Mem. S.A.It. Vol. 76, 868

Memorie della

Solar impact on climate: modeling the coupling between the middle and the lower atmosphere

U. Langematz[1], K. Matthes[1,2], and J. L. Grenfell[1,3]

[1] Institut für Meteorologie, Freie Universität Berlin, Germany, e-mail: lang@strat01.met.fu-berlin.de
[2] National Center for Atmospheric Research, Boulder, USA
[3] Now at DLR Institut für Planetenforschung, Berlin, Germany

Abstract. Solar variability influences the earth's atmosphere on different time scales. In particular, the impact of the 11-year solar cycle is of interest as it provides the major contribution to natural climate variability. Observations show clear 11-year variations in meteorological variables such as temperature or geopotential height from the upper atmosphere down to the troposphere and the earth's surface. In this paper the mechanisms will be discussed which are assumed to be responsible for the downward transfer of the solar signal within the atmosphere. These involve radiative, dynamical and chemical processes which have been studied in detail in model simulations and will be presented here.

Key words. Atmospheric Physics, Solar Variability, Climate, Numerical Modeling

1. Introduction

The earth's atmosphere is influenced by the sun in a complex way. Solar activity varies on different time scales from seconds, over the 27–day solar rotation period, to the 11–year solar sunspot cycle, and to centennial scale variations. While passing through the atmosphere the solar energy is deposited and redistributed from the thermosphere down to the troposphere and the earth's surface. This transfer encompasses various mechanisms: direct absorption of electromagnetic radiation, generation and/or modification of chemically active substances by energetic particles and generation or modification of planetary waves and tides which propagate through the atmosphere and can deposit energy and momentum far away from the source. All these processes ultimately affect the thermal and dynamical structure of the atmosphere. The stratosphere (15–50 km) plays an important role since it is the height region where primary radiative and thermal effects of solar variability overlap with indirect dynamical effects, which then propagate down to the troposphere where they have the potential to impact climate.

This paper addresses the impact of the 11-year solar cycle on climate. We will discuss the mechanisms that create and transfer the solar signal in the earth's atmosphere and focus in particular on aspects of the vertical coupling between the mesosphere, stratosphere and troposphere.

In the following we present theoretical concepts that have been proposed by different authors to explain the observed solar signal in

Send offprint requests to: U. Langematz the atmosphere. These concepts were tested in a series of model simulations with the Freie Universität Berlin Climate Middle Atmosphere Model (FUB-CMAM). The FUB-CMAM is a 3d–General Circulation Model (GCM) including the troposphere, stratosphere and mesosphere. Details of the model formulation can be found in Pawson et al. (1998) and Langematz (2000). The downward transfer of the solar signal involves radiative, dynamical and chemical processes which will be discussed in the following sections.

2. Radiative Coupling

During the 11–year solar cycle the spectrally integrated solar irradiance at the top of the atmosphere TSI (Total Solar Irradiance) varies by only about 0.1% (Fröhlich, 2000). In the ultraviolet (UV) part of the solar spectrum however variations range from 1–5% in the Hartley band of ozone (O_3) which provides the main heat source in the upper stratosphere, and by 5–12% in the Herzberg Continuum and the Schumann–Runge bands of molecular oxygen (O_2) which have a minor effect on heating the mesosphere but are important for photochemical O_3 production. 11–year changes in the 121.6 nm Lyman–α line exceed 50%. They have a negligible impact on radiative heating rates in the mesosphere and further down but strongly influence photochemistry.

The effect of the above changes in solar UV on the shortwave (SW) radiation balance were calculated with the FUB-CMAM using an improved SW radiation scheme featuring a high spectral resolution for a GCM code including 44 bands between 206.2 and 852.5 nm. The changes in the spectral solar flux were provided by Lean et al. (1997). In addition, the secondary effect of the enhanced UV irradiance on the photochemical O_3 production was taken into account by applying off-line calculated O_3 changes for either solar minimum (min) or maximum (max) conditions (Haigh, 1994) to the model's background O_3 climatology. The model was integrated for 20 years under constant solar min and max conditions respectively. The solar signal in all model simulations presented here is equivalent

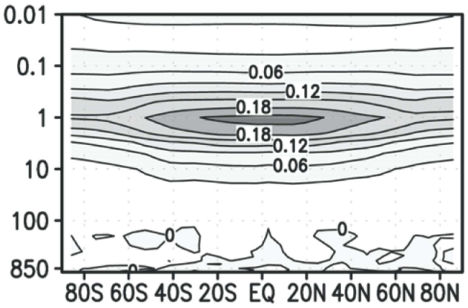

Fig. 1. Annual mean shortwave heating rate difference between solar max and solar min [K/day], calculated with the FUB-CMAM (adapted from Fig. 3 in Matthes et al. 2003).

to the multi-annual mean difference between the solar min and max simulations. Figure 1 shows the change of the zonal mean SW heating rates from solar min to solar max as a function of height and latitude (from Figure 3 in Matthes et al., 2003). In the annual mean the strongest radiative response occurs at the equatorial stratopause around 50 km where the atmosphere is heated more during solar maximum by up to 0.22 K/day. In the tropics, two third of the signal are due to the direct absorption of the enhanced solar irradiance, while one third is due to the solar induced ozone increase leading to a secondary enhancement of solar UV absorption. At solstice over the poles, this secondary absorption effect has about the same order of magnitude as the primary effect of enhanced UV irradiance.

The corresponding temperature signal is shown in Figure 2. Due to the increased SW heating nearly the whole stratosphere heats at solar max. Consistent with the maximum in SW heating increase the temperature increase is strongest at the stratopause at low to mid latitudes reaching more than 1 K. This temperature signal is highly statistically significant (as calculated with a Student's t-test) in the whole stratosphere and lower mesosphere except for polar latitudes where dynamical variability overlaps the solar signal. The correspondence between the SW heating rate and the temperature change patterns implies a direct radiative

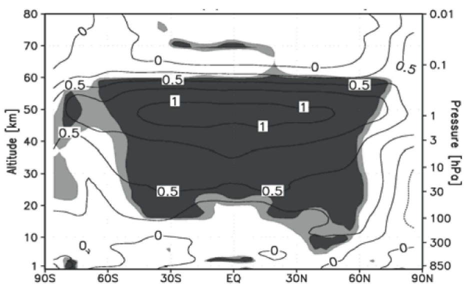

Fig. 2. Annual mean difference in zonal mean temperature between solar max and solar min [K], calculated with the FUB-CMAM. Shadings denote regions with statistical significance higher than 95% and 99%.

effect of the enhanced electromagnetic radiation during solar max on the thermal structure in the stratosphere. Note however that the temperature signal in the lower stratosphere is very weak and no longer statistically significant.

The simulated solar signal lies in the range of the observed solar signal which can be derived from satellite measurements using multiple regression analysis methods. The observed signal varies between 2.5 K at the stratopause (Hood, 2004), 1.75 K around 45 km (Crooks and Gray, 2005), and 0.8 K between 35 and 40 km (Scaife et al., 2000). These differences in the amplitude and spatial pattern of the observed solar signal are partly due to the relatively short time series of satellite measurements including only three solar cycles and make an evaluation of the simulated solar signal difficult. The observed secondary temperature signal in the lower tropical stratosphere could not be reproduced by the model.

3. Dynamical Coupling

The transfer of the initial radiative solar signal in the upper stratosphere described in the previous section into the lower stratosphere is believed to be performed by dynamical processes. Kodera and Kuroda (2002) developed a conceptual model which is based on the feedback between planetary waves and the zonal mean wind as well as changes in the mean meridional circulation (MMC) (Figure 3, from Kodera and Kuroda, 2002). Due to the initial radiatively induced warming of the upper subtropical stratosphere the meridional temperature gradient towards the winter pole is enhanced leading to a westerly wind anomaly in the upper subtropical stratosphere in early winter. This strengthening of the westerly jet in turn leads to a poleward deflection of planetary waves that propagate from higher latitudes or upward from the troposphere into the stratosphere during winter. It is associated with weaker energy dissipation of the waves, weaker deceleration of the westerly jet and thus a further enhanced westerly wind anomaly. This wave-mean flow feedback continues throughout the winter thereby leading to a poleward–downward movement of the wind anomalies as pointed out by Kodera (1995). It thus transports the solar signal down to the lower stratosphere and troposphere at mid to high latitudes in winter. In addition, the reduced planetary wave dissipation is associated with a reduction of the MMC which is characterized by upwelling in the tropical stratosphere, poleward flow in the upper stratosphere and mesosphere in winter and sinking at high latitudes. A reduction is therefore equivalent with reduced tropical upwelling (relative downwelling) and reduced sinking at high latitudes (relative upwelling).

A further dynamical feedback which has been suggested to influence the solar signal is the interaction between the quasi–biennial oscillation (QBO) of the zonal winds in the tropical stratosphere and the intensity of the polar vortex in winter. Labitzke (2003) showed in an analysis of the 30 hPa geopotential height fields in February 1958–2003 that during the QBO east (QBO–E) phase the polar vortex is stronger and more stable in solar max years than in solar min years. In contrast, during the QBO west (QBO–W) phase, the polar vortex is weaker and more disturbed by sudden stratospheric winter warmings in solar max years than in solar min years. This means that the well-known relationship between the QBO and the polar vortex which was explained by Holton and Tan (1982) to be the result of a modification of meridional planetary wave propagation, holds only for solar min years while it is nearly reversed for solar max years. Gray et al. (2001a,b) emphasized that the QBO phase plays an important role not only in the lower and middle stratosphere but also in the upper stratosphere.

The above described dynamical feedback mechanisms were tested in a number of GCM model studies which were compared in the framework of the GRIPS (GCM-Reality Intercomparison Project for SPARC) solar intercomparison sub-project (Matthes et al., 2003). None of these could reproduce sufficiently the poleward–downward transfer of the circulation anomalies. One possible explanation for this systematic discrepancy could be the missing representation of a QBO in the GCMs which is a well-known caveat in low resolution GCMs. Only high-resolution GCMs including sophisticated gravity wave schemes are able to simulate a self-consistent QBO. To test the possible QBO–sun feedback the solar experiments with the FUB-CMAM were repeated but with an additional prescribed relaxation of the tropical stratospheric winds towards either the QBO–E or QBO–W phase. With this model configuration the observed poleward–downward propagation of the zonal wind anomalies could be simulated for the first time (Matthes et al., 2004). The impact of the zonal wind anomalies on the wave propagation during high latitude winter and significant responses in the lower stratosphere and troposphere could be reproduced by the model, as well as the subsequent changes in the MMC. Figure 4a shows the difference between solar min and max years of the zonal mean temperature in the troposphere and lower stratosphere in January. Due to the reduced upwelling, the lower tropical stratosphere warms significantly up to 1 K. This has an impact on the troposphere where a significant weakening of the Hadley circulation occurs in January with a reduction of the upwelling centered at 10°S and of the downwelling over the equator (Figure 4b). This result is in good agreement with Haigh (2003) who showed a similar tropospheric response to implied artificial heat sources in the lower tropical stratosphere of a simplified GCM. The weakened Hadley circulation in turn leads to less cloud cover and precipitation south of the equator and to enhanced cloud cover and precipitation further north. The time lag between the initial solar signal in the upper stratosphere and the troposphere is about two months (Matthes et al., 2005).

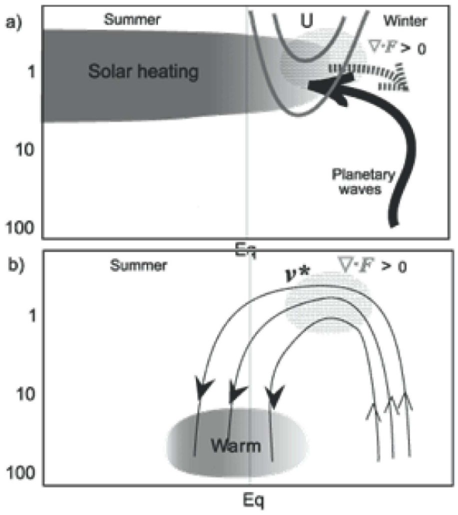

Fig. 3. Schematical illustration of the dynamical influence on the lower stratosphere. a) Westerly wind anomalies in the subtropical upper stratosphere cause deflection of planetary waves. b) Decrease in wave forcing results in edcrease of BD and warming of the lower tropical stratosphere (from Fig. 15 in Kodera and Kuroda, 2002).

4. Chemical Coupling

Although the direct impact of changes in UV irradiance during the 11–year solar cycle on ozone and temperature in the stratosphere seems basically to be understood (see Section 2), large discrepancies occur between 2d–model simulations of the response of stratospheric ozone to these UV changes and the observed solar signal in stratospheric ozone. Different independent analyses of satellite measurements revealed a pronounced ozone enhancement during solar max at mid latitudes in the upper stratosphere above 40 km and a reduction in the low latitude middle strato-

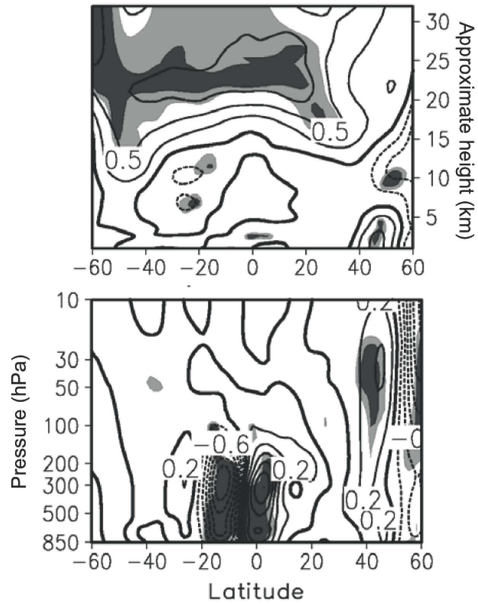

Fig. 4. Difference between solar max and min in January of zonal mean temperature (a) and vertical velocity (b), calculated with the FUB-CMAM. Shadings denote regions with statistical significance higher than 95% and 99%.

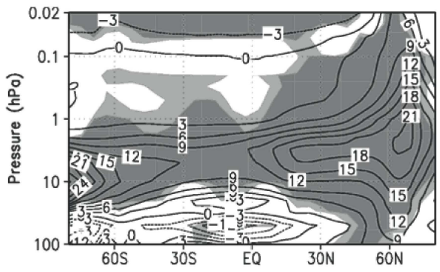

Fig. 5. Difference between solar max and min in January in zonal mean ozone [%] , calculated with FUB-CMAM-CHEM. Shadings denote regions with statistical significance higher than 95% and 99%.

sphere between 30 and 40 km (Lee and Smith, 2003; Hood, 2004). In contrast, 2d–model simulations uniformly show the strongest ozone enhancement during solar max in the middle

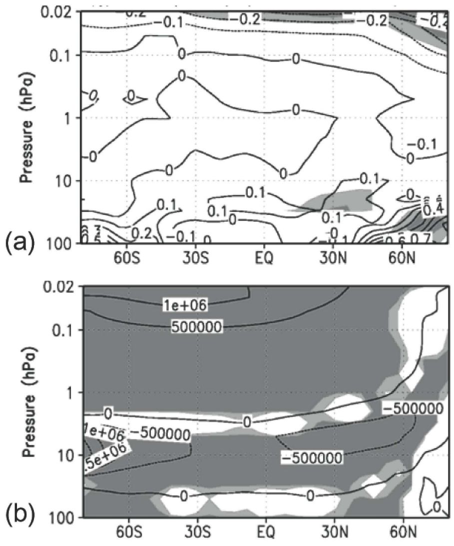

Fig. 6. Difference between solar max and min in January in zonal mean H_2O [ppmv] (a) and OH [molec/cm^3] (b) , calculated with FUB-CMAM-CHEM. Shadings denote regions with statistical significance higher than 95% and 99%.

stratosphere around 35 km with a decrease towards the upper and lower stratosphere (Haigh, 1994; Shindell et al., 1999).

These discrepancies between models and observations may be due to the fact that the ozone signal was calculated in 2d–models which lack the full feedback between radiation, chemistry and dynamics. Another explanation may be that the ozone response to 11–year solar activity variations is not due to UV irradiance changes alone but may be affected as well by variations in energetic particles. The vertical distribution of the particles within the atmosphere depends on the mass and energy of the particles. Medium-energy electrons associated with the auroral flux remain in the thermosphere, while high-energy, relativistic electrons from the outer radiation belt penetrate into the stratosphere and mesosphere (Callis et al., 1991). Energetic particles from solar proton events (SPE) may reach the stratosphere, while galactic cosmic rays have their strongest

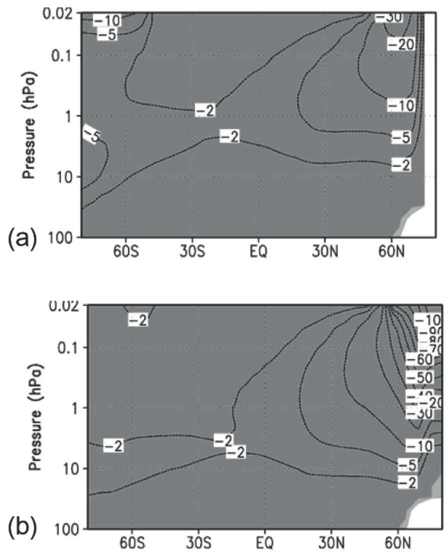

Fig. 7. Difference between solar max and min in January in a) NO [ppbv] and b) NO2 [ppbv] , calculated with FUB-CMAM-CHEM. Shadings denote regions with statistical significance higher than 95% and 99%.

effects in the lower stratosphere and upper troposphere. The energetic particles ionize the atmosphere and, as a consequence, modify atmospheric chemistry. They produce NO_x and HO_x which in the wintertime polar vortex may be transported by the Brewer–Dobson (BD)–circulation into the stratosphere (e.g., Randall et al., 1998), where it destroys O_3. The population density of the different particle types is dependent on the phase of the solar cycle: auroral electrons and solar protons maximize at solar max while relativistic electrons and galactic cosmic rays maximize near solar minimum. It therefore can be anticipated that energetic particles may have an impact on the solar signal in stratospheric ozone.

To investigate this hypothesis we performed a sensitivity study with our chemistry–climate model (CCM) version of the model (FUB-CMAM-CHEM) in which we included an interactive chemistry module and a tracer transport scheme. In addition, we implemented an idealized (over-estimated) NO_x source at high latitudes in the upper mesosphere to parameterize the effect of REP on chemistry. So in our simulation the solar ozone signal is calculated as the response to variations in UV irradiance and in atmospheric chemistry due to energetic particles. Further details are given in Langematz et al. (2005). Figure 5 shows the simulated zonal mean ozone response in January. Ozone decreases significantly during solar max in the upper mesosphere by about 4%. This is due to the enhanced photolysis of H_2O by the more intense irradiance in the Lyman-α line. H_2O decreases up to 0.3 ppmv in the upper mesosphere (Figure 6a) while the concentration of ozone destroying OH molecules increases by about 10^6 molecules/cm^3 (Figure 6b). Figure 5 shows further a significant ozone increase in the mesosphere and stratosphere of the winter hemisphere up to about 20%. This is directly related to a strong and significant decrease in NO (Figure 7a) and NO_2 (Figure 7b). As prescribed in our parameterization, NO_x is reduced during solar max when the concentration of relativistic electrons is smaller. These lower NO_x concentrations are then transported downward in the polar vortex by the BD circulation. Corresponding to the NO_x decrease ozone increases at mid to high latitudes in our simulation. The ozone increase extends to low latitudes in the middle stratosphere and reaches about 10%. This is partially due to meridional transport of the high polar ozone concentrations to lower latitudes as there exists a pronounced interannual variability in polar dynamics in the model. It may also partially be due to the increased solar UV irradiance in the middle stratosphere resulting from the more transparent mesosphere. The lower tropical stratosphere features a negative ozone signal in solar max. Langematz et al. (2005) showed that in the annual mean this feature is partially due to chemical changes during the solar cycle involving enhanced ozone destruction by chemical HO_x reactions. They may as well arise partially from a self-healing effect in which the enhanced ozone in the middle stratosphere absorbs more solar UV irradiance thus leading to a solar UV deficit and less ozone production below.

In summary, the solar signal in stratospheric ozone in our sensitivity simulation yields a stronger ozone signal than the above mentioned 2d–models and also than recent 3d–CCM solar studies which considered UV variations only (Tourpali et al., 2003; Egorova et al., 2004; Rozanov et al, 2004). In the vertical, the strongest signal occurs in the middle stratosphere, thus in agreement with other models and at lower altitudes compared to the observations. The negative signal in the lower stratosphere is unique to our simulation and can therefore be interpreted as a result of our enhanced particle induced NO_x source. However, it must be noted that the negative signal in our model is lower in the stratosphere than that found in the observational analyses (Lee and Smith, 2003; Hood, 2004). Further, our model did not include the important QBO–sun feedback which is assumed to impact the solar ozone signal in the equatorial stratosphere. Nevertheless, our simulation suggests that the effect of energetic particles on atmospheric chemistry leads to non negligible ozone changes. This is confirmed in a very recent CCM study by Rozanov et al. (2005). Further studies will be necessary to include the effects of the different types of energetic particles in a more sophisticated way than was possible so far.

5. Concluding Remarks

According to the current state of knowledge the transfer of the 11–year solar signal from the top of the atmosphere down to the earth's surface is achieved by a combination of radiative, dynamical, and chemical processes which act together in a complex way.

In the upper atmosphere radiative and chemical processes play the major role. Changes in electromagnetic radiation and energetic particle concentrations lead to strong signals in temperature and composition depending on the phase of the solar cycle. The maximum temperature response in the upper stratosphere is due radiative processes leading to differential heating and zonal wind anomalies. The downward transfer of the solar signal into the lower stratosphere and troposphere occurs via dynamical interactions between planetary waves and the zonal background circulation leading to a tropospheric response at mid and high latitudes. The associated changes in the BD circulation have a non-local effect on the thermal structure in the lower tropical stratosphere leading to significant solar signals in e.g. temperature, cloud cover, precipitation in the tropical troposphere. In addition, chemical effects due to changed UV and particle precipitation contribute to the solar signal from the mesosphere down to the lower stratosphere and troposphere.

It must however be noted that many questions concerning the impact of solar variability on the atmsophere are still open. E.g. the observed solar signal in stratospheric ozone can so far not be reproduced by models. The contribution of energetic particles to the solar signal is not yet well understood. Both, the representation of solar variations in state-of-the art CCMs as well the observational data base will have to be improved in the future to achieve a more reliable assessment of the solar signal on climate.

Acknowledgements. JLG was supported under the project MESA (01 LG 0001) funded by the German Ministry for Research and Education, and KM under the European project SOLICE (EVK2-2002-00543). The GCM simulations were performed at the Konrad-Zuse-Zentrum für Informationstechnik, Berlin.

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