Solar cycle modulation of the Arctic Oscillation in a chemistry-climate model

K. Tourpali,[1] C. J. E. Schuurmans,[2] R. van Dorland,[3] B. Steil,[4] C. Brühl,[4] and E. Manzini[5]

Received 14 May 2005; revised 27 July 2005; accepted 29 July 2005; published 3 September 2005.

[1] The structural modulation of the Arctic Oscillation (AO) induced by a realistic enhancement of the ultraviolet (UV) radiation associated with the 11-year solar cycle is investigated with a coupled Chemistry-Climate Model. It has been found that the main features of the modulation are an eastward shift of the surface Atlantic center of action into Europe and a vertical extension into the stratosphere in solar maximum conditions. These model results are in good agreement with observational results in the North Atlantic Oscillation (NAO) centers of action. Confirmation of the modulation effect of solar activity on the NAO spatial structure by a Chemistry-Climate Model simulation gives support to the occurrence of a real solar effect on the tropospheric circulation. **Citation:** Tourpali, K., C. J. E. Schuurmans, R. van Dorland, B. Steil, C. Brühl, and E. Manzini (2005), Solar cycle modulation of the Arctic Oscillation in a chemistry-climate model, *Geophys. Res. Lett.*, *32*, L17803, doi:10.1029/2005GL023509.

1. Introduction

[2] In two consecutive papers *Kodera* [2002, 2003] (hereafter K02 and K03), followed by *Kodera and Kuroda* [2005] (hereafter KK05), convincingly showed that the structure of the North Atlantic Oscillation (NAO) in winter is different if the data are stratified with respect to years of high or low solar activity. For high solar activity years the NAO signal covers a larger part of the Northern Hemisphere in general and extends from the North Atlantic into the Eurasian continent. In low solar activity years the NAO has the classical dipole shape, restricted to the North Atlantic Ocean. These results are based upon sea level pressure data for the Northern Hemisphere since 1900. For the shorter period with available upper air observations, K02 showed in addition that the vertical extension of the NAO signal differs between high and low solar activity years. A number of papers followed, based on observations, in which the relationship and the seasonal links between solar activity and NAO (or the Northern Annular Mode) were examined [*Ogi et al.*, 2003; *Ruzmaikin et al.*, 2004; *Pozo-Vazquez et al.*, 2004].

[3] In this paper we compare the atmospheric climate of two 20- year simulations for high and low solar activity conditions. The simulations are performed with a Chemistry-Climate Model (CCM). Solar activity is characterized by an increase in the solar constant and in the ultraviolet (UV) flux from minimum to maximum, corresponding to the observed changes in the 11- year solar cycle. The CCM's response is overall in good agreement with observed changes between solar minimum and solar maximum [*Tourpali et al.*, 2003]. Mean sea level pressure changes presented by *Tourpali et al.* [2003] revealed differences in the pressure field over the northern hemisphere during the northern winter months, and in particular a decrease of the pressure gradient over the North Atlantic for high solar activity conditions. In order to assess the causes of this feature, we focus here on the analysis of northern winter mean sea level pressure and geopotential height variations along with related changes in zonal-mean zonal winds and temperatures on a hemispheric scale by means of Empirical Orthogonal Function (EOF) analysis. Given the constraints of hemispheric EOF analysis [e.g., discussion in K02], this paper explores the modulation of the northern hemisphere leading mode of variability, namely the Arctic Oscillation (AO) in response to solar-UV variations.

2. Data

[4] The data used are model results from two 20- year runs of the Middle Atmosphere European Centre/Hamburg Model 4 with Chemistry (MA-ECHAM4-CHEM) [*Steil et al.*, 2003], a coupled spectral CCM with the top at 0.01 hPa and T30 horizontal truncation, for high and low 11-year solar cycle conditions, as described by *Tourpali et al.* [2003]. The sea surface temperature is seasonal climatological mean and the model does not simulate the Quasi Biennial Oscillation (QBO).

[5] We use model results of mean sea level pressure, geopotential heights, zonal-mean zonal winds and zonal-mean temperatures, as winter averages of the months December–January–February over the northern hemisphere. We have examined the leading EOFs of the northern hemisphere (20°–90°N) mean sea level pressure (MSLP), and geopotential height fields at 1000, 500, 200, 50, 30, 10, 5 and 1 hPa. This analysis was done for each level separately.

[6] As the methodology used here follows the one used to describe and demonstrate the Arctic Oscillation [*Thompson and Wallace*, 1998], we define as AO-index the normalized leading principal component (PC) of the 1000 hPa geopotential height. Results are presented as winter mean fields regressed on this normalized AO-index (the normalized leading PC of 1000 hPa geopotential height and that of the MSLP are virtually identical). Thus the regression maps have the same units as the anomaly field, and correspond to

[1]Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece.
[2]Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, Netherlands.
[3]Royal Netherlands Meteorological Institute, De Bilt, Netherlands.
[4]Max- Planck Institute for Chemistry, Mainz, Germany.
[5]National Institute for Geophysics and Volcanology, Bologna, Italy.

0094-8276/05/2005GL023509

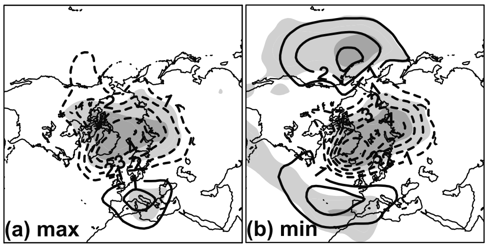

Figure 1. Northern winter (DJF) mean sea level pressure regressed on the normalized Arctic Oscillation (AO)-index (see text) for (a) solar maximum and (b) solar minimum. Contours every 1 hPa, negative contours are dashed. Light shading indicates significance above 98% and darker above 99.9%

anomalies per one standard deviation of fluctuation in the AO-index.

3. Results and Discussion

[7] Figures 1a and 1b show the regression maps for the northern winter MSLP, for solar maximum and solar minimum conditions. The resulting pattern in both cases is similar over the polar areas, but rather different over the mid- to high latitudes. In the case of low solar activity the spatial feature of the NAO pattern in the Atlantic is manifested. In addition, a well marked positive center of action is present in the Pacific, so that the classical image of AO is displayed, as expected by the application of EOF analysis on a hemispheric scale. In solar maximum years, though, there is an eastward shift of the Atlantic positive center into Europe, while the feature over North Pacific vanishes, limiting the seesaw pattern between the Arctic and the North Atlantic/European section. The variance explained by the 1st EOF for the solar maximum and solar minimum cases is 30.3% and 37.1% respectively. Light shading in the figure indicates significant correlations between the AO-index and the anomaly field at levels larger than 98% (correlation coefficient -hereafter ccf- ±0.5), darker shading larger than 99.9% (±0.7). The variance explained by the AO-index variations in the significant regions ranges from 25% up to about 80% (the lowest value of ccf is −0.94 in both cases).

[8] This difference in the spatial structure in the North Atlantic region (the NAO structure) between solar maximum and solar minimum years (i.e. the eastward shift of the steepest gradient into the direction NW- SE) and the lack of the Pacific feature is also evident in the geopotential height analysis throughout the troposphere in the levels we have examined, displaying the same characteristic features. The same spatial structure differences arise also if the index is derived by EOF analysis restricted to the North Atlantic region between 20°–90°N and 60°W–30°E (the amplitudes are slightly different).

[9] In the stratosphere, there are marked differences, not so much in the spatial structure, which in both cases is a manifestation of the polar vortex, but rather in the intensity of the signal in the polar regions. Results for the 50 hPa level (Figure 2) show a difference in the amplitude of the response up to about 30%. Shading indicates significant correlations, and the variance explained by the AO-index fluctuation reaches up to 77% (lowest ccf −0.88 for solar max) and 55% (lowest ccf −0.74 for solar min). Although the results are presented as regression maps of the fields on the AO-index (calculated from 1000 hPa PC1), the individual 1st EOF patterns at all levels display the same features.

[10] At all levels from the troposphere through the stratosphere the differences between the solar max and solar min cases, in the spatial structure as well as in amplitude are highly statistically significant (>95% confidence level), as deduced by a t-test of differences between the amplitudes (regression coefficients and their respective errors).

[11] To examine the vertical extension of the leading mode of variability at solar maximum and solar minimum years we have computed the correlation of the winter average zonal-mean zonal wind and zonal-mean temperatures with the AO-index. A very good agreement of the results with K02 is found (Figure 3). During solar maximum years, zonal-mean zonal winds show high correlation at mid- latitudes, extending from the surface to upper stratosphere and through the mesosphere. This feature is not present during solar minimum years. Zonal-mean temperatures show high correlations in the solar maximum years,

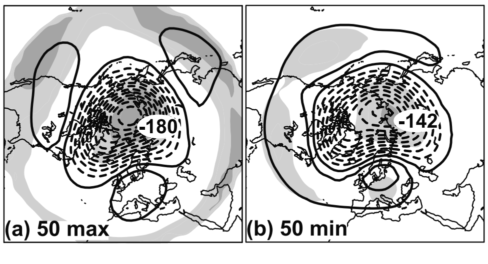

Figure 2. (a and b) Same as Figure 1 for 50 hPa geopotential height (contours every 15m). Lowest values indicated.

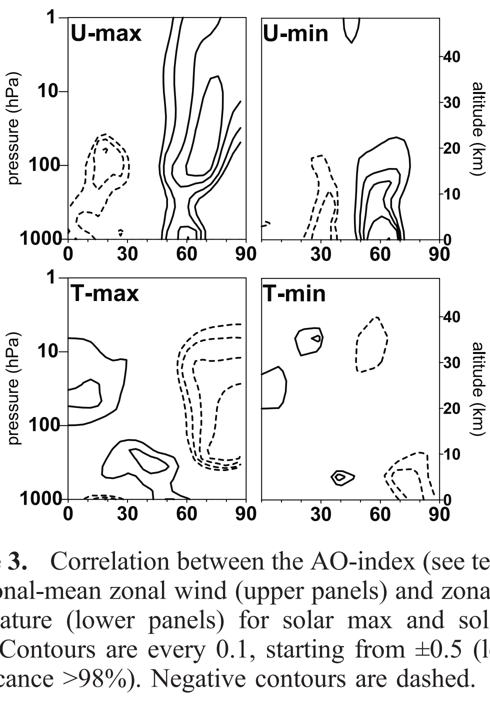

Figure 3. Correlation between the AO-index (see text) and DJF zonal-mean zonal wind (upper panels) and zonal-mean temperature (lower panels) for solar max and solar min years. Contours are every 0.1, starting from ±0.5 (level of significance >98%). Negative contours are dashed.

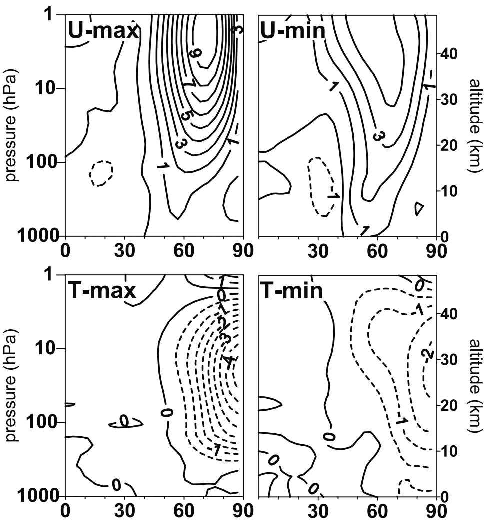

Figure 4. Same as Figure 3, except regression between the AO-index and zonal-mean zonal wind (upper) and temperature (lower). Contours every 1 m/s (wind) and 0.5°K (temperature), corresponding to a one standard deviation anomaly in the AO index.

while in solar min they are restricted to the lower troposphere.

[12] Figure 4 presents the regression of the AO-index with zonal-mean zonal wind (top panel) and zonal-mean temperatures (bottom). The anomalies correspond to a one standard deviation anomaly in the AO-index. The zonal-mean zonal wind anomaly is around 10 m/s in the upper stratosphere, centered between 60°–70°N in the solar maximum case, but drops to 5 m/s in the solar minimum case. Zonal-mean temperatures display a large anomaly in the polar region from the upper troposphere to the stratosphere. The temperature anomaly is almost twice as large in magnitude in the solar max case. Ozone anomalies (not shown) correspond very closely to the temperature anomalies. The lowest ozone concentrations are found in the polar region, significantly correlated to the AO-index from the upper stratosphere to the tropopause in the solar max case. The lowest absolute change is around −0.25 ppmv in the upper stratosphere, corresponding to a −4% change relative to the winter (DJF) average. Negative ozone anomalies found in the upper stratosphere for the solar min case (half in magnitude than for solar max) are not significant. The high solar activity simulation is characterized by an enhanced radiative flux of solar UV-radiation. This is affecting first and primarily the ozone concentration, with the largest effect in the upper stratosphere, and subsequently temperature, winds and stratospheric dynamics [*Tourpali et al.*, 2003]. Enhanced ozone concentration and the interactive feedback on the radiative heating in the CCM therefore play a crucial role in the simulation of the 11-year solar cycle.

[13] The increase in zonal-mean zonal wind and the lower temperatures (Figure 4), in combination to the lower geopotential heights found in the stratosphere (Figure 2) during solar maxima than during solar minima indicate that for a positive AO-index, the vortex becomes stronger during solar max than solar min, and vise-versa (i.e. weaker in solar max for a negative AO-index).

[14] In order to examine the time evolution of the solar signal, we first examined the response of the individual winter months (December, January and February) by performing separate 1st EOF analysis of 1000 hPa geopotential height for each month. It was found that the features described above for the whole winter can be mainly attributed to January and February, and are not as clear in December. In particular, January patterns display almost the same features as the winter average (DJF), both in the solar max and the solar min cases. Therefore we have chosen the normalized leading PC for January (hereafter J-index, ccf. to the AO-index: 0.89 for solar max and 0.82 for solar min) to perform a lagged regression analysis between this index and the individual months from November through April.

[15] Results are presented in Figure 5, for the solar max case (top row) and the solar min (bottom row). The anomalies correspond to a one standard deviation anomaly in the J- index, and the shading indicates significance above 95%. In the solar max case, a positive anomaly appears in the upper stratospheric mid to high latitudes in December

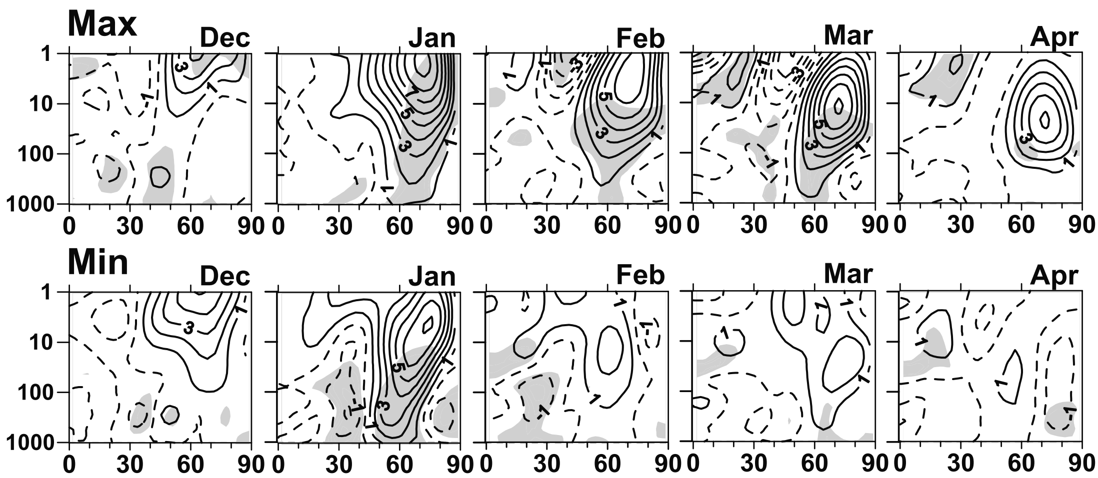

Figure 5. Lagged regression between the J-index (see text) and the zonal-mean zonal wind for solar max (upper row) and solar min (lower row) from December through April. Shading indicates significant correlation (>95%). Contours every 1m/s corresponding to a one standard deviation of the J-index, and negative values are dashed.

(its center located higher up, in the lower mesosphere), it becomes larger reaching down to the surface in January and continues through March with the center moving downwards, significantly correlated to the J-index. This anomaly persists also in April when the center has moved lower (not significant). Calculations performed through July did not reveal related anomalies. In the solar min case we again see positive anomalies starting in December and progressing into January, significant only at lower levels, but the signal becomes less significant or even vanishes in February and March. In both cases, November (not shown) does not show any particular response.

4. Summary and Conclusions

[16] The results presented here indicate that the MA-ECHAM4/CHEM model, forced with enhanced UV, simulates a modulation of the AO-pattern, with the largest tropospheric spatial differences found in the North Atlantic region, in accordance to the one derived from observations by K02, K03 and KK05. The main features of the modulation are: (a) an eastward extension into Europe and (b) a vertical extension into the stratosphere in the solar maximum years. The main difference is that while these studies suggest a zonal character of the NAO in solar maxima, in our case the lower tropospheric pattern is stronger in the North Atlantic-European section. It should be pointed here that in our model simulation the only difference of forcing was the UV-flux difference associated to 11-year solar cycle changes. Therefore, the possible influence of the QBO, El Nino/Southern Oscillation, or volcanic eruptions could explain part of the differences with observation results.

[17] *Tourpali et al.* [2003] and a number of similar studies [*Haigh*, 1996; *Shindell et al.*, 1999] have revealed systematic changes of the tropospheric circulation in response to enhanced solar UV. As discussed in KK05, planetary waves most probably play a crucial role in the downward propagation of stratospheric anomalies. A recent review is presented by *Baldwin and Dunkerton* [2005].

[18] The present analysis indicates that a solar influence on the surface, in this case the spatial modulation of the NAO pattern in northern winter, may become apparent because of the stratospheric extension of the anomaly in solar maximum conditions. One of the implications of the modulation of the spatial structure of the NAO (i.e. the displacement of the strongest gradient from the central North Atlantic to the Greenland-Mediterranean axis at solar maximum years) is a tendency for the classical NAO index, derived from normalized station pressure differences [e.g., *Hurrell et al.*, 2003], to take lower values at high solar activity. The 11-year solar cycle is therefore a factor that needs to be taken into account in the determination of variations (and trends) in the North Atlantic Oscillation Index that occurred during the last decades.

[19] **Acknowledgments.** We thank the anonymous reviewers for their helpful comments and suggestions that helped us to improve the manuscript. K. Tourpali, C. J. E. Schuurmans and R. van Dorland are grateful to the Netherlands Research Program on Global Air Pollution and Climate Change for supporting this study. K. Tourpali thanks A. Bartzokas for useful discussions on the methodology.

References

Baldwin, M. P., and T. J. Dunkerton (2005), The solar cycle and stratosphere-troposphere dynamical coupling, *J. Atmos. Sol. Terr. Phys.*, *67*, 71–82.

Haigh, J. D. (1996), The impact of solar activity on climate, *Science*, *272*, 981–984.

Hurrell, J. W., Y. Kushnir, M. Visbeck, and G. Ottersen (2003), An overview of the North Atlantic Oscillation, in *The North Atlantic Oscillation: Climate Significance and Environmental Impact*, *Geophys. Monogr. Ser.*, vol. 134, edited by J. W. Hurrell et al., pp. 1–35, AGU, Washington, D. C.

Kodera, K. (2002), Solar cycle modulation of the North Atlantic Oscillation: Implications for the spatial structure of the NAO, *Geophys. Res. Lett.*, *29*(8), 1218, doi:10.1029/2001GL014557.

Kodera, K. (2003), Solar influence on the spatial structure of the NAO during the winter 1900–1999, *Geophys. Res. Lett.*, *30*(4), 1175, doi:10.1029/2002GL016584.

Kodera, K., and Y. Kuroda (2005), A possible mechanism of solar modulation of the spatial structure of the North Atlantic Oscillation, *J. Geophys. Res.*, *110*, D02111, doi:10.1029/2004JD005258.

Ogi, M., K. Yamazaki, and Y. Tachibana (2003), Solar cycle modulation of the seasonal linkage of the North Atlantic Oscillation (NAO), *Geophys. Res. Lett.*, *30*(22), 2170, doi:10.1029/2003GL018545.

Pozo-Vazquez, D., J. Tovar-Pescador, S. R. Gamiz-Fortis, M. J. Esteban-Parra, and Y. Castro-Dýez (2004), NAO and solar radiation variability in the European North Atlantic region, *Geophys. Res. Lett.*, *31*, L05201, doi:10.1029/2003GL018502.

Ruzmaikin, A., J. Feynman, X. Jiang, D. C. Noone, A. M. Waple, and Y. L. Yung (2004), The pattern of northern hemisphere surface air temperature during prolonged periods of low solar output, *Geophys. Res. Lett.*, *31*, L12201, doi:10.1029/2004GL019955.

Shindell, D., D. Rind, N. Balachandran, J. Lean, and P. Lonergan (1999), Solar cycle variability, ozone and climate, *Science*, *284*, 305–308.

Steil, B., C. Brühl, E. Manzini, P. J. Crutzen, J. Lelieveld, P. J. Rasch, E. Roeckner, and K. Krüger (2003), A new interactive chemistry-climate model: 1. Present-day climatology and interannual variability of the middle atmosphere using the model and 9 years of HALOE/UARS data, *J. Geophys. Res.*, *108*(D9), 4290, doi:10.1029/2002JD002971.

Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the winter geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300.

Tourpali, K., C. J. E. Schuurmans, R. van Dorland, B. Steil, and C. Brühl (2003), Stratospheric and tropospheric response to enhanced solar UV radiation: A model study, *Geophys. Res. Lett.*, *30*(5), 1231, doi:10.1029/2002GL016650.

C. Brühl and B. Steil, Max- Planck Institute for Chemistry, D-55128 Mainz, Germany.

E. Manzini, National Institute for Geophysics and Volcanology, I-40128 Bologna, Italy.

C. J. E. Schuurmans, Institute for Marine and Atmospheric Research, Utrecht University, 3508 TA Utrecht, Netherlands.

K. Tourpali, Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, Thessaloniki 54 124, Greece. (tourpali@auth.gr)

R. van Dorland, Royal Netherlands Meteorological Institute, 3730 AE De Bilt, Netherlands.