Sensitivity of intensifying Atlantic hurricanes to vortex structure

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1. Introduction

The prediction of tropical cyclone (TC) intensity is a well-known forecasting challenge. When compared with the prediction of TC tracks, which has shown steady improvement over the past several decades, operational TC intensity forecast errors remain virtually flat (National Hurricane Center, 2013). There continues to be room for improvement in the forecast intensity of numerically simulated hurricanes, which contribute to the operational guidance (Davis \textit{et al.}, 2010). Hurricane rapid intensification (RI), defined as an increase of 15 m s\textsuperscript{-1} in the maximum sustained surface wind or decrease of 24 hPa in the minimum central pressure over 24 h, is an exceptional challenge in operational TC forecasting (Kaplan and DeMaria, 2003). Though RI represents the 95th percentile of over-water 24 h forecasts for 96 member ensembles provide the basis for analyses of hurricanes \textit{Bill} (2009), \textit{Earl} (2010), \textit{Igor} (2010), \textit{Katia} (2011) and \textit{Ophelia} (2011). Ensemble sensitivity analysis is used to investigate which patterns in the analysis have a strong influence on the forecast intensity and then a novel sensitivity compositing technique is used to identify common patterns that affect the forecast intensity. We find a common response for increasing intensity associated with an initial increased primary and secondary circulation, an increased warm core, an elevated tropopause and moistening of the rain-band region. Perturbed initial-condition experiments show a linear response for modest initial amplitude and also signs of nonlinearity for large perturbations, indicating that these sensitivity patterns are robust for limited additional strengthening of the hurricane. When initial perturbations are partitioned into dry and moist variables, we find that most of the forecast change is achieved by the dry dynamics. Further investigation into convective indicators reveals that simulations in which only moist variables are perturbed experience less convective development in the eyewall throughout the forecast.

\textit{Sensitivity analysis is performed in order to determine objectively the role of storm structure during periods of rapid intensification in a sample of five Atlantic hurricanes. Weather Research and Forecasting (WRF) model 24 h forecasts for 96 member ensembles provide the basis for analyses of hurricanes \textit{Bill} (2009), \textit{Earl} (2010), \textit{Igor} (2010), \textit{Katia} (2011) and \textit{Ophelia} (2011). Ensemble sensitivity analysis is used to investigate which patterns in the analysis have a strong influence on the forecast intensity and then a novel sensitivity compositing technique is used to identify common patterns that affect the forecast intensity. We find a common response for increasing intensity associated with an initial increased primary and secondary circulation, an increased warm core, an elevated tropopause and moistening of the rain-band region. Perturbed initial-condition experiments show a linear response for modest initial amplitude and also signs of nonlinearity for large perturbations, indicating that these sensitivity patterns are robust for limited additional strengthening of the hurricane. When initial perturbations are partitioned into dry and moist variables, we find that most of the forecast change is achieved by the dry dynamics. Further investigation into convective indicators reveals that simulations in which only moist variables are perturbed experience less convective development in the eyewall throughout the forecast.}

\textit{The statistical-dynamical method of RI forecasting pioneered by Kaplan and DeMaria (2003) and based on the Statistical Hurricane Intensity Prediction System (SHIPS: \textit{e.g} DeMaria and Kaplan, 1994) has had marked success versus climatology in operational forecasting. Known as the SHIPS Rapid Intensification Index (SHIPS-RII) model, this method uses linear discriminant analysis on a number of predictors to estimate the probability that a given TC will intensify rapidly. It is revealing that, in recent versions of SHIPS-RII, the predictor for storm symmetry receives significantly more weight than the intensity predictor, suggesting that storm structure plays an important role in rapid intensification (Kaplan \textit{et al.}, 2010). In addition to statistical prediction, numerous observational and numerical modelling studies of RI have been reported, often exploring the question of whether RI is triggered by asymmetric or axisymmetric forcing. One hypothesis is that intensification occurs through a change in heating and kinetic energy efficiency due to changes in inertial stability, which represents the opposition to radial displacement in a vortex. Thermal efficiency is the amount of heating realized above the amount offset by adiabatic cooling from ascent, while kinetic energy efficiency is the proportion of heat energy converted to wind kinetic energy; both increase with increased inertial stability (Schubert and Hack, 1982; Hack and Schubert, 1986). Thus, an anomalous heat source in the vortex can provoke positive feedback, where the anomalous secondary circulation increases the inertial stability, which increases the}
provides a description of hurricane structure that may point to compositing approach. In particular, compositing of observations (e.g. Moon and Nolan, 2005; Rogers, 2010) has been suggested as triggers for RI (e.g. Smith et al., 2007; Vigh and Schubert, 2009; Pendergrass and Willoughby, 2009). Other research identifies less localized, more symmetric forcing such as weak updraughts, which are generally more uniformly distributed around a TC. For example, using a high-resolution numerical simulation of hurricane Dennis (2005), Rogers (2010) finds that weak and moderate updraughts are responsible for increasing the inertial stability of the vortex, not strong updraughts. They found no discernible change in the population statistics of strong updraughts, an indicator of hot towers. The work of Jiang (2012) came to a similar conclusion as in the non-intensifying cases. Relative to non-intensifying cases, the metric acting as the dependent variable. This calculation highlights the regions or patterns in the initial conditions that contribute to a change in the forecast metric. Due to the sampling error inherent in finite-member ensemble techniques, the regression coefficient should be tested for significance for the desired confidence level (e.g. Torn and Hakim, 2009); here we use the 95% level.

The ensemble sensitivity calculation derives from a linearization about the ensemble mean, which may not apply in certain circumstances in a nonlinear model such as the one used here (Weather Research and Forecasting (WRF) model; see section 3). Thus the next step in our ensemble sensitivity study is to conduct perturbed initial-condition experiments where the initial conditions are perturbed and the model is used to simulate the change in the forecast metric. These experiments must account for spatial (and cross-variable) correlations, so here we reverse

The main mode of asymmetric heating which would provide the initial perturbations to the inertial stability relates to so-called ‘hot towers’, also known as convective bursts, which are strong, highly localized updraughts with enhanced buoyancy (e.g. Smith et al., 2005). Convective bursts co-located with enhanced cyclonic vorticity, termed vortical hot towers (VHTs), have also been suggested as triggers for RI (Montgomery et al., 2006). Other research identifies less localized, more symmetric forcing such as weak updraughts, which are generally more uniformly distributed around a TC. For example, using a high-resolution numerical simulation of hurricane Dennis (2005), Rogers (2010) finds that weak and moderate updraughts are responsible for increasing the inertial stability of the vortex, not strong updraughts. They found no discernible change in the population statistics of strong updraughts, an indicator of hot towers. The work of Jiang (2012) came to a similar conclusion using satellite-derived brightness temperatures to measure the symmetry and intensity of convection in hurricanes undergoing RI. Regardless of the hypothesized trigger for RI, it appears that the symmetry and intensity of convection in hurricanes undergoing RI and high-resolution numerical modelling case studies by using dynamical analysis and numerical modelling methods to identify structural sensitivity common among RI events. This process will serve as both an independent test of the most recent structure compositing results of radar and satellite observations and a source of new insight into rapidly intensifying tropical cyclones. The remainder of the study is organized as follows. The main analysis tool, ensemble sensitivity analysis, is described in section 2 and the data and model configuration in section 3. Section 4 presents both the sensitivity of the intensity of individual TCs and the results of a novel sensitivity compositing method. The robustness of the sensitivity results and the role of dry and moist dynamics in TC intensification are then tested using perturbed initial condition experiments in section 5 and concluding remarks are presented in section 6.

2. Ensemble sensitivity

The type of sensitivity study performed here refers to an objective assessment of perturbed initial conditions that affect a forecast as summarized by a metric (e.g. Hakim and Torn, 2008). Various methods, including adjoint, ensemble and singular vector techniques, have been used to determine the initial-condition sensitivity of numerical simulations of TC recurvature and extratropical transition (e.g. Reynolds et al., 2009; Torn and Hakim, 2009), tropical cyclogenesis (e.g. Mahajan, 2011), midlatitude weather systems (e.g. Ancell and Hakim, 2007; Hakim and Torn, 2008; Torn and Hakim, 2008) and winds at specific locations such as wind farms (Zack et al., 2010). When objective methods are compared, as in Ancell and Hakim (2007), it is found that they are not necessarily equivalent but agree broadly on the most sensitive regions.

Objective sensitivity studies typically start with the choice of a scalar forecast metric, which represents a summary measure of the phenomenon of interest. For TCs, the most well-known measures of intensity are the minimum central pressure and maximum wind speed (e.g. Torn and Hakim, 2009; Chang et al., 2013); however, these point measures may not represent the broader state of the storm and may be sensitive to location. To improve spatial representativeness, a spatial average value, such as average kinetic energy or circulation, may be more appropriate (e.g. Peng and Reynolds, 2006; Doyle et al., 2012; Torn and Cook, 2013). Here we define the forecast metric by the circulation per unit area over a radius of 100 km from the storm centre (i.e. area average relative vorticity) at the third model level (approximately 160 m on average). The choice of metric and location was made after testing several possible metrics and locations (e.g. minimum surface pressure, maximum wind speed, circulation at various levels). The metric used here was found to provide the most robust results as tested by perturbed initial condition experiments, though sensitivity results are not remarkably different among metrics, considering they all measure storm intensity.

One approach to sensitivity analysis treats model variables as independent predictors of $f$, in which case

$$\frac{\partial J}{\partial x^i} \approx \frac{\text{cov}(J, x^i)}{\text{var}(x^i)},$$

Here, cov and var indicate the sample covariance and variance, respectively, and $x^i$ is a vector of perturbations from the ensemble mean at the analysis time of the $i$th state variable. Equation (1) represents linear regression between the ensemble of forecast metrics and the ensemble of $i$th analysis state variables, with the metric acting as the dependent variable. This calculation highlights the regions or patterns in the initial conditions that contribute to a change in the forecast metric. Due to the sampling error inherent in finite-member ensemble techniques, the regression coefficient should be tested for significance for the desired confidence level (e.g. Torn and Hakim, 2009); here we use the 95% level.

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the dependent and independent variables in Eq. (1) in order to determine the initial condition that yields a specified change in the forecast metric. Specifically, the analysis state vector is perturbed according to

$$x^p = x^i + \frac{\partial x^a}{\partial f} \cdot \alpha,$$

(2)

where

$$\frac{\partial x^a}{\partial f} = \frac{\text{cov}(x^a, J)}{\text{var}(J)},$$

(3)

$\alpha$ is the desired change in the forecast metric and $x^p$ is the ensemble of the perturbed initial state variable. The form of Eq. (2) shows that the desired or forecast change in metric $\alpha$ acts as a scaling factor for the sensitivity, while the structure of the sensitivity is determined solely by the covariances between the initial condition and the metric.

3. Data and model

3.1. Selected cases

The tropical cyclones in this study were chosen from sets of ensemble analyses produced by an ensemble Kalman filter (EnKF) data assimilation system over portions of the 2009, 2010 and 2011 North Atlantic hurricane seasons. The assimilation system and also the ensemble forecasts produced for this study use the Advanced Research WRF (WRF-ARW) model version 3.3.1 (Skamarock et al., 2005), the configuration of which is described below. Observations were assimilated using the Data Assimilation Research Testbed (DART; Anderson et al., 2009), which is a version of the ensemble adjustment Kalman filter (Anderson, 2001). For details on the data assimilation system, the reader is referred to Torn and Davis (2012) and Torn (2010). Though the accompanying deterministic forecast system (Advanced Hurricane WRF 4 km, referred to hereafter as AHW4) was initialized every 6 h, the 96 member ensemble analyses are only available once per day, at 0000 UTC. The analyses are used to initialize an ensemble for each RI period chosen, which is then integrated for a 24 h forecast.

The subjective selection of test cases was made after considering the intensity change of the hurricane, its proximity to land and the skill of the AHW4 forecast. Though preference was given to rapidly intensifying storms, they comprise, by definition, only 5% of all over-water intensity changes (Kaplan et al., 2010). Furthermore, some cases of RI were excluded due to the storm’s proximity to land, which would introduce complex interactions and axial asymmetries in storm structure. As a result, additional cases were added that did not reach the 15 m s$^{-1}$ per 24 h definition of RI, but still intensified strongly. The five cases are Bill (2009), Earl (2010), Igor (2010), Katia (2011) and Ophelia (2011). A summary of the test cases, their initialization times and their intensity changes is contained in Table 1. Two forecast periods during Earl’s RI were used, initialized on 29 August 2010 and 30 August 2010; these will be referred to as Earl 29 and Earl 30, respectively.

The selected tropical cyclones are strong, Cape Verde type storms, which generally formed from tropical easterly waves exiting the west coast of Africa south of the Cape Verde Islands and strengthened over the open Atlantic Ocean. With the exception of hurricane Katia (2011), the selected cases intensified moderately or rapidly during the selected forecast period (Figure 1). During the 24 h forecast period chosen for Katia (2011), the TC did not intensify in reality but it intensifies moderately in the simulation. The average ensemble mean forecast metric for the seven ensemble forecasts is $5.6 \times 10^{-5} \text{s}^{-1}$ and the average ensemble standard deviation over the seven ensemble forecasts is $3.4 \times 10^{-5} \text{s}^{-1}$. This average standard deviation will be referred to as $\alpha^*$ and will serve as a reference forecast metric scaling for perturbed initial condition experiments.

3.2. Model configuration

The ensemble forecasts are made on a vortex-following, 12 km resolution grid within a parent domain having 36 km spacing. All grids are configured with the WRF single-moment six-class microphysics scheme (WSM6) with graupel (Hong et al., 2004), Rapid Radiative Transfer Model–GCM (RRTMG) short-wave and long-wave radiation schemes (Iacono et al., 2008), Yonsei University (YSU) boundary-layer scheme (Hong et al., 2006), Noah land-surface model (Ek et al., 2003) and the Tiedtke cumulus parameterization (Zhang et al., 2011). The outer domain spans 320 grid points from east to west and 210 grid points from north to south, encompassing the western portion of the Northern Hemisphere. The inner domain measures 133 grid points on each side and automatically moves to track the centre of the TC as defined by the vorticity centroid at 700 hPa. Two-way nesting, in which information is transferred both from the parent

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Table 1. A summary of the selected test cases, the initialization date (all cases initialized at 0000 UTC on the date indicated) and the 24 h best track intensity change estimate in maximum wind speed (m s$^{-1}$) and minimum central pressure (hPa). Also listed are the ensemble mean ($\bar{J}$) and standard deviation ($\sigma_J$) of the 24 h forecast metric (circulation per unit area; $10^{-4}$ and $10^{-5}$ s$^{-1}$, respectively).

<table>
<thead>
<tr>
<th>Storm</th>
<th>Date</th>
<th>$\Delta V_{max}$</th>
<th>$\Delta P_{min}$</th>
<th>$\bar{J}$</th>
<th>$\sigma_J$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bill</td>
<td>18 August 2009</td>
<td>10.3</td>
<td>−12</td>
<td>6.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Earl</td>
<td>29 August 2010</td>
<td>15.2</td>
<td>−20</td>
<td>5.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Earl</td>
<td>30 August 2010</td>
<td>15.4</td>
<td>−33</td>
<td>7.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Igor</td>
<td>12 September 2010</td>
<td>33.4</td>
<td>−52</td>
<td>4.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Katia</td>
<td>01 September 2011</td>
<td>0.0</td>
<td>0</td>
<td>6.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Ophelia</td>
<td>29 September 2011</td>
<td>10.3</td>
<td>−13</td>
<td>4.9</td>
<td>3.8</td>
</tr>
</tbody>
</table>

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*The average ensemble mean and standard deviation also include Julia (2010), which was ultimately excluded from this study; however, it should be noted that the exact value of $\alpha^*$ is arbitrary and only determines the magnitude of the sensitivity, not the structure.*
to the inner domain and from the inner to the parent domain, is implemented. All domains have 35 vertical levels.

The ‘Advanced Hurricane’ option of WRF is used, which makes modifications to the model parametrizations and surface scheme designed specifically for hurricane simulation. These include alternative formulations for the surface exchange coefficients and include the effects of dissipative heating (Davis et al., 2008). The simulations also include a one-dimensional ocean mixed layer in which a constant initial mixed-layer depth (50 m) and constant deep-water lapse rate (0.20 K m$^{-1}$) are specified and the mixed layer is cooled based on the wind stress (Pollard et al., 1973).

Additional simulations were carried out for Earl 29 (2010) and Igor (2010) using two additional, higher-resolution nested domains of 4 and 4/3 km grid spacing. These two innermost domains resolve convection explicitly and thus do not use a cumulus parametrization scheme, but are otherwise configured the same as the parent domains described above. The initialization of the two higher resolution domains is interpolated from the 12 km domain, as 4 and 4/3 km ensemble analyses were not produced by the EnKF system described above. The initial condition perturbations must then also be interpolated from 12 km and, when perturbed, the behaviour of these simulations may be thought of as the vortex- and convective-scale response to vortex-scale perturbations. A detailed description and analysis of the ensemble sensitivity and evolution of perturbations is reserved for a forthcoming study, but preliminary details describing convective indicators from the 4 km domain will be presented here to assist in the interpretation of the 12 km results, which are the main focus of this study.

4. Sensitivity results

4.1. Individual cases

The ensemble sensitivity of the individual test cases is examined here in a storm-centred domain. The centre of the storm is defined by minimizing the magnitude of the horizontal wind vector within a window centred on the point of minimum pressure.† When multiple levels are considered in section 4.2, the centring process is performed at each level so that the storm is vertically aligned along the centre axis.

Figure 2 shows the sensitivity of the analysis tangential wind at the third model level to the circulation forecast metric for each test

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† A simplex algorithm that maximizes tangential wind (Neldar and Mead, 1965) was tested and identified the same centre point, but was much more computationally expensive.
case (i.e. Eq. (3) multiplied by $\alpha^*$. This indicates the change in the analysis field that will yield a change of $\alpha^*$ ($3.41 \times 10^{-5}$ s$^{-1}$) in the metric 24 h later. In general, the sensitivity patterns in Figure 2 emphasize the core of the storm, with weak sensitivity in the outer areas of the domain. These patterns suggest that, to achieve the prescribed change in the forecast metric, the tangential wind at the initial time should be decreased in the eye and increased around the radius of maximum wind – either in a narrow band such as in Earl 29 (Figure 2(b)), Earl 30 (Figure 2(c)) and Igor (Figure 2(d)), or in a broader region such as in Bill (Figure 2(a)), Katia (Figure 2(e)) and Ophelia (Figure 2(f)). This general pattern is at least partially due to the high spatial correlation between points in the core of the storm vortex that are influenced by the strong primary circulation and highlights the need to consider a method of sensitivity where spatial points are not assumed to be uncorrelated (cf. adjoint sensitivity). In a dynamical sense, an enhanced primary circulation (i.e. greatest positive sensitivity at the RMW) enhances the radial gradient of the tangential wind which, as noted in the conclusions of Rogers (2010), amplifies the inertial stability and thermal efficiency of the hurricane.

The sensitivity pattern also identifies an annular storm structure, as opposed to monopolar, where the vorticity is greatest in the centre. This pattern is evident not only in the sensitivity of the analysis tangential wind, but also in the sensitivity of the analysis relative vorticity, for which the radial profile of the sensitivity is presented in Figure 3. The sensitivity is annular in the case of Bill, Earl 29, Earl 30 and Katia and is monopolar in the case of Igor and Ophelia, each of which has a secondary maximum near the RMW. There is ample observational and theoretical evidence that a ‘hollow tower’ vorticity configuration, or the accompanying U-shaped tangential wind profile, is favourable for the intensification of hurricane-like vortices (e.g. Montgomery et al., 2000; Kossin and Eastin, 2001; Kepert, 2010; Rogers et al., 2013).

Vertical wind shear is generally considered detrimental to the strengthening of TCs, because it disrupts the vertical organization of the secondary circulation (e.g. Kaplan et al., 2010); thus we consider whether this is an important factor in the storms studied here. The ensemble-mean, domain-mean shear vector is defined by taking the spatial mean of the 300–150 and 700–900 hPa layer-mean zonal and meridional wind components (to remove the axisymmetric storm flow), taking their difference and then averaging over the ensemble. By virtue of another characteristic of the selected test cases, i.e. strong intensification, the magnitude of the shear is generally weak (less than 10 m s$^{-1}$) and is summarized in Table 2, along with the sensitivity of the forecast metric to the shear. In this instance, sensitivity refers to the sensitivity of the metric to the analysis: ease in interpreting a single value rather than a two-dimensional pattern. Therefore, the sensitivity values in Table 2 indicate the amount that the forecast metric is predicted to change for a prescribed change of one standard deviation in the analysis-mean shear magnitude. The sensitivity is generally negative, small and not statistically significant. It should be noted that, though shear plays a less significant role during the forecast periods selected here, the mostly negative sensitivity does confirm the conventional view that increased shear is detrimental to TC intensification.

Sensitivity to column integrated water vapour (Figure 4) is found mainly near the centre of the storms or in a ring around the centre in the most intense cases, such as Bill (Figure 4(a)) and Earl on 30 August (Figure 4(c)). The sensitivity patterns also show positive sensitivity in banded structures from the inner core to several hundred kilometres in radius, which indicate that moistening these areas in the analysis leads to increased circulation 24 h later. The banded areas of positive sensitivity appear specifically in regions where relative dryness exists in the analysis: southeast of the storm centre in Bill (Figure 4(a)), north of the storm centre in Earl 29 (Figure 4(b)), southwest of the storm centre in Earl 30 (Figure 4(c)), west of the storm centre in Igor (Figure 4(d)), southwest of the storm centre in Katia (Figure 4(e)) and south of the storm centre in Ophelia (Figure 4(f)); these banded structures are statistically significant with 95% confidence. While there are areas of equally strong negative (drying) sensitivity at larger distances from the storm centre, these are generally not statistically significant. This is an
indication that the inner core and the several hundred kilometres surrounding it constitute an important region for determining hurricane intensification. There is also the interesting implication that moistening outside the inner core has a positive effect on the forecast metric, but a lack of a stronger sensitivity in the eyewall region could merely indicate that the air in that region is already saturated. This will be addressed below, by exploring the axisymmetric sensitivity of water-vapour mixing ratio and relative humidity.

4.2. Composite sensitivity

To reduce dimensionality and determine patterns common to the sample, we now consider the sample-mean axisymmetric component of the sensitivity field. Specifically, we examine the tangential and radial wind, perturbation potential temperature, water-vapour mixing ratio and relative humidity. Sensitivity for each test case is calculated and then interpolated in radius to a common grid for the sample average. The common radial grid is defined as the radius normalized by the radius of maximum

\footnote{Perturbation from a uniform base-state potential temperature of 300 K.}

axisymmetric tangential wind at the level of maximum wind (RMW), \( r^* \).

The composite ensemble mean of the axisymmetric analysis tangential wind and its sensitivity to the forecast metric is shown in Figure 5. The maximum composite sensitivity of 1.3 m s\(^{-1}\) (about 6% of the ensemble mean maximum tangential wind) is co-located with the area of maximum tangential wind at the RMW in the lower troposphere. Away from the area of maximum tangential wind, the sensitivity decreases with both increasing radius and decreasing pressure to zero sensitivity at the tropopause. This sensitivity pattern indicates that a strengthened (weakened) primary circulation in the analysis is associated with a larger (smaller) metric and a stronger (weaker) storm in the 24 h forecast. As with the individual sensitivity fields considered previously, this reveals that a sharper gradient on both the inside and outside edges of the eyewall, enhancing annular structure, is favourable for hurricane intensification.

The composite ensemble-mean analysis axisymmetric radial wind shows canonical boundary-layer inflow and upper-level outflow (Figure 6) and the composite sensitivity of this field highlights these two features, with maximum negative sensitivity of about 1 m s\(^{-1}\) in the boundary layer and maximum positive sensitivity of 0.6 m s\(^{-1}\) near the upper level outflow. Though these maximum sensitivity values are of the same magnitude as
the tangential wind sensitivity, they represent a larger change in the analysis, about 10–12% of the ensemble mean. Because radial inflow is negative, negative (positive) sensitivity centered on an area of negative radial wind indicates that increasing (decreasing) radial inflow is related to an increase (decrease) in circulation 24 h later. This pattern of sensitivity suggests that a stronger secondary circulation in the analysis is associated with a stronger storm in the 24 h forecast. The composite sensitivity of the perturbation potential temperature also highlights strengthening the canonical axisymmetric hurricane structure for a resulting stronger circulation in the 24 h forecast, with positive sensitivity centered on the storm’s warm core (Figure 7). The axisymmetric potential temperature sensitivity also shows an upper-level dipole, with a positive-over-negative pattern near the tropopause, indicating that a higher (lower) tropopause is associated with stronger (weaker) circulation in the 24 h forecast. The increased warm core is associated with a negative sensitivity of the analysis axisymmetric vertical velocity, indicating that the warm core and increased forecast metric are associated with increased initial subsidence in the eye of the hurricane.

Thus far, the composite axisymmetric sensitivity patterns indicate that a stronger hurricane in the analysis will be associated with a stronger hurricane in the 24 h forecast. There is no indication of a secondary maximum in the composite axisymmetric sensitivity of the tangential wind, which is consistent with the observational composite results of Rogers et al. (2013)
and the relatively large weight on the persistence predictor of Kaplan et al. (2010).

In contrast, the composite sensitivity of the axisymmetric water-vapour mixing ratio reveals local maxima in the boundary layer extending from the centre of the storm to two and a half times the RMW and in the mid-troposphere from two to three times the RMW (Figure 8). This pattern implies that an axisymmetric moistening of the rain-band region outside the eyewall, in addition to moistening the boundary layer and lower troposphere in the inner core, should result in stronger circulation in the 24 h forecast. This axisymmetric moisture sensitivity is consistent with the sensitivity of the column-integrated water vapour shown for each test case above. The plan view sensitivity shown in Figure 4 exhibits a spiral band pattern outside the RMW, which projects on the axisymmetric component of the sensitivity. Although this axisymmetric rain-band sensitivity pattern appears in the majority of cases (not shown) and the composite mean, it is generally not accompanied by secondary wind and potential temperature sensitivity maxima.

An alternate assessment of moisture sensitivity is given by the axisymmetric relative humidity (RH) (Figure 9). Common
regions of maximum positive sensitivity are apparent at two to three times the RMW and four times the RMW, in regions where the RH gradient is enhanced but the air is not saturated. The negative RH sensitivity in the centre of the storm is likely attributable to the positive sensitivity to potential temperature at that location, but the areas of positive sensitivity appear to correspond with positive water–vapour mixing ratio sensitivity.

5. Perturbed initial condition experiments

While the previous section identified statistical patterns of possible importance to intensification, they are subject to the assumptions made in the derivation of ensemble sensitivity discussed in section 2. Here, we check the link between initial-condition sensitivity for forecast intensity by performing perturbed initial-condition experiments with the WRF-ARW model. Specifically, the analysis values of the model prognostic variables in each case are perturbed with sensitivity patterns defined by Eq. (2) over a range of $\alpha$. Moreover, certain experiments are designed to test the relative importance of moist and dry variables to intensification.

First, the model response is calculated for perturbations to all of the prognostic variables, for values of $\alpha$ that are multiples of $\alpha^*$ ($3.41 \times 10^{-5}$ s$^{-1}$), up to six times $\alpha^*$; this maximum prescribed $\alpha$ ranges from 27% (Earl 30) to 43% (Igor) of the mean 24 h forecast metric of the test cases. Due to computational constraints, only the ensemble member closest to the ensemble mean (with respect to the 24 h metric) for each test case is perturbed.5 The predicted change and actual change in the forecast metric are generally in good agreement, especially for negative changes in the metric, which show only small deviations from agreement out to $-2 \times 10^{-4}$ s$^{-1}$ for cases such as Bill (2009) and Igor (2010) (Figure 10). Experiments with positive perturbations (increasing storm intensity) tend to deviate further from agreement with the predicted change. This type of asymmetric response to perturbations, with a weaker response than predicted for increasingly positive perturbations, is a hallmark of nonlinearity. From a physical standpoint, because the time period simulated for each test case is already a period of strong intensification for a mature storm, additional intensification may be difficult to achieve, due to thermodynamic constraints on intensification. Katia (2011) and Ophelia (2011) have the weakest response to positive perturbations and it should be noted that these two storms had the smallest observed intensification during the selected forecast period. On the other hand, storms may be weakened substantially, with robust agreement between the modelled response and the predicted change.

The generally linear model response to small and even moderate-amplitude perturbations allows further experimentation on the initial conditions. Motivated by the moisture sensitivity in the outer radii of the composite, experiments are designed to test the relative roles of the dry and moist dynamics in the intensification of the test cases. To test the relative role of dry dynamics, hereafter referred to as the ‘dry’ experiments, perturbations to the water vapour, cloud water, rain water, cloud ice, snow and graupel mixing ratios are set to 0. To test the relative role of moisture, hereafter referred to as the ‘moist’ experiments, perturbations to the zonal and meridional wind, vertical motion and perturbation potential temperature and pressure are set to 0. The results of these experiments show that, in every case, perturbations to the dry dynamics apparently play a larger role than moisture in forecast storm intensity (Figure 11). Particularly in the case of Earl on 30 August 2010 and Igor (2010), the dry experiment has nearly equivalent results to perturbing the full initial conditions, while perturbing only the moist variables has almost no effect. This is a similar result to Mahajan (2011), in which the four cases of tropical cyclogenesis exhibited a larger relative response when perturbations to moisture variables were suppressed than when only moisture variables were perturbed.

To evaluate the behaviour of the three perturbed experiments further, the evolution of the forecast dry potential vorticity (PV) field of each case is considered. The fully perturbed and dry experiments are generally initialized with higher values of PV in the core of the storm than the moist experiment. In cases such as Earl 30 and Ophelia, the axisymmetric PV field evolves from an annulus in the initial conditions to a monopole in which the maximum PV is found in the centre of the storm (Figure 12(c) and (f)). In other cases, such as Earl 29, Igor (after an initial adjustment) and Katia, the radial gradient of PV sharpens as the forecast progresses and is more sharp in the dry experiment than the moist experiment (Figure 12(b), (d) and (e)). This behaviour is similar to that described by Kossin and

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5The closest member is determined by the member with the forecast metric that has the smallest absolute difference from the ensemble mean forecast metric.
Figure 10. The prescribed change in the metric (\(a\), abscissa) versus the actual change in the metric after reforecasting the member closest to the ensemble mean with perturbed initial conditions for each test case.

Figure 11. The prescribed change in metric (\(a\), abscissa) versus the actual change (ordinate) in the forecast metric for each test case when the analysis state vector is fully perturbed (black, as in Figure 10), when only the dry variables are perturbed (red in the online article) and when only the moist variables are perturbed (blue in the online article) for (a) Bill (2009), (b) Earl 29 (2010), (c) Earl 30 (2010), (d) Igor (2010), (e) Katia (2011) and (f) Ophelia (2011).
Sensitivity of Intensifying Hurricanes to Vortices

Figure 12. The axisymmetric potential vorticity (PVU: $10^{-6}$ K m$^2$ kg$^{-1}$ s$^{-1}$) at 850 hPa as a function of radius (km). Shading indicates the analysis (light), 12 h forecast (medium) and 24 h forecast (dark) and the fully perturbed experiment (grey shades), dry experiment (red shades in the online article) and moist experiment (blue shades in the online article). Forecasts are shown for (a) Bill (2009), (b) Earl 29 (2010), (c) Earl 30 (2010), (d) Igor (2010), (e) Katia (2011) and (f) Ophelia (2011). Because dry PV is shown, the analysis of the fully perturbed and dry experiments are nearly identical and the analysis of the moist experiment approximates the unperturbed control analysis.

Eastin (2001) as a vortex transitions from intensifying to its peak intensity to a steady or weakening intensity. While all cases reach a monopole configuration in the moist experiment by the end of the forecast period, in cases such as Katia (Figure 12(c)) and Ophelia (Figure 12(f)), the dry and/or fully perturbed experiment retains an annular profile. In all test cases, the dry and fully perturbed experiments maintain higher PV values throughout the forecast at outer radii when compared with the moist experiment.

As described in section 3.2, two test cases were simulated in higher resolution ensembles that have additional nested domains of 4 and 4/3 km resolution. Convective indicators calculated from the 4 km domains of these additional simulations of Earl 29 and Igor also reveal differences in the evolution of the perturbed experiments. These additional simulations of Earl 29 and Igor have sensitivity at 3 h similar to the composites shown in section 4.2 (because the inner domains are interpolated from the 12 km domain, their sensitivity at the analysis time is identical), as well as a similar model response when perturbed (not shown). Both dry and moist experiments were conducted in the same manner described above. The distributions of the combined eyewall vertical velocities from these two simulations are shown in Figure 13, as selected percentiles (i.e. the 1st, 5th, 25th, 50th, 75th, 95th, 99th and 99.9th percentiles), similar to Rogers et al. (2013); however, here the slope of the eyewall is accounted for by calculating the centre and radius of maximum wind at each level. This is necessary, as simulated hurricanes tend to have a greater eyewall slope than observed storms (Nolan et al., 2013). The eyewall is defined as 0.75–1.25 times the RMW; depending on the RMW, the number of grid points in each height bin for each experiment varies between 10 000 and 11 000. The percentiles are shown as they evolve through the forecast. During the first 6 h of the forecast, the experiments exhibit little difference even at the extreme ends of the updraught distribution (Figure 13(a)). By the end of the forecast (Figure 13(b)), the 95th, 99th and 99.9th percentiles of the fully perturbed and dry experiments peak between 4 and 6 km and generally exceed the peak value of the unperturbed and moist experiments. In contrast, the moist experiment has weaker extreme eyewall updraughts than the control and has stronger extreme eyewall downdraughts than the unperturbed case above 6 km. Even through the middle of the distribution, the moist and unperturbed experiments tend to have stronger downdraughts and weaker updraughts at each percentile than the dry and fully perturbed experiments. Though the percentiles of vertical motion are compared here between different categories of intensifying storms, rather than intensifying and non-intensifying storms as in Rogers et al. (2013), the results are qualitatively similar to those of that study, suggesting that the characteristics of eyewall vertical velocity for intensifying storms exist in a spectrum from non-intensifying through moderately intensifying to rapidly intensifying. Here, as well as in Rogers et al. (2013), the most pronounced differences between groups are found at the extreme ends of the distributions, with stronger intensifying storms having stronger extreme eyewall updraughts. It is also confirmed here that the largest differences in the extreme updraughts are seen above the height of the freezing level (4–5 km).

It is also constructive to consider the radial location of extreme updraughts relative to the RMW, as this determines the efficiency with which their heating is converted into kinetic energy. Here, we define convective burst points, as in Rogers et al. (2013), as the top 1% of updraughts at 8 km height. When considering the combined statistics of Earl and Igor, this results in a threshold of 7 m s$^{-1}$. All of the storms have the largest proportion of convective burst points just inside the eyewall (Figure 14); however, the moist and unperturbed experiments have a larger proportion of convective burst points located outside the eyewall (i.e. greater than 1.25 × RMW) and a smaller proportion located within the eyewall (i.e. 0.75–1.25 × RMW) than the dry and fully perturbed experiment. Although this is not the dramatic result of Rogers et al. (2013), it nevertheless implies that the more intense storms may benefit from preferentially located convective bursts in an area of high inertial stability.

6. Summary and conclusions

Systematic numerical modelling experiments that bridge the current gap in hurricane rapid intensification studies between climatological and composite observational studies and case-study numerical simulations were conducted. The aim of this systematic modelling approach was to conduct novel compositing of ensemble sensitivity analysis to find commonalities in sensitivity to storm structure between six cases of hurricane intensification and then to use this as a guide for further investigation into the mechanisms of intensification. 96 member ensembles were run with the WRF-ARW model for six cases from the Atlantic Basin: Bill (2009), two cases of Earl (2010), Igor (2010), Katia (2011) and Ophelia (2011). During the forecast period for each case, the hurricane intensified either rapidly or nearly rapidly (defined as an increase of 15 m s$^{-1}$ in the maximum 10 m wind speed over 24 h), remained over open ocean and did not undergo intensity oscillations such as those from secondary eyewall replacement cycles.

The results of the composite sensitivity study show that a stronger initial TC is associated with a stronger forecast TC. This applies to the primary circulation, secondary circulation and warm core. The composite sensitivity of the axisymmetric moisture field reveals that a pattern of enhanced moisture outside
Figure 13. (a) The vertical profiles of selected percentiles (1, 5, 25, 50, 75, 95, 99 and 99.9) of the cumulative distribution of eyewall (0.75–1.25 times the RMW) vertical motion from the 4 km domains of Igor (2010) and Earl 29 (2010) for the unperturbed control (green in the online article) and fully perturbed (black), moist (blue in the online article) and dry (red in the online article) experiments for forecast hours 1–6. (b) As (a), for forecast hours 19–24. Each height bin contains between 10 000 and 11 000 points, dependent only on eyewall width.

Figure 14. The relative frequency of convective burst points (updraughts greater than or equal to 7 m s\(^{-1}\) at a height of 8 km) as a function of normalized radial location for the 4 km resolution domains of Igor and Earl.

the RMW is associated with a stronger forecast TC. This pattern of moisture sensitivity is also found in the 3 h forecast, as well as in high-resolution ensembles of two of the test cases (not shown). Increasing outer-core relative humidity can indicate an expanding wind field rather than a truly intensifying hurricane; however, in the cases studied here, the minimum central pressure and the maximum wind speed increase along with increases in the metric when perturbed initial condition experiments are evaluated (not shown). Furthermore, regressions of the analysis axisymmetric tangential wind speed and the water-vapour mixing ratio at twice the RMW and 500 hPa reveal that the increases in the tangential wind associated with increases in outer-core moisture are located at or just inwards of the RMW, except in the case of Bill (2009) (not shown).

Perturbed initial-condition experiments were conducted by scaling the amplitude of the sensitivity fields. In all cases, the actual change in the metric was close to the predicted value, indicating a fairly linear model response for perturbations with a magnitude of up to a quarter of the test-case average ensemble-mean forecast metric. Signs of nonlinearity were evident as larger perturbations were applied, with a longer linear regime for perturbations that weaken the storm. Experiments on the role of moisture showed that dry variables consistently had a relatively larger impact on the forecast. Some cases evolve from a PV annulus to a monopole, while others experience a sharpening PV gradient as the forecast progresses. The dry and fully perturbed experiments generally have higher PV than the moist experiment from the RMW outward and in some cases evolve more slowly.
towards a monopole. Higher resolution simulations of Earl and Igor showed that the dry and fully perturbed experiments exhibit increasingly larger extreme eywall updrafts as the forecast progresses compared with the unperturbed control; however, the moist experiment shows little difference from the control. A detailed analysis of the mechanism by which the dry (kinematic) perturbations in this study induce beneficial convective activity in the higher resolution simulations remains a subject for future research.

The sensitivity and perturbed initial condition results of this study suggest a possible observing strategy to improve TC intensity forecasts by prioritizing kinematic and temperature fields rather than moisture fields. Specific regions of the storm, such as the outflow layer, the boundary layer and the region located at twice the RMW may have the most observational impact. These suggestions only apply to the type of storm studied here, i.e. mature TCs in a relatively quiescent observational impact. These suggestions only apply to the type of storm located at twice the RMW may have the most intensity forecasts by prioritizing kinematic and temperature fields.

The results of this study are broadly consistent with the composited observational results of Rogers et al. (2013), which show that intensifying hurricanes exhibit more convective and kinematic enhancement in the eyewall, inside the RMW, while non-intensifying hurricanes exhibit more convective activity outside the RMW. The kinematic sensitivity results here indicate the same for intensifying storms. The analysis of convective indicators shows that there are differences in both eyewall convective activity and the radial distribution of convection among the perturbed experiments performed here, even though all experiments intensified to some degree. Unlike Rogers et al. (2013), however, we cannot determine from this study whether these results are significantly different from those that a group of non-intensifying TCs might produce, as only intensifying hurricanes were studied here. A logical follow-on study to this research would be to perform a similar analysis on a set of non-intensifying hurricanes.

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