Chemical and dynamical response to the 11-year variability of the solar irradiance simulated with a chemistry-climate model

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Received 16 December 2003; revised 13 February 2004; accepted 25 February 2004; published 24 March 2004.

[1] Atmospheric effects of the solar irradiance variations during 11-year solar cycle are investigated using a chemistry-climate model. The model is enhanced by a more detailed parameterization of the oxygen and ozone UV heating rates. The simulated ozone response to the imposed solar forcing shows a positive correlation in the tropical stratosphere and a negative correlation in the tropical mesosphere, in agreement with theoretical expectation. The model suggests an acceleration of the polar night jets in both hemispheres and a dipole structure in the temperature changes at high latitudes. The model results also show an alteration of the tropospheric circulation air resulting in a statistically significant warming of 1 K in the annual mean surface air temperature over North America and Siberia. This supports the idea of a solar-climate connection. *INDEX TERMS:* 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 1650 Global Change: Solar variability; 3210 Mathematical Geophysics: Modeling; 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342). **Citation:** Egorova, T., E. Rozanov, E. Manzini, M. Haberreiter, W. Schmutz, V. Zubov, and T. Peter (2004), Chemical and dynamical response to the 11-year variability of the solar irradiance simulated with a chemistry-climate model, *Geophys. Res. Lett.*, *31*, L06119, doi:10.1029/2003GL019294.

1. Introduction

[2] There are at least three properties of the sun which may contribute to climate change on Earth [*Reid*, 2000]: (1) total solar irradiance changes, (2) variations in the ultraviolet (UV) part of the solar spectrum, and (3) varying energetic electron and proton precipitation. This paper discusses the effect of the spectral solar irradiance variation with emphasis on changes in UV radiation during the 11-year solar cycle.

[3] Some of the previous attempts to simulate the effects of solar variability on the Earth's climate used 2D models [e.g., *Huang and Brasseur*, 1993]. In the meantime it has become clear that 2D models are not adequate to study solar-climate interactions, as they do not properly represent three-dimensional planetary scale waves. According to *Haigh* [1996] and *Kodera and Kuroda* [2002] this could play an important role in the propagation of the solar signal from the middle atmosphere to the troposphere. Other studies used Global Circulation Models [e.g., *Matthes et al.*, 2003], but with prescribed ozone or simplified chemistry. Fully interactive Chemistry-Climate Model (CCM) calculations have been performed using the UKMO and University of Tokyo models, analyzing the response of total ozone, global mean values of the ozone mixing ratio and temperature [*Labitzke et al.*, 2002]. The MAECHAM4/CHEM and UIUC CCMs have been used concentrating on an analysis of seasonal and monthly means of ozone, temperature and zonal wind [*Tourpali et al.*, 2003, *Rozanov et al.*, 2004]. However, the UIUC CCM does not include the mesosphere and, the treatment of solar heating in MAECHAM4/CHEM is too simplified to simulate a direct solar influence on the middle atmosphere. Here we evaluate the effects of the spectral solar flux variability on chemistry and dynamics from the mesopause to the Earth's surface using a newly developed CCM with more detailed parameterization of the heating rates. The main goals of this paper are to show how sensitive the solar signal is to the introduced model improvements and to evaluate the solar signal in the surface air temperature.

2. Model Description and Experimental Set-Up

[4] To study Sun-climate connections we have developed SOCOL, which couples the MAECHAM4 spectral GCM [*Manzini and McFarlane*, 1998; *Manzini et al.*, 1997] with a chemistry-transport model MEZON [*Egorova et al.*, 2003].

[5] MAECHAM4 is a spectral model with T30 horizontal truncation. In vertical direction the model extends from the surface to 0.01 hPa and has 39 levels. The time step for dynamics and physics is 15 min, and for radiation processes is 2 hours. The model applies the parameterization of gravity waves from *Manzini and McFarlane* [1998], which leads to realistic stratospheric temperature distributions.

[6] The chemical-transport part of the model simulates the atmospheric concentrations of the 41 chemical species, which are determined by 118 gas-phase, 33 photolysis and 16 heterogeneous reactions on/in sulfate aerosol (binary and ternary solutions) and polar stratospheric cloud particles. The chemical solver is based on the implicit iterative Newton-Raphson scheme. The transport of all considered species is calculated using the Hybrid numerical advection scheme. The photolysis rates are calculated 2-hourly with a look-up-

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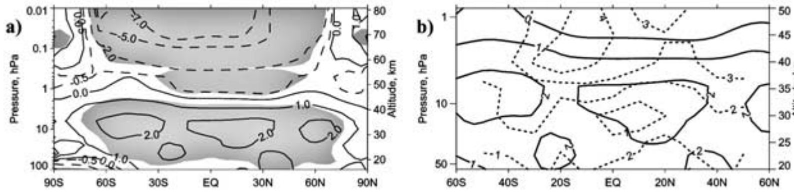

Figure 1. Annual mean zonal mean solar signal (%) in the ozone. (a) Simulated signal, (b) simulated (solid contours) and observed (dotted contours, SAGE I/II from [*SPARC*, 1998]) signals. The shading marks regions with statistically significant solar signal at the 95 % confidence level.

table approach taking into account the radiation in the spectral range between 120 and 700 nm. The MAECHAM4 radiation code has not been designed for solar variability studies: it has only one interval in the UV and visible parts of the solar spectrum and does not account at all for the spectral solar flux below 250 nm. Therefore we have parameterized heating rates, dT/dt (O_2, O_3), due to absorption in the UV by ozone and oxygen, σ^{abs}(O_2, O_3), in the Lyman-α line, Schumann-Runge band, Herzberg continuum and Hartley band, which are important in the stratosphere and mesosphere. This parameterization has been developed on the basis of the *Strobel* [1978] formalism with new coefficients calculated using the detailed radiation code of *Rozanov et al.* [2002].

[7] Using SOCOL we performed two 20-year long steady-state simulations for the present day distributions of sea surface temperature, sea ice, greenhouse gases and ozone destroying substances: one simulation for solar maximum and the other for solar minimum conditions, applying two solar UV spectral irradiance distributions obtained from satellite measurements [*Haberreiter et al.*, 2002]. Visible solar irradiance for the solar maximum case was increased by 0.16%. These solar fluxes have been used in SOCOL to calculate the radiation fluxes, and heating and photolysis rates. The statistical significance of the simulated solar signal is calculated using known T-Student test.

3. Ozone Response

[8] Figure 1 illustrates the simulated and observed annual mean changes in ozone mixing ratio between the solar maximum and solar minimum conditions. In the mesosphere ozone decreases due to intensified H_2O photolysis in the Lyman-α line and subsequent increase of HO_x. The simulated ozone signal by SOCOL is closer to the theoretical expectations [e.g., *Huang and Brasseur*, 1993] than MAECHAM/CHEM, which does not produce an ozone decrease in the mesosphere.

[9] Enhanced solar irradiance also yields a statistically significant ozone increase in the stratosphere, mainly because of an intensification of the oxygen photolysis in the Herzberg continuum. The obtained stratospheric ozone response is similar to other models [e.g., *Huang and Brasseur*, 1993; *Tourpali et al.*, 2003] and consists of an almost homogenous increase over middle and low latitudes, which maximizes around 35 km. Two maxima also appear in the lower stratosphere around 30°N and 30°S reflecting an alternation of the circulation.

[10] In the stratosphere our results still disagree with the ozone response obtained from the analysis of satellite data [*Hood*, 2003; *Stratospheric Processes and their Role in the Climate* (*SPARC*), 1998]. Figure 1b illustrates substantial disagreement in the tropical middle and mid-latitude upper stratosphere. It has been argued by *Lee and Smith* [2003] that the former is the result of problems with the isolation of the solar signal from the short observational records and this minimum would disappear if the QBO and volcanic effects are accounted for. We conclude that our results may therefore agree reasonably well with the observations below 38 km. However, more observational studies are needed to resolve this issue.

4. Stratospheric Temperature and Wind Response

[11] Figure 2a shows annual mean tropical temperature response simulated with and without the dT/dt(O_2, O_3) parameterization. Figure 2b compares the SOCOL results

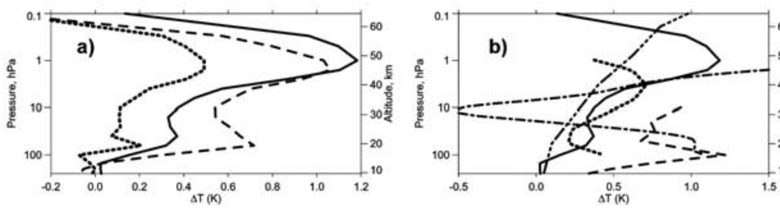

Figure 2. Annual mean difference in the tropical (23°S–23°N averaged) temperature (K) between solar maximum and solar minimum calculated with SOCOL: a) ensemble average including σ^{abs}(O_2, O_3) and dT/dt(O_2, O_3) parameterizations describing the UV absorption by ozone and oxygen (solid curve); a 1-year long run without UV absorption (dotted curve); the first year of the standard run (dashed line); b) the result from SOCOL (solid) in comparison with SSU/MSU (dotted) from *Hood and Soukharev* [2000], CPC reanalysis (dash-dot) from *Hood* [2003], NCEP reanalysis (dashed) from *Labitzke* [2002], and MAECHAM/CHEM simulations (dash-dot-dot) from *Tourpali et al.* [2003].

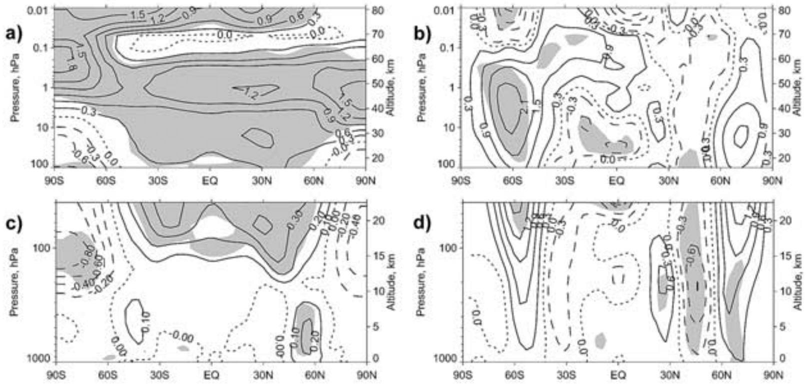

Figure 3. Annual mean zonal mean difference of solar maximum relative to solar minimum in temperature (in K, a and c) and zonal wind (in m/s, b and d). The shading marks regions with statistically significant solar signal at the 95% confidence level.

with three observational data sets as well as with the results of MAECHAM/CHEM. Clearly there is considerable scatter in the data. Notwithstanding the data scatter, SOCOL gives a reasonable description of the stratospheric and mesospheric temperature response. The solar signal in the temperature calculated by SOCOL is more pronounced than that obtained by MAECHAM/CHEM, because *Tourpali et al.* [2003] used the original MAECHAM4 radiation code without special attention to $\sigma^{abs}(O_2, O_3)$ (see Section 2). Given that the stratospheric ozone distributions in the two coupled chemistry climate models are similar, this comparison suggests that the primary temperature changes are caused by the direct radiation heating. To confirm this we have performed an additional 1-year long run for the solar maximum conditions with the $\sigma^{abs}(O_2, O_3)$ parameterization switched off. Figure 2a depicts the temperature response for this short run together with the results from the first year of the standard run and ensemble mean. The results indicate that the model without $\sigma^{abs}(O_2, O_3)$ tends to underestimate the temperature response.

[12] Figure 3 depicts the simulated solar signal in the annual mean zonal mean temperature and zonal wind in the stratosphere. For the temperature we obtained statistically significant warming in most of the stratosphere by up to 1.2 K at the stratopause in the tropics, and more than 1.5 K in the high-latitude upper stratosphere. In comparison with the analysis of temperature observations by SSU/MSU4 [*Hood and Soukharev*, 2000], the simulated signal is located ~10 km higher and is ~30% larger. However, the observational basis is not strong, and in comparison with other data (e.g., NCEP and CPC data) the model underestimates strength of the signal in the lower stratosphere. In the mesosphere the solar signal in temperature is positive and reaches up to 1.5 K over the southern high latitudes and in the tropics.

[13] A pronounced simulated dipole vertical structure develops over the poles in the temperature field, which is associated with an acceleration of the Polar Night Jet (PNJ) by up to 2 m/s in the Southern Hemisphere (SH) and 1.5 m/s in Northern Hemisphere (NH), see Figure 3b. This effect is statistically significant in the SH, where the model noise is lower than in the NH. The results also show a statistically significant strengthening of the easterly winds in the SH tropics and in the NH extra-tropics (between 30° and 60°N). This supports a study of *Haigh* [1996], who argued that an increase in stratospheric temperatures during solar maximum conditions leads to a strengthening of easterly winds, which penetrate into the tropical upper troposphere.

5. Tropospheric Temperature and Wind Response

[14] The analyses of the solar signal in the troposphere suggest the existence of an 11-year period oscillation during the last eight decades. *Van Loon and Shea* [1999] estimated the magnitude of the solar signal in the zonally averaged temperature in the layer 750–200 hPa to be 0.15–0.2 K for the NH, and according to *Gleisner and Thejll* [2003] there is a maximum of the solar signal of 0.45 K around 250 hPa at mid-latitudes. *Haigh* [1996, 1999] also showed changes in the troposphere due to solar variability and explained them by a shift of the Hadley circulation.

[15] Figures 3c and 3d suggest that changes in solar fluxes via the reported changes in the stratosphere lead to statistically significant changes in the simulated tropospheric temperature and zonal wind. In the northern lower troposphere the magnitude of the temperature response from solar maximum to solar minimum exceeds 0.2 K. The zonal mean zonal wind variations reveal a banded structure with easterly and westerly anomalies, in accordance with *Haigh* [1999]. In contrast to the NH stratosphere (Figure 3b) the signal is statistically significant in the NH troposphere (Figure 3d).

[16] Figure 4 presents the simulated solar signal in the surface air temperature. Our results reveal a statistically significant warming of the annual mean surface air by up to 1 K over North America and 1.2 K over Siberia. The pattern in Figure 4 resembles surface temperature changes during positive AO phases [*Thompson and Wallace*, 1998], which implies downward propagation of the solar signal via intensification of the PNJ.

6. Conclusions

[17] We evaluated the solar signal in the atmosphere with a new chemistry-climate model SOCOL, which utilizes a parameterization of the primary solar forcing taking proper account of the heating rates due to oxygen and ozone absorption in the middle atmosphere. Our results reveal that a correct representation of the direct heating rate is an

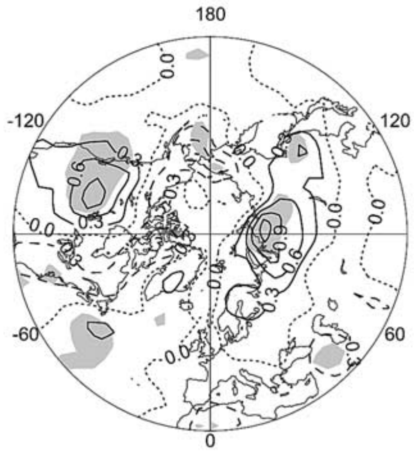

Figure 4. Annual mean solar signal in surface air temperature for the Northern Hemisphere.

essential prerequisite for the simulation of the solar signal in the stratosphere. The simulation suggests more pronounced solar signal in the stratospheric temperature fields compared to previous work implying the necessity of the MAECHAM4/5 radiation code improvement.

[18] In the stratosphere below 38 km the simulated ozone response is in a reasonable agreement with observations, however in the upper stratosphere it is underestimated. A small ozone response in the upper stratosphere is theoretically expected, therefore probably some physical-chemical processes are still missing or the data analysis is not complete. We obtain an acceleration of the PNJ during solar maximum presumably due to an increase in the meridional temperature gradient. The intensification of the polar vortices leads to the formation of vertical dipole structures in the annual mean zonal mean temperature response over both poles, deceleration of the meridional circulation and warming in the lower tropical stratosphere. This warming is in agreement with SSU/MSU4 data, but it is substantially underestimated in comparison with NCEP and CPC data sets. The introduction of the solar flux variations into the model leads to a statistically significant signal in the annual mean surface air temperature of up to 1.2 K over North America and Siberia. This pattern is typical for the positive phase of arctic oscillation and suggests an enhanced stratosphere-troposphere coupling including downward propagation of the UV-triggered signal. Thus, while the simulated solar signals in the stratosphere are in accordance with theoretical expectations a solid validation of the SOCOL results is difficult because of a considerable disagreement between the existing observational analyses.

[19] Further investigation of this solar-climate link and proper attribution of the underlying physical mechanisms are required, including overcoming the steady-state assumption (implying perpetual solar maximum or/and solar minimum conditions), because the solar signal is transient by nature.

[20] **Acknowledgments.** This work is supported by the Swiss Federal Institute of Technology, Zürich. The work was partially supported by INTAS (grant INTAS-01-0432) and Russian Fund of Fundamental Researches (grant N65-399). We thank L. Hood, K. Labitzke and R. van Dorland for providing their results, C. Hoyle for editing the manuscript and two reviewers for their helpful comments.

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