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\begin{document}

\title{The relation between Rossby Wave Breaking events and low-level weather systems}

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\runningtitle{The relationship between Rossby Wave Breaking events and low-level weather systems}

\runningauthor{Talia Tamarin-Brodsky and Nili Harnik}

\firstpage{1}

\maketitle

\begin{abstract}

%Rossby wave breaking events describe the last stage in the life-cycle of baroclinic atmospheric disturbances. These breaking events can strongly influence the large-scale circulation, and are also related to weather extremes such as heat waves, blockings, and extreme precipitation events. Nonetheless, a complete understanding of the synoptic-scale dynamics involved with wave breaking events is still absent. Here we highlight the fundamental relation between low-level weather systems and upper-level wave breaking events in the North Atlantic region, by combining a storm-tracking technique together with a wave breaking detection algorithm. We show that Anticyclonic Wave Breaking (AWB) events are associated with a strong upper-level ridge and a low-level anticyclone to its east, which are both located in the anticyclonic side of the jet. During the breaking, a strong cyclone is often found to the north-northwest of the anticyclone, while a weaker one is often found to its south-southeast. Time evolution composites centered on anticyclones during AWB show that as the downstream trough wraps anticyclonically to the east and south of the ridge, the upper-level jet weakens to the south, hence the upper-level jet becomes more split into an upstream poleward tilted jet, and a downstream zonal jet. In addition, the Sea Level Pressure (SLP) anomalies rotate in an anticyclonic manner relative to each other, such that the initially zonally oriented low-high SLP anomaly dipole become meridionally oriented by the end of the life-cycle (low-above-high). On the contrary, Cyclonic Wave Breaking (CWB) events are associated with a strong upper-level trough and a low-level cyclone to its east, which are both located in the cyclonic side of the jet. An additional anticyclone is often found to the northeast of the cyclone. Time evolution composites centered on cyclones during CWB show that as the downstream ridge wraps cyclonically to the east and north of the trough, the zonal and more southward shifted upper-level jet weakens further to the north. A relative cyclonic rotation is observed at low-levels, such that a high-above-low SLP anomaly dipole is found by the end of the life-cycle. A simple kinematic interpretation is suggested for the poleward and equatorward shifted jets associated with AWB and CWB events, respectively. Anomalous life-cycles of anticyclones during CWB events and cyclones during AWB events are also discussed.

Rossby wave breaking events describe the last stage in the life-cycle of baroclinic atmospheric disturbances. These breaking events can strongly influence the large-scale circulation and are also related to weather extremes such as heat waves, blockings, and extreme precipitation events. Nonetheless, a complete understanding of the synoptic-scale dynamics involved with the breaking events is still absent.

Here we examine how well do idealized life-cycle experiments, which use a specified initial perturbation with a single zonal wavenumber and a prescribed simplified initial zonal jet, capture the life-cycle of real-atmosphere weather systems.

This is done by combining a storm-tracking technique together with a wave breaking detection algorithm, focusing on the North Atlantic. These datasets also allow us to examine whether upper-level wave breaking and low-level weather systems always occur simultaneously, and if we can we identify preferred relations between the sign of the storm and the sign of the upper-level breaking.

We find that in the North Atlantic, most storms are associated with an AWB and/or CWB at some point during their lifetime, while only few cyclones and anticyclones do not involve any upper-level wave breaking (roughly 11\% and 15\%, respectively). Our results imply that composites of cyclones and anticyclones involve a mixture of different types of storm life-cycles, depending on whether they involve a CWB or AWB event, as well as their position relative to the RWB center. Moreover, storm characteristics (including actual and relative positions, intensities, and displacements) differ depending on the associated breaking type. We distinguish between "same-pairing" cases (i.e., cyclones with CWB and anticyclones with AWB) and "opposite-pairing" cases (i.e., cyclones with AWB and anticyclones with CWB). Compositing the cyclones and anticyclones based on this criterion, we find that in similar-pairings the surface system is positioned so that its associated upper-level winds would enhance the breaking (the anomalous circulation is in the same direction as the background shear), but for opposite-pairings, the upper-level winds associated with the surface system do not act to enhance the breaking which occurs in the direction of the background shear.
A better understanding of the different life-cycles of real-atmosphere storms and the upper-level breaking they involve is important for exploring the relation between storm tracks and slowly varying weather regimes and how it is mediated by RWB events.

%We show that the composite evolution and characteristics (including geographical positions, intensity, and displacements) of real-atmosphere cyclones and anticyclones greatly differ, depending on the type of upper-level RWB as well as their position relative to the breaking.

\end{abstract}

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\introduction %% \introduction[modified heading if necessary]
The midlatitude atmospheric circulation is characterized by the continuous passage of propagating synoptic-scale weather systems, which play an important role in the meridional redistribution of momentum, moisture, and heat flux. These anomalous cyclonic and anticyclonic circulations grow via baroclinic instability, as a result of Earth's rotation and the equator-to-pole temperature difference. The waves tend to follow a typical Rossby wave life-cycle, which involves a linear baroclinic growth stage (\citealp{charney1947dynamics,eady1949long}) followed by a nonlinear barotropic decay (\citealp{simmons1978life,Davies1991}). During the decay stage, Rossby wave breaking (RWB) occurs, formally defined as a large-scale and irreversible overturning of the potential vorticity (PV) contours on isentropic surfaces (\citealp{McIntyre1983}). This overturning results in an inversion of the meridional PV gradient, which is often used as a definition of RWB in automated detection algorithms. The PV mixing that occurs in the wave breaking region, and the associated anomalous momentum fluxes, can result in an acceleration/deceleration or

meridional shifts of the upper-level jet. In addition, these breaking events were linked to extreme weather events (\citealp{Martius2016}), such as extreme precipitation (\citealp{Moore2019,deVries2021}), explosive cyclogenesis (\citealp{Hanley2012,Gomara2014}), and tropical cyclone activity (\citealp{Zhang2017,Zhang2018}).

There are two main types of wave breaking, with a very distinct upper-air behaviour, occurring at the end of the baroclinic wave life-cycles (\citealp{simmons1978life,Thorncroft1993}). The first type is dominated by an Anticyclonic Wave Breaking (AWB) (e.g., Fig.~\ref{fig:fig1}a), and is characterized by a southwest-northeast (SW-NE) tilt of the PV contours. The second type involves Cyclonic Wave Breaking (CWB) (e.g., Fig.~\ref{fig:fig1}b) and is characterized by a southeast-northwest (SE-NW) tilt of the PV contours. Previous studies have further distinguished between 'equatorward breaking' and 'poleward breaking' cases (e.g., see Fig.1 in \citet{Tyrlis2008} or Fig.1 in \citet{Gabriel2008} for a schematic illustration). The equatorward breaking cases involve an equatorward extrusion of high-PV air, and were coined LC1 and LC2 by \citet{Thorncroft1993}. In LC2, CWB occurs on the poleward side of the jet where the shear is cyclonic, which leads to the development of wide and strong troughs and prevents the building of strong ridges. In LC1, AWB occurs on the equatorward side of the jet where the shear is anticyclonic, leading to thinning troughs and possibly to the development of a weak cutoff low (\citealp{Thorncroft1993}).

The importance of the two poleward breaking cases (P1 and P2), which involve a poleward extrusion of low-PV air, was introduced by \citet{Peters1996}. In P2, AWB occurs on the equatorward anticyclonic side of the jet, which results in strong blocking-like ridges that tend to develop equatorward of the jet. In P1, CWB occurs on the poleward cyclonic side of the jet, leading to thinning ridges and often to the development of a weak cutoff ridge (\citealp{Peters1996}).
Hence, P2 and LC1 are dominated by AWB, while P1 and LC2 are dominated by CWB. In all four cases, a reversal in the upper-level
meridional PV gradient is observed, but the overturning of the PV contours is weaker in cases P1 and LC1.
Most traditional RWB-detection algorithms that rely on the reversal of PV contours only distinguish between AWB and CWB events, and in practice mostly detect the P2 and LC2 types. This is often not acknowledged in studies, where the more familiar LC1 and LC2 life-cycle terminology is used instead. A further investigation of each one of the four breaking types was performed in several studies (e.g., \citealp{Peters1996,Tyrlis2008,Gabriel2008}).
%Here we use the RWB detection algorithm developed by \citet{Strong2008}, which can detect both poleward and equatorward breaking events. We configure it to detect the equatorward breaking cases, but our results are qualitatively similar if poleward breaking cases are analyzed instead (see Section \ref{sec:methods_RWB} for more details).

Past studies have shown, in idealized baroclionic life-cycle experiments, that the sense in which the wave breaking occurs (AWB or CWB) can be controlled by changing either the initial meridional shear of the background zonal jet

(\citealp{simmons1978life,Davies1991,Thorncroft1993,Peters1996,Hartmann1998,Hartmann2000,Shapiro1999}), the initial zonal wavenumber of the perturbation (\citealp{Hartmann1998,Orlanski2003,Wittman2007}), or the strength of the cyclonic and anticyclonic vortices, achieved by adding external forcing or by adding moisture (\citealp{Orlanski2003}). The type of breaking can significantly modify the low-frequency atmospheric circulation, and therefore influence the jet variability. In general, during AWBs eddy momentum fluxes $u'v'$ are mostly poleward, and the zonal flow is therefore accelerated (decelerated) poleward (equatorward) of the breaking, leading to a poleward shift of the jet. On the contrary, during CWBs momentum fluxes are mainly equatorward, and thus accelerate (decelerate) the zonal flow equatorward (poleward) of the breaking, leading to an equatorward shift of the jet (\citealp{simmons1978life,Thorncroft1993}).
Similar conclusions were reached from a vorticity flux perspective by \citet{Orlanski2003}, who suggested that when anticyclonic circulations are dominant, the eddy vorticity flux $v'q'$ (where q' is the relative vorticity) is positive poleward of the breaking and negative equatorward of it, which acts (through ${\partial{\overline{U}} \over {\partial{t}}} \sim \overline{v'q'}$) to accelerate the zonal flow poleward of the breaking and decelerate it equatorward of it (and vice versa for the case where cyclonic circulations are dominant, see also Fig.~9 in \citealp{Orlanski2003})

%Similarily, \citet{Orlanski2003} suggested that when anticyclonic circulations are dominant, the eddy vorticity flux $v'q'$ (where q' is the relative vorticity) is positive (negative) poleward (equatorward) of the breaking, which acts to accelerate (decelerate) the zonal flow poleward (equatorward) of the breaking through ${\partial{\overline{U}} \over {\partial{t}}} \sim \overline{v'q'}$, and vice versa for the case where cyclonic circulations are dominant (see Fig.~9 in \citealp{Orlanski2003}).

The interaction between the shorter-timescale RWB and the lower-frequency background flow is two-way. On the one hand, the low-frequency patterns of variability were shown to influence the type and frequency of RWB. For example, the frequency of AWB and CWB can be modulated by midlatitude weather regimes (\citealp{Franzke2011,Swenson2017}), the El Ni\~no Southern Oscillation (ENSO) (\citealp{Waugh2000,Shapiro2001}) or the Madden-Julian Oscillation (MJO) (\citealp{Cassou2008}).
On the other hand, RWBs were shown to modify the low-frequency variability by triggering or extending the life-time of weather regimes (\citealp{Michel2011,Michel2012}), and has an important role in the onset and decaying stages of blockings (\citealp{Hoskins1983,Tyrlis2008,Woollings2008,Tyrlis2008,Woollings2011,Masato2012}). More generally, a positive feedback was identified between RWBs and the latitudinal position of the jet, as a more poleward (equatorward) jet implies that AWB is more (less) probable (and vice versa for CWB), hence the jet is pushed or maintained further poleward (equatorward) by the eddy forcing (\citealp{Riviere2009}).

Moreover, it was suggested that the North Atlantic Oscillation (NAO), the leading mode of winter low-frequency variability in the North Atlantic region, can be viewed as variations in the frequency, type, and location of RWB events

(\citealp{Benedict2004,Franzke2004,GwendalOrlanski,Woollings2008,Strong2008,Kunz2009}). Generally, these studies find that AWBs (CWBs) are associated with the positive (negative) polarity of the NAO. \citet{Woollings2008} suggested that the negative NAO can be viewed as a period of more frequent high-latitude blocking events associated with CWB, resulting in a more zonal and southward jet regime, while the positive NAO can be viewed as period in which these events are infrequent, resulting in a more tilted and northward jet regime.

In addition, several previous studies have examined composites of RWB events. For example, \citet{Strong2008} looked at composites of AWB and CWB events in the Northern Hemisphere (NH), and found that AWBs are associated with a negative Sea Level Pressure (SLP) anomaly poleward of the breaking and a positive SLP anomaly equatorward of the breaking center, similar to the SLP signature of the positive NAO (and the opposite for CWB). Similar results were found by \citet{Kunz2009}, who examined upper and lower tropospheric composites of RWB events in a simplified General Circulation Model (GCM), to study the potential of AWB and CWB events to drive NAO-like meridional circulation dipoles. Finally, \citet{Zhang2018} examined composites of AWB in the North Atlantic during the warm season, to highlight the role of diabatic heating in contributing to the wave breaking.

Another motivation to study upper level RWB events has been their strong connection to the evolution of low-level cyclones and anticyclones.
%Here we examine composites of RWB events in the North Atlantic during the winter season, but the focus is on relating the upper-level breaking events to the time evolution and characteristics of the low-level cyclones and anticyclones.
%While the relationship between weather systems and large-scale wave breaking events is well known,
%However, much of our knowledge is based on idealized studies (e.g., \citealp{simmons1978life,Davies1991,Thorncroft1993}) or single-event case studies (e.g., XX). For example, various studies examined the synoptic-scale evolution and baroclinic life-cycle of cyclones, which inherently involve the evolution of the upper-level trough (e.g., \citealp{Shapiro1999_book}). Previous studies have shown how a precursor wave breaking can influence the cyclone's formation. For example, PV streamers associated with AWB are often found as precursors to subtropical, tropical, and Mediterranean cyclones (e.g., \citealp{Appenzeller1996,Davis2010,Galarneau2015,Flaounas2015,Bentley2017,Portmann2021,Flaounas2022}).
For midlatitude cyclones, the existence of simultaneous AWB and CWB events in the eastern North Atlantic was shown to lead to a stronger and more zonally extended upper-level jet, which favors the formation of explosive storms reaching central Europe (\citealp{Hanley2012,Messori2015}). \citet{Michel2012} analyzed the link between surface cyclones and upper-tropospheric Rossby wave breaking during the Scandinavian Blocking (SB) regime. They found differing cyclone trajectories, associated with different types (cyclonic/anticyclonic) of wave breaking occurring during the onset and decay of the SB regime. In addition, \citet{Gomara2014} examined the two-way relationship between RWB and explosive cyclones over the North Atlantic, and found that the latter are associated with enhanced frequency of RWBs several days prior to the cyclone's maximum intensification. They

also found some signature for enhanced occurrence of CWB over southern Greenland and AWB over Europe after explosive cyclogenesis, but only for very intense cyclones.

Taken together, the above studies suggest an underlying picture in which low-frequency large-scale atmospheric weather regimes, typically defined via the mid or upper level flow, interact with surface weather systems via RWB events. A better understanding of this interaction, as it manifests in the real atmosphere, is needed in order for improving our understanding of the processes shaping the large-scale distribution of weather extremes (e.g., \citealp{Coumou2014,Hoskins2015,Kautz2022}), subseasonal weather predictability (e.g., \citealp{Mariotti2020}), and projected future circulation changes (e.g., \citealp{Woollings2018,Coumou2018}).
%e.g., by relating changes in the frequency and positions of RWB events, storm tracks, and the North-Atlantic jet, XX
The observed relationship between RWB and weather regimes is relatively well-established based on statistical analyses of multiple events, especially in the North Atlantic (\citealp{Strong2008,Michel2011,Swenson2017}). However, our understanding of the relationship between RWB and weather systems is mostly based on idealized studies (e.g., \citealp{simmons1978life,Davies1991,Thorncroft1993}) or single-event case studies (e.g., \citealp{Shapiro1999_book}). %However, a comprehensive picture of this relation under realistic settings is still missing.
Thus, a similar comprehensive picture of the relation between RWB and weather systems does not exist in the literature, to the best of our knowledge.
This is the aim of the current study. We address this gap by combining a Lagrangian feature-tracking technique (to identify and track low-level cyclones and anticyclones) together with a wave-breaking detection algorithm (to identify the times and positions of cyclonic and anticyclonic RWB events).
Specifically, we aim to address the following open questions:

 %weather systems and large-scale wave breaking events is well known,

%However, much of our knowledge is based on idealized studies (e.g., \citealp{simmons1978life,Davies1991,Thorncroft1993}) or single-event case studies (e.g., XX).

%A better understanding of the different time-evolution of real-atmosphere storms and the upper-level breaking they involve is helpful for studying weather extremes (XX), for improving weather predictability (XX), for exploring the relation between storm tracks and slowly varying weather regimes (XX), and for improving our confidence in projected future circulation changes (e.g., by relating changes in the frequency and positions of RWB events, storm tracks, and the North-Atlantic jet, XX).

%To complement the above mentioned studies, here we further elucidate the inherent relation between low-level cyclones, anticyclones, and RWB events by combining a Lagrangian feature-tracking technique (to identify and track low-level cyclones and anticyclones) with a wave-

breaking detection algorithm (to identify the times and positions of cyclonic and anticyclonic RWB events).

%The motivation for the current study is to highlight the following open questions:
\renewcommand{\labelitemi}{$\circ$}
\begin{enumerate}
\item What is the relation between RWB events and low-level weather systems? For example, do RWBs and weather systems always occur simultaneously? What are the percentages of storms involved with each type of breaking, and vice versa?
\item How do storm characteristics (including geographical positions, intensity, and displacements) and the composite time evolution differ, depending on the type of upper-level RWB and their position relative to the breaking?
\item How well do idealized life-cycle experiments, which use a specified initial perturbation with a single zonal wavenumber and a prescribed simplified initial zonal jet, capture the life-cycle of real-atmosphere cyclones and anticyclones?
\end{enumerate}

While examining case studies can be very insightful, some of these questions cannot be addressed based on individual cases alone. Using an automated detection algorithm of RWBs and storms can give a more comprehensive picture of possible cases, and therefore supplement existing studies and generalize their results.

%We show that anticyclones are intrinsically related to AWB, while cyclones are intrinsically related to CWB. However, both cyclones and anticyclones are involved with both types of wave breaking events.

%Here we show that composites of cyclones and anticyclones in the North Atlantic in fact mix between cyclonically and anticyclonically breaking storms, which motivates us to decompose the composites according to the breaking type. We find that while both types of storms are associated with both types of wave breaking events, their characteristics differ greatly in each one of the RWB types, including time evolution, strength, actual and relative positions, and tracks.

The paper is organized as follows. Section 2 reviews the data and methods used for the analysis, including the RWB detection algorithm, the Lagrangian storm-tracking technique, and the compositing procedure. In section 3, wave breaking-centered analysis is performed, and the fundamental relation between upper-level RWB events and low-level weather systems is presented, which shows the different characteristics of cyclones and anticyclones involved with AWB and CWB events. Section 4 examines the life-cycle of the storms in different RWB types, which is divided into "same-sense" storm vorticity and RWB type (i.e., anticyclones during AWB and and cyclones during CWB), and "opposite-sense" storm vorticity and RWB type (i.e., anticyclones during CWB and and cyclones during AWB). Conclusions are discussed in section 6.

\section{Data and methods} \label{sec:methods}

In this study we use the six-hourly upper-level (250~hPa) horizontal velocities and Potential Vorticity (PV), PV on the 350K isentropic level, SLP, and lower-level (850~hPa) horizontal wind and vorticity, from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis dataset (ERAI; \citealp{Dee2011}). The data covers the years 1980-2014 during the NH winter (December-January-February, DJF) period. Climatology is defined as the winter-average over these 35 years, while anomalies are defined as deviations from the DJF climatology.
Note that the analysis is performed on the ERAI reanalysis data rather than on the newer ERA5 dataset for consistency between existing analyses of the tracking and wave-breaking detection results. However, we do not expect any major or fundamental differences in our conclusions if the ERA5 dataset was used instead.

\subsection{Lagrangian storm-tracking algorithm} \label{sec:methods_tracking}

For the tracking of the low-level cyclones and anticyclones we use the objective feature-tracking algorithm TRACK of \cite{Hodges1995,Hodges1999}, which is a widely used storm-tracking algorithm. We use the 850~hPa relative vorticity field, and the cyclone and anticyclone centers are then identified by a local maximum and minimum of the vorticity field, respectively. The intensity is determined based on the relative vorticity anomaly (in absolute value) at the center of the storm, with a cutoff value of $10^{-5}~\rm{s}^{-1}$ for the identification of the storm (a threshold customarily used for the identification of cyclones and anticyclones). The background flow is automatically removed by the algorithm prior to the tracking by subtracting all spatial wavenumbers smaller than or equal to 5, to isolate the synoptic-scale features. In addition, the vorticity field is reduced to a T42 grid, and then a spectral tapering is performed in order to suppress Gibbs phenomenon (\citealp{Hodges1995}). The centers of storms are tracked every six hours, and the tracking is performed on the sphere, by first initializing the maxima or minima into a set of tracks using a nearest neighbour method, and then refining these by performing a constrained minimization of a cost function for track smoothness \citep{Hodges1999}. The tracking is performed separately for cyclones and anticyclones, for each winter during the years 1980-2014 (where the year is defined according to January).

%that the intensity of the cyclones and anticyclones is given by the relative vorticity at 850 hPa at the cyclone centre location

\subsection{Rossby wave-breaking detection algorithm} \label{sec:methods_RWB}

Here we use the RWB detection algorithm developed by \citet{Strong2008}, which can detect both poleward and equatorward breaking events. We configure it to detect the equatorward-breaking high-PV tongues associated with anticyclonically and cyclonically overturning PV contours, but our results are qualitatively similar if poleward breaking cases are analyzed instead.

%The RWB detection algorithm used in this study is based on \citet{Strong2008}, and configured here to objectively identify the equatorward-breaking high-PV tongues associated with anticyclonically and cyclonically overturning PV contours.

The RWB distributions depend on the vertical isentropic level chosen, with generally more frequent AWB and less frequent CWB at higher isentropic levels (e.g.,Martius et al., 2007). Here we use PV on the 350K isentropic level (corresponding approximately to the upper troposphere/lower stratosphere) for the identification of RWB events, which has a relatively strong RWB activity. As noted in earlier studies who used the same RWB detection algorithm (e.g., \citealp{Strong2008, Zhang2018}), the 350K level provides a useful representation of both AWB and CWB events over all latitudes, because higher latitude RWB events are deep enough to be detected by higher PV values at this level. Hence, the RWB identification is performed for each PV value between 1.5-7.5 PVU, which allows for detecting RWB in both lower and higher latitudes. Note that similar results were also found by using PV on the 250~hPa level (not shown).

The algorithm identifies large-scale overturning of circumpolar PV contours, on each one of the PV contours, by searching for contours crossing a particular meridian more than once. The algorithm uses the geometry of the overturning PV contour to quantify the zonal extent of the break and to distinguish between anticyclonic and cyclonic overturning (see \citealp{Strong2008} for more details). In the original algorithm, the center of the breaking event is defined as the geographic centroid of the PV tongue (the equatorward PV tongue in our case). This is slightly modified here such that the latitudinal center of the event is chosen between the poleward and equatorward PV tongues (for presentation purposes mainly). The latter is achieved by adding half of the meridional width of the tongue (at its centroid) to the centroid position.

For each breaking event, only the spatially largest overturning is taken among the 1.5-7.5 PVU contours, and further events occurring less than L_x apart (L_x being the tongue's extent) are eliminated. In addition, if RWBs occur on adjacent days, only the day of maximum overturning (spatially largest overturning) is considered. The longitudinal width of an overturning AWB (CWB) is set to be larger than 7° (5°), the area of the breaking larger than $7\cdot10^{-4}$ as a fraction of earth's surface area, and the depth of the breaking (defined is the maximum PV value in the tongue minus the analyzed PV contour) is taken larger than 1~PVU. The spatial extent of the breaking events is chosen different for AWB and CWB, since the former are generally larger and greater in number, but similar qualitative results are obtained for other thresholds.

Finally, only RWB events whose centroid lies within the Euro-Atlantic domain, defined here as the box (15N-75N, 80W-20E) are considered.

Examples of AWB and CWB events detected by the algorithm are shown in Fig.~\ref{fig:fig1}a and Fig.~\ref{fig:fig1}b, respectively.

As can be seen in these examples, AWB (Fig.~\ref{fig:fig1}a) involves a high-PV streamer wrapping anticyclonically around a low-PV ridge. The AWB centroid is located in the equatorward (i.e. anticyclonic) side of the upper-level zonal flow, and the orientation of the PV contours is SW-NE.

In contrast, CWB (Fig.~\ref{fig:fig1}b) involves the cyclonic wrapping of low-PV around a high-PV trough, and the orientation of the PV contours is SE-NW. In addition, the centeroid of the CWB is located in the poleward (i.e., cyclonic) side of the upper-level zonal flow.
The position and tracks of the low-level cyclones and anticyclones are strongly related to these breaking events, but it is difficult to identify any such relations from isolated examples. A deeper investigation of the relation between RWB events and low-level storms is given in Sections \ref{sec:3} and \ref{sec:4}.

%The frequency distribution of the RWB centroids (in units of events per season, Fig.~\ref{fig:fig1}c,d) shows that AWB events (Fig.~\ref{fig:fig1}c) occur more in the downstream region of the Atlantic ocean basin, exteding towards western Europe, and mostly in the anticyclonic side of the time-mean Atlantic jet, while CWB events (Fig.~\ref{fig:fig1}d) occur more in the upstream region of the Atlantic ocean, mainly in the cyclonic side of the time-mean Atlantic jet, in accordance with previous studies
%A secondary maximum in CWB is also found poleward of the African-Asia jet, but in the following analysis we only consider CWB occurring to the west of of 350° (i.e., in the upstream region of the Atlantic storm track), although our results do not change qualitatively if all CWB are considered instead.

%in units of events per season,
The frequency distribution of the RWB centroids (Fig.~\ref{fig:fig1}c,d) shows that AWB events (Fig.~\ref{fig:fig1}c) occur more in the downstream region of the Atlantic ocean basin, maximizing over western Europe, and is sandwiched between the anticyclonic side of the time-mean Atlantic jet and the cyclonic side of the Subtropical time-mean African-Asian jet, while CWB events (Fig.~\ref{fig:fig1}d) occur more in the upstream region of the Atlantic ocean, mainly in the cyclonic side of the Atlantic jet. A secondary maximum in CWB is also found poleward of the African-Asia jet. These results are generally in accordance with previous studies (e.g., \citealp{Strong2008,Zhang2018}).
%In the following analysis we only consider CWB occurring to the west of of 350° (i.e., in the upstream region of the Atlantic storm track), although our results do not change qualitatively if all CWB are considered instead.

Note that we have initially tested a RWB detection algorithm similar to the one used in \citet{Ndarana2010} and \citet{Garfinkel2014}, and found qualitatively similar results (see Fig.~S1 and Fig.~S2 in the SI). However, unexpected extensive CWB activity was detected in the region where AWB is most frequent (Fig.~S3), which is why an alternative algorithm was eventually used. Nonetheless, the equivalency of the results using the two different methods gives confidence in our results.

\subsection{Composites of RWB events}

The RWB identification algorithm and the storm-tracking results are used to construct composites of the flow during breaking events, centered either around the centroids of the breakings, or around the corresponding cyclones and anticyclones. The breaking events are first

separated into AWB events and CWB events, and composites are then constructed by placing a box sized 60 degrees in latitude by 70 degrees in longitude around the breaking centroid. This is performed separately for all AWB and CWB events, which are then averaged together for each type of breaking.

Overall, there are 2,833 AWB events and 2,219 CWB events which satisfy the criterions in Section \ref{sec:methods_RWB}, and are used for the breaking-centered composites.

Note that the composites are performed on pressure levels (the 850 hPa pressure level is used for the low-level flow, for consistency with the tracking algorithm, and the 250 hPa pressure level is used for the upper-level flow), whereas the RWB events are detected on the 350K isentrope. However, similar results are found if RWB detection is performed on the 250 hPa level, or if the composites are performed on the 350K isentropic level instead.

For the storm-ceneterd composites, similar criterions are used, but the composites are now centered on the closest cyclone or anticyclone within a 25 degree distance from the breaking centroid.

In order to fit the meridional extent of the composite box (30 degrees to the north and to the south of the composite center), in practice only RWB events or storms whose center is between 30N-60N are kept for the compositing. In addition, only storms with intensities (in absolute value) larger than 2 (in units of $10^{-5}~\rm{s}^{-1}$) are used for the analysis.

%Overall, 2,085 anticyclones and 1,314 cyclones are identified as closest within a 25 degree distance from the breaking centroid of AWB and CWB events, respectively, and are used for storm-centered composites.

%Overall, there are 2,458 cyclones and 2,085 anticyclones identified as closest to the breaking centroid of AWB, and there are 1,314 cyclones and XX anticyclones identified as closest to the breaking centroid of CWB events. For the storm-centered composites, we further subset the cyclones during AWBs into those residing to the north (1,281 cyclones) or to the south (1,177 cyclones) of the breaking centroid, while for anticyclones during CWBs we use those residing to the east (417 anticyclones). These choices are motivated by the results presented in Fig.~\ref{fig:fig3}, and will become clearer later.

%Overall, there are 5,106 cyclones and 4,136 anticyclones identified as closest to the breaking centroid of AWB, and there are 4,216 cyclones and 3,681 anticyclones identified as closest to the breaking centroid of CWB events. For the storm-centered composites, we further subset the cyclones during AWBs into those residing to the north (N) (2,922 cyclones) or to the south (S) (2,184 cyclones) of the breaking centroid, while for anticyclones during CWBs we use those residing to the east (1,859 anticyclones). These choices are motivated by the results presented in Fig.~\ref{fig:fig3}, and will become clearer later.

Overall, there are 2,785 cyclones and 2,085 anticyclones identified as closest to the breaking centroid of AWB, and there are 1,690 cyclones and 1,558 anticyclones identified as closest to the breaking centroid of CWB events. For the storm-centered composites, we further subset the cyclones during AWBs into those residing to the north (N) (1,424 cyclones) or to the south (S) (1,361 cyclones) of the breaking centroid, while for anticyclones during CWBs we use those

residing to the North-East (NE) (417 anticyclones). These choices are motivated by the results presented in Fig.~\ref{fig:fig3}, and will become clearer later.

%Note that the compositing procedure will inevitably highlight the intensity of the composited feature, and this should be considered wherever claims are made which are based on the intensity of the storm in the composite.

%Additional composites representing anomalous life-cycles are also performed around anticyclones that reside to the east (E) of the breaking centroid for CWB, and around cyclones that reside either 5° to the north (N) or 5° to the south (S) of the breaking centroid for AWB. These choices are motivated by the results presented in Fig.~\ref{fig:fig3}, and will become clearer later. The $\pm{5}^\circ$ criterion is used here to insure separation (due to the NW/SE orientation of the relative cyclone positions during AWB events), but results are not sensitive to this criterion. Overall, there are 1,281 (1,177) cyclones found to the N (S) of the breaking centroid of AWB, and 417 anticyclones found to the NE of the breaking centroid of CWB, which are used for the anomalous life-cycle composites presented in Section \ref{sec:anomalous}.

\section{The relation between RWB events and low-level weather systems} \label{sec:3}

\subsection{Composites of breaking-centered RWB events}

We first examine the wave breaking-centered composites of the upper and lower-level flows at the time of maximum breaking. Consistent with previous studies (e.g., \citealp{Strong2008,Kunz2009}), and similar to the example cases shown in Fig.~\ref{fig:fig1}, the composite of AWB events (Fig.~\ref{fig:fig2}a,b) shows a high PV tongue (trough) wrapping anticyclonically around a low-PV (ridge) with a SW-NE orientation (Fig.~\ref{fig:fig2}a). The composite of the upper-level zonal flow (Fig.~\ref{fig:fig2}b) shows a split jet structure, with a tilted jet in the upstream region, poleward of the AWB center, and a strong decelerated region close to the breaking center. The upstream tilted structure is consistent with the notion that AWB are associated with a poleward shifted jet. However, there is also an additional downstream zonal and more equatorward jet, whose importance has been mentioned in the context of Mediterranean cyclones (e.g., \citealp{Flaounas2015,Flaounas2022}), and is associated with the African-Asian jet. The split jet structure during AWB will be discussed further when investigating the time-evolution composites in Section \ref{sec:4}. The composite of CWB events (Fig.~\ref{fig:fig2}c) shows a low-PV tongue (ridge) wrapping cyclonically around a high-PV tongue (trough), with a general SE-NW orientation. The composite of the upper-level zonal flow during CWB events shows a more zonal and southward jet, which is also slightly decelerated close to the breaking center (Fig.~\ref{fig:fig2}d).

Also shown in Fig.~\ref{fig:fig2} are the composite low-level (850~hPa) vorticity anomaly (black contours in Fig.~\ref{fig:fig2}a,c), and SLP anomaly (black contours in Fig.~\ref{fig:fig2}b,d). The anomalous SLP composites during AWB are similar to those found by \citet{Strong2008} and

\citet{Kunz2009}, with a negative SLP anomaly generally to the north of a positive SLP anomaly (similar to the positive NAO SLP dipole).

Similar results are found for the 850~hPa vorticity composites (Fig.~\ref{fig:fig2}a), with a strong negative anticyclonic vorticity below and slightly to the east of the upper-level ridge, and a positive cyclonic vorticity to its north-northwest. The vorticity composites of AWB events also show an additional weaker cyclonic signature to the south of the anticyclonic vorticity, not seen in the SLP composites. We note that the RWB detection algorithm we employ here identifies the breaking maximum in a relatively more mature and developed breaking stage (measured by the spatial zonal extent of the breaking tongue), which is why the vorticity anomalies during AWB appear more N-S oriented rather than NW-SE. The initially used RWB detection algorithm (based on \citealp{Ndarana2010} and \citealp{Garfinkel2014}), which detects breaking at an earlier stage, highlighted more strongly the NW-SE orientation (e.g., see Fig.~S1 and Fig.~S2). For CWB (Fig.~\ref{fig:fig2}b) we find, consistent with \citet{Strong2008} and \citet{Kunz2009}, a positive SLP anomaly to the N-NE of a negative SLP anomaly (generally similar to the negative NAO SLP dipole). The vorticity composites during CWB (Fig.~\ref{fig:fig2}d) show a strong cyclonic anomaly below and slightly to the east of the upper-level trough, and an anticyclonic anomaly to its NE.

%To examine whether these pressure and vorticity anomalies are signatures of the large-scale, slowly varying flow, or whether they are associated with the synoptic-scale cyclones and anticyclones themselves, we next utilize the storm-tracking algorithm to investigate the characteristics of low-level storms during RWB events.
%What we meant is whether the SLP anomalies are mostly signatures of large-scale, slowly varying flow anomalies, or rather synoptic scale weather systems.

A priori, it is not clear whether these SLP anomalies are mostly signatures of large-scale, slowly varying flow (i.e., signatures of the low-frequency weather regimes), or whether they are associated with the synoptic-scale storms (i.e., high-frequency eddies). For example, it has been suggested that the positive and negative polarities of the NAO (which are low frequency modes) are directly linked to RWB events, or more generally to changes in their frequency and location (\citealp{Benedict2004,Franzke2004,GwendalOrlanski,Woollings2008,Strong2008,Kunz2009}). Here we utilize the storm-tracking algorithm to show a clear relation between RWB events and migrating low-level cyclones and anticyclones, and to investigate the characteristics of low-level storms during RWB events. How these feed back into the slowly varying atmospheric modes is left for further study.

\subsection{Low-level storm characteristics during RWB events}

The relation between upper-level RWB and low-level storms is first investigated by examining the relative positions, intensities, and propagation characteristics of the storms during RWB events.

In the following analysis (presented in Fig.~3-Fig.~5) we use all the cyclones and anticyclones identified within a 25° distance from the breaking centroid, and not just the closest features, as done for the composite analysis.
Overall, there are 5,106 cyclones and 4,136 anticyclones during AWBs, and 4,216 cyclones and 3,681 anticyclones during CWBs.
%We find that in the North Atlantic, most cyclones and anticyclones are associated with an AWB and/or CWB at some point during their lifetime, while very few storms do not involve any upper-level wave breaking (~11$\%$).
For AWBs, in 90$\%$ of the cases there is at least one anticyclone present in its vicinity, and in 94$\%$ of the cases there is at least one cyclone present. For CWBs, these numbers are 92$\%$ and 95$\%$ for anticyclones and cyclones, respectively. In both types of breaking events, it is very rare (less than 1%) that the upper level RWB event occurs without any surface weather system present in its vicinity.

Fig.~\ref{fig:fig3} shows scatter plots of the positions of cyclones (left column) and anticyclones (right column) during RWB events, where color denotes the intensity of the system (absolute valuse, in units of $10^{-5}\rm{s}^{-1}$), relative to the center of the AWB (Fig.~\ref{fig:fig3}a,b) and CWB (Fig.~\ref{fig:fig3}c,d). Clear signatures of preferred relative positions arise in these aggregated scatter plots (see black contours denoting the corresponding Probability Density Functions (PDFs).
During AWB events (Fig.~\ref{fig:fig3}a,b), anticyclone locations are mostly within the upper-level ridge, close and slightly to the north of the AWB center (denoted by the cross symbol), while two distinct locations emerge for cyclones; strong cyclones are typically found to the N-NW of the breaking center, and a secondary region of weaker cyclones is found to the S-SE of the breaking center. Hence, AWBs are often associated with a cyclone-anticyclone-cyclone (C-AC-C) tripole, consistent with the vorticity composites shown in Fig.~\ref{fig:fig2}a.
Analyzing how often this tripole occurs simultaneously reveals that in ~56$\%$ of the cases a C-AC-C structure that is N-S oriented is observed (i.e., at least one anticyclone, with at least one cyclone to its north and one cyclone to its south).
During CWB events, cyclones are typically found at low-levels close to the trough region, slightly to the SW of the CWB center (Fig.~\ref{fig:fig3}c). For anticyclones during CWB, the relative positions are more spread, but slightly stronger anticyclones are found to the E-NE of the breaking center (Fig.~\ref{fig:fig3}d). Note that for the initially used RWB detection algorithm (based on \citealp{Ndarana2010}), the signature of strong anticyclones to the NE of CWBs was much clearer (see Fig.~S2d in the SI).

%Consistent with the vorticity composites shown in Fig.~\ref{fig:fig2}c, anticyclones during CWB reside generally to the E-NE of the cyclones.

%Additional information can be gained by plotting the actual positions, in physical space, of the storms during RWB events (Fig.~\ref{fig:fig4}).

%Indeed, both types of storms reside in slightly different position during the two types of RWB events (as described in lines XX-XX).

The geographical distribution of the storms and their propagation characteristics are important for regional weather (for example in the European-Asian continent and Mediterranean region), and can influence the distribution of, e.g., precipitation and extremes. Since AWB and CWB events occur most frequently in different regions over the Euro-Atlantic region (Fig.~\ref{fig:fig1}c,d), and since the relative distribution of the storms is different in each one of the cases (Fig.~\ref{fig:fig3}), it is also of interest to examine where do cyclones and anticyclone reside, in physical space, during AWB and CWB events.

The thick black contours in Fig.~\ref{fig:fig4} show PDFs of the storm counts (calculated using a kernel density estimator and multiplied by the number of storms in each case), highlighting the locations where storms are most observed. Motivated by the distinct relative positions found in Fig.~\ref{fig:fig3}a for cyclones during AWB, in Fig.~\ref{fig:fig4}a the PDFs are further separated into cyclones residing to the north (black thick contours) and south (gray thick contours) of the breaking center.

Cyclones during AWB events (Fig.~\ref{fig:fig4}a) are generally spread more over the Atlantic ocean basin and the downstream region of the stormtrack, with more cyclones reaching the UK and Scandinavia, compared to cyclones during CWB (Fig.~\ref{fig:fig4}c), which are concentrated more in the western side of the ocean basin, roughly co-located with the region where CWB events are most frequent.

The secondary peak of cyclones residing to the south of the breaking center (gray thick contours in Fig.~\ref{fig:fig4}a) is found mostly in the downstream subtropical Atlantic and in the Mediterranean region.

%Cyclones during AWB events (Fig.~\ref{fig:fig4}a) are spread more equally over the Atlantic ocean basin, with notably more cyclones reaching the UK and Scandinavia, compared to cyclones during CWB (Fig.~\ref{fig:fig4}c). A secondary peak in the cyclones' PDF is found over the Mediterranean. These Mediterranean cyclones, which generally reside to the S-SE of the AWB center, are much weaker compared to cyclones to the NW of the AWB center, and also compared to cyclones during CWB events (Fig.~\ref{fig:fig5}a).During CWB (Fig.~\ref{fig:fig4}c), cyclones are concentrated more in the western side of the ocean basin. These cyclones, as expected, are located close to the region where CWB events are most frequent.

Similarly, anticyclones during AWB events (Fig.~\ref{fig:fig4}b) are found more in the downstream region of the Atlantic ocean basin (close to the region where AWB events are most frequent), while anticyclones during CWB (Fig.~\ref{fig:fig4}d) are found more in the mid and upstream region. The latter also exhibit a secondary local maximum over Greenland.

The storm characteristics are examined more quantitatively by examining the histogram distributions of their intensity (absolute value), spatial position, and longitudinal and latitudinal track displacements during the two types of RWB events (Fig.~\ref{fig:fig5}).

Cyclones to the south of AWB are much weaker compared to cyclones to the north of the AWB center and also compared to cyclones during CWB events (Fig.~\ref{fig:fig5}a), while anticyclone intensities are similar between the two types of breakings (Fig.~\ref{fig:fig5}f).

There is a clear longitudinal separation between the positions of the storms, with both cyclones and anticyclones being located more upstream during CWB compared to those during AWB (Fig.~\ref{fig:fig5}b,g). The latitudinal separation of cyclones during AWB is by construction, but it can also be seen that cyclones during AWB can be found at much lower latitudes compared to cyclones during CWB (thick and thin black lines in Fig.~\ref{fig:fig5}c, respectively). The latitudinal distribution of anticyclones during CWB and AWB is similar, but anticyclones during CWB are slightly more concentrated to the north (difference is statistically significant at the 5$\%$ level).

The storms also have very distinct propagation characteristics, depending on the type of breaking (cyclonic/anticyclonic), and their position relative to the breaking center. Fig.~\ref{fig:fig5}d,e and Fig.~\ref{fig:fig5}i,j show the longitudinal and latitudinal displacements of cyclones during the four days centered around the breaking maximum (i.e., the difference between the position two days after the breaking maximum, r_{b+2}, minus the position two days prior the breaking maximum, r_{b-2}; $\Delta{r}=r_{b+2}-r_{b-2}$). Cyclones during CWB (thin black line in Fig.~\ref{fig:fig5}d,e) mostly propagate eastward and poleward, as expected (e.g., \citealp{Gilet2009,Riviere2012,Tamarin2016}). However, separating cyclones during AWB into those occurring to the N and to the S of the AWB center shows that while cyclones to the N (dashed red lines in Fig.~\ref{fig:fig5}d,e) also tend to move eastward and poleward, cyclones to the S (dash-dotted blue lines in Fig.~\ref{fig:fig5}d,e) are much more stationary zonally and meridionally, and even propagate on average slightly equatorward.
%This is consistent with the anticyclonic (southwestward) wrapping of the trough around the ridge observed during AWB events (as will be shown in Fig.~\ref{fig:fig7}).
%is consistent with previous studies who examined the cyclones that are associated with PV streamers during AWB events
%***The hindering of the eastward and poleward propagation of these weaker cyclones is probably related to the anticyclonic (southwestward) wrapping of the trough around the ridge observed during AWB events (as will be shown in Fig.~\ref{fig:fig7}).
%The propagation characteristics associated with this subset of cyclones could be relevant for Mediterranean cyclones, which have been previously shown to be dynamically linked to AWB in the Atlantic region (\citealp{Flaounas2015,Shira2017,Flaounas2022}).
The propagation characteristics associated with this subset of cyclones (to the S of AWBs), which is expected given the anticyclonic (southwestward) wrapping of the trough around the ridge, could be investigated further for Mediterranean cyclones, for which AWB was suggested to play a crucial role (\citealp{Flaounas2015,Shira2017,Flaounas2022}).
 %could be relevant for Mediterranean cyclones, which have been previously shown to be dynamically linked to AWB in the Atlantic region (\citealp{Flaounas2015,Shira2017,Flaounas2022}).
%is in consistent with expectations cyclones that are associated with PV streamers during AWB events
%could be investigated further, especially for Mediterranean cyclones, for which it has been previously suggested that AWB in the Atlantic region plays a crucial role (\citealp{Flaounas2015,Shira2017,Flaounas2022}).

Finally, anticyclones during AWB and CWB events have similar meridional propagation characteristics (Fig.~\ref{fig:fig5}j, difference is not statistically significant), while the eastward displacements of anticyclones during AWB are slightly larger compared to anticyclones during CWB ((Fig.~\ref{fig:fig5}i, an averaged longitudinal displacement of 31.2° compared to 27.8°, respectively, difference is statistically significant at the 5$\%$ level).

%For the propagation displacements, the differences between cyclones to the N and S of CWB are large and clear, as originally discussed in the manuscript. For anticyclones, the eastward propagation is slightly larger for anticyclones during AWB compared to anticyclones during CWB (difference is statistically significant at the 5\% level, as mentioned in the previous comment), while the difference in the meridional displacements is not statistically significant.

%In the next section we examine the life-cycle of the low-level cyclones and anticyclones during RWB events. Motivated by Fig.~\ref{fig:fig3}, we composite the flow either on anticyclones during AWBs and cyclones during CWBs (denoted hereafter as "same-sense" storm vorticity and RWB type cases), or on anticyclones during CWBs and cyclones during AWBs (denoted hereafter as "opposite-sense" storm vorticity and RWB type cases).

%\section{Time evolution of storm-centered composites during RWBs} \label{sec:4}
\section{The life-cycles of cyclones and anticyclones in the North Atlantic} \label{sec:4}

%the frequencies and positions of RWB events relative to the center of cyclones and anticyclones in the North Atlantic.
 %Fig.~\ref{fig:fig6} shows

We first examine composites of cyclones and anticyclones in the North Atlantic during the time of maximum intensity, overlaid with the coincident RWB PDF frequencies (estimated as Kernel Density Estimators and multiplied by the number events in each case) (Fig.~\ref{fig:fig6}). We also quantify the percentage of cyclones or anticyclones that are associated with RWB in their vicinity (defined as less than 25 degrees to their north/south or east/west) sometime during their time evolution. We find that 69$\%$ of the cyclones are associated with an AWB in their vicinity, 67$\%$ with a CWB in their vicinity (with 47$\%$ having both), while 11$\%$ do not have a RWB occurring in their vicinity during their lifetime. For anticyclones, 65$\%$ are associated with an AWB in their vicinity, 61$\%$ with a CWB in their vicinity (with 41$\%$ having both), while 15$\%$ do not have a RWB occurring in their vicinity during their lifetime. These percentages do not change much when taking only the 50 strongest storms from each season.

The results imply that most cyclones and anticyclones in the North Atlantic are involved with breaking at some point during their lifetime. Interestingly, slightly more cyclones are associated with AWB rather than CWB. This is consistent with the fact that AWBs are generally more frequent, but is also probably related to diabatic heating associated with the warm conveyer

belt, which contributes to the upper-level ridge development (e.g.,
\citealp{Grams2011,Pfahl2015,Methven2015}).
The AWB occurs mostly to the south-east of the cyclones, but the AWB relative positions are
rather spread around the cyclone such that overall, the AWB frequency PDFs around cyclones
are low (Fig.~\ref{fig:fig6}a). On the other hand, for cyclones associated with CWB, the breaking
occurs in a similar position (close to their center and slightly to the north-east), hence the CWB
frequency PDFs are high, even though there are generally fewer CWB events compared to AWB
events (Fig.~\ref{fig:fig6}c).
A similar but opposite picture is found for anticyclones: for those associated with an AWB the
breaking typically occurs in a similar relative position (close to their center and slightly to the
south), hence the AWB frequency PDFs are high (Fig.~\ref{fig:fig6}b), while the CWB positions
are more spread around the anticyclones, hence the frequency PDFs of CWB are lower
(Fig.~\ref{fig:fig6}d). These results are consistent with our earlier findings presented in
Fig.~\ref{fig:fig3} (from the perspective of the breaking center).

Fig.~\ref{fig:fig6} shows that composites of cyclones and anticyclones (which are customarily
performed, at least for cyclones) mix between cyclonically and anticyclonically breaking storms.
This motivates our further decomposition of cyclones and anticyclones into those breaking
cyclonically and anticyclonically, to examine their distinct time evolution and characteristics.
We denote this classification as "same-sense" storm vorticity and RWB type (e.g., anticyclones
with an AWB, and cyclones with a CWB), and "opposite-sense" storm vorticity and RWB type
(e.g., anticyclones with a CWB, and cyclones with an AWB).
The time evolution of the storms during RWB events is investigated by performing composites
relative to the center of the closest storm for each type of RWB (as described in the Methods,
see Section 2).
%The advantage of compositing the flow on the storms is that we have information about their
tracks, and can therefore investigate the time evolution of the flow leading to the event, even
before the breaking had a signature that can be identified by the RWB detection algorithm.

\subsection{Same-sense storm vorticity and RWB type} \label{sec:4a}

We begin with an examination of the cases with same-sense storm vorticity and RWB type.
Fig.~\ref{fig:fig7}a-e and Fig.~\ref{fig:fig9}a-e show composites of the upper-level PV anomaly
and the low-level SLP anomaly (in contours), centered on the anticyclones for AWB and around
the cyclones during CWB, from $T=-3$ days prior to the breaking and up to $T=2$ days after
the breaking. During the time of maximum breaking ($T=0$, Fig.~\ref{fig:fig7}c and
Fig.~\ref{fig:fig9}c), the composites show a structure similar to that obtained by centering the
flow on the corresponding wave breaking type (shown in Fig.~\ref{fig:fig2}). The signal of the
upper-level breaking (e.g., characterized by the overturning of the PV contours) is slightly
weaker in the storm-centered composites. However, the results are otherwise similar, and
capture the different cyclone/anticyclone orientations found for AWB and CWB events. The
same-sense composites also give results similar to those obtained by compositing the flow on
all the storms, regardless of whether an upper-level RWB event has occurred
(Fig.~\ref{fig:fig6}). This is because the centers of anticyclones and AWB events are more co-

located (and similarly for cyclones and CWB events), and hence they dominate the composites. Since the same-sense storm vorticity and RWB cases are more representative of the composite life-cycle of anticyclones and cyclones in the North Atlantic, we explore these cases in more detail, but in Section~\ref{sec:4b} we also compare these cases to the opposite-sense storm vorticity and RWB cases.

%We refer to these composites as the canonical cases, as they are more representative of the life-cycle of anticyclones and cyclones in the North Atlantic, obtained by compositing the flow on the storms, regardless of whether an upper-level RWB event has occurred (Fig.~\ref{fig:fig6}). In the next two subsections we examine these life-cycles for AWB and CWB in detail, and in the Section~\ref{sec:anomalous} the canonical cases are also compared with composites centered on cyclones during AWBs, and around anticyclones during CWBs, which represent anomalous cases.

Note that the compositing procedure will inevitably highlight the intensity of the composited feature, and this should be taken into account wherever claims are made which are based on the intensity of the storm in the composite. For example, compositing on anticyclones during AWB will result with a strong low-level anticyclone and an anomalous anticyclonic circulation at upper levels. Nonetheless, compositing the flow on cyclones during AWB instead still gives a strong anticyclonic circulation at upper-levels, even though the compositing is on the cyclones in this case. In addition, it is also of interest to compare between composites centered on anticyclones during AWB relative to those during CWB. While in both cases the centering is on the anticyclones, the composites reveal quite distinct life-cycles, as will be shown (and similarly for cyclones during AWB or CWB events).

%This should be taken into account wherever claims are made which are based on the intensity of the storm in the composite. Nonetheless, compositing the flow on cyclones during AWB instead (discussed later in Section \ref{sec:4b.b} and shown in Fig.~\ref{fig:fig10}) still gives a strong anticyclonic circulation at upper-levels, even though the compositing is on the cyclones in this case. In addition, it is also of interest to compare between composites centered on anticyclones during AWB relative to those during CWB (discussed later in Section \ref{sec:4b.a} and shown in Fig.~\ref{fig:fig10}). While in both cases the centering is on the anticyclones, the composites reveal quite distinct life-cycles, as will be shown.

\subsubsection{Anticyclones during AWB} \label{sec:4a.a}

The time evolution of composites centered on the anticyclones during AWB (Fig.~\ref{fig:fig7}a-e) reveals some interesting features. Three days prior to the breaking ($T=-3$ days, Fig.~\ref{fig:fig7}a), there is a strong low-level anticyclone residing to the east of an upper-level ridge, and low-level cyclone initially to the west of the anticyclone. Both the ridge and the anticyclone reside in the anticyclonic side of the upper-level jet (Fig.~\ref{fig:fig7}f), as well as in the anticyclonic side of the time-averaged mean jet (this is more visible at $T=-1$, see Fig. S4a,b

in the SI). %Hence, in this case, the anomalies are in the "right side of the shear", and act together with the background shear to reinforce the anticyclonic rotation.

During the build-up of the wave breaking, the anticyclone and the cyclone to its west slightly intensify (Fig.~\ref{fig:fig7}a,b) and the cyclone then rotates in an anticyclonic manner relative to the anticyclone (Fig.~\ref{fig:fig7}a-e), eventually merging with a negative SLP anomaly initially to the northeast of the anticyclone.
Parallel to this, the upper-level trough to the east (downstream) of the ridge is wrapped around the ridge and the classical picture of wave breaking and inversion of meridional PV gradient is found (i.e., a negative PV anomaly to the north of a positive PV anomaly).
 During the decay stage of the wave breaking (Fig.~\ref{fig:fig7}d,e), the anticyclone slightly weakens and the flow becomes more barotropic, and two days after the breaking maximum ($T=2$ days, Fig.~\ref{fig:fig7}f), the low pressure anomaly is entirely to the north of the anticyclone.
The low-level positive NAO-like pressure dipole (the low-above-high pressure anomalies) is in agreement with \citet{Strong2008} and \citet{Kunz2009}, but here the time-evolution of the low-level cyclones and anticyclones leading to this structure is examined.

The total upper-level zonal flow weakens significantly to the south of the ridge during the evolution of the breaking, while the downstream zonal and more southward jet intensifies (Fig.~\ref{fig:fig7}f-j). Hence, the initially more wavy-like upper-level jet (Fig.~\ref{fig:fig7}f) is split into an upstream tilted jet, and a downstream zonal jet (Fig.~\ref{fig:fig7}h). The split jet structure has been noted in several previous studies examining Mediterranean cyclones and their relation to AWB (e.g., \citealp{Flaounas2015,Shira2017}). However, it is not usually discussed in relation to the classical theories concerning the poleward shift of the jet in AWB. Separating the total flow into a time-mean (in this case the climatological DJF mean over all the years) and an anomalous flow, i.e., $u=\overline{u}+u'$ (where an overline represents time-mean and prime represents deviation from that time-mean) shows that it is mainly the time-mean flow that contributes to the downstream jet (note that the composites of the time-mean flow vary with time here since the compositing is centered on the storms which are moving, hence at different locations with respect to the Eulerian time-mean flow). The downstream jet is therefore probably linked to the time-mean subtropical Asian-African jet, as the storms approach the eastern side of the ocean basin.

The negative upper-level meridional wind between the ridge and the trough to its east (Fig.~\ref{fig:fig7}k-o) increases significantly during the breaking, consistent with the intensifying anomalous ridge-trough system. Similarly, the negative anomalous zonal wind between the ridge and the trough which is breaking anticyclonically to its south is also intensifying (see also Fig.~S4f-o in the SI for the anomalous velocities).
The anomalous southwestward upper-level wind is contributing to the breaking of the wave by advecting the anomalous upper-level trough southward and westward around the ridge. This nonlinear advection reinforces the upper-level anticyclonic rotation due to the background anticyclonic shear.

In addition, the anomalous upper-level anticyclonic circulation associated with the ridge induces a relative anticyclonic rotation at low-levels (through interaction between the upper and lower levels PV anomalies, not shown), as it acts to advect the low-level anticyclone equatorward and the cyclone to its west poleward (see SLP anomalies and arrows representing the anomalous circulation in Fig.~\ref{fig:fig7}a-e), in general agreement with \citet{Gilet2009,Riviere2012,Tamarin2016}.

Fig.~\ref{fig:fig8}a-c shows cross sections of the upper-level zonal wind at the longitude crossing the center of the composite box (i.e., the center of the anticyclone) . The peak of the total upper-level zonal flow initially increases slightly and then decreases, while the relative latitude at which this peak is achieved remains roughly the same (Fig.~\ref{fig:fig8}a, see changes in the lines going from black, denoting $T=-3$ days, to blue, denoting $T=2$ days). Southward of the peak in total U, the zonal flow decreases significantly during the breaking, and a secondary peak develops further southward. The strong deceleration of U southward of the anticyclone center is related to the intensification of the negative anomalous zonal wind (Fig.~\ref{fig:fig8}b), due to the intensifying ridge and the anticyclonically wrapping trough to its south.
The climatological (time-averaged) zonal wind (Fig.~\ref{fig:fig8}c) also contributes to the apparent weakening of U, due to the motion of the storms into a region where the time-mean Atlantic jet is weaker, while it contributes to the strengthening of the total U more southward (a signature of the downstream subtropical jet). These changes in the time-mean jet are related to the eastward propagation of the anticyclones, as they propagate away from the Atlantic jet and approach the downstream exit region of the storm track.
Note that the anticyclones are also propagating meridionally. Taking into account the averaged latitudinal displacement of the anticyclones at each time-step (which is poleward in this case, see Fig.~\ref{fig:fig5}d), shows that the peak in the total upper-level U is shifted poleward (see Fig.~S6a in the SI).

The results above are consistent with the usual notion that AWB events are associated with a poleward shift of the zonal mean jet, due to the poleward momentum fluxes that result from the SW-NE tilt of the PV contours. Here we suggest a mechanistic interpretation, in which the poleward shift is a result of the intensification and anticyclonic rotation of the ridge-trough system. The anomalous velocities associated with an isolated intensifying ridge would contribute to a local poleward shift of the jet (a strengthening of the total zonal flow poleward the ridge, and a weakening equatorward of it), similar to what is observed during anticyclonic blocking events (\citealp{Tyrlis2008,Woollings2008}).
However, for a linear wave, this effect will cancel out (in the zonal mean) with the adjacent trough, which will have the opposite net effect. The nonlinearity associated with the breaking results in a relative northeastward motion of the ridge and a relative southwestward motion of the downstream trough (i.e., a relative anticyclonic rotation). This breaks both the zonal and the meridional symmetries. An asymmetry in the meridional velocity forms since it is mainly the negative meridional wind between the ridge and the developing downstream trough that intensifies (as opposed to the positive meridional velocity between the ridge and the upstream trough).

%First, the negative meridional wind between the ridge and the downstream trough becomes stronger than the positive meridional wind between the ridge.
Similarly, a negative anomalous zonal wind forms between the ridge and the trough which is wrapping to its south. These anomalous velocities are not averaged out in the zonal mean in this case. Thus, an intensifying and anticyclonically breaking ridge-trough system results in an intensification of the total zonal flow in the area northward of the breaking and a weakening southward of the breaking.

Overall, for anticyclones during AWB events, we see a downstream trough development, equatorward of the upper-level jet, and an anticyclonic relative rotation at both upper and lower-levels. Hence, in this case, the breaking and relative rotation are in the same sense as the storm circulation (i.e., anticyclonic), which is acting to reinforce it (see also the schematic shown in Fig.~\ref{fig:fig11}a for an illustration of the upper and lower level evolution for composite anticyclones during AWB, discussed in the conclusions).

\subsubsection{Cyclones during CWB} \label{sec:4a.b}

We next examine the time evolution of composites centered on cyclones during CWB (Fig.~\ref{fig:fig9}a-e). Three days prior to the breaking ($T=-3$ days, Fig.~\ref{fig:fig9}a), there is a strong low-level cyclone, residing to the east of an upper-level trough, and poleward of an upper-level jet (i.e. in the cyclonic side, Fig.~\ref{fig:fig9}f). There are also weak signatures of an anticyclone to the west and to the north-northeast of the cyclone.
During the build-up of the breaking (Fig.~\ref{fig:fig9}a-c), both the low-level cyclone and the upper-level trough intensify, while a downstream ridge and a low-level anticyclonic anomaly are intensifying to the east and north-east of the cyclone. A relative cyclonic rotation is observed both at upper and lower-levels, as the downstream ridge starts rotating in a cyclonic manner relative to the trough (Fig.~\ref{fig:fig9}b-d).

During the decay stage of the wave breaking (Fig.~\ref{fig:fig9}d,e) the ridge is weakened and dissipated out (see also black contours in Fig.~\ref{fig:fig9}n,o showing the PV anomaly). At low-levels, the cyclone becomes more barotropically aligned with the upper-level trough, and two days after the breaking maximum ($T=2$ days, Fig.~\ref{fig:fig9}e) the high pressure anomaly is mostly to the north of the cyclone.
These results are generally similar to \citet{Strong2008}, who examined composites of CWB and found a low-level negative NAO-like pressure dipole (a high-above-low pressure dipole), and to \citet{Kunz2009}, who examined CWB in simplified GCM experiments and found a similar dipole at upper-levels (a low-above-high meridional PV anomaly dipole).

The total zonal flow (Fig.~\ref{fig:fig9}f-j) weakens in magnitude, most strongly to the north of the cyclone center, and its peak shifts southward relative to the cyclone center. The weakening and southward shift of the jet in the composites, which are observed also in the composites of the time-mean flow (Fig.~S5a-e, see also Fig.~\ref{fig:fig8}d-f), are probably a result of the

eastward and poleward motion of the cyclones, as they move further away from the time-mean flow and approach the weaker jet exit region.

The anomalous upper-level zonal wind (arrows in Fig.~\ref{fig:fig9}a-e), which is dominated by the upper-level trough, is positive to the south of the trough, but a strong negative anomalous zonal wind is generated between the trough and the ridge which is breaking cyclonically to its north. Similarly, the positive upper-level meridional wind between the trough and the ridge to its east, which is mostly due to the anomalous flow (see also Fig.~S5f-o for the anomalous winds), increases during the evolution of the breaking, as the trough-ridge system grows (Fig.~\ref{fig:fig9}k-o). As in AWB, the anomalous upper-level wind is contributing to the breaking, in this case by nonlinear northwestward advection of the ridge around the trough (i.e., in a cyclonic manner), which reinforces the rotation induced by the cyclonic shear. Hence, the anomalous upper-level wind is contributing to both the downstream development of the ridge (through linear advection), and to the cyclonic rotation (through nonlinear advection). Note that the downstream ridge development in this case is also related to the indirect influence of diabatic heating. Latent heat release associated with the warm conveyer belt of the cyclone contributes to a negative PV tendency aloft. The negative PV tendency is contributing to the ridge development through an upward negative PV advection (not shown, consistent with e.g., \citealp{Grams2011,Pfahl2015,Methven2015}).

The cross sections of the upper-level zonal wind at the longitude crossing the center of the cyclone (Fig.~\ref{fig:fig8}d-f) show that the peak of the total zonal flow (Fig.~\ref{fig:fig8}d) weakens and shifts southward throughout the life-cycle of the breaking. This is mainly due to the time-mean zonal flow (Fig.~\ref{fig:fig8}f), and is related to the eastward and poleward propagation of the cyclones away for the jet core.

In addition, the flow weakens strongly poleward of the breaking. The latter is due to the intensification of the negative anomalous zonal wind (Fig.~\ref{fig:fig8}e), related to the intensifying and cyclonically rotating ridge-trough system.

Adjusting the cross-sections by taking into account the averaged latitudinal poleward displacement of the cyclones at each time-step shows that in this case, the peak in the total upper-level U remains roughly at the same latitude (see Fig.~S6b in the SI). This seems to suggest an interesting asymmetry between AWB and CWB events, namely that during AWB events, the already poleward shifted jet can shift even further poleward, while during CWB, the equatorward shifted jet remains at a similar latitude.

The weakening of the total upper-level jet poleward of the breaking during CWB is consistent with the notion that CWBs are associated with an equatorward shifted zonal mean jet, due to the equatorward momentum fluxes that result from the SE-NW tilt. Similar to AWB, we suggest that this is due to nonlinearity associated with the breaking (i.e., the cyclonic wrapping of the ridge around the trough) which breaks the zonal and meridional symmetries, as it favors a positive meridional wind between the trough and the ridge to its east, and a negative anomalous zonal wind between the trough and the breaking ridge to its north, which are not averaged out in the zonal mean.

Overall, for cyclones during CWB events, we see a downstream ridge development, poleward of the upper-level jet, and a relative cyclonic rotation at both upper and lower-levels. Hence, in this case too, the breaking and relative rotation are in the same sense as the storm circulation (see also Fig.~\ref{fig:fig11}c for a schematic illustration of the upper and lower level evolution for composite cyclones during CWB). Such a development is similar to what is usually observed or expected for cyclones, which reside on average in the cyclonic side of the jet, and experience a cyclonic wrap-up at upper-levels (e.g., Figure 4 in \citealp{Dacre2012}).

%In the following section (Section \ref{sec:4b}), we examine the life-cycle of storms during RWB which is occurring in the opposite-sense to their rotation, and find potentially different time evolutions of the storms.

%\section{Anomalous life-cycles of cyclones and anticyclones} \label{sec:anomalous}
\subsection{Opposite-sense storm vorticity and RWB type} \label{sec:4b}

We next investigate the life-cycle of storms during RWB which is occurring in the opposite-sense to their rotation. For this we examine composites centered on anticyclones during CWB (to the NE of the CWB center), and on cyclones during AWB events, where the latter is separated into cyclones residing to the N or S of the AWB center. We note that similar results are found if the separation is into cyclones residing to the NW or SE of the AWB center, (not shown).

\subsubsection{Anticyclones during CWB} \label{sec:4b.a}

Compositing the flow on anticyclones to the NE of CWBs (Fig.~\ref{fig:fig10}a-e) shows that they are located now to the north of the zonal jet (i.e., in the cyclonic shear), even two days prior to the breaking (Fig.~\ref{fig:fig10}a). These composites are dominated by an upper-level ridge, and a low-level anticyclone with a weaker cyclone to its SW (similar to the orientation found in the CWB composites). Although the anomalous upper-level wind is dominated by the anticyclonic circulation, the cyclone and anticyclone still rotate in a cyclonic manner relative to each other (now it is the cyclone that rotates cyclonically around the anticyclone, due to the centering of the composites around the anticyclones). Similarly, the deepening trough seen to the west of the anomalous ridge (see the 4.5 PVU contour) is clearly not a result of advection associated with the anomalous upper-level anticyclonic circulation, which is in the opposite sense.
One day after the breaking maximum (Fig.~\ref{fig:fig10}e), signatures of AWB start to develop in the downstream region of the ridge.

Overall, in the case of anticyclone composites during CWB, we find that the breaking and relative rotation are occurring in an opposite sense to the anomalous anticyclonic circulation associated with the anticyclone (see also the schematic shown in Fig.~\ref{fig:fig11}b for an illustration of the upper and lower level evolution for composite anticyclones the the NE CWB). This subset includes anticyclones developing from upstream cyclones that involve CWB. A well

studied example of such cases are blocking anticyclones which are preceded by explosive cyclones (e.g., \citealp{Colucci1985,Lupo1995}). Note, however, that from the longitudinal and latitudinal displacement PDFs of these anticyclones (Fig.~\ref{fig:fig5}i,j), stationary blockings constitute only a small subset of these features.

%These anticyclone-centered composites reveal a life-cycle that is quite different from the life-cycle of anticyclones during AWB (Fig.~\ref{fig:fig7} and Fig.~\ref{fig:fig11}a). In both types of life-cycles, the anticyclone is initially to the east of the cyclone, and the anomalous upper-level velocity is dominated by an anticyclonic circulation. However, there are major differences between the two cases. First, the anticyclone and the upper-level ridge are in the anticyclonic side of the jet in AWB (and slightly to the SE of the cyclone), and in the cyclonic side of the jet in CWB (and slightly to the NE of the cyclone). Moreover, it is the downstream trough that deepens in the AWB composites, while it is the upstream one in the CWB composites. Lastly, the relative rotation is anticyclonic for anticyclones during AWBs, while it is cyclonic for anticyclones during CWBs.

%The background cyclonic shear reinforces the developing trough, and by $T=0$ a strong cyclonic circulation is evident at upper-levels (a SW-NE tilted trough-ridge dipole), with strong negative momentum fluxes between the trough and the ridge (consistent with the equatorward shifted jet in the upstream region.

\subsubsection{Cyclones during AWB} \label{sec:4b.b}

For AWB, we separate the composites into those centered on cyclones to the north (N) (Fig.~\ref{fig:fig10}f-j) and to the south (S) (Fig.~\ref{fig:fig10}k-o). In both cases, in addition to the cyclonic upper-level circulation associated with the anomalous trough, there is also a strong anomalous upper-level ridge, even though the compositing is performed on the cyclones.

For cyclones to the N (Fig.~\ref{fig:fig10}f-j), prior to the breaking there is a strong low-level cyclone and an anticyclone to its SE, with the former residing in the poleward (cyclonic) side of the jet, and the latter residing on the equatorward (anticyclonic) side of the jet. There is also another weaker anticyclone initially to the west (upstream) of the cyclone.
The upstream anticyclone rotates slightly cyclonically relative to the cyclone, similar to what was found for cyclone composites during CWB. However, the downstream anticyclone rotates in an anticyclonic manner relative to the cyclone.
%Even though the low-level cyclone is stronger than the anticyclone, the cyclone-anticyclone dipole rotate in an anticyclonic manner relative to each other (this time it is the anticyclone that rotates anticyclonically around the cyclone, due to the centering of the composites around the cyclones).
This anticyclonic rotation is related to the dominance of the anomalous ridge at upper-levels, and is in stark contrast to the low-level cyclonic circulation and the usual cyclonic wrap-up seen at upper-levels during the life-cycle of cyclones (e.g., Figure 4 in \citealp{Dacre2012}). The strong upper-level ridge ultimately leads to an anticyclonic breaking in the downstream region,

by contributing to the growth and anticyclonic breaking of the trough to the east of the ridge. Note that the breaking signal is very weak due to the centering of the flow over the cyclones, which are not necessarily close to the breaking center.

Overall, for cyclones residing to the N of AWB events, we see a relative anticyclonic rotation at both upper and lower-levels, hence the breaking and relative rotation are in the opposite sense to the storm circulation.
However, despite the composite being centered on the cyclone, the anomalous upper-level circulation has a very clear anticyclonic ridge, which enhances the anticyclonic wave breaking and rotation. In this respect, the anomalous circulation is not in an opposite-sense to the wave breaking.
This subset of cyclones likely includes the "upstream cyclones" discussed in the context of blocking events (e.g., \citealp{Colucci1985,Lupo1995}), which often involve AWB (e.g., during the Scandinavian blocking onset studied in \citealp{Michel2012}). It probably also includes cases where the cyclone is in the anticyclonic side of the upper-level jet, which is deflected poleward during the AWB (i.e., cyclones within the ridge area). An example of such a cyclone was presented as a proposed analog to the anticyclonic barotropic shear (LC3) idealized frontal-wave cyclone (\citealp{Shapiro1999}).
This complicates the classification of this subset of opposite-sense cyclones, since it includes a few different cyclone evolutions. We therefore did not include a schematic illustration of this case in Fig.~\ref{fig:fig11}.

%However, in this case, unlike the opposite-sense anticyclone case (anticyclones during CWB, Section \ref{sec:4b.a}), the upper-level anticyclonic shear mainly comes from the anomalous flow, it is in the same sense of the strong upper-level anomalous anticyclonic circulation. We therefore did not include this case, which is slightly less straight forward to classify, in the schematic illustration shown in Fig.~\ref{fig:fig11}.

Finally, centering the flow on cyclones to the S of the AWB center (Fig.~\ref{fig:fig10}k-o) gives, prior to the breaking, a strong anomalous upper-level trough and a weaker anomalous upper-level ridge to its NW. At low levels, there is an anticyclone initially to the W-NW of the cyclone. The anticyclone is relatively strong, given that the composites are centered on the cyclones. The low-level anticyclone-cyclone dipole as well as the upper-level ridge-trough dipole then rotate in an anticyclonic manner relative to each other, with the anticyclone becoming ultimately to the north of the cyclone.
%This contributes to the strong deceleration of the zonal flow between the ridge and the trough (similar to what was discussed in Section \ref{sec:4}a for anticyclones during AWBs). Hence, these cyclones exhibit a composite time evolution that is quite different from both cyclones during CWBs, and from cyclones residing to the N of AWB events. While the former two exhibit a downstream ridge development (with or without a cyclonic wrap-up, respectively), the composite evolution of cyclones to the S of AWBs exhibit an upstream ridge development and an anticyclonic relative rotation. In addition, it can be seen that the cyclonic anomalous winds in this case (arrows in Fig.~\ref{fig:fig10}k-o) do not contribute to the upstream ridge development and the overall relative anticyclonic rotation.

Overall, for cyclones to the S of AWB events, we see an upstream ridge development, and a relative anticyclonic rotation at both upper and lower-levels. Hence, the breaking and relative rotation are in an opposite sense to the storm circulation (see also Fig.~\ref{fig:fig11}d for a schematic illustration of the upper and lower level evolution for composite cyclones to the S of AWB). This subset of opposite-sense cyclones includes subtropical and tropical cyclones (\citealp{Davis2010,Galarneau2015,Bentley2017}) and Mediterranean cyclones (\citealp{Flaounas2015,Shira2017,Flaounas2022}) forming due to PV streamers associated with AWBs (see Fig.~\ref{fig:fig4}a). The similarity between the storm-centered composites for cyclones to the S of AWB (Fig.~\ref{fig:fig10}k-o) and Fig.~10 of \citet{Flaounas2015} showing storm-centered composites for the 200 most intense Mediterranean cyclones is remarkable, which further highlights the importance of Atlantic AWB events in the development of Mediterranean cyclones.

%Such a development is similar to what is usually observed or expected for cyclones, which reside on average in the cyclonic side of the jet, and experience a cyclonic wrap-up at upper-levels (e.g., Figure 4 in \citealp{Dacre2012}).
%Hence, although these cyclones reside in the cyclonic side of an upper-level (more zonal and southward) jet, they are mostly influenced by the anticyclonic shear associated with the strong upstream ridge.
%These cyclones, which are significantly weaker than the cyclones to the N of the AWB, are probably generated as a secondary-development from the breaking upper-level trough (PV streamer).

%As seen in Fig.~\ref{fig:fig4}a, these cyclones are mostly in the subtropical Atlantic basin and in the Mediterranean region. The composite life-cycle is consistent with previous studies who examined subtropical and tropical cyclones forming due to PV streamers associated with AWBs (\citealp{Davis2010,Galarneau2015,Bentley2017}), as well as Mediterranean cyclones (\citealp{Flaounas2015,Shira2017,Flaounas2022}). The similarity between the storm-centered composites for cyclones to the S of AWB and Fig.~10 of \citet{Flaounas2015}, showing storm-centered composites for the 200 most intense Mediterranean cyclones, is remarkable. Our results therefore further highlight the importance of Atlantic AWB events in the development of Mediterranean cyclones.

%encourages further research on the growth, dynamics, and propagation characteristics of Mediterranean cyclones, which would potentially be very different from the canonical cases of Atlantic cyclones.

The opposite-sense composites investigated here show very different cyclone and anticyclone time evolutions compared to the same-sense composites presented in Section \ref{sec:4a}.
%, depending on type of upper-level RWB they are associated with (as well as their position relative to the breaking).
These different life-cycles are often missed when performing composites over all storms.

%Investigating composites of possible configurations of storm sign and breaking type can therefore be helpful for identifying the corresponding storm life-cycles and time-evolutions, with potential implications for improving weather prediction of subsequent storm development.

%For example, it is already well acknowledged that antecedent AWB event can influence subsequent tropical, subtropical, or Mediterranean cyclone development (e.g., \citealp{Appenzeller1996,Davis2010,Galarneau2015,Flaounas2015,Bentley2017,Portmann2021,Flaounas2022}) (which include the cyclones to the S of AWB subset). In addition,\citet{Maddison2019} examined the role of the upstream cyclone on the predictability of block onsets over the Euro-Atlantic Region. They showed that block onset in the case studies is sensitive to changes in the forecast location and intensity of upstream cyclones in the days preceding the onset, and concluded that improvement in the forecasts of upstream cyclone may help improve block onset forecasts. The upstream cyclone and developing downstream block may involve either a CWB or an AWB (or both, for an omega-type block). Given that these time evolutions involve different wave-mean flow interactions and jet shifts, and different storm characteristics such as intensities, positions and displacements, it is of interest to correctly identify them.

\conclusions %% \conclusions[modified heading if necessary]

%This study examines the observed relationship between upper-level Rossby wave breaking events and low-level cyclones and anticyclones. This is achieved by combining a Rossby wave breaking detection algorithm with a storm-tracking technique. The different life-cycles and characteristics of cyclones and anticyclones during AWB and CWB events are examined, by investigating the positions, intensities and propagation characteristics of the storms, as well as by constructing storm-centered composites to examine the time evolution during each type of breaking.

Applying automated detection algorithms of upper-level RWBs and low-level weather systems has allowed us to examine in a more systematic and comprehensive way the relation between storms and RWB events in the North Atlantic, and hence to complement and generalize idealized wave life-cycle experiments (\citealp{simmons1978life,Davies1991,Thorncroft1993}) and single-event case studies (e.g., \citealp{Shapiro1999_book}).
Going back to the first two questions posed in the introduction, the main results can be summarized as follows:
%we address the first two questions:
%The main results and conclusions can be summarized as follows:

%\noindent{\em{The relation between RWB events and low-level weather systems:}}
Composites of cyclones and anticyclones, which are customarily done in studies (at least for cyclones), involve a mixture of different types of storm life-cycles, depending on whether they involve a CWB or AWB event, as well as their position relative to the RWB center. Moreover,

storm characteristics (including actual and relative positions, intensities, and displacements) differ depending on the associated breaking type.

We find that in the North Atlantic, most cyclones and anticyclones are associated with an AWB and/or CWB at some point during their lifetime (more than 60%), with a large portion having both wave breaking types (more than 40%), and few storms having neither (less than 15%, see first paragraph of section~\ref{sec:4}). AWB is generally more frequent than CWB, hence slightly more storms are found with AWB. We also find that the centers of CWBs during cyclones and AWBs during anticyclones are spatially co-located near the respective surface storm center.

During AWB, a low-level anticyclone is found close and slightly to the N of the breaking center. However, two preferred locations of cyclones relative to the center of the breaking emerge, to the S-SE and to the N-NW of the anticyclone (Fig.~\ref{fig:fig3}a,b). Overall, the orientation of the cyclone-anticyclone-cyclone tripole is SE-NW during the breaking development stage, and becomes more S-N oriented by the end of the life-cycle. Geographically, cyclones to the N-NW of AWB are spread more over the upstream and mid-Atlantic ocean basin, while cyclones to the S-SE (which are generally much weaker) are found more over the subtropical eastern Atlantic and the Mediterranean region (Fig.~\ref{fig:fig4}a,b). The propagation characteristics of these two groups of cyclones differ significantly; while the cyclones to the N-NW propagate on average eastward and poleward, cyclones to the S-SE of AWB propagate much less zonally and meridionally.

During CWB, a strong low-level cyclone is usually found close to the CWB center, while anticyclones are found mainly to the NE of the cyclones, such that the cyclone-anticyclones dipole has a SW-NE orientation (Fig.~\ref{fig:fig3}c,d). Geographically, cyclones during CWB are found much more westward (mostly close to the western coast of the North Atlantic ocean basin) and at slightly higher latitudes compared to cyclones during AWBs. Anticyclones during CWBs are also located more upstream compared to anticyclones during AWBs (Fig.~\ref{fig:fig4}c,d).

Given the different storm characteristics summarized above, we distinguish between "same-sense" cases (i.e., cyclones during CWB, and anticyclones during AWB) and "opposite-sense" cases (i.e., cyclones during AWB, and anticyclones during CWB). Compositing the cyclones and anticyclones based on this criterion, we find that in similar pairings the surface system is positioned so that its associated upper-level winds would enhance the breaking which is in the same sense, but for opposite pairings, the upper-level winds associated with the surface system do not act to enhance the breaking which occurs in the opposite sense. Correspondingly, the same-sense and opposite-sense composites show very different life-cycle and time evolutions, depending on the type of upper-level RWB they are associated with, as well as the position of the surface cyclone relative to the breaking in the AWB case. The different evolutions are shown schematically in Fig.~\ref{fig:fig11}.

For anticyclones, we find that in both types of life-cycles, the anticyclone is initially to the east of the cyclone, and the anomalous upper-level velocity is dominated by an anticyclonic

circulation. However, there are major differences between the two cases. First, the anticyclone and the upper-level ridge are in the anticyclonic side of the jet in AWB, and in the cyclonic side of the jet in CWB. Moreover, it is the downstream trough that deepens in the AWB composites, while it is the upstream one in the CWB composites. Lastly, the relative rotation is anticyclonic during AWBs, while it is cyclonic during CWBs. The two types of life-cycles are shown schematically in Fig.~\ref{fig:fig11}a and Fig.~\ref{fig:fig11}b, respectively.

For cyclones, comparing the cyclones during CWB to cyclones to the S of AWB, we find that in both cases the cyclone is initially to the east of the anticyclone, and the anomalous upper-level velocity is dominated by a cyclonic circulation. However, we find a downstream ridge development and cyclonic relative rotation in the CWB case, and an upstream ridge development and an anticyclonic relative rotation in the AWB case. The two types of life-cycles are shown schematically in Fig.~\ref{fig:fig11}c and Fig.~\ref{fig:fig11}d, respectively.

To address the third question posed in the introduction, we compare our results with the idealized life-cycles studied in the literature. We note that in our RWB decomposition, AWB includes both LC1 and P2 type breaking events, while CWB includes both LC2 and P1 type breaking events. We find that the life-cycles of both cyclones and anticyclones during AWB are similar to the later stages of the idealized theoretical LC1 wave life-cycle (see day 6 and onwards in Fig.6 of \citet{Thorncroft1993}, hereafter THM). In both, the dominant motion is a relative anticyclonic rotation of the upstream cyclone and downstream anticyclone.

For the CWB cases, in our results, the dominant evolution is a poleward motion of the anticyclone to the east which is wrapping cyclonically around the cyclone. This is similar to the idealized LC2 life-cycle experiments shown in \citet{Davies1991}, but is different from the LC2 life-cycle of THM, in which the dominant evolution is an equatorward motion of the anticyclones to the west (see their Fig.9).

The general similarity to the idealized life-cycles is not a priori obvious, given that in the idealized simulations the initial perturbation is a pure zonal wave and breaking type is controlled artificially (e.g., by changing the background meridional shear). It is consistent, however, with the fact that the observed RWB is typically found where the background meridional shear is of similar sense.

%For the CWB cases, the poleward motion as part of a cyclonic wrapping of the anticyclone around the cyclone is similar to the idealized LC2 life-cycle experiments shown in \citet{Davies1991}, but is different from the LC2 life-cycle of THM, in which the anticyclones to the west are those that wrap cyclonically around the cyclones by moving equatorward (see their Fig.9).

%\citet{Davies1991} also studied an LC3 life-cycle, in which extra anticyclonic shear was added to the initial state, resulting in ***

%{\color{blue} the surface systems evolve from a pure zonal wave rather than as isolated cyclones and anticyclones.}

%THM the anticyclones to the west of the cyclones move equatorward and are wrapped cyclonically around the cyclones, while in our CWB composites it is the anticyclone to the east of the cyclone that moves poleward.

%LC2 wave life-cycle of THM (see their Fig.9) shows a rather different surface system configuration compared to what we find. In both cases, the relative rotation between the cyclone and the anticyclone is cyclonic. However, in THM the anticyclones to the west of the cyclones move equatorward and are wrapped cyclonically around the cyclones, while in our CWB composites it is the anticyclone to the east of the cyclone that moves poleward. Interestingly, the LC2 life-cycle in XX is consistent with our results.

%The time evolution of composites centered on anticyclones during AWB events shows, prior to the breaking, a low-level anticyclone to the east of a strong upper-level ridge (i.e., with a baroclinic structure), which resides in the anticyclonic side of the jet (see Fig.~\ref{fig:fig11} for a schematic illustration of the upper and lower flow evolution). A low-level cyclone is found initially to the west of the anticyclone, and during the evolution of the breaking the cyclone-anticyclone pair rotate in an anticyclonic manner relative to each other, such that we find a negative SLP poleward of a positive SLP anomaly by the end of the life-cycle. At upper-levels, the trough to the east of the initial ridge grows and then wraps anticyclonically around the ridge. Consistently, the upper-level jet is split into an upstream tilted jet, and a downstream zonal and more southward jet. In this case, the anomalous anticyclonic circulation associated with the ridge is acting to reinforce the anticyclonic shear, contributing to the anticyclonic rotation of the system.

%The time evolution of composites centered on cyclones during CWB events shows, prior to the breaking, a low-level cyclone to the east of a strong upper-level trough, which resides in the cyclonic side of the jet (see Fig.~\ref{fig:fig11}). A low-level anticyclone is found initially to the west of the cyclone, which weakens and disappears while rotating cyclonically (southeastward) around the cyclone. An additional low-level anticyclone and an upper-level ridge develop downstream, to the east of the cyclone, and during the evolution of the breaking the whole system rotates in a cyclonic manner relative to each other, such that a positive SLP anomaly is found poleward of a negative SLP anomaly by the end of the life-cycle. As the ridge wraps cyclonically around the trough, a strong negative anomalous wind is generated, such that the total zonal flow is decelerated poleward of the breaking center. The anomalous cyclonic circulation associated with the upper-level trough is acting to reinforce the cyclonic shear, contributing to the cyclonic rotation of the system.

%In addition, a mechanistic interpretation is suggested here for the poleward shifted jet associated with AWB events, in which the shift is a result of the anticyclonic and cyclonic rotations of the ridge-trough system, and for the equatorward shifted jet associated CWB events, respectively, in which the shift is a result of the cyclonic rotations of the trough-ridge system. To see this, consider a linear wave composed of ridges and troughs superimposed on a background jet. While each anomalous ridge could contribute, in a zonally averaged sense, to a poleward shift of the jet by strengthening the total zonal flow poleward the ridge, and

weakening equatorward of it (and opposite for an anomalous trough), a linear wave composed of ridges and troughs, would not contribute to any net shifts of the zonal mean jet, since these effects would cancel out. However, the nonlinearity results in an anticyclonic wrapping of the trough around the ridge for AWB, and a cyclonic wrapping of the ridge around the trough for CWB, which breaks the zonal and meridional symmetries. For AWB, it favors a negative anomalous meridional wind between the ridge and the trough to its east, and a negative anomalous zonal wind due to the anticyclonic rotation of the trough around the ridge (i.e., to its southeast). For CWB, it favors a positive anomalous meridional wind between the trough and the ridge to its east, and a negative anomalous zonal wind due to the cyclonic rotation of the ridge around the trough (i.e., to its northeast). Crucially, these anomalous southwestward and northwestward velocities (for AWB and CWB, respectively) do not average out in the zonal mean. Note that these anomalous velocities ($v'<0$ and $u'<0$ for AWB and $v'>0$ and $u'<0$ for CWB), are exactly those that constitute the positive (negative) momentum fluxes, which theoretically are associated with a poleward (equatorward) shift of the mean zonal jet in AWB (CWB). Similar argument are commonly used to describe the weakening of the jet in the core of the block and the poleward or equatorward deflections of the jet during blocking events, which are also closely related to RWB events (\citealp{Tyrlis2008,Woollings2008}). Moreover, the upstream cyclones found to the W of the anticyclone during both AWBs and CWBs is related to the upstream cyclone theory suggested for block onset mechanism (\citealp{Colucci1985,Lupo1995}).

%Nonetheless, taking into account the latitudinal motion of the storms shows that while AWB events indeed end-up with a more poleward shifted upper-level jet, the jet during CWB seems to remain at the same (equatorward shifted to begin with) latitude.

%Finally, anomalous life-cycles of cyclones and anticyclones are found, by centering the composites around the anticyclones during CWBs, and around cyclones during AWBs (where the latter is further separated into cyclones residing to the N or S of the AWB center). In all cases, the shear of the total upper-level zonal flow is determining the overall relative rotation, and therefore the type of breaking. For example, anticyclones during CWB reside in the 'wrong' (cyclonic) side of the jet, and therefore experience an atypical life-cycle. Cyclones to the S of the AWB center (e.g., over the Mediterranean region) are strongly influenced by an upper-level anticyclonic circulation, and therefore experience an atypical life-cycle of cyclones, which are usually dominated by an upper-level trough. This motivates further research on the propagation characteristics and growth mechanisms of Mediterranean cyclones compared to Atlantic cyclones.

Taken together, our analysis helps put together the results obtained from idealized life-cycle studies and observational case-studies to obtain a more coherent picture of the relation between RWB and surface weather systems in the North Atlantic.
Note that the methods used in the current study can be easily applied to other regions, e.g., the Pacific storm track or the Southern Hemisphere storm track, where we also expect to find different surface-system and RWB configurations.

%give a more general picture of the relation between RWB and surface weather systems in the North Atlantic, that can't be obtained from idealized life-cycle studies or isolated test cases, and it helps put various studies of observed sub-classes of cyclones or anticyclones into a more general perspective.

%Taken together, our results give a more general picture of the relation between RWB and surface weather systems in the North Atlantic, that can't be obtained from idealized life-cycle studies or isolated test cases, and it helps put various studies of observed sub-classes of cyclones or anticyclones into a more general perspective.

The classification into different sub-classes of cyclones or anticyclones based on configurations of storm signs and RWB types and their corresponding storm life-cycles may have a few potential implications.

Given that the time evolutions of the different subsets involve different wave-mean flow interactions and jet shifts, and different storm characteristics such as intensities, positions and displacements, correctly identifying them may help improve weather prediction of subsequent storm development.

For example, the upstream cyclones found to the W of anticyclones during both AWBs and CWBs may fall under the upstream cyclone theory suggested for block onset mechanism (\citealp{Colucci1985,Lupo1995}). \citet{Maddison2019} examined the role of the upstream cyclone on the predictability of block onsets over the Euro-Atlantic Region. They showed that block onset in the case studies is sensitive to changes in the forecast location and intensity of upstream cyclones in the days preceding the onset, and concluded that improvement in the forecasts of the upstream cyclone may help improve block onset forecasts. The upstream cyclone and developing downstream block may involve either a CWB or an AWB (or both, for an omega-type block).

The subset of cyclones to the S of AWB may be relevant to studies which discuss the influence of antecedent AWB events on subsequent tropical, subtropical, or Mediterranean cyclone development (e.g., \citealp{Appenzeller1996,Davis2010,Galarneau2015,Flaounas2015,Bentley2017,Portmann2021,Flaounas2022}).

It would be interesting to investigate if similar results are obtained, e.g., in a zonally symmetric storm track, or whether some of these findings are shaped by the stationary waves in the North Atlantic.

Another interesting future direction is to incorporate circulation regimes in the North Atlantic, which are recurrent and persistent regimes of the atmospheric circulation. Given that storm characteristics (such as positions, propagation directions, and displacements) are found to alter significantly with the breaking type, and that different North Atlantic weather regimes are largely characterized by different types of wave breaking events, occurring in distinct geographical positions (e.g., \citealp{Swenson2017}), we expect the weather regimes to influence, and be influenced by, the cyclone and anti cyclone life-cycles. The three-way interaction between the storm tracks, RWBs, and the low-frequency flow representing the weather regime is left for further study, but initial results show that distinct and clearly

preferred storm paths, associated RWB positions, and resulting interactions with the low-frequency flow can be found for different weather regimes.
An improved understanding of the relation between storms, RWB events, and weather regimes can also help us improve our understanding of and confidence in projected future circulation changes (e.g., by relating changes in the frequency and positions of RWB events, storm tracks, and the North-Atlantic jet).

%, to examine more deeply the interaction among scales between the high frequency, synoptic-scale weather system, and the low-frequency circulation, and how it is mediated by RWB events.

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\begin{figure*}
%\begin{centering}
\includegraphics[width=18cm]{fig1_new.eps}
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\caption{
Examples of an (a) Anticyclonic Rossby Wave Breaking (AWB), and (b) Cyclonic Rossby Wave Breaking (CWB) event. Shown are the upper-level (250~hPa) Potential Vorticity (PV) in PV Units (PVU, 1 PVU=$10^{-6}\rm{Kkg^{-1}m^2s^{-1}}$) (grey shading), the 250~hPa zonal flow $\rm{U}$ (green contours), and the low-level (850~hPa) tracks of cyclones (blue lines) and anticyclones (red lines), based on ERAI reanalysis data, for (a) Dec 7 1981 00UTC, and (b) Dec 11 1981 18UTC. The blue (red) dots denote the location of the cyclones (anticyclones) at the moment of the breaking, while the triangles denote the origin of the track. The centroid of the AWB (CWB) is denoted by a star (diamond), and the black line denotes the 2.5 (5.5) PVU contour. The lowest contour of $\rm{U}$ is equal to 30 m $\rm{s}^{-1}$ and the contour spacing is 10 m $\rm{s}^{-1}$.
Panels (c) and (d) show the time-mean upper-level (250~hPa) zonal flow $\rm{U}$ (colors) together with the Probability Density Functions (PDFs) (calculated using a kernel density estimator and multiplied by the number of events in each case) of AWB and CWB centers, respectively, with lowest contour equal to 0.4 and contour intervals of 0.25.
\label{fig:fig1}}
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\begin{figure*}[t]
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\includegraphics[width=18cm]{fig2_revised.eps}
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\caption{
Composites of AWB (a,b) and CWB (c,d) events in the North Atlantic region, based on ERA-Interim reanalysis data, which occurred over the years 1980-2014 during December-February (DJF). Panels (a),(c) show the upper-level (250~hPa) PV field (in PVU, colors) and the 850~hPa vorticity anomaly (in 10^{-5} s^{-1}, black contours), while panels (b),(d) show the upper-level (250~hPa) zonal flow (in m s^{-1}, colors) and the SLP anomaly (in hPa, black contours), where the arrows denote the corresponding upper-level velocities. L_y and L_x denote the relative latitudinal and longitudinal distance (in degrees), respectively, from the center of the breaking. The black thick line in AWB (CWB) denotes the 3 (5) PVU contour. The lowest vorticity (SLP) anomaly contour is 0.15 (1), and the contour intervals are 0.1 (1).
\label{fig:fig2}}
\end{figure*}

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\begin{figure*}[t]
%\begin{centering}
\includegraphics[width=18cm]{fig3_revised_all.eps}
%\par\end{centering}
\caption{
The positions of cyclones (a,c) and anticyclones (b,d) during AWB (first row) and CWB (second row), relative to the center of the RWB event (given by the cross symbol).
Color indicates the intensity of the system (in absolute value) as identified by the tracking algorithm, in units of $10^{-5} \rm{s}^{-1}$, and only systems with intensities larger than $2\cdot10^{-5} \rm{s}^{-1}$ are plotted. L_y and L_x denote the relative latitudinal and longitudinal distance (in degrees), respectively, from the center of the breaking. The black thick line in the composites of AWB (CWB) denotes the 3 (5) PVU contour, while the thin lines denote the corresponding PDF (calculated using a kernel density estimator and multiplied by the number of storms in each case) of the storm centers, with lowest contour equal to 1.7 and contour intervals of 0.5.
\label{fig:fig3}}
\end{figure*}

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\begin{figure*}[t]
%\begin{centering}
\includegraphics[width=18cm]{fig4_revised_all_separated.eps}
%\par\end{centering}
\caption{
The actual spatial distributions of cyclones (a,c) and anticyclones (b,d) during AWB (first row) and CWB (second row), where color indicates the intensity of the system (in absolute value) in units of $10^{-5} \rm{s}^{-1}$, and only systems with intensities larger than $2\cdot10^{-5} \rm{s}^{-1}$ are plotted. Thick black contours denote the PDFs of the storm counts (calculated

using a kernel density estimator and multiplied by the number of storms in each case), showing the locations where storms are most found. In panel (a), the PDFs are separated into cyclones residing to the north of the AWB center (black thick contours) and cyclones residing to the south of the AWB center (gray thick contours). The lowest contour is equal to 0.6 and the contour intervals are 0.25. For reference, the thin black contours show the PDFs of AWB (panels a,b) and CWB (panels c,d) as in Fig.~1c,d, with lowest contour is equal to 0.4 and contour intervals equal to 0.25. The magenta star (diamond) denotes the location where AWB (CWB) centroids are most frequently found.
%Overall, there are 3,681 anticyclones during CWB, 4,131 anticyclones during AWB. In addition, there are 4,216 cyclones during CWBs and 5,106 cyclones during AWB, of which 2,922 to the north and 2,184 are to the south of the CWB center.
Overall, there are 5,106 cyclones during AWB, of which 2,922 to the north and 2,184 are to the south of the AWB center (panel a). In addition, there are 4,216 cyclones during CWBs (panel c), 4,131 anticyclones during AWB (panel b), and 3,681 anticyclones during CWB (panel d).
The same storms and RWB events are used to produce Fig.~3.
\label{fig:fig4}}
\end{figure*}

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\begin{figure*}[t]
%\begin{centering}
\includegraphics[width=18cm]{fig5_revised_new_option3.eps}
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\caption{
Storm characteristics during AWB and CWB events. Fitted histogram lines showing the distribution of the intensity (absolute value, in units of $10^{-5} \rm{s}^{-1}$) (a,f), longitudinal positions (in degrees) (b,g), latitudinal positions (in degrees) (c,h), longitudinal displacements (in degrees) (d,i) and latitudinal displacements (in degrees) (e,j) of the cyclones (first row) and anticyclones (second row) during RWB events, for the same storms shown in Fig.~\ref{fig:fig3} and Fig.~\ref{fig:fig4}. For cyclones, these are separated into cyclones during CWB (thin black lines) and cyclones during AWB (thick black lines), where the latter are further separated into cyclones to the north (N) of AWB (red dashed lines) and cyclones to the south (S) of AWB (dotted dashed blue lines). For anticyclones, the separation is only between anticyclones during CWB (thin black lines) and anticyclones during AWB (thick black lines).
%Overall, there are 3,176 (4,960) anticyclones and 5,000 (3,372) cyclones found during AWB (CWB), where 2,704 cyclones are found 5° to the north and 2,296 cyclones are found 5° to the south of the AWB centroid.
%Overall, there are 5,106 cyclones during AWB, of which 2,922 to the north and 2,184 are to the south of the CWB center, and 4,216 cyclones during CWBs (panel a), while there are 4,131 anticyclones during AWB and 3,681 anticyclones during CWB (panel d).
The displacements are calculated as the difference between the position two days after the breaking, minus the position two days prior to the breaking, so only cyclones and anticyclones

lasting for more than 5 days are used in this case (but similar results are found for displacements calculated in different manners).
Hence, in panels (d),(i),(e) and (j), only 1,101 cyclones during AWB are used, where 635 cyclones reside to the north and 657 cyclones reside to the south of the AWB centroid. In addition, only 1292 cyclones during CWB, 640 anticyclones during AWB and 680 anticyclones during CWB are used.
\label{fig:fig5}}
\end{figure*}

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\begin{figure*}[t]
%\begin{centering}
\includegraphics[width=18cm]{fig6}
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\caption{
Composites of cyclones and anticyclones in the North-Atlantic. Upper-level (250~hPa) total PV (colors, in PVU) and PV anomaly (thin contours) centered around cyclones (a,c) and anticyclones (b,d) in the North-Atlantic region (30N-60N and 80W-20E) at the time of maximum intensity. The black contours show the frequency of AWB (a,b) and CWB (c,d) relative to the center of the storms.
L_y and L_x denote the relative latitudinal and longitudinal distance (in degrees), respectively, from the center of the storms. The thick black line denotes the 4.5 PVU contour in panels (a) and (c) , while it denotes the 5.5 PVU contour in panels (b) and (d). The percentages in each panel denote the percentage of storms in each composite with the corresponding RWB sense occurring sometime during their lifetime.
\label{fig:fig6}}
\end{figure*}

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\begin{figure*}[t]
%\begin{centering}
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\caption{
Same-sense storm vorticity and RWB type (anticyclones during AWBs). Composites centered on anticyclones during AWB events, showing the time evolution of AWB in the North Atlantic region, from three days prior to the breaking ($T=-3$), and up to two days after the breaking ($T=2$). Shown are the upper-level (250~hPa) PV in PVU (colors) and the SLP anomaly in hPa (contours) (first row), the upper-level (250~hPa) zonal wind in m s^{-1} (colors) and SLP anomaly in hPa (contours) (second row), and the upper-level (250~hPa) meridional wind in m s^{-1} (colors) and upper-level PV anomaly in PVU (contours) (third row). The arrows in

panels (f-j) show the full upper-level velocities, while in panels (a-e) and (k-o) the anomalous upper-level velocities are shown. L_y and L_x denote the relative latitudinal and longitudinal distance (in degrees), respectively, from the center of the anticyclone. In all panels, the black line denotes the 3.2 PVU contour. The lowest contour for the SLP (PV) anomalies is 1 (0.1), while the contour interval is equal to 1 (0.2), where solid contours denote positive values and dashed contours denote negative values.
\label{fig:fig7}}
\end{figure*}

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\begin{figure*}[t]
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\includegraphics[width=18cm]{fig8_new}
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\caption{
Cross sections of the composite upper-level (250~hPa) (a) total, (b) anomalous (deviation from time mean), and (c) climatological zonal wind (in units of m $\rm{s}^{-1}$), at the longitude crossing the center of the anticyclones during AWB events. Panels (d), (e) and (f) show the same fields, but for cyclones during CWB events. The colors indicate the time, going from black (three days prior to the breaking), to blue (two days after the breaking). L_y is the relative latitudinal distance (in degrees) from the center of the breaking.
\label{fig:fig8}}
\end{figure*}

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\begin{figure*}[t]
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\includegraphics[width=18cm]{fig9}
%\par\end{centering}
\caption{
Same-sense storm vorticity and RWB type (cyclones during CWBs). Same as Fig.~\ref{fig:fig7}, but for composites centered on cyclones during CWB events, showing the time evolution of CWB in the North Atlantic region. In all panels, the black line denotes the 5.8 PVU contour.
\label{fig:fig9}}
\end{figure*}

\clearpage

\begin{figure*}[t]

%\begin{centering}
\includegraphics[width=18cm]{fig10_new.eps}
%\par\end{centering}
\caption{
Opposite-sense storm vorticity and RWB type. Composites centered on anticyclones residing to the northeast (NE) of the breaking center during CWB events (a-e), and around cyclones residing to the north (N) (f-j) and to the south (S) (k-o) of AWB in the North Atlantic region, from three days prior to the breaking ($T=-3$), and up to two day after the breaking ($T=2$). Shown are the upper-level (250~hPa) zonal wind (colors) in m s^{-1} and the SLP anomaly in hPa (contours), while the arrows denote the anomalous upper-level velocities.
L_y and L_x denote the relative latitudinal and longitudinal distance (in degrees), respectively, from the center of the breaking. The black thick line denotes the 4.5 PVU contour in panels (a-e), the 3 PVU contour in panels (f-j), and the 3.5 PVU contour in panels (k-o).
\label{fig:fig10}}
\end{figure*}

\clearpage

\begin{figure*}[t]
%\begin{centering}
\includegraphics[width=18cm]{schematic_fig.jpg}
%\par\end{centering}
\caption{
A schematic illustration showing the composite mean evolution of the upper- and lower-level circulation associated with anticyclones (AC, first row) and cyclones (C, second row) during AWB and CWB events. The left column correspond to the "same-sense" storm vorticity and RWB composites of (a) anticyclones during AWB events, and (c) cyclones during CWB events, while the right column correspond to the "opposite-sense" storm vorticity and RWB composites of (b) anticyclones to the North East (NE) of CWB events, and (d) cyclones to the South (S) of AWB events.
%The large black arrows on the left represent the background jet and the corresponding shear. The black solid line denotes a representative upper level PV contour in each case.
The 'H' and 'L' symbols represent the surface anticyclone and cyclone, respectively, while the 'R' and 'T' symbols represent the upper-level ridge and trough, respectively. The solid red and blue circles represent the cyclonic and anticyclonic anomalous upper level winds, respectively, while the dashed red and blue circles represent the relative rotation between the pressure anomalies. The schematic summarizes the main composite life-cycle evolutions: for same-sense storm vorticity and RWB type cases (a and c), the breaking and relative rotation are in the same sense as the storm circulation, while for the opposite-sense cases (b and d), the breaking and relative rotation are in the opposite sense to the storm circulation.
\label{fig:fig11}}
\end{figure*}

%% Since the Copernicus LaTeX package includes the BibTeX style file copernicus.bst,

%% authors experienced with BibTeX only have to include the following two lines:
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%% \bibliography{example.bib}
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%%
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%% DOI = {10.5194/xyz}

%% LITERATURE CITATIONS
%%
%% command   & example result
%% \citet{jones90}| & Jones et al. (1990)
%% \citep{jones90}| & (Jones et al., 1990)
%% \citep{jones90,jones93}| & (Jones et al., 1990, 1993)
%% \citep[p.~32]{jones90}| & (Jones et al., 1990, p.~32)
%% \citep[e.g.,][]{jones90}| & (e.g., Jones et al., 1990)
%% \citep[e.g.,][p.~32]{jones90}| & (e.g., Jones et al., 1990, p.~32)
%% \citeauthor{jones90}| & Jones et al.
%% \citeyear{jones90}| & 1990

%% FIGURES

%% When figures and tables are placed at the end of the MS (article in one-column style), please add \clearpage
%% between bibliography and first table and/or figure as well as between each table and/or figure.

% The figure files should be labelled correctly with Arabic numerals (e.g. fig01.jpg, fig02.png).

%% ONE-COLUMN FIGURES

%%f
%\begin{figure}[t]
%\includegraphics[width=8.3cm]{FILE NAME}
%\caption{TEXT}
%\end{figure}
%
%%% TWO-COLUMN FIGURES

```
%
%%f
%\begin{figure*}[t]
%\includegraphics[width=18cm]{FILE NAME}
%\caption{TEXT}
%\end{figure*}
%
%
%%% TABLES
%%%
%%% The different columns must be seperated with a & command and should
%%% end with \\ to identify the column brake.
%
%%% ONE-COLUMN TABLE
%
%%t
%\begin{table}[t]
%\caption{TEXT}
%\begin{tabular}{column = lcr}
%\tophline
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%\middlehline
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%\bottomhline
%\end{tabular}
%\belowtable{} % Table Footnotes
%\end{table}
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%%% TWO-COLUMN TABLE
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%\begin{table*}[t]
%\caption{TEXT}
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%\end{tabular}
%\belowtable{} % Table Footnotes
%\end{table*}
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%%% LANDSCAPE TABLE
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%
%%t
%\begin{sidewaystable*}[t]
%\caption{TEXT}
%\begin{tabular}{column = lcr}
%\tophline
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%\middlehline
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%\bottomhline
%\end{tabular}
%\belowtable{} % Table Footnotes
%\end{sidewaystable*}
%
%
%%% MATHEMATICAL EXPRESSIONS
%
%%% All papers typeset by Copernicus Publications follow the math typesetting regulations
%%% given by the IUPAC Green Book (IUPAC: Quantities, Units and Symbols in Physical Chemistry,
%%% 2nd Edn., Blackwell Science, available at:
http://old.iupac.org/publications/books/gbook/green_book_2ed.pdf, 1993).
%%%
%%% Physical quantities/variables are typeset in italic font (t for time, T for Temperature)
%%% Indices which are not defined are typeset in italic font (x, y, z, a, b, c)
%%% Items/objects which are defined are typeset in roman font (Car A, Car B)
%%% Descriptions/specifications which are defined by itself are typeset in roman font (abs, rel, ref, tot, net, ice)
%%% Abbreviations from 2 letters are typeset in roman font (RH, LAI)
%%% Vectors are identified in bold italic font using \vec{x}
%%% Matrices are identified in bold roman font
%%% Multiplication signs are typeset using the LaTeX commands \times (for vector products, grids, and exponential notations) or \cdot
%%% The character * should not be applied as mutliplication sign
%
%
%%% EQUATIONS
%
%%% Single-row equation
%
%\begin{equation}
%
%\end{equation}
%
```

```
%%% Multiline equation
%
%\begin{align}
%& 3 + 5 = 8\\
%& 3 + 5 = 8\\
%& 3 + 5 = 8
%\end{align}
%
%
%%% MATRICES
%
%\begin{matrix}
%x & y & z\\
%x & y & z\\
%x & y & z\\
%\end{matrix}
%
%
%%% ALGORITHM
%
%\begin{algorithm}
%\caption{...}
%\label{a1}
%\begin{algorithmic}
%...
%\end{algorithmic}
%\end{algorithm}
%
%
%%% CHEMICAL FORMULAS AND REACTIONS
%
%%% For formulas embedded in the text, please use \chem{}
%
%%% The reaction environment creates labels including the letter R, i.e. (R1), (R2), etc.
%
%\begin{reaction}
%%% \rightarrow should be used for normal (one-way) chemical reactions
%%% \rightleftharpoons should be used for equilibria
%%% \leftrightarrow should be used for resonance structures
%\end{reaction}
%
%
%%% PHYSICAL UNITS
%%%
```

%%% Please use \unit{} and apply the exponential notation

\end{document}

the arrangement of anomalies is a standard argument in the "blocking" community, i.e., to describe the weakening of the jet in the core of the block and the poleward/ equatorward deflection of the jet.