanic signals. Another analysis was carried out in which all data since January 1958 were used, and the discontinuity at 1978/1979 was included in the regression analysis by means of a step function. The components show very similar patterns to those of figure 3, although with some differences in amplitude. A comparison of figure 4*b* with figure 4*c* shows that use of the longer dataset gives a larger volcanic signal and a somewhat reduced solar signal at that point, but problems with the dataset before 1979 mean that this analysis is probably less reliable.

This multiple regression study suggests that solar influences in the temperature record can be separated from other factors by the different patterns of change that each induce. It also shows that the solar response varies with location, indicating that mechanisms other than direct radiative heating must be involved.

4. Model studies and data interpretation

(*a*) *Energy-balance models*

A fairly straightforward way to study the effects of solar variability, or of other factors introducing a radiative forcing, on surface temperature is to use an energy-balance model (EBM). EBMs are one-dimensional models that estimate the vertical temperature response in the atmosphere, and also sometimes in the ocean, to applied radiative forcings. Stevens & North (1996) used a spatially resolved EBM, and a TSI reconstruction based on sunspot numbers, to deduce space-time patterns of climate response. Using covariance statistics from 1000 year runs of coupled general circulation models (GCMs), they then constructed an optimal filter representing surface-temperature response to solar variability. Projection of this filter onto observed surface-temperature data from 1894–1993 shows a highly significant response to the solar cycle in the data, with maximum amplitude in the global mean surface-temperature response of 0.08 K. White & Cayan (1998) found that a best match between the results of an energy-balance model and the ocean temperatures (White *et al.* 1997) (see § 3 *a*) was achieved by a combination of solar forcing and a linear trend of a magnitude representative of radiative forcing due to GHGs and aerosol.

Crowley & Kim (1996) carried out correlation studies between both the HS and the LBB reconstructed TSI series and both the GL and the BJ temperature series. They found statistically significant correlations for all combinations. They went on to use a global average EBM to estimate the magnitude of the surface-temperature response to the solar indices and, by comparing the results with the observational data, deduced that solar variability may account for 30–55% of climate variance on decadal–centennial time-scales. Subsequently, Crowley (2000) used the same model and studied the surface-temperature response to solar and volcanic influences as well as anthropogenic GHGs and aerosol. In comparison with the MBH temperature reconstruction, he found that, from AD 1000 to the mid-19th century, the variability in the observational record could be well explained by the natural forcings, whereas human factors needed to be included after that date.

(*b*) *General circulation models*

Time-dependent ocean–atmosphere GCM simulations of the response of surface-temperature to solar variability (e.g. Cubasch *et al.* 1997; Drijfhout *et al.* 1999;

Rind *et al.* 1999; Tett *et al.* 1999) show global average changes consistent with the above energy balance estimates but with considerable variation across the globe. This stresses the potential pitfalls of drawing global conclusions from correlations between local climate parameters and solar variability. For example, the 'Little Ice Age' of the 17th century has often been associated with the Maunder minimum in sunspot numbers but it appears (BJ) that the cooler temperatures of this period were largely confined to Eurasia, suggesting that a change in atmospheric or ocean circulations might have been responsible. Shindell *et al.* (2001) use a GCM coupled to a simple representation of the oceans to investigate the response to a reduction in total solar irradiance estimated for the Maunder minimum relative to 100 years later. They find a pattern of winter temperature change mainly represented by a reduced amplitude of the Arctic Oscillation and show that this is similar to the MBH climatology of the period. Bond *et al.* (2001), however, do not see this pattern of response over millennial time-scales. If this disparity is real it suggests that different factors are important on varying time-frames with, for example, changes in deep ocean circulation becoming more significant over periods greater than centuries.

(*c*) *Detection/attribution studies*

From a regression of the patterns in surface temperature, derived from their GCM simulations of responses to solar and GHG forcing, against the observational record Cubasch *et al.* (1997) suggested a possible solar contribution to the mid-20th century warming and a solar contribution of 40% of the observed global warming over the last 30 years. Using a similar technique, with results from the UK Met Office Unified Model, Tett *et al.* (1999) could detect a solar contribution to global mean temperature trend in the 1906–1956 period, but for the remainder of the 20th century they found the solar contribution to be negligible. Subsequent analysis by Stott *et al.* (2002), using improved optimal detection methods, suggests that the GCM simulations may underestimate solar influence by up to a factor of three. A similar result was obtained by Hill *et al.* (2001) using zonal mean, height-resolved, temperature records. If these studies are correct, their result implies the presence of a factor that amplifies solar effects and that is not currently included in GCM simulations. One potential factor is the spectral composition of the solar irradiance variations and the resultant modulation of stratospheric ozone (Haigh 1994), which might affect the thermal and dynamical structure of the middle atmosphere and thus the radiative forcing of, and possibly wave activity in, the troposphere.

5. The role of the middle atmosphere

(*a*) *Solar ultraviolet (UV) and stratospheric ozone*

The Sun emits radiation over the entire electromagnetic spectrum, but its energy peaks in the visible–near infrared: 80% of TSI lies at wavelengths between 400 and 1600 nm. The small variability in TSI, discussed in § 2, represents the changes integrated across the whole spectrum. In the UV, however, the amplitude of variability is much higher. Measurements of the solar UV spectrum made by the SOLSTICE (Rottman *et al.* 1993) and SUSIM (Brueckner *et al.* 1993) instruments on the UARS satellite suggest a decline of *ca.* 7% at 200–208 nm and of *ca.* 3.5% at 250 nm from solar maximum in 1989 to near solar minimum in 1994. These estimates agree well with modelled values (Lean 1997; Solanki & Unruh 1998).

This variation in the spectrum complicates the issue of whereabouts the solar energy is deposited in the atmosphere–surface system. Most of the visible–near-infrared radiation passes through the atmosphere unhindered to the tropopause and hence (apart from scattering by clouds and air molecules) to the surface, although water vapour bands in the near-infrared cause some absorption in the lower troposphere. Shorter, UV, wavelengths, however, are absorbed in the middle atmosphere, where they cause local heating and ozone production. The increased ozone tends to mask the lower atmosphere from the enhanced incident UV, while the warmer stratosphere will cause increased emission of thermal infrared (TIR) radiation into the troposphere (Haigh 1994). Thus, the nature of the changes in the UV and TIR radiation fields depends on the ozone response.

However, the variation of ozone with solar activity is not well established. Multiple-regression analysis of satellite data, as carried out with SBUV data by McCormack & Hood (1996) and SAGE data by Wang *et al.* (1996), suggests that the largest changes occur in the upper and lower stratosphere and zero, or even slightly negative, changes occur in the middle stratosphere. The data, however, are only available over about one-and-a-half solar cycles; have large uncertainties, especially in the lower stratosphere; and may not properly have accounted for the effects of volcanic aerosol (Solomon *et al.* 1996). The true nature of solar-induced changes in stratospheric ozone remains uncertain. Two-dimensional photochemistry transport models of the stratosphere (e.g. Haigh 1994; Fleming *et al.* 1995; Wuebbles *et al.* 1998) predict the largest fractional changes in the middle–upper stratosphere, with monotonically decreasing effects towards the tropopause. Labitzke *et al.* (2002) show results from a GCM with fully coupled stratospheric chemistry that produces a double maximum in the profile of the ozone response but still has a smaller response in the upper stratosphere than is seen in the satellite data.

(*b*) *Adjusted radiative forcing*

The adjusted radiative forcing is the change in net flux at the tropopause after stratospheric, but not tropospheric, temperatures have adjusted to the imposed perturbation. This somewhat artificial definition is used (IPCC 2001) because it has been found that the climate-forcing parameter (see the second footnote on p. 97) is more robust to this definition than to the unadjusted radiative forcing.

Because of the influence of solar variability on stratospheric temperature and composition, discussed above, the adjusted radiative forcing may differ significantly from the instantaneous estimates discussed in § 2*c*. Calculations of the effect of ozone changes on the adjusted radiative forcing due to solar variability, however, show considerable disparities. Haigh (1994) and Myhre *et al.* (1998) found that ozone increases *reduced* the solar radiative forcing at maximum relative to minimum periods of the 11-year cycle, by *ca.* 0.1 $W m^{-2}$ and 0.02 $W m^{-2}$ respectively, and Wuebbles *et al.* (1998) computed a reduction of 0.13 $W m^{-2}$ due to ozone increases since the Maunder minimum. Hansen *et al.* (1997) showed an *increased* forcing of *ca.* 0.05 $W m^{-2}$ from minimum to maximum of a solar cycle due to ozone increases and lower stratospheric warming. This disparity represents the different approaches used and the predominant altitude at which the ozone increase takes place. Hansen *et al.* (1997)

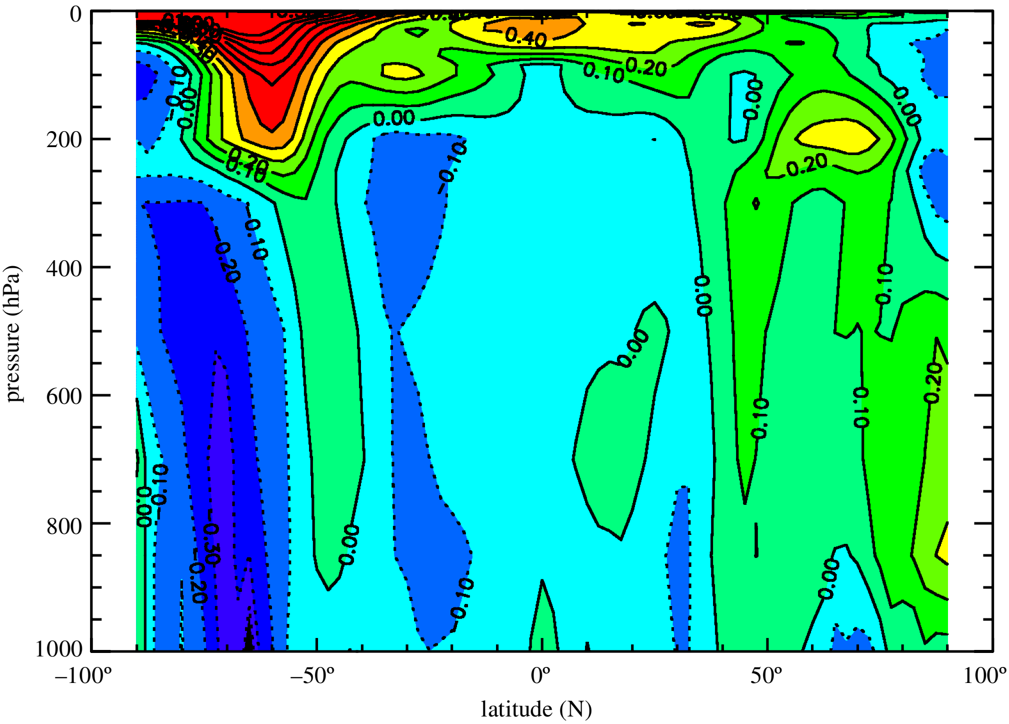

Figure 5. Difference in zonal mean temperature (K) between minimum and maximum of the 11-year solar cycle calculated using an atmospheric GCM in which the spectral composition of the change in irradiance was included in addition to solar-induced changes in ozone (derived off-line using a two-dimensional photochemical/radiative/transport model).

estimated the ozone effect by assuming that all the ozone change was in the 10–150 mbar region and extrapolating from ozone sensitivity studies carried out with a low-resolution GCM. In the other papers, the ozone response was calculated using two-dimensional chemical-transport models in which ozone changes are larger in the upper stratosphere and temperature changes are estimated using the fixed dynamical heating approximation.

Using a GCM in which the temperature response was allowed to fully respond to prescribed ozone changes, Larkin *et al.* (2000) found that the net adjusted radiative forcing did not appear to be sensitive to details of the ozone changes, although the spectral composition of the perturbed radiation field was.

(*c*) *Dynamical interactions between the stratosphere and troposphere*

A few studies have introduced realistic changes in UV and ozone into GCMs and found that the inclusion of the ozone has a significant effect on simulated climate. Haigh (1996, 1999*a*), using a GCM with a lid at 10 hPa and few stratospheric levels, showed a pattern of change in zonal mean temperature which was consistent over a range of assumptions concerning the magnitude of the UV and ozone changes. Larkin *et al.* (2000) found very similar patterns of change to those of Haigh (1999*a*) by using the same solar irradiance/ozone changes but an entirely different GCM with a lid at 0.1 hPa. The difference in annual mean zonal mean temperature, and also zonal wind, between minimum and maximum of the 11-year solar cycle suggested by the model of Larkin *et al.* are shown in figure 5. The pattern in temperature consists of warming in the stratosphere and a vertical banding structure in the troposphere, due to weakening and polewards shifts of the sub-tropical jets. It is interesting to note that this pattern is very similar to that resulting from the multiple regression study discussed in § 3 *b* and shown in figure 3*b*, although it is much smaller in amplitude. However, as the model had fixed sea-surface temperatures, the scope for a full response was limited. Michael Palmer (2001, personal communication) has carried out Maunder minimum experiments with a coupled atmosphere–ocean GCM and shown that the inclusion of ozone changes enhances the solar response in the stratosphere and upper troposphere but that sea-surface-temperature changes dominate in determining the atmospheric response at lower altitudes.

Changes in stratospheric thermal structure may also affect the troposphere through dynamical interactions rather than through radiative forcing. Kodera (1995) suggested that changes in stratospheric zonal wind structure, brought about by enhanced solar heating, could interact with vertically propagating planetary waves in the winter hemisphere to produce a particular mode of response. This mode, also seen in response to heating in the lower stratosphere caused by injection of volcanic aerosol, shows dipole anomalies in zonal wind structure which propagate down, over the winter period, into the troposphere. Haigh (1999*b*) showed a pattern of response to solar activity in Northern Hemisphere winter tropospheric temperatures very similar to that found in satellite data to be the response to volcanic eruptions by Graf *et al.* (1993) and Kodera (1994).

Shindell *et al.* (1999) used a low-resolution GCM with a detailed representation of the middle atmosphere and showed a dynamical response in winter similar to that predicted by Kodera (1995) and changes in 30 hPa heights in the winter hemisphere more like those of Labitzke & van Loon (1997) but with little summer-hemisphere response.

All these GCM experiments suggest that chemical and dynamical factors play a role in enhancing the solar influence. However, further work is needed to establish the response of ozone to solar variability and also to explain the observed summer-hemisphere effects, which are unlikely to be determined by planetary-scale wave activity.

6. Conclusions

It is important to understand how solar variability affects climate, so that human and natural signals may be disentangled in the observational record and thus more reliable predictions of the effects of human activity on future climate may be made. However, the absolute value of total solar irradiance is not known to better than *ca.* 4 W m^{-2}, and reconstructions of past values are uncertain, even over the 20th century and certainly over longer periods.

Analyses of global mean temperature records suggest a detectable signal of solar influence on decadal, centennial and millennial time-scales. Geographical variations of this influence are poorly known but almost certainly do not consist of a uniform surface warming in response to increased solar activity. Vertical patterns of temperature change may provide a method for differentiating solar from other climate perturbations. The warming that occurred during the latter half of the 20th century cannot be ascribed entirely to solar influences.

Mechanisms for the amplification of solar forcing are not well established. Variations in UV and solar-induced changes in ozone may have an effect on radiative forcing but additionally may affect climate through a dynamical response to solar heating of the lower stratosphere. The vertical structure of the ozone response to solar variability is not well known. General circulation models are able to produce some of the observed patterns of response to solar activity but generally underestimate the magnitude.

The multiple regression code was provided by Myles Allen (Rutherford Appleton Laboratory) and developed by Mitchell Thomson (Imperial College). Figure 5 was constructed from GCM runs carried out by Alice Larkin (Imperial College). The NCEP/NCAR reanalysis dataset was acquired from the Climate Diagnostics Center, Boulder, CO, USA, at http://www.cdc.noaa.gov/; the solar 10.7 cm flux data from the National Geophysical Data Center, USA, at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/; the QBO data from B. Naujokat, Free University of Berlin; the El Niño Southern Oscillation ('cold tongue') index from the University of Washington at Seattle, USA, at http://tao.atmos.washington.edu/data_sets/cti/; and the North Atlantic Oscillation index from the University of East Anglia, at http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm.

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