The Environmental Sensitivity of Hurricane Irene's (2011) Structural Evolution

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UNIVERSITY OF MIAMI

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

THE ENVIRONMENTAL SENSITIVITY OF HURRICANE IRENE’S (2011) STRUCTURAL EVOLUTION

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Over the past 20 years, tropical cyclone (TC) track forecasts have improved significantly while intensity forecasts have improved little. Part of the reason for this lack of improvement in intensity forecasts is a lack of understanding behind the physical mechanisms that control the size and structure of a TC. Previous studies on TC structure have largely focused on wind shear, or have been conducted using idealized TC simulations. This study examines the influence of synoptic-scale vorticity interactions and moisture on the structural evolution of a real hurricane. Simulations were conducted using the Advanced Weather Research Weather Research and Forecasting Model (WRF-ARW) in which the initial conditions were perturbed in order to examine which features may have played a role in the structural evolution of Hurricane Irene (2011). Irene was chosen as a case study given the unique forecasting challenges of this storm in which the track was very well forecast, while the intensity and structure were forecast with skill below the five-year average. The experiments showed that Irene showed little structural sensitivity to vorticity perturbations (except in cases of very strong perturbations), indicating that Irene was not exceptionally sensitive to the larger scale synoptics within the model. Irene did however show significant sensitivity with respect to moisture, where even a small perturbation in the core moisture of Irene led to noticeable changes in the track, intensity, and structure of the storm. This study concludes that even storms in
which there is little sensitivity to larger scale synoptic features, significant sensitivity may still exist in other fields, most notably, moisture. This sensitivity emphasizes the importance of properly observing and initializing moisture fields within forecast models.

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Chapter 1: Introduction
1.1 Background and Research Questions

Since 1990, there have been significant improvements in tropical cyclone (TC) track forecasts. The 72-hour track forecast errors from the National Hurricane Center (NHC) have decreased from about 300 nautical miles (556 km) to about 100 nautical miles (185 km) in 2012. On the other hand, there has been little decrease in intensity forecast errors. In 1990, the average intensity error for a 72-hour forecast was about 20 knots (10.3 m s\(^{-1}\)) compared with 17 knots (8.7 m s\(^{-1}\)) in 2012.

While a lot of research focus has been given to intensity forecast errors with respect to maximum sustained winds (\(V_{\text{max}}\)) or minimum sea level pressure (MSLP), what if instead we could predict if a TC would consist of a large, diffuse wind field, or a small, compact intense wind field? The prediction of the storm structure enables users to better understand the areal extent over which hurricane-force winds may arise and how severe those winds may be, rather than just using one value of \(V_{\text{max}}\) since the peak winds will often only be felt very near the center of the TC. Knowing the structure of a TC at landfall could also help forecasters to better predict the areal extent and amount of rainfall a TC may produce over inland areas. This would provide more advanced information on the extent of necessary coastal evacuations, ship rerouting, and the scope of impacts. Additionally, it has been found by Irish et al. (2008) that the coastal storm surge associated with a landfalling TC is strongly related to the size of the wind field. According to the NHC, storm surge poses the greatest threat to life and property along the coast with storm surge being responsible for the most deaths from hurricanes in the United States (Rappaport 2014). The accurate prediction of storm size and structure is therefore crucial to understanding the overall scope of hazards at
landfall, including impacts from wind, rainfall, and coastal storm surge.

Some of the large-scale factors affecting TC genesis, structure, and intensification have been known for some time. Gray (1968) was one of the first studies to discuss the conditions in environments conducive for TC formation and intensification, including warm sea surface temperatures (SST), convective instability, a relatively moist lower and middle troposphere, a minimum distance from the equator, a pre-existing source of relative vorticity, and weak vertical wind shear. His study used observations in tropical cyclone environments to form a climatology of convective instability, low-level wind profiles, vertical wind shear, and relative humidity, as well as SSTs, time of year, and location of storm environments that supported the development and intensification of TCs. Results showed that TCs are most likely to form and strengthen in environments of weak vertical wind shear, relatively humid and deep moisture profiles, and warm SSTs in areas at least five degrees of latitude away from the equator in tropical oceans. These are the factors most commonly taken into account by forecasters when determining whether a TC will intensify or weaken, and while these factors may produce large-scale environments conducive for strengthening or weakening, it is not fully understood if they play a role in the structural evolution of the TC.

Through the use of models, later studies would provide some key findings into where the strongest winds and most intense precipitation are found within a TC. Frank and Ritchie (1999) used numerical simulation of TCs to hypothesize that differential vorticity advection (with height) caused by shear forces large-scale ascent on the downshear, left side of the TC, resulting in low-level convergence, thus allowing for the most active convection to occur in this region of the TC. Rogers et al. (2003) found in simulations of Hurricane Bonnie (1998), in which vertical wind shear profiles were varied in the near-storm environment, that the
most intense convection in a TC, as well as the heaviest precipitation, occurred on the
downshear-left side of the storm. They also found that the rainfall pattern was more
asymmetric when the wind shear direction was along-track rather than across-track. Further
examining the effects of wind shear on precipitation, Uhlhorn et al. (2014) used aircraft
observations from 128 missions between 1998 and 2011 and found that there is a dependence
of the radius of maximum winds (RMW) on the vertical wind shear magnitude, with the
wind maximum being found on the downshear left side of the TC. They found that storm
asymmetries at the surface are not directly linked to storm forward speed, but that vertical
wind shear tends to drive surface asymmetries, with wind and precipitation maxima typically
being found on the downshear-left side of the storm, regardless of the storm’s heading and
shear direction. This tendency for the most intense convection to occur on the downshear left
side of a TC, supported by both modeling (Frank and Ritchie 1999, Rogers et al. 2003) and
observational studies (Uhlhorn et al. 2014).

Another mechanism that is influential on TC structure is the interaction between a TC
and synoptic-scale, midlatitude features. Numerous studies have been conducted on these
interactions. Molinari et al. (1995) examined the interaction between Hurricane Elena (1985)
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that the exact mechanism was uncertain, it was hypothesized to be that the upper-level
potential vorticity (PV) anomaly associated with the approaching trough was strong enough
to support enhanced ascent within Hurricane Elena, but not so strong as to shear the
hurricane apart. Molinari et al. (1995) further stated, “Such outflow-layer interactions represent a fruitful area for further research into tropical cyclone intensity change.” Building on this study in using PV as a diagnostic for TC intensification, Atallah and Bosart (2003) examined the extratropical transition of Hurricane Floyd (1999). They investigated the quasi-geostrophic (QG) dynamics of the synoptic-scale interactions between Floyd and an approaching upper-level trough, and found that the interaction between the hurricane and a midlatitude trough created a baroclinic zone and deep isentropic ascent which lead to large amounts of precipitation production along the east coast of the United States. They found that as the upper-level trough over the Midwestern United States approached Floyd, the thickness gradient between the Floyd and the trough tightened, resulting in large-scale QG ascent over the eastern United States. This large area of enhanced ascent resulted in a very broad area of heavy precipitation north and west of Floyd, extending from coastal South Carolina northwards to Maine. At the time, these processes were difficult to simulate in numerical models due to the strong impact of diabatic heating on the synoptic-scale mass field. Finally, Jones et al. (2003) summarized much of the work on ET up until that time by examining previous studies, as well as compiling a climatology of TC changes during ET. It is fairly well established that as the TC warm core is eroded, a TC tends to accelerate in forward speed, weaken, increase in size, and become more asymmetric during ET due to increases in vertical wind shear. While the vertical wind shear may act to initially weaken a TC undergoing ET, enhanced upper-level divergence associated with the exit region of a jet stream (Uccellini and Kocin 1987), and increasing thermal advection, may allow for a TC that has completed ET to actually reintensify into a powerful mid-latitude cyclone. This process was observed recently in Hurricane Sandy (2012) in which very strong upper-level
outflow and baroclinic forcing acted to intensify and greatly expand the size of the wind radii associated with Sandy (Blake et al. 2013, Galarneau et al. 2013).

Molinari et al. (1995), Atallah and Bosart (2003) and Jones et al. (2003) largely focused on the physical processes at work during ET. In a study to examine these processes in the context of numerical weather prediction, Komaromi et al. (2011) examined initial condition sensitivity of WRF-ARW track forecasts of Typhoon Sinlaku (2008) and Hurricane Ike (2008) by performing relative vorticity perturbations, and rebalancing the mass, momentum, and thermodynamic fields. Their study found that there was substantial track sensitivity when perturbations were performed on synoptic-scale features that are believed to have influenced the track of both storms (Figure 1.1). Similarly, Brennan and Majumdar (2011) assimilated synthetic temperature “observations” into the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) model in order to examine the influence of synoptic-scale features on the track of Hurricane Ike (2008). The perturbed forecasts were then compared against the operational GFS forecasts. The study found “…that multiple sources of error exist in the initial states of the operational models, and the correction of these errors…would lead to improved forecasts of TC tracks…” Majumdar et al. (2013) performed data denial experiments in the GFS to examine the impact of supplemental dropsonde observations from aircraft surveillance as well as rawinsondes on the track forecasts for Hurricane Irene (2011). The study found that the supplemental observations resulted in a small improvement of the track forecasts by correcting the model analyses for an Atlantic subtropical ridge, and upstream mid-latitude shortwave trough over the continental United States.
Figure 1.1: from Fig. 4 in Komaromi et al. (2011), "The 5-day WRF track simulations initialized 0000 UTC 10 Sep 2008 for perturbations at targets (a) S1 and (b) S2. Each dot represents a 1-day forecast increment." The legend refers to the maximum strength of the relative vorticity perturbation. For instance, +0.75ζ refers to a perturbation in which relative vorticity was increased by a factor of 75% (this method is discussed in more detail in Chapter 2).

While the previous studies largely focused on the effects of wind shear, ET, and synoptic-scale interactions, another major factor that has been examined in TC size and structure is moisture. Hill and Lackmann (2009) used the Advanced Weather Research Weather Research and Forecasting Model (WRF-ARW) to perform idealized simulations of TCs in which they varied the moisture in order to examine the effect of moisture on the RMW. They found that increasing the moisture content led not just to a stronger storm, as would be expected (Gray 1968), but also a larger storm (Figure 1.2). They hypothesized “…that the size of a TC wind field is related to environmental relative humidity, to which in turn the intensity and spatial distribution of precipitation outside the eyewall are sensitive.”

This expansion of the precipitation area led to potential vorticity (PV) generation outside of the eyewall, leading to an expansion of the TC vortex, and thus an expansion of the wind field associated with the TC. PV is conserved in frictionless, adiabatic flow regimes. While TCs involve large amounts of heat release via diabatic processes, as Brennan et al. (2008) pointed out, “…it is precisely because PV is not conserved in the presence of diabatic
processes that evidence of nonconservation can be utilized to unambiguously identify the contribution of specific diabatic processes to the PV field…” In other words, we can take advantage of the fact that PV is not conserved when diabatic processes are occurring in order to diagnose PV generation (or destruction) as a direct result of diabatic heating (or cooling). Brennan et al. (2008) additionally pointed out that latent heating associated with precipitation processes increases static stability below the level of maximum heating, lowering geopotential heights, and thus increasing absolute vorticity via flow convergence into the resulting area of lowered pressure. Both of these mechanisms for generating or destroying PV (absolute vorticity increases via pressure falls and convergence, and diabatic heating leading to an increase in potential temperature gradient) will be crucial in this research.
Figure 1.2: from Hill and Lackmann (2009), "Times series of TC wind field parameters for each simulation as specified in the legend, with application of a 1-2-1 smoother: (a) radius of maximum 10-m wind speeds (km) and (b) maximum radius of hurricane-force 10-m wind speeds. Values computed from azimuthally-averaged model 10-m wind speeds." Simulations were conducted with varying moisture profiles ranging from 80% relative humidity ("80RH") to 20% relative humidity ("20RH").

The aforementioned studies predominantly examine the impact of wind shear (Uhlhorn et al. 2014, Rogers et al. 2003), use idealized simulations (Hill and Lackmann 2009), focus on track forecasts (Komaromi et al. 2011, Brennan and Majumdar 2011, Majumdar et al. 2013), or examine precipitation distributions (Atallah and Bosart 2003 and Rogers et al. 2003). This study aims to examine features beyond wind shear, in particular interactions between synoptic-scale features and the TC, and moisture, and study these interactions in the context of the structural evolution of a real TC as opposed to a TC
simulated in an idealized framework. Further, this study will largely investigate the evolution of the TC wind field by performing both initial condition sensitivity experiments similar to the methodology used by Komaromi et al. (2011). Finally, this study will take advantage of PV nonconservation as a useful diagnostic for assessing diabatic heating (Brennan et al. 2008) by varying moisture in the TC environment similar to Hill and Lackmann (2009) in order to determine the role of moisture in the structural evolution of a TC.

There are two main questions that will be investigated in this study:

(1) **How is the structural evolution of a TC sensitive to the model initialization of certain mid-latitude, synoptic-scale features?** In other words, through the use of initial condition sensitivity tests, how do vorticity interactions between the TC, and features such as fronts, longwave troughs and ridges, and shortwave troughs and ridges play a role in the evolution of a TC’s wind field? Do these features affect the size of the wind field? Do these features and interactions play a role in the distribution of rainfall near the core of the TC? This study will expand on Atallah and Bosart (2003) by performing initial condition vorticity perturbations in order to investigate which features may have played a role in the structural development of a real TC, or caused a TC to weaken or intensify, and what physical mechanisms drive these changes (if any).

(2) **How does the structure of a TC evolve within a model given changes in (or differences in analysis of) the initial moisture field?** In this study, the initial moisture field in and around a real TC will be perturbed in order to investigate the sensitivity of the forecast wind field to the initial moisture profile.
1.2 Selecting a Storm to Study: Hurricane Irene (2011)

Hurricane Irene (2011) was a large, destructive storm that caused over $15 billion (in 2011 USD) in damages and 49 fatalities (Avila and Cangialosi 2011). Irene’s genesis was well forecast with the NHC predicting genesis about 24 hours in advance (and a low probability of genesis within 72 hours). The track for Irene was also well forecast, with mean track errors considerably lower than the five-year average. The forecast was also very consistent, with the official forecast track indicating that Irene would affect the east coast of the United States once the storm reached the Bahamas (Figure 1.3a). Avila and Cangialosi (2011) also noted that the GFS and ECMWF models had lower mean errors than the official forecast. The GFS Ensemble Forecast System (GEFS) showed very tight clustering of the track forecasts through at least 144 hours (Figure 1.3d). This indicates that there was potentially little track sensitivity to the large-scale environment within the GFS forecast with respect to cross-track errors, though the GFS did exhibit a slight along-track error with the GFS forecast too slow late in Irene’s life.

On the other hand, the NHC intensity forecasts had larger errors than the five-year average, with a consistent high-bias noted (Figure 1.3b). Avila and Cangialosi (2011) concluded that despite favorable large-scale environmental conditions (warm SST, ample environmental humidity, and weak vertical wind shear), the storm weakened, but the wind field expanded, possibly due to an incomplete eyewall replacement cycle in which the inner eyewall dissipated, but the outer eyewall did not contract, resulting in a large, diffuse wind field (and lower MSLP) instead of a small, compact intense wind field, as was predicted (Figure 1.3c). Avila and Cangialosi (2011) also suggested that there existed a consistent high-bias in the operational analysis of Irene due to the reluctance of forecasters to use the
lower stepped-frequency microwave radiometer (SFMR) winds when the MSLP and observed flight-level winds suggested that the surface winds should be stronger. It is possible that due to the weakened convective activity in the eyewall and spiral bands of Irene, following the incomplete eyewall replacement cycle, high winds aloft were unable to mix down to the surface.

Figure 1.3: From Avila and Cangialosi (2011), (a) all NHC official track forecasts for Hurricane Irene (black) and best-track (white), (b) all NHC official intensity forecasts (colored lines) and best-track intensity (black), (c) all NHC official wind radii forecasts for the northeast quadrant (colored lines) and best-track northeast quadrant gale force wind radius (black), and (d) GEFS forecast for Hurricane Irene initialized at 0000 UTC 23 August 2011 (image source: Clark Evans, University of Wisconsin – Milwaukee).

Given the skillful track forecast from the models and human forecasters, but the below average intensity forecast, arising from not accurately predicting the structural evolution of Hurricane Irene, Irene is an excellent case study for investigating the factors that
may have influenced the storm structure. This study utilizes the perturbation technique developed by Komaromi et al. (2011), and combines it with Hill and Lackmann’s (2009) approach of varying moisture, to modify the forecast of the structural evolution of Irene, in order to identify the synoptic-scale features and environmental factors that played a role in the cyclone’s evolution.

1.3 Meteorological Overview of Hurricane Irene

Irene formed within a vigorous tropical wave at 0000 UTC 21 August 2011 about 220 km east of Martinique. Irene moved west-northwestward, steered by a subtropical ridge to its north, becoming a hurricane by 0600 UTC on the 22nd. Strengthening would be delayed as Irene passed near Hispaniola and interacted with the island’s mountainous terrain. As Irene moved away from Hispaniola on the 24th, it began strengthening once again, reached major hurricane status, attained a peak intensity of 55 m s\(^{-1}\), and a MSLP of 957 hPa at 1200 UTC on the 24th while passing through the Bahamas. At this time, Irene had a small eye of 33 km in diameter and a gale-force wind radius of about 335 km in the northeast quadrant (the largest radius of the four quadrants). Figure 1.4a shows the best-track \(V_{\text{max}}\) and MSLP, and Figure 1.4b shows the best-track gale-force wind radii in each quadrant (Avila and Cangialosi 2011). It is noted that from around 1200 UTC on the 24th until 0600 UTC on the 26th, despite the storm deepening (i.e. MSLP decreasing), the \(V_{\text{max}}\) weakened as the gale force wind radii expanded in all quadrants.
A mid-tropospheric trough developed over eastern North America on the 24th, with the subtropical ridge over the Atlantic Ocean shifting to the east. This allowed Irene to begin a northward turn. At the same time, the wind radii continued to expand in all quadrants. Irene reached its lowest MSLP of 942 hPa at 0600 UTC on the 26th with a radius of gale-force winds in the northeast quadrant of 465 km (an increase of 40% despite a $V_{\text{max}}$ decrease of 20%). Using standard pressure-wind relationships for the North Atlantic (Velden et al. 2006), an MSLP value of 942 hPa suggests that the $V_{\text{max}}$ should have been around 65 m s$^{-1}$, when in fact it was around 45 m s$^{-1}$ at that time.

Irene continued to the north with the peak winds continuing to weaken, and the pressure bottoming out on the 26th at 0600 UTC. Thirty hours later, Irene made landfall near Cape Lookout, North Carolina with $V_{\text{max}}$ of 38 m s$^{-1}$ and MSLP of 952 hPa. By this time, the radius of gale force winds had contracted slightly to 415 km in the northeast quadrant, but was still larger than when Irene was at peak intensity. Irene made its final landfall near Coney Island, New York about 24 hours later as a tropical storm with $V_{\text{max}}$ of 28 m s$^{-1}$ and
MSLP of 965 hPa. Finally, Irene became extratropical at 0000 UTC on the 29th over northern Vermont. As an extratropical cyclone, Irene brought very heavy rains to Vermont, resulting in the worst flooding the state had seen since 1927 (Avila and Cangialosi 2011).

Figure 1.5: infrared satellite imagery of Hurricane Irene at 0000 UTC on the dates indicated (source: University of Wisconsin-Madison Cooperative Institute for Meteorological Satellite Studies). The final panel (August 28th) shows Hurricane Irene exhibiting classic structure for a TC undergoing ET given the large asymmetries in associated cloud cover (Jones et al. 2003), and the expansive area of precipitation to the north of Irene as warm, moist ascent into the baroclinic zone over New England resulted in heavy rainfall production (Klein et al. 2000, Atallah and Bosart 2003).
Chapter 2 : Methodology  
2.1 Model Description

In this study, version 3.5 of WRF-ARW (Skamarock et al. 2005) is used. WRF is well-documented, and is widely used throughout the community, making it a good model for performing meteorological experiments. The model will be integrated at 9 km spatial resolution for 168 hours (7 days). A large domain containing much of the North American continent, the northern Atlantic basin, and the northern Pacific basin is used (Figure 2.1) in order to allow for distant perturbations to be performed. The microphysics parameterization scheme is the WRF Double-Moment Six-Class Scheme (Lim and Hong 2010). Since the model is being run at too coarse of a resolution to resolve convective elements, the Kain-Fritsch Convective Scheme (Kain and Fritsch 1990) is used for cumulus parameterization. The model is initialized at 0000 UTC on 23 August 2011 when Irene was already a mature TC. This initial time was chosen so as to avoid “spin up” issues with tropical cyclogenesis (since genesis is not the subject of this study), and to be able to capture the peak intensity phase on the 24th, the wind field expansion on the 26th, and the extratropical transition on the 29th. Given the skillful forecast from the GFS, the GFS forecast (0.5 degree resolution GRIB2) initialized at 0000 UTC August 23, 2011 is used for the WRF initial and boundary conditions.
Figure 2.1: Domain configuration for WRF-ARW experiments used in this study. A large domain containing much of North America was used in order to perform distant vorticity perturbations.

The WRF output is evaluated using a combination of qualitative and quantitative analysis of fields such as wind, pressure, rainfall, vorticity, and geopotential height. The storm position is computed in order to evaluate track error with intensity forecasts being compared to $V_{\text{max}}$ and MSLP. The structural evolution forecast is evaluated by examining the wind radii in each quadrant, RMW, thickness anomaly, and 200 hPa divergence. DeMaria et al. (2005) used 200 hPa divergence as a proxy for TC outflow. By taking advantage of Green’s theorem (also known as the two-dimensional divergence theorem as shown in Equation 1), it can be shown that the azimuthally, area-averaged divergence of
some vector field $\vec{F}$ is equal to the outward directed flow normal to the boundary enclosing the area. Thickness anomaly is defined as the difference between the azimuthally averaged 850-200 hPa thickness within 1,000 km of the TC center (environmental thickness) and the 850-200 hPa thickness with 100 km of the TC center (core thickness). The WRF forecast is compared against both the NHC best-track and the GFS analysis at each valid time. Finally, a control forecast is performed by using the GFS for initial and boundary conditions and integrating WRF forward in time seven days without any perturbations being used. This control forecast is used as a baseline for comparison between various perturbation experiments.

$$\int\int_D \nabla \cdot \vec{F} \, dS = \oint \vec{F} \cdot \hat{n} \, ds$$ (1)

### 2.2 Vorticity Perturbation Technique

The vorticity perturbation technique used in this study was developed by Komaromi et al. (2011) in order to test initial condition sensitivity of TC track forecasts. The technique allows a user to input the latitude and longitude of a relative vorticity perturbation, the top and bottom of the vorticity perturbation ($p_{\text{top}}$ and $p_{\text{bot}}$, respectively), the radius of the perturbation (R), and the “perturbation parameter” ($\alpha_{\text{max}}$). The perturbation parameter represents the amount by which the original vorticity field ($\zeta_0$) is increased or decreased (by adding/subtracting $\alpha \zeta_0$ to $\zeta_0$ as in Equation 2), and is a dimensionless factor that decays away from the center of the perturbation radius R. The amount of perturbation at some distance away from the center (r) at pressure altitude (p) is given by Equation 3:

$$\zeta_1 = \zeta_0 + \zeta' = [1 + \alpha(a,p)]\zeta_0$$ (2)
The new relative vorticity field \( \zeta_1 \) is expressed as the sum of the original vorticity field \( \zeta_0 \) and the perturbation relative vorticity field \( \zeta' \) as in Equation 3:

\[
a(r, p) = 2 \frac{R-r}{R} \frac{p-p_{top}}{p_{bot}-p_{top}} \alpha_{\max}, r \leq R, p_{top} \leq p \leq p_{\text{mean}}
\]

\[
a(r, p) = 2 \frac{R-r}{R} \frac{p_{bot}-p}{p_{bot}-p_{top}} \alpha_{\max}, r \leq R, p_{\text{mean}} \leq p \leq p_{bot}
\]

\[
a(r, p) = 0, r > R, p \leq p_{\text{top}}, p > p_{\text{bot}}
\]

After perturbing the relative vorticity field, the mass, momentum, and thermodynamic fields must be rebalanced. Given that the streamfunction is the inverse Laplacian of the relative vorticity field, a successive over-relaxation technique can be used to invert the Laplacian and solve for the streamfunction. This process will recalculate the wind field over the entire domain, though the changes tend to be small, but non-zero, far from the initial perturbation. The wind field can then be solved from the streamfunction, then using geostrophy and hydrostatic balance, the height and temperature fields can be derived. An example of a vorticity perturbation in which a mid-latitude trough over eastern Ontario and western Quebec was deamplified substantially is shown in Figure 2.2.
Figure 2.2: (a) 700-300 hPa layer mean relative vorticity difference field (perturbed forecast – control forecast), (b) 500 hPa height (control, solid; perturbed, dashed; difference field contoured), (c) meridional wind difference fields, and (d) a cross-section of the relative vorticity difference field (shading) and control forecast geopotential heights (solid contours) valid 0000 UTC 26 August 2013. The path of the cross-section is indicated by the solid black line in (a). Note the difference in color scales between (a) and (d) due to the differing magnitudes between layer-averaged relative vorticity and the relative vorticity at individual levels. The longwave trough over eastern Canada was deamplified by weakening the relative vorticity in the base of the trough, resulting in weakened southerlies (northerlies) on the west (east) side of the trough.

The vorticity perturbation technique is used to perturb mid-latitude features that may have impacted the track and structure of Hurricane Irene, such as a large mid-latitude trough over eastern North America that caused Irene to turn northward as it passed through the Bahamas or the subtropical ridge over the Atlantic Ocean. This technique will also be used to perturb the TC vortex in order to test the sensitivity of track and structure to vortex depth and intensity.
2.3 Moisture Perturbation Technique

While vorticity perturbations can be useful in testing initial condition sensitivity to synoptic-scale features, moisture may be a more important quantity when it comes to storm structure and intensity (Hill and Lackmann 2009). In this study, a moisture perturbation technique similar to the vorticity perturbation technique used in Komaromi et al. (2011) is used where water vapor mixing ratio is perturbed similarly in which the perturbation magnitude decays with distance away from the center of the perturbation. After perturbing the moisture field, the mass, momentum, and thermodynamic fields can be rebalanced using the hypsometric equation and geostrophy. The equation for the moisture perturbation is identical to Equations 1 and 2, except water vapor mixing ratio (q) is used instead of relative vorticity (ζ). Figure 2.3 is an example of a dry perturbation experiment in which moisture was removed from the environment ahead of Hurricane Irene at 1200 UTC 23 August 2011.

![Figure 2.3](image)

Figure 2.3: (a) moisture perturbation experiment in moisture was removed from the environment ahead of Hurricane Irene at 1200 UTC 23 August 2011, and (b) a vertical cross-section through the perturbation maximum showing the vertical extent of the perturbation applied in the lower troposphere. The black line in panel (a) represents the path of the cross-section and the red dot indicates the center of Hurricane Irene.

In this study, moisture perturbation experiments within the core of the storm will primarily involve drying the storm environment, as supersaturating the storm environment...
could degrade the model forecasts by resulting in excessive heating in the model via the
cconvective parameterization scheme (Mapes, 2014, personal communication). Experiments
will also be done in which moisture in the surrounding storm environment is increased in
areas where the atmosphere is not completely saturated.

2.4 Control Forecast

A WRF-ARW control forecast is used in order to have a baseline to compare the
perturbed forecasts against. WRF is setup using the physics schemes, boundary conditions,
and setting described in Section 2.1 of this study. In order to ensure this control forecast was
an accurate representation of Irene, the control forecast was compared against the GFS
analysis at each valid time. A comparison between the control forecast and GFS analysis
track (a), intensity (b), and radius of maximum winds (c) are shown in Figure 2.4. The WRF
control forecast had very little cross-track error, and was only slightly slow compared to the
analysis. While the intensity varies somewhat between the control and analysis due to the
differences in resolution between WRF (9 km) and the GFS GRIB2 data (0.5 degrees, about
50 km at 30 degrees latitude), the general trends of $V_{\text{max}}$ and MSLP for both are similar.
Finally, both show similar trends in the RMW. For the first 24 hours or so, Irene was fairly
asymmetric, but became fairly symmetric for the period from 0000 UTC on the 24th until the
0000 UTC on the 28th, at which time Irene began the early stages of extratropical transition
(ET). Both the WRF control forecast and the GFS analysis show the steady growth of the
RMW in all quadrants between the early asymmetric period, and the later ET period. Figure
2.5 contains a comparison between the thickness anomaly for the control forecast (a) and the
GFS analysis (b). Given that the control forecast showed similar track, intensity, and
structure to the GFS analysis, the control forecast appears to be a fairly accurate
representation of Hurricane Irene. While the control forecast is initialized at 0000 UTC on the 23\textsuperscript{rd}, the perturbation experiments may be initialized at later times from cold restarts by taking advantage of the “WRF In-Out” capability. That is, when the control forecast was integrated, WRF output files formatted like the original wrfinput_d01 file. These new output files at each valid time could then be perturbed then used to start a new WRF forecast later at that time.

Figure 2.4: comparison between the control (WRF) forecast and GFS analysis for (a) track, (b) intensity, and (c) radius of gale force winds in the northeast quadrant. The WRF forecast was slightly farther west and faster than the GFS analysis. WRF also developed a larger and more intense storm, but the trends in $V_{\text{max}}$, MSLP, and radius of gale force winds were similar with magnitudes varying between the two models due to differences in the spatial resolutions.
Figure 2.5: Thickness anomaly for the control forecast (a) and GFS analysis (b). While the magnitudes of the thickness anomalies vary somewhat, the trend in thickness anomaly is similar for both models.
Chapter 3 : Vorticity Perturbation Analysis for Hurricane Irene

3.1 Selection of Targets

According to the National Hurricane Center (NHC) forecast discussions for Hurricane Irene, there were two main synoptic-scale features that were expected to influence the evolution of Irene. The first was a longwave trough that was forecast to move into eastern North America on August 26\textsuperscript{th} (Figure 3.1a). This trough was the main driver of Irene’s northward turn out of the Bahamas and towards the east coast of the United States. The second was a shortwave trough that was forecast to move through the Great Lakes on the 27\textsuperscript{th} (Figure 3.1b). Irene would be directly interacting with this shortwave trough as it neared final landfall in New York, though in the later GFS analysis, both features would verify to be less amplified than forecast in the control simulation (Figure 3.2).

Figure 3.1: WRF-ARW 9 km control forecast showing 500 hPa height (contours) and 250 hPa potential vorticity (shading) indicating (a) Target #1, the longwave trough over eastern North America at 0000 UTC August 26, and (b) Target #2, the shortwave trough over the Midwest at 1800 UTC August 27.
Since in the cases of both targets one and two, the features verified to be less amplified than was originally forecast by the control forecast, both features were deamplified in the experiments in order to see if “correcting” for this error would result in a forecast comparable to the control forecast. Finally, this study will also examine the sensitivity of storm structure to vortex depth by perturbing the TC vortex directly. It is hypothesized that a shallower vortex could affect the track by modifying the response to deep-layer steering winds, limit outflow and result in a change in the storm size. The vorticity perturbations are performed during the later portion of Hurricane Irene’s life (i.e. after peak intensity) when synoptic scale interactions were likely most important (perturbation experiments on synoptic-scale features during the early phase of Irene’s life had little impact on the evolution of Irene).

### 3.2 Sensitivity to Distant Perturbations

The first vorticity perturbation experiment (henceforth referred to as V1) involved deamplifying a longwave trough that was moving through the northeastern United States and
eastern Canada at 0000 UTC on the 26th. With regards to Equation 1, \( p_{\text{bot}} = 700 \text{ hPa} \), \( p_{\text{top}} = 300 \text{ hPa} \) (making this a mid-tropospheric vorticity perturbation), \( R = 800 \text{ km} \), and \( \alpha_{\text{max}} = -0.95 \). This perturbation was centered near latitude 48.80, longitude -79.20 (or near the town of La Sarre, Quebec). The difference fields for this perturbation are shown in Figure 2.2. While -0.95 represents a virtually unrealistic perturbation that would be well outside of typical model errors, like Komaromi (2010), the idea in this study is to exaggerate synoptic-scale influences in order to test Irene’s sensitivity to a feature, not so much to “correct” the initial conditions (though the “correct” forecast, i.e. the GFS analysis, was taken into account when deciding whether to amplify, or in this case, deamplify, a trough in the initial condition). The comparison between the control and experiment V1 track, intensity, and RMW are shown in Figure 3.3. It is noted that there is a substantial westward shift in the track of Irene in this experiment, especially after the 27th. The longwave trough that was deamplified was the main mechanism for Irene’s recurvature (Avila and Cangialosi 2011), thus deamplifying the trough resulted in less recurvature. This also means that Irene interacted with land more than in the control. In the control, Irene grazed the North Carolina Outer Banks late on the 27th before crossing the tip of the Delmarva Peninsula then making landfall near Cape May, New Jersey on the 28th (in the analysis, Irene was still a little farther east). In experiment V1, Irene makes landfall late on the 27th and never reemerges over water. Despite this increased land interaction in V1, Irene is slightly stronger in V1 than in the control (Figure 3.3b). This may be because as Figure 3.3c shows, the MSLP, especially during the first 48 hours of the V1 forecast is lower compared to the control. Additionally, Figure 3.3d shows a more compact storm with V1 exhibiting a smaller radius of gale-force winds than the other forecasts.
A potential explanation for a stronger, deeper, and more compact storm is that despite the land interactions, the weakening of the longwave trough resulted in a decrease in wind shear, and given that this was later in Irene’s life when the storm was beginning to undergo ET (given the rapidly decreasing thickness anomalies), it is possible that land interaction may not have been as detrimental and that despite the land interactions, increasing pressure gradients resulted in higher wind speeds.

Figure 3.3: track (a), intensity (b), and (c) radius of maximum winds for Vorticity Perturbation Experiment #1. Experiment V1 exhibited a westward shift in track compared to the control, as well as a stronger and deeper storm, though the wind field in V1 was more compact than that in the control forecast.

Irene was not sensitive to all perturbations to this feature however. In another experiment, the same longwave trough is perturbed, but at an earlier time when Irene is at lower latitude, but despite this strong perturbation, the track, intensity, and structure of
Irene changed little. This suggests that Irene was not merely sensitive to certain features, but was sensitive to certain features at certain times.

The second vorticity perturbation experiment (V2) involved virtually removing a shortwave trough over the Midwest at 1800 UTC on the 27th (Figure 3.1b). The perturbations were centered on two points to account for the elongated nature of the vorticity maximum (Figure 3.4). The first point was at latitude 44.27, longitude -88.40, or near Appleton, Wisconsin. The second point was at latitude 41.67, longitude -91.53, or near Iowa City, Iowa. The perturbation was performed in the 700-300 hPa layer, with the radius of the perturbation set at 400 km at both points. Finally, $\alpha_{\text{max}}$ was set to -0.90 in order to nearly remove the shortwave trough. Again, the idea is not to correct the initial conditions, but to exaggerate the perturbation in order to test sensitivity to a specific feature.
Figure 3.4: difference fields for Vorticity Perturbation Experiment V2 for 700-300 hPa layer mean relative vorticity (a), 500 hPa heights (b), 500 hPa meridional wind (c), and relative vorticity vertical cross-section (d). The path of the vertical cross-section is indicated by the black line in panel (a). This vorticity perturbation was performed in two locations (near Appleton, Wisconsin and Iowa City, Iowa) in order to deamplify the elongated shortwave trough.

Perturbation experiment V2 made little appreciable difference to the track, intensity, or structure compared to the control (Figure 3.5). The main reason for this appears to be that the perturbation does not stay in the model forecast. In this particular experiment, as the model is integrated, the larger scale conditions (that were largely unperturbed) forced this shortwave trough to amplify despite the deamplification that was applied in the initial conditions. This is particularly evident in height difference fields where in Figure 3.4b, a clear increase in 500 hPa height is noted over the Midwestern United States, but 24 hours into the forecast, there is very little evidence of this perturbation remaining in the 500 hPa height field (Figure 3.6). This brings up an
important limitation in this research: while in some experiments, such as V1, the perturbation persists in the model and shows a clear effect on the track, intensity, and structure of the TC in question. In other cases, the perturbation does not remain in the model and becomes “washed out” with time. This indicates that in some cases, it may not be so much a question of sensitivity to a feature, but the ability of a model to maintain and track a perturbation. For experiment V2, since the perturbation does not stay in the model, it is difficult to say definitively whether target #2 (the Midwest shortwave trough) played a role in the structural evolution of Irene or not.

Figure 3.5: comparisons of the control (blue), GFS analysis (green), best-track (magenta), and experiment V2 (red) for maximum sustained winds (a), minimum central pressure (b), gale force wind radius in the northeast quadrant (c), and thickness anomaly (d).
Another diagnostic that can be used to analyze the structure of a TC is upper-level divergence as a measure of TC outflow. The outflow is quantified by azimuthally-averaging the 200 hPa divergence between 0 and 1,000 km from the storm center, similar to the technique used in the SHIPS model (DeMaria et al. 2005). Figure 3.7 shows the divergence for vorticity perturbation experiments V1 and V2. In experiment V1, the outflow aloft was weakened slightly. Recall that this is the experiment in which the storm tracked farther west and interacted with land more than the control simulation. This case also produced a smaller radius of gale-force winds. The change in divergence aloft for experiment V2 was negligible outside of a brief 6-hour period on the 29th.
Figure 3.7: Azimuthally-averaged 200 hPa divergence for the control forecast (blue), and vorticity perturbation experiments V1 (red) and V2 (green). The azimuthal averages were computed out to 1,000 km from the storm center.

**3.3 Sensitivity to Direct Perturbations to the TC vortex**

Another experiment was conducted in which a vorticity perturbation was applied directly to the TC vortex at 1200 UTC on the 24th (referred to as experiment “V3”). At this time, at Irene was centered at latitude 22.71, longitude -73.60. The vorticity perturbation was applied in the 700-300 hPa layer over a radius of 600 km with \( \alpha_{\text{max}} = -0.50 \). The difference fields for the initial perturbation are shown in Figure 3.8. The changes in \( V_{\text{max}} \) (Figure 3.9a) and MSLP (Figure 3.9b) relative to the control experiment were negligible, but a small contraction in the radius of gale force winds was noted (Figure 3.9c). This appears to be due to a slight decrease in the divergence aloft (Figure
The weaker vortex resulted in less upper-level divergence, and while this seemed to have little impact on the intensity of the storm, it did impact the structure of the storm by resulting in a smaller storm, despite the PV, while initially lower due to the vorticity perturbation, became larger than the control experiment. This leads one to believe that there may be two physical mechanisms for controlling the size of a TC: divergence aloft and PV generation/destruction, though these processes can be interconnected. Changes in PV can be driven by changes in absolute vorticity, which can be modified by divergence. Stronger heating near the core of the TC causes surface pressures to fall. This in turn leads to enhanced inflow at the surface, and outflow aloft. The PV mechanism is discussed further in Chapter 4 of this study.

Figure 3.8: vorticity perturbation experiment #3 (V3, direct perturbation) difference fields for (a) 700-300 hPa layer mean relative vorticity, (b) 500 hPa heights, (c) 500 hPa
The path of the cross-section is indicated approximately by the black line in panel (a). Note the differences in scale between panel (a) and panel (d). Panel (d) shows that the upper portion of the TC vortex associated with Hurricane Irene was weakened.

Figure 3.9: comparisons of (a) maximum sustained winds, (b) minimum central pressure, (c) radius of gale-force winds in the northeast quadrant, and (d) upper-level divergence for experiment V3.
Chapter 4: Moisture Perturbation Analysis for Hurricane Irene

Perhaps the most peculiar portion of Irene’s life cycle was the 42-hour period from 1200 UTC August 24 to 0600 UTC August 26 during which the MSLP continued to fall (15 hPa pressure drop), but the $V_{\text{max}}$ relaxed (decreasing by 8 m s$^{-1}$, Figure 4.1). The large-scale environment was conducive for strengthening, and several of the intensity forecast models (namely the HWRF, LGEM, SHIPS, and IVCN and ICON consensus models) initialized at 1200 UTC on the 23$^{\text{rd}}$ showed strengthening during the next 60-72 hours (the NHC followed this consensus). Despite this, Irene only intensified for only the first 24 hours then began weakening slowly and never restrengthened after reaching peak intensity of 54 m s$^{-1}$ at 1200 UTC on the 24$^{\text{th}}$ (Figure 4.2). Even as this weakening trend was occurring (partially due to an eyewall replacement cycle), the NHC stated in numerous forecast discussions that they anticipated that strengthening would resume.

Figure 4.1: Best-track intensity for Hurricane Irene (2011) with maximum sustained winds (red) and minimum sea level pressure (blue). The annotated yellow area indicates the 42-hour period of interest.
Figure 4.2: Intensity guidance for Hurricane Irene initialized at 1200 UTC August 23. NHC best-track is indicated by the heavy black line. Note that the maximum sustained winds in this plot are in knots instead of meters per second. The late cycle GFDL and HWRF are shown in this plot.

Moisture is chosen as a perturbed quantity in this experiment as (1) it can be easily perturbed, (2) the other variables can be easily rebalanced, (3) it is a variable that can be directly measured, (4) is crucial to TC development, and (5) similar experiments have been done previously on idealized storms (Hill and Lackmann 2009). Two types of moisture perturbation experiments are performed. In the first set of experiments, moisture is removed from the core of the tropical cyclone. In addition to individual experiments, an ensemble approach is used in order to determine if even small analysis errors in humidity can result in larger errors later in the forecast, particularly with respect to storm structure. Finally,
moisture will be perturbed in the environment around and ahead of the storm in order to test the effect of dry/moist air entrainment on the structural evolution of Hurricane Irene.

There are two times that this study will focus on for moisture perturbations: (1) immediately prior to the deepening/weakening (i.e. the storm was deepening from an MSLP standpoint, but the V_max was weakening) phase beginning at 1200 UTC on the 24^{th}, and (2) during the phase at 1200 UTC on the 25^{th}. These times were chosen since this is the period of time when the forecast and best-track largely diverged from each other.

4.1 Sensitivity to Core Moisture

The first core moisture experiment (henceforth referred to as experiment “M1”) was performed at 1200 UTC on the 24^{th} and involved reducing the low-level moisture in the core of the storm. The perturbation was centered at latitude 22.37, longitude -73.60 (the storm center), with R = 500 km (the approximate radius of the outermost closed isobar), in the 900-600 hPa layer, with α_{max} = -0.50 (Figure 4.3). This perturbation resulted in a slower and more westward track compared to the control. It also initially resulted in a slightly weaker (Figure 4.4a-b) storm, though the intensity later became comparable to the control after 0000 UTC on the 26^{th}. This slight initial weakening (and a shallower vortex) is likely what led to the westward shift in track as a shallower vortex would not be as strongly steered to the north by the upper-level winds. Finally, the perturbation resulted in a smaller storm (Figure 4.4c), similar to Hill and Lackmann (2009). That particular study found that reducing moisture content in and around the storm did not necessarily weaken a storm much, but did in fact result in a smaller storm by limiting the vortex size by reducing the amount of potential vorticity (PV) generation via precipitation processes. Qualitatively, a comparison of the storm structures can be made using simulated radar reflectivity (Figure 4.6 and Figure 4.7).
Figure 4.6 is annotated to show where during the first 24 hours of forecast M1, the south side of Irene is much more ragged. Much weaker convection is noted on the east side of Irene in experiment M1 compared to the control (Figure 4.7). In the control forecast, a nearly closed eyewall with banding in all quadrants is evident in the simulated reflectivity field. In M1, there is no closed eyewall with the banding features much less evident on the southeast side of the storm. This lack of organized precipitation is what likely led to the smaller circulation in M1 compared to the control.

Figure 4.3: 900-600 hPa layer mean mixing ratio (a), 700 hPa heights (b), 700 hPa meridional wind (c), and 900-600 hPa layer mean relative vorticity difference fields for moisture experiment M1. The removal of moisture resulted in little change in the mass field, but did weaken the circulation of Irene slightly.
Figure 4.4: track (a), intensity (b), and RMW information (c) for moisture experiment M1. The track for experiment M1 was to the west and slightly slower than the control. Despite the intensity being similar between M1 and control with respect to $V_{\text{max}}$, the MSLP was higher, and the radius of gale force winds contracted more quickly, though this contract was delayed, similar to the results in Hill and Lackmann (2009).

Figure 4.5: Comparisons of maximum sustained winds (a), minimum central pressure (b), gale-force wind radius in the northeast quadrant (c), and 850-200 hPa thickness anomaly
(d) for M1. Forecast M1 was initially slightly weaker, but eventually recovered to produce an intensity forecast similar to the control. Despite this restrengthening, the radius of gale force winds began to contract after about 36-48 hours.

Figure 4.6: comparison of simulated reflectivity fields (in the lowest model level) for the control forecast (left) and experiment M1 (right) at 1200 UTC on the 24th (top), 0000 UTC on the 25th (middle), and 1200 UTC on the 25th (bottom). The figure has been annotated to highlight key differences in the convective structure of each experiment.
Figure 4.7: meridional cross-sections through the center of Hurricane Irene for the control forecast (left) and experiment M1 (right) showing simulated radar reflectivity (shading) and height (solid contours).

4.2 Ensemble Approach to Core Moisture Sensitivity

Another method for testing storm sensitivity to core moisture is by using an ensemble technique similar to Komaromi et al. (2011) in which that particular study used perturbations of different magnitudes in order to assess if there is a certain “threshold” for sensitivity. Put another way, what magnitude of perturbation, or size of analysis errors, would it take for a storm to show substantial sensitivity?

The various ensemble members in this section are integrated at 27 km resolution. A lower spatial resolution was used in this section in order to be able to quickly perturb and rerun the model (the runtime at 27 km is less than one hour compared to several hours on the University of Miami’s Pegasus II supercomputer), similar to the technique used by NCEP in which the deterministic GFS is run at about 23 km resolution, but the GFS Ensemble Forecast System (GEFS) is run at about 52 km resolution. In the moisture perturbation ensemble experiments, \( \alpha_{\text{max}} \) is set to -0.75, -0.50, -0.25, +0.25, +0.50, and +0.75 in order to create a six-member ensemble. The ensemble system was initialized at 0000 UTC on the 23rd, the same time as the control forecast, and integrated forward 120 hours until 0000 UTC.
on the 28th. The $V_{\text{max}}$ (a), MSLP (b), gale-force wind radius in the northeast quadrant (c), and thickness anomaly (d) are shown in Figure 4.8. The ensemble spread for the experiment is given in Table 1. From Table 4.1, it can be inferred that MSLP and $V_{\text{max}}$ varied the least across the ensemble members compared to the structural quantities of gale-force wind radius and thickness anomaly. This suggests that there is substantial sensitivity of the storm structure to moisture perturbations. There tends to be a strong impact on the intensity and structure amongst the dry perturbations compared to the moist perturbations, likely because the TC core is already near or at saturation, thus increasing moisture to the point of total saturation (or even supersaturation) does not produce much additional heating, and thus not much additional growth in the size of the TC. An early concern was that supersaturating the atmosphere in the TC core could have adverse impacts on the TC forecast as it would result in excessive heating contributions from the cumulus scheme used, but given that increasing moisture only slightly increased the intensity, it did not appear to have a major impact. The increase in moisture in the core of the storm resulting in an expansion of the wind field is consistent with Hill and Lackmann (2009), in which more moist environments resulted in a larger circulation. This effect can be seen more clearly in Figure 4.3 in a separately-conducted experiment in which core moisture was increased in the core of Irene. Larger PV values can be seen in the core of the storm as well as a greater extent of the elevated PV values. This increased PV is a result of increased heating via larger latent heat release from the higher moisture content as shown in Equation 4, where $\rho$ is fluid density, $\zeta_a$ is absolute vorticity, and $\theta$ is potential temperature. Larger thickness anomalies (such as those seen in Figure 4.8d) correspond to larger temperature gradients in the core of the TC. Higher
humidity results in more latent heating, which in turn results in higher potential temperature gradients, and thus increased PV values (Figure 4.9 and Figure 4.10).

\[
PV = \frac{1}{\rho} \zeta_a \cdot \nabla \theta
\]  

(4)

Figure 4.8: maximum sustained winds (a), minimum central pressure (b), radius of gale force winds in the northeast quadrant (c), and thickness anomaly (d) for the moisture ensemble experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ensemble spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Sustained Winds</td>
<td>2.8 m s(^{-1})</td>
</tr>
<tr>
<td>Minimum Central Pressure</td>
<td>7.2 hPa</td>
</tr>
<tr>
<td>Gale-Force Radius in NE</td>
<td>66.0 km</td>
</tr>
<tr>
<td>850-200 hPa Thickness Anomaly</td>
<td>31.8 m</td>
</tr>
<tr>
<td>850 hPa Potential Vorticity</td>
<td>0.168 PVU</td>
</tr>
</tbody>
</table>

Table 4.1: Standard deviation of ensemble members averaged over all times for the moisture ensemble experiment. The \(V_{\text{max}}\) and MSLP only varied slightly while the radius of gale force winds and thickness anomaly varied significantly.
Figure 4.9: 850 hPa azimuthally-averaged potential vorticity (PVU) for all ensemble members showing weaker PV values for dry ensemble members compared to the moist ensemble members. The azimuthal average was computed within 500 km of the storm center.

Figure 4.10: 850 hPa PV and heights comparison between (a) the control forecast, and (b) a forecast for the moisture ensemble member where $\alpha_{\text{max}} = -0.75$. The control simulation shows larger low-level PV values compared to the dry experiment. Additionally, the 850 hPa heights are lower in the control than the dry experiment.
4.3 Sensitivity to Environmental Moisture

It has been demonstrated that Irene had significant structural sensitivity to moisture within the core of the storm (Sections 4.1 and 4.2), but how much of a role did environmental moisture entrainment into the circulation play in the structural evolution of Irene? To test this, three separate perturbations were made in the environment ahead of Irene in order to create a “swath” of dry air (Figure 4.11). Two experiments of this type are performed. The first was conducted early in the storm’s life beginning at 1200 UTC on the 23rd (Experiment EM1). This first period is just before the deepening/weakening phase of Irene while the storm was embedded in a low vertical wind shear environment. The second was conducted in the middle part of Irene’s life beginning at 0000 UTC on the 26th (Experiment EM2). This second period is after the deepening/weakening phase and during a time in which vertical wind shear was increasing as Irene began to interact with the mid-latitudes.

Figure 4.11: 900-600 hPa layer mean mixing ratio difference for experiment EM1.

Results from experiment EM1 are shown in Figure 4.12. The dry air only acted to weaken Irene slightly, and had little appreciable effect on the structure of the storm. The
reason for this lack of influence is likely that Irene was in a low shear environment (Figure 4.13), thus despite dry air in the environment ahead of the storm, this dry air was not effectively entrained into the core. In fact, the moisture perturbation is difficult to track beyond the first 24 hours, other than the “couplet” of increased/decreased mixing ratios which is apparent due to a small shift in the track (Figure 4.14). In addition to the lack of dry air entrainment, it is also possible that Irene’s intensity “recovered” more quickly in this experiment due to strong surface heat and moisture fluxes. At this point in time, Irene was a strong category two hurricane (in WRF). Given these strong surface winds and the fact that Irene was over very warm water, the heat and moisture fluxes are expected to be stronger at this time than at a time when Irene was a weaker hurricane. In other words, it is hypothesized that Irene was more “resilient” to the effects of dry air when it was a stronger storm versus when it was a weaker storm.
Figure 4.12: maximum sustained winds (a), minimum central pressure (b), gale-force wind radius in the northeast quadrant (c), and 850-200 hPa thickness anomaly (d) for experiment EM1.

Figure 4.13: deep layer wind shear magnitude (contours) and direction (streamlines), and infrared satellite. The wind shear magnitude up shear from the center of Hurricane Irene is
only 5-10 knots. (Source: University of Wisconsin Cooperative Institute for Meteorological Satellite Studies, UW-CIMSS).

Figure 4.14: 900-700 hPa layer mean mixing ratio difference field for experiment EM1 at 12-hour intervals beginning at 0000 UTC on the 24th (24 hours into the forecast). Note that the only major difference in the structure of the difference field near the storm center is a “couplet” due to a shift in the track of Irene, but in a storm-relative sense, there is little change.

A second moisture perturbation experiment was performed at a later time in Irene’s life cycle (Experiment EM2) when Irene began moving into a higher wind shear environment (Figure 4.15). For this experiment, multiple latitude and longitude points were used in order to create an elongated area of dry air ahead of Irene (Figure 4.16). The perturbation was performed in the 900-600 hPa layer with $\alpha_{\text{max}}=-0.75$ at the center of the three perturbations.
Figure 4.15: deep-layer wind shear analysis valid at 0000 UTC August 26 indicating 20-30 knots of southwesterly wind shear on the north side of Irene's circulation. It is hypothesized that this increase in deep-layer shear allowed Irene to ingest dry air that was “placed” to its north in Experiment EM2.

Figure 4.16: (a) 900-600 hPa layer mean mixing ratio difference field for experiment EM2, and (b) mixing ratio difference field vertical cross-section valid 0000 UTC on August 26, 2011. The path of the vertical cross-section is indicated by the black line on panel (a). Water vapor was removed from the lower troposphere ahead of Hurricane Irene, indicated by the red dot on panel (a).

The dry perturbation resulted in a small shift in the track to the west relative to the control forecast. Initially, the perturbation had little to no effect on Irene, with EM2 actually
generating a slightly more intense storm (Figure 4.17), but as the dry air began to entrain into the circulation of Irene beyond 24 hours (Figure 4.18), EM2 resulted in a weaker and smaller storm. It is also noted that the thickness anomalies were lower in EM2 than in the control. This is what would be expected as latent cooling in the circulation due to dry air entrainment would weaken the warm core of the TC, resulting in a higher MSLP, and ultimately a weaker storm. This lessening of the temperature gradient by weakening the warm core also results in less PV generation (or even PV destruction), and thus a smaller radius of gale force winds for experiment EM2 relative to the control and EM1.

Figure 4.17: comparison of (a) maximum sustained winds, (b) minimum central pressure, (c) gale-force wind radius in the northeast quadrant, and (d) 850-200 hPa thickness anomaly for the control (blue), EM2 (red), GFS analysis (green), and best-track (magenta). The dry perturbation associated with EM2 produced a weaker and smaller storm than the control.
Figure 4.18: 900-700 hPa layer mean mixing ratio difference field valid at 0000 UTC August 28th (48 hours into the forecast). A substantial dry air intrusion is noted over the center of Irene.

Examining the divergence aloft for the moisture perturbation experiments similarly to the analysis for the vorticity perturbation experiments allows us to determine if the moisture perturbations play a role in TC outflow. Figure 4.19 suggests that neither experiment significantly altered the TC outflow. Conversely, Figure 3.7 showed that the vorticity perturbation experiments did in fact alter the divergence aloft (slightly, but noticeably). These two facts suggest that Irene was only sensitive to upper-level divergence and outflow related to the moisture perturbations when Irene was outside of the deep tropics. This is not to say that upper-level divergence did not play a role early in Irene’s life cycle, but rather Irene’s structural evolution was only sensitive to changes in outflow later as Irene moved into higher latitudes and interacted more with synoptic-scale, mid-latitude features. Figure 4.13 shows that upper-level outflow (indicated by the cirrus banding around the periphery of the TC in the IR satellite imagery) is impeded on the up-shear side of the storm, with more prominent outflow on the downshear side. Despite these conclusions, outflow only varied slightly amongst the various experiments, which suggests that the upper-level outflow was...
not a major contributor to the size of the TC. The upper-level divergence in the moisture ensemble experiment also showed little sensitivity to moisture perturbations (Figure 4.20).

Figure 4.19: upper-level divergence for moisture perturbation experiments M1, EM1, and EM2. The experiments where dry air more effectively reached the core of the storm (either M1 where moisture was removed from the core, or EM2 where dry air was entrained into the core) showed the largest change in divergence aloft.
Figure 4.20: upper-level divergence for the moisture ensemble experiment. Overall, there was little discernable trend between the dry perturbation and moist perturbations with respect to outflow.
Chapter 5: Conclusions and Future Work

In this study, forecast simulations were run using WRF-ARW for Hurricane Irene (2011). The initial conditions in WRF were modified using a perturbation technique similar to the technique developed by Komaromi et al. (2011). The relative vorticity field and mixing ratio field were modified in two different sets of experiments. The relative vorticity field was modified in order to examine the initial condition sensitivity to mid-latitude, synoptic-scale features such as shortwave and longwave troughs. The moisture field was modified in order to test the sensitivity to lower tropospheric moisture in the core of Irene, and in the environment ahead of the storm. A summary of the vorticity and moisture perturbation experiments is provided in Table 5.1.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target</th>
<th>Perturbation Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Longwave trough over eastern North America at 26 / 00</td>
<td>Latitude: 48.80, Longitude: -79.20, ( p_{\text{top}} = 300 \text{ hPa} ), ( p_{\text{bot}} = 700 \text{ hPa} ), ( R_{\text{max}} = 800 \text{ km} ), ( \alpha_{\text{max}} = -0.95 )</td>
<td>Large sensitivity to track, structure, and intensity. Storm tracked to the west of control. More intense, but smaller TC.</td>
</tr>
<tr>
<td>V2</td>
<td>Shortwave trough over Midwest United States at 27 / 18</td>
<td>Latitudes: 44.27, 41.67, Longitudes: -88.40, -91.53, ( p_{\text{top}} = 300 \text{ hPa} ), ( p_{\text{bot}} = 700 \text{ hPa} ), ( R_{\text{max}} = 400 \text{ km} ), ( \alpha_{\text{max}} = -0.90 )</td>
<td>Virtually no sensitivity. Perturbation “washed out” of model with time.</td>
</tr>
<tr>
<td>M1</td>
<td>TC core at 24 / 12</td>
<td>Latitude: 22.37, Longitude: -73.60, ( p_{\text{top}} = 600 \text{ hPa} ), ( p_{\text{bot}} = 900 \text{ hPa} ), ( R_{\text{max}} = 500 \text{ km} ), ( \alpha_{\text{max}} = -0.50 )</td>
<td>Small shift in track to the west, and slightly slower. Weaker TC initially, then comparable later, but smaller TC throughout.</td>
</tr>
<tr>
<td>EM1</td>
<td>TC environment at 23 / 12</td>
<td>( p_{\text{top}} = 600 \text{ hPa} ), ( p_{\text{bot}} = 900 \text{ hPa} ), ( \alpha_{\text{max}} = -0.25 )</td>
<td>Little impact on track, intensity, or structure; likely due to low-shear environment.</td>
</tr>
<tr>
<td>EM2</td>
<td>TC environment at 26 / 00</td>
<td>( p_{\text{top}} = 600 \text{ hPa} ), ( p_{\text{bot}} = 900 \text{ hPa} ), ( \alpha_{\text{max}} = -0.25 )</td>
<td>Slight impact on track, but more impact on intensity and structure, likely due to higher wind shear</td>
</tr>
<tr>
<td><strong>Moisture Ensemble</strong></td>
<td>TC core at 23 / 00</td>
<td><strong>Latitude:</strong> 19.22</td>
<td><strong>Longitude:</strong> -69.30</td>
</tr>
</tbody>
</table>

Table 5.1: summary of moisture and vorticity perturbation experiments conducted in this study.

Hurricane Irene exhibited little sensitivity to synoptic-scale, mid-latitude features, except in cases of strong, unrealistic perturbations. In smaller perturbation experiments, virtually no changes in Irene’s track, intensity, or structure were observed. The only large synoptic perturbation in which Irene showed sensitivity was the deamplification of a longwave trough over eastern North America on the 26<sup>th</sup> at 0000 UTC (experiment V1), but the α<sub>max</sub> of -0.95 represents a virtually unrealistic error in the initial conditions. Perturbations performed within the scope of model errors (α<sub>max</sub> = ±0.25 for example) showed little to no sensitivity. In another experiment involving a shortwave trough ejecting out of the Great Lakes region (V2), Irene again showed virtually no sensitivity, even with a very strong perturbation of α<sub>max</sub> = -0.95. It is unknown whether the lack of sensitivity in the model is due to the feature being meteorologically unimportant, or the fact that the perturbation appears to become washed out with time. That is, the perturbation does not survive in the model for more than 12-24 hours. This represents one of the limitations with this study. It can be nearly impossible to ensure that a perturbation maintains itself once the model is initialized and integrated due to the physics within the model. In the case of experiment V2, a shortwave trough over the Midwestern United States was deamplified, but after only about 24 hours, the shortwave trough “re-amplified” and the perturbation was virtually non-existent. This is likely because the larger scale dynamics suggested that this shortwave trough should
amplify, and thus the shortwave trough amplified despite being significantly weakened in the initial conditions. This is not the case, however, with all perturbation experiments. The initial perturbation in experiment V1 was able to be tracked for the remainder of the forecast period, which is likely why Irene ultimately did respond to this perturbation by shifting farther to the west and intensifying as well as becoming a deeper, more compact storm. Another key component to the sensitivity in addition to the perturbation remaining in the forecast and the location and strength of the perturbation is the timing of the perturbation. Irene did not respond much to perturbations of the same longwave trough earlier in time when Irene was still in the deep tropics. The synoptic-scale perturbations appeared to become more important as the storm gained latitude and interacted more directly with these features.

While Irene did not respond strongly to synoptic-scale vorticity perturbations, it did show substantial sensitivity to moisture perturbations, even small perturbations of $\alpha_{\text{max}} = \pm 0.25$. While the maximum sustained winds did not respond greatly to the moisture perturbations, the minimum central pressure, and especially the radius of gale force winds and thickness anomaly showed significant sensitivity to the perturbations. Hill and Lackmann (2009) hypothesized that increases in environmental moisture led to increase in TC size due to potential vorticity generation on the periphery of the storm from enhanced precipitation processes. Their finding is confirmed in this study in which a clear expansion and intensification of the lower-tropospheric PV field was seen in experiments in which the moisture was increased in the core of the TC. Irene, however, did not show substantial sensitivity to perturbations in which moisture was removed from the environment ahead of the storm early in the storm’s life cycle, likely because early in Irene’s life cycle, the
environmental wind shear was low, preventing this dry air from being ingested into the TC vortex. One crucial limitation of this moisture perturbation technique is that it is difficult, to connect the expansion of the wind field directly to the moisture perturbation itself (though the expansion of the PV field and the changes in the precipitation structure of Irene are likely connected to these changes in the moisture field). Rather than focusing on the question of “Did moisture play a direct role in affecting the size of the storm,” a better way of looking at it is a small perturbation in moisture, or analysis error in the moisture field, can result in great changes in the way the model develops the storm. A change in the moisture field may result in a shallower or deeper vortex, which in turn will affect the track, which could lead to more or less land interaction, and thus a weaker or stronger TC, as well as a smaller or larger gale force wind radius.

Finally, future work in this subject matter could start with performing similar analyses for additional storms. TCs in which there was a large spread in intensity guidance (like Irene), but a small spread in track guidance are ideal since that would suggest little sensitivity to track, and one would not have to worry about affecting the storm intensity and structure greatly just by shifting the track of the storm. In other words, it would be easier to connect intensity and structure changes to the perturbations in the initial condition if the track does not shift significantly in which case, changes in the amount of land interaction, or position of the storm relative to synoptic or oceanic features (like the Gulf of Mexico Loop Current) could be the main drivers in intensity and structural changes. Experiments could also be performed within an idealized framework similar to Hill and Lackmann (2009) in order to develop a more generalized hypothesis regarding the sensitivity to storm structure with environmental and core moisture. While this study used arbitrary values by which the
moisture ensembles were performed, perhaps a more robust technique could determine analysis errors by comparing the GFS analysis directly to dropsonde or other in-situ data. The perturbation magnitude could also be based on differences in the analysis derived from data denial experiments in the initial condition. In other words, we can see how much the mixing ratio values vary between an analysis that assimilated dropsonde/reconnaissance data, and an analysis that did not use this data. This would also allow one to determine how valuable such data would be, and even more so, how valuable this data would be in different situations.

While TC track forecasts have improved greatly over the last 20 years, intensity forecasts have been slow to improve, with very little improvement noted over the last 20 years despite great progress in modeling and data assimilation techniques, as well as computer power available for modeling. A study such as this seeks to determine which variables control a tropical cyclone’s structure and intensity within the model. Understanding this could allow the community to determine which observations are the most crucial, where intensity errors in models arise, and allow forecasters to know which types of larger scale interactions are likely to result in changes in the structure of a tropical cyclone. Being able to accurately predict the structure of a tropical cyclone is important because not only is intensity tied to it, but knowing the size of the storm is crucial from a public perspective. A better understanding of the structural evolution of tropical cyclones would allow forecasters to more accurately warn the public about the types of impacts, their severity, and the areal scope of the impacts, allowing users to make better decisions in the protection of life and property.
Works Cited


