Quantifying the climatological relationship between extratropical cyclone intensity and atmospheric precursors

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We introduce a novel technique in which linear regression analysis is applied to clusters of tracked cyclones to statistically assess the factors controlling cyclone development. We illustrate this technique by evaluating the differences between cyclones forming in the west and east North Atlantic (herein termed west and east Atlantic cyclones). Enhanced cyclone intensity two days after genesis is found to be associated with deeper upper-level troughs upstream of the cyclone center at the genesis time in both west and east Atlantic cyclones. However, whilst west Atlantic cyclones are also enhanced by the presence of strong fronts, east Atlantic cyclones are not. Instead, east Atlantic cyclones exhibit an enhancement when diabatically-generated mid-level potential vorticity is present (with the enhancement being of approximately equal magnitude to that associated with the potential vorticity in the upper-level trough). This is consistent with the paradigm of latent heat release in the warm conveyor belt region playing an important role in the development of east Atlantic cyclones.

1. Introduction

Extratropical cyclogenesis often occurs when a shortwave upper-level pressure trough interacts with a low-level temperature gradient. These conditions are prevalent near the east coast of the US where the upper-level flow is disturbed by the underlying orography, and the land-sea temperature contrast and Gulf Stream create a low-level temperature gradient. As a result, large numbers of cyclones are initiated in the west North Atlantic and are then steered, by the westerly winds, across the North Atlantic reaching western Europe in their decaying stage. By contrast, most of the cyclones that lead to severe wind damage and flooding in Europe are in their developing stage and are generated in the east North Atlantic region where frontal gradients are weaker (e.g. Dacre and Gray [2009]).

Whilst the locations of North Atlantic cyclones are generally well forecast, statistical analysis suggests that there is often a bias towards underestimating their intensity and propagation speed. Froude [2010] showed that there is a bias such that storms propagate too slowly in the forecasts of all of the ensemble prediction systems stored in the TIGGE archive and intensity is underpredicted in the forecasts of most of the ensemble prediction systems. (TIGGE is The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble). These errors may be due to errors in the storms’ vertical potential vorticity (PV) structure. For example, Stoebling [1996] showed in his case study that latent heating was responsible for creating a significant positive PV anomaly above the surface warm front. This PV anomaly enhanced the eastward propagation of the surface wave and slowed the propagation of the upper-level wave thus keeping the upper-level PV wave coupled to the low-level surface wave. Diabatically generated mid-level positive PV anomalies (where mid-level is here defined as approximately between 800 hPa and 500 hPa) can also be associated with enhanced upper-level divergence which expands the downstream ridge leading to the formation of a narrow and deep tropopause fold [Possett and Martin, 2004; Ahmad-Givi et al., 2006]. Stospheric PV anomalies can then merge with the diabatically produced mid-level PV features to form a vertically aligned tower of PV. Davis [1992] and Wernli et al. [2006] both showed that the superposition of stratospheric PV anomalies and moisture-induced mid-level PV core enhance cyclone intensity. Finally, Plant et al. [2003] showed that mid-level PV anomalies, generated in response to latent heating, were important for the development of two so-called type C cyclones. Type C cyclones are characterized by strong (quasi-geostrophic) upper-level forcing, very weak low-level forcing and a vertical upstream tilt that remains constant or increases as the cyclone matures [Deeveson et al., 2002]. Dacre and Gray [2009] found, in a six-year climatology of North Atlantic cyclones, that a larger proportion of east than west Atlantic cyclones showed characteristics of type C development (39% compared to 25%), consistent with the generally weaker low-level frontal gradients in the east North Atlantic. Here we statistically assess the association between the diabatically generated mid-level PV at genesis time and the cyclone intensity 48 hours later for east and west Atlantic cyclones and so test the hypothesis that diabatically-generated mid-level PV may particularly contribute to the development of east Atlantic cyclones.

Various methods have been used to test the sensitivity of forecasts to latent heat release. For example, Langland et al. [1996] used an adjoint model to show how favorably positioned latent heat release was an ingredient that could lead to explosive baroclinic development in their idealized cyclone. Similarly Smith [2000] showed that horizontal heating distributions that differ by small amounts can yield changes in vorticity tendency that can contribute to either development or decay of the underlying cyclone. The sensitivity of cyclone forecasts to finite-amplitude initial PV anomalies was investigated by Beare et al. [2003] using a non-linear 3D quasi-geostrophic model. They found that the most sensitive regions for cyclone intensity changes were at the steering level, over the cold and warm fronts (and remote from the cyclone centre), with positive PV anomalies in these regions giving, respectively, deepening and filling. Whilst all of these methods demonstrate the potential importance of latent heating for cyclone intensification in individual case studies or idealized modeling simulations, there has not been, to the authors’ knowledge, a statistical evaluation of this process in a climatology of cyclones.

Here we introduce a novel technique which combines cyclone tracking and compositing with linear regression analysis, to enable a statistical evaluation of the relationship between extratropical cyclone intensity and a precursor field (such as PV at genesis time) in North Atlantic cyclones.
2. Method

Following the work by Catto et al. [2010], an objective feature tracking algorithm [Hodges, 1994, 1995] has been applied to the six-hourly European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, ERA-Interim, [Dee et al., 2011]. The data covers the period from March 1989 to February 2009. Tracks are identified using the 850 hPa relative vorticity truncated to T42 resolution to emphasize the synoptic scales. Tracks with genesis regions in the east and west Atlantic are selected where the east Atlantic is defined as 10–45°W, 40–55°N and the west Atlantic is defined as 80–55°W, 30–50°N. These regions were selected using plots of the genesis density for all cyclone tracks (not shown).

The required precursor field is then extracted from the ERA-Interim dataset for the selected cyclones within a specified radius surrounding the identified track position. Here the data are extracted at genesis time at 1° grid spacing on a grid of 360 degrees in angle by 2° in radius and 25 levels from 1000-150 hPa. (Note that the data shown in the figures only extends to 15° in radius for clarity). Following Catto et al. [2010], the precursor fields are rotated according to the true direction of travel of each cyclone such that the direction of travel becomes eastward.

The sensitivity of the intensities of the cyclones to the precursor field is then calculated at all gridpoints for the east and west Atlantic cyclone clusters yielding two three-dimensional sensitivity maps for each precursor. Following the ensemble sensitivity method of Garcia et al. [2009] a response function, $J$, is defined; here we use the cyclone intensity (defined as 850 hPa T42-truncated relative vorticity) 48 hours after genesis. A linear regression is calculated at each spatial grid point, $(i,j,k)$, between the values of the response function and difference, $x$, of precursor field from the mean value (over the cluster members), yielding a regression coefficient for the slope of

$$m_{ijk} = \left( \frac{\partial J}{\partial x} \right)_{ijk}.$$ 

A correction factor is applied to filter out weak correlations from the final sensitivity product:

$$\alpha_{ijk} = \begin{cases} 1 & \text{if } r_{ijk}^2 \geq r_{\text{min}}^2 \\ \frac{r_{ijk}^2}{r_{\text{min}}^2} & \text{if } r_{ijk}^2 < r_{\text{min}}^2. \end{cases}$$

where $r_{ijk}$ is the correlation coefficient and $r_{\text{min}}$ is the minimum correlation coefficient for which the raw sensitivities remain unaltered. The value of $r_{\text{min}}$ is set to control the weighting given to sensitivity information at gridpoints at which the regression has a poor correlation coefficient. It is set to 0.05 here which, for example, leaves 5568 of the 180000 gridpoints (3.1%) in the field of sensitivity to PV at genesis time completely uncorrected (i.e. $\alpha_{ijk} = 1$) for east Atlantic cyclones. Although the correction factor thus modifies the large majority of the of the sensitivity values, strong coherent sensitivity signals are retained since large correlation coefficients are preferentially associated with large slope magnitudes in the the data. The standard deviation, $\sigma_{ijk}$, of the precursor field at each gridpoint is calculated from the combined west and east Atlantic datasets. This ensures that sensitivity values for east and west Atlantic cyclones are directly comparable. Finally, the sensitivity, $S_{ijk}$, is given by

$$S_{ijk} = m_{ijk} \alpha_{ijk} \sigma_{ijk}.$$ 

Multiplication of the regression coefficient by the standard deviation means that the units of $S_{ijk}$ are the same as those of $J$ (s$^{-1}$ in this case) and the resulting sensitivity at a gridpoint can then be interpreted as the change in $J$ associated with a one standard deviation increase in the precursor field at that gridpoint. This is a very desirable feature of the method as it allows the sensitivity to different precursor fields to be directly compared. Following previous literature on the ensemble sensitivity method (e.g. Garcia et al. [2009]) we describe the response function as being sensitive to a precursor field but note that mathematically only an association is found and the inference of sensitivity relies on a postulated dynamical mechanism. Note also, that the diagnosis of sensitivity to a particular field in a region relies on the cluster of cyclones including a spread of values in that region.

Sensitivity calculations have been performed for the precursor fields of PV and equivalent potential temperature ($\theta_e$) anomaly; the $\theta_e$ anomaly is calculated by subtracting the mean $\theta_e$ field, averaged over the 20° radius, for each individual cyclone from the $\theta_e$ field for each cyclone at each level and is used in this paper as a measure of the strength of the frontal gradient. An orography mask was applied to the calculated PV to exclude erroneous values obtained where the pressure levels were below the orography (especially noticeable over Greenland).

3. Cyclone intensification and composite structure

There are 644 west Atlantic cyclones and 296 east Atlantic cyclones identified in the 20 years of ERA-Interim data. The cyclone identification algorithm uses a minimum T42 850 hPa relative vorticity (intensity) threshold of $1 \times 10^{-5}$s$^{-1}$ to identify cyclones. Some of these cyclones don’t intensify. Only cyclones that intensify by $>1.5 \times 10^{-5}$s$^{-1}$ and $>1.0 \times 10^{-5}$s$^{-1}$ for west and east Atlantic cyclones respectively are analyzed. These thresholds were chosen to retain a similar percentage of west and east Atlantic cyclones (455 west and 216 east Atlantic cyclones). (The sensitivities have also been computed for the east Atlantic cyclones using a intensity threshold of $1.5 \times 10^{-5}$s$^{-1}$ and the results are very similar – not shown.) Figure 1 shows histograms of cyclone intensity at the genesis time and 48 hours later for all west and east Atlantic cyclones that satisfy the intensification criteria quoted above. The distribution of intensity values at the genesis time is qualitatively similar for west and east Atlantic cyclones. After 48 hours some cyclones have intensified markedly whilst others have intensified rather less. What controls the development and are the controls the same for west and east Atlantic cyclones?

Figure 2 shows the composite cyclone structure for intensifying west and east Atlantic cyclones from ERA-Interim at their genesis time, similar to those in Dacre et al. [2012]. Both west and east Atlantic cyclone composites show cold and warm fronts extending from the surface up to 500 hPa. However the fronts are stronger in the west Atlantic cyclone composite (figures 2(a) and (c)). Both west and east Atlantic cyclones show the presence of an upper-level trough (stratospheric PV values) upstream of the cyclone center (typically to the north-west); however, the trough is deeper (extends to lower levels), and is more wrapped up, in the east Atlantic cyclone composite (figures 2(b) and (e)). A dry slot (low relative humidity values) is evident in both cyclone composites extending from the base of the upper-level trough down to 700 hPa. Both west and east Atlantic cyclone composites show a warm conveyor belt (WCB) flow, with high relative humidity air ascending up over the surface.
4. Dynamical controls on cyclone intensification

4.1. Sensitivity of cyclone development to precursor frontal gradients

Figure 4 shows the composite $\theta_e$ anomaly field at the genesis time. The $\theta_e$ anomaly field is positive in the warm sector, between the cold and warm fronts to the south of the cyclone center, and negative in the cold sector to the north of the cyclone center (figures 4(a) and (d)). Figure 4 also shows the sensitivity of cyclone intensity after 48 hours to the $\theta_e$ anomalies at the genesis time. The sensitivity has a dipole structure in the horizontal at all levels up to 350 hPa, being positive in the warm sector and negative in the cooler air to the north and east. The sense of this dipole is such that an enhanced precursor frontal gradient is associated with more intense cyclones (as would be expected through baroclinic instability). West Atlantic cyclones are much more sensitive than east Atlantic cyclones to the $\theta_e$ anomaly at all levels up to 350 hPa with an increase of one standard deviation in the $\theta_e$ anomaly leading to an increase in intensity of up to $0.8 \times 10^{-4} \text{s}^{-1}$ for the west Atlantic cyclones but only $0.4 \times 10^{-4} \text{s}^{-1}$ for the east Atlantic cyclones.

4.2. Sensitivity of cyclone development to precursor PV

Figure 5 shows the composite PV field at genesis time. Consistent with figure 3, values are low (< 1 PVU) in the troposphere. Figures 5(b) and (e) show that both west and east Atlantic cyclones are sensitive to upper-level PV with an increase of one standard deviation in PV in this region associated with an increase in intensity of up to $0.6 \times 10^{-4} \text{s}^{-1}$. Figure 5(c) and (f) suggest that east Atlantic cyclones are however more sensitive to upper-level PV anomalies associated with precursor tropopause depressions. For west Atlantic cyclones high sensitivity is seen at larger radii than shown in figure 5(c) but are confined to levels above 350 hPa (not shown). In addition, figures 5(a) and (d) show that only the east Atlantic cyclones are strongly sensitive to mid-level PV (here at ~ 700 hPa), particularly in the region where the WCB ascends over the surface warm front, with an increase of one standard deviation in PV here associated with an increase in intensity of up to $0.6 \times 10^{-4} \text{s}^{-1}$ (figure 5(f)). This suggests that mid-level latent heating contributes more positively to the development of east Atlantic cyclones than west Atlantic cyclones.

5. Conclusions

We have used linear regression analysis to quantitatively evaluate the sensitivity of extratropical cyclone intensity to atmospheric precursor fields, specifically frontal gradient and PV at the cyclone genesis time. West Atlantic cyclones are more intense after 48 hours when strong frontal gradients and upper-level troughs are present at the genesis time. This is consistent with type B cyclogenesis in which both low-level and upper-level forcing are important [Petterssen and Smeby, 1971]. East Atlantic cyclones are about half as sensitive to the strength of the frontal zones as west Atlantic cyclones. However, compared with west Atlantic cyclones, their intensity is much more sensitive to the presence of PV in the warm conveyor belt at the genesis time. East Atlantic cyclones are more intense after 48 hours when this mid-level PV and deep upper-level troughs are present at the genesis time (with the sensitivity to the mid-level PV and the PV in the upper-level trough being approximately equal). This is consistent with type C cyclogenesis in which upper-level forcing is important, low-level forcing is weak, and PV anomalies generated by mid-level latent heating contribute to development. Thus it appears that mid-level diabatically-generated PV is more important for enhancing east Atlantic cyclone development than that of west Atlantic cyclones. This is consistent with the higher proportion of type C cyclones found in the east (compared with the west) Atlantic by Dacre and Gray (2009). The greater sensitivity of east Atlantic cyclones to mid-level latent heating implies that they may be more sensitive to changes in climate that affect this process.

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References


Figure 1. Histograms of T42 850 hPa relative vorticity at (a,c) genesis time and (b,d) 48 hours for (a,b) west and (c,d) east Atlantic cyclones.

Figure 2. Composite cyclone structure at genesis time for (a,b,c) west Atlantic cyclones and (d,e,f) east Atlantic cyclones. (a,d) Composite mean 600 hPa relative humidity (RH, shaded), overlaid with composite mean 850 hPa θ_e (dotted). (b,e) Composite mean 300 hPa RH (shaded), overlaid with composite mean 300 hPa PV (in PVU where 1 PVU = 10^{-6} K m^2 kg^{-1} s^{-1}, solid). (c,f) Vertical cross-section of composite mean RH (shaded), composite mean θ_e (dotted) and composite mean PV (solid). Cross-section is taken anti-clockwise around circle CD shown in (a,d).
Figure 3. Vertical cross-sections of composite mean PV overlaid with composite mean $\theta_e$. Cross-sections are taken anti-clockwise around circle CD shown in figure 2(a,d). (a,c) At the genesis time and (b,d) 48 hours after genesis. (a,b) West Atlantic cyclones and (c,d) East Atlantic cyclones.
Figure 4. Sensitivity of cyclone intensity to the precursor frontal gradient for the (a,b,c) west Atlantic cyclones and (d,e,f) east Atlantic cyclones. (a,d) Sensitivity to 700 hPa $\theta_e$ anomaly (shaded), overlaid with 700 hPa composite mean $\theta_e$ anomaly (positive dashed, negative dotted). (b,e) Sensitivity to 300 hPa $\theta_e$ anomaly (shaded), overlaid with 300 hPa composite mean $\theta_e$ anomaly (positive dashed, negative dotted) and 2PVU contour of PV (solid). (c,f) Vertical cross-section of sensitivity to $\theta_e$ anomaly (shaded) overlaid with composite mean $\theta_e$ anomaly (positive dashed, negative dotted) and 2PVU contour of PV (solid). Cross-section is taken anti-clockwise around circle CD shown in (a,d). Note that a sensitivity value of $0.5 \times 10^{-4} \text{s}^{-1}$ signifies that for a 1 standard deviation increase in the $\theta_e$ anomaly there is a corresponding increase in vorticity, after 48 hours, of $0.5 \times 10^{-4} \text{s}^{-1}$. 
Figure 5. Sensitivity of cyclone intensity to the precursor PV for the (a,b,c) west Atlantic cyclones and (d,e,f) east Atlantic cyclones. (a,d) Sensitivity to 700 hPa PV (shaded), overlaid with 700 hPa composite mean PV (dotted), contours every 0.1 PVU up to 1 PVU. (b,e) Sensitivity to 300 hPa PV (shaded), overlaid with 300 hPa composite mean PV (solid), contours every 1 PVU. (c,f) Vertical cross-section of sensitivity to PV (shaded) overlaid with composite mean PV, contours every 0.1 PVU up to 1 PVU (dotted) and every 1 PVU above (solid). Cross-section is taken anti-clockwise around circle CD shown in (a,d). Note that a sensitivity value of $0.5 \times 10^{-4} s^{-1}$ signifies that for a 1 standard deviation increase in the PV there is a corresponding increase in vorticity, after 48 hours, of $0.5 \times 10^{-4} s^{-1}$. 