Mechanisms for solar influence on the Earth’s climate

Joanna D. Haigh

Imperial College London
E-mail: j.haigh@imperial.ac.uk

Solar radiation is the fundamental energy source for the atmosphere and the global average equilibrium temperature of the Earth is determined by a balance between the energy acquired by the solar radiation absorbed and the energy lost to space by the emission of heat radiation. The interaction of this radiation with the climate system is complex but it is clear that any change in incoming solar irradiance has the potential to influence climate. There is increasing evidence that changing solar activity, on a wide range of time scales, influences the Earth’s climate although details of the mechanisms involved remain uncertain. This article provides a brief review of the observational evidence and an outline of the mechanisms whereby rather small changes in solar radiation may induce detectable signals in the lower atmosphere.1

1 Introduction

In the past, although much had been written on relationships between sunspot numbers and the weather, the topic of solar influences on climate has often been disregarded by meteorologists. This was due to a combination of factors of which the key was the lack of any robust measurements indicating that the solar radiation incident on Earth did indeed vary. There was also mistrust of the statistical validity of much of the supposed evidence and, importantly, no established scientific mechanisms whereby the apparent changes in the Sun might induce detectable signals near the Earth’s surface. Another concern of the emergent meteorological profession in the nineteenth century was to distance itself from the popular “astrometeorology” movement (Anderson, 1999; see e.g. Fig. 1). This estrangement of studies of solar-climate links from mainstream scientific endeavour lasted until the late 20th century when the necessity of attributing causes to global warming meant increased international effort into distinguishing natural from human-induced factors. Nowadays, with improved measurements of both solar and climate parameters, evidence of a solar signal in the climate of the lower atmosphere has begun to emerge from the noise and computer models of the atmosphere are providing a route to understanding the sometimes complex and subtle processes involved.

1It is not possible to review here all potential mechanisms for solar-climate links; I restrict this article to those relating to solar irradiance and thus neglect any involving energetic particles.
Solar Influences on the Earth’s Lower Atmosphere

2.1 Measurements and reconstructions

Assessment of climate variability and climate change depends crucially on the existence and accuracy of records of meteorological parameters. Ideally records would consist of long time series of measurements made by well-calibrated instruments located with high density across the globe. In practice, of course, this ideal cannot be met. Measurements with global coverage have only been made since the start of the satellite era about thirty years ago. Instrumental records have been kept over the past few centuries at a few locations in Europe. For longer periods, and in remote regions, records have to be reconstructed from the indirect indicators of climate often referred to as proxy data.

Proxy indicators provide information about weather conditions at a particular location through records of a physical, biological or chemical response to these conditions. Some proxy datasets provide information dating back hundreds of thousands of years which make them particularly suitable for analysing long term climate variations and their correlation with solar activity. One well established technique for providing proxy climate data is dendrochronology, or the study of climate changes by comparing the successive annual growth rings of trees (living or dead). Much longer records of temperature have been derived from analysis of oxygen isotopes in ice cores obtained from Greenland and Antarctica and evidence of very long term temperature variations can also be obtained from ocean sediments.
Figure 2 presents reconstructions of the Northern Hemisphere surface temperature record produced using a variety of proxy datasets. There are some large differences between them, especially in long-term variability, but there is general agreement that current temperatures are higher than they have been for at least the past 2 millennia. Other climate records suggesting that the climate has been changing over the past century include the retreat of mountain glaciers, sea level rise, thinner Arctic ice sheets and an increased frequency of extreme precipitation events. A key concern of contemporary climate science is to attribute cause(s) to these changes, including the contribution of solar variability.

### 2.2 Solar signals in climate records

Many different approaches have been adopted in the attempt to identify solar signals in climate records. Probably the simplest has been spectral analysis, in which cycles of 11 (or 22 or 90, etc.) years are assumed to be associated with the Sun. Alternatively records of observational data are correlated with time series of solar activity. This can be developed to extract the response in the measured parameter to a chosen solar activity forcing factor. A further sophistication allows a multiple regression, in which the responses to other factors are simultaneously extracted along with the solar influence. Each of these approaches gives more certainty than the previous one that the signal extracted is actually due to the Sun and not to some other factor, or to random fluctuations in the climate system, but it should be remembered that such detection is based only on statistics and not on any understanding of how the presumed solar influence takes place.
2.2.1 Millennial, and longer, timescales

On timescales of many millennia the amount of solar radiation received by the Earth is modulated by variations in its orbit around the Sun. The distance between the two bodies varies during the year due to the ellipticity of the orbit which varies with periods of around 100,000 and 413,000 years due to the gravitational influence of the Moon and other planets. At any particular point on the Earth the amount of radiation striking the top of the atmosphere also depends on the tilt of the Earth’s axis to the plane of its orbit, which varies cyclically with a period of about 41,000 years, and on the precession of the Earth’s axis which varies with periods of about 19,000 and 23,000 years (see Fig. 3). Averaged over the globe the solar energy flux at the Earth depends only on the ellipticity but seasonal and geographical variations of the irradiance depend on the tilt and precession. These are important because the intensity of radiation received at high latitudes in summer determines whether the winter growth of the ice cap will recede or whether the climate will be precipitated into an ice age. Thus changes in seasonal irradiance can lead to much longer-term shifts in climatic regime. Cyclical variations in climate records with periods of around 19, 23, 41, 100 and 413 kyr are generally referred to as Milankovitch cycles after the geophysicist who made the first detailed investigation of solar-climate links related to orbital variations.

Ocean sediments have been used to reveal a history of temperature in the North Atlantic by analysis of the minerals believed to have been deposited by drift ice (Bond

![Fig. 3. Top 3 curves: variations in parameters determining the Earth’s orbit. 4th curve: the resulting changes in solar energy flux at high latitude in summer. Lowest curve: global temperature deduced from \(^{18}\)O records in deep ocean cores, grey bands indicate inter-glacial periods (see http://www.globalwarmingart.com/wiki/Image:Milankovitch_Variations.png for further details).]
et al., 2001). In colder climates the rafted ice propagates further south where it melts, depositing the minerals. These materials also preserve information on cosmic ray flux, and thus solar activity, in isotopes such as $^{10}\text{Be}$ and $^{14}\text{C}$. Thus simultaneous records of climate and solar activity may be retrieved. An example is given in Fig. 4 which shows fluctuations on the 1,000 year timescale well correlated between the two records, suggesting a long-term solar influence on North Atlantic temperatures.

2.2.2 Century scale

On somewhat shorter timescales it has frequently been remarked that the Maunder Minimum in sunspot numbers in the second half of the seventeenth century coincided with what is sometimes referred to as the “Little Ice Age” during which western Europe experienced significantly cooler temperatures. Figure 5 shows decadal trends in winter temperatures averaged over the period 1684–1738 as solar activity emerged from its Grand Minimum state. This pattern is symptomatic of the positive phase of the North Atlantic Oscillation indicating that changes in solar activity may influence climate on a regional scale (Luterbacher et al., 2004). There is also some evidence (see Fig. 2) that the temperature averaged over the whole Northern Hemisphere was cooler during the 17th century, hence this period is sometimes referred to as “The Little Ice Age”, but cooler temperatures are not found in all records for the same period across the globe so attribution of the temperature anomalies to solar variability remains uncertain. Crowley (2000) points out that the higher levels of volcanism prevalent during the 17th century, as well as lower solar irradiance, may contribute to the cooler northern hemisphere experienced at that time.
Fig. 5. Winter temperature trends (°C per decade) from 1684 to 1738. The thick solid lines represent the 95% and 99% confidence level. Except for the Mediterranean area, the warming trends are statistically significant over the whole of Europe. (From Luterbacher et al., European seasonal and annual temperature variability, trends, and extremes since 1500, Science, 303, 1499–1503, 2004. Reprinted with permission from AAAS.)

Fig. 6. Time series of the mean temperature of the summer northern hemisphere upper troposphere (750–200 hPa) (solid line) and the solar 10.7 cm flux (dashed line). (From van Loon and Shea, A probable signal of the 11-year solar cycle in the troposphere of the northern hemisphere, Geophys. Res. Lett., 26, 2893–2896, 1999. Copyright 1999 American Geophysical Union. Reproduced by permission of American Geophysical Union.)
2.2.3 Solar cycle

Many studies have purported to show variations in meteorological parameters in phase with the “11-year” solar cycle. Some of these are statistically not robust and some show signals that appear over a certain interval of time only to disappear, or even reverse, over another interval. There is, however, considerable evidence that solar variability on decadal timescales does influence climate. An example is shown in Fig. 6 which presents the mean summer time temperature of the upper troposphere (between about 2.5 and 10 km) averaged over the whole northern hemisphere. This parameter varies in phase with the solar 10.7 cm index with an amplitude of 0.2–0.4 K.

The hemispheric average, however, hides the fact that the solar signal is not uniformly distributed. Solar signals detected in sea surface temperatures (SSTs) by White et al. (1997) show that SSTs do not respond uniformly: at higher solar activity
the pattern shows latitudinal bands of warming and cooling with warmer temperatures in the tropics lagging the peak in solar forcing by 1–2 years. Van Loon et al. (2007) suggest a solar cycle signal in surface temperatures in the Pacific Ocean which bears a close relationship to the negative phase of the ENSO cycle (Fig. 7).
Latitudinal variations have also been found for the solar response in air temperatures. Haigh (2003) presented results of a multiple regression analysis of NCEP/NCAR reanalysis (Kalnay et al., 1996) zonal mean temperatures in which data for 1978–2002 were analyzed simultaneously for ten signals: a linear trend, El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), solar activity, stratospheric aerosol from volcanic eruptions, Quasi-Biennial Oscillation (QBO) and the amplitude and phase of the annual and semi-annual cycles. The patterns of response for each signal are statistically significant and separable from the other patterns. The solar response (Fig. 8) shows largest warming in the stratosphere and bands of warming, of >0.4 K, throughout the troposphere in mid-latitudes. Associated with the temperature response is a signal in zonal mean zonal wind (Haigh et al., 2005, see Fig. 9) which shows an 11-year solar cycle influence in which the effect of increasing solar activity is to weaken the westerly jets and to move them slightly polewards. These temperature and zonal wind patterns are consistent with a situation in which the tropical Hadley cells are broader at solar maximum, as suggested by an analysis of vertical velocity data by Gleisner and Thejll (2003, see Fig. 10). Kodera (2004) finds a suppression of tropical convection when the Sun is more active, and Kodera et al. (2007) relate this to a change in location of the downward portion of the Walker cell, accompanied by non-linear interactions with the phase of ENSO. However, the response of tropical circulations to solar activity is not at all well established: van Loon et al. (2004) find an intensification of the Hadley and Walker circulations at higher solar activity.
3 Variations in Solar Irradiance and Mechanisms for Influence on Climate

3.1 Total solar irradiance and radiative forcing of climate change

Direct measurements of total solar irradiance (TSI) made outside the Earth’s atmosphere began with the launch of satellite instruments in 1978. Previous surface-based measurements could not provide the accuracy required to show solar cycle variations as they were subject to uncertainties and fluctuations in atmospheric absorption that swamped the small solar variability signal. The data from each of half a dozen satellite instruments, however, show consistent variations of approximately 0.08% (~1.1 W m⁻²) in TSI over three 11-year cycles. Nevertheless, significant uncertainties remain with regard to the absolute value of TSI. In particular, data from the newest instrument, the Total Irradiance Monitor (TIM) on the SORCE satellite, is giving values approximately 5 W m⁻² lower than other contemporaneous instruments which disagree among themselves by a few W m⁻². This uncertainty, related to the calibration of the instruments and their degradation over time, is a serious problem underlying current solar-climate research and makes it particularly difficult to establish the existence of any underlying trend in TSI over the past 2 cycles. Fröhlich (2006) reviews the problems encountered in compositing the available satellite data to provide a longer-term record; his assessment shows essentially no difference in TSI values between the cycle minima occurring in 1986 and 1996. The results of Willson and Mordinov (2003), however, show an increase in irradiance of 0.045% between these dates. Such a trend implies an increase in radiative forcing of about 0.1 W m⁻² per decade which is about one-third that due to the increase in concentrations of greenhouse gases (decadal trend averaged over the past 50 years). Data for the current solar minimum, however, suggests that TSI is now lower than in 1996 so that there is clearly no upward secular trend in TSI.

To assess the potential influence of the Sun on the climate on centennial timescales it is necessary to know TSI further back into the past than is available from satellite data so proxy indicators of solar variability have been used to produce an estimate of its temporal variation over the past centuries. There are several different approaches taken to “reconstructing” the TSI, all employing a substantial degree of empiricism and in all of which the proxy data (such as sunspot number) are calibrated against the recent satellite TSI measurements, despite the problems outlined above. Some examples of TSI time series reconstructed over the past four centuries are given in Fig. 11. The estimates diverge as they go back in time due to the different assumptions made about the state of the Sun during the Maunder Minimum. This uncertainty is a major problem for understanding the role of the Sun in recent global warming.

In assessing the role played by different factors in causing climate change a useful parameter is Radiative Forcing (RF). This gives a measure of the imbalance in top-of-atmosphere radiation budget caused by the introduction of a given factor (e.g. an increase in the concentration of greenhouse gases would trap outgoing heat radiation, implying a positive RF; an increase in global albedo would result in greater reflection of solar radiation to space implying a negative RF). Solar RF may be deduced from anomalies in TSI but it is necessary to scale the TSI values by a factor of 0.18 to account of global averaging and global albedo. Thus the range of TSI values of 0.4 to
Fig. 11. Reconstructions of total solar irradiance based on sunspot numbers and different values for secular increase since Maunder Minimum (Lean, 2000), calibrated against MDI images (Foster, 2004), magnetic flux evolution from model (Wang et al., 2005). (Figure courtesy Judith Lean.)

1.5 W m\(^{-2}\) shown in Fig. 11 as the increase since 1750 would translates into a range of RFs of 0.07 to 0.27 W m\(^{-2}\). The Intergovernmental Panel on Climate Change in its 2007 report shows solar radiative forcing since 1750 as 0.12 W m\(^{-2}\) (see Fig. 12) which at the low end of the estimated range. It should be noted that the solar value included in this well-publicised figure might be considerably larger, or smaller, if a different year were assumed for the pre-industrial start-date.

Simulations with computer models of the global circulation of the atmosphere (GCMs) have been carried out to represent the climate from \(~1860\) to 2000 with time-evolving natural (solar and volcanic) and anthropogenic (greenhouse gases, sulphate aerosol) forcings. The GCMs are generally able to reproduce, within the bounds of observational uncertainty and natural variability, the temporal variation of global average surface temperature over the twentieth century with the best match to observations obtained when all the above forcings are included. Separation of the effects of natural and anthropogenic forcing suggests that the solar contribution is particularly significant to the observed warming over the period 1900–1940. However, uncertainties remain with the solar effect, particularly regarding the impact of the choice of TSI reconstruction. Rind (2000) suggests, given some anthropogenic warming and large natural variability, that solar forcing is not necessarily involved in early 20th century warming but the analyses of Stott et al. (2000) and Meehl et al. (2003) do detect a solar influence.

Historically many authors have suggested, based on analyses of observational data, that the solar influence on climate is larger than would be anticipated based on radiative forcing arguments alone. The problems with these studies (apart from any question concerning the statistical robustness of their conclusions) is that (i) they
Fig. 12. Radiative forcing estimates 1750–2005 as compiled by IPCC (2007).

frequently apply only to certain locations, and (ii) they do not offer any advances in understanding of how the supposed amplification takes place. Recently some interesting developments have been made to address these problems based on two different approaches: the first uses detection/attribution techniques to compare model simulations with observations. These studies (North and Wu, 2001; Stott et al., 2003) show that the amplitude of the solar response, derived from multiple regression analysis of the data using model-derived signal patterns and noise estimates, is larger than predicted by the model simulations (by up to a factor 4). This technique does not offer any physical insight but suggests the existence of deficiencies in the models and also shows how the solar signal may be spatially distributed. The second approach proposes feedbacks in the climate system (that may already exist in GCMs) and uses these to explain features found both in model results and in observational data. The proposed mechanisms are generally either concerned with radiative and thermodynamic processes, water vapour feedback and clouds or involve dynamical coupling between upper and lower layers of the atmosphere.

One suggestion (Meehl et al., 2003) is that, because solar heating of the tropical sea surface is larger where there is less cloud, there may be changes in atmospheric circulation associated with anomalies in horizontal temperature gradient. Kodera
(2004) and Kodera et al. (2007) suggest that changes in the stratosphere influence static stability and tropical convection. Van Loon and Meehl (2008) also invoke changes in the stratosphere but find an intensification of tropical precipitation at high levels of solar activity, which appears to be at odds with the Kodera results. The reason for the similarity of the apparent sea surface temperature response to the cold phase of the ENSO cycle (Fig. 7) is also contentious. Van Loon and Meehl (2008) see two separate processes resulting in similar patterns. Emile-Geay et al. (2007), however, find that ENSO is actually modulated by solar activity, through a change in ocean circulations induced by longitudinally asymmetric changes in sea surface temperatures, although this takes several years to become established so may not apply on solar cycle timescales.

3.2 Solar spectral irradiance and photochemical effects in the stratosphere

The peak in the solar spectrum occurs at visible wavelengths but significant energy also resides in the ultraviolet region (Fig. 13(a)). UV radiation is absorbed in the middle and upper atmosphere with shorter wavelengths tending to be absorbed at high altitudes. Uncertainties in the absolute value of spectral irradiance imply uncertainties in the amount of energy absorbed in the atmosphere: Fig. 14(a) shows profiles of heating rates calculated due to absorption of radiation at wavelengths in the range 200–320 nm using two available solar spectra datasets, differences of up to 15% are apparent. This has implications for assessments of middle atmosphere temperatures: Fig. 14(b) shows large differences in the upper stratospheric and mesospheric temperature fields calculated in a general circulation model (GCM) between runs using the two spectra.

Fig. 13. Top: solar spectrum. Bottom: Fractional difference in solar spectral irradiance between maximum and minimum of the 11-year cycle. (From Lean and Rind (1998).)
Measurements of solar spectral irradiance in the visible and ultraviolet show that the amplitude of solar cycle variability is greater at shorter wavelengths (Fig. 13(b)). The result of this is that the response of atmospheric temperatures to solar variability is large in the upper atmosphere, with, for example, variations of 400 K being typical at 300 km over the 11-year cycle, reflecting the large modulation of far and extreme
ultraviolet radiation in that region. At lower altitudes the response is smaller; measurements made from satellites suggest an increase of up to about 1 K in the upper stratosphere at solar maximum; a minimum, or possibly even a negative change, in the mid-low stratosphere with another maximum, of a few tenths of a degree, below.
However, precise values, as well as the position (or existence) of the negative layer, vary between datasets.

Ozone is produced by short wavelength solar ultraviolet radiation and destroyed by radiation at somewhat longer wavelengths. This means that ozone production is more strongly modulated by solar activity than its destruction and this leads to a higher net production of stratospheric ozone during periods of higher solar activity. Observational records show approximately 2% higher values in vertically-integrated ozone amount at 11-year solar cycle maximum relative to minimum. The vertical distribution, as with the temperature signal, appears to show a minimum in the low latitude middle stratosphere (see Fig. 15, top panel) but as the observational data are only available over less than two solar cycles there remains some doubt about the statistical robustness of the signals derived from them.

Nevertheless, it is clear that the temperature and ozone responses are intimately linked and Austin et al. (2008) show that some coupled chemistry-climate GCMs are now able to reproduce the lower stratosphere maxima in temperature and ozone (Fig. 15, lower panel) although details of the mechanism whereby they occur remain uncertain.

3.3 Vertical coupling through the middle and lower atmosphere

3.3.1 Northern hemisphere winter polar stratosphere

During the winter the high latitude stratosphere becomes very cold and a polar vortex of strong westerly winds is established. The date in spring when this vortex finally breaks down is very variable, particularly in the northern hemisphere, but plays a key role in the global circulation of the middle atmosphere. Because variations in solar UV input change the latitudinal temperature gradient in the upper stratosphere, the evolution of the winter polar vortex may be affected. Satellite data suggest that the vortex strengthens in November and December in response to enhanced solar activity. This positive perturbation to zonal mean zonal winds then propagates polewards and downwards, until by February it is replaced by an easterly anomaly (Kodera et al., 1990; Kodera, 1995).

Planetary-scale waves induce a large-scale meridional circulation (Haynes et al., 1991) that is strengthened when the winter polar vortex is more disturbed. The meridional circulation is therefore a prime route for winter polar events to influence the lower stratosphere, not only in polar latitudes but throughout the winter hemisphere and even the equatorial and summer subtropical latitudes, through a modulation of the strength of equatorial upwelling. A dynamical feedback via the meridional circulation would serve to amplify the direct radiative solar influence since the less disturbed early winter conditions in solar maximum lead to a weaker meridional circulation, weaker equatorial upwelling and hence a warmer equatorial lower stratosphere at solar maximum than solar minimum (Kodera and Kuroda, 2002; see their schematic reproduced in Fig. 16). Recent advances in modelling these phenomena have been made (Matthes et al., 2004) but there are still several aspects that are not adequately reproduced or understood, including the apparent modulation of the solar signal by the quasi-biennial oscillation in tropical stratospheric zonal winds (Labitzke, 1987; Gray et al., 2004).
3.3.2 Stratosphere-troposphere coupling

Patterns similar to the solar effects seen in the NCEP temperature and wind data (Fig. 8 and Fig. 9) have been reproduced in GCM simulations of the effects of increased solar UV variability (Haigh, 1996, 1999; Larkin et al., 2000; Matthes et al., 2004); see e.g. Fig. 17. Haigh (1999) showed that the solar response was enhanced if solar-induced ozone changes were included, implying that the additional UV heating in these runs, especially in the lower stratosphere, were important. Shindell et al. (2006), using a GCM with coupled ocean, has also found an enhanced solar effect in the troposphere if stratospheric chemistry is allowed to respond; Fig. 18, from that study, shows a reduced solar impact on tropical precipitation when the chemistry is omitted. The GCM studies also predict a weakening and expansion of the tropical Hadley cells in response to solar activity (see Fig. 19) not dissimilar to that found in observations (Fig. 10).

The similarity of the signals found in the observational data and model runs is intriguing and, by the nature of the model experiments, suggests that changes in the
Fig. 17. Top: Average January zonal mean zonal wind (m s$^{-1}$) from a global climate model. Bottom: Difference in zonal mean zonal wind calculated for solar-cycle changes in solar UV radiation and ozone. (From Haigh, The impact of solar variability on climate, Science, 272, 981–984, 1996. Reprinted with permission from AAAS.)

Fig. 18. Zonal mean changes in precipitation (%) changes from simulations of: red curve—solar irradiance change typical of a solar cycle, without stratospheric chemistry response; blue curve—solar change with coupled stratospheric chemistry; green curve—climate change 1880–2003. For further details see Shindell et al. (2006). (From Shindell et al., Solar and anthropogenic forcing of tropical hydrology, Geophys. Res. Lett., 33, L24706, 2006. Copyright 2006 American Geophysical Union. Reproduced by permission of American Geophysical Union.)
Fig. 19. Zonal mean tropospheric meridional circulation from GCM simulations. Coloured panels show January and July mean fields, positive/negative values indicate clockwise/counterclockwise circulation (major Hadley cell in winter hemisphere). Monochrome panels indicate the difference between solar maximum and minimum simulations, solid/dashed contours indicate positive/negative values; in both seasons the Hadley cell is weaker and broader at solar max. (With kind permission from Springer Science+Business Media: *Space Sci. Rev.*, The effect of solar UV irradiance variations on the Earth’s atmosphere, 94, 2000, 199–214, Larkin et al., figure 4.)
stratosphere, introduced by modulation of solar ultraviolet radiation and ozone, are key. It does not, however, explain the mechanisms whereby such a change in tropospheric circulation is brought about by thermal perturbations to the stratosphere. Haigh et al. (2005) have carried out some experiments with a simplified GCM de-
signed to elucidate some of these mechanisms. The model, using the same basic framework as the dynamical core outlined by Held and Suarez (1994), includes a full representation of the fluid dynamics but diabatic processes are represented by a simple Newtonian relaxation back to an equilibrium state. This means that solar heating is not explicitly included but can be represented by changes in the equilibrium temperature field. The advantages of using such a model are that the dynamical responses are easier to understand and also, because it is much less computationally demanding, that it is feasible to carry out a range of forcing and diagnostic runs. Similar models have been used to investigate stratosphere-troposphere coupling processes, particularly in the context of polar modes of variability (e.g. Polvani and Kushner, 2002).
In the Haigh *et al.* (2005) study perturbations to the stratospheric equilibrium temperature were imposed and the response investigated. Figure 20 presents an example: the perturbation consists of 5 K at the equator decreases by $\cos^2$ (latitude) to zero at the poles, chosen to resemble coarsely the pattern found in the stratosphere.
response to solar variability (Fig. 8), although with larger magnitude. A response is seen, not only in the stratosphere but with vertical bands of warming throughout the troposphere—qualitatively similar to the observed solar signal. Figure 21 shows the response in zonal wind, the weakening and broadening of the mid-latitude jets is again markedly similar to the solar signal shown in observational data in Fig. 9 and in the full GCM experiment of Fig. 17.

From these experiments it was concluded that imposed changes in the lower stratospheric temperature forcing lead to coherent changes in the latitudinal location and width of the mid-latitude jetstream and its associated storm-track, and that wave/mean-flow feedbacks are crucial to these changes. The stratospheric warming, and an associated lowering of the tropopause, weakens the jet and storm-track eddies and it was also found that equatorial stratospheric warming displaces the jet polewards while uniform warming displaces it markedly equatorwards. It was concluded that the observed climate response to solar variability is brought about by a dynamical response in the troposphere to heating predominantly in the stratosphere, that the effect is small, and frequently masked by other factors, but not negligible in the context of the detection and attribution of climate change. The results also suggested that, at the Earth’s surface, the climatic effects of solar variability will be most easily detected in the sub-tropics and mid-latitudes.

Further details of the mechanisms involved in the transfer of the effects of the stratospheric forcing to the troposphere have been revealed by “spin-up” experiments in which the perturbation is imposed on the unperturbed atmosphere and the evolu-
tion of the response diagnosed (Haigh and Blackburn, 2006; Simpson et al., 2009). 10-day averages from an ensemble of such spin-up experiments is shown for temperature, horizontal eddy momentum flux, mean meridional circulation and zonal wind in Fig. 22. What happens in the sGCM, and by implication also in the real atmosphere, although other factors are bound to complicate the process, is as follows: changes to the temperature structure in the tropopause region influence the wind field there and thus the propagation of synoptic-scale waves and the deposition of zonal momentum; the meridional velocity, and by continuity the vertical velocity then respond, transferring the response to the lower troposphere and influencing the zonal winds there. Finally, and crucially, the changes in low level wind affect the propagation of waves and thus provide a feedback on the tropopause level effects. An outline of this mechanism is presented schematically in Fig. 23 providing an indication of how a solar (or indeed any other) perturbation to the lower stratosphere may influence tropospheric climate.

4 Summary

Radiation from the Sun ultimately provides the only energy source for the Earth’s atmosphere and thus changes in solar activity clearly have the potential to affect climate. There is now statistical evidence for solar influence on various meteorological parameters on a wide range of timescales, although extracting the signal from the noise in a naturally highly variable system remains a key problem. Many questions remain concerning details of the mechanisms which determine to what extent, where and when the solar impacts are felt but advances in understanding are being made through the use of global climate models. It is only by further investigation of the complex interactions between radiative, physical, chemical and dynamical processes in the atmosphere that these difficult questions will be answered.

Acknowledgments. The studies at Imperial College London were supported by the UK Natural Environment Research Council.

References


