Stratospheric and tropospheric response to enhanced solar UV radiation: A model study

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[1] The atmospheric response to the 11-year solar cycle is studied using a fully interactive 3-D coupled chemistry-general circulation model with a complete seasonal cycle. The stratosphere-troposphere system shows partly significant response to a realistic solar cycle enhancement of UV radiation. This response consists of increases in stratospheric ozone and temperature, giving rise to changes in the zonal wind from the stratosphere into the troposphere. Computed changes of stratospheric ozone, temperature, zonal wind and geopotential heights are generally in agreement with observed changes between solar minimum and solar maximum. Observed pattern changes of the stratospheric response between early and late winter are approximately reproduced by the model. Our radiative forcing results show that the 11-year solar cycle effect on global mean temperature is negligible, but simulated responses of sea level pressure do suggest that regional effects are probably significant, e.g. by affecting the North Atlantic Oscillation. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 1650 Global Change: Solar variability. **Citation:** Tourpali, K., C. J. E. Schuurmans, R. van Dorland, B. Steil, and C. Brühl, Stratospheric and tropospheric response to enhanced solar UV radiation: A model study, *Geophys. Res. Lett.*, *30*(5), 1231, doi:10.1029/2002GL016650, 2003.

1. Introduction

[2] About ten years ago a discussion started on the attribution of the observed global warming to various natural and anthropogenic factors, among which solar activity as an external, natural climate factor on the atmospheric circulation. Various sources of possible solar activity influence were considered. A comprehensive, unbiased review of the situation around the mid-nineties is given by *Reid* [1999]. *Haigh* [1996] in a modeling study found that significant changes in the structure and state of the lower atmosphere resulted from realistic solar cycle variation of UV and ozone. This study, as well as *Shindell et al.* [1999], and *Haigh* [1999] combined with earlier observational studies [e.g., *Labitzke and Van Loon*, 1995], indicate the possibility of an indirect dynamical response of the lower atmosphere to the radiative forcing of the upper atmosphere. However, a complete mechanism for the influence of solar irradiance changes on atmospheric circulation is still missing. In our model experiment we use realistic variations in solar UV and total solar irradiance, as external forcing to a fully interactive 3-D coupled chemistry-general circulation model, thus avoiding the introduction of observed or prescribed solar cycle ozone changes, as fully interactive model ozone changes are more consistent with concurrent changes in radiation and transport than in a model using prescribed ozone changes. The main aim is to study the nature and extent of the tropospheric response to variable UV radiation and the magnitude and role played by the radiative forcing in causing the response.

2. Model and Experiment Procedure

[3] The model used here is the MAECHAM4/CHEM, where MAECHAM4 is a spectral GCM extending from surface to about 80 km, [*Manzini and McFarlane*, 1998] for the thermodynamics and physics of the atmosphere and CHEM the chemical model for the evolution of chemical species with heterogeneous chemistry [*Steil et al.*, 1998, 2003]. The chemical and radiative relevant species (e.g. H_2O, O_3, NO_x, Cl_x) are typically within 10–20% compared to satellite observations [*Steil et al.*, 2003]. This holds also for chemical ozone budgets. To study the effects of solar UV and total solar irradiance variability on the stratosphere-troposphere system, two separate 20-year runs of the model were performed, one representing maximum solar activity in the 11-year solar cycle, and the other solar minimum. The sea surface temperature is prescribed and held constant, except for its seasonal variation. The solar fluxes in both runs are based on observed data given by *Lean et al.* [1997], introduced at the appropriate wave length bands in the model's radiation scheme as well as in the photolysis rate calculations (for details see *Tourpali et al.* [2000]). As the model does not simulate the Quasi-Biennial Oscillation, this issue is not addressed here.

3. Results and Discussion

[4] In the stratosphere, our model results are in reasonable agreement with observed solar effects. Here we present results only for ozone, temperature and zonal winds, as

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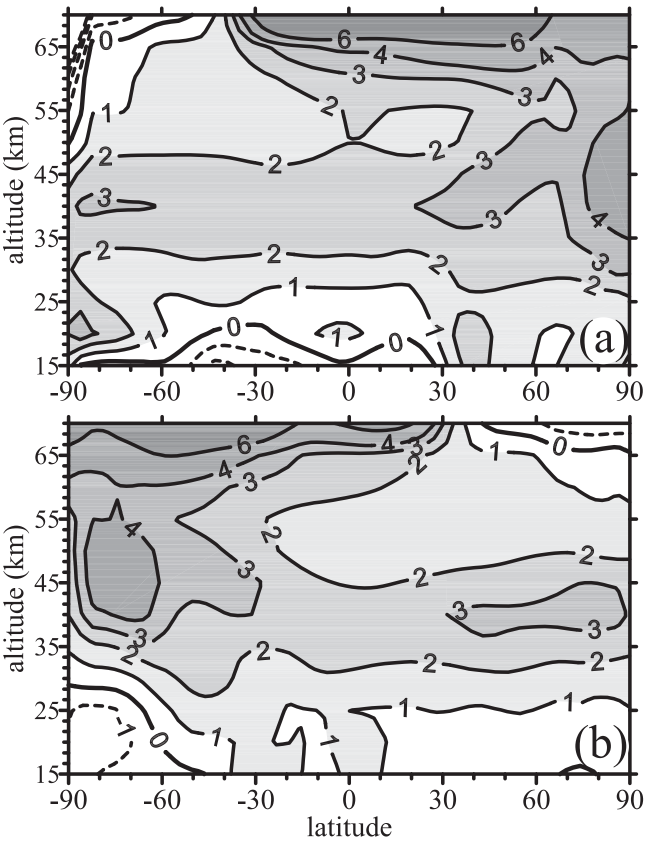

Figure 1. Mean difference of modeled ozone change (in %) for solar maximum relative to solar minimum for (a) northern winter (DJF) and (b) northern summer (JJA).

differences from solar maximum to solar minimum, and t-test analysis is used to calculate the statistical significance. Figure 1 shows the simulated changes in the northern winter (DJF) and northern summer (JJA) mean ozone content (in %). Positive changes of 2–4% dominate, which is in overall qualitative and quantitative agreement with observed [*Stratospheric Processes and Their Role in Climate* (*SPARC*), 1999] and 2D computed [e.g., *Haigh*, 1994] changes in stratospheric ozone from solar minimum and solar maximum. At higher altitudes, negative changes dominate at the respective summer (sunlit) hemispheres. Through radiative processes and stratospheric dynamics the ozone changes are consistently related to changes in stratospheric temperature shown in Figures 2a and 2b (northern winter (DJF) and northern summer (JJA)). At solar maximum the stratosphere is generally warmer than at solar minimum by about 0.5 to 1°K. This is in quantitative agreement with observed changes [*World Meteorological Organisation* (*WMO*), 1999], but in our case the warming is less confined to a layer of maximum response around 40 km. In the lower stratosphere up to 30 km the warming is somewhat lower than in *Zerefos et al.* [2001] derived from observations, for northern summer. At high southern latitudes in southern winter we find a marked cooling (0.3 to 1°K), present also in the individual months (June, July and August). This is not the case for the northern winter. The individual months December, January and February show a general warming of the stratosphere, similar to the seasonal mean (Figure 2a), but at high northern latitudes the responses change from a strong cooling in December to an even stronger warming in February (January showing a nearly zero response at these high northern latitudes). This change of response from December to February reverses the anomalous temperature gradient in the stratosphere from strongly positive to strongly negative, which in terms of the zonal wind anomaly means a positive change of 5–10 m/s at stratopause height in December to an equally large negative change in February. (Figures 3a and 3b). The shading, as well as in Figure 2, denotes statistically significant changes above 95%, but the large stratospheric changes in both months are significant at the 90% level. This result of the model for December and February reproduces reasonably well the observed anomalies attributed to solar activity [*Kodera*, 1995]. The magnitude of the changes is underestimated by up to a factor of 3, nevertheless this result is encouraging for equilibrium simulation. The same behavior was noted by *Shindell et al.* [1999, 2001] in their study of UV-influences on the stratosphere-troposphere system. Finally, our calculated changes for the geopotential heights are in qualitative agreement with observations [*Labitzke et al.*, 2002], but smaller in amplitude.

[5] Focusing on the troposphere (Figures 4a and 4b), the tropics show a decrease of the westerlies (increase of easterlies) at solar maximum, in January as well in July. Moving poleward we see an increase of the westerlies, followed again by a decrease at higher latitudes and so on. This banded structure of the tropospheric response was

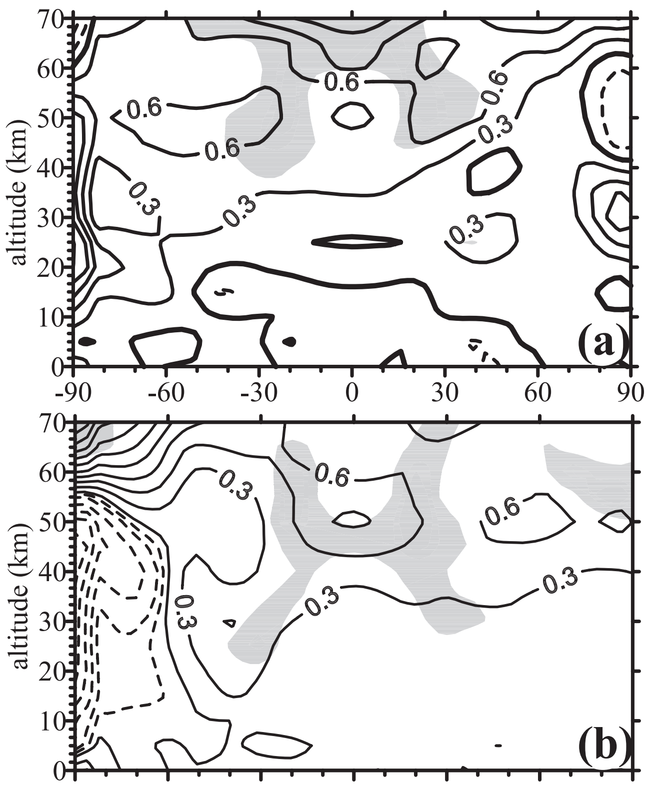

Figure 2. As in Figure 1, but for temperature differences (Kelvin). Shading indicates the 95% significance level.

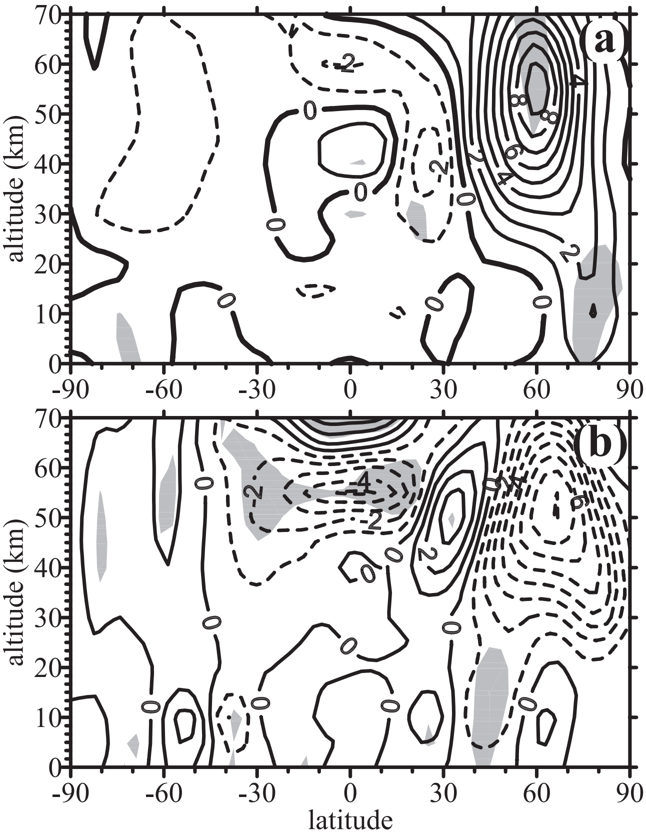

Figure 3. Zonal wind differences (m/sec) for solar maximum relative to solar minimum for (a) December and (b) February. Shading indicates the 95% significance level.

found also in the studies by *Haigh* [1996, 1999]. In fact, the results for individual months show that this banded structure moves more or less north and southward with the sun. For all months we find certain latitude-height positions where the zonal mean changes are statistically significant at the 95% level. This indicates that the solar effect is most probably real and its magnitude is sufficiently large to exceed the natural variability over 20 years. For the northern hemisphere mid latitudes, this

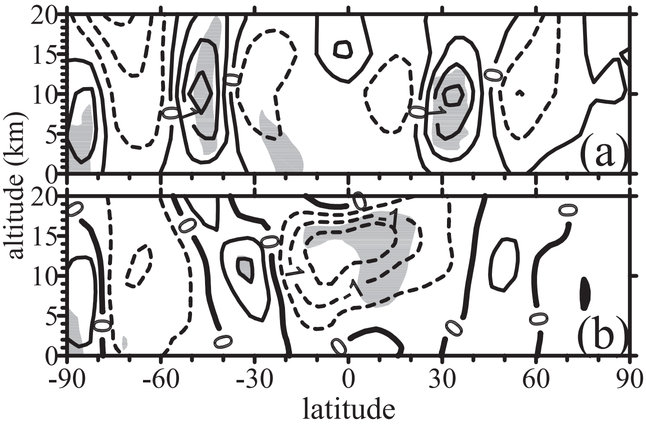

Figure 4. Tropospheric zonal wind differences (m/sec) for solar maximum relative to solar minimum for (a) January and (b) July. Shading indicates the 95% significance level.

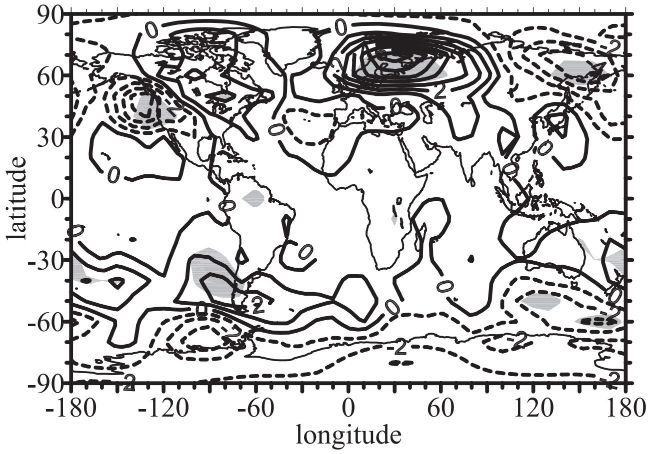

Figure 5. Mean sea level pressure change (hPa) from solar minimum to solar maximum in January. Shading indicates the 95% significance level.

alternating pattern means that there appears a decrease of the zonal mean westerlies in winter and an increase in summer. For the southern hemisphere we find larger response in January (Figure 4a) than in July (Figure 4b). From Figure 5, which shows the computed changes of mean sea level pressure for January, we infer that the idea of regional climate responses to solar activity is not completely unrealistic. What we see in Figure 5 is that the pressure gradient over the North Atlantic is decreased, which would mean a lowering of the NAO (North Atlantic Oscillation) index. According to *Hurrell and van Loon* [1997] this would favor lower temperatures in Western Europe. This is clearly in line with the decrease of January and winter mean temperature in the lower layers of the atmosphere at mid-high latitudes of the northern hemisphere. The above results are also in line with recent work by *Kodera* [2002] on the NAO modulation by the solar cycle. The lower SLP in the polar southern hemisphere occurs in each month in the season (marginally significant in the zonal mean). As the sea surface temperature is kept constant in our model runs, except for the seasonal cycle, we cannot draw firm conclusions regarding the pressure and temperature changes near the surface.

[6] Considering the above, we may conclude that realistic changes of the solar UV radiation influence the stratosphere-troposphere system in a significant way. The pattern of the tropospheric response shows an increase of the tropical easterlies in all seasons, as well as significant changes of the zonal mean westerlies at the temperate latitudes, especially in northern winter. These circulation changes will give rise to regional changes of weather and climate, although the precise nature and sign of these changes have to be further investigated. However, the results of our experiment certainly add to the credibility of the recent claim by *Baldwin and Dunkerton* [2001] that stratospheric processes may act as a precursor of anomalous weather regimes.

[7] In our experiment global mean temperature is not much affected by the UV changes in the 11-year solar cycle. This conclusion is consistent with observational studies, showing a clear lack of an 11-year cycle in global mean temperature [e.g., *Van Ulden and van Dorland*, 2000].

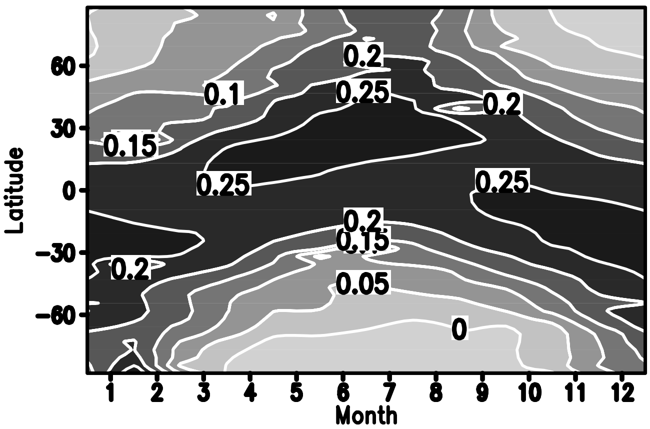

Figure 6. Latitude–month plot of the zonal mean total radiative forcing in Wm^{-2} due to ozone changes and total solar irradiance increase from solar minimum to solar maximum.

[8] Finally, regarding the possible mechanisms involved in the response of the stratosphere-troposphere to radiative conditions at solar maximum we may point out the following: Enhanced UV and partly also the enhanced radiation in the visible part of the spectrum are absorbed in the stratosphere. This results in changes of ozone and temperature, which in turn will give rise to changes of the radiative forcing of the troposphere. This radiative forcing derived from our results for all months and latitudes (Figure 6), is quite small and probably too small to cause the calculated tropospheric effects. Note that it is mainly the short wave solar radiation part of solar irradiance changes that determines the radiative forcing, only slightly modified by the radiative effects of enhanced ozone. The calculated global average radiative forcing is only 0.18 W/m2, much smaller than the calculations of *Haigh* [1999] due to the fact that we find considerable ozone increases in the upper stratosphere tending to a negative radiative forcing.

[9] How do the UV induced changes of the stratosphere affect the troposphere, if radiative forcing is not the cause? A fruitful approach is perhaps by analyzing vertical wave propagation, as suggested in a number of other studies [*Perlwitz and Graf*, 2001; *Kodera*, 1995]. Analysis of the wave structure and amplitudes of our response patterns has shown that at solar maximum in the troposphere wave number 1 is favored at the cost of wave numbers 2 and 3. In the upper stratosphere wave number 1 appears to be the dominant wave component under solar maximum as well as under solar minimum conditions, although in our experiment it appears to be weaker at solar maximum. Although the precise nature and cause of the correspondence between the weakening of wave number 1 in the high stratosphere and its strengthening in the lower troposphere (in summer as well as in winter) is still unclear, it suggests that it could be the result of the Dines' compensation rule. At mid-latitudes, a cold troposphere is associated with a warm stratosphere above it, and oppositely, not only for individual pressure systems, but also for seasonal mean circulations [*Liu and Schuurmans*, 1990].

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