Nonlinear Planetary Wave Reflection in the Troposphere

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Forty-four years (1958-2001) of daily data from two reanalysis datasets are used to investigate the occurrence of nonlinear reflection from planetary wave breaking (PWB). PWB is manifested in the the large-scale and rapid irreversible overturning of potential vorticity (PV) contours on isentropic surfaces in the upper troposphere. PWB takes place as a midlatitude wave train propagates equatorward toward a region of weak background zonal flow. As breaking occurs wave propagation is no longer possible. Linear theory predicts that wave activity will be absorbed in the wave-breaking region following the event. Our results show that almost a third of all PWB events result in nonlinear reflection rather than absorption. The signature of the reflected wave train arching northward and downstream into midlatitudes is very similar to that of nonlinear reflection seen in a hierarchy of modeling studies.

1. Introduction

Potential vorticity (PV) gradients in the upper subtropical troposphere are rather small as a result of mixing by baroclinic eddies. The large-scale, quasi-stationary planetary waves depend on a background PV gradient for their restoring mechanism. They tend to propagate as external Rossby modes (with maximum amplitude near tropopause level) in great circle routes, equatorward from their extratropical source regions [*Held et al.*, 2002]. The westerly background flow gets weaker as the wave train propagates to lower latitudes. Weakly forced wave trains may be "absorbed" close to the critical latitude, the latitude at which the phase speed of the waves matches the background flow. This means that the wave train weakens and disappears (due to radiative damping) without mixing up the PV field and affecting the large-scale flow. If the wave amplitude is large enough, waves may break, and mix up PV over a finite region, rather than dissipate. Planetary wave breaking (PWB) is manifested by the large-scale and rapid irreversible overturning of PV contours on isentropic surfaces [*McIntyre and Palmer*, 1983]. The ability of planetary waves to irreversibly stir up the PV field depends not only on wave amplitude, but also on the strength of the background latitudinal PV gradient. The stronger the PV gradient, the more the PV field can resist wave breaking and the narrower the breaking region. Examples of PWB are shown in Fig. 1. Figure 1a is a horizontal plot of the PV field on the 350K isentropic surface on 25 September 1994. Figs. 1b–d show the same field on subsequent days. Two PWB events in different stages of development are clearly seen. Let us concentrate on the PWB event near the dateline, which evolves as a wave train propagates off the Asian continent and amplifies as it tracks southeastward toward a region of weak zonal flow. The wave breaking is evident in Fig. 1b as seen in the overturning of PV contours. Following the break a long strip of high PV extends equatorward and upstream before pinching off and forming a cut-off low.

PWB may lead to stratosphere-troposphere exchange along quasi-horizontal isentropes between the extratropical lower stratosphere (high PV) and the upper troposphere (low PV) of the subtropics/tropics. This large scale interaction can drastically modify temperature, static stability, moisture content and ozone concentration of the tropical upper troposphere [*Waugh and Funatsu*, 2003]. PWB can also impact the large scale atmospheric circulation both in the tropics and extratropics. For example the intrusion of PV rich air into the tropics has been shown to induce convective outbreaks [*Kiladis*, 1998]. In addition, modeling studies have shown that PWB may result in nonlinear reflection (or re-radiation) of planetary waves into midlatitudes [*Walker and Magnusdottir*, 2003, and references therein]. This can profoundly influence the extratropical flow field. This paper examines observational evidence for nonlinear reflection into the extratropics following PWB.

PWB is episodic and, furthermore, one would not expect all wave-breaking events to result in nonlinear reflection. Nonconservative effects, such as diabatic and other dissipative processes, are important in the real atmosphere. These can lead to the absorption of wave activity within the wave-breaking region. Thus our first step is to identify PWB events and then proceed to detecting those events that result in reflection. Previous studies have not found clear evidence of nonlinear reflection in observations. *Plumb* (1985) calculated the wave-activity flux from NMC analysis of winter seasons from 1965 to 1975. He found no evidence of reflection, possibly because he only used the time average, or possibly because he only considered the winter season. Observational studies [e.g., *Postel and Hitchman*, 1999] have shown that PWB is most prevalent during summer when subtropical PV gradients are weaker than in winter and the zero wind line of the zonal flow reaches the furthest poleward.

2. Data and Analysis

Forty-four years of daily averaged NCEP/NCAR and ECMWF (ERA-40) re-analysis data for the years 1958 to 2001 (inclusive) are used to detect PWB. PV on the 350 K isentropic surface is used to identify PWB events. The detection algorithm is not sensitive to which isentropic surface is chosen as long as it intersects the tropopause at subtropical latitudes.

Most planetary scale breaking events are the result of anticyclonic wave breaking [*Peters and Waugh*, 1996]. They tend to occur on the equatorward (anticyclonic) side of the jet. In such cases the PV field may resemble that of the Kelvin's cats'-eyes pattern whereby high (low) PV is advected anticyclonically far equatorward (poleward) allowing

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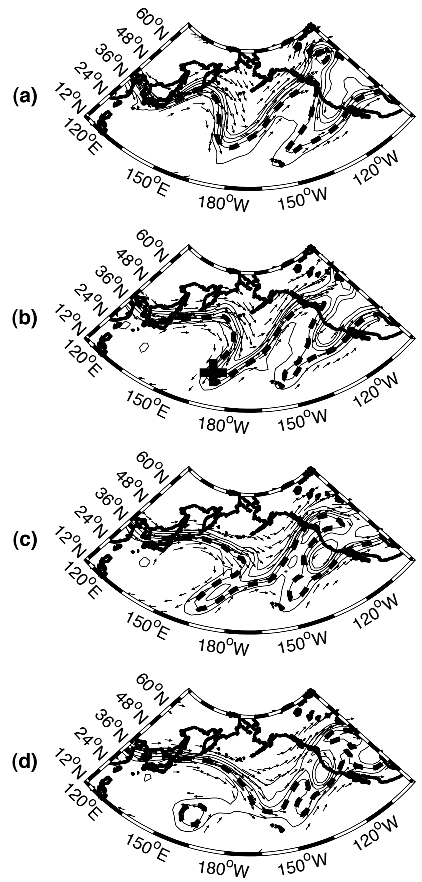

Figure 1. PV on the 350K isentropic surface of a PWB event occurring on 26 September 1994. Daily averaged fields are shown from one day before (a) through two days after the event (d). The spot where breaking is first detected is indicated by a heavy + symbol in (b). PV is shown every 1 pvu (see text for definition of pvu). The 2 pvu contour is denoted by a thick dashed line to emphasize the overturning associated with PWB. Also shown is wind velocity on the 350K surface with windspeed in excess of 20 m s^{-1}.

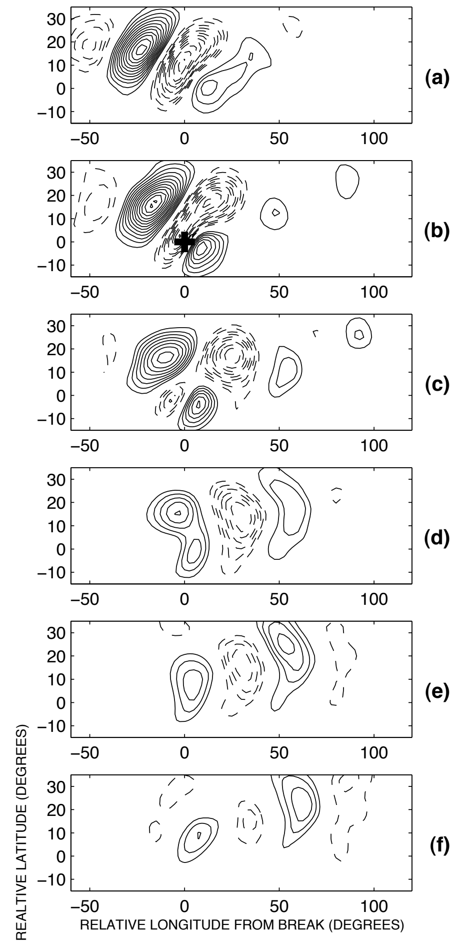

Figure 2. Composite 250 hPa eddy meridional wind for PWB events having a positive latitudinal wave-activity flux, downstream of the breaking region following the break. Daily composites are shown, one day before (a) to four days after (f) the time when the breaking point first appears (b). The contour interval is 1 m s^{-1} for values greater than 2 m s $^{-1}$. Solid (dashed) contours represent poleward (equatorward) flow. The spot where breaking is first detected is indicated by a heavy + symbol in (b).

the wave to crest, and eventually break (see Fig. 1). We aim to capture all episodes of anticyclonic wave breaking resulting in the large scale irreversible mixing of PV. PWB events are identified if they satisfy the following criteria involving the large-scale PV field: (In the Southern Hemisphere (SH) PV is negative. We therefore implement the absolute value of PV in the following algorithm.)

1. There is a substantial reversal in the latitudinal PV gradient about the tropopause such that a region of anomalously high PV (PV > 3 pvu, 1 pvu = 10^{-6} K m^2 s^{-1} kg^{-1}) exists equatorward of a region of anomalously low PV (PV < 1 pvu).

2. There is a localized eastward directed longitudinal PV gradient about the break, consistent with the notion of anticyclonic breaking.

3. The region of high (low) PV must be part of a tongue of PV originating in the extratropics (tropics).

To ensure that only one PWB event is counted per episode, we identify a "breaking point" as the point farthest west and equatorward that satisfies the above criteria the earliest (see Fig. 1b). All other events occurring within 30° longitude or within 4 days are discarded. The above PWB identification algorithm is performed separately on each dataset. Only cases of PWB identified unanimously in both datasets are classified as PWB events.

Upon identifying cases of PWB, we utilize the latitudinal component of the stationary wave-activity flux [*Plumb*, 1985] at 250 hPa (from NCEP/NCAR re-analysis data) to detect those cases that may result in nonlinear reflection. PWB is initiated by a strong negative wave-activity flux associated with the equatorward propagation of a wave train. Nonlinear reflection leads to a wave-activity flux that is directed poleward (positive) and downstream out of the wave-breaking region [*Magnusdottir and Haynes*, 1999]. For each case of PWB we compute the time and area averaged wave-activity flux over the period one to three days following the break and spanning the area 15-60° downstream (longitudinally) and 10-20° poleward of the break (this is at the approximate latitude of the jet where the wave-activity fluxes are strongest). Cases of PWB with a positive latitudinal component of wave-activity flux (poleward directed flux) are designated as cases showing signs of nonlinear reflection. The vertical integral, from 400 to 150 hPa, of the latitudinal component of the wave-activity flux is in all cases in the same sense as the latitudinal component of the flux at 250 hPa as would be expected for a nearly equivalent barotropic structure.

The spatial and temporal evolution of each PWB event is captured using daily averaged 250 hPa meridional wind (from NCEP/NCAR reanalysis data). We extract daily fields from five days prior to the occurrence of the breaking point to 7 days following this occurrence, including the region 60° to the west to 120° to the east, and 15° equatorward to 35° poleward of the breaking point. Eddy fields are then calculated by removing the zonal mean. Furthermore, in order to best represent wave propagation, irrespective of location, we remove the 21-day time mean centered in time on the breaking point. Composites may then be constructed of these spatially and temporally shifted fields.

3. Results

A total of 970 anticyclonic PWB events were identified during the 44 year period. Planetary-wave breaking was found to occur favorably during the warm season over the subtropical ocean basins of the Northern Hemisphere (NH), similar to the results of *Postel and Hitchman* (1999). Only 35 of the 970 PWB events were detected in the SH, mainly during austral summer. Nearly two-thirds of all PWB in the NH took place between June and October, and 98% were concentrated over the North Pacific (160°E-140°W) and North Atlantic (30-70°W). The two ingredients key to PWB are clearly in place in a climatological sense over these regions. Between late spring and early fall we observe a substantial reduction in the latitudinal PV gradient along with a poleward excursion of the zero wind line over the western subtropical ocean basins. This reduces the ability of the flow to support planetary wave propagation and is consistent with a preconditioning of the western and central subtropical ocean basins to PWB. In addition, PWB tends to occur downstream of regions known to excite midlatitude planetary waves. Note that preferred locations of PWB migrate eastward and equatorward across the ocean basins during winter, much in line with the seasonal transition of the minima in the latitudinal PV gradient.

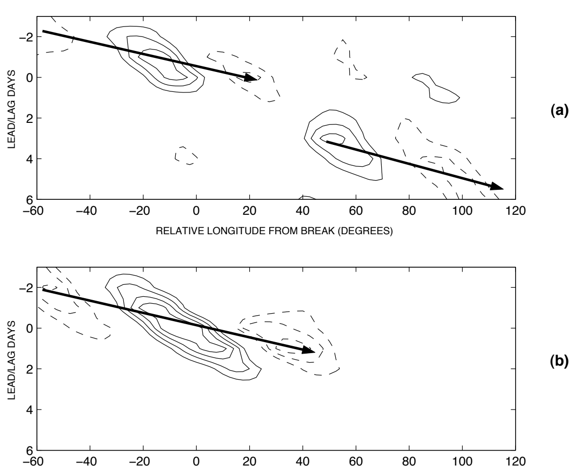

Figure 3. Hovmöller plots (longitude vs. time (in days)) of composite 250 hPa eddy meridional wind averaged between 55°N-65°N. (a) The composite only includes the reflective PWB cases. (b) The composite includes the remaining PWB cases. Positive (negative) contours are shown in solid (dashed) every 1 m s^{-1} in excess of 2 m s^{-1}. Arrows depict the approximate phase propagation.

Over 32% (302 out of 935) of our identified NH PWB events show signs of nonlinear reflection, according to the criterion of a poleward-directed, wave-activity flux downstream and poleward of the wave-breaking region. To verify that these are indeed reflective cases, we examined daily composite lead/lag maps of 250 hPa eddy meridional wind for these cases and compared them to i) such maps where there is equatorward wave propagation with no evidence of PWB, and ii) PWB events where there is no return flux in wave activity. Figure 2 shows such daily composite lead/lag maps, one day prior (a) to four days following (f) breaking points of PWB that show a return flux in wave activity. Prior to breaking, a wave train is seen propagating eastward and equatorward, amplifying as it approaches the critical latitude. As the wave train breaks, the PV field (not shown) becomes irreversibly deformed leading to the abrupt termination of linear wave propagation. Following the breaking point (Fig. 2c), the wave train appears to split. A small signal is evident in the subtropics equatorward of the breaking point, possibly indicative of absorption within the wave-breaking region. However, the dominant signal can be clearly seen from two (Fig. 2d) to four days (Fig. 2f) following the breaking point in Fig. 2b, as a poleward arching wave train propagates downstream from the wave-breaking region. The signature seen here in a composite of PWB events that have a poleward directed wave-activity flux following the event is quite similar to that seen for the same field in a hierarchy of modeling experiments [*Walker and Magnusdottir*, 2003, and references therein].

Composite daily lead/lag maps of the same field for PWB cases with no return flux of wave activity following the break, show a very different signature following the breaking point (not shown). The wave train appears to split with only the smaller southern branch terminating, whereas the northern branch shows equatorward propagation continuing, eventually disappearing several days later. Two days after the break (not shown, but equivalent in time to Fig. 2d) there is still equatorward wave propagation reaching considerably farther in longitude than the equatorward wave train in Fig. 2b. This may be indicative of only partial breaking, or it may be indicative of prolonged breaking (in time), and will be examined in future work. The important point is that no poleward directed wave train is seen in the days following the breaking point, and none would be expected for a non-reflecting case. Rather, the wave train gets absorbed. Similarly, composite lead/lag maps (in this case relative to maximum equatorward propagation) for equatorward, linear, propagating wave trains, with no signs of breaking, showed no poleward directed wave train. Rather, the equatorward wave train weakens and disappears after a few days, indicative of planetary-wave absorption.

Figure 3 shows composite Hovmöller diagrams of 250 hPa eddy meridional wind averaged between 55°N and 65°N for reflective (a) and non-reflective (b) PWB events. This latitudinal band gives a clear indication of extratropical wave propagation as it is displaced sufficiently poleward of the wave-breaking region (where linear wave propagation is not possible) and it is also near the jet, which tends to act as a wave guide. Both cases show the initial wave train that triggers the PWB event. The composite of reflective cases (Fig. 3a) indicates that, in addition, following the termination of the initial wave train, a secondary wave train emerges two to three days later. The time delay is consistent with the predictions of critical layer theory [*Haynes*, 1989]. No such secondary wave train is observed for the composite of non-reflective PWB events (Fig. 3b).

PV intrusion events can lead to episodes of deep convection in the tropics, especially in winter [*Kiladis*, 1998]. Thus it might be suggested that the secondary wave train directed into the extratropics might have been excited by deep convection resulting from PWB. Such deep convection is readily detected in the field of outgoing longwave radiation (OLR). We found no evidence of enhanced convection (as indicated by anomalously low OLR) associated with the reflective PWB events. In fact, PWB is infrequent during the winter and early spring when such convective events have been noted. Upon finding no such signal, we postulate that the secondary wave train is indeed the result of nonlinear reflection.

4. Concluding Remarks

We have found evidence of planetary-wave reflection from PWB episodes in the upper troposphere using 44 years of re-analysis data. Almost a third of the PWB events resulted in a reflected wave train. Relaxing the first criterion of our PWB detection algorithm, so that 2 pvu (instead of 3 pvu) are equatorward of 1 pvu, increases the total number of PWB events (threefold). We find a slight decrease in the the percentage of PWB events resulting in nonlinear reflection among these smaller amplitude events (from 32% to 26%). This suggests that although wave amplitude is an important measure for determining the possibility of nonlinear reflection, other features, e.g., related to the background flow, are equally important.

Composites of the background flow reveal that for reflective events, the jet is more zonally oriented and extends further downstream than for non-reflective events. For reflective events, this translates into an enhanced latitudinal PV gradient downstream of the breaking point, which favors wave propagation. Conversely, the composite background flow for non-reflective PWB shows that the jet abruptly weakens and veers northward, creating a region of weak PV gradients downstream of the break. This reduced PV gradient downstream of the breaking point is not supportive of wave propagation and may lead to prolonged breaking and absorption of wave activity within the wave-breaking region.

Our main objective in this study was to quantify the number of reflective PWB events in observations over the length of the re-analysis record. Undoubtedly, the rather coarse spatial resolution ($2.5^\circ \times 2.5^\circ$) of the data, combined with the daily averages (rather than instantaneous observations) tend to reduce the number of events counted. Since most PWB events occur in certain areas and in certain seasons, anything that smooths the data, such as time averaging over a day and decreasing spatial resolution, will make it even harder to detect non-typical events. Even though other studies, using higher resolution data [e.g. *Scott and Cammas*, 2002] find robust wave breaking in the SH and in certain regions of the NH in winter (eastern Atlantic to Africa), they do note the concentration of events over the NH western Pacific outside of NH winter.

Nonlinear reflection may play a significant role in altering synoptic weather conditions, and possibly intraseasonal climate patterns. While a single breaking event resulting in reflection may play a role in establishing synoptic scale phenomena, repeated reflection episodes over the course of a season may play a larger role in affecting extratropical low-frequency variability. Future work will examine the role that nonlinear reflection plays in affecting low-frequency variability.

Acknowledgments. We thank Prof. Peter Haynes and Dr. George Kiladis for helpful comments on the manuscript, and Dr. Chris Walker for advice on the PWB algorithm. This work was supported by NSF grant ATM-0301800. We would like to thank the NOAA Climate Diagnostics Center for providing us with the NCEP-NCAR Reanalysis dataset as well as the ECMWF for the ERA-40 Reanalysis dataset.

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