Wave breaking along the stratospheric polar vortex as seen in ERA-40 data

John T. Abatzoglou[1] and Gudrun Magnusdottir[1]

Received 1 February 2007; revised 27 March 2007; accepted 5 April 2007; published 27 April 2007.

[1] Planetary wave breaking through the depth of the Northern Hemispheric stratosphere is observed in daily ERA-40 reanalysis data. Strong wave breaking along the vortex edge is objectively diagnosed by noting the large-scale overturning of potential vorticity contours on isentropic surfaces spanning the stratospheric vortex. Breaking events show distinctly different climatologies depending on whether they occur along the upper or lower portion of the stratospheric vortex. During early winter there is a strong negative correlation between the frequency of breaking events in these two regions. Frequent wave breaking in the lower stratosphere in early winter appears to both shield the upper portion of the vortex from wave disturbances and reduce the net upward wave activity flux into the troposphere, thereby allowing the vortex to strengthen into mid-winter. **Citation:** Abatzoglou, J. T., and G. Magnusdottir (2007), Wave breaking along the stratospheric polar vortex as seen in ERA-40 data, *Geophys. Res. Lett.*, *34*, L08812, doi:10.1029/2007GL029509.

1. Introduction

[2] The most dramatic example of nonlinear dynamics in the stratosphere is the phenomenon of planetary wave breaking (PWB). PWB is defined as the large-scale and rapid irreversible overturning of potential vorticity (PV) contours on isentropic surfaces [*McIntyre and Palmer*, 1983]. Figure 1a shows an example of a stratospheric PWB event observed on 16 December 1982 as noted by the overturning of PV on the 1000K isentropic surface. A large wave number 1 breaking event is observed near the climatologically weak flow associated with the Aleutian High. Immediately following breaking, a filament of high PV air peels off the vortex and is mixed into the subtropics, while low PV air intrudes poleward and disturbs the vortex.

[3] *Baldwin and Holton* [1988] analyzed Northern Hemispheric (NH) PWB in the stratosphere by identifying reversals in the latitudinal PV gradient about one fixed value on a single isentropic surface (850 K, ~ 10 hPa) using coarsely grained NMC data from 1964–1982. A natural motivation for the current study is to extend the climatological study of *Baldwin and Holton* [1988] of PWB across the depth of the NH stratosphere. Here we investigate the three-dimensional structure of Rossby wave breaking from observations in the stratosphere, and examine how wave breaking impacts the zonal-mean zonal flow ($\overline{u}$).

[4] Modeling studies have examined the PWB phenomenon in some detail. For example, *Polvani and Saravanan* [2000] showed that the presence of a strong latitudinal PV gradient in the lower stratosphere inhibits breaking at lower levels, instead encouraging vertical propagation of wave disturbances, up the vortex edge, where they amplify with height and eventually break equatorward at upper levels. By contrast, when PWB takes place in the lower stratosphere, the lower stratospheric PV gradient is destroyed, inhibiting propagation above the breaking level, thereby shielding the upper portion of the vortex from the waves.

[5] In this paper we present an objective method to detect strong PWB events along the depth of the stratospheric vortex. We then discuss the climatology of such strong wave breaking events on eight isentropic surfaces spanning the stratosphere. We find a strong anticorrelation between the frequency of upper stratospheric and lower stratospheric PWB during early winter. Early winters that experience multiple lower stratospheric breaking events are followed by anomalously strong and cold mid-winter vortices.

2. Data and analysis

[6] Daily averaged ERA-40 reanalysis data are used to examine cases of stratospheric wave breaking in the NH over 25 winters (Nov–Mar, 1977/78–2001/02). Although the ERA-40 dataset extends back to 1957, significantly different wave breaking statistics are observed prior to the assimilation of satellite observations in the ERA-40 reanalysis. Use of the ERA-40 dataset is advantageous as it extends up to 1hPa (model extends to 0.1 hPa) and provides accurate wind fields in the extratropical middle atmosphere [*Randel et al.*, 2004].

[7] To improve upon previous observational studies of stratospheric wave breaking, we identify PWB on eight isentropic surfaces through the depth of the stratosphere, as opposed to on a single isentropic surface [*Baldwin and Holton*, 1988]. Three surfaces are in the middle-to-upper stratosphere: 1200 K, 1000 K, and 850 K; and five surfaces are in the lower-to-middle stratosphere: 700 K, 600 K, 500 K, 450 K, and 400 K (results were not found to be sensitive to the introduction of additional isentropic surfaces).

[8] While no single unique signature of wave breaking exists [*McIntyre and Palmer*, 1983], we implement an algorithm that detects the presence of coherent anticyclonic overturning isolines of PV along the periphery of the polar vortex edge. This prototype of stratospheric planetary wave breaking has been examined extensively in modeling studies [e.g., *Polvani and Saravanan*, 2000, and references therein] as well as in observational studies in the troposphere [e.g., *Abatzoglou and Magnusdottir*, 2006]. In order to identify breaking along the edge of the stratospheric polar

[1]Department of Earth Systems Science, University of California, Irvine, California, USA.

0094-8276/07/2007GL029509$05.00

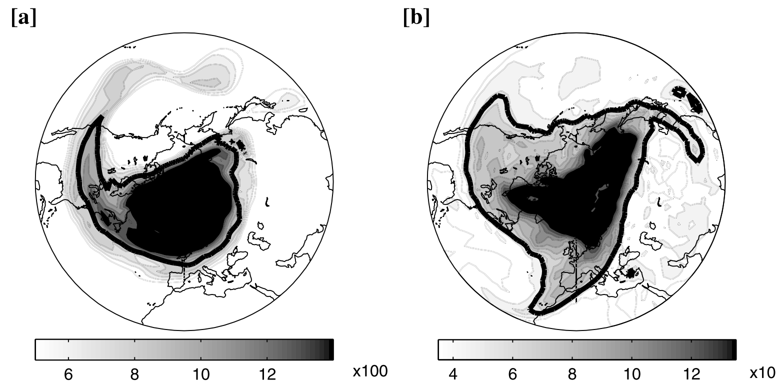

Figure 1. Examples of breaking in the (a) upper stratosphere on the 1000 K isentropic surface occurring on 16 December 1982, and (b) lower stratosphere on the 600 K isentropic surface occurring on 6 January 1979. Potential vorticity (PV) is shaded and shown in PVU, and the bold contour represents the vortex edge (PV_θ) as described in the text.

vortex it is first necessary to define what is meant by the vortex edge. The three-dimensional structure of the stratospheric vortex is rather variable as it evolves over the course of the winter. To accommodate such inherent variability we define the vortex edge dynamically on each day by the PV value that encompasses the sharpest latitudinal PV gradient on an equivalent latitude grid [*Nash et al.*, 1996]. This procedure results in a single PV value for each isentropic surface, referred to as PV_θ. As shown in Figure 1a, PV_θ on the 1000 K surface delineates high PV air within the polar vortex from abruptly lower PV air outside the vortex.

[9] We implement an objective algorithm to detect strong anticyclonic wave breaking, similar to that used to detect tropospheric cases of PWB [*Abatzoglou and Magnusdottir*, 2006]. The algorithm is detailed as follows: (1) There is a reversal in the latitudinal PV gradient such that a region of high PV ($PV \geq 1.2 \times PV_\theta$) exists equatorward of a region of low PV ($PV \leq 0.8 \times PV_\theta$). (2) There is a localized eastward PV gradient about the break, consistent with the notion of anticyclonic breaking. (3) The region of high (low) PV is part of a tongue of PV originating from high (low) latitudes.

[10] In order to assign a location to a breaking event and to ensure that a single PWB event is identified when the PV field satisfies the above criteria, we identify a "breaking point" on each isentropic surface as the southwesternmost point first satisfying the criteria. All other PV reversals for the following 14 days are ignored. In some instances the signature of wave breaking can be simultaneously observed on more than one isentropic surface, especially for the more notable upper-level breaking events. In such cases, we only count the event on the upper-most isentropic surface where PWB is observed (results are not sensitive to this condition as breaking is detected on more than one vertical level in only about 10% of the cases).

3. Climatology

[11] A total of 116 PWB events are observed over the 25 winters. Figure 2a reveals that PWB is identified throughout the depth of the stratosphere. Most PWB events documented in our study are upper-level events, observed on or above 850 K (averaging just over three events per winter season). Subsequent analysis reveals a distinct difference in the climatology of PWB occurring along the middle to upper vortex (850 K to 1200 K) and PWB events occurring along the lower part of the vortex (400 K to 700 K). This justifies making the distinction between PWB events along the mid to upper vortex, hereafter referred to as upper breaking events, and PWB events in the lower portion of the vortex, hereafter referred to as lower breaking events.

[12] All of the observed upper breaking events are characterized by a large-amplitude wave number 1 or 2 overturning of the PV field (Figure 1a). These events tend to take place in mid winter as seen in Figure 2c. During mid winter, strong PV gradients in the lower and middle stratosphere inhibit PWB in the lower stratosphere, instead

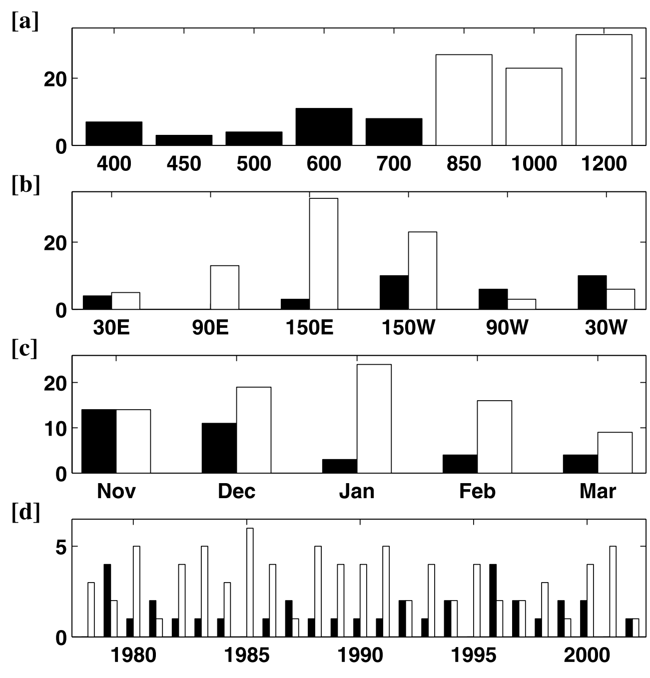

Figure 2. Histogram of identified strong PWB events in the NH stratosphere by (a) isentropic surface, (b) longitude, (c) month, and (d) year. Upper-level PWB events, identified on and above 850 K, are indicated in white. Lower-level PWB events, identified on and below 700 K, are indicated in black.

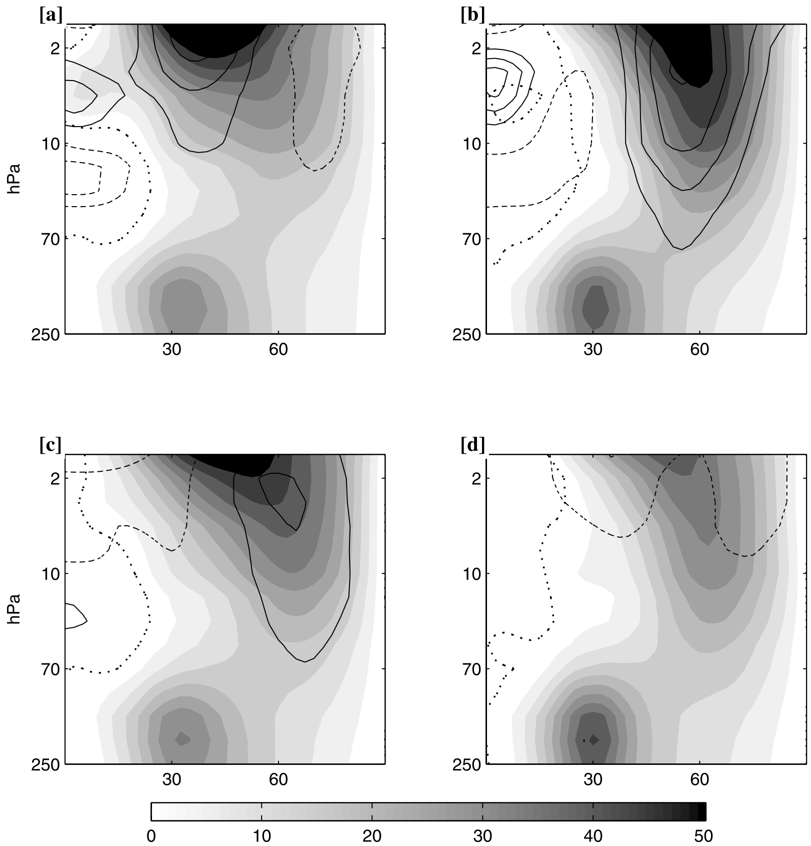

Figure 3. Composite zonal-mean zonal velocity $\overline{u}$ averaged over early winters (1 Nov–31 Dec.) with (a) multiple lower breaking events, and (b) multiple upper breaking events. The composite $\overline{u}$ averaged over mid-winters (21 Dec–10 Feb.) following early winters with (c) multiple lower and (d) multiple upper breaking events. Shading shows $\overline{u}$ values, the dotted contour indicates the zero wind line, and positive (negative) anomalies are shown by solid (dashed) contours with a contour interval of 3 ms^{-1}.

providing a strong vertical waveguide for wave propagation up the vortex edge. Wave trains increase in amplitude exponentially as they propagate vertically into the upper stratosphere where they can break. Figure 2b reveals that these upper stratospheric breaking events tend to occur in the vicinity of the Aleutian High (as found by *Baldwin and Holton* [1988]).

[13] Lower breaking events tend to occur during the developing and decaying stages of the stratospheric vortex in early and late winter, and are less frequent in mid winter (Figure 2c). The weaker PV gradients in the lower portion of the vortex during its evolving and decaying stages are less conducive to vertical propagation up the vortex edge, and more conducive to horizontal propagation and PWB in the lower stratosphere. This finding is consistent with previous modeling studies that document a decrease in upward wave propagation (and upper wave breaking) when the vortex is baroclinic, as is observed in early and late winter [e.g., *Polvani and Saravanan*, 2000]. Wave breaking in the lower stratosphere tends to be more regional in scale (i.e., involving wave disturbances beyond just wave numbers 1 and 2). Figure 2b shows that lower breaking events occur primarily over the eastern Pacific and eastern Atlantic ocean basins, near the exit regions of the jets, similar to the climatology of breaking events in the upper troposphere during this time of year [*Abatzoglou and Magnusdottir*, 2006]. Figure 1b shows an example of a lower breaking event on 6 January, 1979 on the 600 K surface. It has a nice wave-3 signature with breaking occurring, almost simultaneously, over the eastern Pacific and eastern Atlantic basins.

4. Breaking Events in Early Winter

[14] Figure 2d suggests a negative correlation between the number of lower and upper PWB events in each winter. By restricting our focus to the first two months of the winter season (Nov.–Dec.), the anticorrelation becomes stronger ($r = -0.77$, $\geq$99% significant). To examine features associated with active lower-level PWB on one hand, and active upper-level PWB on the other, we select early winters with at least two events occurring either in the lower stratosphere, or upper stratosphere, respectively. No early winter period experienced multiple events in both the upper and lower stratosphere. Seven years were found to have multiple lower stratospheric breaking events, averaging 2.4 lower and 0.3 upper breaking events, while ten years had multiple upper stratospheric breaking events averaging 0.4 lower and 2.3 upper breaking events. Composites of the zonal-mean zonal wind ($\overline{u}$) and Eliassen-Palm (EP) flux are formed using daily averages over the seven (ten) early winters (1 Nov.–31 Dec.) with multiple lower (upper) breaking events.

[15] Early winters with multiple upper breaking events have negative $\overline{u}$ anomalies (anomalies, as defined in this paper, are deviations from the daily-mean climatological

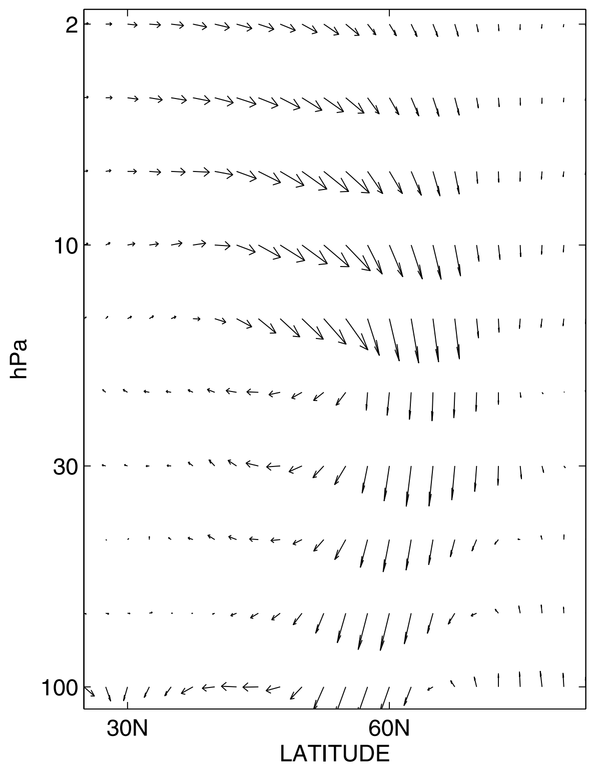

Figure 4. The composite EP flux difference averaged over 1 Nov–31 Dec. for periods with multiple lower breaking events minus periods with multiple upper breaking events, and multiple lower breaking events. Maximum vector shown is of magnitude 1.2×10^5 kg s^{-2}. The EP vectors are scaled by multiplying the horizontal component by 85.

fields; climatological daily means are formed by applying a 20 day low-pass filter to the 25 year daily averages) at low latitudes near 5hPa at the average level of upper breaking, with positive anomalies spanning the middle to upper stratosphere poleward of the climatological polar night jet (Figure 3c). Consistent with this modulation of the flow field, the polar night jet migrates slightly poleward and extends downward into the lower stratosphere, enhancing the PV gradient in the lower and middle stratosphere (not shown), thereby encouraging upward wave propagation into the upper portion of the vortex. The composite EP flux (not shown) reveals an enhanced vertical flux of wave activity into the upper portion of the vortex, with an equatorward component on and above 10 hPa toward the average level of breaking.

[16] Early winters with multiple lower breaking events show a pronounced decrease in low-latitude zonal flow near 30 hPa, along with an unusually strong and baroclinic polar night jet (Figure 3a). Consistent with equatorward propagation of large amplitude waves toward the breaking region, the composite EP flux (not shown) is directed upward and then equatorward toward the average level of lower breaking events near 50 hPa.

[17] Fields of composite $\overline{u}$ for mid winter periods (21 Dec.–10 Feb) following early winters with multiple lower-level and multiple upper-level breaking are shown in Figures 3b and 3d, respectively. Weak negative anomalies straddle both sides of the upper-stratospheric jet in mid winter following early winters with multiple upper stratospheric PWB (Figure 3d). Following early winters with multiple lower stratospheric PWB (Figure 3b), the mid-winter polar night jet is substantially stronger (anomalies exceeding 12 ms) and colder (−10°C anomalies near 5 hPa and poleward of 60°N, not shown). Breaking in the lower stratosphere restricts upward propagation above the level of breaking and allows a stronger upper vortex. This may explain in part why a stronger and colder mid winter vortex follows early winters dominated by lower stratospheric PWB.

[18] Figure 4 shows the result of subtracting the composite EP flux for early winters with multiple upper breaking events from the composite EP flux for early winters with multiple lower breaking events. Figure 4 highlights the large difference in vertical wave-activity flux throughout the stratospheric column. For early winter periods with multiple lower breaking events the vertical component of the flux is significantly reduced (25% reduction) above the average level of breaking (on and above 30 hPa). This is the shielding effect of lower stratospheric breaking on the upper vortex that has been detailed in numerous earlier modeling studies [e.g., *Polvani and Saravanan*, 2000]. Additionally, we find that the vertical component of the EP flux at 100 hPa is anomalously weak for early winter periods with multiple lower breaking events. This implies that there is less wave activity entering from the troposphere at these times. Indeed, the modeling study of *Scott and Polvani* [2004] found that for time-independent forcing in a troposphere that is baroclinically stable, the breaking in the lower stratosphere can reduce propagation into the stratosphere. We can only speculate that this stratospheric control on wave propagation from the troposphere could be due to nonlinear reflection from the low level breaking region.

5. Concluding Remarks

[19] We have objectively documented 116 strong anticyclonic PWB events across the depth of the NH stratospheric vortex using 25 winters of ERA-40 data. Between two and seven events take place in any given winter. While planetary waves propagating upward from the troposphere strongly influence the stratospheric circulation, a feedback involving the lower breaking region acts to decrease upward propagation both above and below the lower breaking region, thereby influencing both the forcing and the mean flow.

[20] The evolution of the polar jet over the course of the winter determines the location of PWB. We found two preferred regions of PWB: one in the upper stratosphere associated primarily with the Aleutian anticyclone in mid winter, and a second in the lower to middle stratosphere primarily over the west coasts of Europe and North America in early and late winter. During mid winter, Rossby waves propagate up the vortex edge due to the strong PV gradient, leading to upper stratospheric wave breaking. By contrast, lower stratospheric breaking is favored during early and late winter, when vertical wave propagation is limited by the less developed vortex edge.

[21] **Acknowledgments.** We are grateful for insightful comments by an anonymous reviewer that greatly improved the manuscript. This work was supported by NSF grant 0301800 and NOAA grant NA06OAR4310149.

References

Abatzoglou, J. T., and G. Magnusdottir (2006), Planetary wave breaking and nonlinear reflection: Seasonal cycle and interannual variability, *J. Clim.*, *19*, 6139–6152.

Baldwin, M. P., and J. R. Holton (1988), Climatology of the stratospheric polar vortex and planetary wave breaking, *J. Atmos. Sci.*, *45*, 1124–1142.

McIntyre, M. E., and T. N. Palmer (1983), Breaking planetary waves in the stratosphere, *Nature*, *305*, 593–600.

Nash, E. R., P. A. Newman, J. E. Rosenfield, and M. R. Schoeberl (1996), An objective determination of the polar vortex using Ertel's potential vorticity, *J. Geophys. Res.*, *101*, 9471–9478.

Polvani, L. P., and R. Saravanan (2000), The three-dimensional structure of breaking Rossby waves in the polar wintertime stratosphere, *J. Atmos. Sci.*, *57*, 3663–3685.

Randel, W., et al. (2004), The SPARC intercomparison of middle-atmosphere climatologies, *J. Clim.*, *17*, 986–1003.

Scott, R. K., and L. M. Polvani (2004), Stratospheric control of upward wave flux near the tropopause, *Geophys. Res. Lett.*, *31*, L02115, doi:10.1029/2003GL017965.

J. T. Abatzoglou and G. Magnusdottir, Department of Earth System Science, University of California, Irvine, Irvine, CA 92697-3100, USA. (gudrun@uci.edu)