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On double Rossby wave breaking in the North Atlantic

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Abstract We discuss the dynamical features associated with double Rossby wave breaking (DWB, concurrent cyclonic and anticyclonic breakings) over the North Atlantic, with a focus on the North Atlantic Oscillation (NAO), the midlatitude jet stream, and surface wind extremes over continental Europe. Objective automated algorithms for detecting wave breaking and determining the location, intensity, and direction of the jet are adopted. The analysis is performed on the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis and the Max Planck Institute Earth System Model (MPI-ESM). We find that DWB events can project onto both phases of the NAO, albeit showing no strong preference for either. Wave-breaking pairs occurring in the northern North Atlantic project onto the positive NAO, while the opposite holds for pairs occurring farther south. DWB also affects the direction and intensity of the jet stream. Events in the eastern half of the basin (EWB) intensify and zonalize the jet, while events farther to the west (WWB) weaken the westerly flow over Europe. An analysis of destructive wind storms over Europe in the last three decades suggests that these are typically associated with a very intense, zonal jet—similar to the case of EWB. Indeed, EWB corresponds to an enhanced likelihood of destructive windstorms over the continent, although there is not a one-to-one correspondence. The MPI-ESM model does not capture this statistical relationship. On the contrary, WWB corresponds to a decreased likelihood of destructive weather.

1. Introduction

Rossby wave breaking (RWB) plays a fundamental role in shaping the atmospheric circulation of the midlatitudes. Major modes of variability such as the North Atlantic Oscillation (NAO) and the Northern Hemisphere Annular Mode have been interpreted as the result of specific wave-breaking patterns [e.g., Benedict et al., 2004; Franzke et al., 2004; Riviere and Orlanski, 2007; Woollings and Hoskins, 2008; Strong and Magnusdottir, 2008a, 2008b; Kunz et al., 2009; Drouard et al., 2013]. Benedict et al. [2004] and Franzke et al. [2004] identified the positive NAO as the outcome of two successive anticyclonic Rossby wave-breaking (AWB) events, the first over the Eastern Pacific and the second over the North Atlantic. The negative NAO was instead characterized as an in situ development in the North Atlantic, related to cyclonic wave breaking (CW). Woollings and Hoskins [2008], related CWB in the North Atlantic to high-latitude atmospheric blocking; the authors envisaged the positive NAO as the basic, unblocked state of the North Atlantic and the negative NAO as a period displaying more frequent wave-breaking occurrences and a weakened zonal flow.

RWB events are identified in the upper troposphere but affect the flow at all tropospheric levels and play an important role in the meridional transport of both tropical and subtropical air masses [Homeyer and Bowman, 2013]. At the surface, AWB drives a positive sea level pressure (SLP) anomaly to the South of the breaking and a negative anomaly to the North, while the converse holds for CWB [Strong and Magnusdottir, 2008a]. A midlatitude AWB (CW) is therefore associated with an enhanced (reduced) SLP dipole over the Atlantic and a more northerly (southerly) jet than usual [Riviere and Orlanski, 2007]. Strong and Magnusdottir [2008a] found the relationship between RWB and the NAO to be strongly dependent on the meridional location of RWB, with AWB (CW) centered around 50°N associated with the positive (negative) phase of the NAO, in agreement with previous studies [e.g., Benedict et al., 2004]. RWB events shifted 20° to the north or south were found to drive the opposite NAO polarity.

More recently, particular RWB patterns over the North Atlantic have also been associated with the development of extreme cyclones and destructive weather events over Europe. Hanley and Caballero [2012, hereafter HC12] computed composites of the large-scale flow evolution preceding 25 historical European windstorms and,
in 22 cases, found basin-scale AWB occurring in the southern half of the North Atlantic basin while CWB simultaneously developed farther north. A simple schematic of this double-wave-breaking (DWB) process and its dynamical impacts is provided in Figure 1. The DWB configuration results in a strong meridional potential vorticity (PV) gradient, by virtue of the positive (negative) PV anomalies driven by the cyclonic (anticyclonic) WB. The relationship between PV and velocity, implied by PV inversion [Hoskins et al., 1985], is such that a westerly flow corresponds to a positive meridional PV gradient. A stronger meridional PV gradient will therefore be in equilibrium with a stronger westerly jet. An alternative interpretation is that AWB causes a poleward eddy momentum flux, while CWB achieves the opposite effect [Thorncroft et al., 1993; Riviere and Orlanski, 2007]. DWB thus results in a convergence of zonal momentum in the region between the two wave-breaking events, enhancing the westerly flow there. In either case, the final result is a strengthened and more zonally oriented jet stream over the North Atlantic. This strong jet can then act to intensify weather systems and steer them toward the European continent, favoring destructive events (HC12). Gómara et al. [2014a] found that explosive cyclogenesis in the eastern North Atlantic is associated with CWB over eastern Greenland and AWB in the subtropical part of the basin; though typically only one of the wave-breaking events is present at any given time, the rare cyclones preceded by the simultaneous occurrence of both AWB and CWB feature particularly high intensities and deepening rates. Finally, Pinto et al. [2014] identified an important link between DWB occurrences and 4 months displaying cyclone clustering in the Euro-Atlantic sector.

If appropriately located, the superposed footprints of concurrent AWB and CWB may yield very intense SLP and surface wind anomalies, pointing to DWB as a feature of considerable dynamical interest. For example, when the SLP anomalies coincide with one of the NAO’s pressure centers, they might lead to a strong positive or negative phase of the oscillation, depending on their latitudinal location. Similarly, if DWB systematically intensifies and zonals the jet stream, the link with high-impact weather events might be broader than the set of historical storms discussed in HC12.

The literature has mostly focused on destructive events, verifying whether selected occurrences also displayed DWB. Less attention has been given to DWB events as a whole, except for brief discussions in Gómara et al. [2014a] and Pinto et al. [2014]. The question of whether DWB events can be good dynamical predictors for storminess over Europe has therefore been left largely open. Our aim here is to take a more comprehensive perspective on DWB than in previous studies, by basing our analysis on the full complement of DWB events as opposed to specific sets of cyclones or windstorms. This enables us to explore the general relation between DWB and the large-scale flow across the North Atlantic, as well as further establishing its link with European windstorms. For these purposes, DWB will be simply defined as the simultaneous occurrence of AWB and CWB in the North Atlantic basin, with the CWB to the north of the AWB. The analysis uses the ERA-Interim data set and will focus on three specific aspects:

1. the interplay between DWB and the phase of the NAO;
2. the impact of DWB on the jet stream; and
3. the statistical relationship between DWB and surface wind extremes over Europe and, in particular, the value of DWB as a predictor for destructive windstorms over the continent.
Windstorms are one of the leading sources of insured losses in Europe [Berz, 2005] and considerable efforts have been devoted to model-based forecasts of changes in their frequency and intensity under future climate conditions [e.g., Leckebusch et al., 2008; Donat et al., 2010; Pinto et al., 2012]. In order to validate these forecasts, it is essential to evaluate how well climate models can reproduce the link between the large-scale circulation and surface wind extremes in the past and current climates. In keeping with the scope of this study, we briefly investigate the relationship between DWB and European wind extremes in the Max Planck Institute Earth System Model (MPI-ESM), as used in part of the CMIP5 simulations. These results are compared to the ones obtained from the reanalysis data.

The analysis in the paper covers, in order, the geographical and temporal distributions of the DWB events (section 3); the link between DWB and the NAO (section 4); the influence of DWB on the jet stream’s tilt, meridional location, and intensity (section 5), and the link between severe windstorms and DWB (section 6). Separate supporting information is also available.

2. Data and Methods

2.1. Reanalysis and Model Data

Unless specified, all the analyses are performed on the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis data [Simmons et al., 2006]. One degree horizontal resolution, 6-hourly fields are considered. The analysis includes 33 winter (December, January, and February, DJF) time series, from January 1979 to December 2011.

All anomalies are computed relative to a moving 30 day mean. If 17 December 2000 is selected, the anomaly will be computed relative to the mean of the period 2 December 2000—1 January 2001, for a total of 121 time steps. This minimizes the impact of interseasonal and longer-term variability on the anomalies. An 8 day low-pass finite impulse recursive filter is then applied to the anomalies, to filter out the influence of individual synoptic systems and focus exclusively on the supersynoptic impact of RWB on the large-scale flow. In order to verify that none of the conclusions drawn in this paper were affected by the above methodology, the anomalies were recomputed following the methodology of Gómara et al. [2014b]. A detailed description of the latter and the relevant figures are provided in the supporting information.

The NAO pattern is computed as the leading empirical orthogonal function (EOF) of the 10 day mean SLP in the region 20°N–90°N, 90°W–45°E. The red circles in Figures 2c and 2d mark the locations of the maximum and minimum values of the leading EOF, hereafter termed the NAO’s pressure centers. A high-frequency NAO index (NAOI) is defined by projecting the NAO pattern onto the 6-hourly SLP time series and normalizing by the standard deviation. Positive (negative) NAO events are defined as periods where NAOI > 1 (NAOI < –1) for more than a day. Lags are computed relative to the peak NAOI.

Part of the analysis on severe European windstorms (section 6) uses data from the MPI-ESM-P model. This is a fully coupled earth system model whose main components are the ECHAM6 atmospheric model [Stevens et al., 2013] and the Max Planck Institute Ocean Model [Marsland et al., 2003; Jungclaus et al., 2013]. The model has a T63 horizontal resolution (1.875°) with 47 vertical levels in the atmosphere and a nominal 1.5° resolution with 40 vertical levels in the ocean. The integration is run under fixed preindustrial (1850) boundary conditions, and we analyze 50 years at equilibrium. For further details on the model, the reader is referred to Jungclaus et al. [2014].

2.2. Definition of Double Wave Breaking

Rossby wave breaking is detected using the algorithm presented in Barnes and Hartmann [2012], which identifies the overturning of absolute vorticity contours on the 250 hPa pressure surface. First, the algorithm applies a linear interpolation to the original data set and identifies the longest closed absolute vorticity contour of a given value which encircles the pole. Next, all latitudes where a single meridian intersects the selected contour 3 times are selected. These intersections are termed overturning points. All overturning points within 500 km of one another are considered to be part of the same overturning event. The center of the event is the centroid, or geographical center, of all the overturning points forming part of that event. This procedure is iterated for contours with different absolute vorticity values; if several overturning events have centers within 2000 km of one another, they are grouped under a single wave-breaking episode. The geographical location of the wave-breaking episode is then defined as the average latitude and longitude of the event’s centers.
Figure 2. Climatological frequency of (a) cyclonic and (b) anticyclonic RWB during DJF and frequency of (c) cyclonic and (d) anticyclonic RWB during DWB events. The units are season$^{-1}$ degree latitude$^{-1}$ degree longitude$^{-1}$. Note that the scales in Figures 2a and 2b, and 2c and 2d are different. The wave breaking is based on absolute vorticity at 250 hPa. The data covers ERA-Interim DJFs over the period 1979–2011. (e) Schematic of the different subcategories of DWB, indicating the location of the AWBs and CWBs in each case. The red box in Figure 2a denotes the full North Atlantic domain considered here; the black boxes show the eastern and western subdomains and the 45° and 55°N limits for the AWBs and CWBs, respectively. The red box in Figure 2b shows the domain used in the potential destructiveness calculation. The black boxes in Figures 2c and 2d show the positive and negative NAO subdomains, respectively. The two red circles in the same panels show the locations of the northern and southern NAO pressure centers.
of all the overturning events which are part of the episode, taking into consideration the spherical coordinate system. Episodes whose centers are located within 2000 km of one another on consecutive days are interpreted as a single wave breaking lasting for more than 1 day. Note that the absolute vorticity field is smoothed before being processed: this is performed by expanding in spherical harmonics to T42 and then truncating at T15. The algorithm further enforces a minimum 5° latitudinal extent for the overturning to qualify as a wave-breaking event, but no minimum temporal threshold is imposed. The results are similar to methods based on isentropic potential vorticity [Barnes and Hartmann, 2012].

The above algorithm provides an objective data set of WB instances, which we then use to identify DWB episodes. The WB distributions and the different regions used to define DWB are summarized in Figure 2. We consider only WB events occurring within the North Atlantic domain (80°W–30°E and 20°–80°N, red box in Figure 2a) and require that AWB occurs within the part of the target domain south of 45°N, while CWB simultaneously occurs north of 55°N. This ensures that AWB and CWB occur on the equatorward and poleward flanks of the climatological jet, respectively. Our analysis is therefore restricted to WB pairs which lead to a meridional convergence of zonal momentum into the jet, as discussed in section 1 above. Simultaneous AWB and CWB, where either occurs outside the above domains, are ignored. To verify that the fixed latitudinal thresholds successfully capture the desired DWB events, the calculation was repeated using a variable meridional threshold for the AWB and CWB domains, based on the time-varying latitude of the jet stream. A full description of this methodology and the relevant figures are provided in the supporting information. Both techniques yield very similar results; here we report only results using the fixed-latitude method.

The two WB events forming part of the DWB must coexist for at least 1 day; for example, if an AWB persists for 3 days and a CWB lasting for a single day is identified on the third day of the AWB’s life, that day qualifies as DWB. A more relaxed criterion whereby the two events can occur within 1 day of each other is also adopted. No temporal constraints on the duration of the individual WB events are imposed.

We further consider western and eastern subdomains spanning 80°–25°W and 25°W–30°E, respectively (bold black boxes in Figure 2a), which we use to define several specific types of DWB. Eastern DWB (EWB) occurs when both the CWB and AWB lie in the eastern subdomain. Similarly, western DWB (WWB) occurs when both wave breakings lie in the western subdomain. The cases where one wave breaking occurs in the eastern portion of the basin and the other in the western portion are termed “misaligned breakings.” These can display either an AWB to the west and a CWB to the east (MA WWB) or, vice versa, an AWB to the east and a CWB to the west (MA EWB). Note that the 45° and 55°N meridional thresholds still apply. Figure 2e provides a graphical summary of the different DWB classes.

Finally, two sets of smaller domains are considered when investigating the link between DWB and the NAO. These are selected in an attempt to maximize the projection of the DWB SLP anomalies onto the NAO dipole. For the positive NAO, only DWB events where the CWB occurs between 65° and 80°N and the AWB occurs between 45° and 55°N are considered. This ensures that the CWB occurs to the north of the NAO’s low-pressure center and the AWB to the south. The southern bound of the CWB domain is actually just south of the NAO’s low-pressure center, but more northerly domains did not yield a sufficient number of DWB events to analyze. The zonal extent of the domain is restricted to 50°W–0°, so that the largest SLP anomalies are roughly aligned with the NAO dipole. For the negative NAO, only events where the CWB occurs between 45° and 55°N and the AWB occurs between 25° and 35°N are considered. This ensures that the CWB occurs to the north of the NAO’s high-pressure center of action and the AWB to the south. The zonal extent of the domain is again restricted to 50°W–0°.

2.3. Jet Stream Indices

Two indices describing the state of the jet stream over the North Atlantic are used. Both consider an Atlantic domain spanning 60° to 10°W and 35° to 80°N, and are computed for upper (200–400 hPa) and lower (700–925 hPa) levels. The first, the Jet Angle Index (JAI), quantifies the tilt of the jet. The zonal and meridional components of the low-pass filtered wind, averaged over either the upper or lower levels, are used to give the wind speed. Following Woollings et al. [2010], we apply a land mask to reduce the noise due to orography, which is especially strong at low levels. Only time steps with at least half of the meridians having a location with zonal wind above 8 m s$^{-1}$ are considered, and maxima in wind speed along each meridian are identified.
If a given meridian has a secondary local wind maximum, such maximum is within 4 m s\(^{-1}\) of the primary one and is well separated (more than 5° latitude apart), then the meridian is ignored. Next, the best fit rhumb line following wind speed maxima across the North Atlantic basin is computed. A rhumb line, or loxodrome, is an arc with a fixed bearing relative to the geographic North Pole. Mathematically, the bearing of a loxodrome joining the (lat, lon) points \((\phi_0, \lambda_0)\) and \((\phi_1, \lambda_1)\), measured clockwise from due North can be expressed as

\[
\beta = \arctan2\left(\lambda_1 - \lambda_0, \ln\left(\tan\left(\frac{\pi}{4} + \frac{\phi_1}{2}\right) / \tan\left(\frac{\pi}{4} + \frac{\phi_0}{2}\right)\right)\right) \tag{1}
\]

Here \(\arctan2\) is the four-quadrant inverse tangent function. The rhumb line will cross all meridians along its path at a fixed angle and is therefore well suited to define the bearing of the jet stream. The jet angle is then defined as the complementary angle to the bearing of the rhumb line. Positive values indicate a northeastward flow, negative ones a southeastward flow.

The second index is the Jet Latitude Index (JLI), similar to the one first proposed by Woollings et al. [2010]. The zonal component of the low-pass filtered wind, averaged over either the upper or lower levels, is used to give the zonal wind speed. For each time step, the index then identifies the latitude of the strongest zonal flow, zonally averaged across the Atlantic domain. This is taken to be the reference latitude for the jet stream. The jet speed is defined as the zonal speed at the latitude identified by the JLI. The JLI is designed to complement the 2-D velocity maps discussed in the analysis, by focusing exclusively on the averaged zonal component of the jet. Further details on both the JAI and JLI, including a comparison of the JLI results to those of Woollings et al. [2010] and a discussion of the choice of domain, are provided in the supporting information.

### 2.4. Destructive Days

Part of the analysis focuses on windstorms over continental Europe. The most destructive windstorms over the 33 winters considered here are selected based on the Klawa and Ulbrich [2003] potential destructiveness index. The PD value at a given grid point for a specific time step is defined as

\[
PD = \left(\frac{v}{v_{98}} - 1\right)^{1.7}, v > v_{98}, 0 < v \leq v_{98} \tag{2}
\]

Here \(v\) is the surface wind speed at the chosen grid point and time and \(v_{98}\) is the climatological 98th percentile of wind speed at the same location. This empirical expression is physically motivated by considerations of surface power dissipation and was found to provide an optimal fit to observed losses resulting from extreme windstorms in Germany [Klawa and Ulbrich, 2003]. The value of PD can thus be used as an approximate metric for the destructiveness of the wind at a given location. The algorithm is applied to all land points over a domain encompassing northern France, Germany, Benelux, and southern Denmark, with vertices at (49°N, 5°W), (54°N, 11°E), (47°N, 12°E), and (46°N, 1°W). The domain is chosen to include the most economically productive and densely populated regions in Europe and is illustrated by the red quadrilateral in Figure 2b. A domain-wide PD value is obtained by simply summing the values at all the individual grid points.

Since the algorithm uses the 98th percentile of climatological wind speed as a lower threshold, most days will have zero destructiveness across the domain. Moreover, when considering days with nonzero destructiveness, there are several instances where only one or two gridboxes within the domain exceed the 98th percentile of wind speed, often only by a small margin. To focus the analysis only on severe events, we classify a time step as a destructive event if it displays winds in excess of the local 98th percentile over at least 20% of the grid boxes within the domain. This provides an average of 8–9 days displaying a destructive event per winter in the reanalysis data and just over 7 days in the MPI-ESM-P model. Reasonable changes in this parameter have been tested (10% and 30%), and the conclusions drawn here were not affected. For completeness, some of the results for the two alternative thresholds are included in the analysis. When only one set of results is discussed, this always refers to the 20% threshold definition.

To test that our threshold-based definition does indeed capture significant destructive events, part of the analysis in the paper was repeated by ranking events based on their peak destructiveness. This is defined as the maximum domain-wide PD value, similarly to the methodology adopted in HC12. The destructive events are then defined as the 50 days displaying the largest peak destructiveness; reasonable variations in this number were tested. Note that, if several consecutive days rank in the top events, only the one displaying the largest PD value is retained. This ensures that the analysis does not consider the same weather system multiple times.
Table 1. Summary of the Different Geographical Domains Used in the Analysis, as Defined in Section 2

<table>
<thead>
<tr>
<th>Domain</th>
<th>Geographical Boundaries</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAO</td>
<td>20°–90°N, 90°W–45°E</td>
<td>Figure 2a</td>
</tr>
<tr>
<td>DWB AWB</td>
<td>20°–45°N, 80°W–30°E</td>
<td>Figure 2a, Meridional extent as for DWB AWB and DWB CWB, Figure 2a</td>
</tr>
<tr>
<td>DWB CWB</td>
<td>55°–80°N, 80°W–30°E</td>
<td>Figure 2a</td>
</tr>
<tr>
<td>EWB</td>
<td>25°W–30°E</td>
<td></td>
</tr>
<tr>
<td>WWB</td>
<td>80°–25°W</td>
<td>Meridional extent as for DWB AWB and DWB CWB, Figure 2a</td>
</tr>
<tr>
<td>DWB NAO+ AWB</td>
<td>45°–55°N, 50°W–0°</td>
<td>Figure 2c</td>
</tr>
<tr>
<td>DWB NAO+ CWB</td>
<td>65°–80°N, 50°W–0°</td>
<td>Figure 2c</td>
</tr>
<tr>
<td>DWB NAO- AWB</td>
<td>25°–35°N, 50°W–0°</td>
<td>Figure 2d</td>
</tr>
<tr>
<td>DWB NAO- CWB</td>
<td>45°–55°N, 50°W–0°</td>
<td>Figure 2d</td>
</tr>
<tr>
<td>JAI &amp; JLI</td>
<td>35°–80°N, 60°–10°W</td>
<td>Figure S6</td>
</tr>
<tr>
<td>Destructive days</td>
<td>(49°N, 5°W), (54°N, 11°E), (47°N, 12°E), (46°N, 1°W)</td>
<td>Vertices of a quadrilateral bounding the domain, Figure 2b</td>
</tr>
</tbody>
</table>

Table 1 provides a summary of all the geographical domains defined in this section.

The significance levels of all the results presented in the paper are estimated using a Monte Carlo approach. One thousand random samples, with the same number of members as the composite being tested for significance, are generated from the full 33 year data set. So, for example, to test a wind speed anomaly composite map based on 50 individual time steps, 1000 random samples of 50 wintertime wind speed anomaly maps are selected. Similarly, to test a JLI value resulting from the mean of 50 individual DWB events, 1000 random samples of 50 wintertime JLI values are selected. The 95% confidence bounds are then derived from the distribution of the random samples.

3. Geographical and Temporal Distribution of Double Wave Breaking

The definition of DWB adopted here is purposefully loose and inclusive, so as to provide a comprehensive overview of the phenomenon. More restrictive definitions such as that in Gómara et al. [2014a] requiring the RWB to exceed a minimum area threshold and to occur in specific geographical sectors have been tested, but it is found that they exclude a large number of events. Indeed, the discussion of DWB in Gómara et al. [2014a] focuses on an extremely limited number of cases (<1% of winter days).

With our definition, DWB is a relatively frequent occurrence, with approximately 12 DWB days per winter across the whole basin (18 for the relaxed temporal overlap criterion), or one every 7.5 (5) days. Of these, around 6 (9) are WWB days, just under 2.5 (5) are EWB days, and the rest are misaligned events. Figures 2a and 2b show the wintertime climatology for cyclonic and anticyclonic wave-breaking events in the reanalysis data, while Figures 2c and 2d display the frequencies on DWB days. AWB typically occurs in a band spanning the southern half of the basin while CWB occurs farther to the north and with lower frequency. Both types of WB show a relatively uniform zonal distribution across the basin. According to our definition of DWB, AWB must occur to the south of 45°N and CWB to the north of 55°N, but Figures 2c and 2d show a considerable frequency of WB events outside these limits. This is because the figures show all WB instances occurring on days displaying DWB. Often, such days will display more than two WBs across the Atlantic basin. The additional WBs, not part of the DWB pair, can be located outside the specified domains.

While the two wave breakings must overlap by at least 1 day, no constraint is placed on the relative timing of their onset. It is therefore interesting to verify whether either of the two cyclonicities systematically precedes the other. It is found that the AWB precedes the CWB on 47% of the cases; the CWB leads on 16% of the cases and the two wave breakings begin on the same day in the remaining events. The AWB therefore leads the development of the DWB almost 3 times as often as the CWB. This is likely linked to the former’s longer-average duration (3.3 versus 1.7 days) and suggests that the CWB could be partly entrained by the large, intense AWB to the south. If the analysis is repeated for the DWB pairs identified using the variable threshold methodology (see section 2.2), the fractional split between the three cases remains almost unchanged.
4. Double Wave Breaking and the NAO

As noted in section 1, there is an extensive literature linking RWB and the NAO. In turn, there is a known connection between the NAO and extreme windstorms in Europe (e.g., HC12). The extent to which DWB projects onto the NAO is an issue of interest in itself, and it may also yield insights into the mechanisms by which DWB ultimately influences European windstorms. As also noted in section 1, RWB is associated with specific SLP anomalies; the location and orientation of the WB determines how these anomalies will project onto the NAO. This is illustrated schematically in Figure 3, which displays the composite SLP anomalies for several thousand AWB and CWB events, centered such that they align with the NAO’s pressure centers [Strong and Magnusdottir, 2008a]. To obtain an optimal alignment between the SLP anomalies and the NAO’s pressure centers, WB events projecting onto opposite phases of the NAO should be meridionally shifted by ~20° [Strong and Magnusdottir, 2008a]. A positive (negative) pressure anomaly develops on the southern (northern) flank of AWBs, while the converse holds for CWBs. If the cyclonic and anticyclonic components of the DWB are located such that their negative pressure anomalies overlap, they may lead to a strong positive or negative NAO, depending on their latitudinal location. Cases where the pressure anomalies due to the two breakings are misaligned will lead to a neutral projection onto the NAO.

We find that DWB events have roughly equal probabilities of leading to positive and negative NAO phases (Table 2). The mean NAOI 2 days after DWB is 0.05, statistically indistinguishable from zero, and an SLP composite over all DWB instances (not shown) displays no statistically significant anomalies over the NAO’s pressure centers. Different lags (0 to 5 days following DWB) have been tested and all show similar results. Adopting a variable meridional threshold for AWBs and CWBs (see section 2.2), does not lead to a significant projection. Indeed, even when the fixed meridional thresholds are removed, the mean locations of DWB pairs occurring during positive and negative NAO phases do not display the large meridional shift one might expect. We have also examined the four different DWB subgroups separately (see section 2.2) and found that, on average, none project strongly onto either polarity of the NAO. Depending on the case, between 51% and 60% of the events are found to match a positive NAO, while the mean NAOI values range from −0.03 to 0.14.

Next we investigate whether, by restricting the geographical domain of DWB, it is possible to identify DWB events that do project strongly onto the NAO. These smaller domains, defined in section 2.2 and Table 1, are meant to identify the DWB pairs driving SLP anomalies aligned with the NAO’s centers of action. Due to the limited area of the domains, the

Table 2. Plus 2 Days Time Lag Mean and Standard Deviation of NAOI Values on All DWB Days and on DWB Days Within the Positive and Negative NAO Domains

<table>
<thead>
<tr>
<th></th>
<th>Mean NAOI</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DWB Clim.</td>
<td>(0.05)</td>
<td>0.97</td>
</tr>
<tr>
<td>NAO+ Box</td>
<td>0.63</td>
<td>1.19</td>
</tr>
<tr>
<td>NAO− Box</td>
<td>−0.46</td>
<td>0.87</td>
</tr>
</tbody>
</table>

*Values in parentheses are not statistically different from the winter-time climatology at the 95% confidence level.
relaxed temporal criterion where the two WB events can occur within 1 day of one another is adopted to increase our sample size. This results in almost three DWB events per winter. The mean and standard deviation of the NAOI values are shown in Table 2, while the associated composite SLP anomalies are shown in Figures 4a (positive NAO) and 4b (negative NAO).

For the positive NAO, likely candidates are WB pairs where the low SLP to the south of the CWB and to the north of the AWB coincides with the NAO's low-pressure center; additionally, the high SLP to the south of the AWB will yield a positive anomaly over the high-pressure center. The selected DWB events have a mean 2 day lag NAOI of 0.63. Note that, even though the NAOI presents a large standard deviation ($\sigma = 1.19$), the mean value is statistically different from the climatological DWB one using a Monte Carlo test at the 95% level. As expected, the SLP pattern displays a large negative anomaly over the NAO's low-pressure center; however, there is no positive anomaly over the high-pressure center.

A similar analysis can be performed for negative NAO events. Here likely candidates are DWBs where the negative SLP anomalies of the two WBs sum over the NAO's high-pressure center. Additionally, the high pressure to the north of the CWB will yield a positive anomaly over the low-pressure center. These events have a statistically significant projection onto the negative NAO, with a mean NAOI value of $-0.46$ for a 2 day lag following the DWBs. The SLP pattern displays a weak negative anomaly over the NAO's high-pressure center, and a similarly weak positive anomaly over the low-pressure center.

The above analysis suggests that the relationship between DWB and the NAO is highly dependent on the geographical location of the former. The large standard deviations seen in the NAOI (Table 2) further suggest that DWB events driving well-aligned SLP anomalies which overlap the NAO's centers of action are relatively rare. These results are discussed further in section 7.

5. Double Wave Breaking and the Jet Stream

The DWB described in section 3 is a large-scale process, with individual events spanning a vast stretch of the North Atlantic basin. Previous studies have suggested that the occurrence of Rossby wave breaking, especially if associated with a positive NAO, has a strong influence on the jet stream [Riviere and Orlanski, 2007; Gómez et al., 2014b; Pinto et al., 2014]. As discussed in section 1, DWB will generally lead to an increased meridional PV gradient in the region between the breakings and to an intensified midlatitude jet. Here we present a comprehensive analysis of the impact of DWB on the jet stream, including its direction, meridional location, and intensity. We use the jet angle index (JAI) and jet latitude index (JLI) defined in section 2.3 above. While the jet latitude has been the subject of extensive analyses [e.g., Woollings et al., 2010; Hannachi et al., 2013; Woollings et al., 2014], less attention has been devoted to algorithms evaluating the jet’s bearing. The two indices provide complementary information, since there is no a priori correspondence between the meridional position and the direction of the jet. The values are computed for both upper (200–400 hPa) and near-surface (700–925 hPa) levels. The lower level values allow for an easier comparison with jet analyses in the literature, while the upper level ones match the level at which the WB is diagnosed. Since the eddy-driven midlatitude jet is reasonably barotropic, the values found at upper levels show many similarities to the surface ones. In order to provide a complete overview of the changes in jet orientation, the mean and upper and lower 5th percentiles of the JAI distributions are analyzed. The results are provided in Table 3.
Table 3. Jet Angle Index, Jet Latitude Index, and Jet Speed Values at Upper and Lower Levels for the Wintertime Climatology and Different Subsets of Winter Days$^a$

<table>
<thead>
<tr>
<th>Events</th>
<th>Pressure Levels</th>
<th>Angle</th>
<th>5th Percentile</th>
<th>95th Percentile</th>
<th>Latitude</th>
<th>Speed (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Wint. Clim.</td>
<td>700–925 hPa</td>
<td>16.4</td>
<td>–7.8</td>
<td>40.4</td>
<td>48.2</td>
<td>13.9</td>
</tr>
<tr>
<td></td>
<td>200–400 hPa</td>
<td>14.8</td>
<td>–10.0</td>
<td>40.0</td>
<td>48.6</td>
<td>34.1</td>
</tr>
<tr>
<td>(ii) NAO+</td>
<td>700–925 hPa</td>
<td>20.2</td>
<td>–2.6</td>
<td>40.6</td>
<td>49.8</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>200–400 hPa</td>
<td>19.4</td>
<td>–4.4</td>
<td>40.3</td>
<td>50.0</td>
<td>36.4</td>
</tr>
<tr>
<td>(iii) DWB Clim.</td>
<td>700–925 hPa</td>
<td>14.8</td>
<td>(–10.4)</td>
<td>39.8</td>
<td>47.1</td>
<td>(13.9)</td>
</tr>
<tr>
<td></td>
<td>200–400 hPa</td>
<td>(13.8)</td>
<td>(–8.2)</td>
<td>39.0</td>
<td>47.5</td>
<td>(34.2)</td>
</tr>
<tr>
<td>(iv) NAO+/DWB</td>
<td>700–925 hPa</td>
<td>(19.5)</td>
<td>3.9</td>
<td>40.2</td>
<td>49.3</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>200–400 hPa</td>
<td>20.3</td>
<td>3.0</td>
<td>40.8</td>
<td>(49.9)</td>
<td>36.0</td>
</tr>
<tr>
<td>(v) WWB</td>
<td>700–925 hPa</td>
<td>(15.8)</td>
<td>(–8.1)</td>
<td>39.9</td>
<td>47.1</td>
<td>(13.6)</td>
</tr>
<tr>
<td></td>
<td>200–400 hPa</td>
<td>(15.5)</td>
<td>(–7.2)</td>
<td>40.3</td>
<td>(47.8)</td>
<td>(33.7)</td>
</tr>
<tr>
<td>(vi) EWB</td>
<td>700–925 hPa</td>
<td>11.5</td>
<td>(–10.4)</td>
<td>30.6</td>
<td>46.4</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>200–400 hPa</td>
<td>10.4</td>
<td>(–6.7)</td>
<td>35.1</td>
<td>46.5</td>
<td>35.2</td>
</tr>
<tr>
<td>(vii) MA DWB</td>
<td>WWB 700–925 hPa</td>
<td>(14.6)</td>
<td>(–10.5)</td>
<td>40.6</td>
<td>47.0</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>EWB 200–400 hPa</td>
<td>(14.8)</td>
<td>(–18.9)</td>
<td>38.4</td>
<td>46.9</td>
<td>(13.9)</td>
</tr>
<tr>
<td></td>
<td>WWB 700–925 hPa</td>
<td>(13.8)</td>
<td>(–8.6)</td>
<td>39.8</td>
<td>47.3</td>
<td>(35.3)</td>
</tr>
<tr>
<td></td>
<td>EWB 200–400 hPa</td>
<td>(13.7)</td>
<td>(–10.0)</td>
<td>40.1</td>
<td>47.1</td>
<td>(34.0)</td>
</tr>
<tr>
<td>(viii) Windstorms</td>
<td>700–925 hPa</td>
<td>12.3</td>
<td>(–12.3)</td>
<td>28.5</td>
<td>(48.4)</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>200–400 hPa</td>
<td>12.3</td>
<td>(–8.8)</td>
<td>30.7</td>
<td>(49.2)</td>
<td>39.1</td>
</tr>
</tbody>
</table>

$^a$The values shown correspond to (i) the DJF climatology; (ii) positive NAO phases; (iii) all DWB events; (iv) DWB events occurring during a positive NAO phase; DWB events occurring in the (v) western and (vi) eastern portions of the North Atlantic; (vii) misaligned DWB events; (viii) destructive events. Case (vii) is further split depending on the location of the AWBs. The values in brackets are not statistically different from the wintertime climatology at the 95% confidence level. Note that the values for DWBs occurring during a positive NAO phase were tested for statistical significance relative to the positive NAO-only value, as opposed to the wintertime climatology.

The mean jet angle for the wintertime (DJF) season is found to be 16.4°, capturing the climatological southwest to northeast tilt of the North Atlantic circulation (see supporting information). The index also successfully captures the increase in the average jet tilt associated with the positive NAO [cf. Pinto and Raible, 2012]. Next, the angles for different subsets of DWB events are studied. All values are tested for statistical significance relative to the wintertime climatological angle. The one exception is DWB occurring during positive NAO phases, which is tested for significance relative to the positive NAO-only values. Since the maximum anomalies in the jet typically lag the WB events by 1 to 3 days, the values displayed in Table 3 correspond to an average over the 3 days following the DWB events. The single-day values for the day of the DWB and each of the three following days were also analyzed individually, and the differences in JAI relative to the multiday mean were found to be small.

DWB events as a whole present a systematically smaller tilt than the wintertime climatology. In order to obtain a clearer picture, the DWB events are separated according to NAO phase and geographical location. The mean angle associated with DWB events which occur during positive NAO phases is relatively close to that found for all positive NAOs. A small, albeit significant, increase in mean tilt is found at upper levels. Next, we consider DWB events occurring in the western (80.0°–25.0°W) and eastern (25.0°W–30.0°E) North Atlantic separately. EWB events tend to zonalize the jet relative to the DJF climatology, at both upper and lower levels. The median (not shown) and the 95th percentiles also show decreases, suggesting both a systematic shift of the upper 50th percentiles of the distribution and that large tilts are comparatively uncommon during EWB events. WWBs have no statistically significant effect on jet tilt. However, if only DWBs west of 35°W are considered, the mean tilt is increased at both levels (not shown). This suggests that DWBs in the far western portion of the basin actively increase the mean jet tilt, while those occurring closer to the center of the basin leave it essentially unchanged.

Upper level wind speed composites over all DWB, EWB, and WWB events are shown in Figures 5a–5c, respectively. For conciseness, we only show plots at lag +2 days, which correspond to the strongest anomalies. The anomalies associated with DWB events as a whole (Figure 5a) are relatively weak, with a tendency toward an intensified jet at the lower latitudes and a decrease of the wind speed north of approximately 55°N. This is consistent with the smaller tilts detected by the algorithm. WWB (Figure 5b) drives a strengthened jet in the western part of the basin and a weakened flow in the jet exit region. EWB (Figure 5c) also displays a band...
Figure 5. Composites of the 250 hPa horizontal wind speed anomaly (m s$^{-1}$) at lag +2 days for (a) All DWB events, (b) Western, (c) Eastern, (d) misaligned WWB, and (e) misaligned EWB. Shadings show anomalies relative to the DJF climatology; black contours show net values (starting from 15 m s$^{-1}$, interval 7.5 m s$^{-1}$). Only anomalies exceeding the 95% confidence level derived from a random Monte Carlo sampling procedure are shown. The data range is the same as in Figure 2.
of enhanced flow in the western basin, but the largest anomalies are seen farther East, where an intense tripolar pattern develops. The flow is strengthened over continental Europe, and weakened elsewhere. In particular, there is a strong negative anomaly over the Nordic seas, effectively shifting the jet exit region south of its climatological position. This results in a more zonal jet path, as detected by the algorithm. Note that if the more relaxed criterion whereby the two breakings can occur within 1 day of one another is considered, the tripolar anomaly pattern in the composite is weakened.

We turn next to the cases where the two RWB instances leading to the DWB are misaligned; that is, the cases where one is in the western portion of the basin and the other in the eastern portion. The upper level wind speed composites are shown in Figures 5d and 5e. Both misaligned cases show a modest decrease in mean jet tilt relative to the wintertime climatology, although the results are not statistically significant due to the relatively small sample sizes for these WB configurations. The western case displays a strengthening of the jet across most of the basin, with a moderate southward shift of the exit region relative to the climatological flow (cf. Figure S6b). A negative anomaly in the high latitudes is also present, and the overall effect is of a slightly more zonal than usual jet. The eastern AWB composite, on the contrary, shows very weak anomalies across the Atlantic domain. We therefore conclude that, regardless of level, most DWB configurations tend to systematically zonalize the jet stream. The fact that some DWB subsets present opposite anomaly patterns (e.g., EWB and WWB), while others display stronger anomalies than the full DWB composite (e.g., EWB and MA WWB) suggests that the latter suffers from cancelation.

A similar analysis can be repeated for the JLI. Even though the distribution of latitude values is quite broad (the 5th and 95th near-surface percentiles for DJF are 36° and 64°N, respectively), most of the cases considered in Table 3 display relatively similar means. This suggests that none of the selected WB configurations systematically corresponds to either of the tails of the JLI distribution. At both upper and near-surface levels, the positive NAO case displays a slightly more northerly position than the wintertime climatology, while the DWB composites display a slightly more southerly location. In most cases, the mean latitudinal locations correlate well with the JAI values. Figure 6 illustrates the probability density estimates for the wintertime climatology (continuous curves), positive NAO (dash-dotted curves), and EWB (dashed curves) cases at both upper and near-surface levels. At upper levels (Figure 6a), all distributions cover a broad range of latitudes, with the NAO case displaying a marked peak in the upper half of the climatological JLI range. At the near-surface levels (Figure 6b), the wintertime climatology presents a trimodal character, similar to that found by Woollings et al. [2010] (see also Figure S8). The EWB climatology retains this trimodal structure, while the NAO distribution again favors more northerly locations. Neither distribution projects onto a single peak, resulting in similar mean values. The relatively uniform nature of the JLI results will be discussed further in section 7.

Lastly, the jet stream’s speed is analyzed. This is defined as the zonally averaged zonal velocity at the latitude identified by the JLI (see section 2.3). The climatological low-level wintertime value is 13.9 m s⁻¹, with increased values during positive NAO phases. This is in line with results in the literature (e.g., Woollings et al. [2010] find a wintertime mean of 14 m s⁻¹). Both EWB events and MA WWB events display a small
intensification of the jet, which for the EWB case is significant at both levels. These DWB types share a CWB in the northeastern portion of the domain, suggesting that this might play a role in the intensification of the jet. This intensification agrees with the anomalies shown in the upper level velocity composites. EWB (Figure 5c) displays a positive anomaly centered over the eastern portion of the basin, while the misaligned DWB (Figure 5d) displays a strengthened flow across most of the basin. When computing the zonal mean flow, the effects of these geographically different positive anomalies are very similar. Note that caution should be employed when comparing the magnitudes of the anomalies in the figures to the values shown in Table 3. The zonally averaged speeds do not necessarily relate to wind speed anomalies at fixed spatial locations. Rather, they provide additional information relative to the velocity maps by focusing exclusively on the averaged zonal component of the jet. We conclude that, as for the JAI, the EWB composite is the WB category displaying the largest statistically significant anomalies and leads to an intensification of the jet over the domain of interest.

6. Double Wave Breaking and Destructive Windstorms

Previous work has shown that wave-breaking configurations similar to the EWB pattern are conducive to explosive cyclogenesis (Gómara et al. [2014a], based on a small fraction of Atlantic explosive cyclones) and cyclone clustering (Pinto et al., based on 4 months displaying multiple cyclones over Western Europe), while DWB precedes a large portion of the 25 most damaging storms which affected continental Europe during 1958–2001 (HC12). However, in the latter study, no automated algorithm for the detection of the WB was applied. Here we present a more systematic analysis of the link between DWB and destructive wind storms over Europe. This link is dynamically grounded in the flow anomalies associated with DWB, outlined in sections 1 and 5 above. We also compare the results found for the reanalysis data to those from a 50 year integration of the MPI-ESM-P model.

6.1. Destructive Windstorms

Destructive events over continental Europe are selected, as described in section 2.4. These events project weakly onto the positive NAO, with a mean NAOI value of 0.26. This is not surprising, since the positive phase of the NAO displays more frequent and intense storms than the climatology and favors explosive cyclogenesis [Gómara et al., 2014b], but also tends to increase the tilt of the jet stream. Figure 7 displays the upper level wind composites on the days leading up to destructive events. Note that, in comparing these to the DWB composites, a temporal lag between the two events should be considered. At day −6, there is an initial strengthening of the jet stream. By day −4 a tripolar anomaly pattern has formed over the North Atlantic basin, and the intensified winds extend over northern continental Europe. A strong negative anomaly develops around Iceland, as a result of the meridional shift in the jet exit region. At lag −2 the jet is almost fully zonalized and the exit region is over northern France. During the destructive event, the jet extends into eastern Europe, and the positive anomaly over continental Europe peaks. This eastward extension agrees very well with the wind pattern seen in HC12. The tripolar anomaly pattern which appears around lag −4 retains the same structure but is shifted farther east, following the intensified background flow. The more zonal configuration associated with the destructive events is also observed in sea level pressure composites (not shown) and is reflected in the JAI. The windstorms are found to correspond to a very zonal jet (12.3° at 200–400 hPa) with a higher than average speed (Table 3). The values in the table represent an average over the 12 h preceding and following the destructive event, for a total of five time steps. This matches the period over which the jet attains its maximum zonality (Figure 7b). With the exception of eastern DWB, the destructive events composite is the one that displays the lowest mean jet angle at both levels (Table 3). Moreover, the fact that the largest velocity anomalies extend over continental and into eastern Europe, outside the domain of the JAI, actually leads the latter to overestimate the jet angle. The selected events therefore represent extreme cases not only in terms of their impacts on the continent, which is implicit in our selection methodology, but also in terms of the zonality and intensity of the large-scale atmospheric flow.

To further confirm the robustness of our analysis, the above calculations were repeated by considering the top 50 days ranked by domain-wide destructiveness (see section 2.4). Both the orientation of the jet and the velocity anomaly patterns (Figure 57) were found to be qualitatively similar. A minor difference is that the velocity anomalies on the day of peak destructiveness yield even lower JAI values (mean and median angles at upper levels below 10°).
6.2. The Relationship With DWB

A comparison of the upper level wind anomalies in Figures 5c (EWB) and 7d (destructive events) highlights a very similar tripolar anomaly pattern over Europe, with a strengthening of the jet over the continent and a weakening of the flow to the north and south. However, it should be noted that the windstorm composite presents a more marked eastward shift of the jet stream’s core and stronger positive anomalies over the continent. Figure 8a displays the composite of absolute vorticity for destructive days, which further confirms the link with EWB. A very marked large-scale anticyclonic breaking is seen in the southeastern Atlantic, while a weaker cyclonic inversion occurs over Iceland. Note that the absolute vorticity field has been filtered as described in section 2.2.

Figure 7. Same as Figure 5 but for destructive events with lags of: (a) −6, (b) −4, (c) −2, and (d) 0 days.

None of the other WB composites show a similar wind anomaly structure. In fact, WWB (Figure 5b) actually displays a tripo lar anomaly pattern of the opposite sign. These considerations are in good agreement with the results of the jet stream analysis presented in section 5. EWB results in an extremely zonal jet, which
matches the low JAI values found for the windstorm days. WWB, on the other hand, is the DWB configuration with the largest jet tilts. Furthermore, both EWB and the destructive days are associated with a significantly intensified jet.

In order to test this link more systematically, we verify whether eastern DWB increases the likelihood of the occurrence of a destructive day above climatological values. For comparison, we also examine the effects of conditioning on the positive NAO or on other DWB classes. To test the robustness of the results, we adopt different definitions of destructive days as discussed in section 2.4. Following the analysis in section 5, a DWB event is considered to overlap a destructive day if such a day occurs in any of the 3 days following the DWB. To provide a suitable comparison, the wintertime climatology is expressed both as the fraction of winter days displaying a destructive event and as the fraction of 3 day intervals including at least one destructive event. Values for the different WB scenarios should be compared to the 3 day climatology, while the positive NAO phases should be compared to the single-day climatology.

For the single-day (3 day) wintertime climatology, between 6.1% (13.5%) and 12.3% (24.2%) of days qualify as destructive, depending on the chosen threshold (Table 4). The positive NAO significantly increases the frequency of destructive days for all thresholds. Even though the jet stream is typically more tilted, positive NAO phases correspond to more frequent, more intense Atlantic storms, and it is therefore not surprising that some of these storms may lead to strong surface winds over the continent. DWB taken as a whole does not increase the likelihood of a destructive day relative to the wintertime climatology. As could be surmised from

Figure 8. Minus 2 days time lag composites of 250 hPa absolute vorticity (s⁻¹) for destructive days in (a) the ERA-Interim reanalysis data and (b) the MPI-ESM-P model. The black contours show net values (starting from $0.1 \times 10^{-4}$ s⁻¹, interval $0.1 \times 10^{-4}$ s⁻¹). (c) Difference between the ERA-Interim and MPI-ESM-P values. The white contours bound anomalies exceeding the 95% confidence level derived from a random Monte Carlo sampling procedure. The data range for the reanalysis is the same as in Figure 2. The model data cover 50 DJFs. The vorticity field is truncated at T15.
the upper level wind composites discussed in section 5, WWB actually decreases the likelihood of destructive weather over the continent, almost halving the frequencies to between 7.7% and 13.1% of winter 3 day periods. EWB, on the other hand, displays the most frequent destructive days over Europe, with values significantly higher than those of both the wintertime climatology and the other DWB cases. When the most severe destructive events are considered (30% column in Table 4), EWB almost doubles the climatological frequency. The fractional increase in destructive event frequency due to EWB is systematically larger than that associated with the positive NAO. There is relatively little overlap between the two sets, since only 15% of EWB instances correspond to an NAOI > 1. If only moderate or negative NAO phases are considered, the difference in destructive day frequency between EWB and the climatology is further enhanced (not shown). The contrasting effects of EWB and WWB can partly explain the weak impact DWB as a whole has on the frequency of destructive events. A note should be made regarding the misaligned DWB. The MA WWB case systematically displays the second highest values in the table, following eastern DWB. Unfortunately, it is difficult to relate this to the results of the JAI analysis, due to the limited statistical significance of the MA WWB results.

So far, we have tested whether the days immediately following the occurrence of DWB display destructive events. Next, we verify the inverse link, namely, how often destructive events are preceded by DWB. The values in Table 4 imply that, given our definition of destructive days, most of them will not be preceded by a DWB. Indeed, there are approximately 12 DWB events and eight or nine destructive days every winter. If only ~20% of the DWBs precede a destructive day, this corresponds to no more than two to three destructive days per winter (or around 75 over the whole time series considered). The same reasoning holds for EWB, which best matches destructive days.

A further test can be performed by applying a more restrictive definition of destructive event, namely, the 50 most destructive days in the full time series. These could in theory all be preceded by a DWB event, in view of the fact that around 75 destructive days are preceded by DWB over the whole time series. In reality, it is found that only 13 (20 if DWB is defined using the relaxed temporal overlap criterion) of the top 50 days are preceded by a DWB; of these, 5 (6) correspond to an eastern DWB. If only the 25 most destructive days are considered, similar results are found: 6 (10) match DWB and 3 (3) match EWB.

6.3. A Comparison With Model Simulations

Previous studies on DWB have mainly focused on reanalysis data [e.g., HC12; Gómara et al., 2014a; Pinto et al., 2014], and it is unclear how well models can capture the link between this specific large-scale wave pattern and surface wind extremes. Here we present a brief comparison of the above reanalysis results with the output from the MPI-ESM-P model (see section 2.1). The model was selected because it reproduces closely the DWB frequencies seen in the ERA-Interim data (see supporting information). As is the case in many models, the jet stream is climatologically more zonal than in the reanalysis (Figure S6c), with a mean wintertime tilt of 12.8° at upper levels.

Table 4. Frequency of Destructive Days Over Continental Europe as a Fraction of Total Number of Days

<table>
<thead>
<tr>
<th>Definition</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Wint. Clim. Single</td>
<td>12.3%</td>
<td>9.5%</td>
<td>6.1%</td>
</tr>
<tr>
<td>3 day</td>
<td>24.2%</td>
<td>19.7%</td>
<td>13.5%</td>
</tr>
<tr>
<td>(ii) NAO+</td>
<td>16.6%</td>
<td>13.7%</td>
<td>9.0%</td>
</tr>
<tr>
<td>(iii) DWB Clim.</td>
<td>(22.2%)</td>
<td>(18.8%)</td>
<td>(14.2%)</td>
</tr>
<tr>
<td>(iv) WWB</td>
<td>13.1%</td>
<td>9.3%</td>
<td>7.7%</td>
</tr>
<tr>
<td>(v) NAO+/DWB</td>
<td>(27.4%)</td>
<td>(24.2%)</td>
<td>(17.9%)</td>
</tr>
<tr>
<td>(vi) EWB</td>
<td>34.6%</td>
<td>33.3%</td>
<td>25.9%</td>
</tr>
<tr>
<td>(vii) MA DWB WWB</td>
<td>(28.7%)</td>
<td>27.1%</td>
<td>19.7%</td>
</tr>
<tr>
<td>EWB</td>
<td>(19.8%)</td>
<td>13.5%</td>
<td>(11.7%)</td>
</tr>
</tbody>
</table>

* A destructive day is one in which more than X% of the domain’s grid boxes display a nonzero destructiveness, where X is either 10, 20, or 30. The values shown correspond to (i) the DJF climatology, both for single days and 3 day intervals; (ii) positive NAO phases; (iii) all DWB events; (iv) DWB events occurring during a positive NAO phase; DWB events occurring in the (iv) western and (v) eastern portions of the North Atlantic; (vii) misaligned DWB events. Case (vii) is further split depending on the location of the AWBs. The values in brackets are not statistically different from the wintertime climatology at the 95% confidence level. Note that the values for DWBs occurring during a positive NAO phase were tested for statistical significance relative to the positive NAO-only value, as opposed to the wintertime climatology.
Figures 9a and 9b display the upper level wind and wind anomaly composites associated with destructive events and EWB, respectively, in the MPI model. The destructive events bear some qualitative similarity to the reanalysis results (Figure 7d), but the modeled anomalies are weaker than those in the reanalysis, as discussed further in section 7. For the EWB, both the anomaly pattern and the zonalizing effect of EWB (which reduces the jet’s tilt from 12.8° to 9.4°) are qualitatively similar to the reanalysis, but again with weaker amplitudes. This is consistent with the comparison of absolute vorticity composites over destructive days, illustrated in Figures 8a (reanalysis), 8b (model), and 8c (reanalysis-model). The model successfully captures the large-scale anticyclonic breaking in the southeastern Atlantic, albeit with significantly higher vorticity values in the overturning tongue, while it struggles to reproduce the weaker cyclonic inversion in the northern part of the domain. The resulting meridional gradient inversions are thus much weaker than in the reanalysis.

The difficulties of the model in reproducing the ERA-Interim results are mirrored by the lack of a statistically significant link between EWB and destructive days. The climatological frequency of destructive days over 3 day intervals in the model is 17.3%, very close to the 19.7% found in the reanalysis. The EWB case, however, corresponds to a decreased frequency of destructive days (14.2%), and none of the other DWB cases considered here correspond to a statistically significant frequency increase relative to the wintertime climatology.

7. Discussions

The role of DWB in affecting the jet stream is consistent with a simple PV view of the circulation, whereby the sharpened meridional PV gradient is instrumental in determining the location and strength of the jet. The fact that EWB intensifies and zonalizes the jet, while WWB presents a similar tilt to the wintertime climatology, can be largely explained by a geographical argument. If DWB occurs near the jet entry region in the western part of the Atlantic basin (WWB), the effect on the direction of the jet will be weak, because no constraints are in place in the exit region farther to the East. EWB, on the contrary, will place a stronger dynamical constraint on the jet’s bearing, since the two wave breakings will effectively determine the location of the jet exit region. The sharpened PV gradient will also act to intensify the zonal flow over continental Europe. Previous studies have indeed found that DWB in the eastern part of the Atlantic basin is effective in constraining the jet’s latitude [Pinto et al., 2014]. The location of the sharpened gradient over the eastern North Atlantic is typically
farther south than the climatological location of the jet, thus reducing its tilt. The reduction in tilt is associated with a small, yet significant, meridional shift of the jet. The average latitude of the low-level jet for EWB is 46.4°, compared to a climatological position of 48.2° N. This shift compounds the zonalizing effect to bring the jet exit region over Europe. This is again broadly consistent with Pinto et al. (2014) who found that DWB events drive a moderate southward shift of the JLI distribution at low levels. One should, however, note that the domains chosen in the two papers, and hence the resulting JLI distributions, are different. Other studies have identified distinct preferred meridional locations of the jet, which are typically separated by 10° latitude or more [Woollings et al., 2010]. An analysis of the distribution of jet latitudes obtained from the JLI confirms that the jet ranges over a wide latitudinal band and that none of the selected WB configurations systematically corresponds to either of the tails of the JLI distribution. It should finally be noted that the choice to focus on a domain excluding the Caribbean region has the advantage of giving more weight to the behavior of the jet toward Europe, our region of interest for destructive windstorms, but will largely overlook changes in the location of the jet entry region and thus presumably underestimate the impact of WWB.

The zonalization and intensification of the jet associated with EWB is conducive to the occurrence of destructive windstorms over Europe, by favoring the explosive intensification of storms [Rivière and Joly, 2006] and steering Atlantic weather systems toward the continent. Statistically, EWB corresponds to a 43–92% increase in the frequency of destructive days over the continent, depending on the exact definition of the latter. The positive NAO phases also correspond to significantly higher than normal rates of destructive days over the continent, but the fractional increase is systematically lower than that found for the EWB (Table 4). In addition to this, the destructive events project weakly onto the positive NAO. These findings suggest that EWB is a better statistical precursor to destructive European windstorm events than the NAOI. Studies focusing on explosive cyclones in the North Atlantic have found that these are favored by positive NAO phases [Gómara et al., 2014b]. The positive NAO, however, typically corresponds to a more tilted jet stream, which steers the weather systems away from continental Europe.

The destructive events systematically display an anomalously intense jet, suggesting that in many cases additional mechanisms for strengthening the jet must be at play. The JAI analysis shows that, while the positive NAO increases the average jet tilt, there is a large variability and a small part of the positive NAO cases display an extremely zonal jet. Positive NAO phases with a zonal jet orientation could therefore provide very favorable conditions for destructive days over Europe. Interestingly, DWB was found not to zonalize the jet if occurring during a positive NAO phase. This suggests that positive NAO/zonal jet events are possible candidates for the many destructive days not associated with a DWB.

Contrary to the above, WWB roughly halves the frequency of destructive windstorms over Europe. Previous analyses have linked WWB with a statistically significant increase in the development of explosive cyclones [Gómara et al., 2014a]. However, WWB weakens the jet stream over Europe, thus reducing the likelihood that such storms result in destructive events. The vorticity anomalies associated with WWB (not shown) suggest that the latter might suppress anticyclonic wave activity in the eastern North Atlantic and are consistent with a reduced westerly flow over continental Europe. An alternative interpretation is that a selection of WWB events will, by construction, exclude days when there is a large-scale WB in the eastern North Atlantic, unless a separate WB event is also found farther west. The full wintertime climatology, on the opposite, will include all EWB instances. A composite over WWB events is therefore likely to display a weaker wave activity in the eastern portion of the basin. The contrasting dynamical and statistical roles of EWB and WWB help to explain why DWB events as a whole display a weak link to destructive events over Europe.

The MPI model fails to capture the statistical relationship between EWB and windstorms. The jet in the model is climatologically more zonal than in the reanalysis, such that on average the jet exit region is located over the UK and France (Figure S6c). Therefore, an eastward extension of the jet over Europe does not require a strong zonalization of the flow, and the climatological jet is already well positioned to bring stormy weather over the continent. This weakens the dynamical link between destructive events and EWB; in fact, while EWB does further strengthen and zonalize the jet, this does not lead to an increase in destructive winds over continental Europe. The more zonal climatological jet also partly explains why the velocity anomalies for destructive events in the model are weaker than in the reanalysis. In the model the location of the jet on these days corresponds to the climatological jet exit region, which is already characterized by a strong zonal flow. This is not true of the reanalysis, where the jet instead shifts to a region which experiences a weak climatological
westerly flow. Many models struggle to fully capture the tilt of the Atlantic circulation, although the more recent simulations show some improvement [e.g., Zappa et al., 2013]. The lack of correspondence between EWB and destructive days could therefore not be limited to the MPI-ESM model but might instead be a common dynamical shortcoming of climate simulations.

The above discussion highlights the complex role played by DWB in affecting the large-scale circulation of the Euro-Atlantic sector. In view of this, one might naively expect DWB to have a strong connection with the leading mode of climate variability in the region, namely, the NAO. The NAO has been repeatedly investigated as a major driver of both Atlantic storminess and jet stream anomalies [e.g., Woollings and Blackburn, 2012; Pinto and Raible, 2012; Gómara et al., 2014b]. It has also been interpreted as the outcome of specific WB configurations [e.g., Benedict et al., 2004; Franzke et al., 2004; Riviere and Orlanski, 2007; Strong and Magnusdottir, 2008a, 2008b; Kunz et al., 2009; Drouard et al., 2013], and WB frequency over localized regions of the North Atlantic has been found to account for a very high fraction of both the interannual and intra-seasonal NAOI variability [Strong and Magnusdottir, 2008a]. A strong projection onto the NAO requires the SLP anomalies associated with the WB to be positioned close to the NAO pressure centers. A priori one might assume that DWB events will have a stronger footprint on the NAO than isolated AWBs or CWBs, due to the sum of the SLP anomalies associated with each individual breaking. Contrary to expectations, we find that DWB events have a weak projection onto the NAO, regardless of their geographical location. DWB therefore has significant impacts on the circulation of the Euro-Atlantic sector, but at the same time a feeble connection to the NAO. This implies that DWB can be regarded as a largely independent predictor of destructive European windstorms relative to the NAO.

The present study has also tested the ability of the automated RWB detection algorithm described in Barnes and Hartmann [2012] to identify DWB. Previous studies have found a very strong correspondence between intense Atlantic storms and DWB: 22 out of the 25 most destructive storms affecting continental Europe during 1958–2001 in HC12 and 48% of intense clustered cyclone days in Pinto et al. [2014]. Our results show a weaker statistical link; destructive days are not systematically preceded by DWB events, with only 5 of the 50 most destructive windstorms over Europe being preceded by EWB. We ascribe these discrepancies primarily to the different techniques used to define WB (a visual evaluation in HC12; an algorithm based on potential temperature on the 2 potential vorticity unit surface (θ2PV) in Pinto et al. [2014]), the different geographical constraints placed on DWB and the different sets of Atlantic storms/destructive events considered.

The detection algorithm we adopt here applies a spectral smoothing to the absolute vorticity field and enforces a minimum longitudinal extent of the overturning regions prior to identifying the wave-breaking events. Similar smoothing procedures are implemented in other wave-breaking detection algorithms [e.g., Postel and Hitchman, 1999; Masato et al., 2012] to reduce the noise in the unfiltered fields. Even though a particular day might present an area of disturbed vorticity, it is not always sufficiently prominent to be classified as a full-scale WB after the smoothing. This ensures that only large-scale, intense events are selected, which are presumably those that will have a stronger influence on the atmospheric flow over the North Atlantic. However, it will also result in lower detection rates of high-latitude CWB, which is typically shallower than the AWB occurring in the southern part of the domain. The chosen smoothing and scale parameters mediate between these two competing considerations.

To illustrate the difficulty in unequivocally identifying large-scale wave-breaking events, we compare the smoothed absolute vorticity field used by the algorithm to a different field commonly used to detect RWB: θ2PV. A cyclonic (anticyclonic) WB will correspond to a tongue of anomalously low (high) θ2PV or high (low) absolute vorticity, leading to a large-scale reversal of the respective meridional gradients—namely, a positive θ2PV gradient and a negative absolute vorticity gradient. Figure 10 displays the θ2PV and absolute vorticity fields for two destructive windstorms. The wave-breaking regions are marked by boxes. Figures 10a and 10c show the archetypal DWB destructive event, with both the AWB and CWB presenting strong, large-scale θ2PV and absolute vorticity gradient inversions over the North Atlantic basin. Figures 10b and 10d, on the contrary, illustrate a typical weak CWB case. Figure 10b displays a narrow cyclonic inversion of the meridional vorticity gradient to the east of Greenland, but the penetration of the subpolar air mass is relatively shallow. A second inversion is seen over Scandinavia. The truncated absolute vorticity field only captures an elongated zonal vorticity anomaly, but smooths out the clear overturning structures seen in the θ2PV field. In the detection code, neither of these features is therefore identified as a cyclonic wave breaking.
The algorithm therefore primarily identifies WB resulting in intense gradient reversals and may provide a lower bound on the number of DWB events compared to alternative metrics. In terms of the results discussed in section 6, a larger number of DWB events would naturally lead to an increase in the number of destructive events preceded by DWB. However, it would not necessarily result in an increase in the fraction of DWB events followed by destructive occurrences. In fact, weaker PV gradient inversions will presumably have a weaker effect on the large-scale circulation. The algorithm is therefore well suited to our analysis, and there is no reason to expect the “missing” DWB events to have a closer relationship to destructive weather over Europe than the detected DWB.

8. Conclusions

We have studied the general relation between the large-scale flow and double Rossby wave breaking over the North Atlantic. Double wave breaking is defined as the occurrence of simultaneous cyclonic and anticyclonic wave breaking, with the former to the north of the climatological jet stream and the latter to the south. In the ERA-Interim reanalysis, this is a relatively common phenomenon, occurring approximately every 7.5 days during the winter months (DJF). We adopted an objective detection method to diagnose both the occurrence and cyclonicity of the wave breaking (section 2.2) and further applied automated algorithms to define the bearing (Jet Angle Index, JAI) and meridional position (Jet Latitude Index, JLI, section 2.3) of the North Atlantic jet stream. The analysis focused on the following three points:

The interplay between DWB and the phase of the NAO. The present paper finds that DWB events as a whole do not preferentially project onto any particular phase of the NAO. To verify that the weak projection is not an artifice of the broad domain over which DWB is defined, the analysis is repeated over smaller geographical domains, designed to optimize the alignment of the WBs’ SLP anomalies with the NAO’s pressure centers. The DWB events within these restricted domains have statistically significant, albeit weak, projections on both phases of the NAO. We therefore conclude that DWB events driving well-aligned SLP anomalies are relatively rare and that DWB events as a whole do not constitute a good dynamical precursor to the NAO. As discussed in section 7 above, this is perhaps surprising in view of the link between individual WB events and the NAO and in light of the link between DWB, the jet stream, and storminess over Europe.

The impact of DWB on the jet stream. The North Atlantic jet stream is characterized by a climatological southwest to northeast tilt. The DWB pattern has a zonalizing effect on the jet, reducing its tilt relative to the wintertime climatology. On the other hand, the tilt is typically enhanced during positive NAO phases.
As a result, DWB events which coincide with a positive NAO show no systematic change in the mean jet tilt. Further analysis reveals that DWB over the Eastern Atlantic and Europe leads to a strong zonalization and a moderate intensification of the jet, while DWB occurring farther west has a smaller effect on jet tilt and weakens the westerly flow over the continent. The influence of DWB on jet tilt therefore largely depends on the former’s geographical location, while the concomitant presence of a strong positive NAO phase seems to overshadow the breakings’ zonalizing effect.

Concerning the jet’s meridional position, DWB generally displaces the jet to the south of its climatological position, although the shifts found in this study for the various WB configurations are small. The upper level jet ranges between 46.5° and 47.8°N for the different DWB cases, compared to a climatological position of 48.6°N. In the case of EWB, this small meridional shift compounds the zonalization of the jet to bring the jet exit region over Europe.

The statistical relationship between DWB and surface wind extremes over Europe. Windstorms are a significant source of both social and economic damage in Western Europe [Berz, 2005]. The present study extends previous analyses by using objective algorithms to detect DWB and define destructive windstorms and presents a more systematic overview of the link between the two. Destructive weather affecting Europe coincides with a zonal, intense jet stream. DWB occurring in the eastern portion of the Atlantic basin zonalsizes and intensifies the circulation of the Euro-Atlantic sector, closely reproducing a “storm-like” large-scale pattern and resulting in a 43–92% increase in the frequency of destructive days over the continent. This increase is larger than that ascribed to the NAO, suggesting that EWB is a better predictor for destructive events over Europe. Nonetheless, there is no one-to-one match between EWB and destructive windstorms, implying that it is neither a necessary nor a sufficient condition for their occurrence. In contrast to this, DWB in the western North Atlantic decreases the likelihood of destructive days over the continent by 43–53%. As for the jet stream, the relationship between DWB and destructiveness is therefore complex and strongly dependent on the geographical location of the former.

We further find that the MPI-ESM model partly captures the large-scale zonal flow anomalies driven by EWB but does not reproduce the statistical link between EWB and destructive days over Europe. This is linked to the failure of the model to reproduce the climatological wintertime tilt of the Atlantic circulation. Since this bias is common to many models, the lack of correspondence between EWB and destructive events might be a common dynamical shortcoming in climate simulations.

The DWB analysis presented here is phenomenological and focuses on the impact of DWB on the large-scale flow, while it does not attempt to determine the dynamical origin of the different DWB patterns. There is therefore ample scope for future investigation. A first, promising path would be to focus on an idealized modeling approach, along the lines of Franzke et al. [2004] and more recently Drouard et al. [2013]. Open questions which could be addressed by such studies include the following: verifying whether the high-latitude CWB is facilitated by poleward propagating wave activity triggered by the large-scale AWB and verifying whether any other upstream dynamical precursors differentiate the zonalized and tilted jet cases. Answering the latter question is particularly relevant for the development of an early warning framework for the specific large-scale conditions which favor destructive windstorms over continental Europe. In this context, it could be interesting to explore the link between the DWB pattern and the zonal circulation associated with the storms and the persistent jet regimes described in Franzke et al. [2011], which show a degree of predictability.

A second natural development of the present study would involve applying the same tools and analysis to long model runs, such as the multicentennial CMIP5 control simulations. These runs could provide the opportunity to study the long-term variability of DWB and destructive storm occurrences and could also be used to further test the ability of simulations to correctly reproduce the complex links between DWB, jet stream tilt and location, and windstorms. The brief analysis presented here suggests that models might struggle to reproduce some of these links, warranting a more systematic and thorough study of the issue.

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References


