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Eleven-year solar cycle variations in the atmosphere: observations, mechanisms and models

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Abstract: The understanding of natural and anthropogenic climatic change is an important issue in recent studies. The influence of the Sun (11-year solar cycle) as a natural variability factor on the atmosphere is discussed. Statistical studies with observational data (NCEP/NCAR re-analyses) covering four solar cycles show high correlations between the 11-year solar signal and meteorological parameters, e.g., the geopotential heights and temperatures, in the lower stratosphere and troposphere. Studies with general circulation models (GCM) have discussed the possibility of an indirect dynamical response to direct changes in solar irradiance and ozone in the stratosphere. A physical mechanism explaining the solar influence on the atmosphere is still missing. Part of the mechanism understood so far and ideas from model and observational studies are presented.

Key words: Numerical modelling experiments, solar cycle, climatic change, mechanisms, observational data, meteorological parameters, Sun.

Introduction

Much effort in observational as well as in model studies has been applied to date to understand recent climatic changes. One of the key issues is the importance of natural versus anthropogenic change. The high present-day concentration of greenhouse gases (GHG), e.g., carbon dioxide or methane, has never before been observed, and it is very likely that much of the recent global temperature increase is mainly anthropogenic in origin. Nevertheless, past climatic changes, e.g., from the Maunder Minimum to the first half of the twentieth century, can only be explained if solar variability changes are taken into account. Figure 1 (from Hansen, 2000) shows the estimated global climate forcings between AD 1850 and 2000 separated into anthropogenic (GHG and others) and natural (Sun and volcanoes) forcings. It can clearly be seen that the net radiative forcing from natural sources like the Sun (which can be regarded as an external forcing parameter) and volcanoes (which can be regarded as an internal forcing) is not negligible compared to the anthropogenic ones.

Solar irradiance variations can be observed on different timescales, e.g., the 27-day rotational period, the 11-year solar cycle (Schwabe cycle), the 88-year (Gleisberg) cycle, a ~200-year cycle, and much longer ones of 20000 and 40000 years due to changes of the orbital parameters. In the following, we will only focus on

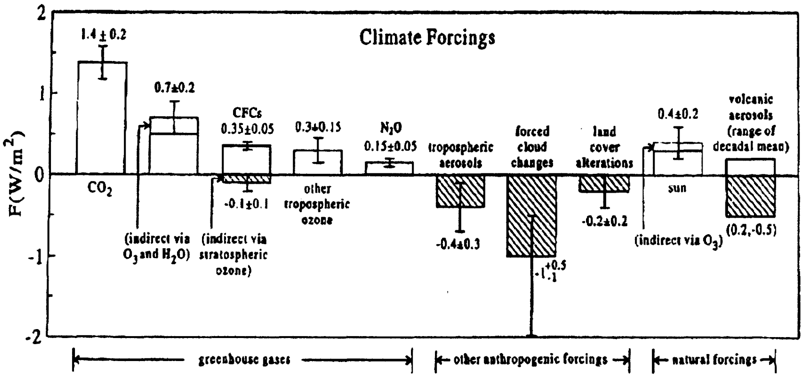

Figure 1 Estimated global climate forcings between 1850 and 2000 (Hansen, 2000).

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the 11-year solar signal and its influence on atmospheric circulation patterns.

Sun-climate interactions have only been accepted for a relatively short time because reliable measurements of the total or spectral solar irradiance have only been available since the advent of satellite-borne radiometers starting from 1978. This is also the reason why detailed model studies – with realistic wavelength-dependent irradiance changes – could not be done in the past. In Figure 2 a combined total solar irradiance (TSI) time series from different satellite instruments shows the relative shortness of direct solar irradiance measurements (Fröhlich, 2000; Pap, 2003). The short-term variations seen in Figure 2 are related to solar oscillations and the passage of individual sunspots, sunspot groups and faculae across the solar disk. Variations of the 11-year solar cycle from solar maximum to minimum integrated over the whole electromagnetic spectrum are of the order 0.1% and are too small to directly cause the observed changes in Earth's surface temperature. However, changes in the ultraviolet part of the spectrum – the part which is responsible for ozone production and loss in the stratosphere – can reach more than 8% (Figure 3) and are no longer negligible. During solar maximum, increased UV radiation enhances the photochemical production of ozone in sunlit areas of the stratosphere. Enhancement of UV radiation and ozone together enhances the short-wave heating in the stratosphere and hence induces a meridional temperature gradient in the upper stratosphere which can further alter the circulation in the whole atmosphere via changes in the planetary wave propagation on the winter hemisphere (see below). Spectral irradiance variations in the visible part of the spectrum need also to be considered for climate studies because the absorption of visible light warms the Earth's surface (therefore the sea surfaces are affected as well, because a great part of the surface is covered by water). That is why two sensitive regions in the Earth's atmosphere are warmed through absorption of solar irradiances: the upper stratosphere due to absorption of UV light and the Earth's surface (oceans) due to absorption of visible light. The latter mechanism is excluded in the model studies mentioned below because a general circulation model (GCM) with coupled ocean is very expensive to run. Therefore most GCMs use fixed sea-surface temperatures (SSTs) and only account for the stratospheric changes.

Observations of the Sun-climate relationship

The Sun-atmosphere relationship has been studied for a long time because the Sun is the energy source for the climatic system and therefore it is reasonable to assume that variations in solar output can be found in climate records (e.g., Bates, 1981). The satellite era has enabled more accurate measurements of the total solar irradiance and hence better data have been available since that time. Based on four solar cycles, the global structure of the 11-year sunspot cycle (SSC) in the stratosphere and troposphere was examined in several studies, using linear correlations between the 10.7 cm solar flux (which is an objectively measured radiowave, highly and positively correlated with the SSC; no causal relationship is implied by the use of this parameter) and meteorological parameters such as the geopotential height and temperature (e.g., Labitzke, 1987; 2001; Labitzke and van Loon, 1988; van Loon and Labitzke, 2000).

The solar signal in the annual mean

The vertical structure of the linear correlations of the zonally averaged annual mean temperatures from 1000 to 10 hPa (sea level to about 32 km) is shown in Figure 4 (top) together with the resulting temperature differences between maxima and minima of the SSC (Figure 4, bottom). Correlations larger than 0.5 are shaded. Most of this part of the atmosphere is positively correlated with the 11-year SSC, with maxima over both subtropics in the stratosphere, reaching to higher latitudes in the troposphere. This is valid throughout the year, except for the late northern winters (see below). The positive correlations coincide with positive temperature differences (Figure 4, bottom). It means that during solar

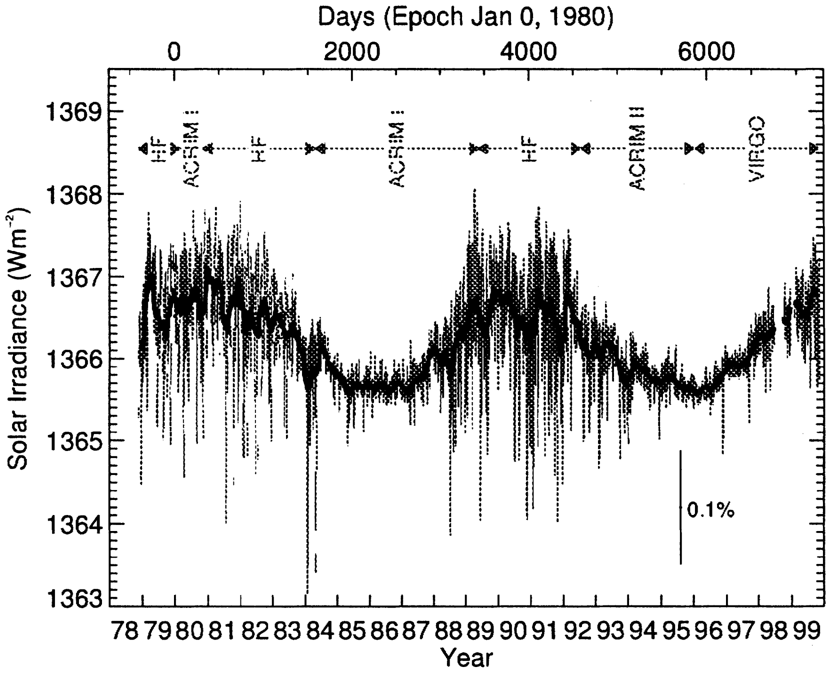

Figure 2 Composite total solar irradiance (TSI) with indication of which time series are used at different times (Fröhlich, 2000).

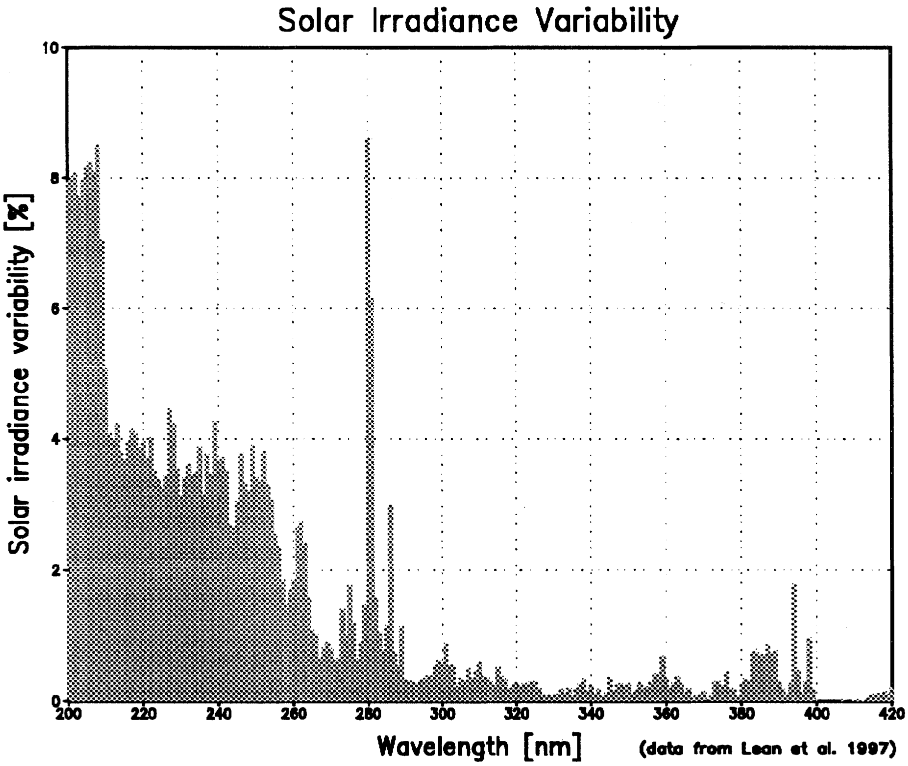

Figure 3 Variability of the ultraviolet part of the solar spectrum from 200 to 420 nm in percent; data from Lean *et al.* (1997).

maximum years temperatures are generally higher than during solar minimum years. The largest temperature differences of about 1.5 Kelvin can be found around 100 hPa between the equator and 30°S; a secondary maximum is apparent in the lower stratosphere around 25°N. Positive temperature anomalies can also be seen down to the troposphere.

Figure 5 shows the time series of the 10.7 cm solar flux and the annual mean 70 hPa temperatures (and their three-year running means, near 18 km) at a gridpoint (30°N/136°W) where the correlation exceeds 0.7; that is, where half of the interannual variance of the temperatures is associated with the solar cycle.

Northern summer

The solar signal is strongest during northern summer (July/August). The horizontal structure of the correlations between the 30 hPa geopotential heights (near 24 km) and the SSC is shown in Figure 6, together with the height differences between solar maxima and minima. The extensive belts with high correlations over both hemispheres stand out clearly (top), as well as the maxima of the geopotential height differences. This pattern suggests a connection with the meridional circulation cells in the troposphere (Hadley circulation), with increased subsidence during solar maxima in the subtropical high-pressure belts (Labitzke and van Loon, 1995).

Northern winter

We have shown several times that during northern winters the solar signal is weak over the whole globe, if one uses a full series of stratospheric heights or temperatures for correlations with the SSC. The Quasi-Biennial Oscillation (QBO), a wind oscillation in the equatorial lower stratosphere where easterly and westerly winds change nearly every two years, modulates the solar signal

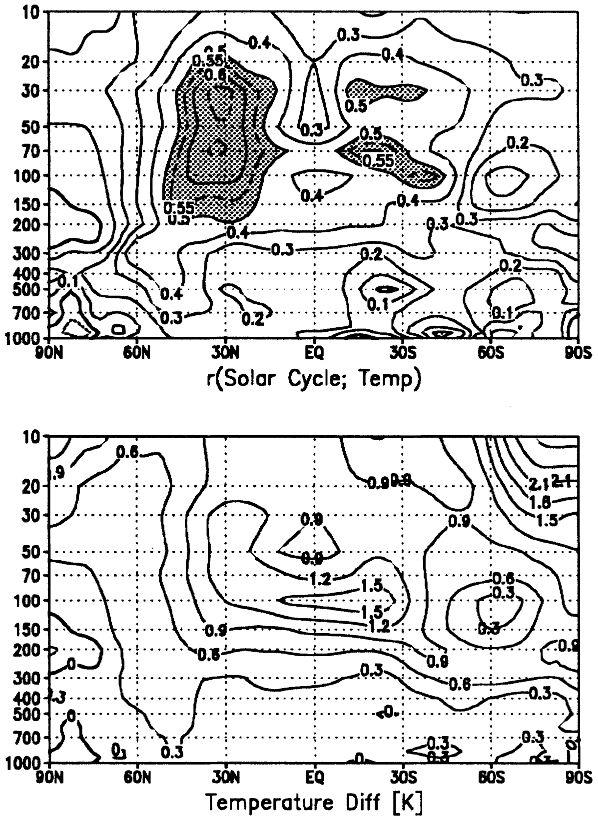

Figure 4 Vertical meridional sections for the period 1968–98. Top: linear correlations between the zonally averaged annual mean temperatures (detrended) and the 11-year solar cycle (shaded for emphasis where the correlations are above 0.5). Bottom: the zonally averaged temperature differences (K) of the annual means between solar maxima and minima (NCEP/NCAR re-analyses; Labitzke, 2001; Figure 3).

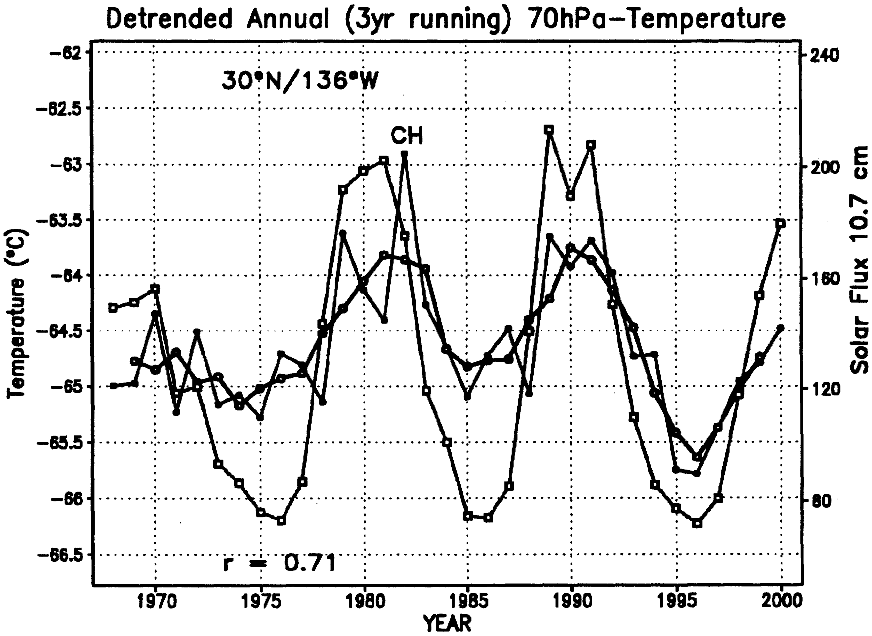

Figure 5 Time series of the 10.7 cm radio flux (dashed line) and of the annual mean 70 hPa temperatures (and their three-year running means) at a gridpoint (30°N/136°W) where the linear correlation exceeds 0.7 (NCEP/NCAR re-analyses).

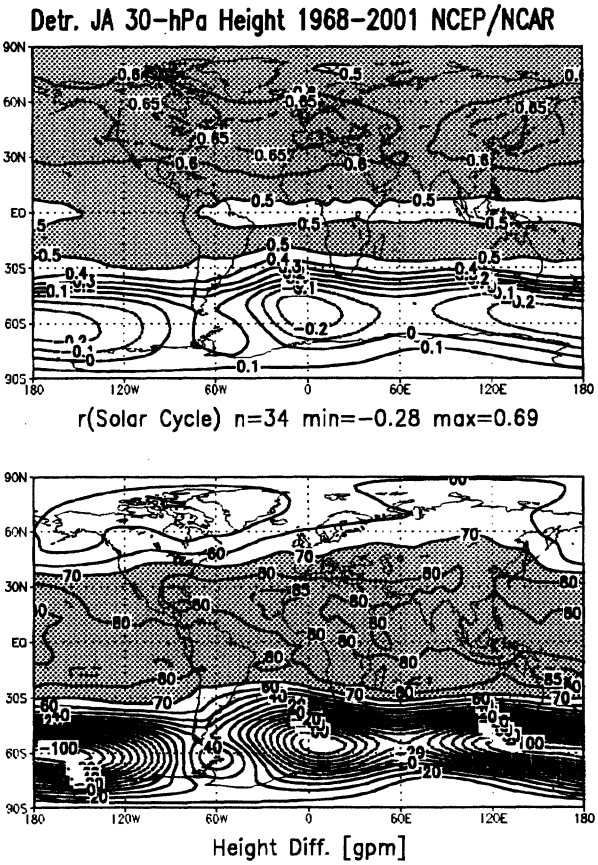

Figure 6 Top: correlations between the 11-year solar cycle and the 30 hPa heights in July/August, 1968–2001 (detrended and shaded for emphasis where the correlations are larger than 0.5). Bottom: height differences (gpm) between solar maxima and minima (shaded where the differences are above 70 geopotential metres) (NCEP/NCAR re-analyses).

and it is necessary to group the winters into years when the QBO in the lower stratosphere (about 45 hPa) is in its west phase or in its east phase, respectively (Labitzke, 1987). The signal is most pronounced during the latter part of the winter. Figure 7 shows the linear correlations between geopotential heights and the SSC in February, with the winters during the east phase of the QBO on the top and the winters during the west phase of the QBO on the bottom. During the east phase, the structure of the correlations is similar to the annual mean (Figure 4) with maxima over the tropics and subtropics. The negative correlations over the Arctic

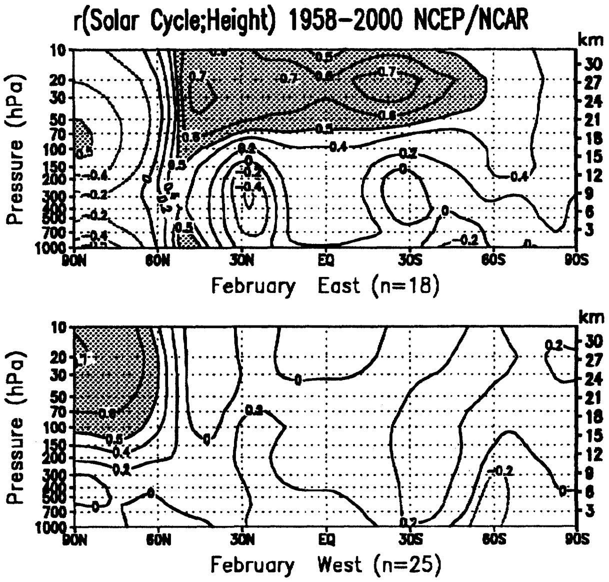

Figure 7 Vertical meridional sections for the period 1958–2000 of the correlations between the zonally averaged heights in February and the 11-year solar cycle (shaded for emphasis where the correlations are above 0.5). Top: for winters in the EAST-phase of the QBO. Bottom: for winters in the WEST-phase of the QBO (NCEP/NCAR re-analyses; Labitzke and van Loon, 2000; update of Figure 6).

are a dynamical response (adiabatic rising => cooling) to the solar-induced warming (positive correlations) over the subtropics. The pattern of the correlations is completely reversed during the winters in the west phase of the QBO, with a maximum of the correlations over the Arctic and only weak correlations over the rest of the globe.

The positive correlations over the Arctic during the west phase of the QBO are connected with the occurrence of 'major midwinter warmings' during solar maxima, in opposition to the east phase winters, when such Arctic warmings tend to take place predominantly during solar minima (Labitzke and van Loon, 1988).

The major warmings in the stratosphere are connected with widespread sinking motion (adiabatic warming) over the Arctic and rising motion connected with cooling over the rest of the globe. In the west phase of the QBO this takes place during solar maxima, and the connected cooling outside the Arctic counteracts the solar-induced warming over the subtropics, which leads to the weak correlations outside the Arctic in the bottom panel of Figure 7.

The high correlations shown above indicate a Sun-atmosphere relationship even though no complete physical mechanism for the solar influence on different atmospheric levels has so far been found. Experiments with atmospheric general circulation models (GCMs) indicate that the high correlation with the SSC in the lower stratosphere is an indirect, dynamical result of interaction between ozone and solar UV radiation in the upper stratosphere. Several model experiments have simulated some of the northern winter features (e.g., Haigh, 1996; 1999; Balachandran *et al.*, 1999; Larkin *et al.*, 2000; Shindell *et al.*, 1999; 2001), but simulations for the northern summer still show a response which is too weak. The following paragraphs will give a short overview of recent understanding of solar influence on climate as well as on recent model studies.

Mechanisms

Model studies agree that 11-year solar irradiance variations have a direct impact on the radiation and ozone budget of the middle atmosphere. The importance of ozone changes during the solar cycle was established by Haigh (1994) who calculated the ozone variability during a solar cycle with a 2-D chemical model. Recent model studies (Haigh, 1996; 1999; Larkin *et al.*, 2000; Shindell *et al.*, 1999; 2001) take the interaction between direct irradiance changes and ozone changes (through direct irradiance changes) into account. Enhanced ultraviolet radiation during solar maxima leads to an enhanced ozone production in the upper stratosphere (maximal 3% near 5 hPa from the subtropics to higher latitudes, estimated by 2-D chemical models; the observed ozone signal is even higher) depending on the time of the year (Figure 8). The enhanced UV radiation as well as the enhanced ozone lead to a greater short-wave heating rate in the stratosphere during solar maxima than during solar minima. The thermal gradient induced directly in the upper stratosphere (near the stratopause at a height of 50 km) can alter the whole mean meridional circulation from the stratosphere down to the troposphere by affecting the planetary wave propagation in the winter hemisphere. Kodera (1991) pointed out that the Sun, as well as the QBO, produces wind anomalies in the upper subtropical stratosphere in early winter (December). Such wind anomalies change the propagation properties for planetary waves and affect the polar night jet formation at higher latitudes through wave-mean flow interactions. The wind anomalies propagate, via this positive feedback mechanism, poleward and downward during wintertime from the upper stratosphere at lower latitudes to the lower stratosphere at higher latitudes. Kodera (1991; 1995) confirmed the observed modulation between solar and QBO signals (Labitzke and van Loon, 1988) during winter and assumed that the solar activity, as well as the QBO (and volcanic eruptions), triggers the interannual variability of the stratosphere. New studies indicate that the stratosphere is mainly in a radiatively controlled state during early winter and switches to a dynamically controlled state during later winter (Kodera and Kuroda, 2002). During solar maximum years, the radiatively controlled state seems to last longer. Still unknown is the interaction between the solar and the QBO signal. Salby and Callaghan (2000) detected an 11-year solar cycle in the QBO data itself. The length of the QBO westerly phases is different during solar maximum and minimum years. Gray *et al.* (2001a; 2001b) recently pointed out that not only equatorial winds in the lower stratosphere but also winds up to the stratopause (at a height of 50 km) are important for the circulation at high latitudes during northern winter.

Model studies

Various studies with GCMs show the main features of the observed solar influence (Haigh, 1999; Larkin *et al.*, 2000; Shindell *et al.*, 1999; 2001) but the magnitude of the simulated response is too small, especially at low latitudes and during summer. Tropospheric circulation changes can be detected in GCMs, but they are smaller than observed and, in the case of the observed strengthening of the Hadley circulation during solar maxima, models show the opposite response with a weakening and broadening Hadley cell (Haigh, 1999). It is possible that the missing variation of sea-surface temperatures (SSTs) in the model can partly explain this discrepancy.

As an example, model studies with the Berlin Climate Middle Atmosphere Model (FUB-CMAM) similar to those from Haigh (1999), Larkin *et al.* (2000) and Shindell *et al.* (1999; 2001) are presented here. The FUB-CMAM is a spectral general circulation model with 34 vertical levels extending to 0.0068 hPa (~83 km) and a horizontal resolution of 5.6° × 5.6° (T21).

To simulate the 11-year solar cycle in a GCM without fully interactive chemistry, the wavelength-dependent solar irradiance changes between solar maximum and minimum from 200 to 420 nm (Figure 3; Lean *et al.*, 1997) as well as the resulting ozone differences (Figure 8; calculated by a 2-D chemical model from the Imperial College London; Haigh, 1994) have been implemented in the FUB-CMAM. Two 20-year runs, one representing solar minimum and the other representing solar maximum conditions, have been performed, both in annual cycle mode. The prescribed changes were the same as defined for the GRIPS – GCM Reality Intercomparison Project for SPARC (Stratospheric Processes And their Role in Climate) – solar forcing initiative, thus enabling the intercomparison of the model results with similar studies (Matthes *et al.*, 2003).

Results

The 20-year mean differences between solar maximum and minimum simulations show a direct impact of the radiation changes (in the UV part of the solar spectrum) and the ozone changes, upon the temperature distribution, similar to the above-mentioned GCM studies. In Figure 9, the annual mean temperature difference between solar maximum and solar minimum is shown indicating higher temperatures during solar maximum conditions throughout the year in the tropical and subtropical stratosphere. The largest response of more than one Kelvin, which is statistically significant, can be found around the stratopause (~50 km). Higher temperatures during solar maximum are also seen in the upper troposphere. The polar regions, especially the northern higher latitudes, are characterized by a large interannual variability during winter

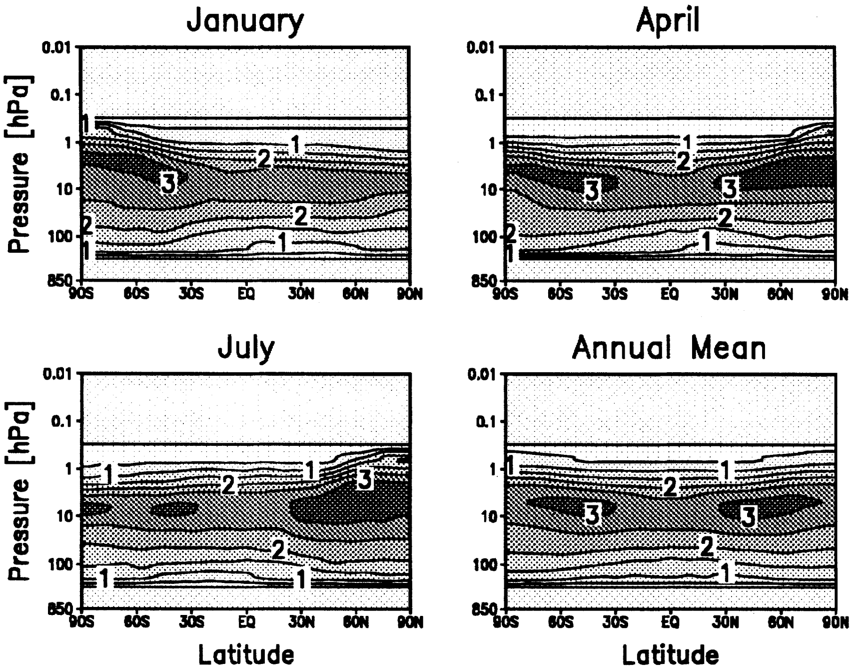

Figure 8 Ozone variability between solar maximum and minimum in percent for January, April, July and the annual mean estimated by a 2-D chemical model at the Imperial College London (Haigh, 1994).

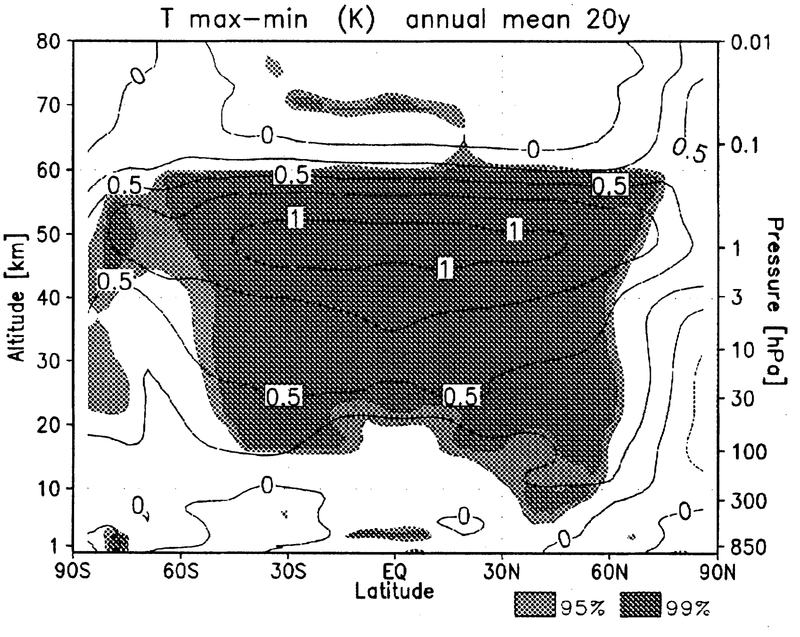

Figure 9 Annual mean temperature difference between 20 solar maximum and 20 solar minimum years in the FUB-CMAM model experiments. Contour interval: 0.25 K. Light (heavy) shaded areas indicate the 95% (99%) significance level (Student t-test).

leading to no statistically significant regions (Figure 9). Significant temperature differences are confined here to the summer stratosphere (not shown). The magnitude of the stratospheric temperature response is comparable to several estimates from observational studies which lie in the range of 0.75 to 2 Kelvin in the upper stratosphere (e.g., Hood, 1993; WMO, 1999). A secondary temperature maximum in the lower stratosphere (compare Figure 4, bottom) is missing in all model experiments performed so far. Reasons for that could be, for example, the coarse vertical resolution of GCMs in the region of the tropical tropopause or missing chemical reactions in the models. Results for the summer (not shown) show that the signal in the FUB-CMAM is – similar to other GCM studies – weaker than observed but it is of the same sign. While the main features of a stronger and colder polar vortex during northern winter of solar maximum years is captured in the FUB-CMAM, the observed poleward and downward propagation of the zonal mean wind anomalies is not represented properly. This discrepancy with observations can mostly be explained by the difference between the modelled and the observed wind climatology. A common problem of GCMs is to properly simulate the polar night jet in the winter stratosphere. In observations the polar night jet tilts equatorward, whereas this tilt is missing in GCMs. The modelled jet is too strong (due to missing or insufficiently represented gravity waves) and leads to a cold-bias in polar temperatures. A relatively small solar signal which has been shown to interact with the zonal mean flow in the subtropical stratopause region in early winter (Kodera and Kuroda, 2002) can probably therefore not be transported to higher latitudes through wave-mean flow interaction (compare, also, Matthes *et al.*, 2003). A factor which further complicates the solar signal is the QBO interacting with the solar signal during northern winter. So far the FUB CMAM with artificially imposed QBO westerlies in the lower stratosphere is still not able to reproduce the observed features, that is, more stratospheric warmings during QBO west and solar maximum conditions.

Further model studies are needed to find the mechanism of solar and QBO influences on the atmosphere. The observed strong solar signal during summer and the association with the Hadley circulation especially need to be investigated in more detail.

Conclusions

Positive correlations between the 11-year solar cycle and meteorological parameters can be found in the annual mean throughout the atmosphere, reaching their largest values during northern summer. Under solar maximum conditions the atmosphere is up to 1.5 Kelvin warmer than during solar minimum years, especially in the tropical and subtropical latitudes. This induced meridional temperature gradient alters the whole atmospheric circulation through changes in the wave-mean flow interaction and changes in the Brewer-Dobson circulation. During winter the interaction between the solar and the QBO signal has to be taken into account. While Major Stratospheric Warming events occur under QBO east conditions during solar minimum years, they appear only during solar maximum conditions in QBO west years.

We have shown that GCMs are able to simulate parts of the 11-year solar cycle effect even if the response, especially at lower latitudes and during summer, is too weak compared with observations. Temperatures are up to 1 Kelvin higher around the tropical and subtropical stratopause region for the solar maximum simulation – that is in good agreement with estimations from observations. There are several possible explanations for the shortcomings. The GCM experiments are very idealized because, instead of a realistic 11-year solar cycle, the models are run under perpetual solar maximum or minimum conditions; no realistic QBO is so far included in the model experiments and one therefore cannot achieve interactions between QBO and solar signals. Another problem could be the model climatology: the stratospheric polar night jet is often too strong and does not tilt equatorward – maybe it is not surprising that the observed poleward downward propagation of the wind anomalies cannot be represented correctly.

Future studies will try to perform more realistic simulations which take into account, for example, the QBO, and should shed more light on the mechanism of Sun-climate interactions.

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