

On the direction of Rossby wave breaking in blocking

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Abstract The direction of Rossby wave breaking at the onset of large-scale atmospheric blocking events is shown to relate closely to its position relative to the location of the climatological storm tracks. Using ERA-Interim reanalysis data from October 1989 to March 2009 and a dynamically-based blocking index, Rossby wave breaking is shown to occur preferentially cyclonically to the north, and anticyclonically to the south of the average storm tracks location. Therefore the results support existing theory on the relation between Rossby wave breaking direction and barotropic shear of the background wind. The further away from the storm tracks the breaking occurs, the stronger this preference in breaking direction. Regional differences can also be explained. For the European region on average 70 % of the detected blocking took place after anticyclonic Rossby wave breaking event that occurred on average 6° south of the climatological storm tracks position. Over Western Pacific wave breaking prior to blocking occurs predominantly cyclonically and on average 6° north of the storm tracks. Differences in blocking duration and intensity are found to be within estimated error margins at most longitudes, except for the Atlantic-Europe sector where the

blocking events following anticyclonic blocking are also the strongest.

Keywords Blocking · Rossby wave breaking · RWB direction · Climatology

1 Introduction

Atmospheric blocking is considered one of the most important meteorological “anomalous-flow” conditions (e.g. Tibaldi and Molteni 1990; Tyrlis and Hoskins 2008a, hereafter TH08a). The mid-latitudes are characterized by a climatologically prevailing westerly circulation. At times, however, large-scale, long-lasting interruptions of the westerly circulation occur, in which the instantaneous jet is displaced to the north or south, thus leading locally to “blocked” conditions. Atmospheric blocking is important, first of all because of its pronounced impact on local weather conditions (temperature and precipitation extremes, e.g. Sillman and Croci-Maspoli 2009), and second because of its large-scale nature and its persistence (Barriopedro et al. 2010).

Unfortunately no unifying theory exists that explains in detail occurrence, intensity and evolution, i.e., the dynamics of atmospheric blocking. Instead, most studies focus on a statistical description of atmospheric blocking as diagnosed by an objective “blocking index”, i.e., assessing geographical location, frequency, lifetime and sometimes intensity of events that have met certain blocking classification criteria (for a review of different blocking indices, see Barriopedro et al. 2010). Literature is not clear about the objective field nor about the conditions that need to be met. In the past, blocking indices were often defined based on reversed meridional gradients of the geopotential height

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field at a specific latitude characteristic for blocking (50° – 60° N). Nowadays, it has become more fashionable to use two-dimensional indices (e.g. Barriopedro et al. 2006; Berrisford et al. 2007), or to use a different objective field such as potential temperature θ on the dynamic tropopause (Pelly and Hoskins 2003) (hereafter PH03). The latter approach will be taken in this paper for reasons that are explained below.

Atmospheric blocking is dynamically driven, therefore a description of blocking in terms of PV-thinking (Hoskins et al. 1985) might be useful. PH03 exploited this idea and introduced a novel blocking diagnostic. Their diagnostic is based on a large-scale reversal of the meridional gradient of θ on the dynamic tropopause, defined as the surface where the potential vorticity is equal to 2 PVU ($1 \text{ PVU} = 1 \cdot 10^{-6} \text{ m}^2 \text{ K kg}^{-1} \text{ s}^{-1}$, e.g. Hoskins 1997). Because of the continuous nature of the potential temperature field and because of the mostly adiabatic dynamics occurring at mid-latitudes on the 2PVU surface, the large-scale reversal occurs as a result of northward movement of air with anomalously high θ and/or southward movement of air with anomalously low θ . This will occur in the form of Rossby wave breaking (RWB). First evidence for RWB in the stratosphere was provided by McIntyre and Palmer (1983).

If RWB lies at the heart of atmospheric blocking, the next question is whether atmospheric breaking associated with blocking has any preference for occurring in a cyclonic or an anticyclonic way. Tyrlis and Hoskins (2008b) (hereafter TH08b) addressed this problem. They used the PH03-index to create composites for blocking events taking place over northern mid-latitudes. Their composites showed marked regional differences. Over the Atlantic and Western Europe the winter blocking composites display signs of anticyclonic RWB behavior. In the Pacific the composite shows a cyclonic pattern. In summer the situation is opposite, with cyclonic RWB around West-Europe and anticyclonic RWB in the Pacific.

What determines the direction of RWB in atmospheric blocking? Idealized baroclinic life-cycle experiments conducted by Thorncroft et al. (1993) showed that the sign of the horizontal shear of the background flow determines the sign of RWB. Peters and Waugh (1996) expanded on this by further distinguishing between poleward and equatorward RWB, thus leading to 4 types of atmospheric RWB. Tyrlis and Hoskins (2008b) suggested that blocking is mainly related with the cyclonic LC2 cycle out of Thorncroft et al. (1993) and the anticyclonic P2 cycle out of Peters and Waugh (1996). Gabriel and Peters (2008) used a wave activity method to distinguish between the four different life cycles. Their study again confirms that the direction of RWB is tightly coupled to the background shear, but that RWB direction might change during the life cycle.

A background flow might be well defined for a numerical experiment where one starts from small initial perturbations. However, identifying a background flow from observations is non-trivial, due to the chaotic character and the nonlinear dynamics of the atmospheric flow. In practice, often a time-average state is used, with the time-averaging period greatly exceeding the time-scale of the phenomenon of interest. Here we adopt the simplest possible strategy, and use the climatology to define the average position of the storm-tracks. As in PH03 the storm tracks are defined as the latitude where the climatological mean of the transient eddy kinetic energy at 300 hPa attains its maximum. Since the mid-latitude jet is maintained by baroclinic eddies (Lee and Kim 2003), the TEKE maximum gives a good approximation of the location of the mid-latitude jet (PH03), and therefore the background flow.

The present paper investigates whether the sign of RWB occurring at the onset and during atmospheric blocking is related to and can be deduced from the latitudinal deviation of the breaking from the climatological mean position of the storm tracks. The composites of TH08b suggest a preference of anticyclonic blocking over Europe and cyclonic blockings over the Pacific. Can this preference for anticyclonic breaking be directly related to the RWB occurring more to the south and north respectively of the climatological mean position of the storm tracks, as would be expected from the idealized life-cycle experiments? Are there further differences between cyclonic and anticyclonic blocking events (e.g., lifetime, intensity)?

Tyrlis (2005) concluded in his thesis by applying a manual selection criterion, that the “cyclonic” blocking examples over Europe are in general shorter-lived and weaker than its “anticyclonic” counterpart. Martius et al. (2007) looked at differences in the direction of breaking of large-scale waves. Masato et al. (2011) used the zonal θ gradient to distinguish between cyclonic and anticyclonic blocking events. Both studies found mainly RWB over Europe and Asia and cyclonic RWB over the oceanic basins. Also Gabriel and Peters (2008) found similar results. But neither of these studies looked directly at the effect of the latitudinal deviation of the climatological storm tracks, which might show considerable differences.

An outline for the paper is given below. In Sect. 2 the methodology is discussed. As discussed above the blocking index is based on PH03. In particular we need a method to distinguish anticyclonic from cyclonic RWB events. This method is taken from Martius et al. (2007). Section 3 discusses the main results, the relation between the direction of wave-breaking at blocking onset and the position relative to the mean climatological storm tracks. Section 4 describes regional differences, as well as differences in lifetime and intensity. Conclusions and outlook are given in Sect. 5. An appendix has been added to further expand on the methods.

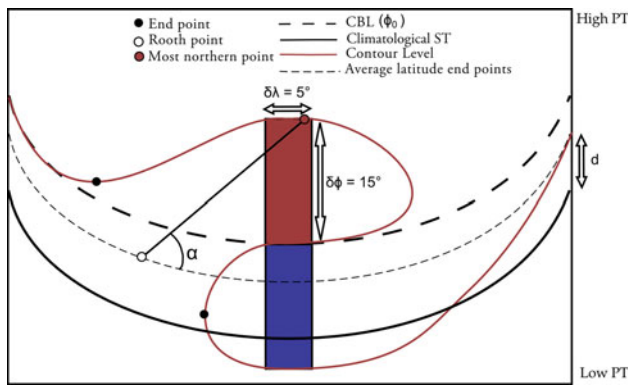


Fig. 1 Schematic overview of the algorithm used in this study to determine direction of breaking for a blocking event. The *red contour line* is a characteristic contour level of θ for the blocking event. This is calculated from “the northern box” in the calculation of $\mathcal{B}$. α indicates the angle, as calculated from the average latitudinal location of the end points (black dots, for explanation see text) and the most northern point (red dot)

2 Methodology

2.1 Blocking index

Blocking occurring between October 1989 and March 2009 is detected using the blocking index $\mathcal{B}$ introduced in PH03 (hereafter called PH03-index) and using data from the ERA-Interim reanalysis project (Simmons et al. 2007). The index requires potential temperature θ on the 2PVU surface, which has been explicitly archived at ECMWF at 6-hourly time steps. Data has been interpolated to a regular lon-lat grid with 1° resolution and daily means have been calculated. As explained in the Introduction, the PH03-index is devised to detect RWB of θ on the 2PVU surface. A schematic overview of the calculation of $\mathcal{B}$ is given in Fig. 1. The PH03-index $\mathcal{B}(\lambda, t)$ is defined for a given longitude λ and time t as the difference between the average θ in a box to the north (red) and a box to the south (blue) of a latitude $\phi_0(\lambda)$ called the central blocking latitude (hereafter CBL). A longitude λ is called blocked at time t if $\mathcal{B}(\lambda, t) > 0$ (warm air to the north of cold air).

As in PH03, the CBL ($\phi_0(\lambda)$) used in the computation is chosen for each longitude as the latitude at which climatological annual mean high-pass filtered transient eddy kinetic energy at 300 hPa reaches its maximum. For this study the 21 year climatological mean TEKE between 1989 and 2009 of the Era-Interim data is used. A climatological mean is used, but only in summer the location of the CBL deviates substantially from its yearly mean (PH03). The high-pass filter (<6 days) is required to select that part of the wind field that is associated with high synoptic activity. PH03 took the maximum of $\mathcal{B}$ in a latitudinal band of 5° around the CBL. In order to investigate

the relation between breaking direction and distance from the mean CBL, in this study $\mathcal{B}$ is archived for a broad band (11° on both sides of the CBL) of latitudes around the CBL. Values for $\delta\lambda = 5$ and $\delta\phi = 15$ are chosen as in PH03. The 5° longitudinal width removes most small-scale features.

2.2 Blocking events

The blocking index $\mathcal{B}$ is calculated for each longitude and time step for the 21 winters. For the summer season the high pass TEKE is located more to the north with respect to other seasons (PH03). Moreover, the polar jet is less active in summer and therefore the background shear will be less, which makes it more difficult to test the dependence of the direction of breaking on the background shear. Therefore only winter half year data are used in this study. As in PH03, a longitude is called locally and instantaneously blocked (LIB) if $\mathcal{B}(\lambda, t) > 0$. To account for the longitudinal size of a block, we follow TH08a and define sectors of 45° of longitude centered around each longitude. A sector is said to be sector blocked (SB) if a zonal band of at least 15° of longitude is LIB blocked within the sector. The 15° of longitude corresponds to a zonal size of at least the Rossby radius of deformation (PH03).

Masato et al. (2009) modeled blocking occurrence with a first order Markov model. Although there was “striking agreement” on the location and frequencies of SB blocking, the model had problems with the estimation of the length of blocking. Masato et al. (2009) concluded that this can be explained by the slower decay of long-lived blocking. To account for this temporal persistence of blocking, sector blocking episodes (SBE) are defined. TH08a selected blocking events of at least the synoptic time scale. A sector blocking episode (SBE) is said to occur if SB occurs in a sector for at least 5 consecutive days (TH08a). Note that this is 1 day longer than in PH03. The three indices are used to analyze the spatial and temporal variability of blocking in the northern hemisphere.

2.3 Breaking direction and location

An adapted version of the algorithm of Martius et al. (2007) is used to find the direction of breaking associated with SBE events (Fig. 1). The algorithm is preferred above the one of e.g. Kunz et al. (2009), which uses differences in zonal and meridional stretching to distinguish between cyclonic and anticyclonic RWB, because this algorithm is directly applicable to the schematic picture of blocking as a breaking RWB (PH03, Fig. 2). Moreover, it is found that this approach automatically excludes the features detected by the blocking index which are not directly related to RWB, like large scale high θ cut-offs.

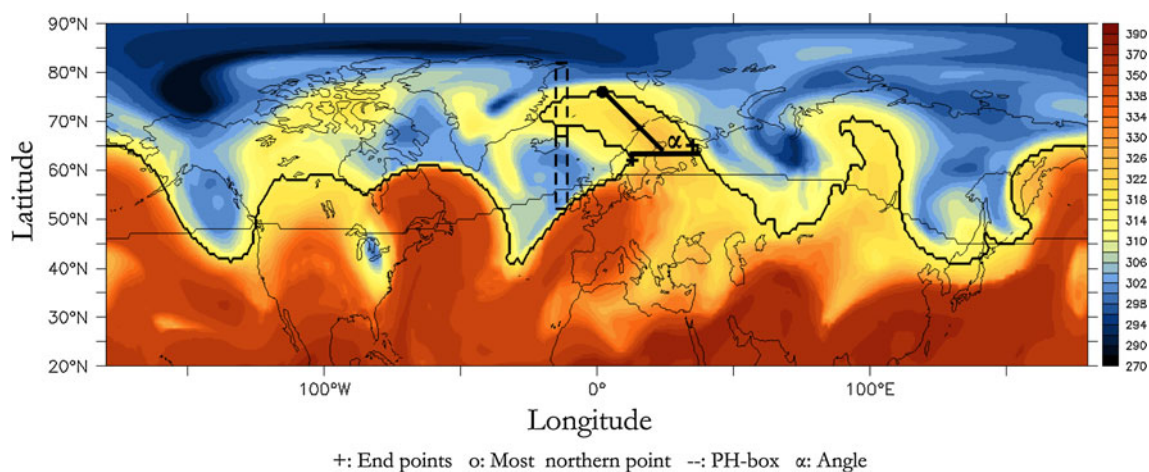


Fig. 2 Example of algorithm for 21 October 1989. The *thin black line* denotes the location of the storm tracks, *dashed box* indicates the calculation of $\mathcal{B}$, from which the *contour line* (solid black line) is

determined. On this contour the two end points (denoted by a *plus*) are found and the most northern point, from which the angle α of the breaking wave is calculated

The algorithm consists of four basic steps. A characteristic contour level is found, thereafter the end points on this contour are determined. As in Martius et al. (2007), two points are sought which are close in euclidean distance, but far apart along a contour. These are used to calculate the breaking angle α . Lastly the location with respect to the storm tracks is calculated. One important difference is that here a characteristic blocking θ contour is used, instead of the 2PVU surface as in Martius et al. (2007). Note that since this algorithm expects that the θ contour encircles the north pole, most cut off blockings will not be included in the results, since they do not satisfy this criterion. Details of the algorithm can be found in the “Appendix”.

A non-parametric percentile bootstrap method (e.g. Wilks 2011) is applied to estimate confidence intervals for the results. Use of a bootstrap makes only sense when the underlying samples are independent from each other (Wilks 2011). Therefore, the data is divided into 20 winter half years ranging from October 1989 to March 2009. For each of these winters blocking events are detected and the breaking direction is calculated for each of these events. These 20 half years serve as independent samples for the bootstrap. In the bootstrap, 10,000 times 20 random winter half years are chosen from the blocking data. These serve to produce 10,000 equally likely blocking climatologies, and are used to estimate the mean values and the 90 % confidence intervals.

3 General results

Figures 2 and 3 show the result of the breaking-direction algorithm applied to two blocking events in October and

November 1984 respectively. Both blocking events were detected at the sector centered, according to the SB definition, around 0°E. The first case consists of a cyclonically breaking wave, which is detected correctly with an angle of 120.2°. The calculated angle of the November case is 64.5°, again in line with the observations. The average θ in the northern box, calculated at the maximum θ reversal, gives a good estimation of the characteristic θ of the breaking wave for both cases. The end points are located at the neck of the breaking wave, as expected. Therefore this will probably give a good estimate of the location which determines the direction of the breaking wave, as discussed before. The average location of the end points for the October case is 63.5°N, while the average location of the storm tracks is at 58°N. For the November case the end points are located further south at 50°N, which can explain the anticyclonic breaking.

It is noticed that we do not take into account the instantaneous position of the storm tracks, but rather the time mean of it. It is therefore remarkable to see that in both situations the direction of breaking is tightly coupled to the latitudinal position relative to the mean location of the storm tracks, i.e., anticyclonically if the breaking is to the south of the CBL and cyclonically if the breaking occurs to the north of the CBL.

Figure 4 displays the distribution of SBE events as a function of the distance from the storm tracks. This figure reveals the importance of the storm tracks and CBL as the primary location to search for blockings: the distribution is almost Gaussian, and centered slightly to the north of the storm tracks. The pdf seems to be askew to the north, this is due to an increase of RWB occurrence north of the ST over East-Europe and Asia. A Lilliefors test (e.g. Wilks 2011) was applied to the distribution and normality was rejected.

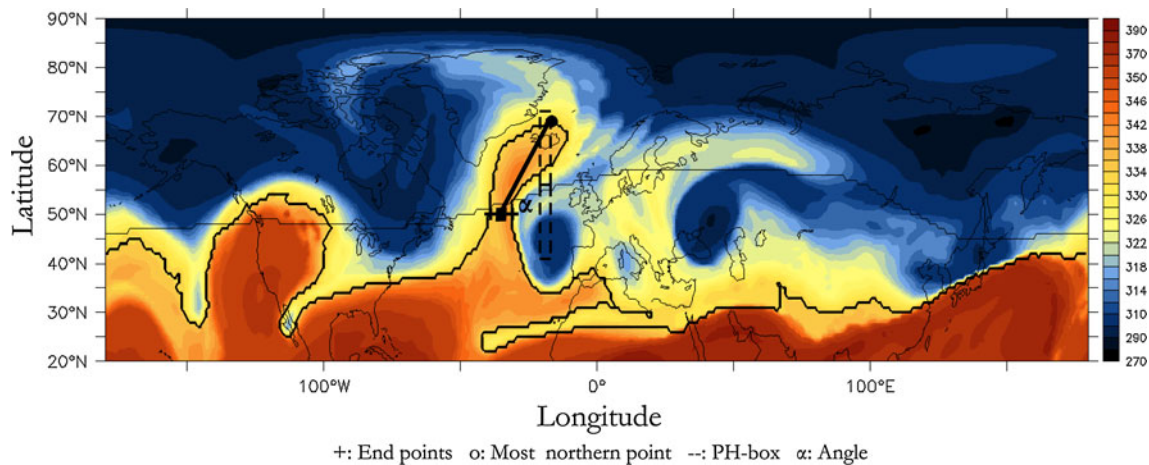


Fig. 3 As in Fig. 2, but now for 19 November 1989

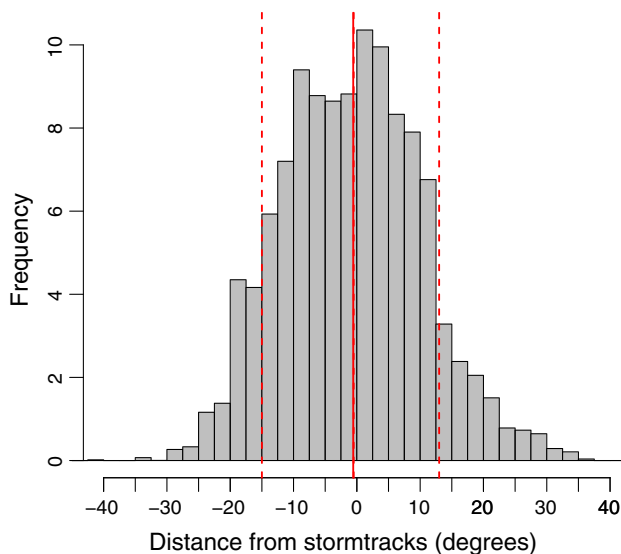


Fig. 4 Distribution of blocking events as function of distance from the storm tracks, which is defined by Eq. 1. Frequencies are calculated as a mean number of events per sector. The bin size for d_{EP} is set to 2.5° of latitude. The solid red line and dashed red lines indicate the mean and 25/75 % percentiles respectively

But also the moment-based skewness was positive, as one would intuitively guess out of Fig. 4. Non-parametric tests gave opposite results and smaller deviations, therefore no general conclusion could be made.

Although the calculation of $\mathcal{B}$ is limited to 11° latitude from the storm tracks, there is no reason to assume that the end points (black dots in Fig. 1) are also located within this limits. The algorithm is only linked to the blocking index for the choice of the θ contour, but the end points can be located on this contour anywhere where the ratio between the direct distance and the distance over the contour is maximal. About 90 % of the events for which the algorithm detects a breaking wave is located within 17.5° of latitude in Fig. 4.

3.1 Latitudinal dependence of breaking

As demonstrated in the two examples of the previous section, the direction of breaking appears to be depending critically on the distance with respect to the storm tracks. To examine whether this relation holds more generally, a distribution of breaking signature as a function of breaking distance is created. Figure 5 shows the result, which confirms that the two examples shown before were no exception. There is a strong relation between direction of breaking and the relative distance with respect to the time-mean storm tracks position. Mainly cyclonic RWB occurs north of the storm tracks and anticyclonic RWB south of the storm tracks. Although the cyclonic RWB north of the storm tracks is less dominant compared with anticyclonically breaking waves south of the storm tracks, the turning point almost coincides with the central position of the storm tracks. This is remarkable given the fact that we used a time-mean position of the storm tracks and not one based on local instantaneous position of the jet. Also by looking at the breaking angle directly as function of the distance to the storm tracks (not shown), one can see a continuous increase of the breaking angle (i.e. more cyclonic breaking) going north. The results therefore fully support the idealized theoretical baroclinic life-cycle results of Thorncroft et al. (1993) i.e., that the background shear strongly affects the direction of breaking.

4 Regional differences in RWB characteristics

Using composite analysis of blocking events TH08b found regional and seasonal differences in the direction of wave-breaking for blocking. These differences can also be understood by differences in the location with respect to the storm tracks. The direction of breaking as function of

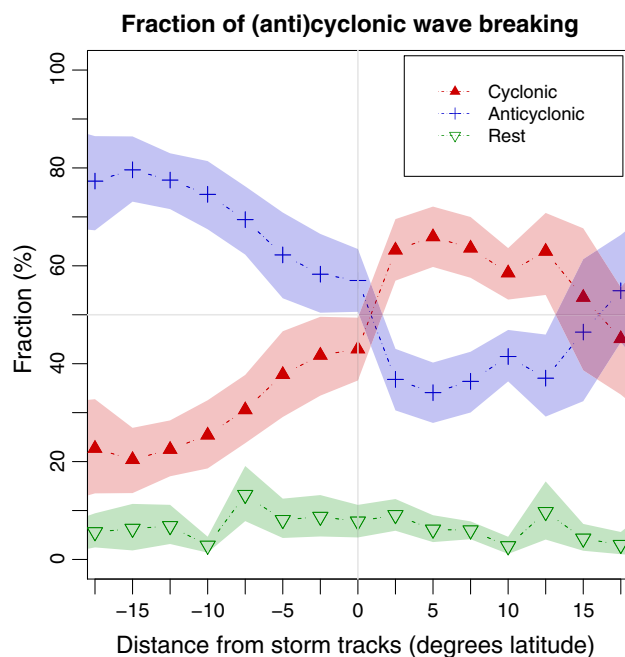


Fig. 5 Breaking fraction as function of distance with the storm tracks. Shaded regions indicate 5 and 95 % percentiles, determined from a bootstrap (see text)

longitude is shown in Fig. 6a, were the shaded areas again indicate the 5 and 95 % confidence estimates. The results are smoothed using a moving average over the sector (45°), since there are some variations due to small differences in the number of blocking events between two consecutive longitudes. Therefore the fraction of blocking events that breaks cyclonic or anticyclonically also differs.

Figure 6 shows that there is a preferable breaking direction over Europe. About 70 % of the waves causing blocking break anticyclonically. This explains why the composite of TH08b has anticyclonic structure. Over West-Pacific the waves predominantly break cyclonically (about 70 %). At the other maximum (in the Pacific around 130°W), the difference between the two fractions is negligible. There is a preference for anticyclonically breaking waves to the east of the maximum and a preference for cyclonically breaking waves to the west of the maximum. Over West-Atlantic the preferable breaking direction is cyclonic, but blocking is not very common in this area, so one could ask if this is really significant. The results are in line with the study of Martius et al. (2007), who found that in general the cyclonic streamers are found in the areas of the Pacific and Atlantic storm tracks and anticyclonic streamers downstream of the planetary ridges. The results are also consistent with Masato et al. (2011), who used a different algorithm to distinguish between cyclonic and anticyclonic RWB.

Figure 5 showed a strong connection between breaking distance and breaking signature. To examine whether the

connection holds locally, Fig. 6b displays the average breaking distance as a function of longitude. The picture is broadly consistent with Fig. 6a, with some small deviations. Over Europe, where anticyclonic RWB dominates, the wave breaks on average south of the storm tracks. Over West-Pacific the situation is reversed, here most waves break northward of the storm tracks. This is consistent with the dominance of cyclonically breaking waves. Although it is based on much less cases, the cyclonic direction of RWB over West-Atlantic is also consistent with this picture.

An interesting question is what causes the waves to break mainly southwards or northwards for a specific region. Without going into detail it is noted that there is a tendency for the waves to break south of the storm tracks over Atlantic/Europe where the storm tracks are deviated to the north. Moreover, over Russia/Asia the storm tracks and the polar jet deviate to the south and the preferential breaking area is north of the storm tracks. This is consistent with the findings of Peters and Waugh (1996) who noted that an anticyclonic curvature of the mean background flow can lead to more poleward breaking, or the P2 and P1 cases out of Tyrlis and Hoskins (2008b). Because blocking is mainly associated with the anticyclonic P2 cycle and less with the cyclonic P1 cycle (Tyrlis and Hoskins 2008b) this can clarify the increase of anticyclonic RWB over Europe.

4.1 Intensity/Duration

For each blocking event the average duration and intensity are also calculated. Following Tyrlis (2005) the duration of a blocking event is defined as the length of an SBE and the intensity is defined as the average θ reversal during an SBE. The average θ reversal during an SBE event is proportional to the easterly flow. Again the results are smoothed over the sector of 45° of longitude. In Fig. 7a it is observed that for the duration of blocking events that the 90 % confidence bands overlap at all longitudes, although the mean values show minor differences (e.g., 1-day longer average duration of anticyclonic events over Europe and 1-day longer average duration of cyclonic events over West-Pacific).

In contrast, Fig. 7b reveals that there are regions where there are detectable intensity differences between cyclonic and anticyclonic blocking events. The intensity of anticyclonic blocking events is clearly larger over the Atlantic and a large part of Europe, which is in line with the findings of Tyrlis (2005). For the West-Pacific the intensity of cyclonic events is larger, but again the confidence estimates are largely overlapping. There are some small differences in intensity of blocking events at East-Pacific and the West-Atlantic. The overall picture that emerges is that cyclonic (anticyclonic) events are more intense in regions where cyclonic (anticyclonic) events dominate. Over Europe/Atlantic the preferential direction of breaking is

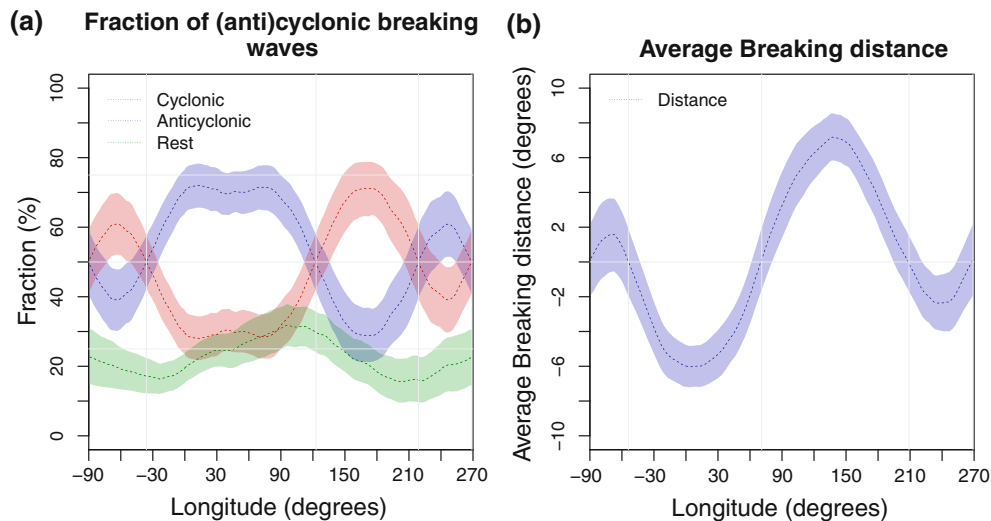
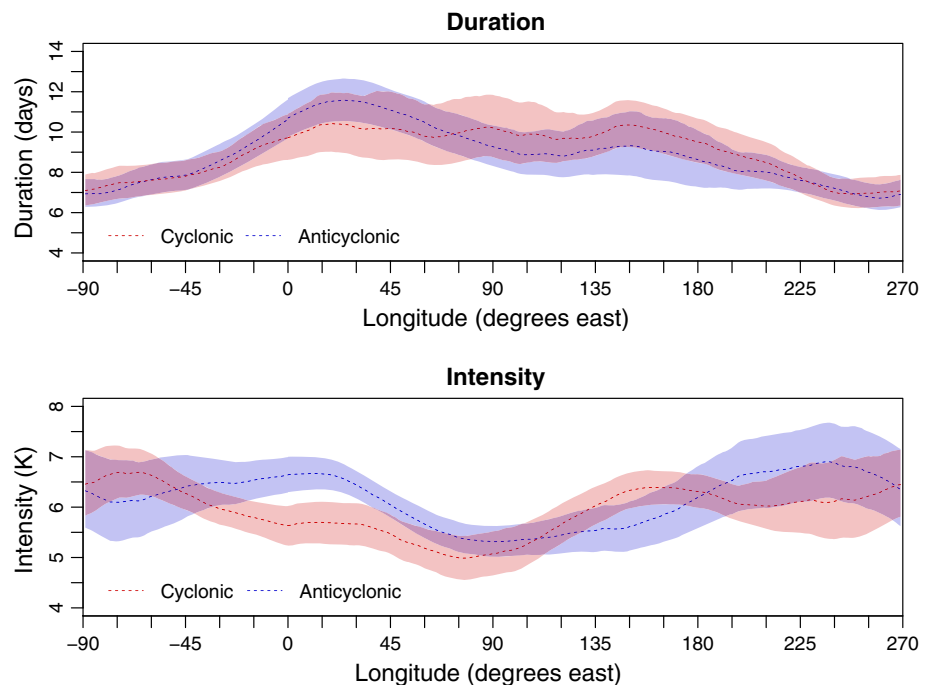


Fig. 6 **a** Breaking fraction as function of longitude. **b** Average breaking distance (in degrees latitude) from the storm tracks as function of the longitude. The definition based on the location of the

end points is used (see Eq. 1 in the “Appendix”). Shaded regions indicate 5 and 95 % percentiles, determined from a bootstrap (see text)

Fig. 7 Upper frame shows average duration of cyclonic and anticyclonic blocking events. Lower frame shows the average intensity, again for cyclonic and anticyclonic blocking events. Shaded regions indicate 5 and 95 % percentiles, determined from a bootstrap (see text)



anticyclonic and these events are also the most intense. Over Asia where cyclonic RWB dominates, the cyclonic events are the most intense.

5 Conclusion

In this paper the direction of wave-breaking prior to atmospheric blocking has been examined, and in particular, the relation between breaking direction and the latitude at which the breaking occurs. The climatological latitudinal

position of the storm tracks has turned out to be important, with mostly cyclonic wave-breaking occurring to the north of it, and anticyclonic RWB to the south. Using ERA-Interim data and an algorithm to detect the direction of breaking, all blocking events were divided into cyclonic, anticyclonic or unclassified events. Up to 75 % of the blocking events south of the storm tracks break anticyclonically and up to 65 % of the blocking events occurring north of the storm tracks break cyclonically. Over the Atlantic and Europe most blocking is caused by anticyclonically breaking Rossby waves. Further to the east

cyclonic breaking is dominant. These regional differences in the breaking direction of large-scale Rossby waves are consistent with theoretical considerations based on baroclinic life-cycle experiments: the average breaking location in regions where cyclonic (anticyclonic) breaking events dominate is north (south) of the storm tracks. Differences between the duration of cyclonic and anticyclonic blocking events are generally small and within error bounds. Differences in blocking intensity are only outside estimated error bounds over Europe, where the anticyclonic blockings events are also most intense. There appear to be signs that also in other sectors the intensity of blocking is highest for that wave-breaking type (i.e., cyclonic or anticyclonic) that is most abundant in that sector. The results are consistent with and extend the findings of Tyrlis (2005) and Tyrlis and Hoskins (2008a) who looked at composites of blocking events at the storm tracks, as well as with Martius et al. (2007), Gabriel and Peters (2008) and Masato et al. (2011).

One of the questions not addressed in the present study is what causes the existence of regional preferences in wave-breaking location. Why do most breaking waves over Europe occur to the south of the climatological storm tracks? An important role could be played by the tilt of the storm tracks, which is south to north over the Atlantic and north south over Asia. Although further research is required, it is worth noting that the findings in this article are consistent with the results of Peters and Waugh (1996). They found that in general P2 breaking occurs in regions with weak zonal winds with anticyclonic curvature. For blocking, the P2 cyclone is equivalent with anticyclonic wave breaking, because the LC1 cycle shows a weaker θ reversal and may decay on synoptic time scales (TH08b). Our results can also explain some of the findings of TH08b, who found that in summer RWB over Atlantic and Europe has a more cyclonic preference. This is consistent with the decrease in the tilt in the atmospheric jet in summer.

A remarkable result of this study is that the direction of the RWB depends on the position of the climatological storm track. Intuitively, one expects RWB to react on a more instantaneous background flow. However on the instantaneous time scale the position of the storm track is directly linked to RWB, as has been pointed out by e.g. Tyrlis (2005), who concluded that there is a northward (southward) displacement of the instantaneous storm tracks prior to anticyclonic (cyclonic) blocking. It is therefore difficult to use the instantaneous storm tracks to measure objectively the distance to the storm tracks. Although we demonstrated here that the position of the climatological storm track characterizes the RWB, it might be that shorter time averages, of for instance a month or season are more suitable. The relation with the study of Barnes et al. (2010), who found that the equator displaced jet is more persistent

than the poleward displaced jet, is also unclear. Further research with a more instantaneous storm tracks is required to answer these questions.

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Appendix: Details methodology

The following steps and criteria are used to determine the angle of breaking:

1. Select contour:

Martius et al. (2007) looked for breaking waves on the 2PVU contour on several isentropic levels. Because the contour level must be some characteristic θ for the breaking wave, which will vary considerably from case to case, one can not use the same θ level for all events. However, one can make use of the results of the calculation of $\mathcal{B}$, which already calculates two characteristic potential temperatures for the atmospheric block north and south of a central latitude. The algorithm first searches for the longitude in the sector where $\mathcal{B}$ is maximum for the first 3 days of the blocking event. For this longitude the average of θ in the northern box in Fig. 1 is then used to select the contour level. The northern box is used, because composites of blocking events showed that there was always some northward displacement of high θ air, but not always advection of low θ air to the south. The contour is traced with a 1° of longitude precision and as in Martius et al. (2007) only cases with θ contours which encircle the pole are used.

The choice to select the location for the first 3 days is based on two opposing problems. First sometimes a high θ is cut off, for which no θ contour can be found which encircles the poles. Secondly, especially the blocking onset is related to RWB, therefore it is not desirable to look too far away from blocking onset. As a trade-off, a time-frame of 3 days is chosen. Figures 5 and 6a were found not to change qualitatively when using a single day (1 or 2 days after blocking onset).

2. Find end points:

On the contour the algorithm searches for pairs of grid points which have a distance over the contour d_c at least twice the great circle distance d_g . If multiple pairs satisfy this condition, the pair with the biggest ratio $R \equiv d_c/d_g$ will be used. Martius et al. (2007) used an upper limit of 800 km on the direct great circle distance and a lower limit of 1,500 km of the contour length. Since the definition of the blocking index already includes size criteria, this can be

slightly loosened. To rule out extreme cases, we use an upper limit of about 5,000 km for the direct distance and a lower limit of 2,000 km for the contour length. Another difference with the approach is that we allow the end points to vary up to 10° of latitude. There is no reason to limit the end points to the same latitude and this new approach is found to be more flexible.

Not in all cases one can find end points which satisfy all before mentioned criteria. This is mainly the case if the blocking consists of a high θ air which has been cut-off poleward. For these cases the algorithm selects a θ value characteristic for the cut-off, which is too high, and it finds no breaking wave (i.e. no end points). When this happens step 1 and 2 are repeated with the average θ of the northern and the southern box in Fig. 1.

3. Angle:

On the contour the most northern point will be used for calculating the breaking angle (see Fig. 1). We will not use the most western (eastern) point for cyclonically (anticyclonically) breaking waves, which from a kinematic view point is a better way to define the angle. This is, however, impossible to implement, because one needs to know apriori the breaking direction of the wave which is exactly the objective of the algorithm. Because the purpose of the algorithm is to determine the direction of breaking, not the exact angle of breaking, the most northern point appears to be a suitable choice. Cases with an angle smaller than 85° will be stored as anticyclonic and the cases with an angle larger than 95° are stored as cyclonic. Note that these criteria are slightly more loose than used by Martius et al. (2007). They found, however, using sensitivity tests that their results were not very sensitive to these criteria. The rest of the cases, which consist of cases with an angle between 85° and 95° (8 % of the total number of SBE events) and the cases for which no end points could be found (about 17 % of the total number of SBE events), will be stored as undetermined.

4. Location:

For the longitudinal location the sector in which the RWB event took place is used. We use a wave-based definition by using the meridional location of the end points. These end points are located generally at the neck of the breaking wave (i.e. the place where the direct distance is small, see Fig. 1). Composites of blocking events show that this is a good estimation for the location where the wave starts to break. The distance to the storm tracks is defined as,

$$d_{EP} = \frac{\phi_{ep1} - ST(\lambda_{ep1}) + \phi_{ep2} - ST(\lambda_{ep2})}{2}. \quad (1)$$

Here ϕ_{ep1} and ϕ_{ep2} are the latitude of the two end points, $ST_{\lambda_{ep1}}$ and $ST_{\lambda_{ep2}}$ are the location of the storm tracks at the longitude of the end points.

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