2010-01-01


William A. Komaromi
University of Miami, wkomaromi@rsmas.miami.edu

Follow this and additional works at: https://scholarlyrepository.miami.edu/oa_theses

Recommended Citation
https://scholarlyrepository.miami.edu/oa_theses/61

This Open access is brought to you for free and open access by the Electronic Theses and Dissertations at Scholarly Repository. It has been accepted for inclusion in Open Access Theses by an authorized administrator of Scholarly Repository. For more information, please contact repository.library@miami.edu.
SYNOPTIC SENSITIVITY ANALYSIS OF TYPHOON SINLAKU (2008)  
AND HURRICANE IKE (2008)  

By  
William A. Komaromi  

A THESIS  

Submitted to the Faculty  
of the University of Miami  
in partial fulfillment of the requirements for  
the degree of Master of Science  

Coral Gables, Florida  

August 2010
SYNOPTIC SENSITIVITY ANALYSIS OF TYPHOON SINLAKU (2008)
AND HURRICANE IKE (2008)

William A. Komaromi

Approved:

Sharanya J. Majumdar, Ph.D.
Assistant Professor of Meteorology
and Physical Oceanography

Terri A. Scandura, Ph.D.
Dean of the Graduate School

David S. Nolan, Ph.D.
Associate Professor of Meteorology
and Physical Oceanography

Rolf H. Langland, Ph.D.
Senior Scientist
Naval Research Laboratory
Monterey, California

Christopher S. Velden
Senior Scientist
CIMSS / University of Wisconsin
Madison, Wisconsin
This thesis seeks to identify locations in which errors in numerical model initial conditions may compromise skill in tropical cyclone (TC) track forecasts. Two major TCs that made landfall in 2008 are analyzed: Hurricane Ike and Typhoon Sinlaku. In order to examine the sensitivity of the TC to selected synoptic features, a vorticity perturbation technique is developed. Within a chosen radius and atmospheric depth, the vorticity is amplified or decreased, followed by a re-balancing of the fields. The following questions are proposed: (1) How does the TC track vary with respect to initial perturbations of differing amplitude, spatial scale and distance to the storm? (2) How does the evolving perturbation act to modify the synoptic environment surrounding the TC, and thereby the track? (3) Is it best to follow an objective technique to determine the sensitive areas, or is it better to use a subjective method based on fundamental synoptic reasoning?

Utilizing the Weather Research and Forecasting (WRF) model, the ‘control’ simulation for each TC is found to replicate forecast errors evident in the operational global models. For Sinlaku, this includes a premature recurvature in the forecast. For Ike, this comprises a landfall too far south along the Texas coast due to no recurvature being forecast.

The size, magnitude and location of vorticity perturbations to the control analysis are chosen subjectively. For Sinlaku, these locations include a large mid-latitude shortwave trough around 3000 km to the north-northwest, a smaller upper-level shortwave immediately to the north, a low-level monsoon trough to the west-southwest, a weak tropical storm to the
northeast, and a local perturbation in the immediate environment. It is found that WRF forecasts of Sinlaku exhibit high sensitivity, with large modifications to its track arising from the perturbation of each selected targets in the synoptic environment. The greatest improvement in the track forecast occurs by weakening the vorticity associated with each of two shortwaves to the north of Sinlaku, suggesting that either or both of the shortwaves may have been initialized too strongly in the model analysis, thereby contributing to an erroneous recurvature.

For Ike, the perturbation locations include a large mid-latitude shortwave trough 2500 km to its north, an upper-level cutoff low to the east-northeast, a low-level shortwave trough to the northwest, a tropical storm in the East Pacific, and a local perturbation in the immediate environment. In contrast to Sinlaku, the perturbation of synoptic targets around Ike produces less sensitivity, likely due to the fact that Ike is not in a position of imminent recurvature. The only perturbation that leads to an accurate 4-day forecast of recurvature and landfall in North Texas is the strengthening of the large mid-latitude shortwave trough, suggesting that the shortwave may have been initialized too weakly in the operational models.

Finally, a comparison of targets selected objectively by the Ensemble Transform Kalman Filter (ETKF) versus the above subjectively-chosen targets suggests that while the ETKF effectively indicates similar target regions to those selected subjectively, it may be less effective in ranking the relative sensitivities of those targets. Overall, it is found that the TC track is more sensitive to perturbations of larger amplitude and spatial scale, and less so to the distance between the perturbation and the TC, and sensitivity is confined to specific regions of the flow. The perturbation methodology employed here may be used to offer suggestions of locations in which extra high-density satellite data may be assimilated.
Acknowledgements

I would like to thank my advisor, Dr. Sharanya J. Majumdar, for his enormous support, insight, and guidance. I would like to thank my committee, Dr. David S. Nolan, Dr. Rolf H. Langland, and Christopher S. Velden for their support, and constructive criticism! I would also like to thank Eric D. Rappin for proving much of the code used as a starting point for this study, as well as teaching me to run WRF. I would like to thank Michael J. Brennan for partaking in insightful discussions about Hurricane Ike. I like to thank Shin-Gan Chen for providing ETKF analyses, as well as Chiaying Lee for ECMWF data. I would also like to give a big thanks to the Rosenstiel School of Marine and Atmospheric Science and the Office of Naval Research for funding this research.

Finally, I would like to thank all of my friends and fellow graduate students at RSMAS for being there for me!
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td></td>
<td>Chapter</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>METHODOLOGY</td>
<td>8</td>
</tr>
<tr>
<td>2.1</td>
<td>Modeling Framework</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>Vorticity Perturbation Technique</td>
<td>10</td>
</tr>
<tr>
<td>2.3</td>
<td>ETKF Technique</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>SYNOPTIC SENSITIVITY ANALYSIS FOR TYphoon SInlaku (2008)</td>
<td>15</td>
</tr>
<tr>
<td>3.1</td>
<td>Synopsis of Sinlaku</td>
<td>15</td>
</tr>
<tr>
<td>3.2</td>
<td>Vorticity Perturbation Analysis</td>
<td>19</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Selection of Targets</td>
<td>19</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Sensitivity to Upper-Level Targets</td>
<td>26</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Sensitivity to Low-Level Targets</td>
<td>51</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Sensitivity to Near-TC Perturbations</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>SYNOPTIC SENSITIVITY ANALYSIS FOR Hurricane IKE (2008)</td>
<td>63</td>
</tr>
<tr>
<td>4.1</td>
<td>Synopsis of Ike</td>
<td>63</td>
</tr>
<tr>
<td>4.2</td>
<td>Vorticity Perturbation Analysis</td>
<td>70</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Selection of Targets</td>
<td>70</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Sensitivity to Upper-Level Targets</td>
<td>74</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Sensitivity to Low-Level Targets</td>
<td>92</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Sensitivity to Near-TC Perturbations</td>
<td>100</td>
</tr>
<tr>
<td>4.3</td>
<td>Vorticity Perturbation Ensemble</td>
<td>103</td>
</tr>
<tr>
<td>5</td>
<td>CONCLUSIONS AND FUTURE WORK</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>Appendix A</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>WORKS CITED</td>
<td>117</td>
</tr>
</tbody>
</table>
List of Figures

1.1 ................................................................................................................................. 3
3.1 ................................................................................................................................. 16
3.2 ................................................................................................................................. 17
3.3 ................................................................................................................................. 18
3.4 ................................................................................................................................. 20
3.5 ................................................................................................................................. 22
3.6 ................................................................................................................................. 23
3.7 ................................................................................................................................. 27
3.8 ................................................................................................................................. 29
3.9 ................................................................................................................................. 30
3.10 ............................................................................................................................... 31
3.11 ............................................................................................................................... 34
3.12 ............................................................................................................................... 35
3.13 ................................................................................................................................ 37
3.14 ................................................................................................................................ 38
3.15 ................................................................................................................................ 39
3.16 ................................................................................................................................ 41
3.17 ................................................................................................................................ 45
3.18 ................................................................................................................................ 46
3.19 ................................................................................................................................ 46
3.20 ................................................................................................................................ 47
3.21 ................................................................................................................................ 50
3.22 ................................................................................................................................ 51
3.23 ................................................................................................................................ 53
3.24 ................................................................................................................................ 53
3.25 ................................................................................................................................ 54
3.26 ................................................................................................................................ 55
3.27 ................................................................................................................................ 56
3.28 ................................................................................................................................ 58
3.29 ................................................................................................................................ 59
3.30 ................................................................................................................................ 61
3.31 ................................................................................................................................ 62
4.1 .................................................................................................................................. 63
4.2 .................................................................................................................................. 64
4.3 .................................................................................................................................. 65
4.4 .................................................................................................................................. 67
4.5 .................................................................................................................................. 68
4.6 .................................................................................................................................. 69
4.7 .................................................................................................................................. 71
4.8 .................................................................................................................................. 72
4.9 .................................................................................................................................. 73
List of Tables

3.1 .................................................................................................................... 28
3.2 .................................................................................................................... 32
4.1 .................................................................................................................... 74
4.2 .................................................................................................................... 82
Chapter 1

Introduction

Tropical cyclones (TCs) pose a significant threat to life and property, with risks in the form of high winds, storm surge, inland freshwater flooding, and tornadoes. The effectiveness of preparations and evacuations is directly dependent upon the amount of time provided between the issuance of a forecast for an event and the occurrence of that event, or the forecast lead-time. Less than half a century ago, tropical cyclone forecasting was a very young science, based primarily upon a persistence forecast using surface and ship observations as the only data source (Emanuel 2005). In contrast, modern forecasting of TCs comprises an array of global numerical models and higher-resolution regional models that are centered on the TC. All models require accurate initial conditions, which in turn rely on a vast observational network and a scheme to assimilate these observations. Data assimilation schemes produce this initial analysis field by combining a first guess, namely a short-range forecast from the previous initialization, with all new available observational data.

In contrast to the observational network over land which includes radiosonde stations, observations over the oceans are comparatively sparse. As such, numerical weather prediction (NWP) models of tropical cyclones, which spend most of their lifetime over the ocean, are more dependent on data from aircraft and satellite platforms (Langland 2005). To partially alleviate this data deficiency, aircraft are deployed in order
to sample the TC and its environment, particularly when the TC is a threat to land. Aircraft deploy dropwindsondes to sample a vertical profile of wind, temperature and moisture through a depth of troposphere. The USAF C-130 and NOAA WP-3D (P-3) fly through the TC to sample mesoscale features (e.g., Henderson 1978, Barnes et al. 1983), where mesoscale refers to features on the order of 100 km and lasting between minutes and hours (Holton 1992). On the other hand, the NOAA G-IV jet samples the synoptic environment surrounding the TC during synoptic surveillance missions (Aberson and Franklin 1999, Aberson 2010). By synoptic, we refer to features associated with scales of 1000 km or more, lasting many hours to a few days (Holton 1992). Since 2003, the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) program has flown frequent surveillance missions to sample the environments of TCs threatening Taiwan (Wu et al. 2005, 2007). Assimilation of dropsonde data has been shown to be beneficial to TC track forecasts within the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) model (Aberson 2010). An example of the spatial distribution of dropwindsonde data during a DOTSTAR mission for Typhoon Sinlaku (2008) is shown in Fig. 1.1a.

Although in situ observations from aircraft such as dropwindsondes are accurate, they are only available over a limited area. For this reason, remotely sensed satellite data are relied upon for the diagnosis of TC structure and for assimilation in numerical models. The Atlantic Ocean is monitored by two geostationary satellites: the United States GOES-13 and the European Meteosat-8 (Smoot and Meyer 2009). Similarly, the Pacific Ocean is monitored by the United States GOES-11 and the Japanese MTSAT-1R and MTSAT-2. Both oceans are also monitored by a variety of polar-orbiting satellites.
In addition to temporally-continuous cloud-top temperature and water vapor measurements, geostationary satellites serve a very important role in estimating atmospheric motion vectors (AMVs) through cloud tracking (Velden et al. 2005). In doing so, it is possible to estimate wind shear and vorticity from the satellite-based AMVs, usually in conjunction with a numerical model. The ECMWF model assimilates over 100,000 AMVs per data assimilation cycle (ECMWF, 2010). An example of the operational AMV density is shown in Fig. 1.1b.

![Fig. 1.1: (a) 500 hPa dropsonde winds for Typhoon Sinlaku, 00Z September 9th 2008 (left, EOL 2008), (b) Hurricane Emily (2005) with GOES-11 IR imagery and operational 150 – 200 hPa wind vectors (top-right), (c) Hurricane Emily (2005) with GOES-11 IR imagery and rapid scan 150 – 200 hPa wind vectors (lower-right, Berger and Velden, 2009).](image)

Conventionally, operational numerical weather prediction systems such as GFS only assimilate satellite-based AMVs every 6 hours (Kleist et al. 2009). With recent upgrades, the (NOGAPS) and Canadian Meteorological Center (CMC) Global
Environmental Multiscale (GEM) now assimilate hourly satellite data (JCSDA Quarterly 2009, and Laroche et al. 2005). While not yet assimilated by the operational models, AMVs can also be sampled at much higher temporal resolution in a special rapid scan mode. Rapid scan can be activated to provide high-density satellite scans in 4 minute intervals, as opposed to the standard 30 minute increments at a lower spatial density. This activation is generally reserved for tropical systems threatening land due to the fact that rapid scan produces an additional power drain. Fig. 1.1c depicts the additional wind vectors derived from rapid scan mode beyond what is available in the absence of rapid scan (Fig. 1.1b). While Fig. 1.1 demonstrates the capability of rapid scan to provide additional information regarding the TC structure, rapid scan also allows for better resolution of synoptic and mesoscale features (troughs, ridges, fronts) that affect the TC motion. By comparison, the amount of data provided by aircraft missions is limited (Fig. 1.1a).

Only a limited number of studies that investigate the impact of assimilating rapid-scan data have been performed to date. Langland et al. (2009) examined the impact in the global NOGAPS system, and found improvements to track forecasts of Hurricane Katrina during the 84-120 hr timeframes. Pu et al. (2008) showed that the assimilation of extra GOES-11 satellite wind data into the regional Weather Research and Forecasting (WRF) model improved the track, intensity and precipitation forecasts of Tropical Storms Cindy and Gert (2005) up to the time of landfall. Pu et al. also demonstrated that assimilating rapid-scan winds at high resolution (9 km) provided more accurate tropical cyclone forecasts than a regular 6-h analysis cycle at coarse resolution (27km). Despite
the potential benefits demonstrated in these studies, it is still unclear about how best to target the activation of rapid-scan mode in order to optimally improve a TC forecast.

In order to explore the efficacy of targeting available data from satellites and aircraft to improve numerical predictions of TCs, theoretical and practical investigations have been undertaken by agencies including the U.S. Navy, NOAA, NASA, Japan Meteorological Agency (JMA) and Taiwan Central Weather Bureau (CWB). In particular, the multi-national Tropical Cyclone Structure-2008 (TCS-08) and THORPEX Pacific Asian Regional Campaign (T-PARC) field campaigns sought to investigate this issue in unprecedented depth. The T-PARC experiment is particularly significant given the normal lack of targeted data in the West Pacific as compared with the Atlantic basin. In addition to the extra aircraft dropwindsonde data collected during T-PARC, supplemental rapid-scan satellite data were also collected during this field campaign using MTSAT-2. The decision making process for rapid-scan activation was coordinated by JMA whenever a TC threatened Japan. The rapid-scan mode for MTSAT-2 was activated at 15-, 7-, and 4-minute intervals for 3-hour periods over limited targeted areas during the course of the life-cycles of Typhoons Sinlaku and Jangmi (Berger et al. 2009).

The T-PARC field experiment offered the opportunity for several groups to explore different data targeting methodologies, such as those explored in Majumdar et al. (2006), Reynolds et al. (2007) and Wu et al. (2009). These numerical methodologies, which are objective in the sense that they are automated, are all based on the premise that the correction of initial condition errors in sensitive regions will lead to improved numerical forecasts. In this study, sensitive means that the response of a given metric
(such as TC track) to an initial perturbation in a sensitive area is larger than that resulting from a corresponding perturbation in other areas.

Among the more widely used objective techniques are Singular Vectors (Palmer et al. 1998, applied first for TCs by Peng and Reynolds 2006) and the Ensemble Transform Kalman Filter (ETKF, Bishop et al. 2001, applied first for TCs by Majumdar et al. 2006). While these and other techniques have been used, there is no consensus solution, and it is yet to be determined whether they are effective for selecting sensitive areas for targeting extra observations. Moreover, due to assumptions of linearity and an imperfect (or non-existent) data assimilation scheme, these techniques are far from perfect, and the physical interpretation of these sensitive regions is often unclear. In fact, it is not even clear whether objective techniques are superior to subjective techniques.

In order to gain a more fundamental synoptic-dynamic understanding of locations in which to target observations, we expect that a subjective perturbation method in a basic modeling framework that avoids complications due to errors in the observations and the data assimilation would yield more insight. Given that a TC forecast will likely be more sensitive to initial condition errors in certain regions than others, it is important to develop a hypothesis as to where the TC forecast is most sensitive to perturbations in the synoptic environment. For example, such a hypothesis could be focused in order to offer suggestions on the optimal locations for assimilating AMV data. To do this, we propose to apply perturbations of vorticity directly to the model initial analysis, to explore the sensitivity of TC tracks to changes in the synoptic environment. Such a study could be extended to TC genesis, structure and intensity, but unless otherwise stated, our evaluation metric is the track. In this thesis, we seek to address the following questions:
(1) How does the TC track vary with respect to initial perturbations of differing amplitude, spatial scale and distance to the storm?

(2) How does the evolving perturbation act to modify the synoptic environment surrounding the TC, and thereby the track?

(3) Is it best to follow an *objective* technique to determine the sensitive areas, or is it better to use a *subjective* method based on fundamental synoptic reasoning?

In Chapter 2, we describe the regional WRF modeling framework employed throughout the thesis, the vorticity perturbation technique, and the subjective and objective methods to select the locations for perturbation. In Chapters 3 and 4, the above questions are addressed for two significant tropical cyclones: Typhoon Sinlaku (2008) and Hurricane Ike (2008) respectively. Concluding remarks and implications are given in Chapter 5.
Chapter 2

Methodology

2.1 Modeling Framework

This study employs the regional Advanced Research Weather Research and Forecasting model (WRF-ARW), which is presently widely used for tropical cyclone simulations in research. WRF is a mesoscale model that simulates fully compressible atmospheric dynamics with high-order advection schemes (Skamarock et al. 2005). Davis et al. (2008) demonstrated the ability of WRF-ARW to produce forecasts of position and intensity for five Atlantic hurricanes that were competitive with, and occasionally superior to, operational forecasts. They employed a 12 km resolution WRF grid containing a nest of 4 km resolution. Though several general characteristics of TC motion and structure were replicated, recurring errors occurred in simulations of TC intensity and surface fluxes.

In this study, Version 3.1.1 of WRF-ARW is used, with a single, fixed grid with a horizontal grid spacing of 21 km, and 41 vertical levels. Since this study focuses on synoptic-scale influences on TC motion, with storm structure and intensity being of secondary importance, we concluded that a resolution of 21 km would be adequate to capture the relevant processes. The size of the domain is chosen such that all synoptic targets are included, while working within realistic computational constraints. For the Typhoon Sinlaku case, the size is 8946 x 7056 km, while for the Hurricane Ike case, the
corresponding size is 6510 x 5880 km. The following physics options are used: Rapid Radiative Transfer Model (RRTM) longwave radiation (Mlawer et al. 1997; Iacono et al. 2000); Dudhia shortwave radiation (Dudhia 1989); WRF Single-Moment (WSM) 6-class microphysics (Dudhia 1989; Dudhia et al. 2008); and the Mellor-Yamada-Janjic (MYJ) boundary layer scheme (Mellor and Yamada 1982; Janjic 1990). A second order diffusion scheme is employed, and no damping is used.

Several candidate global models were examined for potential use as initial and boundary conditions for WRF. Initially, the NCEP GFS and NOGAPS global models were used; however, it was found that without the insertion of a synthetic (or ‘bogus’) vortex at the TC location, the basic structure of the TC was unrealistic. The introduction of the ECMWF model was found to provide a superior WRF simulation of TC track and intensity, without the need for a synthetic vortex. Further details of these simulations and the synthetic vortex are provided in Appendix A. From here on, the 12-hourly ECMWF analyses are used to provide initial and boundary conditions, with no synthetic vortex. For both TC cases, several parallel WRF simulations are integrated to 120 hours, and these are analyzed to address the three main questions listed in Chapter 1. This study employs model *simulations*, in which domain boundary conditions are supplied in 12 hr increments by a new model analysis. A WRF *forecast* would differ by having new boundary conditions supplied by a global model forecast. The parallel simulations comprise a ‘control’ (non-perturbed) simulation, and an array of ‘perturbed’ simulations in which the initial conditions are modified by local, balanced perturbations of vorticity in the synoptic environment. The ‘sensitivity’ to a given location is then determined by
the change in TC track associated with a particular vorticity perturbation. The vorticity perturbation technique is described in the next subsection.

2.2 Vorticity Perturbation Technique

The direct modification to the initial conditions is achieved by creating a vorticity perturbation and then rebalancing the remaining fields. This technique follows a process similar to the scheme of Davis and Low-Nam (2001), in which the non-divergent winds, geopotential and temperature are recalculated after removal of a local area of vorticity. Following this, the vorticity field is inverted in a manner similar to Davis (1992), but instead of inverting the full potential vorticity field as in his study, only the relative vorticity is inverted here.

This method begins with the user specifying the location (latitude and longitude) of the center of the perturbation. A discussion of how these locations are chosen will be described in Chapters 3 and 4. A radius of perturbation “R”, as well as upper and lower pressure levels (P<sub>top</sub> and P<sub>bot</sub>) to determine the depth of perturbation, is also specified. Finally, the user specifies the maximum amplitude of perturbation α<sub>max</sub>, which is varied between -1 and +1 in this study. The perturbation α(r) is reduced linearly outward with r from the center point to a perturbation of 0 at specified radius R

\[
\alpha(r) = \frac{R-r}{R} \alpha_{\text{max}}, \quad r \leq R
\]

\[
\alpha(r) = 0, \quad r > R
\]

The new, perturbed relative vorticity ζ<sub>1</sub> is then expressed as a scalar multiple of the original vorticity, ζ<sub>0</sub>:

\[
ζ_1 = (1 + \alpha(r)) \cdot ζ_0
\]
For example, a value of $a_{\text{max}} = -1$ refers to an entire removal of vorticity at the center of the perturbation, while $a_{\text{max}} = +1$ corresponds to a doubling of the vorticity. The perturbation vorticity $\zeta'$ is then defined as:

$$\zeta' = \zeta_1 - \zeta_0$$  \hspace{1cm} (3)

The perturbation is applied vertically from $P_{\text{top}}$ to $P_{\text{bot}}$.

The next step is to re-balance the perturbed fields. This begins with the definition of stream function for the non-divergent wind, where $\zeta'$ is given as:

$$\zeta' = \nabla^2 \psi'$$  \hspace{1cm} (4)

Stream function $\psi'$ is then solved for using an iterative method known as the *successive overrelaxation technique* (Tannehill et al. 1997). $\psi'_{i,j}$ is set to zero for the first iteration, with a maximum number of iterations set to $10^4$.

This value is then plugged into the following:

$$\psi'^{n+1}_{i,j} = \psi^n_{i,j} + \omega \tau$$  \hspace{1cm} (5)

where

$$\tau = \psi^n_{i+1,j} + \psi^n_{i-1,j} + \beta \left( \psi^n_{i,j+1} + \psi^n_{i,j-1} \right) - 2(1 + \beta)\psi^n_{i,j} - \zeta'_{ij}$$  \hspace{1cm} (6)

and the relaxation parameter $\omega$ can be set to an optimal value for the fastest convergence

$$\omega = \frac{1}{2 + \sqrt{\left(4 - \left(\cos \frac{\pi}{n_x-1} + \cos \frac{\pi}{n_y-1} \right)^2\right)}}$$  \hspace{1cm} (7)

where $i$ and $j$ are the $x$ and $y$ grid locations, $n$ is the current iteration number, and $\beta$ is the grid aspect ratio, $dx/dy$. Through a sufficient number of iterations, it is possible to solve for $\psi'_{i,j}$ (Tannehill et al. 1997). Once found, the perturbation wind field $\mathbf{v}'_{\psi}$ is calculated:

$$\mathbf{v}'_{\psi} = \hat{k} \times \nabla \psi'$$  \hspace{1cm} (8)
Finally, $v_\psi$ for the new field is given as:

$$v_{\psi_1} = v_{\psi_0} + v'_\psi$$  \hspace{1cm} (9)

Since only the non-divergent wind field is perturbed, and the perturbation non-divergent wind is added to the initial wind field, the divergent wind remains unchanged.

Next, the geopotential is adjusted via geostrophic balance:

$$\varphi' = \frac{f_0}{g} \psi'$$  \hspace{1cm} (10)

where, using the $f$-plane approximation, $f_0$ is the Coriolis force at the center of the perturbation. Finally, the vertical temperature fields are adjusted through hydrostatic balance:

$$T_1 = -\frac{1}{R} \frac{\partial \varphi_1}{\partial \ln (p)}$$  \hspace{1cm} (11)

This process ensures that the initial fields are in geostrophic and hydrostatic balance prior to commencement of model integration.

The perturbation technique allows for as large or as small a perturbation as desired. While setting $a_{\text{max}} = 0.75$ (a 75% vorticity perturbation) seems unrealistically large in comparison to errors associated with a data-assimilation procedure, factors of this magnitude were used in this study to exaggerate the synoptic influence of individual features on the TC.

It should also be noted that in solving for $\nabla \psi_1^i$, the Laplacian must be inverted over the entire domain. This method generates an initial velocity perturbation, however small, over the entire domain. Therefore, while a perturbation may be set to a radius of a few hundred kilometers, areas well outside of this radius may be perturbed by as much as one or two m/s, including at the TC.
2.3 Ensemble Transform Kalman Filter (ETKF) Technique

In addition to the vorticity perturbations that are made in subjectively chosen areas, perturbations are also created in locations deemed optimal for targeting observations via an objective technique, the ensemble transform Kalman filter (ETKF). The ETKF uses ensemble Kalman filtering theory (Evensen 1994) to provide a framework for estimating the effect of assimilating observations on forecast error covariance (Bishop et al. 2001). The ‘T’ in ETKF refers to a linear transformation of a matrix comprising ensemble perturbations, which are commonly defined as the difference between an ensemble forecast and the ensemble mean or a control forecast. This transformation is first used to predict the analysis error covariance matrix associated with the operational observational network at some future analysis time $t_a$. The analysis error covariance matrix pertaining to a set of supplemental, targeted observations is then computed via a second transformation. The resulting reduction in forecast error variance at a time $t_v > t_a$ is then estimated via the same transformation of ensemble forecast perturbations valid at time $t_v$. This process can be repeated rapidly for any number of hypothetical configurations of targeted observations. The ETKF “summary maps” represent the reduction in forecast error variance in the verification region at time $t_v$ as a function of the observation location. In other words, the ETKF is an “observation sensitivity” method that attempts to determine the location in which the assimilation of an observation is most likely to produce a significant impact on a given forecast. For further details on the application of the ETKF theory to targeted observations in field programs, the reader is referred to Majumdar et al. (2002, 2010).
In this thesis, ETKF summary maps (provided courtesy of Shin-Gan Chen, National Taiwan University) provide an estimate of the reduction in wind forecast error variance within a 10° x 10° verification region centered on the tropical cyclone, as a function of the location of the targeted observations. The observation variables are \( u, v, T, \) and \( q \), at 850, 500 and 200 hPa. A 50-member ECMWF ensemble is used in the ETKF computations, and the optimization time \( t_v - t_a \) is 48 hr. Locations for initial vorticity perturbations are selected in regions of local maxima on the ETKF summary map, and the relative effectiveness of perturbing vorticity in these areas versus subjectively chosen areas is one issue that will be addressed in the next two Chapters.
Chapter 3


Now that the motivation, previous relevant studies, and the tools we will be using in this study have been established, we will now progress in Chapters 3 and 4 to present the results in applying the vorticity perturbation technique to synoptic targets. Chapter 3 will cover these results for Typhoon Sinlaku (2008) while the results presented in Chapter 4 will be from the Hurricane Ike (2008) aspect of the study.

3.1 Synopsis of Sinlaku

Typhoon Sinlaku (2008) originated from an easterly wave propagating along the south side of the West Pacific monsoon trough. The location of genesis and track of Sinlaku are shown in Fig. 3.1. Sinlaku was declared a Tropical Depression by JTWC 00Z September 8th, upgraded to a Tropical Storm by 18Z, and became a typhoon at 06Z on the 9th. Sinlaku was situated in a region of very weak (~ 2-4 m/s) 850-200 hPa deep layer steering flow between two anticyclones (Fig. 3.2), one to the west over China and another to the east over the open Pacific. In the absence of a dominant steering pattern, Sinlaku appears to have beta-drifted to the NNW over the course of several days, from 00Z Sept. 10th through 00Z on the 13th (EOL 2009). The process of beta drift is one in which the tropical cyclone propagates to the NNW due to differences in the Coriolis force.
around the cyclone (Fiorino and Elsberry 1989; Wang and Li 1992). In the absence of an ambient steering current in the deep tropics, beta drift can dominate the TC track.

**Typhoon Sinlaku: best track, date and location of initialization and verification**

![Typhoon Sinlaku track and initialization](image)

**Fig. 3.1**: The track of Typhoon Sinlaku (September 2008), with dates and times for reference.

One particularly notable feature within the environment of Sinlaku was a shortwave trough to the north of the TC that, during its closest approach to Sinlaku, bypassed the TC by only 1200 kilometers on the 10th. This shortwave became cut off from the mid-latitude jet on the 8th over north-central China, propagated to the south into the sub-tropics just north of Taiwan, and merged with the mid-latitude jet again east of Japan late on the 12th. Two much larger troughs propagated from west to east across Russia and into Japan north of Sinlaku. These two troughs made their closest passes to Sinlaku on the 11th and the 15th, the second of which resulted in recurvature. Two additional features of note include a region of monsoon-induced convection southwest of
Sirlaku over Cambodia, and Tropical Storm 16W, which formed south of Japan and never reached Typhoon status (JTWC). These features can be seen at 00Z September 10th in Fig. 3.3a and 3.3b.

Fig. 3.2: 850-200 hPa deep layer mean wind field in the environment of Sirlaku vortex removed, 00Z September 10th.

The motivation for selecting Sirlaku as a case study arose from the high degree of uncertainty in its forecast. While Sirlaku presented significant forecast challenges during genesis, recurvature, and extra-tropical transition, this study will focus on the uncertainty immediately prior to and during recurvature. This uncertainty peaked at 00Z September 10th when the entire package of operational global models depicted a recurvature within
96 hours, whereas recurvature did not occur until the 120 hour time frame. The 00Z ECMWF ensembles, which produced an ensemble mean that was very close to verification, nonetheless depicted the large amount of spread in the forecast, with a significant number of members (including the ensemble mean) well to the east of verification (Fig. 3.3c). NCEP and JMA ensemble suites were even further east. This spread demonstrated the large degree of uncertainty in the models due, at least in part, to the cutoff low. While the majority of operational global model guidance depicted Sinlaku recurving within 90 hr of 00Z Sept 10th, Sinlaku remained far enough south and east of the shortwave for this not to occur.

Fig. 3.3: (a) CIMSS 500 – 100 hPa satellite-derived wind vectors and water vapor, 00Z September 10th (upper left); (b) CIMSS 850 – 300 hPa winds, derived from satellite winds and NOGAPS analysis (upper right); (c) ECMWF ensemble 00Z on the 10th, individual members (pink) and ensemble mean (light blue), (lower left); (d) 120 hr control simulation of Sinlaku, initialized 00Z September 10th, along with best track for that time frame (lower right).
The WRF control simulation for Sinlaku is initialized using the ECMWF analyses from 00Z September 10\textsuperscript{th}. Similar to the majority of available operational guidance, this simulation represented the track of Sinlaku adequately during the first 48 hours, but then recurved the system much too soon (Fig. 3.3d). It is possible that the early recurvature may be attributed to the interaction of Sinlaku with the cutoff shortwave to the north.

3.2 Vorticity Perturbation Analysis

3.2.1 Selection of Targets

As in the control simulation, all vorticity perturbation simulations are initialized on 00Z September 10\textsuperscript{th}. Perturbation targets are initially selected subjectively. Intuitively, regions of strong vorticity gradients, associated with shortwave troughs for example, are more likely to be resolved poorly by the observational network than longwave troughs or ridges. For this reason, shortwave troughs are a natural target for the vorticity perturbation technique. Two upper-level (500-200 hPa) and two low-level (850-700 hPa) targets have been selected subjectively (Fig 3.4 and 3.5, respectively) and are designated S1 – S4.

Target S1 is a large, upper-level trough over southeast Russia and Mongolia. This trough is associated with a mid-latitude surface cyclone over East Asia, and exists both upstream and downstream of large anticyclones in a highly amplified pattern. A line of low-level vorticity extending southward into China (Fig. 3.5) is associated with a cold front ahead of this trough. The center of the perturbation will be set to 44.0 N, 111.0 E, with a radius of perturbation of 600 km. This radius is similar to the radius of curvature
in the base of the trough, beyond which the flow becomes more dominated by the surrounding ridges than by the S1 trough. Since target S1 is associated with both a large spatial extent of vorticity, and with a large maximum value of vorticity, it is hypothesized that modifying this trough would have a major impact on the steering flow of Sinlaku. With the target being 3200 km away from the cyclone, it is believed that it would take several days before the effect of modifying the trough would generate any noticeable deviation to the track of Sinlaku. However, this did not turn out to be the case!

![Typhoon Sinlaku: upper-level target regions](image)

**Fig. 3.4:** ECMWF analysis within WRF domain, 500-200 hPa layer mean relative vorticity September 10th at 00z. Sinlaku is the vorticity maximum southeast of Taiwan. S1 and S2 are upper level targets for the vorticity perturbation technique.

Target S2, centered on the point 29.0 N, 126.0 E, is a much smaller upper-level trough than S1 that becomes cutoff from the jet 00Z September 8th only to re-join the jet
by 12Z on the 11th. The low-level reflection of this feature is weak (Fig. 3.5). However, the strength of this shortwave at the upper-levels, as well as its proximity to Sinlaku makes S2 a good candidate target for perturbation. The main challenge in perturbing S2 is doing so without strengthening or weakening the vorticity in Sinlaku and its immediate environment. Unintentionally perturbing Sinlaku with S2 would make it impossible to discern between the modification to the track associated with S2, and that associated with perturbing the northern edge of Sinlaku. The radius of perturbation is reduced to 400 km for this target to account for the smaller size of the shortwave. We hypothesized that, due to the combined strength and proximity of S2 to Sinlaku that S2 would be a target of high sensitivity.

Our third target, S3, is a low-level monsoonal trough over Vietnam and Cambodia centered on the point 11.0 N, 106.0 E. The radius of perturbation is set to 500 km, greater than the radius used for the smaller S2 shortwave but smaller than the radius used in perturbing the larger S1 shortwave. Of all four sensitivity targets for Sinlaku, S3 is associated with the area of weakest vorticity. S3 is a very shallow vortex, with almost no indication of an upper-level cyclonic circulation (Fig. 3.4). Perturbing a nearby synoptic feature at the low levels should primarily affect the low level steering flow. For the above reasoning, and the fact that Sinlaku is a deep, powerful TC in which the mid to upper level steering would likely dominate (Velden and Leslie 1991), we hypothesized that Sinlaku would not be particularly sensitive to perturbations at S3. Finally, it should also be noted that while S1 is deeply rooted in the mid-latitude jet, and S2 is temporarily detached from the mid-latitude jet, S3 is completely unassociated with any mid-latitude features. Therefore, unlike after perturbing S1 and S2, it seems likely that by perturbing


S3 there would not be an immediate amplification or deamplification of the large scale pattern, and it should therefore be difficult for the signal generated in perturbing S3 to propagate outward.

**Fig. 3.5**: 850-700 hPa layer mean relative vorticity September 10th at 00z. Sinlaku is the vorticity maximum southeast of Taiwan. S3 and S4 are low level targets for the vorticity perturbation technique.

The fourth target feature, S4, is Tropical Storm 16W located approximately 1000 km SE of southern Japan. S4 is associated with a strong but compact vortex, associated with a stronger maximum in vorticity at the lower levels than upper levels, but certainly stronger at the upper levels than S3 (Fig. 3.4 and 3.5). Since 16W is a compact vortex, the radius of perturbation is set to 400 km, the same radius used for S2.
The typical mechanism by which two cyclones interact is commonly referred to as the Fujiwhara effect (Fujiwhara, 1921). Brand (1970) demonstrated that the Fujiwhara effect occurs when two TCs are within approximately 1200 km of one another. At model initialization Sinlaku and 16W are 2500 km apart, and it is unlikely that they are directly influencing each other’s steering flow. If anything, since Sinlaku is the far more powerful cyclone, the effect of Sinlaku on 16W should far exceed the effect of 16W on Sinlaku. However, this is not to say that significantly weakening or strengthening 16W will not result in small changes in wind, temperature and geopotential heights that grow to modify the entire West Pacific monsoonal gyre.

![Diagram](image)

**Fig. 3.6:** Regions S1 through S4 determined to be of synoptic significance to the track of Typhoon Sinlaku (blue cyclone symbol) compared to sensitive regions determined using ETKF analysis of ECMWF ensembles (courtesy Shin-Gan Chen).

While the two neighboring anticyclones appear to have played major roles in the synoptic steering for Sinlaku, these features are not nearly as distinct in the vorticity field as the aforementioned targets S1 through S4. Since the vorticity perturbation technique is
based upon the modification of some initial vorticity, we opted to identify the most robust
signals in the vorticity field. Also, from an operational standpoint, it would be much
easier to target small vorticity maxima with dropsondes or rapid-scan than attempting to
target an entire subtropical high.

Targets S1 through S4 are all features associated with high values of relative
vorticity and high vorticity gradient, but are all of different strengths, sizes, and distances
from Sinlaku. S1 and S2 are features that are more pronounced at the upper levels, while
S3 and S4 are more robust at the lower levels. In having such a wide array of targets of
varying distances from Sinlaku and varying intensities, it is possible to answer the
primary questions of this study. First, by comparing the effects of performing small-radii
perturbations to the small targets, S2 and S4, to larger perturbations of the larger targets,
S1 and S3, it will be possible to address question (1) and elucidate whether the TC is
more sensitive to small uncertainties or perturbations close to the storm, or large
uncertainties in features far from the storm. Also, since the targets are of varying
distances from Sinlaku, it will be possible to address question (1) as to the relationship
between the distance of a perturbation from the TC and the time it takes for that
perturbation to generate a change in track (of 100 km, for example), in comparing the
control simulation to the perturbed run. By analyzing the simulation output in 6-hourly
increments in an attempt to better address question (1), it will also be possible to track the
evolution of the perturbation with time, and how the perturbation modifies the
surrounding synoptic environment to answer question (2).

Perturbations will be performed for all synoptic targets using $\alpha_{\text{max}} = \pm 0.75$. This
value is somewhat arbitrary, but is large enough to exaggerate the synoptic influences of
individual targets on the surrounding environment without being so large that the negative perturbation completely eliminates the target feature (as would be the case for $\alpha_{\text{max}} = -1.00$). While it is unrealistic that the model analysis would over- or under-represent the actual vorticity by a factor of 0.75 (or 75%), a scale factor this large is used to make the synoptic influence of the targets on Sinlaku as obvious as possible.

Since the vorticity perturbation technique generates a wind perturbation proportional to the magnitude of the initial vorticity, a vorticity perturbation using $\alpha_{\text{max}} = \pm 0.75$ at both S1 and S2 will generate a different $|v'|_{\text{max}}$ at each target. Therefore, to allow for comparison of equal initial wind perturbations, $\alpha_{\text{max}}$ will be empirically adjusted at S1 to replicate the $|v'|_{\text{max}}$ at S2.

Finally, we will perform simulations in which the environment 200 km downstream of Sinlaku is perturbed by a value of $\alpha_{\text{max}}$ that produces an initial wind perturbation at the TC of order 1 m/s. This is because, in calculating the new stream function following a perturbation, a perturbation as far away as S1 will produce an initial wind perturbation at Sinlaku as large as 1 m/s. This experiment will assist in determining the significance of an asymmetric wind perturbation at TC of ~1 m/s, and therefore help differentiate the effect of a true modification to the synoptic environment from the effect of a small initial modification to the TC.

To address question (3), as to whether or not it is more effective to select targets using a subjective vorticity analysis or an objective ETKF technique, we will compare the relative effects of perturbing features in regions of low sensitivity in Fig. 3.6, such as S1 and S4, against the effect of perturbing features S2 and S3 in regions of higher sensitivity. It will be particularly enlightening to compare the relative effects of
perturbing targets S3 to S4, as both are low-level cyclones of similar distance to Sinlaku, but S3 is associated with very high sensitivity according to the ETKF technique, while S4 is associated with virtually no sensitivity by the same technique.

Finally, to further address question (3), we will compare the effect of perturbing S1 along the center of the trough, where the vorticity gradient is the highest, against a perturbation upwind of the trough, where the ETKF technique highlights the greatest sensitivity. In doing so, it will be possible to address the issue of using an objective versus subjective method having the same target as a control variable. All targets will receive both positive and negative vorticity perturbations to verify robustness in the results.

3.2.2 Sensitivity to Upper-Level Targets

The first model simulations performed for Sinlaku involved perturbing the vorticity associated with target S1. The initial 500-200 hPa layer mean relative vorticity of the control is shown in Fig. 3.7a, with the modified initial state following a vorticity reduction (Fig. 3.7b) and increase (Fig. 3.7c) also displayed. The maximum magnitude of the vertically-averaged wind perturbation $|v'|_{max}$ is 15.5 m/s at the target and 0.59 m/s at the TC (Table 3.1). “At the target” refers to anywhere within the radius of perturbation, while “at the TC” refers to anywhere within a 300 km radius of the TC.

The initial negative vorticity perturbation is shown as a negative perturbation in the vorticity difference field in Fig. 3.8c. The difference in the re-balanced height field at 500 hPa is shown in Fig. 3.8a, overlaid on the background 500 hPa geopotential heights from the control simulation. In weakening the vorticity within the trough, a positive
height perturbation is generated. The modification to the wind field is shown in Fig. 3.8b. Wind vectors of the control (black) and perturbed (red) simulations are shown. In weakening the shortwave, negative $v$ perturbations are generated downstream of the trough (weaker southerly component) while positive $v$ perturbations are generated upstream of the trough (weaker northerly component). Fig. 3.8d also depicts a zoomed version of the perturbation to the wind field closer to the storm, in which it is possible to observe the very small differences between the control and perturbed wind vectors close to Sinlaku. The initial conditions for the positive perturbation are nearly identical, but with values inverted.

Fig. 3.7: ±0.75 $\zeta$ perturbation of S1. (a) The center of the perturbation is indicated on the left with the initial 500-200 hPa layer mean relative vorticity (left); The vorticity fields following (b) the reduction (upper right) and (c) enhancement (lower right) at S1 are shown.
| Target | $\alpha_{\text{max}}$ | $r_{\text{pert}}$ (km) | Distance (km) | $|v'|_{\text{max at target}}$ (m/s) | $|v'|_{\text{max at TC}}$ (m/s) | $\Delta t_{100 \text{ km}}$ (hr) $(-\alpha / +\alpha)$ |
|--------|-----------------|-----------------|---------------|-------------------------------|-------------------------------|------------------|
| S1     | 0.75            | 600             | 3200          | 15.6                          | 0.59                          | 21 / 21          |
| S1a    | 0.75            | 600             | 3400          | 7.3                           | 0.03                          | 85 / 76          |
| S2     | 0.75            | 400             | 1200          | 4.9                           | 0.57                          | 30 / 31          |
| S1     | 0.23            | 400             | 3200          | 4.9                           | 0.18                          | 59 / 63          |
| S3     | 0.75            | 500             | 2300          | 4.9                           | 0.67                          | 48 / 54          |
| S4     | 0.75            | 400             | 2500          | 3.1                           | 0.08                          | 58 / 72          |
| S0     | 0.16            | 500             | 200           | 0.6                           | 0.59                          | $\infty / 107$   |

Table 3.1: Summary of results for Typhoon Sinlaku. Listed is $|v'|_{\text{max}}$ at the target and at the TC, which is the 850 – 200 hPa vertically-averaged magnitude of the maximum wind perturbation within the radius of perturbation or 300 km radius of the TC, respectively. $\Delta t_{100 \text{ km}}$ is the amount of time from initialization it takes a given perturbed simulation to produce a track deflection of at least 100 km from the control for the negative and positive perturbations, respectively.
Fig. 3.8: $-0.75 \zeta$ perturbation of S1 at initialization: (a) 500 hPa geopotential height difference (m) (upper left); (b) 850-200 hPa deep layer mean vector wind, control (black) and perturbed (red), $v$-difference (m/s) shaded (upper right); (c) 850-200 hPa vector wind, relative vorticity difference ($x10^{-4}$ s$^{-1}$) shaded (lower left); (d) 850-200 hPa vector wind, $v$-difference (m/s) zoomed (lower right). The hurricane icon indicates the location of Typhoon Sinlaku at that time.
sinlaku accelerates northward simulation, is 220 km shown in Fig. 3.9. S1 is denote location of sinlaku at 0, 24, 48, 72, 96 and 120 hr.

Fig. 3.9: ±0.75 ζ perturbations at S1: 5-day best track (white), control simulation (red), -0.75 ζ at S1 (light blue), -1.00 ζ at S1 (dark blue), +0.75 ζ at S1 (pink), +1.00 ζ at S1 (purple). Circles denote location of sinlaku at 0, 24, 48, 72, 96 and 120 hr.

The modification to the track of Sinlaku associated with perturbing the vorticity at S1 is both robust and immediate. The JTWC best track (white), control simulation (red), \( \alpha_{\text{max}} = -0.75 \) vorticity reduction (light blue) and \( \alpha_{\text{max}} = +0.75 \) vorticity increase (pink) are shown in Fig. 3.9. In the case of weakening the vorticity within the base of the trough, Sinlaku continues to propagate at roughly the same forward speed but the propagation vector is deflected well to the west of both the control simulation and the best track. The forecast WRF sensitivity, in terms of track difference between the perturbed and control simulation, is 220 km at 48 hr, and 1086 km at 120 hr (Table 3.2). On the other hand, Sinlaku accelerates northward when strengthening the shortwave. The positive vorticity
perturbation is accompanied by a much smaller eastward change in longitude than the corresponding westward track change associated with the negative perturbation. Whereas Sinlaku is still nearly 500 kilometers south of Korea at day five in the control, the storm has already made landfall in Korea in the perturbed simulation by day four. The 48 and 120 hr modifications to the track associated with the strengthened shortwave are 120 and 1066 km, respectively (Table 3.2).

Fig. 3.10: As in Fig. 3.8b. 850-200 hPa deep layer mean vector wind, control (black) and perturbed (red), v-difference (m/s) shaded for -0.75 ζ perturbation of S1, seen at simulation hours 00 (a), 12 (b), 24 (c), 36 (d) and 48 (e). The TC icon indicates the location of Typhoon Sinlaku at each time in the perturbed simulation.
<table>
<thead>
<tr>
<th>Target</th>
<th>$\alpha_{\text{max}}$</th>
<th>$r_{\text{pert}}$ (km)</th>
<th>Distance (km)</th>
<th>ETKF Sensitivity (normalized by max value)</th>
<th>48 hr WRF Track Modification (km) ($-\alpha/\alpha$)</th>
<th>120 hr WRF Track Modification (km) ($-\alpha/\alpha$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.75</td>
<td>600</td>
<td>3200</td>
<td>0.65</td>
<td>220 / 120</td>
<td>1086 / 1066</td>
</tr>
<tr>
<td>S1a</td>
<td>0.75</td>
<td>600</td>
<td>3400</td>
<td>0.89</td>
<td>38 / 8</td>
<td>362 / 255</td>
</tr>
<tr>
<td>S2</td>
<td>0.75</td>
<td>400</td>
<td>1200</td>
<td>0.79</td>
<td>246 / 110</td>
<td>1108 / 633</td>
</tr>
<tr>
<td>S3</td>
<td>0.75</td>
<td>500</td>
<td>2300</td>
<td>0.92</td>
<td>107 / 80</td>
<td>464 / 270</td>
</tr>
<tr>
<td>S4</td>
<td>0.75</td>
<td>400</td>
<td>2500</td>
<td>0.56</td>
<td>84 / 60</td>
<td>771 / 338</td>
</tr>
<tr>
<td>S0</td>
<td>0.16</td>
<td>500</td>
<td>200</td>
<td>0.87</td>
<td>27 / 27</td>
<td>38 / 97</td>
</tr>
<tr>
<td>S1</td>
<td>0.23</td>
<td>400</td>
<td>3200</td>
<td>0.65</td>
<td>60 / 38</td>
<td>577 / 405</td>
</tr>
</tbody>
</table>

Table 3.2: Additional pertinent data for Typhoon Sinlaku. The radius of vorticity perturbation is listed as $r_{\text{pert}}$, in km; the distance from the center of perturbation to Sinlaku is listed as Distance, in km; the ETKF diagnosed sensitivity at the center of each perturbation is listed as ETKF Sensitivity, and is non-dimensional; the 60 and 120 hr WRF sensitivities are listed for both the positive and negative perturbations, with sensitivity measured as the distance between each simulation and the control.

The effect of perturbing S1 is straightforward from a synoptic standpoint. When the trough is weakened, the southerly flow downstream of the trough axis is reduced. The environmental winds from Sinlaku are cyclonic, and hence easterly to the north of the cyclone. As indicated in Fig. 3.10b, the southward extension of negative $v$ perturbations into the immediate environment of Sinlaku at hour 12 depicts both stronger northerlies behind the trough and weaker southerlies ahead of the trough. Stronger northerlies allow Sinlaku to remain further south. From hours 24-48, the negative $v$ perturbations associated with the initial shortwave retreat to the northeast (Fig. 3.10c,d,e). However, at the same time a new region of negative $v$ perturbations develops associated with the east side of the subtropical anticyclone over China. In weakening the S1
shortwave, the anticyclone over China is able to propagate further east in a shorter period of time. A significant portion of the anticyclone is north of Sinlaku in the perturbed simulation (Fig. 3.10e), suppressing Sinlaku to the south.

In addition to the negative vorticity perturbation at S1 modifying the meridional location of Sinlaku, the perturbation also modifies the zonal position of the TC. The region south of 25°N is dominated by subtropical easterly winds, while the region north of 25°N is dominated by mid-latitude westerly winds. By modifying S1 in a manner that suppresses the track of Sinlaku to the south, Sinlaku is forced to remain in an environment of easterly flow. Therefore, Sinlaku also propagates much further west in the $\alpha_{\text{max}} = -0.75$ simulation. Also by weakening S1, Sinlaku remains far enough south to avoid the influence of the S2 trough. Therefore, S2 does not force an early Sinlaku recurvature, and the TC is correctly simulated making a Taiwan landfall. Ultimately, the typhoon incorrectly fails to recurve near the end of the simulation and makes a second landfall in southeast China.

It should also be noted that in modifying a single synoptic feature, various other features both upstream and downstream are modified (Fig. 3.11). In weakening the trough at S1, a positive height perturbation is generated within the center of the trough. With time, a small amount of this positive height perturbation propagates upstream further west than any of the initial perturbation. Additionally, negative height anomalies are generated in the axis of the downstream ridge. This indicates that by deamplifying a single synoptic feature within the jet, it is possible to deamplify other features further along the jet. This will also hold true for the case of amplifying targets.
It should also be noted that positive perturbations in the region of stronger westerlies, the TC also travels further east in this simulation. Instead, Sinlaku remains under the influence of the near subtropical anticyclone. Instead, Sinlaku is not longer influenced as significantly by the subtropical anticyclone. This acts to advect Sinlaku further north. By amplifying the pattern at S1, the entire pattern becomes so amplified that the propagation of synoptic systems begins to slow. Sinlaku is not longer influenced as significantly by the subtropical anticyclone over China. Instead, Sinlaku remains under the influence of the near-stationary S1 trough over the course of 3 to 4 days (Fig. 3.12b,c,d,e). Since Sinlaku now tracks further north into the region of stronger westerlies, the TC also travels further east in this simulation. It should also be noted that positive \( \psi \) perturbations in a region of already strong...

Fig. 3.11: - 0.75 \( \zeta \) perturbation of S1 seen at hr 72, 0Z on the 13th; 500 hPa geopotential height difference (m); positive height perturbations in the base of the trough, coupled with negative height perturbations in the crest of the ridge, result in a net deamplification of the synoptic pattern. The hurricane icon indicates the location of Typhoon Sinlaku at that time.

When strengthening the vorticity at S1, the same logic applies to explain the track of the perturbed simulation as in the case of weakening the vorticity, only in reverse. By strengthening S1, an initial positive \( \psi \) perturbation is generated ahead of the trough (Fig. 3.12a). This acts to advect Sinlaku further north. By amplifying the pattern at S1, the entire pattern becomes so amplified that the propagation of synoptic systems begins to slow. Sinlaku is not longer influenced as significantly by the subtropical anticyclone over China. Instead, Sinlaku remains under the influence of the near-stationary S1 trough over the course of 3 to 4 days (Fig. 3.12b,c,d,e). Since Sinlaku now tracks further north into the region of stronger westerlies, the TC also travels further east in this simulation. It should also be noted that positive \( \psi \) perturbations in a region of already strong...
southerlies generates an extremely strong southerly flow in the environment of Sinlaku. This allows Sinlaku to propagate nearly twice the forward distance over the course of five days than traveled in the control simulation (Fig. 3.9).

Fig. 3.12: As in Fig. 3.10, but for +0.75 \( \zeta \) perturbation of S1, seen at simulation hours 00 (a), 24 (b), 48 (c), 72 (d) and 96 (e).

One slightly unexpected result is the fact that the track of Sinlaku deviated from the control in the perturbed simulations almost immediately, despite the fact that Sinlaku is well outside (~3200 km) of the radius of perturbation (~600 km). At the beginning of the simulation the cyclone is nearly stationary. Thereafter, both perturbed simulations and the control all initially move due northwestward. During the first 24 hr, the tracks begin to diverge, with a track difference of 100 km achieved by 21 hr for both the negative and positive perturbations (Table 3.1). As seen in the progression from Fig. 3.10a to 3.10b (Fig. 3.12a to 3.12b) the southward extension of the negative (positive) \( \nu \) perturbations is evident during the first 12 (24) hr of simulation. Therefore, the signal of
a perturbation as far from a TC as 3200 km can still potentially impact the TC, and therefore the track of the TC, in less than one day.

While we have defined a distance metric for measuring sensitivity at two time increments (48 and 120 hr), it is also possible to define a characteristic time associated with a given distance to quantify sensitivity slightly differently. We will define a $\Delta t_{100 \text{ km}}$ (hr) associated with 100 km track difference between the perturbed and control simulations. While the choice of 100 km is arbitrary, this threshold will be re-examined below to delineate the initial track deflections associated with the small (~1 m/s) wind perturbations at the TC associated with balancing the initial wind field versus the later track deflections associated with an actual modification to the synoptic environment.

The perturbations to S1 are then repeated using $\alpha_{\text{max}} = \pm 1.00$ to check for consistency in the results, and to discern whether or not any additional information could be gained by further increasing $\alpha_{\text{max}}$. Ultimately, the tracks of Sinlaku for the $\pm 1.00$ perturbations are sufficiently close to the $\pm 0.75$ perturbations (Fig. 3.9) that any synoptic diagnostics of these simulations will be neglected (Fig. 3.9).

Although the ETKF technique depicts a target region at S1, much greater sensitivity is indicated just downstream of the trough (Fig. 3.6). Since this area is not a distinct target, but instead just a separate region associated with target S1, this new target area will be referred to as S1a, or “downstream of S1”. The radius of perturbation, the depth of perturbation, and $\alpha_{\text{max}}$ are all the same for S1a as they are in perturbing S1. The only difference is the location, which has been changed to 49.0 N, 132.0 E. The initial 500-200 hPa layer mean relative vorticity of the control is shown in Fig. 3.13a, with the modified initial state following a vorticity reduction (Fig. 3.13b) and increase (Fig. 3.13c)
also shown. Since the magnitude of the vorticity being perturbed at target S1a is lower than the initial vorticity at S1, the initial wind perturbations are correspondingly lower. \( |\mathbf{v}'|_{\text{max}} \) at S1a is 7.3 m/s at the target and only 0.03 m/s at the TC (Table 3.1). Since the magnitude of the initial vorticity is less at S1a than S1, a perturbation of equal \( \alpha_{\text{max}} \) produces a correspondingly smaller initial wind and height perturbation (Fig. 3.14).

![S1a perturbation](image)

Fig. 3.13: As in Fig. 3.7, but for \( \pm 0.75 \zeta \) perturbations at S1a.
Fig. 3.14: As in Fig. 3.8, but for perturbation of $-0.75 \zeta$ at S1a.

The JTWC best track (white), control simulation (red), vorticity reduction (blue) and vorticity increase (purple) for the perturbations at S1a are shown in Fig. 3.15. While there is a clear modification to the track associated with perturbing S1a, it is certainly less pronounced and less immediate than what is seen in the perturbation of S1. In fact, the deviations from the control for both negative and positive perturbations at S1a are virtually zero for the first two and a half days, before the tracks finally begin to diverge thereafter. Quantitatively, the 48 hr modifications to the track for the positive and negative vorticity perturbations are only 8 and 38 km, respectively. These are roughly an order of magnitude less than the track modifications seen for target S1. Near the end of
simulation the modification to the track becomes more apparent, but still significantly less than the previous case, to 255 km at 120 hr for the positive perturbation and 362 km at 120 hr for the negative perturbation. Unlike in the case of perturbing S1, the vorticity reduction at S1a does not deflect the track far enough west for a landfall in China, or even a landfall in Taiwan for that matter. Although this track is both south and west of the control, unlike in the S1 case, the cyclone is not far enough south to avoid recurvature during the final 18 hours of simulation. Additionally, while the positive perturbation at S1a does accelerate the forward motion of the cyclone, it does so much less than for perturbing S1.

Fig. 3.15: As in Fig. 3.9, but for ±0.75 ζ perturbations downstream of northern shortwave. 5-day best track (white), control simulation (red), -0.75 ζ at S1a (blue), +0.75 ζ at S1a (purple).
Major differences exist between the evolution of the S1a perturbations and the S1 perturbations. In the case of S1, the strengthening of vorticity along the axis of the shortwave directly led to a deepening of the trough. In contrast, S1a is situated between a trough to the west and a ridge to the east. Both the eastern edge of the upstream trough and the western edge of the downstream ridge fall within the radius of perturbation of the target. So, when performing the vorticity reduction, the technique is designed to scale the cyclonic vorticity within the trough down by 75%, while also scaling the anticyclonic vorticity in the crest of the ridge down by 75%. Once the height field is re-balanced, the vorticity reduction at S1a is raising the heights on the east side of the trough and lowering the heights on the west side of the downstream ridge. However, the maximum amplitudes within the trough and ridge are outside of the radius of perturbation, and therefore remain unmodified. For this reason, while the S1 perturbations modify the maximum amplitude of the trough, the S1a perturbations instead modify the width of the trough, the width of the downstream ridge, and the trough/ridge height and wind gradient. The general eastward propagation of the perturbation along the trough/ridge interfaces and failure to modify the maximum amplitude of troughs and ridges is shown in Fig. 3.16. As the effect of reducing the vorticity at S1a reduces the gradient of upper-level heights, as explained above, the effect of strengthening the vorticity at S1a strengthens the gradient of upper-level heights via the same logic.
Despite the fact that the negative vorticity perturbation leads to small $v$ perturbations almost immediately directly over Sinlaku, this does not lead to a change in forecast track until the 60 hour timeframe. It appears that, in this case, the small initial perturbation at the TC generates no more than very minor fluctuations in track during the initial timeframe. This should not come as a surprise, as the initial $|v'|_{\text{max}}$ at the TC for S1a is only 0.03 m/s. It appears that since we are not perturbing the amplitude of the axis of the trough, or the magnitude of the maximum vorticity, there is no immediate change to the far-field environmental winds associated with perturbing S1a as there is in perturbing S1. Since the modification to both the $u$ and $v$ components of wind in and around Sinlaku is much more apparent in the case of S1 than with S1a, it appears that the environment of Sinlaku, and therefore the track of Sinlaku, has a much greater sensitivity to the depth of the trough than it does to either the width of the trough or the trough/ridge height gradient. However, the greater sensitivity to S1 may also be attributed in part to
the fact that the vorticity perturbation technique multiplies the initial vorticity by a scalar. Therefore a target, such as S1, with high vorticity to start with will be subject to a larger initial perturbation. Perturbations to the wind field at S1a have less influence on the environment of Sinlaku than those at S1, and tend to simply propagate downstream. Troughs and ridges are not as clearly amplified as in S1, but they do experience a change in phase. This can be seen at various forecast hours in Fig. 3.16.

For the negative and positive vorticity perturbations using $\alpha_{\text{max}} = 0.75$ at S1, the respective $\Delta t_{100 \text{ km}}$ values are 21 / 21 hr, where the first (second) number in the ratio is the time it takes for the track of Sinlaku in the negative (positive) perturbation to deviate from the control by 100 km (Table 3.1). This means that for all the above S1 perturbations, the tracks begin to diverge significantly within the first day. However, with the S1a perturbations, $\Delta t_{100 \text{ km}}$ for the negative and positive perturbations increases to 85 and 76 hours, respectively (Table 3.1). This marked increase in $\Delta t_{100 \text{ km}}$ corresponds to the additional time it takes for perturbations at S1a to develop sufficiently large perturbations to the large-scale synoptic environment to modify the track of Sinlaku. Since S1a and S1 are both approximately the same distance from the TC, the amount of time it takes the TC to become sensitive to a synoptic scale perturbation appears to have less to do with the distance between the perturbation and the TC as it does with the feature being perturbed. Ultimately, this returns to the discussion of modifying the maximum depth of the trough versus modifying the downstream trough/ridge interface.

While the results of the S1a perturbation allowed for an investigation into the perturbation distance versus time ratio, the main purpose in performing this perturbation
is to investigate the effectiveness of the ETKF technique in selecting the optimal regions to perturb in order to observe the maximum sensitivity. Quantitatively, ETKF diagnosed a maximum sensitivity of 0.89 (unit-less, and normalized by 1.00) downstream of the trough and only 0.65 within the base of the trough. Clearly, if one is to use change in TC track as the primary determinant of cyclone sensitivity, the subjective analysis has proven superior in this particular example. The cyclone is shown both greater maximum track deflection and earlier track deflection in the case of the S1 perturbations than exhibited in the S1a perturbations.

While the ETKF technique is employed to locate targets of maximum sensitivity objectively, it may have been ineffective in this case. However, conclusions made from equal $\alpha_{\text{max}}$ perturbations are inherently flawed by the fact that the magnitude of the wind perturbation differs between targets. Before forming a definitive conclusion, it will be necessary to examine perturbations of equal $|v'|_{\text{max}}$ at both targets. However, discrepancies between the ETKF and the vorticity perturbation techniques may arise from the differences between the techniques themselves. While the vorticity perturbation technique is designed to test the sensitivity of TC tracks to synoptic perturbations in the environment surrounding the cyclone, the ETKF technique uses forecast perturbations to predict the reduction in forecast error variance produced by targeted observations. For this reason, using ETKF to discern targets to be used by the vorticity perturbation technique is subject to inherent inconsistencies.

One final point of interest is that $|v'|_{\text{max}}$ at the TC following the S1a perturbation is essentially zero at 0.03 m/s. While the difference in track associated with the S1a perturbation is relatively small by comparison to those associated with S1, track
deflections of several hundred kilometers result at and beyond day four. This shows that even with a very small initial perturbation in the vicinity of the cyclone, the modification to the far-field synoptic pattern may significantly influence the track of the TC.

The next target is S2, the upper-level low just to the north of Sinlaku. While very close to Sinlaku, it is possible to modify S2 with a minimal impact on the TC (Fig. 3.17). The tracks of both the positively and negatively perturbed simulations for S2 are highly similar to the tracks for the S1 perturbations (Fig. 3.18). The synoptic reasoning behind the results is also similar. Both involve a local modification to the center of a trough north of Sinlaku, changing the maximum amplitude of that shortwave while inciting little or no phase change at the initial time. The only appreciable difference is the size and distance of the trough being modified. Once again, when the shortwave is strengthened, south-westerly flow downstream of the trough increases and advects Sinlaku to the northeast. When the shortwave is substantially weakened, south-westerlies subside to the point that the prevailing background subtropical easterlies begin to dominate, steering the storm to the west. Negative $v$ differences appear within the region between S2 and Sinlaku, as well as along the west side of the subtropical ridge (Fig. 3.19c,d). Additionally, positive $\zeta$ perturbations again appear in the base of the trough following the positive vorticity perturbation 120 hrs after initialization, along with negative $\zeta$ perturbations in the crest of the downstream ridge (Fig. 3.20). Again, this is indicative of downstream amplification. Downstream deamplification occurs following the vorticity reduction at S2.
Fig. 3.17: As in Fig. 3.7, but for perturbations at S2.
Fig. 3.18: As in Fig. 3.15, but for $\alpha_{\text{max}} = \pm 0.75$ at S2.

Fig. 3.19: As in Fig. 3.10, but for $-0.75 \zeta$ perturbation of S2, seen at simulation hours 00 (a), 12 (b), 24 (c), 36 (d) and 48 (e).
Originally, the question was posed: is the tropical cyclone more sensitive to small perturbations of close synoptic features or larger perturbations to synoptic features further away? The 48 hr WRF positive and negative perturbation modifications to the track for S1 ($\alpha_{\text{max}} = \pm 0.75$) are 120 and 220 km, and similarly are 110 and 246 km for S2 (Table 3.2). The 120 hr track modifications are also very close to matching, with the exception of the positive perturbation for S2, at 1066 / 1086 (+/-) for S1 and 633 / 1108 (+/-) for S2. While it would be necessary to perturb multiple targets for a variety of TCs to answer this question with statistical significance, the results from the initial part of the Sinlaku study indicate no clear preference.

Timescales associated with sensitivities of features of various distances to the TC have also been assessed with target S2. As is the case with the perturbations centered on

Fig. 3.20: - 0.75 $\zeta$ perturbation of S2 at 0Z on the 15th. Downstream development of strengthened trough leads to net amplification of pattern.
S1, 100 km track deflections associated with the perturbation appear around 20 hr into the simulations (Table 3.1). S2 is much closer to Sinlaku than either S1 or S1a, around 1200 km from the typhoon, but is associated with $\Delta t_{100 \text{ km}}$ of around 30 hr. Therefore, the amount of time it takes for the perturbation to generate a significant change in storm track does not appear to be a function of distance between the perturbation and the TC. With a $\Delta t_{100 \text{ km}}$ of 30 hr for S2 and ~80 hr for S1a, it is clear that Sinlaku is more sensitive to perturbing the cut-off shortwave than it is to the region immediately downstream of the mid-latitude trough. However, this depends upon the size and the strength of the perturbation.

While the above simulations demonstrated the concept of synoptic sensitivity, an important issue remains to be addressed. Although comparisons have been made between S1 and S2, the magnitude of the initial wind perturbation at the target differs between the two cases. At the two targets, $|v'|_{\text{max}}$ is over three times as great for S1 (15.6 m/s) as it is for S2 (4.9) (Table 3.1). This is simply a product of the fact that, given an equal initial $\alpha_{\text{max}}$, the region of higher initial background vorticity will be subject to a greater wind perturbation. A discrepancy also existed between the initial radius of perturbation, which is set to 600 km for S1 and 400 km for S2. This is to best approximate the radius of curvature of the corresponding features, but makes it difficult to compare the two experiments on equal grounds. It should be noted that, although the initial wind perturbations at the targets differed substantially between S1 and S2, $|v'|_{\text{max}}$ at the TC is (coincidentally) nearly equivalent for the two simulations. By this metric, the above results still have grounds for comparison.
To account for the $|v'|_{\text{max}}$ discrepancy at the targets themselves, $\alpha_{\text{max}}$ is empirically adjusted until a value is attained in which $|v'|_{\text{max}}$ at S1 is equal to 4.9 m/s, or the value at S2 given $\alpha_{\text{max}} = \pm 0.75$. It is found that a value of $\alpha_{\text{max}} = \pm 0.23$ at S1 would produce this initial wind perturbation. A new simulation is performed using this new $\alpha_{\text{max}}$ and $R_{\text{pert}}$ of 400 km. It is not surprising that the perturbations using a reduced $\alpha_{\text{max}}$ produce a much less drastic change to the initial vorticity field (Fig. 3.21).

The track sensitivity in the new simulation is much lower than in the previous simulations for S1 and S2. Whereas the tracks for the previous S1 simulations deviated 100 km from the control in less than 24 hours, the new negative and positive perturbations using $\alpha_{\text{max}} = 0.23$ deflect 100 km in 59 hr and 63 hr, respectively (Table 3.1). The track of the perturbation in which a positive perturbation is applied is much closer to the control than the perturbation of equivalent $|v'|_{\text{max}}$ with S2, while the track of the negatively-perturbed simulation is very close to the best track (Fig 3.22).
These results suggest that based upon the definition of an equal perturbation, a different interpretation is necessary. If the perturbations at S1 and S2 have an equal \( \alpha_{\text{max}} \), the greater magnitude of perturbation associated with modifying higher background vorticity compensates for the additional distance between the TC and the target, making Sinlaku more sensitive to S1 than S2. However, if we are to choose different \( \alpha_{\text{max}} \) for the two targets, but one in which the initial \( |v'|_{\text{max}} \) is equal, Sinlaku is more sensitive to the closer target.
3.2.3 Sensitivity to Low-Level Targets

Having completed the perturbations of the upper-level targets, we now progress to perturbations of the low-level target regions. The first such region is target S3, the monsoonal trough southwest of Sinlaku. In perturbing S3 (Fig. 3.23), the initial $W'_{\text{max}}$ is 4.9 m/s at the target (coincidently equal in magnitude as for S2) and 0.67 m/s at the TC (Table 3.1). Perturbing S3 resulted in substantial track deflections for Sinlaku (Fig. 3.25). While track changes are less than for targets S1 and S2, they are nonetheless greater than hypothesized. The 48 and 120 hr modifications to the track are 80 / 107 km (+/-) and 270 / 464 km., respectively (Table 3.2). While S3 is to the south of Sinlaku,
unlike any of the prior targets, the environmental influence of S3 on Sinlaku is once again in the form of south-westerly cyclonic flow on the east side of the feature, particularly at the lower levels. Strengthening the vorticity associated with S3 strengthens the south-westerly flow, as weakening the vorticity at S3 does the opposite, as is the case for targets S1 and S2.

A clear connection between the $\nu$ difference signal produced at S3 and Sinlaku is difficult to discern. However, when performing a vorticity reduction at S3, an initial negative $\nu$ perturbation is generated along the eastern periphery of the target, indicating weakened southerly winds (Fig. 3.24a,b). With time, negative $\nu$ differences also develop much closer to Sinlaku, allowing the TC to remain further south (Fig. 3.24c,d,e). Once again, with a more southerly track, the TC remains in the environment of deep tropical easterly flow, and therefore travels further west, or closer to the best track (Fig. 3.25).
Fig. 3.23: As in Fig. 3.7, but for perturbations at S3, and for the 850-700 hPa layer.

Fig. 3.24: As in Fig. 3.10, but for -0.75 \( \zeta \) perturbation of S3, seen at simulation hours 00 (a), 24 (b), 48 (c), 72 (d) and 96 (e).
The modifications to the track associated with S3 are greater than those associated with S1a, especially during the first 48 hours of simulation. $\Delta t_{100\,\text{km}}$ for the negative and positive vorticity perturbations to S3 are 48 and 54 hr, respectively (Table 3.1). Although S3 is closer to Sinlaku, S1a is associated with a larger trough that exists through a greater depth of the troposphere. The fact that a time lag is observed in the track sensitivity to S1a and not S3 can be explained by either the fact that S3 is much closer to Sinlaku, or that the perturbation of the amplitude of a synoptic feature generates a more immediate modification to the track than phase changes. Results from the comparison between S1 and S1a suggest the latter.

Fig. 3.25: As in Fig. 3.15, but for $\alpha_{\max} = \pm 0.75$ at S3.
While strengthening or weakening a mid-latitude shortwave can result in a long-lasting modification to the amplification of an entire trough-ridge train, we hypothesized that modifying a tropical cyclone would not produce such a lasting effect. This is because, by arbitrarily strengthening a TC in an unfavorable environment (16W is in an environment of increasing vertical shear and decreasing SSTs) the cyclone would not be able to maintain its new intensity for more than a few hours, and would quickly revert to its prior strength. Similarly, by weakening a TC in an unfavorable environment, it is only encouraging dissipation of the cyclone in an environment in which dissipation is already imminent. Reverse arguments could be made for perturbing TCs in a very favorable environment.

Fig. 3.26: As in Fig. 3.7, but for perturbations at S4.
environment. Ultimately 16W dissipates at approximately 00Z on the 13th in the control and both perturbed simulations, reinforcing this idea. Following this reasoning, it is not surprising that the ETKF technique depicted low sensitivities, of only 0.56, in the region of 16W.

The initial $|v'|_{\text{max}}$ associated with the S4 perturbation (Fig. 3.26) is 3.1 m/s at the target, and only 0.08 m/s at Sinlaku (Table 3.1). Despite the aforementioned arguments, perturbing S4 led to a significant change in track for Sinlaku (Fig. 3.27). The 48 hr track modifications are 60 / 84 km (+/-), and the 120 hr track changes of 338 / 771 km (+/-) are greater than the track changes in both S1a and S3 (Table 3.2). Even more surprising,
strengthening 16W allowed Sinlaku to recurve more quickly than before, while weakening the storm caused Sinlaku to travel much further westward. Since 16W is to the east of Sinlaku, the winds on the west side of 16W are from the north, and strengthening 16W \textit{should} result in a strengthening of the northerlies, one would expect the vorticity enhancement to cause a westward motion. However, this is not the case.

In order to diagnose the reason behind the results for the S4 perturbations, it is necessary to examine the evolution of heights. TC 16W is a small tropical cyclone within an environment otherwise dominated by a much larger subtropical anticyclone. By weakening the vortex at S4, the new, re-balanced height field has a much stronger and better consolidated ridge in place. Not only is the perturbed ridge stronger at the initial time, but the ridge continues to build throughout the first few days of simulation. Despite the fact that the negative vorticity perturbation is only applied to the low levels of the cyclone, the net impact to the heights within the ridge are obvious throughout the troposphere. The strengthening ridge to the east of Sinlaku, along with the attendant build-up of mass and development of a blocking pattern, acts to deflect the jet stream further north over the crest of the ridge. This, in turn, allows the prevailing easterlies to dominate and advect Sinlaku further west (Fig. 3.29a). Although the strongest signal of the perturbation at S4 is propagated downstream, enough of the signal propagates upstream to modify the track of Sinlaku (Fig. 3.30).
Conversely, when strengthening the vorticity associated with 16W, heights fall within the center of the subtropical ridge, and the blocking east of Sinlaku begins to

Fig. 3.28: (a) 500 hPa height differences on the 12th at 0Z for the removal of 16W (top) and (b) on the 11th at 12Z for the strengthening of 16W (bottom).
weaken. Although the strengthened cyclone begins to weaken rapidly, as it is in an unfavorable environment, the negative height perturbations remain pronounced through at least 48 hours. With a weaker ridge in place, the easterlies rapidly decay, the jet dips further south, and Sinlaku is advected much further west (Fig. 3.28b).

Fig. 3.29: As in Fig. 3.10, but a 0Z on the 13th for -0.75 $\zeta$ perturbation at S4.

Target S4 is closer to Sinlaku than either target S1 or S1a, but further from Sinlaku than either S2 or S3. The modification to the track associated with negative and positive vorticity perturbations at S4 produced a track difference of 100 km within 58 hr and 72 hr, respectively. This means that the tracks spread more rapidly for S4 than for S1a, but less so than any of the other preceding targets. The 48 and 120 hr track modifications associated with S4 are greater than those shown to S1a, less than what is seen with either S1 or S2, and comparable to the track deflections associated with S3. The radius of perturbation “R” for S1 and S1a, the largest targets associated with the
broadest cyclonic vorticity, is set to 600 km for both targets. S2 is a slightly smaller feature, and is perturbed using R of 500 km. S3 and S4 are the smallest features, and are hence perturbed using an R of 400 km. If one were to examine perturbations of S1, S3 and S4 on their own, one could conclude that the TC is more sensitive to perturbations of large features far from the storm (S1) than it is to perturbations of smaller features closer to the typhoon (S3 and S4). However, if one were to examine S1a, S2, S3 and S4 alone, one could conclude that the TC is most sensitive to perturbations of small features closest to the storm (S2), slightly less sensitive to moderate sized features a bit further away (S3 and S4), and the least sensitive to large features that are very far from the storm (S1a).

### 3.2.4 Sensitivity to Near-TC Perturbations

One issue that became apparent is the inability to separate the sensitivity of Sinlaku to the perturbed evolution of synoptic-scale features from the sensitivity of the TC to the initial perturbation at the TC. In order to investigate the sensitivity of the TC to very close perturbations that do not perturb the far-field synoptic environment, a new perturbation is created, called S0. S0 is a target region 200 km NNW of Sinlaku, directly in the path of the cyclone. A perturbation of $a_{\text{max}} = 0.16$ with 500 km radius produced a value of $0.59 \text{ m/s } |v'|_{\text{max}}$ at the TC, specifically chosen to match the perturbation at Sinlaku associated with the S1 perturbation (Table 3.1). A radius of 500 km is chosen such that a perturbation 200 km ahead of the TC could perturb the entire TC environment (defined as 300 km for our search radius). This perturbation is too small to be evident in a visual comparison of the vorticity fields (Fig. 3.30).
Fig. 3.30: As in Fig. 3.7, but for perturbations at S0.

A small perturbation very close to the TC resulted in minimal sensitivity for both the positive and negative perturbations (Fig. 3.31). The perturbation in which the vorticity is increased led to a TC track deflection of 100 km in 107 hr, the slowest yet. The perturbation in which the vorticity ahead of Sinlaku is decreased never produced a 100 km track deflection throughout the entire simulation. Since the S1 perturbation (using $\alpha_{\text{max}} = 0.75$) produced an equivalent perturbation at Sinlaku as the present S0 perturbation, yet S1 is associated with very large track deflections while S1 is associated with little to no track deflections, it is apparent that the modification to the synoptic...
environment and the evolution of the perturbations to synoptic features dominates the track sensitivity.

![Typhoon Sinlaku: 120 hr simulation tracks for $\xi$ perturbation at S0](image)

Fig. 3.31: As in Fig. 3.15, but for $\alpha_{\text{max}} = \pm 0.16$ at S0.

It is evident that Typhoon Sinlaku exhibited a high degree of sensitivity to a variety of targets in both the near and far synoptic environment. The TC is likely particularly sensitive to perturbations in the synoptic field due to its location in a bifurcation point. A very small shift in the track of Sinlaku would have resulted in either an early recurvature due to the S2 trough, or the system remaining in the subtropics until a far upstream trough can interact with the TC. In the next chapter, we shall see that for a different TC, at not quite so critical a juncture as Sinlaku, smaller sensitivity will be observed.
Chapter 4

Synoptic Sensitivity Analysis for Hurricane Ike (2008)

4.1 Synopsis of Ike

Hurricane Ike (2008) originated from an African easterly wave, developed into a tropical storm September 1, 2008 and further developed into a hurricane on the 3\textsuperscript{rd}. The track and corresponding intensity of Hurricane Ike is shown in Fig. 4.1. By 00Z on the 9\textsuperscript{th}, the time of interest for this study, Ike had crossed mainland Cuba and was traveling

![Hurricane Ike: best track, date and location of initialization and verification](image)

Fig. 4.1: Track of Hurricane Ike (September 2008) with important dates and times for reference.
northwestward in the Caribbean. Ike was in a region of stronger deep layer (850-200 hPa) flow than Sinlaku (~ 4-6 m/s), dominated by easterly zonal flow (Fig. 4.2) (Berg 2009).

Several potentially significant synoptic features exist within the environment of Ike, including a large subtropical anticyclone north, northeast, and east of Ike, along with an upper-level low east of the Bahamas. Further away, but also potentially significant, are a trough just to the west of the Great Lakes and Tropical Storm Lowell south of Baja

Fig. 4.2: 850-200 hPa deep layer mean wind field in the environment of Ike at initialization, vortex removed.
California (Fig. 4.3a and 4.3b). As the anticyclone slowly retreated to the east, Ike continued on its course to the northwest along the western periphery of the high. By mid-day on the 13th, the time of landfall in north Texas, Ike began to fall under the influence of an approaching shortwave over the southwest U.S. This shortwave, that had been off the coast of the state of Washington on the 9th, propagated almost due south before separating from the mid-latitude jet, then was later captured by the subtropical jet and ejected northeastward on the 12th.

The initialization time used in this study will be 00Z September 9th, 2008. This time was noteworthy due to the fact that earlier model forecasts correctly depicted a landfall along the north Texas coast, with very little spread. However, by 00Z on the 9th,
the global model consensus incorrectly shifted dramatically further south (Fig. 4.3c). Investigating why the forecast deteriorated for Ike at this time motivated this case study.

The WRF control simulation, not surprisingly, exhibited the same southward model error as seen in the global models at that time (Fig. 4.3d), but it is not until beyond 48 hours that the control begins to deviate to the south of the best track. With time, this southward error is exaggerated. Ultimately, the control keeps Ike too far south to recurve via the southwestern U.S. cut-off low. The location of Ike at the start of the WRF simulation, and at 120 hr verification, is shown in Fig. 4.1. We will investigate the mechanisms that produce the more northward turn on the 10\textsuperscript{th}, as well as the recurvature on the 12\textsuperscript{th}.

The initial northward turn of Ike is associated with the strong southerly flow out ahead of the Great Lakes shortwave trough. While Ike is very far south of this trough, environmental southerlies during the day on the 9\textsuperscript{th} and early 10\textsuperscript{th} are induced over the northern Gulf Coast due to this trough, visible in the 500-100 hPa AMVs from the 10\textsuperscript{th} at 12Z (Fig. 4.4a). This allows Ike to drift northward relative to the persistence storm track. However, once the trough axis is positioned to the east of Ike 12 hr later, the winds begin to develop a more northerly component (Fig. 4.4b). This brings a sudden halt to the northward jog of Ike, and a continuation of a track closer to the previous path of Ike commences.
In order to identify the mechanism that caused recurvature in reality, but not the control simulation, a comparison between the WRF control run output and both the ECMWF and GFS analysis at 12z on the 12th (the time at which Ike begins to recurve) will follow.

Since the ECMWF analysis has been used for initializing WRF at 00z on the 9th, the ECMWF analysis and the control simulation are initially identical. However, 60 hours later, large-scale synoptic differences begin to emerge. While there appears to be an apparent phase difference in the majority of mesoscale features and shortwaves, a much larger problem appears to have emerged. The entire longwave pattern is noticeably more amplified in the 60 hour ECMWF analysis than the WRF forecast. A series of shortwave troughs entering the western U.S. at this time are much more positively tilted at 500 hPa in the simulation than in verification. Also, the $u$ component of the subtropical jet crossing from Baja California through the upper Great Plains is greater than $v$ in the simulation by almost 2 to 1, but in the ECMWF analysis, the two are comparable, and in places $v$ is greater than $u$. 

Fig 4.4: Satellite water vapor imagery and 500-100 hPa Atmospheric Motion Vectors for Hurricane Ike at (a) 12Z Sept. 10th (left), and (b) 00Z Sept. 11th, right.
By hour 84, at 12Z September 12th, the difference in amplification of the longwave pattern becomes even more pronounced (Fig. 4.5). It is apparent that the highly amplified longwave trough, which has now begun to propagate across the western U.S., has allowed the embedded shortwaves along the southern end of the trough to propagate as far south as the latitude of Ike. Strengthened southerlies downstream of these shortwaves are ultimately what cause Ike to recurve. However, in the control simulation, these shortwaves west of Ike have not moved nearly as far south, and hence have a much smaller influence on the cyclone. The diminished synoptic influence of these shortwaves on Ike is exemplified by the fact that the control simulation predicts Ike to be further south than verification, further increasing the meridional distance between the two.
Examination of vertical cross sections along a fixed latitude through Ike reveals additional evidence for recurvature in the verification but not the control. In the control, a 20 – 25 m/s southwesterly jet can be seen at and above 200 hPa west of Ike, centered on 118 W (Fig. 4.6b). The ECMWF analysis at the same time reveals the same feature as being stronger: 25 – 30 m/s, lower: centered on 300 hPa, and closer to Ike: 116 W (Fig. 4.6a). While the shortwave was closer to Ike in the analysis than in the control, the cross sections illustrate the fact that the jet is too weak and too elevated in the control. Traditionally, features above 300 hPa are assumed to have little influence on the TC motion. Therefore, it is not surprising that Ike does not recurve in the control simulation with the southwesterly jet at 200 hPa.
4.2 Vorticity Perturbation Analysis

4.2.1 Selection of Targets

As for Sinlaku, four targets are selected subjectively for Ike. All of these targets are again associated with local maxima in vorticity. Two distinct upper-tropospheric targets are evident in Fig. 4.7. First, feature I1 is a large shortwave trough associated with a mid-latitude cyclone diving into the Great Lakes region. It is similar in distance and magnitude to feature S1 in the Sinlaku case. This feature is also evident at the lower levels; however, it is much more pronounced at the upper levels and is thus labeled there. A perturbation of 600 km radius will be performed at I1, centered on 44.0 N, 92.0 W. This perturbation radius is the approximate radius of curvature of the trough. If a larger radius were to be chosen, the perturbation would not only modify the trough but the neighboring ridges. On the other hand, a smaller radius would produce an unrealistic local minimum of vorticity at the center of the trough.

A second upper level target feature is an upper level low, labeled I2, 1000 kilometers east of Florida. Unlike I1, there is virtually no evidence of this feature in the lower level vorticity field (Fig. 4.7, 4.8). I2, located at 28.0 N, 67.0 W, has an associated maximum vorticity of a meager $3 \times 10^{-4}$ s$^{-1}$, almost an order of magnitude lower than the vorticity associated with any of the other targets for Ike. However, the upper low is significantly large (radius of ~500 km) and close to Ike (~1500 km center to center) that we hypothesized that I2 would be a target of moderate sensitivity.
In the lower troposphere, target I3 is a region of enhanced vorticity along the tail end of a cold front over the Southern Plains (Fig. 4.8). The target is located at the point 33.0 N, 102.0 W, and will be perturbed using a radius of 400 km. Zhang et al. (2003) showed that there is an upscale transfer of perturbation energy from the convective scales to the synoptic scales on a timescale of just over one day. It is plausible that a perturbation in the mesoscale would modify the synoptic scale in this situation. However, this feature may be too small and detached from the mid-latitude jet, limiting the sensitivity of Ike to I3.
Fig. 4.8: 850-700 hPa layer-mean relative vorticity September 9th at 00z. Ike is the vorticity maximum centered over Cuba. I3 and I4 are low level targets for the vorticity perturbation technique.

Finally, target I4 is a weakening Tropical Storm Lowell approaching the Baja California region. The cyclone is located at 20.0 N, 146.6 W, and is perturbed using a 400 km radius of perturbation. Although Lowell is a weak TC and generally below synoptic scale in size, it is at the same latitude as Ike at a time Ike is traveling west while Lowell traveled east. For this reason, along with the fact that Tropical Storm 16W was a target of sensitivity for Sinlaku, we hypothesized that Lowell would also be a potentially significant synoptic target.
All targets I1 through I4 are first perturbed using $\alpha_{\text{max}} = \pm 0.75$. To serve as a basis for comparison between I1 and I2 using equal initial wind perturbations, simulations will be presented in which $\alpha_{\text{max}} = \pm 0.22$ perturbing target I1.

Fig. 4.9: ETKF reduction in wind forecast error variance due to targeted observations of $u$, $v$, $T$, and $q$ at 850/500/200 hPa. Contour: ensemble mean level-weighted streamline at targeted time using 49-member ECMWF ensemble.

ETKF target regions are in full agreement with our subjective analysis in identifying I1, I3 and I4 as potential targets (Fig. 4.9). While the ETKF technique does not identify I2 as clearly as the other three targets, there is certainly evidence that the ETKF is responding at least moderately to the location of the upper-low. However, ETKF again analyzes the region downstream of the mid-latitude shortwave as a more important target than the base of the trough. For this reason, we will again add an additional target downstream of the 1st target. This target will be designated I1a.
4.2.2 Sensitivity to Upper-Level Targets

The I1 perturbations generated a $|v'|_{\text{max}}$ of 11.6 m/s at the target, and 1.08 m/s at the TC (Table 4.1). The perturbation can be seen in Fig. 4.10. While the track for the $\alpha_{\text{max}} = -0.75$ simulation is well south of the control run, strengthening I1 produces a track much closer to the best track (Fig. 4.11). The fact that the simulation in which the shortwave is strengthened produces a comparable change in track as the simulation in which the shortwave is weakened, but in the opposite direction, supports the idea that the vorticity perturbation itself is responsible for the changes shown, and not just the growth of random noise. Since the simulation in which the I1 shortwave is strengthened produced a significantly improved landfall location, one may propose that the shortwave over the Great Lakes is initialized too weakly. To evaluate this argument, the evolution of the perturbation in the WRF forecasts is investigated in more detail. First, it is worth

| Target | $\alpha_{\text{max}}$ | $r_{\text{perturbation}}$ (km) | Distance (km) | $|v'|_{\text{max}}$ at target (m/s) | $|v'|_{\text{max}}$ at TC (m/s) | $\Delta t_{100\text{ km}}$ (hr) (-$\alpha$ / +$\alpha$) |
|--------|---------------------|-------------------------------|---------------|----------------------------------|-------------------------------|----------------------------------|
| I1     | 0.75                | 600                           | 2700          | 11.6                             | 1.08                          | 21 / 19                           |
| I1a    | 0.75                | 600                           | 2600          | 10.7                             | 0.71                          | 26 / 28                           |
| I2     | 0.75                | 500                           | 1500          | 3.3                              | 0.27                          | 116 / 111                         |
| I3     | 0.75                | 400                           | 2400          | 2.0                              | 0.13                          | 109 / 116                         |
| I4     | 0.75                | 400                           | 3400          | 5.4                              | 0.15                          | 90 / 90                           |
| I0     | 0.04                | 400                           | 200           | 1.2                              | 1.08                          | 96 / 96                           |
| I1     | 0.22                | 500                           | 2700          | 3.3                              | 0.27                          | 53 / 92                           |

Table 4.1: As in Table 3.1, but for Hurricane Ike.
Fig. 4.10: $\pm 0.75\zeta$ perturbation of I1. The center of the perturbation is indicated on the left with the initial 500-200 hPa layer mean relative vorticity. The vorticity fields following the reduction (upper right) and enhancement (lower right) at I1 are shown.

Noting that the track forecast in the control is closer to the best track than the perturbed run for the first 24 hours, while the $+0.75\zeta$ perturbed track is too far to the north. Therefore, the initial northward displacement of the perturbed run led to a better storm placement at landfall, but possibly for the wrong reasons.
Thereafter, near-neutral trough (Fig. 4.12d,e) while leads to a sudden stop in the northward advancement of Ike later times, Ike is briefly within the environment of negative southerly dominate the environment of Ike (Fig. 4.12a,b,c). During this time, the enhanced 0 – 1.0 relative vorticity perturbation of I1 (blue), and +1.0 relative vorticity perturbation of I1 (purple) strengthening I1 will be explained first and to greater detail. From hours 0 – 24, a southward extension of positive v perturbations originating from I1 begins to dominate the environment of Ike (Fig. 4.12a,b,c). During this time, the enhanced southerly wind steers Ike to the north, causing the initial northward track deflection. At later times, Ike is briefly within the environment of negative v anomalies behind the I1 trough (Fig. 4.12d,e) while leads to a sudden stop in the northward advancement of Ike. Thereafter, near-neutral v anomalies commence, and Ike propagates parallel to the control simulation, before ultimately recurving.

Fig. 4.11: 5-day NHC Best track (white), control simulation (red), -1.0 relative vorticity perturbation of I1 (blue), and +1.0 relative vorticity perturbation of I1 (purple) beginning 00Z September 9th. Circles denote 0, 24, 48, 72, 96 and 120 hr locations of Ike.

Since the +0.75 perturbation produces a track closer to verification, the consequences of strengthening I1 will be explained first and to greater detail. From hours 0 – 24, a southward extension of positive v perturbations originating from I1 begins to dominate the environment of Ike (Fig. 4.12a,b,c). During this time, the enhanced southerly wind steers Ike to the north, causing the initial northward track deflection. At later times, Ike is briefly within the environment of negative v anomalies behind the I1 trough (Fig. 4.12d,e) while leads to a sudden stop in the northward advancement of Ike. Thereafter, near-neutral v anomalies commence, and Ike propagates parallel to the control simulation, before ultimately recurving.
Fig. 4.12: As in Fig. 3.10, but for +0.75 $\zeta$ perturbation of I1, seen at simulation hours 00 (a), 12 (b), 24 (c), 36 (d) and 48 (e).

The recurvature has much to do with the evolution of a shortwave trough off the northwestern coast of the United States. From hours 0 through 48, the deepened shortwave lifts to the northeast while a ridge builds in from the west. This ridge is more amplified in the perturbed simulation than the control. During day 2, a new shortwave has made landfall over the Pacific Northwest and is beginning to drop south. 72 hours after the +0.75 $\zeta$ perturbation, a phase difference is visibly associated with the approaching shortwave over the northern Rockies (Fig. 4.13). However, this time the positive vorticity perturbations are to the west of the negative perturbations, indicating that the trough is approaching more slowly in the perturbed simulation. The positive vorticity perturbations associated with this trough also extend further south than the negative perturbations, indicating that the trough in the perturbed simulation is deeper. Similarly, there is a large negative vorticity perturbation in the crest of the ridge over the north-central United States, indicating a stronger ridge in the perturbed simulation.
Whereas weakening the vorticity at II clearly deamplified the large-scale synoptic pattern, strengthening the vorticity at II amplified the pattern. A more amplified pattern generates more meridional flow, hence strengthening the southerlies and northerlies in regions that they are occurring. In the environment of Ike, this implies a strengthening of the deep layer environmental southerlies, and therefore Ike makes landfall further north.

Fig. 4.13: Upper level relative vorticity difference between control simulation and simulation in which the trough at II is strengthened by 1.0 $\zeta$, 72 hours after initialization.

Almost the exact opposite effect occurs following the weakening of II. Within 24 hours of initialization, the perturbed trough begins to lift out to the northeast as a trailing ridge begins to replace it. In the perturbed simulation, this ridge is already less amplified than in the control. By 48 hours, the deamplification of the ridge becomes even more pronounced, as a new shortwave begins to drop in from Canada. This shortwave is also
less amplified in the perturbed than the control simulation. 60 hours after weakening the Great Lakes shortwave, there is a clear modification to the large-scale synoptic pattern (Fig. 4.14). A phase difference has emerged in regard to a new shortwave associated with the polar jet over the northern Rockies into the north-central United States. The presence of deeper negative vorticity perturbations to the west of a shallower positive vorticity perturbation indicates the fact that the new trough is faster in the negatively perturbed simulation, and also less deep. Similarly, to the east of this shortwave, positive vorticity perturbations in the crest of the ridge indicate a weaker ridge in the perturbed simulation. Both of these factors are indicative that weakening the initial shortwave has deamplified the large-scale synoptic pattern. In turn, this has generated a more zonal flow throughout the region and weaker southerlies in the environment of Ike. Hence, with weakened southerlies, Ike makes landfall further south.

As is performed for Sinlaku, the characteristic timescale “$\Delta t$” associated with the time at which the difference between control and perturbed simulations exceeds 100 km will be calculated for Ike, and is another way to measure the sensitivity of the cyclone to the perturbation. For the perturbations using $\alpha_{\text{max}} = 0.75$, $\Delta t_{100 \text{ km}}$ for the negative and positive perturbations are only 21 and 19 hr, respectively (Table 4.1). Clearly Ike is very sensitive over very short timescales to the strength of the Great Lakes shortwave.
Fig. 4.14: Upper level relative vorticity difference between control simulation and simulation in which the trough at I1 is strengthened by 1.0 $\zeta$, 60 hours after initialization.

While the tracks diverge almost immediately following initialization for the I1 perturbations, there is actually a two-step process occurring. There is only a slow divergence of the tracks during the first 18 hours, beyond which they diverge more rapidly. We believe that the small initial track perturbation is associated with the initial $\sim 1$ m/s wind perturbation at the TC. Thereafter, as the perturbation at the target evolves, the TC becomes sensitive to the modification of features beyond the initial perturbation at the TC. Ike is far enough from the continental jet stream that during the early stages of the synoptic evolution occurring to the north, there is little influence on the system. Beyond 18 hours, the synoptic signal has finally propagated down to the tropics, and the tracks begin to diverge more rapidly.
One interesting phenomenon that only occurs in the positively perturbed simulations is a significant northward component to the track 24-36 hours into the simulation, followed by an abrupt halt to the northward progress and a resumption of the original westward track. This is due to the enhanced southerlies downstream of the strengthened shortwave advecting Ike strongly to the north. However, since both the I1 shortwave and the polar jet are so far to the north, as the shortwave bypasses Ike to the north, Ike does not merge with the mid-latitude system nor continue its recurvature. Instead, Ike becomes subject to the northwesterly flow upstream of the trough, forcing the TC to the south. As the shortwave ejects to the northeast, a now-stronger anticyclone moves to the south to replace it. Anticyclonic flow around the base of the ridge strengthens the easterlies, accelerating the westward movement of Ike towards the Texas and Louisiana coasts. The positively perturbed simulations at I1 are both very close to the NHC best track for days 4 and 5, albeit too slow, despite the fact that the track during the first two days deviates significantly from the best track. As Ike approaches the Texas coast from hours 84-90 (for both $a_{\text{max}} = +0.75$ and $+1.00$), the model correctly simulates the sudden recurvature seen at the end of the best track. This motion is not seen in either of the negatively perturbed simulations or the control.

Unlike for the perturbations of targets S1 and S2 for Sinlaku, where the modification to track at 120 hr is nearly an order of magnitude greater than the modification to track at 48 hr, the I1 track perturbations at 120 hr are only about twice as large as at 48 hr. The I1 sensitivity for the $+0.75 \zeta$ perturbation increases from 284 km at 48 hr to 584 km at 120 hr (Table 4.2). Similarly, the modifications to the track associated with the $-0.75 \zeta$ perturbation varies from 283 km at 48 hr to 616 km at 120 hr. It would
appear that the effect of comparable perturbations to Sinlaku and Ike produces more significant modifications to the track of Sinlaku than Ike.

<table>
<thead>
<tr>
<th>Target</th>
<th>$\alpha_{max}$</th>
<th>$r_{perturbation}$ (km)</th>
<th>Distance (km)</th>
<th>ETKF Sensitivity (normalized by 1.00)</th>
<th>48 hr WRF Track Modification (km) (-$\alpha$/+$\alpha$)</th>
<th>120 hr WRF Track Modification (km) (-$\alpha$/+$\alpha$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>0.75</td>
<td>600</td>
<td>2700</td>
<td>0.70</td>
<td>283 / 284</td>
<td>616 / 584</td>
</tr>
<tr>
<td>I1a</td>
<td>0.75</td>
<td>600</td>
<td>2600</td>
<td>0.91</td>
<td>198 / 198</td>
<td>292 / 411</td>
</tr>
<tr>
<td>I2</td>
<td>0.75</td>
<td>500</td>
<td>1500</td>
<td>0.65</td>
<td>21 / 20</td>
<td>148 / 127</td>
</tr>
<tr>
<td>I3</td>
<td>0.75</td>
<td>400</td>
<td>2400</td>
<td>0.75</td>
<td>20 / 21</td>
<td>132 / 107</td>
</tr>
<tr>
<td>I4</td>
<td>0.75</td>
<td>400</td>
<td>3400</td>
<td>0.78</td>
<td>9 / 20</td>
<td>216 / 319</td>
</tr>
<tr>
<td>I0</td>
<td>0.04</td>
<td>400</td>
<td>200</td>
<td>0.80</td>
<td>21 / 0</td>
<td>107 / 122</td>
</tr>
<tr>
<td>I1</td>
<td>0.22</td>
<td>500</td>
<td>2700</td>
<td>0.70</td>
<td>93 / 66</td>
<td>319 / 164</td>
</tr>
</tbody>
</table>

Table 4.2: As in Table 3.2, but for Hurricane Ike.

One occurrence that has been observed in many perturbation simulations, but is particularly prominent in the perturbation of I1 for Hurricane Ike, is the upstream propagation or upstream development of the perturbations with time. With I1, the deamplification of the shortwave led to a more zonal pattern thousands of kilometers upstream 4 and 5 days later. Similarly, amplifying this shortwave led to a more meridional pattern upstream. Fig. 4.15 demonstrates the upstream propagation of a positive height perturbation in a cross section through an Ike simulation. The importance of this is that it shows sensitivity of a location to targets both up- and down-stream. For tropical cyclones, this shows that additional observations may be needed both downstream of and upstream of the cyclone.
We hypothesize that the upstream signal propagation is the propagation of a wave along the potential vorticity gradient, where the mid-latitude jet is acting like a Rossby wave. The phase speed of a Rossby wave is given by

\[
\text{phase speed} = \frac{U}{k^2 + l^2 + \beta}
\]

where \(U\) is the mean westerly flow, \(\beta\) is the change in Coriolis force with latitude, \(k\) and \(l\) are zonal and meridional wave numbers (Holton 1992). In a winter scenario, where the jet (and therefore the background velocity for the Rossby wave) is significantly stronger,
it is possible that signals propagating upstream relative to the perturbation would still be traveling downstream.

Similar to what was done for S1, ±1.00 perturbations were applied to I1 in order to investigate whether or not any additional insight could be gained by further increasing $\alpha_{\text{max}}$. The tracks of Ike following these positive (purple) and negative (blue) perturbations are shown in Fig. 4.11. These tracks of these simulations are consistent with the ±0.75 perturbations, but provided little additional information.

To maintain consistency in verifying the effectiveness of the ETKF technique in identifying sensitive areas with what is done for Sinlaku case, a similar target to S1a downstream of I1 has been designated “I1a”. A perturbation of 600 km radius, using a perturbation scalar of 0.75 is centered on 42.0 N 89.0 W (Fig. 4.16). While the center of the trough at I1 only had an ETKF sensitivity of 0.70, the sensitivity to I1a is as high as 0.91. Since this perturbation is slightly ahead of the trough, and the background vorticity is slightly lower at I1a than I1, the corresponding $\mathbf{v}$ perturbations are also slightly lower. The wind perturbations corresponding to ±0.75 $\zeta$ at I1a are 10.7 m/s at the target and 0.71 m/s at the TC (Table 4.1).
Fig. 4.16: As in Fig. 4.9, but for ±0.75 $\zeta$ perturbations at I1a.

Once again, the sensitivities have been shown to be greater for vorticity perturbations of equal radii using equal scalar multipliers if the perturbation is applied to the center of the shortwave, rather than downstream of the shortwave where ETKF sensitivity is greatest. One significant result that is not seen when comparing S1 to S1a is that with I1, the modification to the track is primarily cross-track, but for I1a, the track deflection is primarily along track (Fig. 4.17). Since the I1 perturbations generate a greater modification to the amplification of troughs and ridges than the I1a perturbations, the corresponding $v$ perturbation is larger for I1 than for I1a. Conversely, the I1a perturbation modifies the zonal phase propagation of troughs and ridges along the mid-latitude jet, corresponding to a slightly greater $u$ perturbation for I1a than I1. Since Ike is
primarily traveling along the direction, $u$ perturbations have a greater effect on the along track component of TC motion, while $v$ perturbations will have a greater effect on the cross track component. Fig. 4.18 depicts the greater $v$ sensitivity north of Ike when I1 is perturbed than I1a. While it is difficult to see in the figures provided, a comparison of the red (perturbed) wind vectors indicates that $u$, on the other hand, is more amplified when I1a is perturbed than I1.

Fig. 4.17: As in Fig. 4.11, but for $\pm 0.75$ $\zeta$ perturbation at I1a. 5-day NHC Best track (white), control simulation (red), $-0.75$ $\zeta$ perturbation at I1a (blue), and $+0.75$ $\zeta$ perturbation at I1a (purple) beginning 00Z September 9th.

As is the case with I1, track sensitivity begins to emerge almost immediately. However, we once again see a very gradual modification to the track during the initial 18 hours, followed by a much more rapid growth. It is also not until 18 hours that the wind
change (seen in the wind difference fields) propagating southward from the initial perturbation reaches Ike, producing a continuous change between Ike and the perturbed region. For IIa, $\Delta t_{100\ km}$ is increased somewhat to between 26 and 28 hr (Table 4.1). Ike is still very sensitive to the region ahead of the Great Lakes trough, but not quite as sensitive as it is to the trough itself.

Upon comparison of the evolution of the synoptic environment to the west of Ike between II and IIa, a significant difference arises. In the case of II, the cut-off shortwave over the western U.S. digs further south in the more amplified regime. In IIa, this shortwave does not dig as far south and never quite becomes cut-off from the mid-latitude flow. Since the trough interaction with Ike occurs at the time of recurvature in the $+\zeta$ perturbation of II, while Ike does not interact with the trough in IIa, this
phenomenon is likely the reason behind the difference between recurvature and non-recurvature. The negative height perturbations in the base of the western U.S. trough are more prominent following the positive perturbation at I1 (Fig. 4.19a) than at I1a (Fig. 4.19b).

The I2 perturbations (Fig. 4.20) reveal virtually no sensitivity to the upper low east of Florida in terms of track changes (Fig. 4.21). It appears that, while the target is large, the weakness of the circulation and the fact that the target is not associated with any jet features makes I2 a highly non-sensitive target.
While it is clear that Ike is sensitive to perturbations of I1 that produce track deflections of hundreds of kilometers, and non-sensitive to perturbations at I2 that produce deflections of less than 150 km, this does not imply that it is always more important to perturb distant large-scale synoptic features than small synoptic features closer to the TC. The modification to the tracks is much more significant for I1 than I2. At the same time, it is important to note that these perturbations cannot be compared directly, since they are of different size and magnitude. However, they do provide a useful qualitative idea of the types of perturbations that are most important in modifying the track.
This new perturbation is indicated in Fig. 4.22. The initial wind perturbation at \( I_2 \) is replicated at \( I_1 \). The initial \( |v'| \) perturbation is 3.3 m/s. Through empirical adjustment of \( \alpha_{\text{max}} \), we are able to replicate the initial wind perturbation from \( I_2 \) at \( I_1 \) by setting \( \alpha_{\text{max}} = 0.22 \). The radius of perturbation is also adjusted down from 600 km to 500 km to match the perturbation. This new perturbation is indicated in Fig. 4.22.

Fig. 4.21: As in Fig. 4.17, but for \( \alpha_{\text{max}} = \pm 0.75 \) at \( I_2 \).

Earlier comparisons have been made between \( I_1 \) and \( I_2 \), but the perturbations at each target are of very different size and strength. To allow for an equal basis for comparison, the \( I_1 \) perturbation will be repeated such that the initial wind perturbation at \( I_2 \) is replicated at \( I_1 \). The initial \( |v'|_{\text{max}} \) perturbation at \( I_2 \) associated with an \( \alpha_{\text{max}} = 0.75 \) perturbation is 3.3 m/s. Through empirical adjustment of \( \alpha_{\text{max}} \), we are able to replicate the initial wind perturbation from \( I_2 \) at \( I_1 \) by setting \( \alpha_{\text{max}} = 0.22 \). The radius of perturbation is also adjusted down from 600 km to 500 km to match the perturbation.
The track sensitivity to I1 is significantly reduced when the amplitude of perturbation is reduced (Fig. 4.23). However, the sensitivity of the TC to I2 is so low that even a very small perturbation to I1 produces a greater track deflection. The evolution of the new perturbation at I1, while small, generates a series of perturbations propagating both upstream and downstream along the polar jet. The perturbations to I2, on the other hand, only seem to affect the immediate environment, with little adjustment beyond the upper low even after 4 to 5 days. While I2 is much closer to Ike than I1, even when given a wind perturbation of equal magnitude, Ike is still significantly more sensitive to I1. Therefore, this is truly a case in which the sensitivity of the target has to do with the nature of the target itself, and the ability of the target to transfer the signal of a
perturbation to the surrounding synoptic environment, and not have the signal just remain stationary or dissipate.

Fig. 4.23: As in Fig. 4.17, but for $\alpha_{\text{max}} = \pm 0.22$ at I1.

4.2.3 Sensitivity to Low-Level Targets

Since I3 is a small target associated with relatively low background vorticity, the magnitudes of the initial $v$ perturbations are also quite small, as is the case with I2. The initial $|v'|_{\text{max}}$ at the target is only 2.0 m/s, while $|v'|_{\text{max}}$ at the TC is very near zero, at 0.13 m/s (Table 4.1). The removal and amplification of I3 can be seen in Fig. 4.24. Modifications to the track associated with perturbing I3 are smaller than those associated with any other target seen for either Ike or Sinlaku, including I2 (Fig. 4.25). 48 hour
modifications to the track associated with I3 are comparable to those for I2, at 21 and 20 km for positive and negative perturbations, respectively (Table 4.2). By hour 120, the lack of sensitivity to I3 becomes even more pronounced, with track changes of only 107 / 132 km (+/- perturbations). Like I2, I3 is closer to Ike than I1, yet produced far smaller modifications to the track. In this particular case study of Ike, the TC is more sensitive to perturbations (representing uncertainties) of large features further from the storm than uncertainties of smaller features closer to the cyclone.

Fig. 4.24: As in Fig. 4.9, but for perturbations at I3, and for the 850-700 hPa layer.
While the ETKF technique may be a useful tool in aiding the selection of synoptic targets, ETKF may have less skill in ranking those targets for Ike. The normalized ETKF sensitivity for I3 (0.75) is greater than the sensitivity to I1 (0.70). However, the WRF simulations demonstrate that a significantly greater modification to the TC track occurs following the perturbation at I1 than I3.

The I4 perturbation results in a 5.4 m/s $v'_{\text{max}}$ at Lowell and 0.15 m/s at Ike (Table 4.1). The vorticity preceding and following these perturbations can be seen in Fig. 4.26. It should also be noted that ETKF diagnosed high sensitivity to I4, around 0.78 on its center. Unlike in the previous two cases, where only small signals of the perturbation can be seen beyond a few hundred kilometers of the original perturbation, both the
strengthening and weakening of Tropical Storm Lowell results in significant height and vorticity perturbations that propagate downstream several thousand kilometers. By strengthening the vorticity at I4, the small shortwave over Southern California does not dig as far south. This can be seen as the positive-over-negative couplet in the vorticity difference field at simulation hour 42 in Fig. 4.27. Eventually this feature generates a phase difference that displaces a series of small shortwaves embedded in the subtropical jet. The signal of the perturbation propagates downstream within the subtropical jet all

![Image of vorticity perturbation](image)

**Fig. 4.26:** As in Fig. 4.9, but for perturbations at I4.

the way to the northeastern U.S. by day three and out into the Atlantic by day four. Also note the phase difference associated with Lowell in Fig. 4.27. The positive vorticity perturbations to the west of negative vorticity perturbations indicate that Lowell
propagates further westward when strengthened. Since the positive perturbation is larger than the negative perturbation, the modified vortex is still stronger than the initial vortex.

Fig. 4.27: Low level relative vorticity difference between control simulation and simulation in which Lowell is weakened, 48 hours after initialization.

In the case of weakening Lowell, the approaching shortwave dives further south, which can be seen as the negative-over-positive couplet in the vorticity difference field in Fig. 4.28 at 00Z on the 11th. With time, both the phase difference associated with this initial shortwave and a number of other small shortwaves within the subtropical jet propagate northeastward, just as is the case with strengthening Lowell (Fig. 4.29). The I4 perturbations are a classic example of the downstream propagation of perturbations, showing the lasting influence of an initial perturbation up to 5 days and 5000 km away.
Despite a very clear modification of the subtropical jet and various features downstream of Lowell following the I4 vorticity perturbation, the impact of this perturbation is less than the impact of I1 (Fig. 4.30). While the I4 perturbation has a greater effect on the synoptic environment than I2 or I3, and Ike is correspondingly more sensitive to I4 than the other two, the effect of perturbing Lowell on the track of Ike is not as large as one might expect considering the magnitude of the evolved perturbations in the far field. It appears that while the I4 perturbation modifies the jet to the north of Ike,
Fig. 4.29: Low level relative vorticity difference between control simulation and simulation in which Lowell is weakened, 84 hours after initialization. The thick black arrow indicates the approximate location of the subtropical jet.

The prevailing deep layer winds advect the majority of the signal of this perturbation well north of Ike. Although the phase displacement of the shortwaves embedded in the subtropical jet appears to be quite significant in the vorticity difference plots, these displacements are all of small, local shortwaves. While the initial perturbation generates numerous small perturbations to the east of a longwave trough in the western U.S. and to the west of a longwave ridge in the eastern U.S., the net modification to either of these longwave features appears to be small. Since the perturbation of I4 has so little impact on the longwave pattern, which is the main steering for Ike, this perturbation produces a much smaller change to the storm track than the II perturbations.
The modification to the track associated with I4 during the first 84 hours of simulation is minimal. The 48 hour track differences associated with the positive and negative perturbations are only 20 and 9 km, respectively. Thereafter, the negatively perturbed simulation begins to shift slightly north of the control, while the positively perturbed simulation shifts slightly further south. However, a more obvious sensitivity that emerges is in the forward velocity of Ike. While the control makes a Gulf Coast landfall at hour 108, the $+\zeta$ simulation does so by hour 96, and the $-\zeta$ simulation is delayed until nearly hour 120. While the initial track differences are small, they become quite large at later time periods. This forward velocity difference, along with a slight track deflection, results in 120 hour modifications to the track upwards of 319 km for the
+ζ simulation, and 216 km for the −ζ simulation. While this track deflection seems small in comparison to what is seen for I1 or any of the Sinlaku simulations, it is clearly greater than the effect of perturbing either I2 or I3. Also, while the vorticity difference between I2 / I3 and the control shows a rapid decay of the perturbation signal, with any sign of the perturbation beyond noise disappearing within 36 hours, evidence of the perturbation remains discernible in the I4 difference fields throughout the simulation. For this reason, we believe that the sensitivity seen in I2 and I3 are either sensitivities to noise and the rebalanced stream function, or associated with very weak dynamic sensitivity. The sensitivities to I1 and I4 appear to be associated with a more robust synoptic signal.

I4 is the furthest, and equal with I3 for the smallest, of all the targets from Ike. While a small feature, I4 is also associated with higher maximum vorticity than any of the other targets for Ike. While the results cannot be generalized, they demonstrate that Ike is more sensitive to a perturbation of a large synoptic feature of high vorticity (I1) or a small feature of very strong maximum vorticity (I4), than to a perturbation of smaller (I3) and weaker (I2) vorticity maxima closer to the cyclone.

4.2.4 Sensitivity to Near-TC Perturbations

In addition to distant synoptic perturbations, we also test the sensitivity of Ike to small perturbations in the near-TC environment. Similar to the approach for Sinlaku, a positive and negative upper-level (500-200 hPa) perturbation is applied 200 km west-northwest (directly in the path) of the TC. This perturbation, using $\alpha_{\text{max}} = 0.04$, is empirically computed to provide a maximum wind perturbation within 300 km of the TC to be identical to that found at the TC associated with the $\alpha_{\text{max}} = 0.75$ I1 perturbation.
While an $\alpha_{\text{max}}$ of 0.16 is needed to produce a wind perturbation of ~ 1 m/s for Sinlaku, a vorticity perturbation of one fourth this size is needed to produce an equivalent wind perturbation for Ike. This is due to the fact that Ike is such a large cyclone and the winds 200 km ahead of the storm are still strong. As expected, this perturbation is too small to see on the vorticity plots (Fig. 4.31).

As is the case with Sinlaku, perturbations associated with modifying the winds at the cyclone by 1 m/s do not produce a significant impact on the storm track (Fig. 4.32). The simulation tracks do not deviate from the control by 100 km until 96 hr. There is also little to no far-field environmental influence of these initial perturbations.
Difference fields, even 4 to 5 days out, reveal little to no change in the strength or location of the shortwave trough over the northern high plains or the cutoff low to the west.

Fig. 4.32: As in Fig. 4.17, but for Many of the results for Typhoon Sinlaku. Overall, the storm track of Ike has been less sensitive than that of Sinlaku. However, for both cyclones, features of greatest sensitivity have been those associated with the highest initial vorticity and features synoptically associated with jets and the large-scale flow. Additional comparisons and the significance of these findings will be addressed in Chapter 5.
4.3 Vorticity Perturbation Ensemble

All the subjectively selected targets were present in regions of local vorticity maxima in the mid-latitudes and tropics. If an “ensemble” is constructed with positive and negative perturbations, ideally of equal size, a spread of tracks is evident. In the case of Sinlaku, the ensemble mean is closer to the best track than the control (Fig. 4.33), though the control is superior for Ike (Fig. 4.34). Nonetheless, for both systems, the best track is well within the ensemble spread, suggesting a certain effectiveness of the technique. These results suggest that ensemble perturbation techniques in regional models may benefit from the perturbation of vorticity maxima.

![Fig. 4.33: Ensemble forecast generated for Typhoon Sinlaku, 0Z September 10th, using the vorticity perturbation technique. White is the JTWC best track, red is the control run, yellow tracks are the individual ensemble members, and blue is the ensemble mean.](image-url)
Fig. 4.34: Ensemble forecast generated for Hurricane Ike, 0Z September 9th, using the vorticity perturbation technique. White is the NHC best track, red is the control run, yellow tracks are the individual ensemble members, and blue is the ensemble mean.
Chapter 5

Conclusions and Future Work

Although there have been numerous studies in the field of targeted observations, the optimal targeting strategy for satellites and aircraft to improve tropical cyclone forecasts is still unclear. It is often difficult to obtain consistent conclusions due to the fact that the data, data assimilation, and the models themselves differ from study to study. By perturbing the model analysis itself, the “vorticity perturbation technique” proposed herein bypassed any errors and biases associated with observations and data assimilation. In this thesis, we have sought to answer the following: (1) How does the TC track vary with respect to initial perturbations of differing amplitude, spatial scale and distance to the storm? (2) How does the evolving perturbation act to modify the synoptic environment surrounding the TC, and thereby the track? (3) Is it best to follow an objective technique to determine the sensitive areas, or is it better to use a subjective method based on fundamental synoptic reasoning?

Two major TCs that made landfall in 2008 have been analyzed: Hurricane Ike in the Atlantic basin and Typhoon Sinlaku in the West Pacific basin. Utilizing the Weather Research and Forecasting (WRF) model version 3.1.1 and ECMWF analyses as initial and boundary conditions, a control simulation was produced for each TC. These control simulations replicated forecast errors evident in the operational global models, including
a premature recurvature in the forecast for Sinlaku and a landfall too far south along the Texas coast for Ike.

A vorticity perturbation technique has been developed to test the sensitivity of TC behavior to local dynamic perturbations in their surrounding environment. These perturbations were then applied to, and compared against, respective control simulations. The size, magnitude, and location of vorticity perturbations were chosen subjectively. For Sinlaku, these locations included a large mid-latitude shortwave trough around 3000 km to the north-northwest (denoted by S1), a smaller upper-level shortwave immediately to the north (S2), a low-level monsoon trough to the west-southwest (S3), a weak tropical storm to the northeast (S4), and a local perturbation in the immediate environment (S0). Two separate methods of comparison have been explored in this study. The first method involves the comparison of the sensitivity of the TC to perturbations of equal $\alpha_{\text{max}}$. However, by this metric, the resulting sensitivity was biased towards perturbations of targets with a greater initial vorticity. To compensate for this issue, additional perturbations were performed in which $\alpha_{\text{max}}$ was empirically adjusted at a given target such that the maximum magnitude of the initial wind perturbation is equal between targets being compared. It was found that WRF forecasts of Sinlaku overall exhibited high sensitivity, with large modifications to its track arising from the perturbation of each selected targets in the synoptic environment. The greatest improvement in the track forecast occurred by weakening the vorticity associated with each of two shortwaves to the north of Sinlaku, suggesting that either or both of the shortwaves may have been initialized too strongly in the model analysis, thereby contributing to an erroneous recurvature.
For Ike, the perturbation locations included a large mid-latitude shortwave trough 2500 km to its north (I1), an upper-level cutoff low to the east-northeast (I2), a low-level shortwave trough to the northwest (I3), a tropical storm in the East Pacific (I4), and a local perturbation in the immediate environment (I0). As was the case for the Sinlaku part of the study, comparisons were made between target regions for Ike by both the equal $a_{\text{max}}$ and equal $|v'|_{\text{max}}$ methods. In contrast to Sinlaku, the perturbation of synoptic targets around Ike produced less sensitivity, likely due to the fact that Ike is not in a position of imminent recurvature. The only perturbation that led to an accurate 4-day forecast of recurvature and landfall in North Texas is the strengthening of the large mid-latitude shortwave trough, suggesting that the shortwave may have been initialized too weakly in the operational models. It should also be emphasized that for both Ike and Sinlaku, perturbations to the immediate TC environment replicating the initial perturbation at the TC produced by synoptic perturbations resulted in much smaller track changes than any of the mid-latitude shortwave perturbations. Therefore, the actual modification to the synoptic environment dominates over any effect of the initial perturbation of the TC.

A comparison of targets selected objectively by the Ensemble Transform Kalman Filter (ETKF) versus the above subjectively-chosen targets suggested that while the ETKF effectively indicates similar target regions to those selected subjectively, it may be less effective in ranking the relative sensitivities of those targets. The most obvious example of this is that, while the ETKF technique designated S1, S1a and S2 as all potential target areas, it incorrectly diagnosed S1a as the region of greatest sensitivity. Despite the fact that the S1a($a_{\text{max}}=0.75$) perturbation produced a greater initial wind
perturbation at the target than either $S2(\alpha_{\text{max}}=0.75)$ or $S1(\alpha_{\text{max}}=0.23)$, both perturbations at $S2$ and $S1$ resulted in greater modifications to the track of Sinlaku than the $S1a$ perturbation.

Finally, we have suggested that an “ensemble mean” of a variety of positive and negative perturbations may produce a track forecast competitive with the control simulation. The results herein also suggest that ensemble perturbation techniques in regional models may benefit from the perturbation of vorticity maxima.

Overall, it is found that the TC track is more sensitive to perturbations of larger amplitude and spatial scale, and less so to the distance between the perturbation and the TC, and sensitivity is confined to specific regions of the flow. This research has demonstrated that the track of a tropical cyclone can be highly dependent upon the initialization of synoptic features, and is hence sensitive to local perturbations in these features at initialization. The magnitude of the sensitivity early on appears to be primarily driven by phase and amplitude differences associated with shortwaves very local to the TC. In the case of Sinlaku, the modifications of $S2$ meant the difference between recurvature and non-recurvature. Since there were no significant shortwaves in the immediate environment of Ike, one to two day recurvatures were not produced in any simulations. On the other hand, the modification to the day-4 and -5 TC track several days after initializing the model may be highly dependent upon the upstream or downstream propagation of the evolved perturbation, as was more significant in determining recurvature for Ike.

It should be noted that the magnitudes of many of the perturbations in this study exceed the magnitude of errors associated with a data assimilation scheme or changes
expected in the model analysis by adding additional data. Large perturbations were implemented in this study to exaggerate the sensitivity of the cyclone to various synoptic targets and more clearly delineate between sensitive and non-sensitive areas. Future work may incorporate smaller, more realistic perturbations.

The extension beyond this research will be to advance the understanding of the synoptic sensitivity of tropical cyclones to better determine the optimal target locations for observational systems. The perturbation methodology employed here may be used to offer suggestions of locations in which extra high-density satellite data may be assimilated. This implies activating rapid-scan where insufficient satellite data are present, or reducing the data thinning where sufficient satellite AMVs or radiances exist, but are not used by the data assimilation. The perturbation technique in this thesis could be utilized in future studies as a retrospective diagnostic tool. It would even be possible to automate the vorticity perturbation procedure by either targeting local vorticity maxima or through use of objective strategies, in which sensitive areas could be identified, targeted, and implemented into the next operational model cycle.

Future work will incorporate model forecasts (as opposed to simulations), additional tropical cyclones as case studies, and the inclusion of real satellite data. This work may offer hypotheses as to optimal target locations or sensitive areas, such as the axes of shortwave troughs, for data denial or data addition experiments. Future work may incorporate comparisons to data-denial experiments in a global model, with an investigation into routine operational feasibility.
Appendix A

This study began as an investigation of the ability of global models to simulate the genesis of Typhoon Sinlaku, as well as forecast track, intensity and structure following genesis. While the ECMWF model performed adequately, the GFS and NOGAPS produced markedly inferior genesis, intensity and structure forecasts. We believed that by embedding a regional nested WRF model with superior resolution within the GFS and NOGAPS we could produce and improved forecast. Once it became apparent that the initial vortex was too weak in the WRF-GFS and WRF-NOGAPS simulations, a “bogus” vortex was introduced. Ultimately, a non-bogussed WRF-ECMWF simulation produced a forecast superior to even the bogussed WRF-GFS simulation.

A.1: WRF Initialized with NOGAPS and GFS

Forecasts of Sinlaku were consistently inaccurate, beginning with its genesis which was not accurately captured by most operational models even 1 day in advance. In comparing GFS initializations from 0Z September 8th (the time at which Sinlaku was declared a tropical depression) with MTSAT satellite-derived vorticity, it appears that GFS incorrectly depicts the location and structure of the low-level vortex (Fig. A.1). Not only does the initial vortex appear to be too weak, but a 48 hour forecast produced by GFS at 0Z on the 8th shows Sinlaku remaining a disorganized, asymmetric vortex at a time when the actual storm has already developed into a typhoon (Fig. A.2). NOGAPS and UKMET experienced similar problems as GFS, yet ECMWF did not. We hypothesized that superior performance of ECMWF was due to the initial vortex being
more adequately initialized in that model as compared to the other global models, as well as a more accurate representation of the surrounding environment. This is likely due to superior use of satellite data in the ECMWF assimilation system.

Fig. A.1: GFS 0z Sept 8th analysis (left) vs. MTSAT derived wind field (right) at 0z Sept 8th, 850 rel. vorticity.

Given the inability of three out of four global models to develop and maintain a realistic TC structure, a nested high-resolution version of the Advanced Research Weather Research and Forecasting (WRF-ARW) 3.1.1 model was employed at 18/6/2 km resolution. This was to test whether insufficient resolution of the global models, incapable of resolving inner-core dynamics, was the primary factor in their difficulties in the development of Sinlaku. WRF was first provided GFS data for initial and boundary conditions. The resulting intensity and structure forecasts were poor, with a minimum sea level pressure achieved in the model at hr 72 of 996 mb, far from the 935 mb of verification (Fig. A.3). The simulated TC vorticity structure also remained disorganized.
throughout the simulation. The track forecast was more acceptable. Although the center of the low was difficult to track due to the disorganized nature of the TC in the simulation, the WRF-GFS simulation was never more than 200 km away from the best track (Fig. A.4).

Fig. A.2: GFS 0z Sept 8th 48-hour forecast (left) vs. MTSAT derived wind field (right) at 0z Sept 10th, 850 rel. vorticity.

Fig. A.3: WRF-ARW model comparisons of forecast minimum central sea-level pressure for Sinlaku out to 72 hours. (a) Experiments of changing resolution and bogussing (left) and (b) comparison of ECMWF data to selected previous simulations (right).
Since the WRF-GFS simulation was still incapable of correctly resolving the structure and intensity of Sinlaku at 18/6/2 km resolution, the next step was to examine whether the difficulties were a product of a poor initial analysis. To test this hypothesis, WRF was initialized using NOGAPS fields in hope that NOGAPS would possibly be better. Unfortunately, the WRF-NOGAPS results were even worse than the WRF-GFS results in terms of track, intensity and structure. Minimum central pressure after 72 hours was a meager 1004 hPa (A.3), and the storm motion was completely off (A.4). It appears that both NOGAPS and GFS had difficulties in their initialization of the Sinlaku vortex and the local surrounding environment.

Fig. A.4: 72-hour track forecasts for Typhoon Sinlaku, initialized 0Z September 8th. The best track is black, with motion from south to north.
In order to better contrast the differences in initial conditions between the GFS and NOGAPS, 700 hPa water vapor and 850 hPa vorticity difference fields were generated (Fig A.5). NOGAPS depicted higher moisture west of the Philippines and just south of Japan at hour zero, while GFS indicated higher moisture east of China and associated with the Sinlaku vortex itself. The moisture differences are alarmingly high for an initial analysis. West of the northern Philippines, NOGAPS mixing ratios are as much as 5 g/kg higher than GFS at 700 hPa. This difference would be significant at the surface, but at 700 hPa this is even more extreme due to the fact that mixing ratios decay with height. The vorticity difference fields clearly indicated that GFS was initializing a broader circulation than the compact vortex initialized in NOGAPS. Again, the magnitudes of the differences are quite large, with differences as high as $4 \times 10^{-4}$ s$^{-1}$ associated with a convectively active region in the monsoon trough north of Malaysia.

Once ECMWF data became available, difference fields between all three models were generated (not shown). The difference between ECMWF and either of the other two models is comparable to the differences between the GFS and NOGAPS.

Fig. A.5: “Difference fields” – NOGAPS mixing ratios subtracted from GFS mixing ratios at 700 hPa (left), and NOGAPS absolute vorticity subtracted from GFS absolute vorticity at 850 hPa (right). Units for the moisture difference are g/kg from -5 to 5. Units for the absolute vorticity difference are s$^{-1}$ from $-10 \times 10^{-4}$ to $10 \times 10^{-4}$. 
A.2: Inclusion of Bogus Vortex

In order to compensate for the inability of the WRF-GFS and WRF-NOGAPS to correctly initialize a realistic TC vortex, a synthetic “bogus” vortex was utilized. The bogussing procedure begins with a removal of the weak initial TC vortex as analyzed by the global model by performing a vorticity perturbation at the location of the TC using $\alpha_{\text{max}} = -1.00$ (see sub-chapter 2.2). A new axisymmetric Rankine vortex is then generated following Davis and Low-Nam (2001) and added to the background field. The maximum winds and radius of maximum winds were set to 30 kt and 50 km to best represent Sinlaku at 00Z September 8th. Finally, thermal wind balance is applied to the resulting field, generating a warm core within the cyclone.

The WRF-GFS simulation with the inclusion of a bogus vortex produced a much more realistic 953 mb minimum sea level pressure for Sinlaku (Fig. A.3), along with a more organized and symmetric vorticity pattern (Fig. A.4). The track forecast does not improve, but the problem appears to be associated with a large erroneous westward displacement of the TC during the first 12 hr of simulations.

A.3: Addition of ECMWF Analyses

After completing the WRF-GFS and WRF-NOGAPS simulations, ECMWF data became available for use in this study. While the ECMWF initial analysis should not be better than the NOGAPS or GFS analyses if the necessary data simply is not there, it would be better than the other two if the ECMWF has a better data assimilation scheme. Ballish et al. (2009) demonstrated that while the GFS model itself is competitive with ECMWF, the 4-D var ECMWF data assimilation scheme is superior to the 3-D var scheme used by the GFS. While 4-D var has since been incorporated into the NOGAPS
model, NOGAPS was still using 3-D var during the T-PARC campaign, which may be a source of initial error in NOGAPS analyses as well. The ECMWF has also shown superior skill to the other models in satellite data assimilation.

WRF-ECMWF simulated intensity was not only better than both the WRF-GFS and WRF-NOGAPS, but it was even superior to the bogus WRF-GFS. The WRF-ECMWF captures the gradual intensification through 48 hours observed in the actual storm, followed by a rapid intensification (Fig. A.3). The ability of the WRF-ECMWF to outperform the bogus WRF-GFS in terms of intensity forecasts was very surprising. The overall shape and structure of the forecast track from the WRF-ECMWF mimicked the best track, but occurred a few degrees longitude too far west (Fig. A.4).

Ultimately, the drastically improved results from the WRF-ECMWF over the other two simulations led us to trust the ECMWF initial analysis over the other two models. For this reason, the synoptic sensitivity analyses herein are performed using the ECMWF for initial and boundary conditions.
References


Earth Observing Laboratory (EOL), 2008. Available online at (http://catalog.eol.ucar.edu/tparc_2008/).

ECMWF, 2010. Available online at http://www.ecmwf.int/products/forecasts/d/charts/monitoring/coverage/dcover/


