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# Solar modulation of the Northern Hemisphere winter trends and its implications with increasing $CO_2$

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[1] The origin of the recent trends in the Northern Hemisphere (NH) winter circulation is investigated. Linear trends are calculated separately for low solar (LS) and high solar (HS) winters. Trends during HS exhibit a North Atlantic Oscillation (NAO)/Arctic Oscillation (AO)-like pattern that is related to a stronger stratospheric polar vortex. Whereas during LS, decreasing trends of sea-level pressure appear over the northeastern Pacific in association with warming trends in the tropical troposphere which lead to a strengthening of the subtropical jet and a weakening of the polar night jet. These two trends compare well with those found in previous numerical model simulations where the $CO_2$ was doubled in either the troposphere or the middle atmosphere. This suggests that the stratospheric cooling effect due to increased $CO_2$ manifests in the troposphere through nonlinear interaction with solar cycle.

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## 1. Introduction

[2] Recent winter warming of the Northern Hemisphere (NH) has been attributed to positive trends of the North Atlantic Oscillation (NAO) [*Hurrell*, 1996] or the Arctic Oscillation (AO) [*Thompson et al.*, 2000]. Whether positive trends of the NAO/AO are due to natural variability or increasing greenhouse gases is being debated [*Shindell et al.*, 1999, 2001; *Fyfe et al.*, 1999; *Gillett et al.*, 2002; *Rodwell et al.*, 1999; *Hoerling et al.*, 2001]. However, surface trends cannot be explained only in terms of the NAO or the AO. Trends in the Pacific sector should also be taken into account to identify the nature and origin of the recent trends [*Raible et al.*, 2005].

[3] In this study we demonstrate that trends in the sea-level pressure (SLP) in the Atlantic and Pacific sectors can be both related to increased greenhouse gas effects, but that the solar activity modulates the spatial structure.

## 2. Result

[4] Figure 1 shows the linear trends of DJF-mean SLP for 1958/1959 to 2004/2005 calculated using NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996]. The statistical significance of the trends is estimated by the Mann-Kendall test. The recent SLP trend pattern somewhat differs from the AO pattern of *Thompson et al.* [2000]. It was shown, however, that trends in the NH winter can be divided into two types, one related with the stratospheric polar vortex and the other with the equatorial SSTs [*Kodera and Koide*, 1997]. It is interesting to note that the two types can be distinguished spontaneously by stratifying the data according to the solar activity. Figure 2 plots the same linear trends as in Figure 1 but calculated separately for low solar (LS) and high solar (HS) winters. Here solar activity is measured by the 10.7 cm solar radio flux. Twenty-one winters are classified as LS winters and 16 winters are classified as HS winters depending on whether the activity is higher or lower than the mean value ±0.25 standard deviation. Trends of 50 hPa geopotential height are also included in Figure 2. Trends of SLP during HS can be characterized by a seesaw pattern between the polar and midlatitudes, which is most prominent over the Euro-Atlantic sector. A decrease of polar pressure is related to a stronger stratospheric polar vortex at 50 hPa. This hemispherical seesaw pattern is similar to a NAO appearing during HS [*Kodera and Kuroda*, 2005].

[5] Consistent with a local NAO response during LS found by *Kodera and Kuroda* [2005], SLP trends of LS exhibit a weak regional Icelandic Low–Azores High seesaw confined over the North Atlantic Ocean. Trends of the SLP during LS are characterized by negative pressure over the northeastern Pacific sector. This pattern transforms to a more PNA-like structure in the middle troposphere accompanying positive trends over the American continent (not shown). Geopotential height trends in the lower stratosphere exhibit a more zonal structure superposed with zonal wave number 1 and 2 patterns (high over the American sector and low over Eurasia extending from Atlantic to Pacific). This pattern resembles that associated with the warm phase of the ENSO [*van Loon and Labitzke*, 1987; *Hamilton*, 1993].

[6] To better understand the origin of the winter trends, linear trends are calculated for each month from November through January for zonally averaged temperatures and zonal winds for LS and HS (Figure 3). Reanalysis data are problematic in the equatorial upper stratosphere where the observations are sparse. Therefore one should be careful to interpret trends in this area. Zonal wind trends in January, which are more or less similar to the winter mean, are characterized by a nearly opposite seesaw pattern: a stronger polar night jet and a weaker subtropical jet for HS, but a stronger subtropical jet and a weaker polar-night jet for LS.

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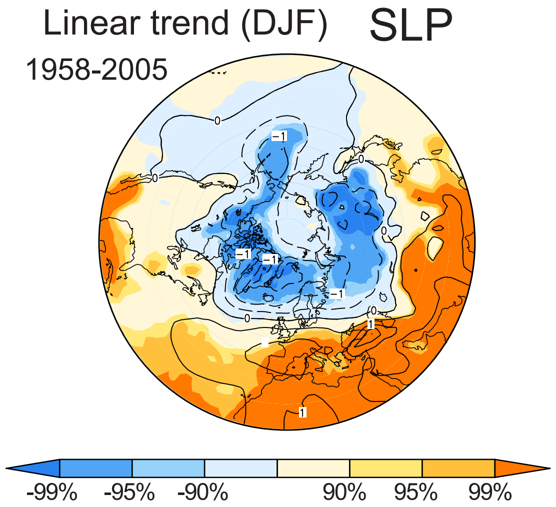

**Figure 1.** Linear trends of DJF mean SLP in the NH (20°N–90°N). Contour interval is hPa/10-year, and color indicates the statistical significance of trends according to the Mann-Kendall test.

It should be noted that the zonal-wind response to an external forcing is generally characterized by a meridional seesaw pattern due to the interaction with planetary waves in the winter stratosphere [*Kodera*, 1995].

[7] Trends in November exhibit more similarity between LS and HS. Significant westerly trends are located around 50°N to 60°N in the stratosphere. The location of stronger westerlies shifts equatorward with time for LS, whereas for HS easterly trends develop in the subtropics until they form an opposite polarity seesaw pattern in January. The similarity of the structure is also evident in November temperatures: cooling in the polar stratosphere and warming in the tropical troposphere. This implies a larger meridional temperature gradient and a stronger westerly jet. For LS, however, there is more warming of the tropical troposphere and less cooling of the polar stratosphere, consistent with a strengthened westerly jet in lower latitudes compared to that of HS. This difference develops during the winter, and the cooling trend of the polar region during LS disappears and is even replaced by warming trends, while cooling trends in midlatitudes increase slightly and form a temperature structure consistent with a stronger subtropical jet and a weaker polar-night jet in January.

[8] The development of the trends from the similar structure in November suggests a common origin. The warming of the troposphere and cooling of the stratosphere in November may be attributed to an increased concentration of greenhouse gases. Numerical experiments by *Sigmond et al.* [2004] indicate that increases of $CO_2$ in the middle atmosphere (mesosphere + stratosphere) and the troposphere exhibit nearly opposite dynamical responses in the NH winter (Figure 3c). Increasing $CO_2$ in the troposphere warms the troposphere and cools the lower stratosphere in the equatorial region due to a stronger upward motion (Figure 3d).

[9] A tropospheric $CO_2$ increase also cools the midlatitudes of the lower stratosphere (Figure 3d) but warms the polar stratosphere in association with a strengthening of the subtropical jet and a weakening of the polar night jet (Figure 3c). In contrast, increasing $CO_2$ in the middle atmosphere cools the stratosphere except for the region just above the tropopause.

[10] A strong similarity can be seen between the tropospheric $CO_2$ impact and trends of LS, and also between the middle-atmospheric $CO_2$ impact and trends of HS. A similarity is also found in the evolution of the structure during the winter. Monthly mean fields of the model simulation show also a development of zonal wind anomaly from the stratosphere to the troposphere (figure not shown). This suggests that, although spatial patterns of trends of LS and HS are very different, both may be induced by an increased concentration of $CO_2$. The difference is that the tropospheric effect dominates during LS, whereas the middle-atmospheric effect dominates during HS.

[11] Given that both trends originate from an increased concentration of $CO_2$, why and how does the solar activity interplay? Note that the primary dynamical impact of the solar cycle is found in the lower mesosphere and the stratopause region in winter [*Crooks and Gray*, 2005]. During early winter of LS when the subtropical stratopause jet is weaker, planetary waves can propagate into the upper stratosphere. In contrast, during HS the subtropical stratopause jet is stronger, planetary waves are deflected from the upper stratosphere, and the interannual variation of the stratopause jet is characterized by a meridional seesaw pattern [*Kodera and Kuroda*, 2005].

## 3. Discussions and Concluding Remarks

[12] The results of the analysis show that the trends of SLP in the NH winter can be related to increased green-

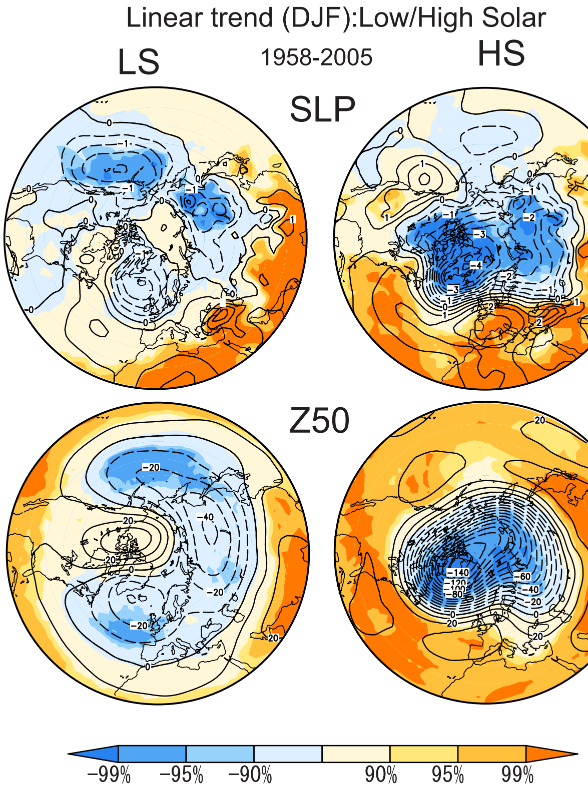

**Figure 2.** Same as in Figure 1 except for the linear trends calculated separately for (left) LS and (right) HS winters. (top) SLP and (bottom) 50 hPa geopotential height. Contour interval is 20 m/10-year.

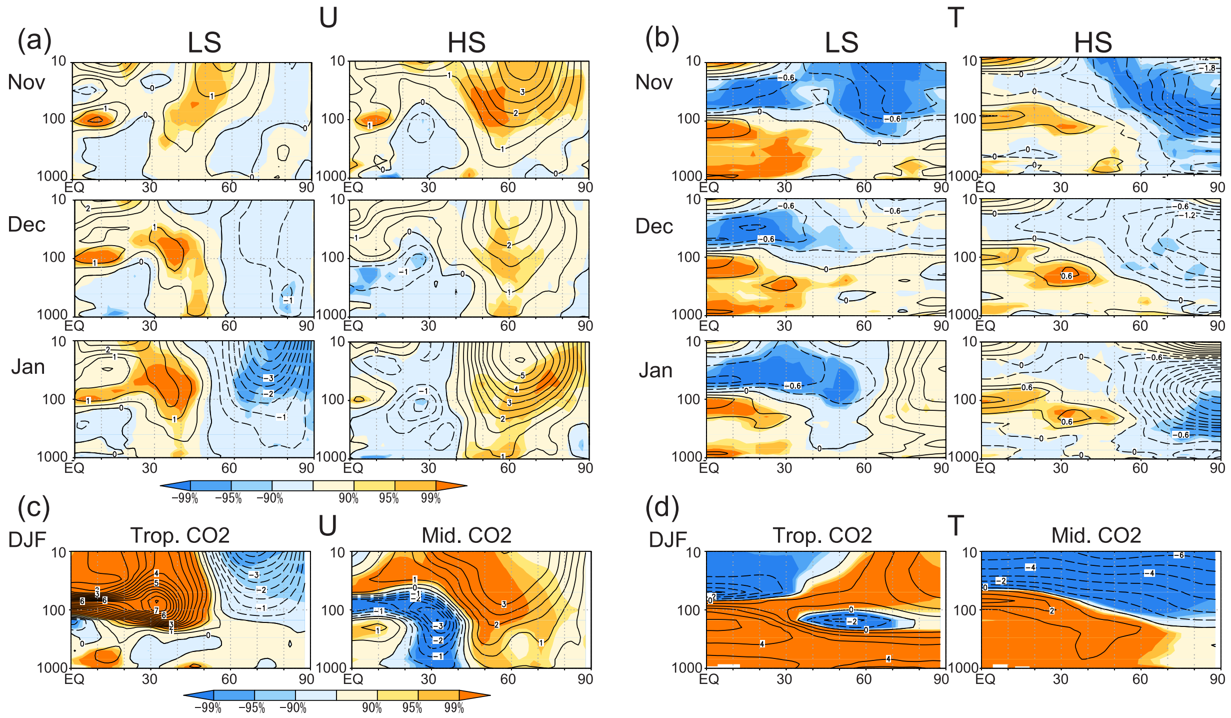

Fig. 3

**Figure 3.** (a) Same as in Figure 2, except for the linear trends of monthly mean zonally averaged zonal winds. (top) November, (middle) December, and (bottom) January for (left) LS and (right) HS. (b) Same as in Figure 3a but for temperature trends. Contour interval is 0.5 $\mathrm{ms}^{-1}$/10-year for zonal wind and 0.3 K/10-year for temperature trends. (c) The difference of the zonally averaged DJF mean zonal wind between control and experiments of doubled $CO_2$ (left) in the troposphere and (right) in the middle atmosphere. (d) Same as in Figure 3c but for the temperature differences. Contour interval is 0.5 $\mathrm{ms}^{-1}$ for zonal wind and 1 K for temperature differences. Shading denotes level of statistical significance. Figures 3c and 3d are reproduced from *Sigmond et al.* [2004].

house gas effects, but modulated by the solar activity. Trends during high solar (HS) activity exhibit a NAO/AO-like pattern that is related to a stronger stratospheric polar vortex, whereas during low solar (LS) activity, negative trends of SLP appear over the northeastern Pacific in association with warming trends in the tropical troposphere which is related to a strengthening of the subtropical jet and a weakening of the polar night jet. These two trends compare well with those found in numerical model simulations [*Sigmond et al.*, 2004], where the $CO_2$ was doubled in either the troposphere or the middle atmosphere. This suggests that the stratospheric cooling effect due to increased $CO_2$ manifests in the troposphere through nonlinear interaction with solar cycle. The depletion of stratospheric ozone may also cause coolings in the stratosphere, however in the polar night region its effect may not be important.

[13] Now let's consider what the response to increased $CO_2$ would be under a different circulation condition due to solar activity. Figure 4 schematically illustrates a possible process. The primary dynamical effects produced by increased $CO_2$ would be (1) increased wave activity from the troposphere due to tropical warming [*Butchart and Scaife*, 2001; *Gillett et al.*, 2002] and (2) a stronger polar night jet due to polar cooling.

[14] During LS, the stratopause jet is weaker, so that the stratosphere is more sensitive to increased wave activity due to increased greenhouse gases. This causes a stronger Brewer Dobson Circulation (BDC), more adiabatic warming in polar regions, which offsets the radiative cooling. This is similar to what *Sigmond et al.* [2004] found in their tropospheric $CO_2$ impact experiment: stratospheric wave forcing increased due to tropospheric $CO_2$ doubling, making the BDC stronger and the polar lower stratosphere warmer. In contrast, during HS, the stratopause jet is stronger, so that it is less sensitive to increased wave activity due to increased greenhouse gases and the jet shifts poleward consistent with the increased polar cooling. This is similar to what *Sigmond et al.* [2004] found in their middle atmospheric $CO_2$ impact experiment: the stratospheric wave forcing increased less due to middle atmospheric $CO_2$ doubling compared to the tropospheric $CO_2$ doubling, so that radiative cooling effects in the middle atmosphere dominated in that experiment.

[15] In addition to the extratropical processes, convective activity is suppressed over the equatorial region during HS [*Kodera and Shibata*, 2006; *Matthes et al.*, 2006], and the tropical troposphere is less sensitive to change in the equatorial SSTs [*Kodera*, 2005]. It is also noted that the stratospheric polar vortex is less sensitive to equatorial SST

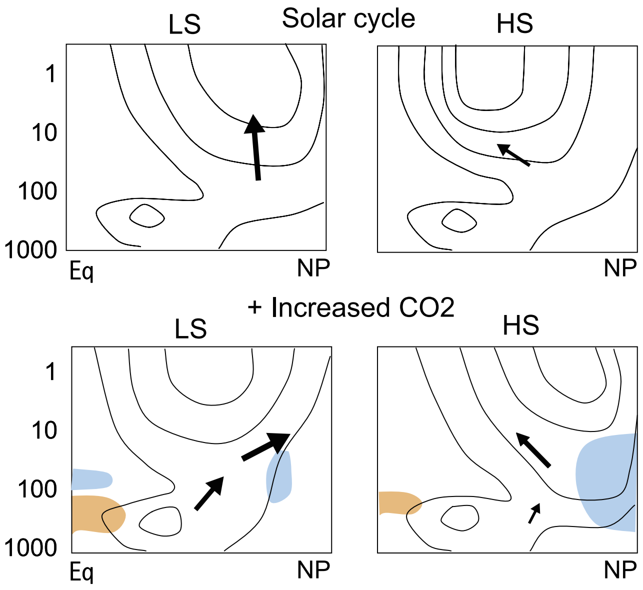

**Figure 4.** Schematic presentation of solar and $CO_2$ effects on zonal winds (contours) and planetary wave propagation (arrows) in Northern Hemisphere winter. (top) Solar cycle difference: (left) LS and (right) HS. (bottom) Same as the top but under for increased $CO_2$. Blue and red colors denote cooling and warming (see text).

changes such as ENSO events during HS [*Kryjov and Park*, 2007]. This may also explain why tropical trends near the surface and in the upper troposphere are less significant for HS and the impact of the tropospheric effect of the $CO_2$ is less during HS.

[16] The present study suggests that the $CO_2$ increase in the troposphere and the stratosphere has competing effects in the NH winter. Depending on the strength of the solar forcing, the tropospheric or middle-atmospheric effect tends to dominate the other. Whether or not the solar influence is real, it is very important to recognize that there exist two possible responses to increased $CO_2$ in the Northern Hemisphere winter. This may help to explain the large discrepancy among the model simulations of increased $CO_2$.

[17] A global warming experiment by *Shindell et al.* [1999] using a middle atmospheric general circulation model predicted a stronger polar-night jet and positive AO-like circulation pattern similar to the trend pattern of HS. However, a similar simulation by *Gillett et al.* [2002] led to a weakening of the polar-night jet, and the greatest impact on the SLP is seen not over the polar region but over the northeastern Pacific region, similar to the LS. The discrepancy of the increasing $CO_2$ impacts could arise from differences of model sensitivity due to the difference of the basic states: the former model would be more sensitive to the cooling effects of the $CO_2$ increase in the middle atmosphere, while the latter one would be more sensitive to the warming effects in the troposphere. Underestimation of the simulated trends in the NAO/AO without additional forcing in the stratosphere to reproduce a stronger stratospheric polar vortex [*Scaife et al.*, 2005] could also arise from a deficiency of the middle atmospheric cooling effect of the increased $CO_2$ because the model tops are too low.

[18] In this paper we showed that the impact of increase of the greenhouse gas problem is much complicated than a simple argument based on the radiative forcing usually considered. It produces warmings in the troposphere, but it also produces coolings in the stratosphere. This cooling effect, usually discarded, can manifest itself in the troposphere due to a nonlinear interaction with solar influence. For a realistic climate simulation this effect should be correctly represented in the model.

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