Sensitivity of intensifying Atlantic hurricanes to vortex structure

Bonnie R. Brown* and Gregory J. Hakim

University of Washington, Department of Atmospheric Sciences

*Correspondence to: Box 351640, Seattle, WA 98195. E-mail: bonnie@atmos.washington.edu

Sensitivity analysis is performed to objectively determine the role of storm structure during periods of rapid intensification in a sample of five Atlantic hurricanes. Weather Research and Forecasting (WRF) model 24-hour forecasts for 96-member ensembles provide the basis for analysis of hurricanes Bill (2009), Earl (2010), Igor (2010), Katia (2011), and 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, a raised tropopause and moistening of the rain band region. Perturbed initial-condition experiments show a linear response for modest initial amplitude, and also signs of non-linearity 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 reveal that simulations in which only moist variables are perturbed experience less convective development in the eyewall throughout the forecast. These findings are consistent with recent observational studies of intensifying tropical cyclones.

Key Words: hurricanes; typhoons; tropical cyclones; rapid intensification; ensemble sensitivity; numerical modeling

1. Introduction

The prediction of tropical cyclone (TC) intensity is a well-known forecasting challenge. When compared to the prediction of TC track, which has experienced steady improvement over the past several decades, operational TC intensity forecast errors remain virtually flat (DeMaria et al. 2013). Hurricane rapid intensification (RI), defined as an increase of 15 m s$^{-1}$ in the maximum sustained surface wind or decrease of 24 hPa in the minimum central pressure over 24 hours, is
an exceptional challenge in operational tropical cyclone (TC) forecasting (Kaplan and DeMaria 2003). Though RI represents the ninety-fifth percentile of over-water 24-hour TC intensity changes, improved understanding of these extreme events may provide a large benefit to overall intensity forecasting. In fact, while the prediction of small intensity changes has shown improvement, these gains are masked overall by an increasing number of large intensity changes, the prediction of which has not shown improvement (Moskaitis 2012). As with the general intensity forecasting problem, the difficulty in forecasting RI is often attributed to an incomplete understanding and model representation of the multi-scale interactions that govern hurricane intensification (Rogers 2010).

The statistical-dynamical method of RI forecasting pioneered by Kaplan and DeMaria (2003) has had marked success versus climatology in operational forecasting. Known as the SHIPS-RII (Statistical Hurricane Intensity Prediction Scheme - Rapid Intensification Index) model, this method uses linear discriminant analysis on a number of predictors to estimate the probability that a given TC will rapidly intensify. 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 et al. 2010). In addition to statistical prediction, numerous observational and numerical modeling 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 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, which is controlled by inertial stability; thus, larger inertial stability promotes greater thermal efficiency (Schubert and Hack 1982). Therefore, an anomalous heat source in the vortex can provoke a positive feedback, where the anomalous secondary circulation increases the inertial stability, which increases the thermal efficiency, which then causes the heating source to have further positive impact on the intensity (as measured by the tangential wind) (e.g. Pendergrass and Willoughby 2009; Schubert and Vigh 2008; Nolan et al. 2007).

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 updrafts with enhanced buoyancy (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 updrafts, 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 updrafts are responsible for increasing the inertial stability of the vortex, not strong updrafts. They found no discernible change in the population statistics of strong updrafts, an indicator of hot towers. Regardless of the hypothesized trigger for RI, it appears that the location of anomalous heating, and thus the vortex-scale structure of the storm itself (whether described by inertial stability or some other metric), is critical to intensification (e.g., Moon and Nolan 2010; Didlake and Houze 2013).

Recent observational studies of RI have employed a compositing approach. In particular, compositing of observations provides a description of hurricane structure that may point to mechanisms or characteristics unique to RI events. Wu et al. (2012), composite nine years of humidity data from the Atmospheric Infrared Sounder (AIRS) instrument aboard the Aqua satellite according to hurricane quadrant (relative to the storm motion vector). They find that environmental relative humidity is significantly higher in the near (radius of 200 to 400 km) and intermediate (radius of 400 to 600 km) environment for cases with both higher intensities and intensification rates, but also find that rapidly intensifying hurricanes have a significantly sharper radial gradient of relative humidity in the front-right quadrant between the near and intermediate environment. Rogers et al. (2013) compare the structure of intensifying hurricanes and non-intensifying hurricanes using airborne Doppler radar observations. They find that RI cases show a stronger primary and secondary circulation, as well as a vorticity ring structure rather than a vorticity monopole as in...
the non-intensifying cases. The eyewall upward motion, located inside the radius of maximum wind, is stronger in the mid- to upper-troposphere while there is weak downward motion at radii of less than half the RMW for the composite of intensifying cases compared to the composite of non-intensifying cases. The non-intensifying composite exhibits a possible secondary tangential wind maximum outside of the radius of maximum wind (RMW) co-located with weak updrafts that the authors suggest is indicative of rain band or even secondary eyewall activity.

Previous research reviewed above illustrates that RI studies generally fall into two categories: statistical analysis of RI climatology, or a numerical modeling or observational case study of one RI event. Recently, observational compositing studies have documented structure of RI hurricanes, which motivates the need for a complementary approach from numerical modeling studies. Here we bridge the gap between statistical analyses and high-resolution numerical modeling case studies by using dynamical analysis and numerical modeling 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., Torn and Hakim 2009; Reynolds et al. 2009), tropical cyclogenesis (e.g., Mahajan 2011), midlatitude weather systems (e.g., Ancell and Hakim 2007; Torn and Hakim 2008; Hakim and Torn 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 broadly agree 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; Torn and Cook 2013; Doyle et al. 2012). Here we define the forecast metric by the circulation per unit area over a radius of 100 km from the storm center.

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

$$\frac{\partial J}{\partial x_i} \approx \frac{\text{cov}(J, x_i^a)}{\text{var}(x_i^a)}$$  (1)

Here, $\text{cov}$ and $\text{var}$ indicate the sample covariance and variance, respectively, and $x_i^a$ 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 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.
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 propagated forward again. These experiments must account for spatial (and cross-variable) correlations, so here we reverse the dependent and independent variables in Eqn. 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

\[ x^p_i = x^a_i + \frac{\partial x^a_i}{\partial J} \cdot \alpha, \]

where

\[ \frac{\partial x^a_i}{\partial J} = \frac{\text{cov}(x^a_i, J)}{\text{var}(J)}, \]

\( \alpha \) is the desired change in the forecast metric and \( x^p_i \) is the ensemble of the perturbed \( i^{th} \) state variable.

### 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, as well as the ensemble forecasts produced for this study, use the 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 of the data assimilation system, the reader is referred to Torn and Davis (2012) and Torn (2010). An ensemble of 96 analyses were available at 0000 UTC every day during the lifetime of each storm described below.

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 Advanced Hurricane WRF 4 km 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 hours definition of RI, but still strongly intensified. 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 change can be found in Table 1. Two forecast periods during Earl’s RI are used, initialized on 29 August 2010 and 30 August 2010 and 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 hour forecast period chosen for Katia (2011) the TC did not intensify in reality, but intensifies moderately in the simulation. The average ensemble mean forecast metric for the seven ensemble forecasts (including Julia (2010), which is excluded from this study) is \( 5.6 \times 10^{-4} \) s\(^{-1}\) and the average ensemble standard deviation over the seven ensemble forecasts is \( 3.4 \times 10^{-5} \) 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.
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 hour 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 hour forecast metric (circulation per unit area; $10^{-4}$ m\(^2\) s\(^{-1}\) 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 Aug 2009</td>
<td>10.3</td>
<td>-12</td>
<td>6.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Earl</td>
<td>29 Aug 2010</td>
<td>15.2</td>
<td>-20</td>
<td>5.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Earl</td>
<td>30 Aug 2010</td>
<td>15.4</td>
<td>-33</td>
<td>7.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Igor</td>
<td>12 Sep 2010</td>
<td>33.4</td>
<td>-52</td>
<td>4.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Katia</td>
<td>01 Sep 2011</td>
<td>0.0</td>
<td>0</td>
<td>6.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Ophelia</td>
<td>29 Sep 2011</td>
<td>10.3</td>
<td>-13</td>
<td>4.9</td>
<td>3.8</td>
</tr>
</tbody>
</table>

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 6-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 11,484 km from East to West and 7,524 km from North to South, encompassing the western portion of the Northern hemisphere. The inner domain is 1,584 km on each side and automatically moves to track the center of the TC as defined by the vorticity centroid at 700 hPa. Two-way nesting, in which information is transferred both from the parent to the inner domain and from the inner to the parent domain, is implemented.

The “Advanced Hurricane” option of WRF is used which makes modifications to the model parameterizations 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 and constant deep-water lapse rate 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 km and 4/3 km grid spacing. These two innermost domains explicitly resolve convection and thus do not use a cumulus parameterization 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 km and 4/3 km ensemble analyses were not produced by the EnKF system described above. The initial condition perturbations must also then be interpolated from 12 km, and when perturbed the behavior 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-centered domain. The center of the storm is defined by minimizing the magnitude of the horizontal wind vector within a window centered on the point of minimum pressure. When multiple levels are considered in Section 4.2, the centering process is performed at each level so that the storm is vertically aligned along the center axis.

Figure 2 shows the sensitivity of the analysis tangential wind at the third model level to the circulation forecast metric for each test case. This indicates the change in the analysis field that will yield a change of $\alpha^* (3.41 \times 10^{-5} \text{ s}^{-1})$ in the metric 24 hours 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 (Fig. 2b), Earl 30 (Fig. 2c) and Igor (Fig. 2d), or in a broader region such as in Bill (Fig. 2a), Katia (Fig. 2e) and Ophelia (Fig. 2f). 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 enhances the radial gradient of 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 promotes an annular storm structure, as opposed to a monopole where the vorticity is greatest in the center. This pattern is not only evident in the analysis tangential wind, but also the analysis relative vorticity, the radial profile of the sensitivity of which is presented in Figure 3. The sensitivity is annular in the case of Bill, Earl 30, and Katia, and has a secondary maxima away from the center in the case of Earl 29 and Ophelia. There is ample observational and theoretical evidence that this vorticity configuration is essential for the intensification of hurricane-like vortices (e.g., Rogers et al. 2013; Montgomery et al. 2000; Kossin and Eastin 2001). A vorticity annulus can be barotropically unstable, leading to mesovortices and asymmetric flow structures on the eyewall, which are hypothesized to contribute to hurricane intensification through potential vorticity mixing (e.g., Schubert et al. 1999; Kossin and Schubert 2001).

Figure 2. The storm-centered ensemble mean (contours, m s\(^{-1}\)) and sensitivity to the forecast metric (shading, m s\(^{-1}\)) of the analysis tangential wind at the third model level for (a) Bill (2009), (b) Earl 29 (2010), (c) Earl 30 (2010), (d) Igor (2010), (e) Katia (2011), and (f) Ophelia (2011). Areas which are statistically significant at the 95\% confidence level are unstippled. The horizontal and vertical axes indicate kilometers East and North from the center of the hurricane, respectively.
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 if 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 to 150 hPa and 700 to 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 other characteristics 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 for 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.

Sensitivity to column integrated water vapor (Figure 4) is found mainly near the center of the storms or in a ring around the center in the most intense cases, such as Bill (Fig. 3a) and Earl on 30 August (Fig. 3c). The sensitivity patterns also show positive sensitivity in banded structures from the inner core to several hundred kilometers in radius, which indicate that moistening these areas in the analysis leads to increased circulation 24 hours later. The banded areas of positive sensitivity specifically appear in regions threatened by dry intrusions: southeast of the storm center in Bill (Fig. 4a), north of the storm center in Earl 29 (Fig. 4b), southwest of the storm center in Earl 30 (Fig. 4c), west of the storm center in Igor (Fig. 4d), southwest of the storm center in Katia (Fig. 4e) and south of the storm center in Ophelia (Fig. 4f); 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 center, these are generally not statistically significant. This is an indication that the inner core and the several hundred kilometers surrounding it is an important region for determining hurricane intensification. There is also the interesting implication that moistening outside of 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 not only the axisymmetric sensitivity of water vapor mixing ratio, but also the sensitivity of the analysis relative humidity.

4.2. Composite sensitivity

To reduce dimensionality and determine patterns common to the sample, we consider now the sample-mean axisymmetric component of the sensitivity field. Specifically, we examine the tangential and radial wind, perturbation potential temperature\(^*$, water vapor 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

---

\(^*$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, a stronger (weaker) storm, in the 24-hour 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 important 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 hours later. This pattern of sensitivity suggests that a stronger secondary circulation in the analysis is associated with a stronger storm in the 24-hour 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-hour 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-hour forecast.

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-hour 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 vapor mixing ratio reveals local maxima in the boundary layer extending from the center of the storm to two and a half times the RMW, in the mid-troposphere from two to three times the RMW, and in the lower troposphere in the eye and eyewall region (Figure 8). This pattern implies that an axisymmetric moistening of the rainband region outside of the eyewall, in addition to moistening the boundary layer and lower troposphere in the inner core, should result in a stronger circulation in the 24-hour forecast. This axisymmetric moisture sensitivity is consistent with the sensitivity of the column integrated water vapor shown for each test case above. The plan view sensitivity shown in Fig. 4 exhibits a spiral band pattern outside of the RMW, which projects upon the axisymmetric component of the sensitivity. Although this rainband sensitivity pattern appears in the majority of cases (not shown) and the composite mean, it is apparently accompanied by little or no secondary wind and potential temperature sensitivity maxima.

An alternate assessment of moisture sensitivity is given by the axisymmetric relative humidity (RH) (Fig. 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 center 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 vapor 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 cases are perturbed with sensitivity patterns defined by Equation (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 of all of the prognostic variables, for values of $\alpha$ which are multiples of $\alpha^* \,(3.41 \times 10^{-5}\,\text{s}^{-1})$, up to six times $\alpha^*$; this maximum prescribed $\alpha$ ranges from 27% (Earl 30) to 43% (Igor) of the mean 24-hour forecast metric of the test cases. Due to computational constraints, only the ensemble member closest to the ensemble mean (with respect to the 24-hour metric) for each test case is perturbed. 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 $-2 \times 10^{-4}\,\text{s}^{-1}$ 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 non-linearity. 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 modeled 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 the ‘dry’ experiments, perturbations to the water vapor, cloud water, rain water, cloud ice, snow and graupel mixing ratios are set to zero. To test the relative role

---

\[ r^* (r/RMW) = \frac{r}{RMW} \]

\[ q_{jp} = q_{j} - q_{p} \]

Figure 8. As above, but for the analysis axisymmetric water vapor mixing ratio (kg kg$^{-1}$).

Figure 9. As above, but for the analysis axisymmetric relative humidity (%).
of moisture, hereafter the ‘moist’ experiments, perturbations to the zonal and meridional wind, vertical motion, and perturbation potential temperature and pressure are set to zero. The results of these experiments show that in every case except Earl on 29 August 2010, 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 further evaluate the behavior of the three perturbed experiments, the evolution of the forecast 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 center of the storm (Figure 12c, 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 (Fig. 12b, d, e). This behavior is similar to that described by Kossin and 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, in cases such as Katia (Fig. 12e) and Ophelia (Fig. 12f) the dry and/or fully perturbed experiment retain an annular profile. In all test cases, the dry and fully perturbed experiments maintain higher PV values throughout the forecast at outer radii than the moist experiment.

As described in Section 3.2, two test cases were simulated in higher resolution ensembles which have additional nested domains of 4 km 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 hours 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 similar model response when perturbed (not shown). Both a dry and moist experiment 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), as in Rogers et al. (2013). The eyewall is defined as .75 times the RMW to 1.25 times the RMW; depending on the RMW, the number of grid points in each height bin for each experiment varies between 10000 and 11000. The percentiles are shown as they evolve through the forecast. Throughout the forecast, the middle of the distribution is virtually identical for all experiments and the control, but differences emerge at the tails of distribution. During the first six hours of the forecast, all perturbed experiments have stronger updrafts than the control in the higher end of the distribution, and the moist experiment has stronger downdrafts between 4 and 6 km at the extreme low end of the distribution compared to the other experiments (Fig. 13a). By the end of the forecast (Fig. 13b) the 99.9th percentile of the fully perturbed and dry experiments are nearly 5 and 2 m s^{-1} greater than the control in their strongest extreme updrafts located at a height of 6 km. In contrast, the moist experiment has weaker extreme eyewall updrafts than the control at all but a few heights (e.g., 5 km), and has stronger extreme eyewall downdrafts than the unperturbed case above 6 km. 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 intensifying storms exist on a spectrum from non-intensifying through moderately intensifying and 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 updrafts. It is also confirmed here that the largest differences in the extreme updrafts are seen above the height of the freezing level (4 to 5 km).

6. Summary and Conclusions

Systematic numerical modeling 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 through this systematic modeling approach was to conduct novel compositing of ensemble sensitivity analysis to find commonalities in sensitivity to storm structure between several cases of hurricane intensification and then to use this as a guide for further

---

Figure 11. The prescribed change in metric ($\alpha$, 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), and when only the moist variables are perturbed (blue) for (a) Bill (2009), (b) Earl 29 (2010), (c) Earl 30 (2010), (d) Igor (2010), (e) Katia (2011), and (f) Ophelia (2011).
Figure 12. The axisymmetric potential vorticity (PVU; $10^{-6} \text{Km}^2\text{kg}^{-1}\text{s}^{-1}$) at 850 hPa as a function of radius (km). Shading indicates the analysis (light), 12 hour forecast (medium), and 24 hour forecast (dark), and the fully perturbed experiment (gray shades), dry experiment (red shades), and moist experiment (blue shades). 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). Dry PV is shown, therefore the analysis of the fully perturbed and dry experiments are nearly identical and the analysis of the moist perturbed approximates the unperturbed control analysis.

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 of the RMW is associated with a stronger forecast TC. This pattern of moisture sensitivity is also found in the three hour forecast, as well as in high-resolution ensembles of two of the test cases (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 non-linearity 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 toward a monopole. High resolution (4 km and 4/3 km) simulations of Earl and Igor showed that the dry and fully perturbed experiments exhibit increasingly larger extreme eyewall updrafts as the forecast progresses compared to the unperturbed control; however, the moist experiment shows little difference from the control. Rogers et al. (2013) showed that this type of difference is associated with a stronger and deeper layer of updraft mass flux in Doppler observations of hurricanes.

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 of the RMW. The sensitivity results here indicate the same for intensifying storms, with the exception of the moisture sensitivity. Unlike Rogers et al. (2013) though, it cannot be determined 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.

Acknowledgement

The authors are grateful to Prof. Ryan D. Torn of the University at Albany, State University of New York, for providing the ensemble analyses of the test cases shown here. We also wish to thank Professors Dargan Frierson and Robert A. Houze, Jr., for their input on this work as members of the first author’s PhD thesis committee. This work was funded in part by NSF grant AGS-0842384. Computing resources were made available on NCAR CSDL’s Yellowstone high-performance computing resources (Laboratory 2012).
References


