J1.7

OPPOSING EFFECTS OF REFLECTIVE AND NON-REFLECTIVE PLANETARY WAVE BREAKING ON THE NAO

John T. Abatzoglou* and Gudrun Magnusdottir
University of California, Irvine, California

1. Introduction

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. As a wave train propagates to lower latitudes, where the westerly background weakens, the wave amplifies and acquires a strong NE-SW tilt (i.e. poleward momentum flux). 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). Figure 1 shows an example of a PWB event over the North Atlantic on 4 Feb. 1996.

Strong poleward eddy momentum fluxes associated with these "anticyclonic" PWB events (so-called because the breaking takes place on the anticyclonic side of the jet) may serve as a catalyst in exciting the most prominent mode of low-frequency variability over the North Atlantic, the North Atlantic Oscillation (NAO). Although upper tropospheric PWB is most frequently observed during the summer (JJA) over the western North Pacific and North Atlantic basins (Abatzoglou and Magnusdottir, 2004), a region of recurrent PWB (a so-called "surf zone") is evident in re-analysis data over the central and eastern subtropical North Atlantic during winter. Benedict et. al. (2004) investigated the synoptic characteristics of the intraseasonal NAO and found evidence that positive and negative NAO indices result from the remnants of anticyclonic and cyclonic wave breaking, respectively. Feldstein (2003) found that the life-cycle of the (high-frequency) NAO has a timescale of around two weeks and is driven primarily by nonlinear eddy vorticity fluxes. These results have been verified by simple dynamic modeling studies which have elucidated that the spatial and temporal characteristics of the intraseasonal NAO arise through variations in momentum fluxes (e.g. Vallis et al, 2004).

PWB can impact the large scale atmospheric circulation both in the tropics and extratropics. Studies in a hierarchy of models have shown that PWB may result in nonlinear reflection (or re-radiation) of planetary waves into midlatitudes (Walker and Magnusdottir 2003; Walker and Magnusdottir 2002; Magnusdottir and Walker 2000; Magnusdottir and Haynes 1999; Brunet and Haynes 1996) . This can profoundly influence the extratropical flow field. We have recently (Abatzoglou and Magnusdottir, 2004) found evidence in observations for nonlinear reflection into the extratropics following PWB. Here we will examine the consequences of PWB over the North Atlantic basin in winter on extratropical atmospheric flow. In particular, we will compare and contrast PWB events that are followed by nonlinear reflection to those events where wave activity is mostly absorbed at low latitudes.

We utilize daily mean upper tropospheric flow over 45 winters (Dec. 1958 to Feb. 2003) from NCEP-NCAR reanalysis to detect PWB over the subtropical North Atlantic sector. We objectively identify individual PWB

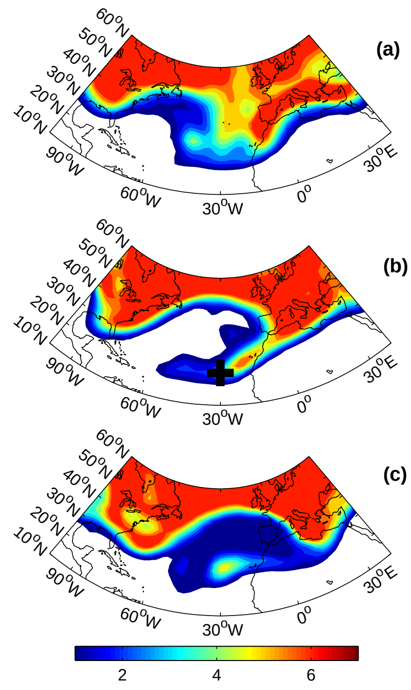

FIG. 1: A PWB event occurring on 4 Feb 1996. PV on the 340K isentropic surface is shown (a) two days prior, (b) on the day of, and (c) two days after PWB. The spot where breaking is first detected (according to the criteria in §2) is indicated by a heavy + symbol in (b).

*Corresponding author address: John T. Abatzoglou, Earth System Science, Croul Hall, Irvine, CA 92697-3100. email: jabatzog@uci.edu

events, and classify them according to whether they result in nonlinear reflection or not. We then composite all PWB events resulting in nonlinear reflection on the one hand, and all PWB events resulting in low latitude absorption on the other hand. We note strikingly different responses in the dynamics of the NAO life-cycle dependent on whether the PWB event results in nonlinear reflection of wave activity into midlatitudes or whether following PWB the wave activity is absorbed locally.

2. Methodology

We focus on PWB events occurring over the Atlantic sector between the months of December and February. PV on the 360, 350, 340 and 330K isentropic surfaces are examined to detect PWB. PWB events are diagnosed if they satisfy the following criteria involving the large-scale PV field:

1. There is a reversal in the latitudinal PV gradient about the tropopause such that a region of high PV (PV $>$ 2 PVU[1]) exists equatorward of a region of 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 is part of a tongue of PV originating in the extratropics (tropics).

To ensure that only one PWB event is counted per episode, all other events occurring within 30° longitude or within 4 days are discarded. Furthermore, in the case that PWB is simultaneously found on more than one level we only count the event on the highest isentropic surface.

Nonlinear reflection is diagnosed by using the latitudinal component of the 250hPa stationary wave-activity flux (Plumb, 1985). This diagnostic aims to capture events whereby the initial large equatorward wave-activity flux associated with the equatorward propagating Rossby wave train is reversed (i.e. directed poleward) downstream following the break (Magnusdottir and Haynes, 1999). The wave-activity flux is constructed from a nine-day average about the day when the PWB event is initially diagnosed. Reflection is noted if the area-averaged flux is poleward over the region 15-60° east and 10-20° poleward of the break (at the approximate latitude of the jet where the wave-activity flux is well defined). The strongest signal of reflection is observed in this area relative to the location of the wave breaking (as was seen in previous modeling studies (e.g., Walker and Magnusdottir 2003).

3. Results

A total of 491 PWB events are identified over the 45 winters. Most of these events were detected primarily on

[1] 1 PVU = 10^{-6} K m^2 s^{-1} kg^{-1}

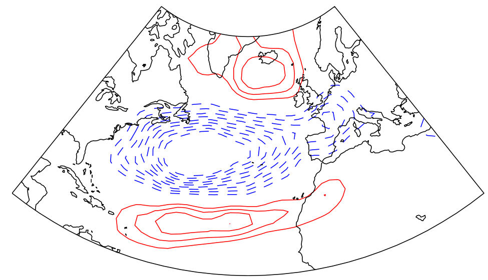

FIG. 2: Composite anomalous PV on the 350-K isentropic surface on the day of PWB. Contours exceeding 0.15 PVU are shown every 0.05 PVU.

the 330-K and 340-K surfaces coincident with the climatological three-dimensional structure of the subtropical tropopause (approximately the 2 PVU PV surface) over the North Atlantic. An example of such an event occurring on 4 Feb. 1996 over the eastern North Atlantic is shown in Figure 1. This breaking event exemplifies the meridional advection of low PV air poleward toward the Azores, and high PV air equatorward into the subtropics. The advection of low PV air over the Azores leads to a dramatic increase in geopotential heights. Concurrently, we observe a decrease in geopotential heights over the subpolar basin (approximate location of the Icelandic low). While the latter is not a direct consequence of wave breaking, it is a likely response manifested through anomalous eddy momentum fluxes which project onto the largest mode of internal variability over the North Atlantic region.

Composites of both reflective and non-reflective events are formed by shifting analyzed fields in time with respect to the day of the initial PWB diagnosis. Note that since these composite fields are not shifted with respect to the exact location of the break, we de-emphasize synoptic scale features, and instead focus on the evolution of large scale patterns over the North Atlantic. We examine both anomalous (deviation from 45-year daily mean) 300 hPa streamfunction fields, as well as the 300 hPa wave activity fluxes. While we focus on results at 300 hPa, the equivalent barotropic structure associated with these wave-like features holds throughout the depth of the troposphere over the North Atlantic region.

Reflective and non-reflective events show similar synoptic features prior to breaking. Precluding the PWB event we observe a zonally oriented wave train propagating over the North American continent along a strong PV gradient. Upon reaching the western North Atlantic the PV gradient (as well as zonal wind) drastically weakens thus allowing the wave to propagate equatorward toward the central subtropical North Atlantic basin. As the wave train approaches the critical layer in the subtropics, it amplifies and imposes a strong poleward momentum flux before nonlinearities take over and breaking occurs.

Directly resulting from PWB, low PV air (of tropo-

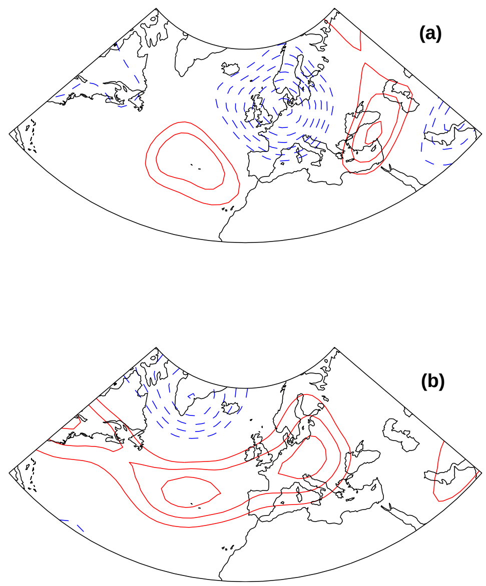

FIG. 3: Anomalous 300hPa streamfunction five days after PWB, for (a) reflective PWB, and (b) non-reflective PWB. Contours exceeding 2 x 10^6 m^2 s^{-2} are shown every 1 x 10^6 m^2 s^{-2}.

spheric origin) is advected anticyclonically poleward and eastward toward the Azores, while high PV air (of stratospheric origin) is advected equatorward and westward into the subtropics. Unique to PWB over the Atlantic, anomalously high PV is concurrently observed near the Icelandic low. This allows for the formation of a meridionally oriented tripole stretching from the subtropics to the subpolar region, of which the northern two nodes characterize the NAO (Fig. 2). Although the subtropical origin of wave breaking does not directly impact the subpolar node of the NAO, anomalous eddy momentum fluxes associated with PWB appear to excite this mode of variability.

Even though synoptic features prior to breaking are similar, profound differences arise between reflective and non-reflective events following the break. For reflective events (29% of all PWB), anomalies over the North Atlantic are rapidly translated into a poleward arching wave train over the Eurasian continent in the ensuing days. While hints of this wave train are evident two days following the break, a clear signal is seen extending well over Europe and into the Middle-East five days after the break (Fig. 3a). The signal of reflection is characterized by noting the reversed tilt (NW-SE) of the wave train emanating away from the breaking region.

Conversely, non-reflective events do not show evidence of wave propagation outside of the North Atlantic basin. Figure 3b shows the composite 300hPa streamfunction anomalies five days after the break. In the days following breaking, the subpolar and midlatitude anomalies amplify and remain stationary as a meridional dipole, akin to the NAO, while the subtropical anomaly dissipates (see Fig. 3b).

A composite of quasi-stationary wave activity flux is shown in Fig. 4a for the reflective PWB events. Reflection is clearly observed by noting how the strong southeastward directed flux off the North American continent is redirected northeastward poleward of the breaking region. The orientation of the wave activity flux vectors over the eastern North Atlantic and western Europe is indicative of export of wave activity out of the Atlantic basin, and is consistent with wave propagation over the continent (see Fig. 3a) . Associated with these quasi-stationary wave fluxes is a region of divergence (i.e. wave source) near the Azores, and a weaker region of convergence (i.e. wave sink) further poleward. Wave activity diagnostics imply a weakened or reversed eddy momentum flux, which acts to diminish the subpolar and mid-latitude anomalies over the North Atlantic, leading to the rapid decay of the NAO.

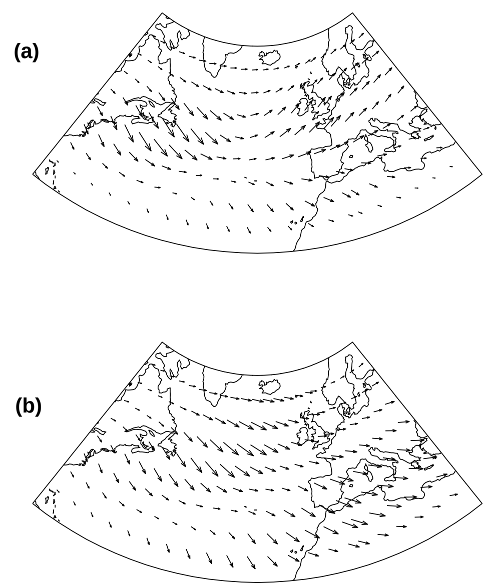

FIG. 4: Stationary wave activity flux for (a) reflective, and (b) non-reflective PWB events. Largest vector shown is of magnitude 100 m^2 s^{-2}.

For non-reflective events wave activity fluxes are clearly directed equatorward over the North Atlantic and Europe (Fig. 4b). A noted region of divergence exists at subpolar latitudes, while a region of convergence (wave absorption) lies over the Azores. In stark contrast to the reflective events, the quasi-stationary wave fluxes over the North Atlantic associated with nonreflective PWB appear to amplify the NAO through an enhanced poleward eddy momentum flux. Furthermore, continued equatorward wave activity flux over the basin encourages further wave breaking. These two features lead to the amplification of the positive phase of the NAO following nonreflective PWB.

The impact of transient features associated with

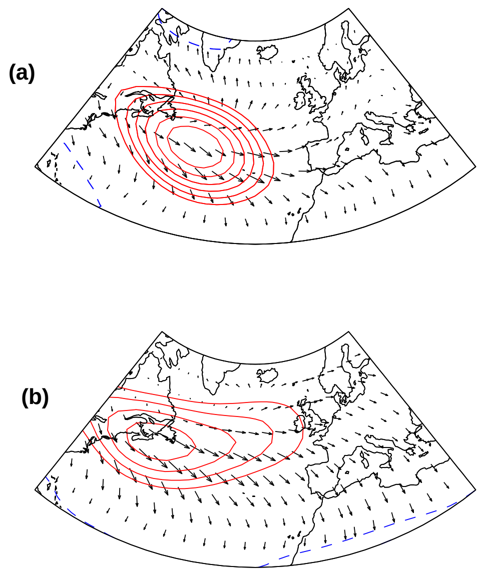

FIG. 5: 300hPa barotropic **E**-vectors and divergence for (a) reflective, and (b) non-reflective PWB events. Divergence (convergence) are shown by solid (dashed) contours exceeding 1 x 10^{-5} m^2 s^{-2} are shown every 5 x 10^{-6} m^2 s^{-2}.

PWB events are investigated by incorporating **E**-vectors (Trenberth, 1986), computed as 10-day high-pass filtered features averaged between four days before and four days after PWB. **E**-vectors detail both the shape and group velocity of the transients, while their divergence (convergence) implies acceleration (deceleration) of the westerlies. For both reflective and non-reflective composites of PWB, we observe large divergent **E**-vectors directed southeastward over the western Atlantic associated with the wave train responsible for PWB. Significant differences are apparent over the central basin. For reflective events **E**-vectors are directed poleward over the northern basin with a region of divergence extending southeastward toward the Azores (Fig. 5a). Non-reflective events show a general pattern of southeastward directed **E**-vectors across most of the basin with a more zonally oriented region of divergence extending eastward toward the United Kingdom (Fig. 5b). Wave-mean flow diagnostics indicate that transients associated with reflective (non-reflective) breaking act to accelerate, or shift, the jet equatorward (poleward). These results suggest that the high-frequency transients associated with reflective and non-reflective PWB also promote the decay and enhancement of the NAO, respectively.

As an objective means of documenting the opposing impact observed between reflective and non-reflective PWB we compute a time series which approximates the NAO index (NAOI). The NAOI is computed by applying the leading time series (i.e. principal components) of the first rotated EOF of daily 300hPa geopotential heights, following Feldstein (2000). A 4-day low-pass filter is then

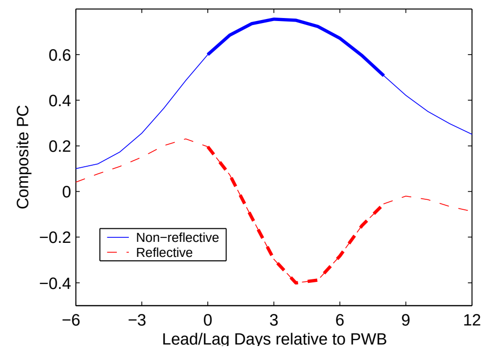

FIG. 6: Composite lead-lag NAOI for reflective (red dashed), and non-reflective (solid blue) PWB events. Bold lines show region where difference exceeds the 99% confidence interval.

applied to this time series to filter out sub-synoptic scale features. Daily lead/lag values mapped onto reflective and non-reflective cases of PWB are shown in Fig. 6. For reflective cases the NAOI peaks just prior to breaking, after which it rapidly subsides. Conversely, for non-reflective events, the NAOI becomes rather large and peaks four days after the break, persisting in a positive phase nearly ten days after the break.

4. Conclusion

This study detailed the opposing impacts of reflective and non-reflective subtropical PWB events on the intraseasonal behavior of the NAO. For reflective cases poleward reflection from the critical layer allows for the export of wave activity poleward and downstream over the Eurasian continent. However, for non-reflective cases, wave activity piles up within the North Atlantic basin, as if forming a cavity, resulting in the projection of what onto the NAO. Wave activity diagnostics suggest that the stationary and transient components act in tandem to organize the Rossby wave response following PWB.

Although the subtropical origin of wave breaking does not directly impact the subpolar node of the NAO, we suggest that perturbing the subtropical/midlatitude node of the NAO, results in the excitation of this internal mode of variability. Anomalous poleward eddy momentum fluxes concurrent with the PWB event also appear to play a role in the development of the NAO. In our study, the positive phase of the NAO develops as a wave train propagates equatorward near the jet exit toward weak zonal winds, imposing a strong poleward eddy momentum flux before breaking in the subtropics and leaving behind a meridional PV tripole (Fig. 2). While the most southerly node quickly dissipates through diabatic processes, the two northerly nodes remain strong as they overlap with the preferred mode of variability over the North Atlantic. In terms of simple eddy momentum flux arguments, non-reflective events exacerbate the anomalous poleward flux thus amplifying the NAO while reflective events reverse the momentum flux leading to the demise of the NAO.

We find a strong interannual correlation between the winter-mean NAOI and the number of PWB events. Changes in the basic state associated with the positive phase of the NAO lead to stronger equatorward wave activity flux and weaker subtropical winds, both of which act to precondition the subtropical Atlantic to PWB. While the basic state over the North Atlantic appears to influence wave breaking, we also suggest that the result of PWB, being reflective or non-reflective in nature, can feed back onto the basic state. By both amplifying the NAO and encouraging continual PWB, non-reflective PWB may form a positive feedback by which the NAO may be maintained over the course of a winter season.

5. Acknowledgment

This work is supported by NSF grant ATM-0301800.

REFERENCES

Abatzoglou, J. T. and G. Magnusdottir, 2004: Nonlinear planetary wave reflection in the troposphere. *Geophys. Res. Lett.*, **31**, 9.

Benedict, J., S. Lee, and S. B. Feldstein, 2004: Synoptic View of the North Atlantic Oscillation. *J. Atmos. Sci.*, **61**, 121–144.

Brunet, G. and P. H. Haynes, 1996: Low-Latitude Reflection of Rossby Wave Trains. *J. Atmos. Sci.*, **53**, 482–496.

Feldstein, S. B., 2000: The Timescale, Power Spectra, and Climate Noise Properties of Teleconnection Patterns. *J. Climate*, **13**, 4430–4440.

Feldstein, S. B., 2003: The Dynamics of NAO Teleconnection Pattern Growth and Decay. *Q.J.Roy.Meteorol.Soc.*, **129**, 901–924.

Magnusdottir, G. and P. H. Haynes, 1999: Reflection of Planetary Waves in Three-Dimensional Tropospheric Flows. *J. Atmos. Sci.*, **56**, 652–670.

Magnusdottir, G. and C. C. Walker, 2000: Nonlinear Planetary Wave Reflection in an Atmospheric GCM. *Q.J.Roy.Meteorol.Soc.*, **126**, 2725–2745.

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

Plumb, A. R., 1985: On the Three-Dimensional Propagation of Stationary Waves. *J. Atmos. Sci.*, **42**, 217–229.

Trenberth, K. E., 1986: An Assessment of the Impact of Transient Eddies on the Zonal Flow during a Blocking Episode Using Localized Eliassen-Palm Flux Diagnostics. *J. Atmos. Sci.*, **43**, 2070–2087.

Vallis, G. K., E. P. Gerber, P. J. Kushner, and B. A. Cash, 2004: A Mechanism and Simple Dynamical Model of the North Atlantic Oscillation and Annular Modes. *J. Atm. Sci.*, **61**, 264–280.

Walker, C. C. and G. Magnusdottir, 2002: Effect of the Hadley circulation on the reflection of planetary waves in three-dimensional tropospheric flows. *J. Atmos. Sci.*, **59**, 2846–2859.

Walker, C. C. and G. Magnusdottir, 2003: Nonlinear Planetary Wave Reflection in an Atmospheric GCM. *J. Atmos. Sci.*, **60**, 279–286.