Blocking and Rossby Wave Breaking on the Dynamical Tropopause in the Southern Hemisphere

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ABSTRACT

Rossby wave breaking on the dynamical tropopause in the Southern Hemisphere (the –2-PVU surface) is investigated using the ERA-40 dataset. The indication of wave breaking is based on reversal in the meridional gradient of potential temperature, and persistent large-scale wave breaking is taken as a strong indication that blocking may be present. Blocking in the midlatitudes is found to occur predominantly during wintertime in the Pacific and is most vigorous in the east Pacific, while during summertime, the frequency of blocking weakens and its extent becomes confined to the west Pacific. The interannual variability of blocking is found to be high. Wave breaking occurs most frequently on the poleward side of the polar jet and has some, but not all, of the signatures of blocking, so it is referred to as high-latitude blocking. In general, cyclonic wave breaking occurs on the poleward side of the polar jet, otherwise anticyclonic breaking occurs. However, at least in wintertime, wave breaking in the New Zealand/west to mid-Pacific sector between the polar and subtropical jets is a mixture between cyclonic and anticyclonic types. Together, episodes of wave breaking and enhanced westerly flow describe much of the variability in the seasonal Antarctic Oscillation (AnO) index and give a synoptic manifestation of it with a focus on the date line and Indian Ocean that is in agreement with the centers of action for the AnO. During summertime, anticyclonic wave breaking in the upper troposphere is also to be found near 30°S in both the Pacific and Atlantic, and appears to be associated with Rossby waves propagating into the sub tropics from the New Zealand region.

1. Introduction

Blocking in the atmosphere can have a major impact on all time scales of weather and climate. The synoptician may consider that blocking occurs when the usual midlatitude westerlies and transient weather systems are diverted to the north and south so that easterlies occur for several days on a spatial scale larger than the synoptic scale. Blocking in the Northern Hemisphere has been the subject of many studies, though its theoretical description is not complete and its prediction can still be problematic. However, blocking in the Southern Hemisphere is less well documented.

There has been some debate in the literature on the exact location of Southern Hemisphere blocking. That there are varying opinions on the location of blocking could be due to the different methods of identifying blocking, differing qualities of the datasets used, or real variability on interannual and longer time scales. However, the consensus of opinion seems to be that persistent anomalies including blocking are concentrated in the Pacific during wintertime where peaks can be found between 55° and 65°S in the west and east Pacific (Sinclair 1996). During summertime, this region shrinks and moves westward (Kiladis and Mo 1999). In winter and summertime, persistent anomalies are also to be found poleward of 50°S in the west Atlantic and in the mid latitude Indian Ocean (Trenberth and Mo 1985; Kiladis and Mo 1999).

Hoskins and Berrisford (1988) and Hoskins (1997) discussed the advantages of presenting diagnostics on
the surface where the potential vorticity (PV) magnitude is 2 PVU [where 1 potential vorticity unit (PVU) = $10^{-6}$ m$^2$ s$^{-1}$ K kg$^{-1}$], a surface that is thought to closely follow the position of the tropopause$^1$ and is referred to as the dynamical tropopause. On spatial scales relevant to blocking, reversal of the usual meridional gradient of potential temperature on the dynamical tropopause will generally be associated with an anomalously (potentially) warm tropopause on the poleward side and cold tropopause on the equatorward side. Furthermore, according to the invertibility principle (Hoskins et al. 1985; Hoskins 1997) a potentially warm (cold) tropopause is usually associated with anticyclonic (cyclonic) flow over some depth, which is consistent with the nature of blocking. Consequently, the reversal of the gradient of potential temperature on the dynamical tropopause is very likely to be associated with easterlies, and the westerlies will be displaced north and southward.

Rossby wave breaking is a process whereby the contours of PV on potential temperature surfaces, or of potential temperature on PV surfaces (and in particular potential temperature on the dynamical tropopause), become irreversibly deformed leading to mixing. This entails removal or reversal of the usual meridional gradients and as such, shares common features with blocking. If the wave-breaking process occurs on spatial and temporal scales similar to those of blocking then it might be expected to be recognized synoptically as a block. However, Hitchman and Huesmann (2007) found wave breaking prevalent in much of the troposphere and stratosphere and, even though they included smaller scale and transient breaking waves, it would not be expected that all wave breaking found here would be associated with blocking.

There are at least two distinct morphologies of wave breaking that are relevant to the Southern Hemisphere. In the first (Fig. 1a), the low potential temperature air on the dynamical tropopause moves equatorward and eastward to the west of high potential temperature air that moves poleward and westward. In the second structure (Fig. 1b), the equatorward and westward movement of the “cold” air is to the east of the poleward and eastward movement of the “warm” air. In the following, we will refer to wave-breaking structures with these morphologies as cyclonic and anticyclonic breaking structures, respectively. The distinction between these two morphologies is important because they have different synoptic characteristics, and different transport and mixing properties are likely.

$^1$ Note that for the Southern Hemisphere the relevant surface is ~2 PVU.

With the above discussion in mind, Pelly and Hoskins (2003, hereafter PH) documented Northern Hemisphere blocking using a daily index based on meridional differences of potential temperature on the dynamical tropopause. They looked for a reversal of the usual equatorward gradient of potential temperature in the region where the storm track usually occurs, the latitude of which was allowed to vary with longitude. Using their methodology, they found general agreement with a blocking climatology based on the Tibaldi and Molteni (1990) 500-hPa geopotential index at a constant latitude. However, they also found substantial differences, which were mostly related to the use of a constant latitude in Tibaldi and Molteni (1990). The methodology of PH is attractive because it is based on the PV/potential temperature framework with its theoretical and conceptual advantages and associates blocking with the unique physical process of wave breaking.

For the Northern Hemisphere, PH found that blocking has two characteristic time scales. The short time scale, 2 days, is thought to be related to synoptic activity whereas the midrange time scale, nearly 4 days, is probably more associated with slow processes such as the radiative decay or migration of large-scale cut-off PV anomalies, and reinforcement through the organization of transient eddy fluxes of PV (Shutts 1983; Hoskins and Sardeshmukh 1987).

In this work we investigate Rossby wave breaking on the dynamical tropopause in the Southern Hemisphere using the latest 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis dataset (ERA-40). The primary interest of this work is to study blocking, so the main focus is on wave breaking that is likely to be associated with blocking. Using a wave-breaking index similar to that of PH the seasonal dependence and spatial location of the frequency of wave breaking is investigated in both 1D and 2D geographical frameworks and any characteristic time scales are determined. The morphologies of the composite
structures of wave breaking in certain regions are presented and it is discussed whether or not they resemble blocking as commonly understood. Finally, the occurrence of wave breaking is correlated with the Antarctic Oscillation (Thompson and Wallace 2000), which is the leading mode of variability in the Southern Hemisphere.

This paper is organized in the following way. The methodology and data sources are described in section 2. In section 3, wave breaking centered along a single line around the Southern Hemisphere is investigated while in section 4, wave breaking is investigated as a function of both latitude and longitude. Section 5 gives examples of wave-breaking structures found in various regions of the Southern Hemisphere, and section 6 presents correlations between wave breaking and the Antarctic Oscillation (AnO). Finally, section 7 presents some discussion and conclusions.

2. Methodology and data

The methodology of PH is used here to define wave breaking as a reversal of the usual equatorward gradient of potential temperature on the dynamical tropopause over suitable spatial and temporal scales. The basic measure is the instantaneous wave-breaking index computed in the following manner. The daily average of the difference is taken between the average potential temperature in two regions of dimensions 15° latitude by 5° longitude. The first region is immediately poleward of a certain latitude, called the central wave-breaking latitude, and the second is immediately equatorward of it. The calculation is repeated at 4° to the north and south of the central wave-breaking latitude and the highest value is chosen as the wave-breaking index value. The index is evaluated at 5° longitude intervals. For the study of wave breaking in 1D, the central wave-breaking latitudes are specified to be along the axis of the storm track. Following PH, this is defined as the location of the meridional maximum of the smoothed 250-hPa transient eddy kinetic energy (TEKE), which is calculated from the 2- to 6-day band-pass-filtered ERA-40 winds (Kallberg et al. 2005). For the study of wave breaking in 2D, the central wave-breaking latitudes range from 25° to 73°S, using a 4° latitude interval. When the wave-breaking index is positive; that is, the potential temperature in the poleward region is higher than in the equatorward region, instantaneous wave breaking is said to occur.

Instantaneous wave breaking described above takes no account of the longevity or longitudinal scale of the reversal. Large-scale wave breaking is defined to occur when the wave-breaking index is positive for a minimum of approximately 1100 km in the longitudinal direction, corresponding to about 15° of longitude in the midlatitudes. A wave-breaking “event” is said to occur at a particular longitudinal point when large-scale wave breaking occurs within 10° of longitude of it. It might be questioned whether this definition should involve searching for large-scale wave breaking over a fixed length scale, which would be expected to increase the frequencies at high latitudes.

The wave-breaking lifetime is the duration of the wave-breaking event. A wave-breaking “episode” is defined to occur when the lifetime is at least 4 days. An experiment using at least 5 days gave similar results but with frequencies reduced by about 25%. This is consistent with the tropospheric circulation in the Southern Hemisphere being more transient in nature than in the Northern Hemisphere where, for example, 5 days was used by PH. Throughout this work, the wave-breaking episode frequency (WEF), defined as the percentage of days when an episode is present, is used as the basis for discussion.

Following PH, the determination of wave-breaking time scales is carried out by first calculating the natural logarithm of the average number of cases where the wave-breaking lifetime is at least a given number of days. Linear regression is then used to compute the slope of the straight line fit and hence the synoptic time scale for cases lasting up to 3 days, and the midrange time scale for days 5 to 15.

The monthly values of the AnO index were downloaded from the Climate Prediction Center. The daily wave-breaking index is defined from the ERA-40 dataset for the period December 1957 to November 2001 using the 6-hourly potential temperature on the 2-PVU surface interpolated to the full-resolution, full Gaussian grid (approximately 1.125° × 1.125°). It should be noted that in the Southern Hemisphere these reanalyses suffer from a lack of observational data, particularly in the early years. However, the quality of the reanalyses is better after 1978, when satellite data became abundant, and is thought to subsequently approach that of the Northern Hemisphere (Uppala et al. 2005). Here, we will refer to the period December 1957 to November 1978 as the presatellite era and December 1978 to November 2001 as the satellite era.

Because PV changes sign between the two hemispheres, the ±2-PVU surfaces cannot be located in the ERA-40 data for grid points close to the equator. When this occurs during interpolation of fields to these surfaces, the ECMWF postprocessor inserts the value of the field on the model level closest to 96 hPa. At this level, tropical values of potential temperature are of the order of 380 K. So, in the following, it must be remem-
bered that where such values occur it probably indicates that the $-2$-PVU surface is not present.

3. Wave-breaking frequencies in 1D

Figure 2 shows the latitudes of the meridional maxima in the smoothed 250-hPa TEKE as a function of longitude for the Southern Hemisphere for the solstitial seasons and the annual mean. It can be seen that in the Australian/west Pacific sector the climatological wintertime jet stream is split into subtropical and polar branches, the latter being the eddy-driven jet at the base of the polar night jet. Both of these branches are associated with a local maximum in TEKE. The polar maximum extends near to 60°S while the subtropical maximum extends near to 30°S and the latitude of the subtropical maximum varies by more than 15° around the globe while that of the polar maximum varies by more than 20°. Furthermore, these latitudes are far from the annual (and summertime) mean values, which are single valued everywhere and vary from about 47° to 53°S, showing less latitudinal variation than their Northern Hemisphere counterparts. Because of the difficulty associated with the split jet in winter, the annual mean TEKE latitudes are used to define the central wave-breaking latitudes for both summer and wintertime. The resulting latitude values are similar to those of Tibaldi et al. (1994) who used 50°S ± 3.75°.

The 1D WEFs show that during wintertime (June–August; JJA) wave breaking is concentrated in the Pacific and neighboring regions (Fig. 3a), while during summertime (December–February; DJF) the frequencies are smaller and, at least during the satellite period, are concentrated in the west Pacific (Fig. 3b). This result agrees with the consensus of opinion on blocking discussed in the introduction. For the satellite years, during JJA, the WEFs are at least 10% between 150°E and 70°W with a peak approaching 15% in the west.
Pacific and 13% in the east. The latter is nearly twice as high as that found by Tibaldi et al. (1994). Also for the satellite years in DJF, the WEFs are near 6% between 180° and 140°W, which is only about 60% of that found by Tibaldi et al. (1994). The WEFs in the presatellite period are much smaller than in the satellite years, with the peak reduction in JJA about 28% and in DJF about 65%.

For both winter and summertime the high values of WEF are downstream (and upstream) of high values of zonal wind and TEKE (Fig. 3), in agreement with the findings of PH and the observation that wave breaking is confined to regions of weak zonal winds (Peters and Waugh 1996, 2003). This probably occurs because large PV gradients, which are usually associated with strong winds, allow the propagation of Rossby waves but tend to form a barrier to mixing (McIntyre and Palmer 1983), so the waves can only break where the winds become smaller. This is consistent with the behavior of the simplified system of Swanson (2000), where the wave activity accumulates and the geopotential field experiences strong local amplification when the local zonal wind decreases through some threshold value.

Figure 4 shows the annual WEF as a function of longitude for the 44 years from December 1957 to November 2001. Again, it is apparent that there is a concentration of wave breaking from 120°E eastward to 60°W. It is also apparent that wave breaking is more prevalent in the satellite period than the presatellite period. This increase in frequency almost certainly reflects the lower observational data quality and volume in the earlier years. For this reason, from this point onward, the time period of interest will be restricted to the relatively data rich satellite years.

The new and striking aspect seen in Fig. 4 is the large interannual variation that is present even within the satellite years. For example, near the date line in 1988, the WEFs are below 5%, whereas in 1992 they reach over 20%. Indeed, WEFs are mostly above 10% from 1991 to 1995 over much of the region between 170°E and 110°W.

On defining the central wave-breaking latitudes using the wintertime TEKE latitudes for both the polar and subtropical jets, the WEF during JJA decreases to nearly zero in places. This large sensitivity suggests the necessity that this aspect should be investigated more thoroughly and this is done in the next section.

4. Wave-breaking frequencies in 2D

In this section, the WEFs are determined as a function of latitude as well as longitude, that is, in 2D. The WEFs are displayed at the central wave-breaking latitude. The associated anticyclones and cyclones will be located poleward and equatorward of this latitude, respectively, and will have spatial scales consistent with our methodology; that is, of order 15° of latitude and at least 1100 km in the longitudinal direction.

Figure 5 shows the wintertime 2D WEFs for the satellite period of ERA-40. In midlatitudes (from about 45° to 55°S) a region extends eastward from about 150°E to 70°W in which the values of WEF are greater than 10%. In the midlatitudes, WEFs are highest in the east Pacific where values are greater than 15% between about 110° and 80°W. Additionally, WEFs are greater than 5% in the midlatitudes of the eastern Indian Ocean and Australian sectors. At high latitudes (from
about 60° to 70°S), there is another band of large WEFs with values above 10% beginning near 170°W and extending eastward to about 110°E. Between about 150° and 15°W, the WEFs are greater than 15% with a peak exceeding 20% in the Atlantic near 40°W.

The midlatitude wave-breaking results are consistent with the consensus of opinion discussed in the introduction that blocking is concentrated in the Pacific during JJA. The high frequencies in the high-latitude east Pacific have some similarities with the results of Sinclair (1996) and Kiladis and Mo (1999), while in the west Atlantic there is some agreement with Trenberth and Mo (1985). Nevertheless, the present results do appear to emphasize wave breaking at high latitudes, though they are not inconsistent with the prevalence of high-latitude wave breaking found in the troposphere and lower stratosphere by Hitchman and Huesmann (2007).

It is clear from Fig. 5 why the 1D results for JJA are sensitive to the choice of central wave-breaking latitude. The annual mean TEKE latitudes sample the midlatitude wave-breaking region seen in the 2D results giving rise to the 1D picture shown in Fig. 3. However, the wintertime TEKE latitudes for the polar and subtropical jets sample low- and high-latitude regions where the values of WEF are very different.

Blocking may be interpreted as an interruption of the usual westerly flow and eastward movement of transient weather systems. To discuss whether the events in all locations may be described as blocking, it is necessary to discuss the location of the wintertime wave-breaking regions with respect to the storm track and the ambient zonal flow at the tropopause and close to the surface. The subtropical jet on the dynamical tropopause picks up in the Indian Ocean and reaches a maximum in the west Pacific (Fig. 6a). In the Atlantic, the jet is in middle latitudes, and in the Indian and Pacific Oceans, the polar jet spirals in toward Antarctica. The same field at 10 m (Fig. 6b) shows a ring of maxima around middle latitudes that is nearer the pole in the Pacific and has its largest values in the Indian Ocean. The 250-hPa TEKE distribution (Fig. 6c) generally reflects that of the tropopause zonal winds but the highest values are in the middle latitudes from the east Pacific through the Atlantic to the Indian Ocean. The midlatitude band of frequent wave breaking is located on the

![Fig. 6. JJA climatologies during the satellite years of (a) zonal wind on −2 PVU with contours every 10 m s$^{-1}$, an additional contour at 15 m s$^{-1}$ in bold and the zero contour is omitted, (b) zonal wind at 10 m with contours every 4 m s$^{-1}$, the bold contour is 4 m s$^{-1}$ and negative values are dashed, and (c) 250-hPa TEKE with contours every 25 m$^2$ s$^{-2}$ and the bold contour is 50 m$^2$ s$^{-2}$. In each case, the shading indicates a WEF of at least 10% and the domain extends to 20°S.](http://journals.ametsoc.org/jas/article-pdf/64/8/2881/3494653/jas3984_1.pdf)
poleward side of the polar jet in the east Indian Ocean near 105°E. It crosses the poleward spiraling jet so that in the New Zealand region through to the mid-Pacific, it is located on the equatorward flank of the polar jet downstream from the large TEKE. In the east Pacific, frequent midlatitude wave breaking occurs within the region of weak westerly winds at the end of the polar jet on the poleward flank of the subtropical jet and maximum in TEKE. The high-latitude band of frequent wave breaking in the Pacific, Atlantic, and Indian Oceans is located on the poleward side of the polar jet.

It is clear that in the Pacific, apart from the very high latitudes, the region of wave breaking with WEF greater than 10% is in a region where the average tropopause westerlies are greater than 15 m s⁻¹ (Fig. 6a), near surface westerlies are greater than 4 m s⁻¹ (Fig. 6b) and 250-hPa TEKE is greater than 50 m² s⁻² (Fig. 6c). So it might be reasonable to refer to the wave breaking here as blocking. However, the regions with WEF greater than 10% in the Atlantic and Indian Oceans and in the very high latitudes in the Pacific are to the poleward side of the mean upper jet, where the mean surface winds are quite weak and the mean TEKE is relatively small. Therefore, it is debatable whether such wave-breaking events should be considered to be blocking.

From the number–longevity plot in Fig. 7 it is apparent that during JJA wave breaking at high latitudes (61° to 69°S) is longer lived than in the midlatitudes (45° to 53°S). Fitting straight lines in the two time ranges indicates that the midlatitude structures have a synoptic time scale of 1.7 days and a midrange time scale of 2.1 days whereas at high latitudes the time scales are 2.0 and 2.5 days, respectively. Consistent with the more transient nature of the Southern Hemisphere troposphere, the midlatitude time scales are smaller than those found by PH for the Northern Hemisphere. Furthermore, the midrange time scales are only about 25% greater than their synoptic counterparts compared with a near 100% increase for the Northern Hemisphere.

WEFs in 2D for summertime are shown in Fig. 8. The midlatitude band of high WEF is now apparent only from the 5% contour in the west Pacific between about 170°E and 130°W and peak values are less than 7%. Again, this is consistent with the 1D results in section 3 and with the consensus of opinion discussed in the introduction that Southern Hemisphere blocking is weak during the summertime and concentrated in the west Pacific. The high-latitude band of WEF is more intense than during JJA with values throughout much of the region above 20%, and peak values greater than 30% near 90°W and 30°E. There are also two further areas of high WEF situated at low latitudes. The first stretches from Australia to the east Pacific and the second from South America to the mid-Atlantic. (There is a third such region in the west Indian Ocean but the values there only just exceed 5%.) The two main regions exhibit peak frequencies above 15% centered on 29°S in the mid-Pacific and west Atlantic. Wave breaking in similar regions was also identified by Postel and Hitchman (1999) and found to be associated with subtropical highs.

For DJF the subtropical jet is very weak and confined near the date line (Fig. 9a). The polar jet encircles the globe, being strongest between 30°W and 130°E, and is weakest in the west and central Pacific. The 250-hPa TEKE is maximized near the polar jet and is relatively weak in the Pacific and west Atlantic (Fig. 9b).
only region with WEF greater than 5% and significant westerly flow and TEKE is that in the midlatitude Pacific between 170°E and 130°W and is situated in the weakest part of the polar jet downstream from the TEKE maximum. The majority of the high-latitude regions of frequent wave breaking are now poleward of both the main westerly flow and regions of high TEKE. The areas of frequent wave breaking at low latitudes are on the equatorial side of the jet and region of significant TEKE. Therefore, only the wave breaking in the midlatitude Pacific appears to be a strong candidate for being referred to as blocking.

Again, the wave-breaking time scales appear to depend on latitude (Fig. 10). The low-latitude (29° to 33°S) structures have a synoptic time scale of 1.8 days and a midrange time scale of 2.4 days, in midlatitudes, the time scales are 1.4 and 2.0 days, and at high latitudes, the time scales are 2.5 and 3.3 days, respectively. So for DJF, the midrange time scales are at least 30% greater than the synoptic ones.

On the whole, wave breaking in the presatellite period is less frequent than in the satellite period, although the distributions of WEF are quite similar (not shown). For the early period, WEFs in the midlatitudes do not reach much above 10% during JJA while in DJF they are below our (arbitrary) contour threshold of 5%.

5. Wave-breaking structures

In previous sections the distribution of frequent wave breaking was explored and it was discussed whether all such wave breaking could be considered to be blocking.

As a further contribution to this discussion, the structure of the phenomena will now be examined by creating composites for wave-breaking episodes at representative point locations in regions of interest. These composite structures are also of interest for the indications they give of the nature of wave breaking in different regions. The mature phase of a wave-breaking episode is defined as the period of the episode omitting its first and last days, and the onset day is its first day.

In the previous section it was found that wintertime wave breaking is concentrated in midlatitude and high-latitude bands. Investigation of the composites suggests a slightly different characterization. The structures and their development appear to be related to their position relative to the polar jet. The location of the composites is indicated in Fig. 5 by a letter that refers to the order of their position in the figures in this section. Structures
located within or on the equatorward side of the jet will be discussed first.

In the New Zealand/west Pacific region, small-amplitude Rossby waves on the dynamical tropopause appear to propagate along the polar jet, as seen one day before the onset of wave breaking in Fig. 11a. The waves begin to break in an anticyclonic fashion but when the equatorward moving potentially cold tropopause air² (from here on the word potentially will be omitted) approaches the subtropical jet they appear to break in a cyclonic fashion and become cut off, consistent with advection in the cyclonic environment of the subtropical jet. In some individual cases, the poleward displaced warm tropopause air is advected downstream, but can be reinforced by advection to the east of the cut-off cold tropopause air and from upstream. The net result is the mature phase dipole system containing a rather diffuse warm region and cut-off cold region whose composite is shown in Fig. 12a. Wave breaking here could be described as a mixture between cyclonic and anticyclonic types.

In the mid-Pacific, the cyclonic breaking becomes more dominant, which is consistent with the subtropical jet extending farther poleward. In the east Pacific, where the subtropical jet is relatively weak, the waves break in an anticyclonic fashion, as shown by composites for one day before the onset of wave breaking in Fig. 11b and the mature phase in Fig. 12b. For the mature phase, it can be seen that the western tip of the trough has cut off from the main trough, consistent with its thinning and weakening as it is pulled westward away from the main trough.

These structures located on the equatorward side of the polar jet are deep, having signatures that reach the ground as indicated by their mean sea level pressure (MSLP) composites (Figs. 13a,b).

Wintertime wave-breaking structures located on the poleward side of the polar jet occur in the midlatitude east Indian Ocean and in the high latitudes at all longitudes outside of the region 120°E to 180°E, where the polar jet reaches its most southern position. From the composites one day before the onset of wave breaking in Figs. 11c–f and the mature structures in Figs. 12c–f, it is evident that these episodes break in a cyclonic fashion, consistent with advection in the cyclonic environment of the polar jet. The mature structures are mostly dominated by the region of polar tropopause air in the trough (Figs. 12c,d,f), though the lower latitude air is quite evident in the Pacific (Fig. 12e). Except in the Atlantic where the trough is cut off to give a dipole structure (Fig. 12f), the trough usually remains connected to the polar vortex (Figs. 12c–e). The MSLP signatures appear to be dominated by the cyclonic regions (Figs. 13c–f). However, studying the composite MSLP anomalies reveals an anticyclone situated over most of the Antarctic continent, which is usually strongest at the longitude of the cyclone, an example of which is shown for the high-latitude Indian Ocean in Fig. 14.

Inspection of individual episodes and composites leading up to the mature phase of wave-breaking episodes in the high-latitude Atlantic indicates that this can be preceded by midlatitude wave breaking in the east Pacific. The troughs of the anticyclonically breaking waves in the midlatitude east Pacific can subsequently move downstream and give rise to the troughs of cyclonically breaking waves seen in the high-latitude Atlantic. Further evidence for this association is that the WEFs for both phenomena are larger during El Niño winters than La Niña winters (not shown).

Figure 15 shows composites of potential temperature on the dynamical tropopause for various locations in DJF, and Fig. 16 shows four of the corresponding composites of MSLP. The position of these composites is indicated in Fig. 8 with the labels “a” to “f”. The structure of midlatitude wave breaking in the New Zealand region during DJF is that of a cyclonically breaking wave (Fig. 15a). Farther east where the zonal winds of both the polar and subtropical jets are slightly weaker, wave breaking has an anticyclonic structure (Fig. 15b). Again, these midlatitude structures are deep with a signature at the surface (Figs. 16a,b). Wave-breaking episodes on the poleward side of the polar jet only occur at high latitude in DJF, again outside of the region 120°E to 180°E and, as for JJA, break in a cyclonic fashion. In the east Pacific, the polar tropopause air forms a cutoff to produce a dipole system (Fig. 15c), while in the western Indian Ocean the polar tropopause air tends to remain connected to the polar vortex (Fig. 15d). The high-latitude structures are visible at the surface, but the anticyclonic components in particular are weak (Figs. 16c,d).

The summertime structures in the subtropical mid-Pacific and west Atlantic exhibit anticyclonic wave breaking (Figs. 15e,f). The signatures do not extend down to the lower troposphere as equivalent barotropic structures, though a weak anticyclonic anomaly is present equatorward of the one situated at the tropopause. The natural ratio of scales suggests that the vertical penetration of PV anomalies of a fixed size is proportional to the Coriolis parameter and, furthermore,
Fig. 11. Composites of potential temperature on ~2 PVU during JJA for one day before the onset of wave-breaking episodes at (a) 53°S, 165°W, (b) 53°S, 90°W, (c) 65°S, 90°E, (d) 53°S, 110°E, (e) 61°S, 120°W, and (f) 61°S, 30°W. The approximate positions of these composites are marked in Fig. 5 with the labels “a” to “f” and here with a dot. The contour interval is 2.5 K below 325 K, then 5 K above and the bold contour is 330 K. In each case, the domain extends to 30°S.
Fig. 12. Composites of potential temperature on ~2 PVU during JJA for the mature phase of wave-breaking episodes at (a) 53°S, 165°W, (b) 53°S, 90°W, (c) 65°S, 90°E, (d) 53°S, 110°E, (e) 61°S, 120°W, and (f) 61°S, 30°W. The approximate positions of these composites are marked in Fig. 5 with the labels “a” to “f” and here with a dot. The contour interval is 2.5 K below 325 K, then 5 K above and the bold contour is 330 K. In each case, the domain extends to 30°S.
Fig. 13. Composites of MSLP during JJA for the mature phase of wave-breaking episodes at (a) 53°S, 165°W, (b) 53°S, 90°W, (c) 65°S, 90°E, (d) 53°S, 110°E, (e) 61°S, 120°W, and (f) 61°S, 30°W. The approximate positions of these composites are marked in Fig. 5 with the labels “a” to “f” and here with a dot. The contour interval is 5 hPa and the bold contour is 1000 hPa. In each case, the domain extends to 30°S.
the height of the tropopause increases equatorward. Therefore, it is to be expected that the signature of wave breaking on the dynamical tropopause will penetrate down to the surface more readily at higher latitudes than at lower latitudes.

These summertime subtropical structures are associated with subtropical highs and their downstream mid-ocean troughs (Postel and Hitchman 1999). It appears that material from higher latitudes can be drawn equatorward and westward on the eastern flanks of the subtropical highs resulting in amplification of the climatological midocean troughs. Composites of 250-hPa streamfunction anomalies leading up to and including the mature phase of wave breaking indicate that these structures may be the result of the propagation into the subtropics of Rossby wave trains emanating from the New Zealand and Australian sectors and possibly farther west. This is illustrated for one day before the onset of wave-breaking episodes in Fig. 17. For the Pacific case there also appears to be an influence from the tropical Pacific (not shown).

6. Correlations with the AnO

The AnO is associated with anomalous winds concentrated in the 50° to 70°S band (Wallace and Thompson 2002). Wintertime wave breaking in the Southern Hemisphere is associated with easterly winds in a similar latitude band so it would not be unreasonable to suspect an association between wave breaking and the AnO. This possibility is supported by the (anti)correlation between the seasonal WEF and the seasonal AnO index for the 23 winters from 1979 to 2001 (Fig. 18). The magnitude of the correlation is above the 95% confidence threshold of 0.44 in the New Zealand sector (where the maximum magnitude is about 0.7) and the mid- to east Indian Ocean.

Using the wave-breaking index it is also possible to consider the opposite situation to wave breaking, that is, episodes involving strong potential temperature gradients with associated enhanced westerly winds. Strong episode frequencies (SEFs) for JJA were constructed in a similar manner to WEFs by considering cases when the wave-breaking index was less than −10 K. The correlation between the seasonal SEF and the seasonal AnO index is above the 95% confidence threshold near 60°E and eastward from the mid-Indian Ocean toward South America (Fig. 18). The largest values (above 0.7) are to be found in the Australian sector.

7. Discussion and conclusions

This study has focused on producing winter and summertime climatologies of wave breaking on the dynamical tropopause (the −2-PVU surface) in the Southern Hemisphere. Although the midlatitude wave breaking is either situated downstream, or on the flank, of the polar jet and its associated transient activity, it nevertheless occurs in regions where the climatological wind and transient activity are still significant. Consequently, the wave-breaking structures in these regions will deflect or block the westerly flow and transient eddies. Furthermore, these structures span the troposphere and so it is reasonable to assume that these wave-breaking episodes depict blocking as commonly understood. The midlatitude wave-breaking frequencies are in general qualitative agreement with the consensus of opinion that Southern Hemisphere blocking is predominantly a wintertime phenomena that is concentrated in the Pacific and maximized in the east Pacific, while during summertime it is less frequent and confined to the west Pacific.

The morphologies of wave-breaking episodes depend on the approximate position of the central wave-breaking latitude relative to the polar jet and are consistent with the environmental shear of the climatological flow. In general, episodes situated on the poleward side of the jet break in a cyclonic fashion, otherwise they break in an anticyclonic fashion. However, during wintertime at least, the climatological split jet complicates this straightforward picture. A mixture between cyclonic and anticyclonic wave breaking occurs in the...
Fig. 15. Composites of potential temperature on ~2 PVU during DJF for the mature phase of wave-breaking episodes at (a) 53°S, 170°W, (b) 53°S, 145°W, (c) 69°S, 90°W, (d) 69°S, 30°E, (e) 29°S, 125°W, and (f) 29°S, 35°W. The approximate positions of these composites are marked in Fig. 8 with the labels “a” to “f” and here with a dot. For (a)–(d) the contour interval is 2.5 K below 325 K, then 5 K above, while for (e) and (f), the contour interval is 5 K. In all cases, the bold contour is 330 K. The shading in (e) and (f) indicates where the climatological DJF total column heating is at least 50 W m⁻². For (a)–(d) the domain extends to 30°S, and for (e) and (f) the domain extends to 0°S.
midlatitude New Zealand/west Pacific region on the equatorward flank of the polar jet, in the vicinity of the cyclonic environment of the poleward side of the subtropical jet. The cyclonic breaking becomes more dominant through to the mid-Pacific as the subtropical jet spreads poleward. In the midlatitude east Pacific, however, where both the subtropical and polar jets are relatively weak, anticyclonic breaking occurs.

For wintertime the 1D results suggest that wave breaking is more frequent in the midlatitude west Pacific than the east Pacific. However, the 2D results show the opposite and other work supports this (Sinclair 1996; Kiladis and Mo 1999). (In this case, the 1D results are slightly misleading because in the east Pacific the central wave-breaking latitudes defined by the axis of the storm track do not sample the region of highest WEFs.) Furthermore, requiring the wave-breaking index to be greater than some positive value (rather than zero) diminishes WEFs in the midlatitude west Pacific relative to those in the east (not shown) and the amplitude of the Rossby waves appears to be stronger in the east Pacific than the west (cf. Fig. 11b with Fig. 11a). The difference in the strength of midlatitude blocking between the east and west Pacific might be because the east Pacific could be influenced by synoptic eddies from both the polar and subtropical jets, or possibly the east Pacific is in a better position to be influenced by wave trains emanating from the near equatorial west Pacific region of convective organization. However, the major reason is probably that the east Pacific is downstream from the polar jet, so is situated in a region where both wave breaking and blocking are usually thought to occur (Peters and Waugh 1996, 2003; Swanson 2000; PH). Blocking in the midlatitude west Pacific occurs on the

![Fig. 16. Composites of MSLP during DJF for the mature phase of wave-breaking episodes at (a) 53°S, 170°W, (b) 53°S, 145°W, (c) 69°S, 90°W, and (d) 69°S, 30°E. The approximate positions of these composites are marked in Fig. 8 with the labels “a” to “d” and here with a dot. The contour interval is 5 hPa and the bold contour is 1000 hPa. In each case, the domain extends to 30°S.](image-url)
flank of the polar jet where it might be expected that the wave-breaking dynamics are very different to those near the end of the jet.

Hitchman and Huesmann (2007) found high-latitude wave breaking to be prevalent in the troposphere and lower stratosphere and the current work showed that the largest values of WEF are situated on the poleward side of the polar jet where magnitudes can be greater than 20% in winter (Fig. 5) and 30% in summer (Fig. 8). These cyclonically breaking episodes occur in the mid-latitude eastern Indian Ocean during JJA and at many longitudes poleward of 60°S in both winter and summertime. Although their structures span the troposphere, they tend not to block the westerly flow and transient eddies because their location is on the poleward side of the region of large climatological westerlies and TEKE. Furthermore, at least in wintertime outside the Pacific, the potential temperature structures on the dynamical tropopause are dominated by the polar air. The high-latitude wave-breaking episodes have some of the signatures of blocking, but not all. However, particularly in the Pacific during wintertime, there appears to be a continuum between the middle-latitude events that have all the characteristics of blocking and the very-high-latitude wave-breaking events. Here, we have taken a pragmatic approach and chosen to associate wave breaking with classical blocking when the structures span the troposphere, have the synoptic appearance of blocking, and occur in a region where the climatological westerly flow is greater than 15 m s⁻¹ on the dynamical tropopause, greater than 4 m s⁻¹ near the surface, and where the 2- to 6-day 250-hPa TEKE is greater than 50 m² s⁻². On the poleward side of such regions, we refer to the phenomena as high-latitude blocking.

In wintertime, wave breaking (which is associated with easterly winds) occurs in the latitude band between 50° and 70°S, which is similar to that of the anomalous winds in the AnO. The latter is the leading
mode of variability in the Southern Hemisphere and wave breaking is significantly (anti)correlated with it in the New Zealand sector and in the mid- to east Indian Ocean. Both of these regions are situated in the vicinity of the centers of action of the AnO (Wallace and Thompson 2002). Interestingly, the AnO is weakest in the midlatitudes of the east Pacific, which is the only region where anticyclonic wave breaking occurs. The latitudinal signature of blocking and wave breaking, where an anticyclone lies on the poleward side of a cyclone (see the composite MSLP anomaly for high-latitude blocking in Fig. 14), is similar to that of the negative phase of the AnO. Unlike that of the AnO, the signature of a wave-breaking episode does not occur on a hemispheric scale, although these local wave-breaking episodes do occur at many longitudes. However, it must be remembered that the AnO is not an


nular because of strong correlations within the outer (midlatitude) ring, but because points in the outer ring are highly anticorrelated with points in the polar cap (Wallace and Thompson 2002). Again, this is reminiscent of the signature of wave breaking. It is possible, therefore, that wave breaking and blocking are a local manifestation of the negative phase of the AnO and separate wave-breaking episodes at many longitudes contribute to a broad pattern of an outer ring anticorrelated with the polar cap. In this case, the occurrence of wave breaking would control a large part of the variability in the AnO.

In wintertime, the occurrence of strong westerly wind episodes is significantly correlated with the AnO (again in the latitude band between 50° and 70°S) near 60°E and eastward from the mid-Indian Ocean toward South America, which again highlights the centers of action of the AnO. The signature of strong westerly wind episodes have a cyclonic region on the poleward side of an anticyclonic region, reminiscent of the positive phase of the AnO. So it is possible that the occurrence of strong westerly wind episodes contributes to variability in the AnO. However, this correlation may occur merely because westerly winds are anticorrelated with the easterlies associated with wave breaking. Indeed, the negative correlation between wave-breaking and strong westerly wind episodes for the winter seasons from 1979 to 2001 is typically between 0.5 and 0.7. So it is a matter for further investigation as to whether or not the occurrence of strong westerly wind episodes make an important contribution in their own right to the variability of the AnO.

Consistent with the findings of Postel and Hitchman (1999), regions of frequent upper-tropospheric wave breaking were also found at low latitudes in the Pacific, Atlantic, and possibly the Indian Ocean (Fig. 8). The anticyclonic wave-breaking episodes (Figs. 15e,f) involve amplification of the midocean climatological troughs on the eastern flanks of the subtropical highs. The structures are not equivalent barotropic and do not block the westerly flow to a great degree, being situated on the equatorial side of the jet and region of large TEKE. They have so few of the qualities related to blocking that this name will not be used for them. These episodes appear to be the result of the propagation into the subtropics of Rossby wave trains emanating from the New Zealand and Australian sectors (Fig. 17). Such behavior is seen in the observations of Hsu and Lin (1992) and the idealized modeling of Hoskins and Ambirzzi (1993). Given that upper-tropospheric troughs (high-PV anomalies) can induce low static stability and ascent (Hoskins et al. 1985), it is possible that the amplified troughs associated with the low-latitude wave-breaking episodes could induce flaring of convection in the South Pacific convergence zone and South American convergence zone. Indeed, the wave-breaking structures are in close proximity to the regions of large heating within these convergence zones (Figs. 15e and 15f). Interestingly, the Pacific structures are a strong feature of La Niña seasons while those in the Atlantic are a strong feature of El Niño seasons (not shown). This association is the subject of further investigation.

The wave-breaking frequencies shown here exhibit large interannual variability and appear to be much smaller in the presatellite years compared with the satellite years. It is known that the quality of the ERA-40 data in the Southern Hemisphere is higher in the satellite years compared with the presatellite years (Uppala et al. 2005), so it is probable that the low frequencies in the early years are a result of this. However, there is still considerable interannual variability in the satellite years and this may explain why previous studies have not totally agreed on the spatial distribution of Southern Hemisphere blocking. Renwick (1998) and Renwick and Revell (1999) showed that interannual variability of blocking in the southeast Pacific is related to ENSO and our own preliminary work indicates that for both winter and summertime in the midlatitudes, wave-breaking frequencies are more extensive and larger for El Niño years compared with La Niña years. A goal of further work will be to determine the mechanisms responsible for the interannual variability exhibited in our results. Renwick and Revell (1999), for example, produced evidence suggesting that blocking in the southeast Pacific was linked with the propagation of

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3 The ERA-40 total column heating is described in Kallberg et al. (2005).
Rossby waves forced by tropical convection, while Mo and Higgins (1998) demonstrated a link between tropical convection and the two leading low-frequency modes in the Southern Hemisphere, which have large amplitude in the Pacific-South American area.

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