Antarctic Ozone Depletion and trends in tropospheric Rossby wave breaking

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ABSTRACT

The connection between Antarctic ozone depletion and trends in upper tropospheric Rossby wave breaking (RWB) is examined using meteorological reanalyses and model integrations. The reanalyses show significant changes in the occurrence of RWB during southern summer over the last thirty years: There are large increases in RWB on the equatorward side of the tropospheric jet, where there has been a deceleration of zonal flow due to the poleward shift of the mean jet position, and weak decreases in RWB on the poleward side. Comparable changes in RWB and jet location are found in time-slice integrations of an atmospheric general circulation model whose stratospheric ozone distributions differ between 1960 and 2000 levels, but not in integrations that differ only in their greenhouse gas concentrations and sea surface temperatures. The simultaneous change in RWB and jet location is also found in a series of idealized dynamical core integrations, where the strength of the stratospheric polar vortex is increased. Taken together, these results show that the formation of the ozone hole and strengthening of the stratospheric polar vortex has lead to changes in the frequency of RWB during southern summer. These changes in RWB are likely to play a role in the stratosphere-troposphere coupling and the frequency of synoptic weather systems.

1. Introduction

There have been numerous changes in southern hemisphere (SH) tropospheric climate over the last thirty years, including an increase in zonal mean sea-level pressure difference between the mid- and high latitudes, a poleward shift in the tropospheric westerly jet, and a poleward expansion of the Hadley cell and subtropical dry zone (e.g., Thompson and Solomon 2002; Hu and Fu 2007; Previdi and Liepert 2007). Furthermore, modeling studies indicate that stratospheric ozone depletion is the primary cause for the changes during southern spring and summer (e.g., Gillett and Thompson 2003; Son et al., 2009; Polvani et al. 2011, McLandress et al. 2011). Given these changes in the large-scale tropospheric circulation one might expect trends in synoptic-scale systems.

Here we examine changes in SH upper tropospheric Rossby wave breaking (RWB) events (McIntyre and Palmer 1983). Changes in these events are of interest as they are linked to synoptic weather systems (e.g.,
cut-off lows, blocking highs), extreme weather events (e.g., heavy rainfall and floods), and stratosphere-troposphere exchange of trace gases (e.g., Sprenger et al. 2007; Pelly and Hoskins 2003; Ndarana and Waugh 2010). Furthermore, changes in RWB could play a role in the movement of tropospheric jets (e.g., Riviere 2009) and the dynamical coupling between the stratosphere and troposphere. The climatological structure and occurrence of near-tropopause RWB in the SH has recently been examined by Ndarana and Waugh (2011) and Wang and Magnusdottir (2011). Wang and Magnusdottir (2011) also examined interannual variations, and showed an increasing trend in anticyclonic RWB between 30-60°S, that closely matched the trend in the Southern Annular Mode.

In this paper, we examine the observed trends in RWB using National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalyses (Kalnay et al. 1996), using a different algorithm and different isentropic surfaces than in Wang and Magnusdottir (2011). We further examine the occurrence and cause of trends in RWB in “time-slice” atmospheric general circulation model integrations that differ in the specified ozone and greenhouse gas (GHG) concentrations and sea surface temperatures (SSTs) (Polvani et al., 2011), and in a series of idealized atmospheric dynamical core integrations in which the strength of the polar vortex is varied (Gerber and Polvani 2009). Our analysis shows consistent changes in the observations and models, with an increase in the frequency of RWB on the equatorward side of the jet as the jet moves poleward (in response to ozone depletion and a strengthening of the stratospheric vortex).

2. Data and methods

We study the trends in Southern Hemisphere RWB events between 1979 and 2009 using the climatology of these events constructed from NCEP/NCAR reanalyses by Ndarana and Waugh (2011) (NW11, hereafter). The RWB events of interest here occur around the tropopause, and are identified by the overturning of PV = -1.5 to -2.5 PVU contours on isentropes between 310 and 350 K (see NW11 for details). RWB events are separated into anticyclonic and cyclonic wave breaking events (AWB and CWB, respectively), using the meridional component of the wave activity flux (AWB events have larger positive fluxes, whereas CWB have
larger negative fluxes; see NW11). Whereas NW11 focused on the variation of RWB on individual isentropes we here group together all RWB events within a given latitude range, regardless of which isentrope they occur on, and examine variations with latitude.

The occurrence of RWB events is also examined in four “time-slice” integrations of the Community Atmosphere Model 3 (CAM3; Collins et al. 2006) described in Polvani et al. (2011). The first (“REF1960”) is a reference simulation in which the SSTs and concentrations of well mixed GHGs and ozone are specified using values representative of the year 1960. In the other integrations at least one of these fields was changed to year 2000 values: In the “OZONE2000” integration the ozone fields were specified at 2000 levels while the other forcing components are kept at 1960 levels; in “GHG2000” all the forcing fields except ozone were changed to 2000 levels; in “BOTH2000” all forcings are set to 2000 levels. In all integrations the SSTs and sea ice concentrations are obtained from the Hadley Center dataset (Rayner et al. 2003), GHG concentrations are from the SRES A1B scenario, and the ozone fields are those used for the CMIP5 model intercomparison project (Cionni et al. 2011). The algorithms used to identify RWB and COL events in the NCEP/NCAR reanalyses are applied to 10 years of daily output from the end of 50-year integrations.

We also examine RWB in a series of integrations of the NOAA/GFDL Flexible Modeling System dynamical core performed by Gerber and Polvani (2009). We consider three integrations that have the same tropospheric relaxation temperature and surface topography (zonal wavenumber 2 and height $h_o = 3000$ m), but winter stratospheric relaxation lapse rate $\gamma = 0, 4$ and $6$ K km$^{-1}$, respectively. These are integrations 7, 9 and 10 in Table 1 of Gerber and Polvani (2009), and correspond to integrations with no vortex, a medium strength vortex and a very strong vortex, respectively. Daily output was archived for 5500 day integrations, and RWB were identified using the same algorithms as for the NCEP/NCAR reanalyses and CAM3 integrations.

3. NCEP/NCAR Reanalyses

As discussed in the Introduction, large changes in the SH tropospheric circulation during December to February (DJF) have been observed over the last thirty years. In middle latitudes, specifically, there has
been a weakening of the wind on the equator side of the jet (40°S) and a strengthening on the polar side (60°S) (Fig. 1a), which corresponds to a poleward shift of the tropospheric jet (Fig. 1b).

Before examining whether there have been any corresponding long-term changes in RWB occurrence we first revisit the climatological variation of RWB occurrence with latitude. As shown in the black curve in Fig. 1c, there is local minimum in the frequency of RWBs around 50°S, which is the mean location of the jet core (see Fig. 1a). Local maxima occur at 30°S and 65°S, which are regions of large meridional velocity gradients. On the equator side of the jet there is anticyclonic shear, and the RWB in this region is almost exclusively anticyclonic (red curve in Fig. 1c), see also NW11, Gong et al. (2010), and Wang and Magnusdottir (2011). Similarly, on the polar side the shear is cyclonic and the majority of the RWB is cyclonic (blue curve), although the difference between AWB and CWB events is smaller than on the equatorward side of the jet.

To explore whether there are any long-term changes in RWB occurrence, we examine the temporal variations in the number of RWB events per DJF. We consider first the RWB on the equator side of the jet, where the zonal flow has decelerated as the jet has moved poleward. The red curve in Fig. 1d shows the temporal variation for RWB events within 30-40°S. There are considerable year-to-year variations in the number of RWB events, but there is a clear positive trend. The number of RWB events per season has increased by around 70% over the thirty year period (this trend is significant at the 99% confidence level). Similar, positive trends in RWB are observed for all latitudes between 25°S and 50°S, see Fig. 1e. Thus, there has been a long-term increase of RWB events on the equator side of the jet, as the jet has moved poleward. This link between RWB frequency and jet location also occurs for year-to-year variations, with a significant correlation between interannual anomalies in jet latitude and RWB frequency (not shown).

The trends in RWB on the polar side of the jet differ from that on the equator side. There is still year-to-year variability but there are only very weak decreasing trends in the frequency of RWB around 60°S that are not statistically significant, see Figs. 1d and 1e.

The trends in RWB presented above are consistent with an independent analysis of trends in SH RWB recently performed by Wang and Magnusdottir (2011). They use a different algorithm to identify RWB events and considered RWB only on the 350 K surface, but they also report an increasing trend in anticyclonic RWB between 30-60°S. They further showed that this trend closely matches the trend in the Southern Annular
4. CAM3 integrations

The relative impact of increasing GHGs and ozone depletion on RWB and COLs cannot be determined from the above data analysis alone. However model integrations can be used to infer the cause of these changes, and in this section we repeat the above analysis using the Polvani et al. (2011) CAM3 integrations.

The zonal mean jet structure in the BOTH2000 integration is similar to that for the NCEP/NCAR reanalyses (compare blue contours in Figs. 1a and 2a), although it is notable that the climatological jet in the model is stronger and slightly equatorward compared to the reanalyses. The differences in winds between the REF1960 and BOTH2000 integrations are also similar to the observed trends (compare Figs. 2a and 1a), with deceleration of zonal winds equatorward and acceleration poleward of jet. Comparison of the four integrations shows that the changes in zonal winds are dominated by ozone depletion in the stratosphere (Polvani et al. 2011), see Fig. 2b: The location and strength of the jet in OZONE2000 and BOTH2000 differ significantly from REF1960, whereas the jet location in GHG2000 is similar to that in REF1960.

The latitudinal variation of RWB events in BOTH2000 is also similar to that for the reanalyses, with local maxima in RWB either side of the jet maximum, compare Figs. 2c and 1c. There is, consistent with the observations, a corresponding change in the RWB events among the integrations. In particular, in the BOTH2000 integration there is an increase in the number of RWB events on the equatorward side of the jet relative to the reference REF1960 integration, and a slight decrease in RWB events on the poleward side, see Fig. 2c, and compare with Fig. 1e. Similar differences are found for the OZONE2000 integration (blue symbols in Fig. 2d), but there are only very small differences in RWB between GHG2000 and REF1960 (black and red symbols). These results support the hypothesis that it is stratospheric ozone depletion, and not increases in GHGs, that has caused the observed changes in RWB.
5. Idealized Integrations

We finally examine RWB in a more simplified setting using the dynamical core simulations of Gerber and Polvani (2009): This enables the dynamics of the atmosphere to be isolated from other processes. We consider three integrations in which the stratospheric relaxation lapse rate, and thus the strength of the resulting polar vortex, varies ($\gamma = 0$, $4$ and $6$ K km$^{-1}$). The differences in the zonal mean wind between $\gamma = 0$ and $6$ K km$^{-1}$ together with the climatological jet (from the $\gamma = 0$ integration) are shown in Fig. 3a. As in the observations (Fig. 1a) and CAM3 integrations (Fig. 2a), there is a reduction in zonal wind speed on the equatorward side of the jet and an increase on the poleward side, for a stronger polar stratospheric vortex. The poleward movement of the jet with increasing vortex strength is shown in Fig. 3(b), where the zonal mean zonal wind at $60^\circ$S and 10 hPa is used as a measure of the vortex strength.

With increasing lapse rate and vortex strength there is an increase in the total number of RWB on equator side of the jet, that is due to an increase in the frequency of AWB events (there is little change in frequency of CWB events) (Fig. 3c). In contrast there is a reduction in RWB on the polar side, that is due to a reduction in the frequency of CWB events (Fig. 3d). These changes in RWB are consistent with the studies of Rivière (2009) and Rivière et al. (2010) that showed that there are more AWB events and less CWB events for jets at higher latitudes. Furthermore, the changes in RWB in the idealized model are consistent with both the observations and CAM3 integrations presented above, and indicate that the strengthening of the stratospheric polar vortex is the cause of the observed changes in RWB.

6. Concluding Remarks

Examination of NCEP/NCEP reanalyses for the last 30 years shows that during austral summer there have been simultaneous changes in the location of the eddy-driven jet and the number of RWB events, with an increase in the number of RWB events on the equatorward side of the jet and weak decrease on the poleward side of the jet. These changes are captured within time-slice CAM3 integrations in which stratospheric ozone is changed from 1960 to 2000 conditions, but there are only small changes in RWB frequency when GHGs and SSTs alone are changed. This indicates that stratospheric ozone depletion is
likely the dominant cause of the changes in the RWB. Idealized dynamical core integrations further indicate that the changes in RWB frequency are the result of the dynamical coupling between the stratosphere and troposphere: For integrations with a stronger vortex there is a more poleward location of the tropospheric jet, with more (anticyclonic) RWB events on the equatorward side and fewer (cyclonic) RWB events on the poleward side of the jet.

The results presented here raise several issues that deserve further investigation. For example, it will be of interest to examine if there are trends in synoptic weather systems. Preliminary examination of cut-off lows (COLs) in NCEP/NCAR reanalyses (using statistics from Ndarana and Waugh (2010)) shows a statistically significant positive long-term trend in mid-latitude COLs during December-February over the last 30 years that closely follows the RWB trend, see Fig. 1(f). The similarity in COL and RWB trend may be expected as Ndarana and Waugh (2010) have shown that the vast majority of COLs are linked to RWB events. Further analysis is needed to examined if the RWB trends are linked to trends in other weather systems, e.g., blocking highs, or precipitation events (e.g., Kang et al., 2011).

The dynamics controlling the changes in RWB, and the connections with the movement of the jet, also needs to be examined further. Previous studies have shown the existence of a positive feedback involving frequency/type of RWB and location of jets (e.g., Riviè re 2009, Barnes and Hartmann 2010). Further analysis is needed to determine whether such a feedback is occurring in the SH, and how ozone depletion (and recovery) alters the jet and RWB characteristics.

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REFERENCES


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