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Key Points:
- The dynamical patterns associated with clustering changes dependent on clustering location
- RWB anomalies precede jet anomalies by 2 days, acting as a precursor to clustering
- Two-sided RWB is positively correlated with clustering, but there is considerable spread

Supporting Information:
- Supporting Information S1

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Rossby wave breaking, the upper level jet, and serial clustering of extratropical cyclones in western Europe

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Abstract Winter 2013/14 was the stormiest on record for the UK and was characterized by recurrent clustering of extratropical cyclones. This clustering was associated with a strong, straight and persistent North Atlantic jet and was also associated with Rossby wave breaking (RWB) on both flanks, pinning the jet in place. The occurrence of RWB and cyclone clustering is further studied in 36 years of the ERA-Interim Reanalysis. Clustering at 55°N is associated with an extended and anomalously strong eddy-driven jet flanked on both sides by RWB. However, clustering at 65(45)°N has a dominance of RWB to the south (north) of the jet, deflecting the jet northward (southward). A positive correlation was found between clustering and RWB occurrence to the north and south of the jet. However, there is considerable spread in these relationships.

1. Introduction

Intense extratropical cyclones are the primary natural hazard affecting western and central Europe [*Della-Marta et al.*, 2010] and are responsible for 70–85% of precipitation in these regions [*Hawcroft et al.*, 2012]. Cyclone clustering can lead to greater impacts than those which would have occurred from individual cyclones [*Vitolo et al.*, 2009], since the capacity to respond and the resilience of society is weakened with each subsequent event. Consequently, the clustering of extratropical cyclones is of great interest to insurance industry, civil protection, and policy makers.

Observations suggest that winter 2013/2014 was the stormiest in over 20 years with record-breaking amounts of rainfall (165% of the UK average) [*Matthews et al.*, 2014; *Kendon and McCarthy*, 2015]. The season was characterized by clusters of cyclones affecting the UK. Similar behavior has been identified in other winter months (e.g., January 2007) [*Pinto et al.*, 2014]. Previous studies have found that the trajectories of intense North Atlantic cyclones were commonly influenced by Rossby wave breaking (RWB) on both sides of the North Atlantic jet [*Hanley and Caballero*, 2012; *Gómara et al.*, 2014; *Pinto et al.*, 2014; *Messori and Caballero*, 2015]. Cyclonic RWB is most commonly found on the northern flank of the jet, with anticyclonic RWB mostly on the southern flank [*Nakamura and Plumb*, 1994]. *Barnes and Hartmann* [2012] showed how this presence of RWB acts to flux eddy momentum into the core of the jet, resulting in an acceleration of the upper level flow between these two regions. Large-scale modes of atmospheric variability, such as the NAO (North Atlantic Oscillation) [*Hurrell et al.*, 2003], have also been shown to be related with the clustering of extratropical cyclones [*Mailier et al.*, 2006; *Vitolo et al.*, 2009]. *Woollings et al.* [2010] found that an NAO+(-) pattern is associated with the jet being in a more northerly (southerly) position, which then controls the location and direction of cyclone tracks over the North Atlantic [*Pinto et al.*, 2009].

Pinto et al. [2014] investigated mechanisms associated with cyclone clustering. They found that clustering events influencing the UK were associated with a zonally extended eddy-driven jet flanked by RWB to the north and south. Clustering can also be influenced by mesoscale processes, for example, *Pinto et al.* [2014] also highlighted the importance of secondary cyclogenesis during clustering. Secondary cyclones can be very destructive [*Dacre and Gray*, 2009] and commonly form in trailing cold fronts of extratropical cyclones. However, the development of secondary cyclones is more unpredictable and is influenced by other mechanisms such as the associated deformation strain [*Renfrew et al.*, 1997], frontal shear [*Chaboureau and Thorpe*, 1999], latent heat release [*Joly and Thorpe*, 1990], and boundary layer friction [*Adamson et al.*, 2006].

The aim of this study is to characterize the clustering of extratropical cyclones over the North Atlantic and their relationship with RWB and the upper level jet. We focus on clustering not just for the UK but also at two other regions of Western Europe to the North and South of the UK. Section 3 investigates clustering during winter 2013/2014, while clustering across a 36 year period is investigated in section 4. Section 5 examines the temporal evolution of RWB and the jet anomalies during clustering, with the variability of RWB and jet examined in section 6. We will conclude our findings in section 7.

2. Data and Methods

In this study, the European Centre for Medium-Range Weather Forecasts Interim Re-Analysis (ERA-Interim) data set [*Dee et al.*, 2011] is used. ERA-Interim has a horizontal resolution of T255 and 60 vertical levels. We use all December–February (DJF) months from 1979/1980 to 2014/2015. To identify extratropical cyclones, the cyclone tracking algorithm of *Murray and Simmonds* [1991] is applied to ERA-Interim. Cyclones are identified by the Laplacian of mean sea level pressure (MSLP)($\nabla^2 p$). The nearest MSLP minima is located to the maxima in the $\nabla^2 p$ field. The tracking algorithm used was adapted for Northern Hemisphere cyclones by *Pinto et al.* [2005] and performs similarly to other tracking methodologies [*Neu et al.*, 2013]. Following *Pinto et al.* [2009] cyclones are only selected if they adhere to the following criteria: (1) cyclone lifetime, ≥ 24 h, (2) minimum MSLP <1000 hPa, (3) maximum $\nabla^2 p > 0.6$ hPa degree latitude^{-2}, and (4) maximum $\frac{d}{dt}\nabla^2 p \geq 0.3$ hPa degree latitude^{-2} d^{-1}.

We follow the definition of *Pinto et al.* [2014] for cyclone clustering. An area is defined with a 700 km radius about a latitude-longitude point, and cyclones that adhere to the criteria above and pass through this area are counted. The cyclones are recorded when at peak intensity within this area, with the intensity measured as minimum MSLP. To ensure that only the most intense cyclones are considered, we discard any cyclones with a pressure in the highest 95% of MSLP climatology at that latitude-longitude point. A day is identified as clustered if the 7 day running sum of the remaining cyclones is greater than or equal to 4. We perform this analysis for three locations along 5°W, with the radius centered at 55°N, 5°W; 45°N, 5°W; and 65°N, 5°W (cf. Figure S1 in the supporting information), hereafter denominated as 55°N; 45°N; and 65°N. The 95th percentiles used as an intensity threshold are 999 hPa at 45°N, 984 hPa at 55°N, and 972 hPa at 65°N. We have also compared the results of the above method with one based on 850 hPa relative vorticity [*Hodges*, 1995], with consistent cyclone numbers and clustering periods found across both methods, with the conclusions being unaffected by the method (not shown).

An adapted version of the jet latitude method from *Woollings et al.* [2010] is used to analyze the behavior of the eddy-driven jet. The original metric uses the daily zonal mean zonal wind at 850 hPa from 25 to 75°N, 60 to 0°W. We performed tests for several longitudinal extensions, with each providing consistent results and robust conclusions. However, to focus on the eastern North Atlantic and western Europe, we use 40–0°W in our analysis. To generate the anomaly field a long-term daily climatology of the zonal wind is removed with the resulting field being low-pass filtered (Lanczos, 10 day cutoff [*Duchon*, 1979]) to remove any synoptic influences. The jet latitude on each day is the latitude of maximum wind speed following the removal of the climatology and filtering.

To define and identify RWB, we use the 2-D B index from *Masato et al.* [2013], which was originally defined by *Pelly and Hoskins* [2003]. The B index uses the potential temperature (θ) field on the 2 potential vorticity unit surface (dynamical tropopause; 1 PVU = 1×10^{-6} K m² kg⁻¹ s⁻¹) which is used as a daily average. The B index is a field that identifies where the meridional gradient of θ is reversed with positive values indicating the presence of RWB. No persistence criteria is applied in order to identify RWB at each 6-hourly interval. Analysis is also performed on a zonally averaged field; this being from 25 to 75°N, 40 to 0°W. As with the eddy-driven jet metric, conclusions were found to be insensitive to the exact choice of longitudinal extent.

3. RWB and Cyclone Clustering in the Winter of 2013/2014

The winter season of 2013/2014 was the stormiest on record in the UK [*Matthews et al.*, 2014]. Figure 1a shows the 39 cyclone tracks that passed within 700 km of 55°N throughout January and February 2014; with 26 of these exceeding the local 95th percentile of MSLP. The enhanced cyclone activity is made further apparent when examining the anomaly in cyclone days per month for January and February 2014 (Figure 1b). A statistically significant anomaly of over 12 cyclone days month⁻¹ degree latitude⁻² can be seen near the west coast
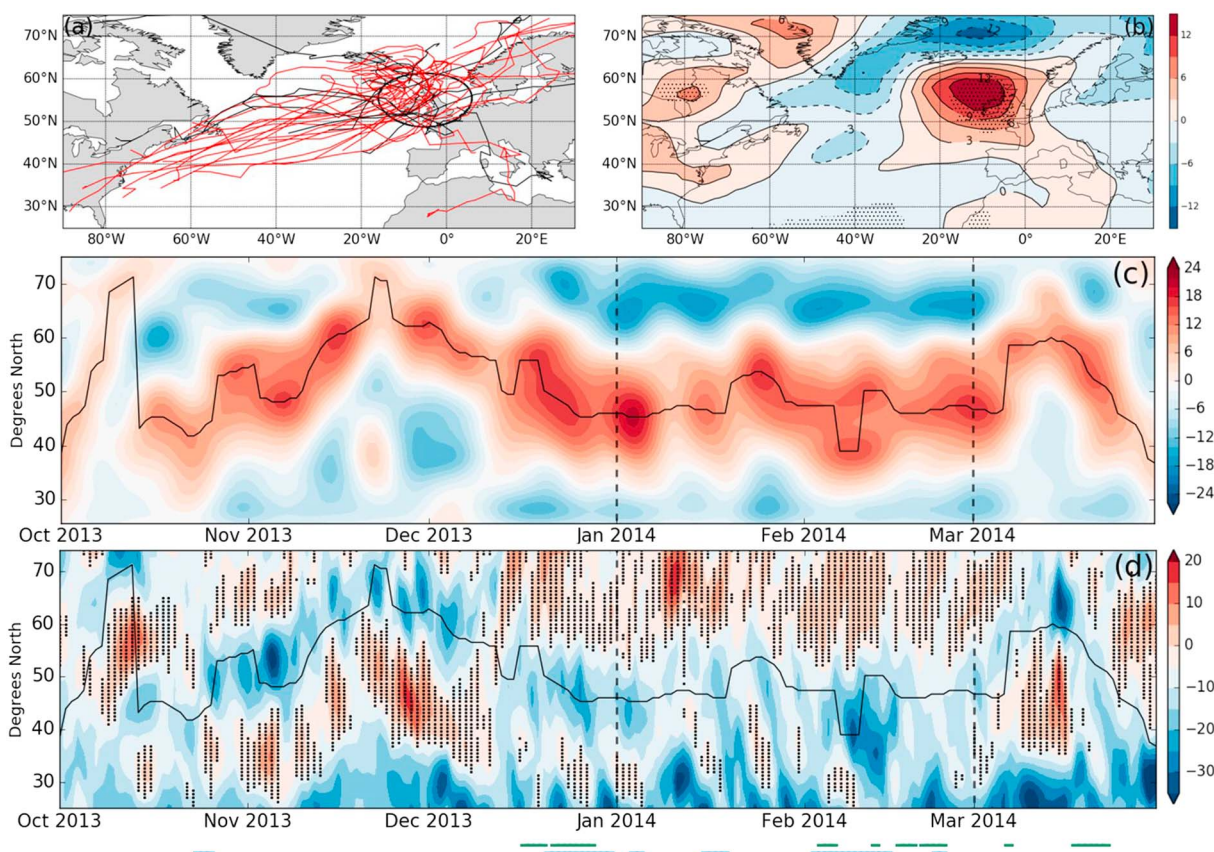
Figure 1. (a) Tracks of cyclones that pass within 700 km of 55°N (black circle) during January and February 2014. Tracks that exceed the 95th percentile of MSLP are red; others are black. (b) Anomalous track density for January and February of 2014 compared to the climatology. Units are cyclone days month^{-1} degree latitude^{-2}. (c) The eddy-driven jet for October to March 2013/2014. Shaded contours are the anomalous wind speeds (m s^{-1}). The black line represents the jet latitude. (d) RWB in the North Atlantic for October–March 2013/2014. Shaded contours represent the zonally averaged B index on each day; black dots indicate positive values. The black line is the jet latitude. The vertical dashes in Figures 1c and 1d indicate the period used in Figures 1a and 1b. The green dashes below the figure indicate clustering for tracks that pass within 700 km of 65°N, blue are for 55°N, and red are for 45°N (see Figure S1).

of Scotland. A majority of the UK had an increase of at least six cyclone days per month. In this context one cyclone day month^{-1} degree latitude^{-2} corresponds to that latitude square being characterized by cyclonic activity on 1 day of the month.

A number of clustered days are identified for 55°N during DJF of 2013/2014. These are 20–30 December; 3–4 and 15–18 January; and 2–14 and 22–23 February. These dates are indicated by the blue dashes below Figure 1d. Figure 1c shows that the latitude of the 850 hPa jet varies only a little during January/February 2014, with the latitude being between 40°N and 50°N on 71% of days. It is also anomalously strong, with anomalous speeds of 24 m s^{-1} in early January, while for the majority of DJF 2013/2014 speeds are above 10 m s^{-1} greater than the climatology. This is in contrast with late autumn 2013 and early spring 2014, when the jet is weaker and varies more latitudinally.

RWB occurrence over the North Atlantic shows a clear distinction between clustered and non-clustered periods. Clustering at 55°N is consistently accompanied by RWB on both the northern and southern flanks of the eddy-driven jet (Figure 1d). RWB to the south is more intermittent (similar to *Pinto et al.* [2014, Figure 3]), with the RWB to the north being more persistent for much of DJF 2013/2014. The presence of RWB to both the north and the south will act to enhance the thermal gradient in the upper troposphere, allowing for a more intense jet extended toward western Europe. This extension will steer cyclones further toward western Europe, which can cause significant impact and losses if landfall occurs.

We have repeated this analysis for different latitudes. The 700 km radius was moved both 10° north and south of 55°N. The dashes at the bottom of Figure 1d show when we identify clustering at 65°N (green) and 45°N
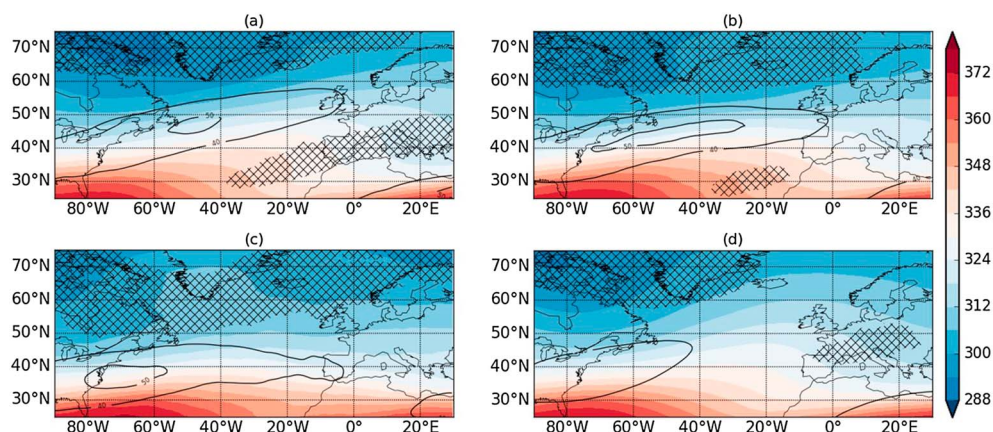
Figure 2. Composites of clustered days at (a) 65°N, (b) 55°N, and (c) 45°N. (d) Climatology. For all panels the colored contours are θ on the 2 PVU surface (K). Black contours are the 250 hPa wind speed from 40 m s^{-1} and every 10 m s^{-1} above. The crossed hatchings are where RWB was occurring on at least 30% of days.

(red). The clustering at these latitudes occurs at different times; however, there are some periods of overlap which may be a result of slight overlap of the 700 km radii (see Figure S1). The green dashes (65°N) are often associated with the jet in a more northern position (middle of December 2013; early middle of March 2014), and also with a greater presence of RWB to the south (e.g., middle of March 2014). Clustered periods for 45°N (red) appear to coincide with the clustering at 55°N. However, the jet has a very large latitudinal range for the period in early February 2014, with peak speeds occurring nearer to 40°N. Hence, the more southerly jet latitude would be steering some of the cyclones further south.

4. RWB and Cyclone Clustering in ERA-Interim

The results presented above for 2013/2014 are consistent with findings from *Pinto et al.* [2014], which were based on the analysis of four other winters. We now extend this analysis to investigate if the dynamical patterns identified for clustering in winter 2013/2014 are valid for all clustered periods in ERA-Interim.

An upper troposphere composite for clustered days (≥ 4 intense cyclones in 7 days) in the DJF season from 1979/1980 to 2014/2015 (387 out of 3240 days) at 55°N can be seen in Figure 2b. It shows an eastward extended and intensified jet that is also straighter than would normally be seen (Figure 2d). This jet is flanked by RWB on both sides, with a sharper thermal gradient between the two regions of RWB than is present in the same region of Figure 2d. It is apparent from Figure 2b that this pattern will cause cyclones that form in the North Atlantic or off the east coast of the USA to be steered eastward along the axis of the jet. This pattern resulted in very stormy conditions at 55°N, as was seen in winter 2013/2014 and is consistent with that identified in Figure 1 and also the schematic in Figure 7f of *Pinto et al.* [2014].

The composite image for clustering at 65°N (Figure 2a) (450 out of 3240 days) demonstrates a different pattern to that shown in Figure 2b. For clustering at 65°N, the jet is much more tilted from SW to NE, with more RWB to the south and less to the north when compared to Figure 2b. For clustering at 45°N (Figure 2c) (183 out of 3240 days) the jet is zonal until the exit region and is then tilted from NW to SE. Figure 2c is also characterized by a large amount of RWB to the north, with little RWB to the south. Finally, when days are classed as non-clustered at 55°N (Figure S2) (2853 out of 3240 days) the jet is not extended beyond the western North Atlantic and is also weaker than the clustered days. It is characterized by a large area of RWB across western Europe, indicative of anticyclonic blocking, which will steer cyclones to the north or south of western Europe. This is very similar to Figure 2d and also the non-clustered composites for 45°N and 65°N (Figure S2).

Figure 2 shows that clustering at different latitudes is associated with different dynamical patterns in the North Atlantic. The presence of RWB in various locations in the eastern North Atlantic is associated with the tilt and latitudinal location of the jet, and hence, the direction in which the cyclones are steered. This is consistent with findings in previous studies [*Benedict et al.*, 2004; *Woollings et al.*, 2010; *Franzke et al.*, 2011].
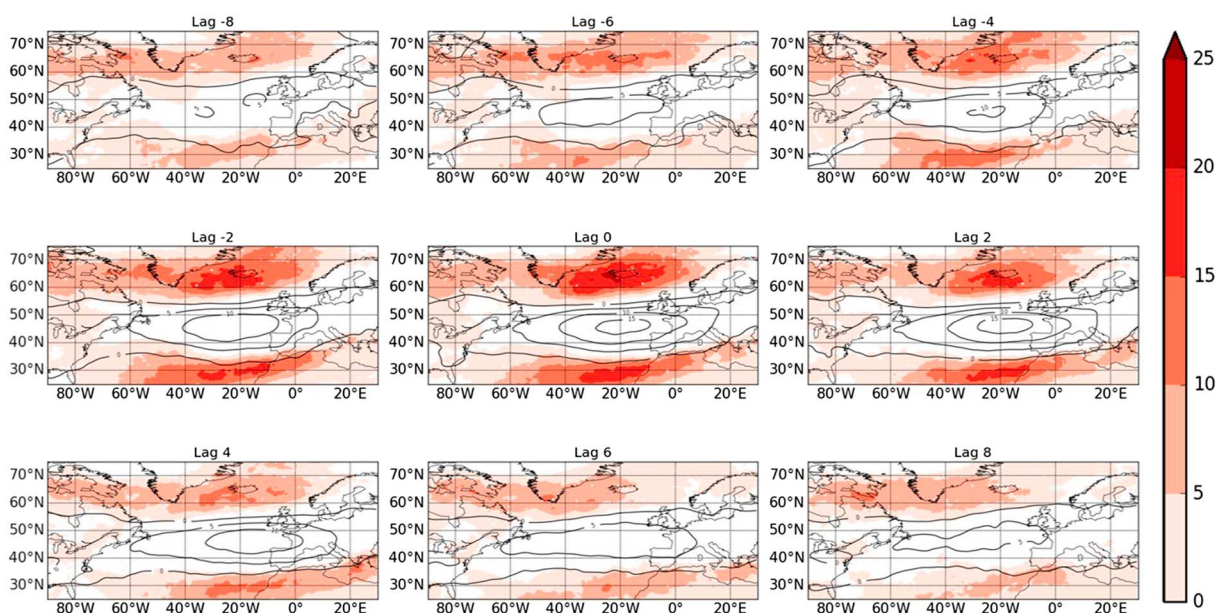
Figure 3. Composite images of North Atlantic RWB and jet anomalies on days lagged to clustered days at 55°N. The red shading is the percentage increase in the *B* index compared to climatology (Figure 2d). Black contours are the 250 hPa wind speed anomalies (m s^{-1}). Shown is from lag −8 days to lag +8 days at 2 day intervals.

5. The Temporal Evolution of the RWB and the Jet During Clustering

Figure 3 shows how the RWB and jet anomalies develop in the days before and after clustering at 55°N. A lagged composite analysis of clustered days further highlights the importance of anomalous RWB in the eastern North Atlantic for clustering. We lag to the clustered days identified for 55°N to infer how the dynamical features develop. At lag −8 days jet anomalies are weak, with only isolated regions greater than 5 m s^{-1}. The RWB flanking the jet is also similar to climatology (Figure 2d), although some increases of up to 10% are present in the regions of box a and box c (see Figure S1). At lag −4 days the jet has accelerated further with localized anomalies over 10 m s^{-1} and a further increase in RWB with up to 15% more RWB in the eastern North Atlantic. RWB activity reaches its maxima at lag −2 days with anomalies of 15–20% and jet speeds similar to those previously. The jet anomaly peaks on lag 0 days with speeds of more than 15 m s^{-1}. Patterns are consistent at lag 2 days; however, by lag 4 days the presence of RWB and the wind speeds begin to decrease. At lag 8 days the presence of RWB in the eastern North Atlantic has almost disappeared, with anomalous wind speeds nearer to 0 m s^{-1}. Figure 3 suggests that RWB activity in the eastern North Atlantic peaks before the anomalies in the jet speed. This is consistent with RWB enhancing the upper tropospheric thermal gradient at lag −2 days, which will strengthen wind speeds at 250 hPa and extend the jet eastward; which peaks at lag 0 days. This acceleration can be thought of as a convergence of eddy momentum in the jet core from the RWB on each flank, which is consistent with *Barnes and Hartmann* [2012].

Similar patterns to Figure 3 are found when we inspect the lagged composite for clustering at 45°N and 65°N (Figures S3 and S4). In both instances the increases in RWB reaches values of up to 20% above climatology (Figure 2d) at lag −2 days, which then broaden by lag 0 days and even marginally increase. The RWB in Figure S3 does not peak as clearly at lag −2 days as in Figures 3 and S2. As with Figure 3 both Figures S3 and S4 also see peak wind speeds at lag 0 days.

The composites on lag 0 days also further illustrates the preferential positions of RWB for clustering that can influence western Europe that we identified from Figure 2. Figure 3 suggests that the presence of RWB on one or both sides of the jet is highly important for controlling the strengthening of the upper level jet toward any of our clustering latitudes and hence is a precursor for the observed clustering. This provides a more robust conclusion to the results of *Pinto et al.* [2014] as analysis was performed using a considerably larger data set.
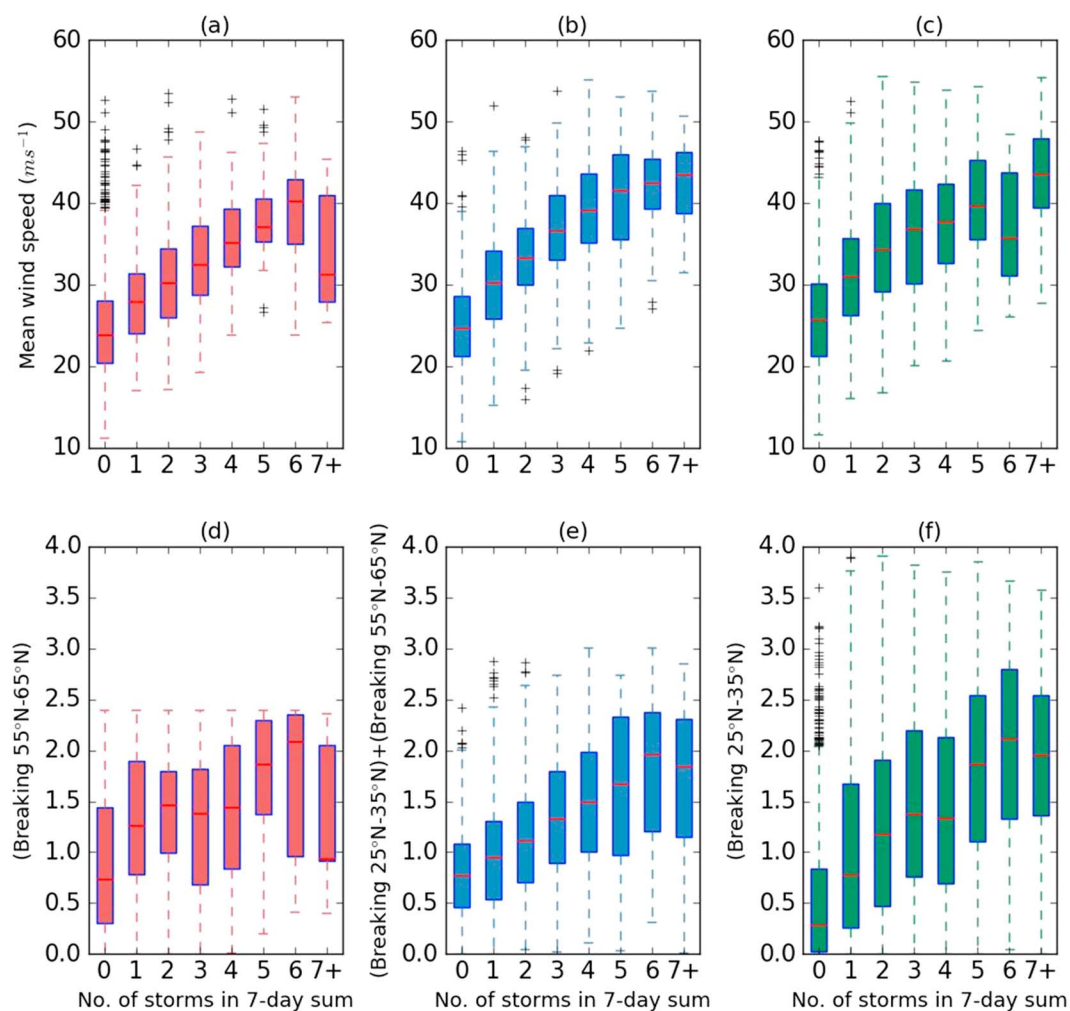
Figure 4. (a–c) Average wind speeds at 250 hPa in box b of Figure S1 (for 55°N) $\pm$ 10° latitude (for 45°N/65°N) against the number of cyclones in each days 7 day sum. (d–f) The amount of RWB that takes place in a combination of boxes a and c in Figure S1. Figures 4a and 4d are for 45°N. Figures 4b and 4e are for 55°N. Figures 4c and 4f are for 65°N. The red lines represent the medians, with the edges of the boxes being the upper/lower quartiles. The whiskers extend to either 1.5 times the interquartile range or the value furthest from the median. Crosses are outliers.

6. Dynamical Variability of Clustering

Composites such as in Figures 2 and 4 focus on averages. To examine the relationship between the jet and clustering at the different latitudes, we define an area from 40 to 50°N, 30°W to 10°E (box b in Figure S1; chosen based on examination of Figure 2) and take an average of the 250 hPa wind speed within this. This box is shifted 10° south(north) for the jet relationship with clustering at 45°N (65°N) (a full description of this can be found in the caption of Figure S1).

Figure 4b illustrates the relationship between the 250 hPa wind speed and clustering at 55°N. A positive correlation (r=0.69) is apparent with increasingly clustered activity being associated with stronger 250 hPa wind speeds. Mean 250 hPa wind speeds increase from approximately 25 m s^{-1} on days with no cyclones, to around 40 m s^{-1} for the most clustered days. This is consistent with a stronger and more extended jet directing cyclones eastward across the North Atlantic. There is considerable spread in this relationship (which can be inferred from the size of the box and whiskers in Figure 4b). Consequently, a strong and extended jet may not always be associated with clustered cyclone activity.

The jet relationship for 45°N (65°N) can be seen in Figure 4a (Figure 4c). As in Figure 4b a positive correlation is apparent ($r = 0.45$ for 45°N; $r = 0.54$ for 65°N (all latitudes are statistically significant)), with days that are

associated with the clustering of cyclones also being characterized by a stronger and extended jet. However, there is still considerable spread in these relationships, as in Figure 4b. There is also considerably less cases at the more clustered end of the axis, so this part of the relationship may not be as robust.

The differences in RWB between non-clustered and clustered days is also examined. To achieve this, we define two further areas: the first being from 55 to 65°N, 40 to 0°W (box a in Figure S1) and the second from 25 to 35°N, 40 to 0°W (box c in Figure S1). These boxes were chosen as they capture the areas of RWB to the north and south across all three latitudes (Figure 2). The amount of RWB in each box is calculated by determining the number of latitude-longitude points with a positive B index on each day and then normalizing this relative to climatology. Using this method, a value of 1 relates to a climatological amount of RWB. For clustering at each latitude we take contributions from different boxes based on where RWB is most likely from an examination of Figure 2. For clustering at 45°N we use box a, for clustering at 55°N we use the average of boxes a and c after they have been normalized, and finally, for 65°N we use only box c.

Figures 4d–4f suggest that given a large amount of RWB in either box a or box c (or a combination of the two) is associated with an environment that is favorable for clustering, although this is less clear for 45°N. These preferential locations for RWB have been previously identified to be associated with an enhanced jet and intense cyclones propagating toward western Europe [*Gómara et al.*, 2014; *Messori and Caballero*, 2015]. This pattern was identified in *Pinto et al.* [2014], but this is the first time such activity has been linked to all clustering events in a 36 year data set. However, as with the jet (Figures 4a–4c) these are dominated by large spread.

It is seen in Figure 4 how the conditions that are favorable for clustering may often be achieved without the presence of multiple cyclones near western Europe. This may be as a result of other properties that are not directly associated with the normal development mechanism of baroclinic instability. For example, the development of secondary cyclones that contribute to clustering have been shown to be dependent on factors such as deformation strain rate, frontal shear, latent heat release, and boundary layer friction. If any of these properties are not favorable for secondary cyclone formation, then this may not result in the presence of the multiple cyclones needed to satisfy our clustering criteria, despite the presence of a favorable large-scale environment. However, this is not investigated in this study.

7. Conclusions

The aim of this study is to characterize the clustering of extratropical cyclones over the North Atlantic and their relationship with RWB and the upper level jet. Using the ERA-Interim reanalysis, cyclone clustering in the North Atlantic and its relationship with RWB has been specifically investigated for the winter 2013/2014 and more generally for the winter seasons of 1979/1980–2014/2015. The following are the main conclusions of the study:

1. Cyclone clustering at 55°N is associated with an extended and anomalously strong eddy-driven jet flanked on both sides by RWB. However, for clustering at 65°N there is a dominance of RWB to the south of the jet, deflecting the jet exit northward and tilting the jet SW-NE tilt. Conversely, for clustering at 45°N, there is more RWB to the north of the jet, and the jet has a slight NW-SE tilt in its exit, deflecting cyclones further south.
2. RWB activity in the eastern North Atlantic peaks 2 days before the occurrence of clustering and the strongest anomalies in the 250 hPa jet speed. This is consistent with RWB enhancing the upper tropospheric thermal gradient and extending the North Atlantic jet eastward, resulting in cyclone clustering.
3. A positive correlation was identified between the 250 hPa wind in the jet exit and extent of cyclone clustering for 36 winters of ERA-Interim data. A positive correlation was also identified with the RWB when assessing how much RWB was occurring to the north and south of the jet. All latitudes showed an increase in jet speed and RWB activity when there was a greater presence of cyclones. However, there is considerable spread in all of these relationships.

Future research directions include exploring the projected changes in clustering under future climatic conditions in global circulation models [e.g., *Economou et al.*, 2015] and specifically the role of the RWB dynamics we have identified in any potential clustering changes. Additional research directions include exploring the role of secondary cyclogenesis during clustering and the various mesoscale processes that are associated with the development of these cyclones.

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