Improving Hurricane Intensity Forecasts Using 4DVAR Data Assimilation of Airborne Doppler Radar Winds

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IMPROVING HURRICANE INTENSITY FORECASTS USING 4DVAR DATA
ASSIMILATION OF AIRBORNE DOPPLER RADAR WINDS

By

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IMPROVING HURRICANE INTENSITY FORECASTS USING 4DVAR DATA
ASSIMILATION OF AIRBORNE DOPPLER RADAR WINDS

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Over the last decades, researchers have focused on improving tropical cyclone (TC) forecasts. Accurate TC predictions are very important in order to protect life and property. Scientists examine two important pieces regarding TC prediction: where the storm is going and how strong it will be in the future. These are referred as track and intensity forecasts. TC track forecast has improved tremendously over the last several decades. However, hurricane intensity forecasts continue to be a great challenge in operational and research communities. Previous studies have found that the lack of progress in intensity forecasts is partly due to the lag in the ability to specify the initial vortex in the numerical weather prediction (NWP) model, in addition to the lag in representing the observed inner-core storm intensity, structure and internal dynamics. Researches have introduced various data assimilation (DA) techniques to address the problem of determining the initial vortex. However, in order to better represent these features, there must be sufficient observations in the inner-core region along with a data assimilation method that can effectively use the data to accurately estimate the initial vortex. Some of the challenges in the TC data assimilation are: (1) scarcity of systematic data assimilation in the inner-core region, and/or, (2) absence of enough information
about this region, and/or (3) the model resolution is inadequate to capture the structures at these smaller scales.

This study examines the impact of assimilating high-resolution inner-core Airborne Doppler Radar (ADR) winds on two major hurricanes, Ike (2008) and Earl (2010). The primary objective is to understand its impact in the initial vortex structure and how it translates to the resulting forecasts. With the development of advanced data assimilation techniques, ADR data can improve the specification of the vortex and potentially improve intensity and structure forecasts. Nevertheless, there are two important factors that can affect the effectiveness of the method: (1) resolution on the grid where DA is performed and (2) the background error covariance used. This work focuses on improving the 4-Dimensional Variational (4DVar) data assimilation technique by using a high-resolution DA domain of 4-km in order to better represent convective scales features and by generating a new static background error covariance more suitable for the current DA experiment. This static error covariance includes the vortex structure information. The impacts of these two aspects were revealed by comparing the analyses and forecasts generated by 4DVar with relatively coarse resolution of 12-km that used the standard background error covariance file (that do not contain any vortex information), a 4DVar at 4-km that used the same background error covariance, and with a 4DVar at 4-km that used the newly generated covariance. This method is first applied on Hurricane Ike. The second experiment performed on Hurricane Earl only included one 4DVar setup: 4-km DA domain with the new static covariance that contains the vortex information.

The results for Hurricane Ike experiment showed that increasing the resolution from 12-km to 4-km in 4DVar largely improved the initial vortex structure, enhancing the
small eye and the inner-wind maximum. The newly generated vortex specific background covariance used in 4DVar helped to remove some unrealistic features in the wind field showed by the 4-km 4DVar that used the non-vortex static covariance. The adjustment in the initial condition brought the intensity and structure forecast to be in better agreement with the observations. The mean errors of the maximum wind speed and track forecasts by both 4-km 4DVar experiments were smaller than those by the 12-km 4DVar. In contrast, the mean errors of the sea-level pressure forecast showed that the 12-km 4DVar produced a lower pressure at earlier stages of the forecast. This was attributed to the fact that in the higher-resolution 4DVar analyses, the model was not able to maintain the very small eye, double eyewall and strong pressure gradient features for a longer time. Detailed diagnostics of the surface structure revealed that the asymmetry was well maintained by all the 4DVar cases. However the 4-km 4DVar that used the vortex-specific background covariance gave a better fit with the observations. The control experiment in which no data was assimilated did not develop the inner-core structure and continuously over-estimated the storm intensity.

Results from the second experiment performed on Hurricane Earl further demonstrated the advantages of using 4DVar to correct the initial conditions of a hurricane forecast model. For this case, the ADR winds were continuously assimilated during a period of 5 days. Overall the analyses showed that having continuous DA events better estimated the long-term intensity of the storm. The errors of the 4DVar intensity forecasts were evidently smaller than the forecasts with no DA (non-DA) initialized with GFS. The initial conditions were clearly adjusted to match the observed structure. Detailed verification of vertical structures showed that the 4DVar analyses constantly
improved the inner-core structure reproducing the inner-wind maximum and maintaining the small eye during the intervening forecasts. This work also demonstrated one of the advantages of assimilating 3D winds in 4DVar since it was able to simulate the deepening and strengthening of the vortex during the rapid intensification event clearly observed by the ADR data.
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Chapter 1: INTRODUCTION

1.1 Motivation

Tropical Cyclones (TC) have been the subject of considerable attention. In addition to their unpredictability, they are among the deadliest and costliest natural disasters. Population growth, wealth and infrastructural development in coastal zones are each proportionately related to an increase in hurricane land-falling damages. However, tropical cyclones related fatalities have significantly decreased over recent years. This is generally attributed to improvements in the tropical cyclone forecasting and warning systems. Therefore, it is essential to invest in resources so the research effort can continue to optimize already known methods. These research initiatives can potentially lead to improvements in TC formation, track, intensity change and rapid intensification. Despite the significant progress achieved, there is still a lot of room for improvement. For instance, the National Hurricane Center (NHC) described that in the period between 2000 and 2010, the official 48-h track forecast error decreased up to 50%, while the intensity forecast error over the same period practically remained unchanged (Rogers, et al 2012).

TC intensity is usually defined by the maximum wind speed (MWS) and minimum sea-level pressure (MSLP), which vary during a storm’s lifetime. This is a multi-scale process (e.g., Marks and Shay 1998), associated with the evolution of the storm’s internal structure (e.g., Houze Jr. et al., 2007) as well as the complex interactions with the storm’s environment-especially vertical wind shear (Rogers et al., 2003; Chen et al., 2006), low-to-midlevel dry air and coupled atmosphere-wave-ocean processes (Chen
et al. 2007, 2013; Lee and Chen 2012). In contrast, it is widely recognized that the storm track changes are primarily determined through the steering of the large-scale environment flow in which the TC is embedded. Track forecasts have improved significantly, partially as a result of the use of observations (e.g., satellite derived wind vectors and radiosonde wind data) to better initialize and simulate the large-scale TC environmental flow.

Part of the difficulties in the lack of improvement in hurricane intensity forecast originates from: (1) the deficiencies in the NWP models used to forecast TC intensification, (2) the lack of proper understanding of the physical mechanism that lead to the hurricane intensity change and (3) the fact that the inner-core structure is not well resolved. Several studies have concluded that intensity prediction can only be improved if models are able to initialize the inner core dynamics and thermodynamic structure of the storm properly (Jordan 1961, Chen et al. 2007; Rogers et al. 2006, House et al. 2007; Pu et al. 2009). However, the inner-core details that control intensity forecast (e.g., the eye and eye-wall dynamics) require very high vertical and horizontal resolution to be adequately initialized and forecasted (Chen et al. 2007). Running a global model at a very-high resolution results in large computational costs. Alternatively, high-resolution regional model provide higher accuracy and the ability to reproduce smaller-scale phenomena. Chen et al. (2007) have shown that with a regional model at 1.67-km horizontal resolution the inner-core details of a TC can properly simulated, while at low resolution these features are not resolved.
On the downside, regional models require lateral boundary conditions at the borders of the horizontal domain, providing another potential source of error. Additionally, there is an initial-value problem. The regional forecast model requires an appropriate initial condition and lateral boundary condition from the global model. Otherwise the solution of this model quickly deteriorates. This is often done by interpolating the global analysis to finer grids of the regional model. However, if the vortex from the global analysis is not representative of the real TC vortex in terms of resolving the small scale dynamical and physical processes, merely interpolating to a finer grid do not solve the issue of incorrect initialization. The mismatch in the grid resolution could lead to a continuous vortex adjustment at the initial condition (Kurihara et al. 1993) and therefore result in large errors in the short-range intensity and structure forecast. It is then clear that the determination of the initial condition in regional models is not only important but complex, and just running a very-high resolution regional model is not sufficient to reduce the error in the TC intensity forecast.

Better initial TC vortices that are consistent with the observed may be necessary for successful hurricane intensity forecasts. One way to solve this problem is to produce initial conditions through a combination of observations and short-range forecast—background field. This approach is known as data assimilation (DA). DA is the process of combining observations with a previous model forecast—also known as first-guess—and their error statistics in order to obtain an improved estimate (the analysis) of the atmospheric flow (Talagrand, 1997). In the past decades, different data assimilation techniques have been used to study the hurricane initialization problem. A short review of recent studies is detailed in the next section.
1.2 Hurricane Vortex Initialization

Researchers have used different approaches to address the hurricane initialization issue. In the earlier experiments, simple hurricane models with idealized initial conditions were used in order to understand this problem. Many of these studies performed numerical simulation using simple 2-Dimensional and 3-Dimensional hurricane models (Anthes 1973). They found that in order to have realistic forecasts of TC for operational purposes, two important ingredients are necessary. First, it requires adequate (high quality) observations of the hurricane and second, a reliable data assimilation method with which to assimilate the observations. In order to understand the problem of initializing a hurricane model, several types of real observations were analyzed. Two main conclusions were found in this study: (1) determining which kind of observations are the best and where are they most useful and (2) how to use this data to be consistent with the model in order to conserve a balanced state and prevent the formation of inertia-gravity waves in the domain.

There are several possible approaches when formulating an objective analysis scheme. In this case, developing a dynamic initialization technique was the key to address this last issue. In this method the equations were integrated forward in time for 12-h period prior to the regular forecast. Then, during this period and using an artificial diffusion term in the equations, the model grid values were nudged towards the nearby observations. The dynamical processes in the model modified the remaining variables that were not observed. The nudging was performed continuously, therefore, producing a balanced initial state consistent with the observations. The main result of this work was
finding that inner-core and lower level hurricane observations are producing more effective and accurate analysis than the observations located in the outer region (~300 km) and in the upper troposphere. Additionally, in terms of type of observations, the temperature and tangential wind speed were found to contribute the most to the reduction of forecast errors.

These results have suggested that better and more accurate observations at radial distances close to the storm, along with a suitable data assimilation schemes are needed in order to have an improved TC initial condition. However, a shortfall of this work is that, during the process of combining the observations and model field, their errors were not considered. In this technique the observations are assumed to be perfect, thus an observation at a grid point will determine the field variable at that point. This method is commonly referred to as successive correction (SC) (Gustafsson 2007). However, this technique has a problem in terms of not considering their errors. For example, if there are bad observations, they might replace a good background (first-guess) field. It is also important to recall that a relatively simple forecast model is used in this study.

For researchers, the next approach to solve the hurricane initialization problem was to improve the not well-defined, underestimated, and sometimes misplaced vortices from the global models. It was evident that the environment initialized with global models was relatively good, however, in terms of reaching accurate short-range forecasts the initial vortex needed to be improved. Many studies have adopted the vortex relocation and/or bogussing (e.g., Liu et al 2000; Zou and Xiao 2000) techniques. Zou and Xiao (2000) proposed an approach that was based on using simplified models to specify a
synthetic vortex, which then were implanted in the large-scale analysis. This technique showed some improvements in the hurricane forecasts. However, they highlighted that instead of using simplified models to specify the vortex, a full hurricane prediction model could be used as a strong dynamical constraint to modify the model fields simultaneously. To understand this issue, Zou and Xiao (2000) introduced the variational Bogus Data Assimilation (BDA) technique. This method assimilates the satellite-derived water vapor wind vectors (WVWVs) observations and a bogus surface low pressure (SLP field) from observations to estimate parameters. They were assimilated in the model using a four-dimensional variational data assimilation (4DVar) framework. The benefit of using 4DVar method in the hurricane forecast model was to let the model spin up and correct, at the same time, the other state variables not observed such as temperature, moisture, and 3D winds. The BDA helped to produce better dynamic and thermodynamic structures in the initial vortex, which resulted in improvements in the prediction of the hurricane track, intensity changes, and structure of Hurricane Felix (1995).

While positive results of assimilating SLP, wind field (Xiao et al. 2000; Pu and Braun 2001), and satellite derived data (Zou et al. 2001; Zhang et al. 2007) were showed by using the BDA scheme in the hurricane prediction models, hardly any inner-core wind data was integrated. Large efforts were made in the area of computing the wind field from satellite data (Zhu et al. 2002), however the observations are too sparse to resolve TC vortex inner structures or contaminated by heavy precipitation near the inner-core region (Xiao et al. 2009).
The high-resolution airborne Doppler radar (ADR) 3D wind data has been collected from the National Oceanic and Atmospheric Administration (NOAA) P3 aircraft for many years, and it has been recently used in data assimilation for the inner-core model initialization. Pu et al. (2009) tested a case using 3-dimensional variational (3DVar) DA. They pointed out some issues. For instance, there is a spatial coverage limitation of only the inner-core part of the storm, and the sparse temporal distribution. Furthermore, they are not necessarily available at the traditional synoptic hours (00, 06, 12, 18 UTC). Nevertheless, an important advantage of this type of data is that they are sampled at very high resolution (at least 5 km), giving the opportunity to capture the TC vortex dynamic, thermodynamic and hydrometeors structures (Xiao et al. 2009).

Previous studies have indicated that the assimilation of ADR observations has corrected many aspects of storm-scale features that result in an improvement of short-term forecasts (Weygandt et al., 2002; Sun 2005). Therefore, in order to obtain the most information from this data, a high-resolution data assimilation scheme was needed. Xiao et al. (2009) used the Weather Research and Forecasting (WRF) model’s (3-Dimentional Variational) 3DVar data assimilation scheme and demonstrated the potential for improving the hurricane intensity forecast using both the 3-D ADR wind field and reflectivity for model initialization. The simulations were performed for three TC cases: Hurricane Jeanne (2004), Katrina (2005) and Rita (2005). Four experiments were tested: a control run using a NCEP/GFS analysis (with no data assimilated), a run in which only the convectional Global Telecommunication System (GTS) (i.e. Satellite, synoptic, sounding etc.) are assimilated, the third experiment assimilates GTS data and ADR winds, and finally, the fourth experiment combines both ADR 3-D winds and reflectivity
data as well as GTS. The conventional GTS data was assimilated at a relatively coarse resolution of 12-km. Some of their results are summarized as follow.

In terms of each experiment’s performance, Xiao et al. (2009) found that assimilating only GTS had a small impact in both: vortex initialization and succeeding forecast. This attributed to the fact that this low-resolution data was already assimilated in their background (first-guess) analysis that came from interpolated NCEP/GFS global analysis, no additional information was added, and the absence of GTS data in the hurricane inner-core region. Conversely, the assimilation of high-resolution ADR wind data improved significantly the hurricane vortex initial condition, and helped to reduce the intensity, track, and structure errors out to about 36 h into the forecasts. When the reflectivity data was assimilated, the thermodynamic structure of the storms were improved in terms of producing a more realistic eyewall and reorganizing the region of strong convection in the principal rainbands. In general, using this high-resolution and inner-core data for TC initialization demonstrated the potential for improving the intensity forecasts.

Some limitations were also discussed in Xiao et al. (2009) work. They found that the benefits of the 3DVar are reduced for rapid developing storms like Katrina and Rita (2005). This was attributed to the lack of flow dependence in their 3DVar’s background error (BE) covariance and failure to include time dependence in the assimilation. The variational method uses the traditional National Meteorological Center [NMC; known as the National Centers for Environmental Prediction (NCEP)] method to calculate the background error (Parrish and Derber, 1992; Wu et al. 2002; Barker et al. 2004a). The
NMC method does not specify the background for the hurricane case in particular. In 3DVar technique, this static background covariance plays an important role spreading out the information and the impact of the observations. Unlike the 4DVar scheme, the 3DVar does not include a forecast model and the data is assimilated at one time period only. Therefore, 3DVar increments are less dynamically consistent than 4DVar’s.

The study made by Pu et al. (2009) used the same type of dataset (ADR), model, and variational DA scheme. Their experiments were performed on Hurricane Dennis (2005). However, no GTS data was assimilated, and their first-guess was a spun-up vortex derived from a 59-h WRF forecast. Their results demonstrated that when only radar reflectivity data was assimilated, the impact in the thermodynamic structures of the storm was significant, but only a small influence was found in both maximum wind speed and MSLP. When only 3-D winds were assimilated the inner-convection conditions as well as the track and MWS were improved, but only small impacts on the SLP field. Only when both the Doppler radar reflectivity and 3-D winds were assimilated, these parameters were improved and resembled closely those of the observed storm. While this study was based only on one case, it revealed the advantage of assimilating inner-core high-resolution wind data since their results showed that the errors in hurricane intensity forecast could be reduced.

These studies have highlighted the need for either an appropriate BE that would include vortex specific information or an advance data assimilation technique (e.g., 4DVar and ensemble Kalman filter) that includes either explicit or implicit flow dependent error structure. A recent work by Gordon (2011) focused on the very inner-
core of the storm, using the same type of ADR 3-D wind data, but for both 3DVar and 4DVar. The experiment was performed on Hurricane Ike (2008) and the DA was over a 26-h cycle period. One of the objectives of Gordon’s work was to investigate the effects of assimilating inner core data on the dynamic and thermodynamics of the storm’s initial condition; and to examine if there was improvement. Both techniques were compared to a control run (in which not DA was performed) to verify if the 4DVar revealed flow dependent analysis increments relative to 3DVar homogeneous and isotropic increments. Impacts on the intensity and structure forecasts were also analyzed. Two sets of forecasts were tested: (1) short-term (less than 12-h) forecasts initialized from the DA analysis within the cycles in order to study the relative impact of both methods, and (2) the extended forecasts after the last DA cycle in order to study the impact of DA in a 60-h time period. The results demonstrated that the inner wind structure was assimilated appropriately. Additional improvements were also seen in both the SLP and rainfall structure of Ike. Both experiment improved the short-term intensity forecast, but 4DVar was closer to the best track observation. The results also showed that the overall quality of 4DVar analysis is better than that of 3DVar, adjusting other state variables in a dynamically consistent manner. In contrast, 3DVar analysis fit closely to observations but the inner-core structures features were not maintained as long in time as with 4DVar. Additionally – and notwithstanding the previous results described – it was noted in this study that during the forecast phase both experiments seemed to lose the inner-core feature quickly.

Similar to previous studies, this work had the limitation of using a static background error covariance with no TC information that may not be optimal for this
data assimilation experiment, because it does not specify the background for the hurricane case particularly. Consistent with other studies, Gordon (2011) suggested that the use of flow dependence covariance could help improve the results and better represent the observed hurricane intensity, structure and internal dynamics.

To address this background covariance issue, recent works have explored the use of ensemble-based DA techniques to initialize hurricane forecasts and have shown positive results (Wang et al. 2011; Zhang et al. 2009a, 2011; Zhang and Zhang 2012). One example is ensemble-variational DA method (Wang et al. 2008a,b, 2009; Liu et al. 2008; Li et al. 2012). This technique uses an ensemble of short-range forecast to determine the flow-dependent spatial and cross correlation for DA. The ensembles are derived from an Ensemble Kalman Filter (EnKF). This method incorporates the flow-dependent covariance derived from the ensembles into the VAR framework (Wang 2011; Li et al. 2012). The standard variational method uses one single deterministic first-guess; but this method uses an ensemble of forecast as the first-guess. Studies have demonstrated that this method can improve the VAR technique because it includes the flow-dependent ensemble covariance (Wang et al. 2007a; Wang et al. 2008a,b, 2009; and Buehner et al. 2010ab). Another example is a recent work done by Wang (2011). The experiments were performed on Hurricanes Ike and Gustav (2008) and the data assimilated was the conventional GTS observations. The objective was to study the impact and the differences of the flow-dependent background covariance versus a static covariance in the track forecasts. Wang (2011) demonstrated that the errors of the track forecasts initialized with the ensemble-variational DA were smaller than the experiments initialized with 3DVar. In addition, it was found that unlike the 3DVar, the ensemble-
variational method was able to systematically adjust the position of the storms during the assimilation period. Nevertheless, it is important to mention that in this work no inner-core data was assimilated.

Li et al. (2012) was able to address the issue of using inner-core data in this assimilation system. The study was focusing on the assimilation of inner-core observations using the radial velocity data from two coastal Doppler (WSR-88D) radars during Hurricane Ike (2008) before and after landfall. The experiments were also compared with 3DVar method with static BE. They found that all the DA analyses were consistent with the radial velocity data. However, the ensemble-variational method produced a more realistic temperature increments at the storm center that agrees with the warm core structure, versus 3DVar that was weaker and smoother. Overall, the ensemble-variational experiments showed a deeper warm core structures. In terms of the forecasts, the ensemble-variational analyses produced more and better dynamical estimations that lead to smaller forecasts errors. These studies suggest that more investigation is necessary in order to understand and improve the method.

Li et al. 2012 point out an important issue of having the pre-defined static covariance in variational data assimilation: the covariance is not able to reflect the mesoscale and convective-scale nature of hurricanes. This may be not the optimal model of the static background-error covariance appropriate for hurricane experiments. To solve this problem, Wang et al. 2011 recalculated the static covariance using background-forecast ensembles following the method used by Wang et al. (2008b). Both papers describe each step on how it was calculated. What is important to know of this study is
that the ensemble was computed for a 1-week period during the 2005 hurricane season, which includes several storms but for a big and relatively coarse domain. Then, the ensemble of forecast was used to compute this newly static covariance following Skamarock et al (2005). Previous studies have documented the positive impact of using this covariance (Wang et al. 2008b; Meng and Zhang 2008). They found that the newly generated covariance performed slightly better or comparable to the default covariance for the analyses and forecasts performed over the continental US domain. However, this has not been explored in a smaller and higher-resolution domain setup, like for the hurricane inner-core data assimilation experiments.

An important aspect that could impact the effectiveness of doing DA and have not been well studied is the importance of error in the observations and how is computed in the DA system. The current WRF Data Assimilation system (WRFDA) does not consider wind direction error when wind speed data is assimilated. This is relevant, because the observations used in the previous works and in our study are the ADR 3-D wind speed dataset. ADR wind observations are collected in the form of speed and direction. These observations are then transformed to $u$, $v$, and longitudinal and latitudinal components prior to assimilation and then processed to determine the observations’ errors. Huang et al. (2013) presents an innovative method for assimilating winds in the WRFDA framework that uses both the speed and direction and formulates its error by taking into account both terms. This study was performed on a non-tropical cyclone DA case—an ideal framework to test this method. A comparison between this new approach and the convectional method of determining the $u$ and $v$ observation error is also shown. The motivation comes from the statement that $u$ and $v$ observations’ error
are correlated and influenced by the wind direction’s error, which has not been included in the conventional method. These results would impact the analysis and potentially improve the previous results. To test the hypothesis Huang et al. (2013) worked on a single observation pair experiment and an idealized experiment. The analyses from new method turn out to be more accurate and lead to an improved forecast—better than the conventional method results. While this study was done on idealized cases, the same authors are implementing additional tests that include real observations experiments. Thus, further investigation and research is necessary in order to understand how can this part of the DA framework impact the area of high-resolution tropical cyclone data assimilation system.

1.3 Scientific Questions and Research Objectives

As mentioned before, Gordon (2011) emphasized the impact of assimilating winds from the airborne Doppler radar for Hurricane Ike (2008). Hurricane Ike was a challenging storm to forecast operationally. The assimilation technique employed was the variational method (i.e. 3DVar and 4DVar) in order to study the effects on the initial inner-core dynamics and thermodynamic structure of the TC. One of the main results is to be able to successfully prove that both DA methods help to define the inner wind maximum, which in turn solved the initialization problem that a control with no data assimilation could not accomplished. However, Gordon’s study highlighted two main weaknesses: (1) the relatively coarse resolution of 12-km where the assimilation of inner core observations are performed, and (2) the use of a static non-vortex specific BE.
The objective of this present work is to address these issues and understand how this technique can be improved in order to further demonstrate and conclude how data assimilation is a valuable approach in helping us understand the hurricane intensity prediction problem. The first step is to increase the horizontal resolution of the DA from 12-km to 4-km in order to better represent convective scales features. The purpose of this part is to investigate the changes in the vortex structure and in the intensity forecast by incorporating ADR wind assimilation in the WRF 4-km resolution domain. The second step is to re-calculate the background error covariance file. Previous studies have observed the benefits of using the 4DVar technique, however they have also stated that the background error covariance in the variational method can still be improved (Rabier et al. 2000; Navon et al. 2005). Instead of using the default and conventional static BE, a more suitable vortex specific covariance computed from an ensemble of forecasts may impact the track and intensity forecast and potentially reduce their errors.

The study is organized as follows: First, in the methodology section, we include a detailed description of how the assimilation framework is developed and organized. This also includes both the description of the airborne Doppler radar and the verification dataset. Then, the experimental design section of this work is divided in two parts, which include a brief overview of the two case studies. The following chapters will present results that compare data assimilation analyses versus no data assimilation and its impact on the intensity and structure forecast. The first part focuses on continuing the analysis of Hurricane Ike (2008). In the second part, a very different storm is evaluated, Hurricane Earl (2010). The main reason of choosing Hurricane Earl was to compare a tropical cyclone that rapidly-intensified to a hurricane versus a relatively steady-state hurricane
with secondary eyewalls such as Ike. Moreover, since the same methodology is applied to
two different storms, the technique of performing high-resolution data assimilation
presented in this work will be revised.
Chapter 2: METHODOLOGY

2.1 Numerical Model

The Weather Research and Forecasting (WRF) (Skamarock et. al. 2008) model version 3.2 is used in the first part of this study to calculate the background error (BE) statistics and the forecasts after the data assimilation of Hurricane Ike. In addition, the Advanced Research WRF (ARW) dynamical core is used in this work. In order to have a consistent comparison between the results presented in this document with the work done by Gordon (2011), it was necessary to use the same forecast model. For the second part, where the impact of DA is investigated on a second and new TC case (i.e. Hurricane Earl), a more recent version (3.4.1) of WRF-ARW is used. A short description of the model is included in this section as well.

WRF-ARW is a fully compressible and nonhydrostatic model with a run-time hydrostatic option. The vertical coordinate is a terrain following hydrostatic pressure coordinate. Thirty-six vertical levels are used in this research; the lowest level is located near 40 m above the surface and there are 9 levels within the Planetary Boundary Level (PBL). The physical parameterization schemes include the full physics option for sub-grid scale processes including PBL, microphysics and cumulus. The Yonsey University (YSU) scheme is employed for the planetary boundary layer processes, (Hong et al. 2006), because it accounts for explicit entrainment of heat and momentum at the top of the PBL. The WRF single-moment five-class (WSM5) (Hong and Lim, 2006) is used for the microphysics scheme. It has been found that this scheme is appropriate for the study of hurricanes and their strong convection since it allows for mixed-phase processes and
super-cooled water to exist. For the cumulus parameterization we used the Kain-Fritsch scheme (Kain, 2004), and used in all domains.

Three two-way nested model domains are used for the forecasts (Fig 2.1). All domains have thirty-six vertical levels. The coarsest domain (domain 1) has 250x200 horizontal grid points (at 12 km spacing), the middle mesh (domain 2) has 181x181 grid points (at 4 km spacing), and the innermost mesh (domain 3) has 301x301 grid points (at 1.3 km spacing). The inner two domains are auto-movable centered on the storm’s center using the WRF model’s vortex following algorithm.

![Figure 2.1: Maps describing each domain size and coverage for both Ike (left) and Earl (right); Domain 1 (D1) (Ike: 250x200 and Earl: 450x400) 12-km resolution, Domain 2 same size for both (D2) (181x181) 4-km resolution, and for Domain 3 same size for both (D3) (301x301) 1.33-km resolution. The second domain is used for the DA experiments.](image)

2.2 4DVar Data Assimilation in WRF

In this study, the Advanced Research WRF model (ARW-WRF) Data Assimilation (WRFDA) program is used as the platform to investigate all the DA approaches. The version used here is the 3.3.1, which was designed for the three-dimensional (3D) and four-dimensional (4D) component (Huang et al., 2009). WRFDA
(3DVar and 4DVar) is a variational type technique, which attempts to find the optimal (true) state by iteratively minimizing a cost function. This function represents quadratic distances from this true state, however for the 4DVar it also includes a numerical (non-linear) forecast model. The 4DVar is a generalization of 3DVar for observations distributed in time. The detailed description of the 3DVar formulation was documented in Gordon (2001). The advantages of using 4DVar instead of the three-dimensional (3DVar) are the following: (1) 4DVar compares observations with background model fields at the correct time and at different times in a way that reduces analysis error, and (2) it propagates information horizontally and vertically in a meteorologically more consistent way (Huang et al., 2010). This study focuses on using the 4DVar technique. The mathematical formulation of the WRF 4D-Var that minimize a cost function $J$ is expressed as follow:

$$J = J_b + J_o + J_c$$  \hspace{1cm} (2.1)

Equation 2.1 represents the quadratic measure of distance between the analysis, the background $J_b$, observation $J_o$, and a balanced solution $J_c$. The background term is defined as:

$$J_b = \frac{1}{2}[(x^n - x^{n-1}) + (x^{n-1} - x^b)]^T B^{-1}[(x^n - x^{n-1}) + (x^{n-1} - x^b)]$$ \hspace{1cm} (2.2)

where $x^b$ is the background (first-guess) that comes from a short-range forecast from a previous analysis and $x^{n-1}$ is the guess vector. The $B$ is the background error covariance matrix, which in this work is derived from ensemble-based forecasts with vortex specific
estimates. The observations term $J_o$ for the 4DVar implies that the observations are distributed over a time-window. It represents the distance between the analysis $x^n$ through the linearized form of the WRF forecast model or tangential linear model (TL) $M_k$, the tangent linear observation operator $H_k$ and the observations. This equation is given by:

$$J_o = \frac{1}{2} \sum_{k=1}^{K} [H_k M_k(x^n - x^{n-1}) - d_k]^T R^{-1} \times [H_k M_k(x^n - x^{n-1}) - d_k]$$

(2.3)

The $M_k$ and $H_k$ propagates the guess vector and the analysis increment $x^n - x^{n-1}$ over the $k^{th}$ time window. The TL model does not include microphysics parameterization and uses a constant coefficient vertical diffusion. Here, $R$ is the observation error covariance. Finally, $d_k$ is the innovation vector. The equation is given by:

$$d_k = y_k - H_k [M_k(x^{n-1})]$$

(2.4)

where $H$ and $M$ are the nonlinear observation operator and simplified WRF nonlinear model, respectively. For the purpose of this research, 4DVar is performed over two-outer loops ($n=2$). This innovation vector is computed once at the beginning of each outer-loop. The last term in the equation 2.1 is the balancing cost function term. It measures the quadratic distance between the analysis and a balanced state. The purpose is to have a dynamically consistent 4D-Var by removing the high-frequency waves in the analysis. This is accomplished by including a digital filter in WRF 4D-Var.
The next step is to solve the cost function by iteratively minimizing its value. This is accomplished by estimating the gradient of the cost function with respect to the control variable. As previously mentioned, the 4DVar assimilates the data over a time window; hence, the evaluation of the gradient requires an adjoint model. The adjoint model is used to efficiently compute (in reverse mode) the gradient of the cost function (Rihan et al. 2005). It represents the transpose of the model, and it is used to integrate backward in time from the end of the time window to the beginning.

The 4DVar procedure can be summarized as follows. It performs several forward and backward integrations to minimize the cost function. In the first step, the background field (first-guess) is propagated over the time window using a simplified non-linear WRF model, where the cost function is estimated. The adjoint model then integrates back to the beginning of the time window, and the gradient of the cost function is determined. To minimize the gradient, the succeeding forward and backward integrations in an inner-loop are computed using the TL and adjoint model, respectively. Theoretically, this should be done until the gradient reaches zero. However, due to computational cost, this study considered the final solution minimized when the gradient is reduced by two orders of magnitude and/or a total of 35 inner-loop iterations. In the final step, the increments are added to the basic state and the first outer-loop is finished. This procedure is repeated one more time, and the second outer-loop is completed. Therefore, the final analysis will work as the initial condition for the following forecast.
2.3 Background Error Covariance

As previously introduced, part of this study focuses on the impact of the vortex-specific vs. non-vortex specific BE covariance in the inner-core data assimilation. A detailed description of each method is included in this section. The background error covariance in Gordon (2011) work and in one of the 4DVar cases of this work (referred as non-vortex BE) is static and prescribed by the NMC method (Parrish and Derber 1992). It assumes homogeneous and isotropic correlations for a set of control variables, including stream function, unbalanced potential velocity, unbalanced surface pressure and the moisture control variable as the unbalanced part of pseudo-relative humidity. The latest version of the NMC method (cv6) includes a regression coefficient for the balance between moisture and winds. The NMC-based perturbations are derived from the difference between the 24-h and 12-h forecasts valid at the same time (i.e., every 0000 and 1200 UTC) during a period of 2-month over the region of Gulf of Mexico (Gordon, 2011). In this previous work, different formulations of BE were tested and it was found that the cv6 was appropriate for TC studies due to the relation between the moisture and wind control variables.

Past studies have noted the benefits of including flow-dependent background error covariance (using EnKF) in variational DA (Wang et al. 2008a; Wang 2011; Li et al. 2012). However, constructing a covariance that only includes the vortex-specific information from a specific storm has not been well explored. The main reason to develop a vortex-specific BE is to introduce a covariance that is able to estimate the error of a real tropical cyclone system rather than using the climatology of a region. This newly generated static covariance is calculated using the ensemble method approach. The inputs
are the ensemble forecasts, and the model perturbations are the transformed ensemble perturbations. We used an ensemble forecast of 10 members from Hurricane Earl (2010) to re-calculate the static BE file. From each ensemble forecast we selected each 0000 UTC model outputs from a 5-days (120 h) forecast. The perturbations are calculated by subtracting each ensemble member from the mean. In constructing the BE, the WRFDA executable packages (GEN_BE) codes were used to determine the length scales and vertical correlation EOFs (Barker et al. 2004). A brief explanation of how this calculation was performed is included in the following discussion.

The algorithm consists of five stages. The first stage involves calculating the stream function and velocity potential from the input model space $u$ and $v$ variables. The perturbations from the ensemble of forecasts are then calculated from the control variables, stream function ($\psi$), velocity potential ($\chi$), surface pressure ($p_s$), temperature ($T$) and relative humidity ($r_h$). To calculate these perturbations or also called transformed ensemble perturbations, each ensemble member is subtracted from the ensemble mean. Next, the variances of these perturbations are calculated along with the multivariate covariance of the respective fields, which includes the balanced and unbalance part. The unbalance part is defined as the remainder of the full field minus the balance (correlated) part. The importance of using multivariate covariance in the DA scheme is to allow the information from one field (e.g. winds) to influence the analysis/increment of another field (e.g. temperature or relative humidity) via statistical regression (Barker et al. 2004). The vertical error covariance is calculated in the next stage. For each control variable the vertical component of the background covariance is calculated by using Empirical Orthogonal Functions (EOFs). The eigenvector
decomposition is performed which includes the eigenvectors and eigenvalues. The purpose is to project the vertical error onto orthogonal functions in EOFs space where the coefficients are linearly independent. The final step is to represent the horizontal error correlations. Since this study is classified in the regional scale DA, these correlations are calculated between grid-points of each 2D field, binned as a function of distance (Skamarock et al. 2008; Barker et al. 2004). The function used to fit the data takes the form of a Gaussian curve:

\[ B(r) = B(0) e^{\frac{r^2}{8s^2}} \]  \hspace{1cm} (2.5)

The impact of the BE at distance \( r \) from a particular grid point is computed from this equation. The \( s \) is the length-scale, which represent the eigen mode (vertical component) for each variable.

Previous studies have described (Ingleby 2001; Wu et al. 2002) that in variational DA system, these covariances might require some tuning to optimize the performance of the application (Skamarock et al. 2008). In Gordon (2011) it was found that the length-scales parameter needed to be tuned to about 10 % of their original values in order to obtain realistic analysis in the TC inner-core area. The impact of reducing the length-scale, \( s \), in equation 2.5 is to reduce the effect of \( B \) at the distance \( r \). Although the method employed here was to compute a more realistic and suitable BE for the current assimilation experiment, the length-scale tuning was also necessary to restrict the influence of each observation.

The newly generated static background covariance was used in both DA experiments on Hurricanes Ike and Earl. Hurricane Earl was chosen because the forecasts included its entire lifecycle, from tropical cyclone (TC) to a major hurricane. This gave
the data assimilation process the most general case of using a BE statistics file with vortex-specific information included. The implications of using a derived BE from an ensemble of Hurricane Earl on Hurricane Ike DA analysis are discussed in the final chapter of this thesis.

2.4 Data

The data provided to this study is being divided in two groups, first the assimilated data, which are the airborne Doppler radar data, and second, the data used to verify the numerical simulations (analyses and forecasts).

2.4.1 Assimilated data

Remotely sensed observations, i.e. airborne Doppler radars, have been valuable inclusions to numerous studies that have tried to correct hurricane initialization using assimilation of high-resolution observations. The important benefit is that these types of remotely sensed observations may cover the inner-core areas, which have demonstrated large improvements on hurricane initialization analysis. (Weng and Zhang, 2012).

The data assimilated in this study is the airborne Doppler radar (ADR) retrieved 3D \( u \) and \( v \) components from the radial and tangential winds observed by the radar onboard the aircraft. The research aircraft used to measure the winds is the National Oceanic and Atmospheric Administration’s (NOAA) P-3. The data is quality controlled at (NOAA’s) Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD) (Gamache et al., 2005). The horizontal and vertical resolution of the data available for Ike is at 3-km and 0.5-km, respectively. It is well known that the
surface data contain large errors; hence the lowest data assimilation levels used is 0.5-km. An additional step is necessary to process the data into the WRFDA format. The obsproc utility from the WRFDA system helps with performing the last quality control and estimates the observations errors.

2.4.2 Verification dataset

The data used for model analysis and forecast verification is summarized in this section:

a. **NOAA Hurricane Research Division (AOML-HRD) Surface Wind Analysis (H*Wind):** This project is an integrated tropical cyclone observing system in which wind measurements from a variety of observation platforms (buoys, ships, coastal platform, dropsondes, and flight level data adjusted to the surface) are used to develop the analysis of the distribution of wind speed in a hurricane. The data is composited relative to the storm center over a 4-6 h period. This product is designed to improve the assessment of hurricane size, asymmetry and intensity (Powell and Houston 1998; Powell et al., 1996). Analysis from the H*Wind data was provided for both Ike and Earl. They were used as verification method for 1) make comparison with other observations, and 2) evaluating the model’s performance in terms of size and asymmetry.

b. **Flight-Level measurements of Wind Speed:** The data used in this study are provided by the United States Air Force Reserve (USAFR) 53rd Weather Reconnaissance Squadron and from the NOAA WP-3D Aircraft. As the aircrafts navigates the storm over a 3-h period, measures this type of in-situ observations that provides more accurate evaluation of model’s performance. The data are collected at 1 Hz, and for some parameter at 40 Hz. The flight-level height wind speed used was
from approximately 3-km in altitude during the aircraft’s SW-NE, N-S or NW-SE flight legs compared with sampled cross-section from model-simulated wind speed and sea level pressure at similar angles.

c. **Step Frequency Microwave Imager (SFMR):** Provides operational estimates of surface (10-m) wind speed (Uhlhorn et al. 2007). These estimates of surface wind speed are calculated assuming a linear relationship between wind speed and ocean brightness temperature. The instrument can also recover the rainrate because of the “stepping” procedure (frequencies of 4.5 and 7.2 GHz) used to correct the rain-induced effects in the estimates of wind speed. Similar analyses as with the flight level verification, the SFMR (for the flight legs) observations are compared with model derived surface wind speed. The purpose is to introduce a qualitative assessment of the vertical structure of these hurricanes by combining measurements of the SFMR surface wind with flight-level wind measurements.

d. **Doppler Radar platforms:** Provides ground-based radar reflectivity to compare model estimated TC reflectivity when available. In this study, both the Cuban ground-based Radar and the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar based in San Juan, Puerto Rico are used.

e. **Standard model verification method:** i.e. comparison of maximum sustained surface wind (MWS) and minimum sea level pressure (MSLP) between NHC best-track analysis and model prediction.
2.5 Experimental Design

There are two case studies in this work, Hurricane Ike (2008) and Hurricane Earl (2010). Each experiment is designed in two parts: data assimilation and forecast parts. This research focuses on the impact of the assimilating ADR winds over a selected period. For Ike the period was 26 h cycle where the storm was over the Gulf of Mexico and for Earl the period was 96 h cycle from being a tropical storm up to a major hurricane. The DA method used in this study is referred as cycling method. First, the model is corrected as the ADR observations are assimilated over time. Second, a short forecast is performed to propagate the model solution from one cycle to the next. These steps are repeated for each of the follow-on cycles. Extended forecasts are also performed after each cycle. In the second experiment (Earl) a total of 10 cycles are analyzed. The extended forecasts are performed every 12-h between the period of 29 August at 0000 UTC and 1 September at 1200 UTC.

As mentioned before, the purpose of the first part of this study is to investigate the changes in the vortex structure and in the intensity forecast by incorporating ADR wind assimilation in the WRF 4-km resolution domain and having a newly generated static covariance. This experiment is conducted on Hurricane Ike and using the 4DVar technique. The new 4DVar analyses are compared with a lower resolution domain (12-km) 4DVar and control. Each DA event contains a 1-h time window. The second part of the experiment includes the analysis of Hurricane Earl. Here, the control simulation is compared with both 3DVar and 4DVar techniques. The framework of the DA also includes the 4-km resolution domain and the vortex-specific background covariance.
2.5.1 Experiment 1: Hurricane Ike (2008)

2.5.1.1 Synoptic view

Ike was a long-lived Cape Verde hurricane that caused extensive damage across portions of the Caribbean and along the coast of Texas and Louisiana in September 2008. It reached its peak intensity as a Category 4 hurricane (on Saffir-Simpson Hurricane Scale) while over the open waters of the central Atlantic, directly impacting the southeastern Bahamas before affecting Cuba. Ike and its associated storm surge caused extensive damage across parts of the northwestern Gulf Coast when it made landfall along the upper Texas coast as a strong Category 2 hurricane (NHC/Tropical Cyclone Report, 2010).

By August 28 a well-organized tropical wave developed from the west coast of Africa. The system intensified and became Tropical Storm (TS) on the 1200 UTC September 1. Further intensification was controlled because of the dry conditions in the environment as Ike gradually turned west-northwestward over the following days. However, by 1200 UTC September 3 the system became more organized and was classified as a hurricane. Ike reached its peak intensity of 125-kt (Category 4) 18 hours later, an increment of 70-kt over a 24 h period. Its first landfall was on the Island of Cuba at 0200 UTC September 8 as a Category 4 Hurricane with maximum winds of 115-kt. The interaction with Cuba disrupted the storm’s inner-core; however, the wind field expanded as it advanced into the Gulf of Mexico around 2030 UTC September 9.
As the storm moved northwestward to the Gulf of Mexico, the maximum winds were near 65-kt and the minimum sea level pressure was around 966 mb. By this time the storm had two wind maxima; an inner-core maximum and an outer wind maximum. The eyewall replacement cycle began with outer maximum enclosing the small eyewall (Fig 2.2); however the outer eyewall did not contract enough to complete the cycle. Eventually the inner wind maximum collapsed as it moved into the gulf. This likely prevented rapid intensification of the system as it was expected, since the storm was interacting with the warm water of the Gulf of Mexico. In addition, the tropical storm and hurricane force winds field increased, and reached as far as 240 m and 100 nm, respectively. The environmental condition of stronger vertical wind shear prevented its further intensification. The estimated wind shear magnitudes were around 20-30 kt, between September 11 and 12. The asymmetry in the storm precipitation and deep convection was one of the effects of this strong shear. The presence of the shear in the environment was one of the reasons why most of the models over-predicted the storm intensity. Ike’s center made landfall with maximum winds of 95-kt on Galveston Island, Texas, at 0700 UTC 13 September.
Figure 2.2: MIMIC product developed for tropical cyclones, which combines different low-Earth orbiting microwave satellite instruments. This is a snapshot taken on September 7, where Ike clearly has two eyewalls. Image courtesy UW-CIMMS

2.5.1.2 Data Assimilation and Forecast Phases

The period of study is from September 9-13, 2008. Each DA event is selected according to the sets of ADR observations taken by the P-3 aircraft. In the data assimilation phase, a total of four cycles are studied. The first event is at 2100 UTC September 9 according to the first set of observation taken by the aircraft. The purpose of this DA event was to modify the gaps between the first-guess from the global scale model (GFDL) and the observations. The following events are selected to be at 2300 UTC September 9, 1100 UTC and 2200 UTC September 10 (Fig. 2.3 and Table 1). The complete set of the assimilated ADR wind field observations is shown in Fig. 2.4. In the forecast phase, there are two sections, the forecasts performed from one cycle to the next cycle and the extended forecast, after the last DA event. The verification part includes the comparison between the analysis and forecasts with independent observations.
There are four experiments in this study, two new 4DVar analyses compared with one previous 4DVar case and one control (with no DA). The previous case is the 12-km 4DVar (from Ronald, 2011) and the new analyses: 4-km non-vortex BE and 4-km vortex-BE. In this part, we explore the impact of the resolution and background covariance in the data assimilation technique. Figure 2.3 shows the time-line chart of how the cycles are distributed during the period of study. In the data assimilation results section, only the last three DA cycles are presented.

Figure 2.3: Time-line diagram for the different phases in the experiment. The DA part is in red and yellow arrows, and the forecast part in green.
Airborne Doppler Radar (ADR) dataset for **Hurricane Ike (2008)**

<table>
<thead>
<tr>
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<th>Time (UTC)</th>
<th>Time (UTC) where data was placed for DA</th>
</tr>
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<td>September 10</td>
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Table 2.1: Dates and times for the assimilated data (ADR retrieved 3D u and v wind components) used in Hurricane Ike. The first and third cycle includes two observation sets.

Figure 2.4: 15-km and 3-km horizontal resolutions ADR wind speed (ms\(^{-1}\)) and direction at 3-km height-level. These observations were assimilated during the DA phase on September 9 and 10.

### 2.5.2 Experiment 2: Hurricane Earl (2010)

#### 2.5.2.1 Synoptic view

Similar to Hurricane Ike in 2008, Earl was a Cape Verde storm that crossed the Atlantic Ocean. It caused damage in the northern Leeward Islands and eventually made landfall in Nova Scotia, Canada as a Category 1 hurricane. Earl formed from a strong tropical wave originated from the West African coast on 23 August. As the associated
thunderstorm became organized a closed-surface circulation developed along the wave axis at 0000 UTC 24 August. On August 25 at 0600 UTC this low-pressure was considered a tropical depression when it was located west-southwest of Cape Verde Islands. Twelve hours later, the system strengthened to a tropical storm. Gradual intensification occurred when the storm was over sea surface temperature of 28-29 °C and with an environment of light to moderate shear. Reports from both NOAA and Air Force reconnaissance aircrafts showed that Earl became a hurricane by 1200 UTC 29 August. A weakness in the subtropical ridge caused Earl to turn northwestward. During a 36 h period, from around 0900 UTC 29 August to 2100 UTC 30 August, Earl underwent rapid intensification (RI) intensifying from a 55-kt tropical storm to a 115-kt major hurricane (Category 4). The entire RI event was well sampled by NOAA and Air Force hurricane hunter aircraft. Those flights provided excellent inner-core and environmental coverage, very important to study the roles of environmental, vortex and convective structures in RI (Rogers et al. 2012).

Further intensification was halted since Earl experienced an concentric eyewall replacement cycle when it was passing north of the island of Puerto Rico. On August 31st the southwesterly shear increased, which made Earl weaken back to a Category 2 hurricane. However, conditions became more favorable as the deep convection increased and gained symmetry. By 1800 UTC on 1 September, Earl was re-classified as a Category 4 hurricane. Twelve hours later it reached its peak intensity of 125 kt when it was centered around 380 n mi southeast of Wilmington, North Carolina. A period of weakening started as Earl accelerated, turned northward and environmental conditions became unfavorable. It was caused as the combination of south-southwesterly shear,
cooler waters, and a drier air mass. Eventually, it made the first landfall around 1500 UTC 4 September as a weak 65-kt hurricane near Liverpool, Nova Scotia in Canada and the second landfall as a strong tropical storm (60-kt) on Prince Edward Island about 4 h later. A montage of Earl including the infrared imagery and the official (NHC) storm track is shown in Fig. 2.5 to see the overall progress of the storm over the Atlantic region.

Figure 2.5: Satellite infrared estimate of clouds for Earl from Aug 25 – Sep 5, 2010 and its best track based on NHC’s storm center position. Image courtesy UW-CIMSS

The DA experiments made on Hurricane Earl begin at 2100 UTC August 28 when it was a moderate tropical storm consistent with the first NOAA P-3 aircraft sampling. The maximum wind speed at this time was 50-kt. Subsequently, the experiments were selected during the window where Earl underwent RI, including before, during and after the RI event.
2.5.2.2 Data Assimilation and Forecast Phases

The DA cycling period for Hurricane Earl starts from August 28 to September 2, 2010. Similar to Ike’s experiment, each DA event is selected according to the sets of ADR observations. However, Earl was particularly more sampled by the NOAA aircraft than Hurricane Ike, providing tremendous inner-core coverage during the RI event. In the data assimilation phase, a total of seventeen cycles are studied over an 84-h period, including the time prior to RI onset, through the intensification phase, and after RI. The complete set of the assimilated ADR wind field observations is shown in Fig. 2.6 and Table 2.2. The first event is at 2100 UTC August 28 according to the first set of observation taken by the aircraft when the Earl was a moderate tropical storm.

There are two experiments in this part. (1) 4DVar analyses compared with (2) control (which no ADR wind data is assimilated). During each 4DVar experiments two sets of observations are assimilated within a 1-h time window. The purpose of this study is to analyze the impact of a continuous cycling of high-resolution hurricane DA with the appropriate configuration. This including the horizontal resolution in DA of 4-km corresponding to the resolution of the data and using a more suitable background error covariance (vortex-specific information BE). The figure 2.5 shows a time-line diagram that contains the DA cycles and forecast phases. Each DA consist of a 1-h time-window 4DVar DA. The forecast phase involves the shorts forecast performed from one cycle to the following cycle, and six extended forecasts initialized every 0000 UTC and 1200 UTC between August 29 and September 1. Earl 4DVar analyses and forecasts were also verified against additional observations.
Time evolution for the Data Assimilation and Forecast Period

Figure 2.6: Time-line diagram for the DA cycling and forecast phases. Extended forecasts were performed each 0000 UTC and 1200 UTC from Aug 29 to Sep 01.

<table>
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<th>Date</th>
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Table 2.2: Dates and times for the assimilated data (ADR retrieved 3D u and v wind components) used in Hurricane Earl.
Figure 2.7: 3-km Level Wind speed (ms$^{-1}$) and direction for the ADR wind fields assimilated during the DA cycle period between August 28 and September 1, 2010. The panels include the time (UTC) and date. The black lines are used to separate the days.
Chapter 3: HURRICANE IKE (2008): HIGH-RESOLUTION 4DVAR DATA ASSIMILATION AND FORECAST VERIFICATION

In this chapter, we present the results of assimilating ADR $u$ and $v$ wind components in the inner-core structure and intensity of Hurricane Ike. We evaluate the impact and sensitivity of the results due to changes in horizontal resolution and background error covariance in the data assimilation technique. The goal of this experiment is to understand whether or not these two aspects improve the vortex structure in the initial condition and how the differences in the analysis could contribute to differences in the intra-cycle and extended forecasts. These forecasts are also compared and verified with NHC best track data.

3.1 Data Assimilation

3.1.1 Impact of increasing horizontal resolution

A. Cycle 1: 2300 UTC September 9, 2008

This cycle is selected to be the first data assimilation analysis right after Hurricane Ike emerged off Cuba. During this time, the storm’s maximum wind speed estimated by the NHC was around 65 kts (33.5 ms$^{-1}$) and minimum sea level pressure was approximately 966 mb. The structure was extremely complex, as demonstrated in the Cuban Radar at 2300 UTC (Fig. 3.2). Certain features, such as a very small eye, the presence of an inner and outer eyewall, and the large east-west asymmetry were evident. Moreover, the stronger winds region shown in Fig 3.1 matched the strong convection present in the NW side of the center. However, the lack of small-scale features in the
H*Wind analysis reveal the deficiency of the low-resolution analysis.

Figure 3.1: Surface (10-m) wind speed estimated by H*Wind analysis, valid at 2230 UTC Sept. 9. Analyzed maximum winds: 61 kts (31.4 ms\(^{-1}\)), NW of the center.

Figure 3.2: Radar Reflectivity (dBZ) estimated by the Cuban Radar at 2300 UTC right after Ike emerged from the coast of the island. Bright colors represent stronger convection while dark blue is the rain-free region.

In this section, the impact of increasing horizontal resolution from 12-km to 4-km in 4DVar is presented. Figure 3.3 shows the 3-km level wind speed for the first-guesses, the assimilated ADR wind observations, and the 4DVar analyses for the first cycle valid at 2300 UTC September 9. For this first cycle, both analyses start from the same background field (first-guess). The only difference is that, in the higher-resolution experiment, the first-guess is just interpolated to 4-km. In order to correspond the model resolution in the 12-km 4DVar experiments, the high-resolution ADR wind speed observations were thinned to match this coarser resolution, while in the 4-km 4DVar cases, the radar data was used in their default resolution of 3-km. Their difference is clear; there is more spatial coverage in the higher resolution data. After data assimilation,
all the analyses corrected the size of the inner eyewall and the small wind maximum region in the NE quadrant, which is consistent with the ADR observation. The main difference between the 4-km 4DVar and the 12-km 4DVar is that the higher resolution analysis is able to capture smaller-scale features with more details in the vortex structure. In addition to simulating a smaller eye, the DA runs produced a minimum wind region over the island (southeastern quadrant).

Figure 3.3: 3-km Level Wind speed (ms\(^{-1}\)) and direction (black vectors) for the first-guess (FG), the ADR assimilated, and the 4DVar analyses at the first cycle: 2300 UTC September 9. The ADR wind observations are valid at (a) 2300 UTC and (b) 0000 UTC, for 12-km experiment (top panels) and 4-km experiment (bottom panels). The black line indicates the flight leg of the aircraft during this time.
To quantify the impact of performing data assimilation in this cycle, the flight-level (at 3-km height) wind speed cross section is verified along one of the flight legs (SW-NE line). The model simulations are compared with both ADR winds and flight-level observations. The results are presented in Figure 3.4. The control simulation in which no-DA is performed is also included in order to see the improvement in the DA analyses. It is important to notice however, the differences in both observations. It seems that the ADR winds are a smoother version of the flight-level observations, which are sampled at higher resolution. It is clear that the 12-km 4DVar analysis corrected the small eye and reproduced the inner/outer eyewall; however, its intensity and size were overestimated. Increasing the DA resolution from 12 km to 4 km imposed a large impact on the results, improving the double eyewall size and intensity and matching the observations very well.

Figure 3.4: SW-NE Flight-Level (3-km) cross-section of wind speed (kt) along a diagonal line for the control (brown), 12-km non-vortex BE 4DVar (green), and 4-km 4DVar (blue) verified against the ADR (black) and NOAA flight-level observations (grey); valid at 2300 UTC Sep 9.
Short-term (12-h) forecasts were then performed to the second DA cycle at 1100 UTC September 10, one initialized from 12-km 4DVar and the other from the 4-km 4DVar. These forecasts served as the first-guess in the second cycle. The second cycle is performed over a 1-h time window starting at 1100 UTC September 10. The ADR observation is valid at 1100 UTC. The analyses are also compared with the control experiment.

B. Cycle 2: 1100 UTC September 10, 2008

The first feature to notice is that the first-guess is different for each experiment (Fig. 3.5). After 12-h of forecast, the first-guesses did not maintain as much of the inner eye and inner core winds. However, the 12-km first-guess did retain the asymmetry revealed by the ADR observations at this time. This result indicates that the model was not able to maintain the small-scale features and lost the small eyewall produced by the 4-km DA during the forecast period. After DA, both 4DVar analyses show quite different structure improving the inner-wind maximum. The 12-km 4DVar was able to predict the wind structure similar to the observation in terms of reducing the size of the eye. However, Fig. 3.5 shows that in comparison with the thinned data used in this experiment, the high-resolution observations used in the 4-km 4DVar analysis include a lot more information about the inner-core structure. The analysis of the 4-km 4DVar reflects the improvement in the inner-core wind structure by assimilating higher-resolution data. Nevertheless, all the analyses are more consistent with the observed ADR winds than the first-guesses. It appears that errors introduced in the intervening forecasts are fixed by assimilating the new data.
Figure 3.5: Similar to Fig. 3.3, but for cycle 2 valid at 1100 UTC September 10.

The flight-level cross-sections verification analysis (Fig. 3.6) is used to quantify the performance of the DA in this cycle (1100 UTC September 10). Similar to the previous cycle, it is clear that both observations have some differences in the wind speed structure. Nevertheless, it is important to note that only ADR observations are assimilated in the experiments. In terms of the 4DVar analyses, all of them show a stronger SW-NE asymmetry. The control (with no DA) shows the general feature, but is missing the inner core details. Contrary to the 12-km 4DVar analysis, the higher-resolution 4DVar turns out to be more accurate when providing the vortex structure that better represents the observed storm. The 4-km 4DVar fitted both inner and outer eyewalls sizes and intensities observed.
Figure 3.6: Similar to Fig. 3.4, but for cycle 2 valid at 1100 UTC September 10.

C. Cycle 3: 2200 UTC September 10, 2008

Following the second cycle, another pair of forecast was generated to the third cycle, which is at 2200 UTC September 10. The results are shown in Figures 3.7 and 3.8. Once again, the first-guesses show that the model is unable to maintain the inner eyewall within the 12-h of forecast. It is important to notice that similar to the cycle-1, the 4DVar for this cycle also use two sets of ADR wind observations over the 1-h time-window. This allows more information about the vortex structure within this period and potentially helps the 4DVar to provide the best initial condition. For example: (1) the observations show that the asymmetry in the storm was still a dominant feature, and (2) the outer eyewall became more organized and stronger. These features are more obvious in the high-resolution (3-km) ADR data used in the 4-km 4DVar analysis. The higher-resolution ADR data will not only provide this information to the 4-km 4DVar, but also
more spatial wind structure far from the center of the storm. Therefore, it is important to mention that the disparity in the coverage of the ADR datasets could explain some of the differences in the 12-km and 4-km DA runs.

At this time Ike had intensified with MWS of 85 kt (43.7 ms$^{-1}$) and MSLP at about 950 mb. It is clear that after assimilation the wind field has been modified, especially in the eyewall region. The spatial wind field maps (Fig. 3.7) reveal that the 4-km 4DVar experiment captured well the inner-core structure and small-scale features. This is a large improvement from the 12-km 4DVar case. However, neither DA analyses were able to reduce the strong outer winds located in the northeast quadrant. The flight level cross section results demonstrate that both 4DVars are fairly good matching the observations. The 4-km 4DVar again improved the inner eyewall size, however, in terms of the intensity, there is a difference of 3-4 ms$^{-1}$ between the ADR data and the 4DVar analysis (Fig. 3.8).

The trend seen over these cycles so far represents one piece of the impact of high-resolution data assimilation in the experiment. Increasing the horizontal resolution of DA from 12-km to 4-km in 4DVar has clearly improved the inner-core wind speed structure; particularly the inner and outer eyewall’s size and intensity. Additionally, the results have shown that the 4-km 4DVar was able to fit better to the observations and better simulate the small-scale features observed by the ADR wind data. Despite the improvements demonstrated in this section, the BE covariance used for both experiments was the same.
Figure 3.7: Similar to Fig. 3.3, except for cycle 3 valid at 2200 UTC September 10 and the ADR are valid at (a) 2200 and (b) 2300 UTC. Top (12-km 4DVar), bottom (4-km 4DVar)
As mentioned in previous chapters, this static covariance was calculated on 12-km domain without any vortex information. However, the direct use in higher-resolution DA may not be appropriate. For that reason, a more suitable static BE in this 4DVar technique was necessary in order to match the 4-km domain and the storm-scale DA. In the next section, we present the results of using this newly generated BE covariance in 4-km 4DVar over the three cycles.

### 3.1.2 Impact of the vortex specific background error covariance in 4DVar.

In this section, we examine the impact of the newly generated BE covariance versus the 12-km static (non-vortex) BE covariance in the 4-km 4DVar framework. The new 4DVar experiment (now referred as vortex-BE 4DVar) is performed for the same three cycles over the period of September 9-10. These results are compared with the 4-km
4DVar that used the non-vortex BE covariance and for reference with the control experiment.

A. Cycle 1: 2300 UTC September 9, 2008

Similar to the preceding analysis of cycle-1, the first-guess for both 4-km 4DVar experiments are the same. Additionally, both 4DVar assimilated the same ADR wind observations within a 1-h time window. This is true for the cycle-2 and 3. The observations used in cycle-1 are valid at 2300 UTC September 9 and 0000 UTC September 10. The results for the first cycle are shown in Fig. 3.9 and 3.10. After DA, both analyses corrected the inner-core wind field. Small-scale structures and details are also evident. However, there is no large difference between both 4DVar experiments. They accurately assimilate the small eye and the weaker winds located in the SW quadrant. This is evident in the flight-level cross-section analysis. Both curves are very close to each other and to the observed line. These results demonstrate that for this cycle the large improvement in the analysis came from increasing the horizontal resolution in 4DVar from 12-km to 4-km.
Figure 3.9: Similar to Fig. 3.3, except for the case of 4-km 4DVar and vortex-BE 4DVar for cycle 1 valid at 2300 UTC September 9. The ADR wind observations are valid at (a) 2300 UTC and (b) 0000 UTC.

Figure 3.10: Similar to Fig. 3.4, except for the case of 4-km 4DVar and vortex-BE 4DVar for cycle 1 valid at 2300 UTC September 9.
B. Cycle 2: 1100 UTC September 10, 2008

Like in earlier analyses, short-term forecasts were made to the second cycle. The first-guesses for the cycle-2 show similar behaviors to the previous analyses. The inner-core structure is lost and the eye is much broader. (Fig. 3.11) Both 4DVar analyses were able to recover these features clearly observed by the ADR. There are some odd features in the 4-km 4DVar that seem to be corrected when the vortex-specific BE is used in 4DVar. Figure 3.11 also shows different wind field distributions between both analyses. The 4-km vortex-BE 4DVar produces stronger winds in the SE quadrant, however this feature is also present in the first-guess and there are no ADR winds over this location to verify this with. The cross-section analysis is consistent with the cycle-1 results. Both 4DVar curves are very close to each other and fit very well with the observations.

C. Cycle 3: 2200 UTC September 10, 2008

Figure 3.13 and 3.14 shows the results for the 4DVar analyses of the third cycle. As expected, the model is incapable of retaining the inner eyewall within the 12-h of forecasts. After the ADR wind assimilation, both 4DVars again modified the inner wind maximum and structure. However, the cross-section plot shows that the 4-km vortex-BE 4DVar further improve the 4-km 4DVar analysis in terms of fitting the inner-eyewall size and intensity to the observed values. The 4-km 4DVar inner-eyewall was either too intense or too weak.
Figure 3.11: Similar to Fig. 3.3, except for the case of 4-km 4DVar and vortex-BE 4DVar for cycle 2 valid at 1100 UTC September 10.

Figure 3.12: Similar to Fig. 3.4, except for the case of 4-km 4DVar and vortex-BE 4DVar for cycle 2 valid at 1100 UTC September 10.
Figure 3.13: Similar to Fig. 3.3, except for cycle 3 valid at 2200 UTC September 10 and the ADR are valid at the beginning and the end of the time-window at (a) 2200 and (b) 2300 UTC.

Figure 3.14: Similar to Fig. 3.4, except for the case of 4-km 4DVar and vortex-BE 4DVar for cycle 3 valid at 2200 UTC September 10.
3.1.3 Verification of the surface wind structure

The results from assimilating ADR wind data in 4DVar have shown encouraging products in terms of improving the initial condition structure of the Hurricane Ike. But one piece of the verification analysis is still absent. In order to have a more complete evaluation of the model performance, we need to study the model estimates for the surface wind structure. Using different observations, such as H*Wind, SFMR, dropsondes, NDBC buoys, and selected ships will help to validate not only the storm’s intensity but also its surface wind structure. Figure 3.15 shows a snapshot of the observed storm at September 12 at 1330 UTC, including H*Wind (contour map), SFMR (flight track and points), dropsondes (wind barbs), NDBC buoys (circles) and ships (crosses). Figure 3.16 shows an alternative way to analyze Ike’s structure. The purpose is to show how the winds are distributed as a function of their distance from the center of the storm. Here, we selected the H*Wind, NHC best track, SFMR and dropsonde datasets. This technique helps to indicate the presence of some features like the inner structure (inner/outer eyewall) and asymmetry (how spread out are the points); and the location of the peak winds. This method is also useful for comparing the observations with each other. For this particular case, H*Wind is generally consistent with the SFMR. Both observations show the primary and secondary eyewall. However, neither measured the peak wind estimated by the NHC best track (blue line in Fig. 3.16). This analysis can be applied to validate the forecasts.
Figure 3.15: Surface wind speed field analysis by multiple surface observations platforms valid for the interval 1100-1500 UTC Sept 11. It includes the available observations at this time: H-Wind (contour map), SFMR (flight paths with dots), dropsondes (wind barbs), NDBC buoys (big dots), and selected ships (crosses).

Figure 3.16: Wind speed as function of their distance from the center of the storm. The observations included are the H-Wind, (light green crosses), SFMR (black dots), dropsondes (red dots), and NHC best track peak winds (blue line).

The model verification results are shown in Fig. 3.17. In the first row, the observations are compared with each model cycle-1 DA forecast that is the same as the first-guess for the cycle-2. In the second row, the DA analyses valid for the cycle-2 are compared with the observations. The third and the fourth row are the first-guess and the DA analysis for cycle-3, valid at 2200 UTC September 10. It should be noted that these results show that Ike was very complex and observed differently by SFMR and H*wind analysis datasets, since there are some discrepancies between them. In general, it seems that the H*Wind analyses did not capture the inner-core wind structure, like the inner eyewall. This would cause some problems when the model is only compared with H*Wind and the verification will be inaccurate.

As previously mentioned, this method is also helpful in order to compare the
location of the peak wind from the best track versus other observations. For instance, it is noticed that at 1100 UTC Sep 10, the maximum wind estimated by the best track is coming from the inner region, around 10-15 km from the center. This is consistent with the location of the maximum surface wind observed by SFMR. However, it is clear that at 2200 UTC Sep 10, the peak wind from SFMR is not collocated with the H*Wind maximum wind. The SFMR peak wind is found in the inner eyewall region, while the H*Wind localizes it in the outer region, around 125-km from the center. In the verification process the location of the maximum winds is very important, since it describes to some extent the storm’s structure. Therefore, if a model forecast is only verified using the maximum wind speed analysis, the conclusion that determines the forecast performance might be imprecise. There might be cases where the peak wind values are similar but their locations are very different. This produces unrelated storm structures and therefore, different storms.

In terms of the model’s performances, the control forecast always misrepresents the storm structure since there are no inner core details. All the first-guesses seemed to lose the inner eyewall feature. It was formerly shown that each DA event helped to capture back this feature. With this verification method, this statement is supported. In general, both 4-km 4DVar analyses are closer the SFMR data in terms of size and intensity. They also represent the correct wind field in the outer region. Nevertheless, these results bring back one of the model’s deficiency of retaining the “corrected” double eyewall structure. This can be partially attributed to the model physics and not to the DA.
Figure 3.17: Similar to Figure 3.16, but including model-simulated surface winds valid at three stages: the first-guesses valid at 1100 UTC and 2200 UTC September 10, (1st row and 3rd row) and the DA analysis (2nd and 4th row) valid at those times. Each column represents the control and each 4DVar experiments.

3.1.4 Summary

A clear tendency has been observed after the DA phase of the experiment. Improvements in the inner-wind structure and maximum are evident at each DA event, due to increasing horizontal resolution and using the vortex-BE covariance in 4DVar approach. To summarize the overall impact of assimilating ADR wind data in the three
4DVar experiments, we compute the mean error of the flight-level cross-section analyses. The results are presented in Fig. 3.18. The experiments are compared with both flight-level wind observations and the assimilated ADR winds. The results indicate a clear reduction in the error from both 4-km 4DVars when they are compared with the ADR wind data. This evidently validates the advantages of increasing the horizontal resolution and in 4DVar. However, the errors of all the 4DVar analyses are fairly similar if the analyses are compared with the flight-level observations.

Figure 3.18: Flight-Level (3-km) wind speed mean error of the cross-sections for control, and each 4DVar experiment verified against the ADR winds (left) and flight-level observations (right).

3.2 Impact on the primary circulation and multivariate response.

The preceding results suggest that increasing the DA horizontal resolution and including the vortex-specific BE in the 4DVar had improved the initial condition in terms of the spatial distribution of winds. Some factors, such as the multivariate response to assimilated wind, the impact in the dynamics of the primary and secondary circulation, and the distribution of the thermodynamics, have not yet been explored and will be
studied in this section. In order to perform the analysis, the storm relative coordinate frame is used. Then, the azimuthal mean of the tangential wind speed ($\text{ms}^{-1}$), and temperature perturbation ($\text{K}$) is calculated and examined in the height vs. radius (distance from the center) plane. The experiments shown are the control, the 12-km 4DVar, the 4-km 4DVar and the 4-km vortex-BE 4DVar valid for the third DA event (2200 UTC September 10).

The azimuthal mean tangential wind speed plot (Fig. 3.19) reveals that in comparison with observations, all the 4DVar analyses including the 12-km case captured the inner and outer eyewall feature. Despite the relatively coarse resolution of the 12-km 4DVar, it was the analysis that fit closely to the observations. The 4-km vortex-BE 4DVar also produced this structure but with weaker inner eyewall winds. It is evident that the control experiment does not reproduce this feature.

The time-averaged over the entire DA phase (2300 UTC Aug 9 – 2200 UTC Aug 10) temperature perturbation is presented in Fig. 3.20. The warm core structure is clearly seen in this plot. The results show that the 12-km 4DVar develops a warm-core that extends over a deeper vertical layer than both 4-km 4DVars. The maximum temperature anomaly is found between 4-6 km in all the 4DVars, but the 12-km and 4-km 4DVar exceeds the 6 K value. One of the effects of the shallower warm core in both 4-km 4DVar runs was to produce a higher surface pressures in comparison with the observations. This is verified in the next section, where the minimum sea level pressure forecasts are evaluated.
Figure 3.19: Azimuthal mean Tangential Wind Speed (ms$^{-1}$) for the third cycle: 2200 UTC September 10. From left to right: ADR observations, Control, 12-km 4DVar, 4-km 4DVar and vortex-BE 4DVar. White shaded area in the observation panel is where there is no data available.

Figure 3.20: Azimuthal mean Temperature Perturbation (K), averaged over entire DA period (2300 UTC Sep 9-2200 UTC Sep 10). From left to right: Control, 12-km 4DVar, 4-km 4DVar and vortex-BE 4DVar.
3.3 Impact of ADR wind data assimilation on the extended forecast

The next step is to analyze the impact of data assimilation on the extended forecasts of Hurricane Ike. It has been shown that the initial conditions were modified to be as representative of the true state as possible over the DA cycles. The errors in the initial conditions were reduced to as small a value as possible. It is anticipated that these errors are smaller than the errors of the initial conditions from the no-DA experiments, and they would take more time to grow during the forecast.

Three sets of forecasts were performed and evaluated: (1) the no-DA/control experiment initialized with GFDL analysis interpolated onto the WRF forecast domains, (2) 4-km 4DVar and (3) the 4-km vortex-BE 4DVar. The vortices of the DA experiments were implanted in GFDL environment. This study follows the same methodology as the previous work where the 12-km 4DVar was evaluated and now compared with the new 4DVar experiments. The forecast period for this study is from 0000 UTC September 10 and extends to 1200 UTC September 13. After each DA cycle, a set of extended forecasts is performed.

3.3.1 Verification of intensity, track and structure

To evaluate each model performance, intensity (MWS, MSLP) and track are compared with the NHC best track data (Figs. 3.21-3.23). The figures also include the forecast error to quantify the impact of DA through the entire period of study. In the error plots the NHC official forecast errors are also included for reference. The forecasts initialized after assimilating ADR are closer in predicting the observed intensity than the
control. Like in the 12-km case, the 4-km and vortex-BE 4DVars initial conditions for MWS for the first two cycles match the best-track estimates, but for the initial condition after the third cycle (at 0000 UTC September 11), the peak winds are weaker than the observed.

Overall, errors in the MWS and MSLP are greatly reduced after assimilating ADR wind data in all the experiments. For the 12-km 4DVar, the MWS error grows more quickly than both 4-km 4DVars. After 24-h of forecast the 12-km 4DVar error increased from ~5 kt to more than 10 kt in 12-h. On average, the error of the 12-km 4DVar was 7.6 kt, for the 4-km 4DVar was 6.3 kt, for the 4-km vortex-BE 4DVar was 5.3 kt, for the no-DA was 11.7 kt and for the NHC official forecast was in between with 8.7 kt. In terms of the MSLP, the results are the opposite. The 12-km 4DVar errors were smaller for a longer time, with an average of 4.8 mb. These are interesting results, despite this might not be statistically significant given the small sample sizes. The forecasts initialized from the 4-km 4DVar and the 4-km vortex-BE 4DVar did not produce the lower surface pressure as observed by the best track during the period of September 10-12. This is evident in the forecasts initialized at 0000 UTC September 11. The tendency of the models for the first 12-24 h of forecast was to increase the surface pressure, instead of keeping the lower pressure observed by the best track. This confirm that the higher surface pressures in the 4-km 4DVar simulations are the result of a shallower warm anomaly in those runs in comparison with the 12-km 4DVar.

The results for the track forecast are presented in Fig. 3.23. The first thing to notice is that the earlier forecasts produces a westward shift in the track. The second and
third forecast improves the track and better match the best track. In general there is no large difference between the no-DA forecast versus the DA forecasts. This is evident in the last panel. As expected, the errors grow as the forecast times increases. The error from the no-DA and 4-km 4DVar are smaller for most of the times. In the mean sense, the NHC official forecast is expected to have smaller error with 28.9 nm. Then the no-DA and 4-km 4DVar are close to each other with 31.5 nm 32.3 nm, respectively. The last two are the 4-km vortex-BE 4DVar with 35.5 nm and the 12-km 4DVar with 36.7 nm. The small impact of the DA produced in the track forecast was expected because this study focuses on assimilating inner-core data, and is the environment around the storm that mostly influences the track forecast.

It is important to note that just using the standard parameter of MWS for model verification is not sufficient to verify the accuracy in which the model simulates the storm. Hence, analysis of storm structure is also necessary on longer range forecast. The first method is to evaluate the model’s surface level (10-m) wind speed with the observations. Here, H*Wind analysis and SFMR data are used. The first verification is selected to be at 0400 UTC September 4, when the storm’s MWS is 85 kt (43.8 ms$^{-1}$). The H*Wind analysis valid at 0430 UTC (Fig. 3.24) shows that the storm’s asymmetry was still maintained and the strong winds were located in the NE quadrant. The peak wind was around 48.8 ms$^{-1}$; a fair $\sim$5 ms$^{-1}$ difference from the best-track peak value.
Figure 3.21: Maximum wind speed (kt) forecasts and their mean error over the DA and forecast period. The 12-km 4DVar (blue), 4-km 4DVar (green), 4-km vortex-BE 4DVar (red), no-DA (cyan), and the NHC official (black) forecasts are verified with best track.
Figure 3.22: Minimum Sea-Level Pressure (mb) forecasts and their mean error over the DA and forecast period. The 12-km 4DVar (blue), 4-km 4DVar (green) and 4-km vortex-BE 4DVar (red) and no-DA (cyan) forecasts are verified with best track.
Figure 3.23: Track forecasts and their mean error (in nm) over the DA and forecast period. The 12-km 4DVar (blue), 4-km 4DVar (green), 4-km vortex-BE 4DVar (red), no-DA (cyan), and the NHC official (black) forecasts are verified with best track.

The model surface level (10-m) wind speed maps are also included in Fig. 3.24. It is evident that the control forecast is the strongest with MWS of 53.1 ms\(^{-1}\). The vortex-BE 4DVar analysis simulates the weakest storm in comparison with the other
simulations, with an intensity of 48.9 m\textpersecond, similar to H*Wind estimates and with a \(\sim 5\) m\textpersecond difference to the official estimate of 46.4 m\textpersecond. In comparison to H*Wind, it appears that all the models have some of the asymmetry.

At this point in the study, surface data from the SFMR is also available for model verification. The SW-NE cross-section of 10-m wind speed is revealed in Fig. 3.25. The SFMR still shows some signal of the inner wind maximum in the NE side, which all the models have already dissipated. The H*Wind cross-section is included to demonstrate its error in comparison with the observed storm. Differences of over 10 m\textpersecond are evident. Nevertheless, it is important to recall that the SFMR data is not exempt of errors.

Figure 3.24: Surface Level (10-m) wind speed map (m\textpersecond). On top: H*Wind analysis and Control forecast. Bottom: 12-km, 4-km non-vortex BE, and 4-km vortex-BE 4DVar forecasts. The diagonal line represents the SW-NE cross-line. The forecasts are valid at 0400 UTC and the H*Wind analysis valid at 0430 UTC September 12.
Figure 3.25: SW-NE Surface level (10-m) cross-section of wind speed (ms\(^{-1}\)) for the control (cyan), 12-km non-vortex BE 4DVar (green), 4-km non-vortex BE 4DVar (blue), and 4-km vortex BE 4DVar (red), verified against SFMR observations (black); valid at 0400 UTC Sep 12, and compared with H*Wind analysis (dashed-black).

The second verification is selected 13-h later, at 1700 UTC September 12. The storm’s MWS has increased to 90 kt (46.4 ms\(^{-1}\)) (official NHC report valid at 1800 UTC). By this time, the inner-core maximum is no longer a dominant feature of Ike. Instead, the asymmetry of the storm has a great impact on how the storm evolves during this stage. The H*Wind surface wind speed map in Fig. 3.26 reveals the strong east-west asymmetry.

It is also shown that the model forecasts captured this large-scale asymmetry. The SW-NE-cross-section plot (Fig 3.27) shows the asymmetry and the large improvement made from increasing the resolution from 12-km to 4-km and using the vortex specific BE. It should be noted that all the models seem to have a stronger storm with a smaller eyewall on the NE side.
Figure 3.26: Similar to Fig. 3.24 but the forecasts models are valid at 1700 UTC and the H*Wind analysis is valid at 1630 UTC September 12.

Figure 3.27: Similar to Fig. 3.25 but for SFMR and model valid at 1700 UTC Sept 12 and H* Wind analysis valid at 1630 UTC.
In summary, the MWS verification revealed that the new 4DVar experiments are more accurate when compared with NHC best-track estimates. However, these impacts are eroded after 24-h of forecast. In terms of structure, it was previously discussed that the initial double wind maximum of the DA storms likely prevented early intensification closer to the observed storm. However, the results in this section showed that eventually all the model simulations lost this feature. Therefore, this can be one of the reasons why all the 4DVar experiments over intensified the storm during the period of September 12-13 (24-42 h of forecast) (Fig. 3.21). As the inner-core maximum collapsed, its impact on the dynamics of the storm was replaced by the large-scale asymmetry.

### 3.4 Summary

In this chapter, results of the Hurricane Ike experiment were presented. Both data assimilation and forecasts phases were investigated. It was clearly shown that increasing the horizontal resolution from 12-km to 4-km in 4DVar made the larger impact improving data assimilation analysis of the inner eyewall of the storm. While the newly generated vortex-specific background covariance used in 4DVar made a small contribution to the analysis; it helped to remove some unrealistic features shown by the non-vortex BE case in cycle-2. Further, assimilation of inner core data had a positive impact on the short-term forecasts; however, the smaller scale features were not maintained after few hours within each 12-h period.

The adjustment in the initial condition state due to increasing resolution and including a vortex BE in DA made the intensity (MWS) forecast to be in better agreement to best-track estimates, at least for ~24-h. The control forecast in which no DA was included did not develop an inner-core structure, the MWS were stronger and its
trend was different than the observed storm. Verification of surface wind speed field and cross-sections showed that the asymmetry was well maintained by the all 4DVar models, however the new higher-resolution DA experiments showed an evident improvement over the 12-km 4DVar case.
The second experiment of this study was conducted on Earl in 2010, another major hurricane. As previously discussed, the motivations of choosing Earl was to examine how high-resolution data assimilation impact a tropical storm that rapidly intensified with a hurricane near steady-state intensity such as Ike. Furthermore, because this particular storm was well sampled by the NOAA aircraft, it provided valuable inner-core ADR wind speed data to analyze. Earl was sampled during its entire lifecycle: tropical storm, the RI phase and eventually when it became a major hurricane. Based on the inner-core data availability, data assimilation becomes a useful tool to analyze how continuous DA events impact the hurricane inner-core structure at different stages.

4.1 4DVar data assimilation and forecast cycles

As described in the methodology chapter, this experiment also included two phases: the DA phase and forecast phase. In the DA part we continuously assimilated ADR wind speed data in an 84-h period from August 28 to September 1st 2010. A total of 10 cycles are analyzed within this period. After each data assimilation cycle, short forecasts are performed from one cycle to the other cycle. The forecast phase, which includes the extended forecasts are conducted every 12-h starting from 0000 UTC 29 August to 0000 UTC September 4. Figure 4.1 shows a time-line diagram to illustrate the sequence of the experiment. Each DA cycle is marked chronologically from the first event on 2100 UTC 28 August (cycle-1) to the last event at 1100 UTC 1 September (cycle-10).
The results are organized as follows: (1) we compare the intensity and track forecasts initialized from the resulting 4DVar analysis versus the forecasts initialized with no data assimilation (no-DA). The purpose of this section is to give the reader the general idea and the overall results of the impact of having a continuous DA technique. (2) Discuss and investigate how each DA cycle continuously impact the initial condition inner-core structure that subsequently results in improving the hurricane intensity forecast.

**Time evolution for the Data Assimilation and Forecast Period**

Figure 4.1: Time-line diagram for the DA cycling and forecast phases. Extended forecasts were performed each 0000 UTC and 1200 UTC from Aug 29 to Sep 1st.
4.2 Evaluation of the intensity, track and storm structure forecasts.

This section introduces the overall impact of having continuous DA cycles correcting Hurricane Earl’s initial condition. First, we verify the intensity and track forecast against the NHC best track estimates. The resulting 4DVar analyses were used as the initial conditions and potentially represent—as much as possible—the true state. The extended forecasts were performed every 0000 UTC and 1200 UTC times (Figs. 4.2-4.6). The plots also include the no-DA forecasts initialized at the same times. These are just the WRF model simulations with GFS global initial and boundary conditions and without ADR data assimilation. The control experiment in this study is referred to as the first WRF forecast initialized on August 28 at 0000 UTC that served as the first-guess/background field of the first DA cycle.

To evaluate the accuracy of the intensity forecasts (Figs. 4.2-4.5), we first need to analyze how the models performed for the initial condition and then for the rest of the forecast period. Figures 4.2 and 4.3 includes each forecast in separate panels to better compare the impact of DA vs. no-DA. In terms of the initial conditions, the 4DVar analyses are closer to the observed storm than the no-DA for all simulations. In contrast, the initial conditions of the no-DA forecasts that came from GFS were always weaker, far from the reality. However, it was clear that the model tried to correct this issue and tried to intensify the storm. The resulting intensity forecasts from the DA simulations show an overall improvement that matches the best track, especially the one initialized at 0000 UTC August 31st. The error of the forecasts were calculated to verify this statement, but will be discussed in the following paragraph. In the summary figures (4.4 and 4.5) is evident that for most of the cases the 4DVar also improved the first-guess (or earlier
forecast) estimates. However, for some cases, such as at 1200 UTC August 30, the 4DVar did not correct the maximum wind speed (Fig. 4.2e), but it improved the minimum sea level pressure (Fig. 4.3e). Another particular result was found for the 4DVar forecast initialized at 0000 UTC August 31st (Fig. 4.2f). At this time, the 4DVar improved the maximum surface winds but missed the minimum pressure in comparison with the best track (Fig. 4.3f). The initial condition for MWS matched almost perfectly the best track and remained close for most of the forecast times. However, in terms of MSLP, the initial condition and the trend of the 4DVar simulation indicate a stronger storm than the one observed. The 4DVar initial condition for MSLP is lower than best track and remained lower for most of the forecast times. This result reveals an important piece of the TC research area that has not been considered: the wind-pressure relationship, which relates the minimum sea level pressure and the maximum surface wind in tropical cyclones. The results found in this study, suggest that the wind-pressure relationship of the model is different than the NHC best track estimates. It is known is that this relationship is also function of the storm size. The results presented in Fig. 4.8 imply that the model produced a smaller storm with smaller radius of maximum winds (RMW) values in comparison with the observed size from best track. This is consistent with the fact that the model simulated a small and a tight eyewall during the period where the storm was very strong (August 31-September 2). As a result, the model estimated lower MSLP. To test this statement and how each DA impacts the forecast of Earl, we need to verify not just the intensity but also the storm structure. Nevertheless, the results indicates that the forecasts initialized from assimilating ADR wind data are better able to predict the intensity of the storm than the no-DA simulations. As expected, no significant
improvement in the track forecast is found by assimilating inner-core wind data only (Fig. 4.6).

Figure 4.2: Maximum wind speed (kt) forecast over the DA cycling period from 0000 UTC August 28 to 0000 UTC September 2, 2010. Each panel represents the forecasts initialized every 12-h: (a) 28-00 UTC, (b) 29-00, (c) 29-12, (d) 30-00, (e) 30-12, (f) 31-00, (g) 01-12 UTC. The no-DA (dashed lines) forecasts are initialized at same times as the DA (solid lines) forecasts.
Figure 4.3: Similar to Fig. 4.2 but for Minimum Sea-Level Pressure (mb) forecasts.
Figure 4.4: Summary of the maximum wind speed (kt) forecasts over the DA cycling period. The no-DA (dashed lines) forecasts are initialized at same times as the DA (solid lines) forecasts. The initial conditions are marked with a dot.

Figure 4.5: Similar to Fig. 4.4 but for Minimum Sea-Level Pressure (mb) forecasts.
In order to quantify the accuracy of the 4DVar and the no-DA forecasts, we calculated the intensity (MWS and MSLP) and track errors of each forecast. The next step was to construct a composite by taking their average based on the forecast hours (Fig. 4.7). The results demonstrate that the 4DVar reduced the initial condition error to less than 10 kt for the MWS. In contrast, the no-DA initial condition error is found to be around 30 kt. It should be noted that the initial condition for the no-DA forecast comes from a GFS global model analysis field, which consistently simulated a weaker storm. The deficiencies of the GFS initial vortex can be attributed to the coarse resolution of 12-km and the large initial vortex. However, the WRF model was then able to reduce this error during succeeding forecasts. Overall, the figures show that the intensity errors in the 4DVar forecasts are smaller in comparison with the no-DA forecast errors. In addition to these two experiments, the NHC official forecasts of MWS and track were also evaluated against the best track. It is clear that for the first 12-h of forecast, the NHC official forecast for MWS has the smaller error, but then is found to be similar or larger than the
4DVar forecasts. The results demonstrate that after 72-h of forecasts the NHC official forecast for both intensity and track are similar or worse than both model (4DVar and no-DA) forecasts. On average, the 4DVar forecast has the smaller error for MWS with 10.7 kt, than the NHC forecast with 11.7 kt and the no-DA error with 15.2 kt. For the MSLP total error the 4DVar still has the lower error with 8.0 mb, in comparison with the 13.5 mb from the no-DA. The track forecast error, however, shows that the 4DVar and no-DA errors are analogous. This supports the fact that the track is not significantly affected when assimilating only inner-core data with the DA method used in this study. The total average for both experiments are approximately 65 nm.
Figure 4.7: Mean forecast error for the intensity (MWS and MSLP) and track for 4DVar (red), no-DA (blue) and the NHC official forecasts (black).

As stated previously, to better evaluate the model’s performance of Hurricane Earl, the analysis of its structure must be included in the verification process. The purpose is to understand how the numerical model predicts the magnitude and distribution of the surface wind field. The radius of maximum winds (RMW), and the 34-kt and 64-kt wind radii are calculated from the models and compared with the best track estimates. Figures 4.8 and 4.9 illustrates each 4DVar and no-DA model forecasts values for the three parameters. The RMW analysis shows that in general the 4DVar clearly improves the location of the maximum winds. The 4DVar initial conditions corrected the RMW in all the forecasts. However, despite the improvement of the 4DVar at initial time, the tendency of the model to reduce the RMW is evident. The fact that the value remains smaller suggests that the model prefers a specific value for the RMW. There are several reasons why the WRF model prefers those levels. Such reasons are beyond the scope of this study.
Figure 4.8: Radius of Maximum Wind (nm) as a function of forecast time for Best Track, no-DA (dashed lines) and 4DVar (solid lines) simulations.

The next step is to evaluate the impact of the ADR wind data assimilation on the location of the radius of tropical cyclone and hurricane winds. Figure 4.9 presents the 34- and 64-kt wind radii from the 4DVar and no-DA forecasts. Overall, the results are consistently indicating that the impacts of assimilating ADR wind observations in these parameters are limited. There is no large difference between the 4DVar and no-DA simulations, especially in the 34-kt wind radii. This is an expected result, given that this study only considers the inner-core data.
To investigate the impact of the model forecast on the vortex structure, the time-radius Hovmöllers diagram of the axisymmetric 3-km level tangential wind is analyzed and shown in Fig. 4.10. The black line in the panels indicates the estimated RMW values for the simulations. The ADR derived Hovmöllers are compared with the no-DA and 4DVar forecasts initialized every 12-h from 0000 UTC August 29 to 1200 UTC August 30. It is important to notice that the ADR Hovmöllers panels are constructed using the observation sets, however, since the data is sparse in time it needs to be smoothed. Nevertheless, observations clearly show the evolution of the size and intensity of Hurricane Earl. The early evolution was more complex, then the storm rapidly intensified and the size of the eyewall was reduced. In general, the plots reveal that the 4DVar initialized storm fit very close to the observations. For most of the times, the no-DA predicted a weaker storm with a broader eyewall due to the lack of inner-core assimilation in the initial conditions. The 4DVar forecasts show a large improvement in
both initial conditions and in the evolution of the storm. This is evident in the forecast initialized at 1200 UTC August 31\textsuperscript{st} (Fig. 4.10d), where the 4DVar is better able to maintain the inner-core structure. Also noted is that the impact of 4DVar in the outer winds is reduced. This result is expected because only inner-core data is assimilated in this study. Overall, there is no large difference between the no-DA and 4DVar forecast for this region. This analysis shows the importance of capturing the dynamical features seen in the 4DVar versus No-DA wind field and how it translates into the forecast. Furthermore, this suggests that the combination of inner-core data assimilation and a good outer region estimates provided by the large-scale GFS model, would translate to a more accurate forecast.
Figure 4.10: Time-radius Hovmöller diagram of axisymmetric wind at 3-km level for the ADR, the no-DA and the 4DVar forecasts initialized at (a) 0000 UTC August 29, (b) 1200 UTC, (c) 0000 UTC August 30, and (d) 1200 UTC. The black lines in the forecasts are the estimates of the radius of maximum winds (RMW) using a 3-h smoother for visual purposes.

4.3 Data Assimilation Results

In the following sections the 4DVar cycles/analyses are described in order to understand how ADR wind data assimilation continuously influences the initial condition of the model. As previously discussed, these initial conditions showed positive results in the forecast of Hurricane Earl. It is important to note that the continuous 4DVar cycling is performed for a 1-h time window during the period of August 28 to September 1, 2010.

4.3.1 Analysis of the 3-km level wind field

A. Day-1: August 28, 2010

The first DA cycle (2100 UTC August 28) is chosen during the time Earl was a moderate tropical storm with peak winds of 28.2 ms\(^{-1}\) (55 kts) and minimum sea level
pressure of approximately 991 mb. Earl was located near the eastern Atlantic over sea surface temperature of 28°-29° C with light to moderate shear environment. This time corresponds to the first NOAA P-3 aircraft mission. The H*Wind surface wind analysis valid at 1930 UTC summarizes the structure of Earl 2-h before the first DA event (Fig. 4.11). The asymmetry can be attributed to the wind shear and storm motion (west-northwest).

![Figure 4.11: Surface (10-m) wind speed estimated by H*Wind analysis, valid at 1930 UTC Aug 28. Analyzed maximum winds: 29.3 ms$^{-1}$ (57 kt), NNW of the center.](image)

Figure 4.12 presents the 3-km level wind speed results for the first DA cycle. These include the first-guess, the two assimilated ADR data and the 4DVar analysis. For this cycle the first-guess is coming from the 21-h control forecast initialized at 0000 UTC August 28. It is evident that the first-guess captured Earl’s asymmetry, which is consistent with the ADR observations. There is a clear difference between the first-guess and the DA analysis. The 4DVar was able to better define the storm’s asymmetry. This is clear when the flight-level cross section analysis are plotted (Fig. 4.13). The cross sections for both the model and ADR winds are sampled along the flight leg (SW-NE). For reference, the models are also compared with the aircraft flight-level wind
observations. The figure reveals two main features: (1) a strong SW-NE asymmetry; and (2) evidence that the 4DVar analysis is closer to both observations. In terms of the asymmetry, the difference in wind speed (approximately 15 ms\(^{-1}\)) between the NE and SW quadrants is well defined. The results also show that the SW region of the eyewall from the 4DVar is much weaker and broader than the observations.

Figure: 4.12: 3-km Level Wind speed (ms\(^{-1}\)) and direction (black vectors) for the first-guess, the two ADR assimilated (a) 2100 and (b) 2155 UTC, and the 4DVar analysis at the Cycle-1: 2100 UTC August 28.

Figure 4.13: SW-NE Flight-Level (3-km) cross-section of wind speed (ms\(^{-1}\)) along the flight leg of the aircraft for control/FG (grey) and 4DVar (red). They are verified against the ADR (black) and NOAA flight level observations (grey), valid at 2100 UTC Aug 28.
B. Day-2: August 29, 2010

The 4DVar analysis served as the initial condition for the succeeding forecast. The forecast was used as the first-guess in the 2\textsuperscript{nd} DA cycle. This DA event (0900-1000 UTC August 29) is selected according to the second set of ADR observations (valid at 0900 and 0955 UTC). During that time the system became better organized and slightly intensified, but it was still a tropical storm. During a period of 51-h, Earl experienced rapid intensification (RI), increasing from a 55-kt TC to a 115-kt major hurricane in the 36-h between 0900 UTC August 29 and 2100 UTC August 30. The impact of the data assimilation in the analysis of Earl during this RI event is discussed in the following paragraphs.

The results from cycle-2 are shown in Figs. 4.14-4.15. The first-guess has a broader eye that is inconsistent with the observations, but the asymmetry is still present. It can be seen from the 4DVar analysis that the impact of DA for this cycle is small. The main difference between both simulations is that 4DVar slightly reduced the intensity of the winds in the north quadrant near the eyewall region. The flight level cross-section results (Fig. 4.15) confirm that for this cycle the DA inner-core impact—although small—was able to correct the outer wind structure observed by the ADR and flight level data.
Figure 4.14: Similar to 4.12 but for cycle-2: 0900-1000 UTC August 29. The two ADR assimilated are valid at (a) 0900 and (b) 0955 UTC.

Flight-Level Wind Speed N-S Cross-section valid at 09 UTC 29 Aug

Figure 4.15: Similar to Fig 4.13 but for control, FG (green) and 4DVar analyses valid at 0900 UTC August 29.

The next DA event is 2-h after the last cycle. This set includes the 1200 UTC and 1255 UTC ADR wind observations. The time coincides with the time when Earl was classified as hurricane. Observations from a reconnaissance aircraft indicate that Earl became a hurricane when centered about 220 n mi east of northern Leeward Islands. Figure 4.16 shows that the first-guess is weaker in comparison to the observations, but the 4DVar was able to correct this aspect. The cross-section plot (Fig. 4.17) clearly shows
that the 4DVar improved the wind speed structure, reduced the error introduced by the preceding forecast. Furthermore, the DA effectively suppressed the rapid early intensification as was seen in the control.

Figure 4.16: Similar to 4.12 but for cycle-3: 1200-1300 UTC August 29. The two ADR assimilated are valid at (a) 1200 and (b) 1255 UTC.

**Flight-Level Wind Speed SW-NE Cross-section valid at 12 UTC 29**

Figure 4.17: Similar to Fig 4.13 but for control, FG and 4DVar analyses valid at 1200 UTC August 29.
At this point Earl started to experience rapid intensification. The observations (ADR and flight-level) and the 4DVar seem to show that the peak wind speed is intensifying but as much larger radius than what the control run is estimating (Fig. 4.17). As previously mentioned, the RI event was well sampled and the following set of DA cycles clearly shows the evolution of the RI. The next two DA events include four sets of observations, two in each cycle valid for a period of 4-h from 2100 UTC August 29 to 0000 UTC August 30. The results of the two DA events performed at 2100 UTC (cycle-4) and 2300 UTC (cycle-5) are shown in Figs. 4.18-4.21. The main feature to notice is that the first-guesses maintain some of the inner-core structure. As new observations are assimilated, the first-guess is continuously improved, particularly modifying the size of the eye. This demonstrates that the 4DVar provided the correct analysis for the model to be able to maintain these features. The resulting 4DVar analyses show further improvements in inner-core wind maximum and eyewall structure. The 4DVar for cycle-5 (Fig. 4.20) shows that the stronger winds are located in the NE quadrant far off from the center, however, there is no evidence in this region with which this could be corroborated.

Figure 4.18: Similar to 4.12 but for cycle-4: 2100-2200 UTC August 29. The two ADR assimilated are valid at (a) 2100 and (b) 2155 UTC.
Figure 4.19: Similar to Fig 4.13 but for control, FG and 4DVar analyses valid at 2100 UTC August 29.

Figure 4.20: Similar to 4.12 but for cycle-5: 2300-2400 UTC August 29. The two ADR assimilated are valid at (a) 2300 and (b) 2355 UTC.
Figure 4.21: Similar to Fig 4.13 but for control, FG and 4DVar analyses valid at 2300 UTC August 29.

C. Day-3: August 30, 2010

By 1200 UTC September 30, Earl had intensified to a Category 3 hurricane with MWS of 105 kt (54.1 ms\(^{-1}\)) and MSLP at 965 mb. The strengthening of the vortex and development of the strong and small eyewall are clearly seen in the next set of observations. The results of cycles 6 and 7 (Figs. 4.22 and 4.25) are valid at 1100 UTC and 1200 UTC. They are consistent with the previous DA events’ results, in which the first-guess is able to maintain some of the inner-core features. At this point the 4DVar analyses helped to correct the intensity and further improve its structure. The cross-section verification analyses shows that the 4DVar fit very close to the ADR observations, while the control run again produces a stronger storm with a pretty tight eye (Figs. 4.23 and 4.25).
Figure 4.22: Similar to 4.12 but for cycle-6: 1100-1200 UTC August 30. The two ADR assimilated are valid at (a) 1100 and (b) 1155 UTC.

Flight-Level Wind Speed W-E Cross-section valid at 11 UTC 30 Aug

Figure 4.23: Similar to Fig 4.13 but for control, FG and 4DVar analyses valid at 1100 UTC August 30.
Figure 4.24: Similar to 4.12 but for cycle-7: 1200-1300 UTC August 30. The two ADR assimilated are valid at (a) 1200 and (b) 1255 UTC.

Figure 4.25: Similar to Fig 4.13 but for control, FG, and 4DVar analyses valid at 1200 UTC August 30.

Data from the reconnaissance aircraft indicated that Earl intensified by 40 kt over 24 h, becoming a Category 4 hurricane by 1800 UTC 30 August. The next set of ADR observation includes the period from 2100 UTC to 2300 UTC August 30. The results for cycle 8 and 9 are summarized in Figs. 4.26-4.29. The observation panels in Figs. 4.26 and 4.28 show a storm with a very small and tight eye and with large NE-SW asymmetry.
due to the interaction with the islands. The first-guesses suggest that the model is able to maintain some of the inner structure like the small eye feature. This is clear but expected in the cycle-9 first-guess, which is the 1-h forecast from the cycle-8 4DVar analysis. This is not the case for cycle-8 where it shows that during the intervening 9-h forecast (between 1200-2100 UTC), the model weakens the vortex and increases its size. Another interesting result of this cycle is that 4DVar produces an isolated region of weaker winds south of the center, near the small islands. However, no observations near this location can verify this feature. The results of the cross-section analyses are consistent with the results found in previous cycles: the 4DVar continues to improve the storm structure. This is evident even though the first-guess for cycle-9 slightly matches the observed wind structure. Also noted in these cycles is the fact that the control simulation slightly matches the observations. At this point Earl was a very strong storm, and it seemed that the control simulation was finally able to fairly match the observations.

Figure 4.26: Similar to 4.12 but for cycle-8: 2100-2200 UTC August 30. The two ADR assimilated are valid at (a) 2100 and (b) 2155 UTC.
Figure 4.27: Similar to Fig 4.13 but for control, FG and 4DVar analyses valid at 2100 UTC August 30.

Figure 4.28: Similar to 4.12 but for cycle-9: 2200-2300 UTC August 30. The two ADR assimilated are valid at (a) 2200 and (b) 2255 UTC.
Figure 4.29: Similar to Fig 4.13 but for control, FG and 4DVar analyses valid at 2200 UTC August 30.

**D. Day-4: September 1, 2010**

During the morning of September 1, a NOAA buoy (41046) reported that Earl had weakened a little. However, by the afternoon, the deep convection increased and the storm gained some symmetry; probably due to a decrease in shear. The last DA cycle is performed at 1100 UTC. The observations confirm that Earl became a little more symmetric in the N-S quadrant (Fig. 4.30). At this point the first-guess overestimates the wind speed near the eyewall region. The 4DVar helps to correct this feature and reduce the error. The cross-section analysis shows, however, that Earl E-W asymmetry is still a dominant feature (Fig. 4.31).
Figure 4.30: Similar to 4.12 but for cycle-10: 1100-1200 UTC September 1. The two ADR assimilated are valid at (a) 1100 and (b) 1155 UTC.

Figure 4.31: Similar to Fig 4.13 but for control, FG and 4DVar analyses valid at 1100 UTC September 1.

The trend seen thus far is that during each DA event, the inner-core maximum and structure is better defined and slightly maintained during the intervening forecast. To summarize the impact of a continuous DA cycles, we compare the cross-sections from the 4DVar, the first-guesses and the control to the flight-level observations by computing
mean absolute error of all the cross-sections. The resulting field is a function of the radius on each side of the storm. To quantify the overall error for each case, the mean of the resulting field is calculated. The results are shown in Fig 4.32. The 4DVar has the smallest error of the three, with values less than ~5 ms$^{-1}$. The first-guess error is slightly larger than 4DVar. The control simulation produces the larger error, which fluctuates between 5 ms$^{-1}$ and ~10 ms$^{-1}$. Overall, the results reveal that the 4DVar match the observations very well, especially the case during the second flight (1200 UTC August 29).

![Flight-Level Wind Speed Mean Errors](image)

Figure 4.32: Flight-Level (3-km) wind speed Mean Error of the cross-sections for control, first-guess and 4DVar (versus Flight-Level observations).

### 4.3.2 Surface wind speed analysis

In general, the 4DVar was able to correct the inner-core intensity and structure of Earl for most of the DA events. However, as indicated in the Fig 4.2, in terms of the surface winds, some of the 4DVar forecasts underestimated the peak intensity in comparison with best track. This was particularly evident during the RI event where the
storm intensified to approximately ~115-kt in a very short time period. Therefore, in order to better evaluate the performance of each simulation, it is necessary to verify not only the peak intensity but also the structure. The control, first-guess, and 4DVar analyses are compared with other surface observations, such as H*Wind, SFMR and dropsondes. A few cycles were selected—when data was available. Figure 4.33-4.44 shows the analyses of four DA events valid at 1100 UTC (cycle-6), 1200 UTC (cycle-7), 2100 UTC (cycle-8) and 2200 UTC (cycle-9) August 30.

The results for cycle-6 demonstrate that the 4DVar is slightly more intense than the H*Wind analysis (Fig. 4.33). However, the cross-section analysis shows that both first guess and 4DVar could not produce the actual peak intensity of ~50 ms⁻¹ (Fig. 4.34). The third verification method used in this section consisted of plotting the surface wind speed for the model and the observations as a function of the radius from the center of the storm. This is also referred to as wind scatter analysis. The results for cycle-6 simulations are shown in Fig. 4.35. These suggest that although the 4DVar missed the peak wind intensity estimated by the SFMR in the flight leg cross-section analysis, the 4DVar wind scatter analysis generally agrees with the SFMR and dropsondes. In contrast, the best track peak wind estimate is stronger than the other observations. This in turn implies that the best track is estimated from a different type/source of observations—at least for this cycle.

Overall, the results show that for the rest of the cases, the 4DVar produces a weaker storm in comparison to the observed storm. The 4DVar wind scatter plots fit better the H*Wind analysis in terms of the eyewall size but not as the intensity. The size of the eyewall from the SFMR was smaller. Outside the very inner-core region, the
4DVar seems to match better with the SFMR and the dropsondes. However, it should be noted that for the surface level analysis, only a few cases were studied due to the fact that only in limited cases was the SFMR data available and was representative of the real storm.

Figure 4.33: Surface Level (10-m) wind speed map (ms\(^{-1}\)) valid for the cycle-6: 1100 UTC August 30, for the First-Guess, H*Wind analysis and 4DVar analysis.

Figure 4.34: Surface Level wind speed cross-section valid at 1100 UTC Aug 30 for the control, first-guess, 4DVar, SFMR, and H*Wind analysis.

Figure 4.35: Wind speed as function of distance from the center of the storm valid at 1100 UTC Aug 30. Includes the 4DVar, H*Wind, SFMR, dropsondes, and best track peak winds.
Figure 4.36: Similar to Fig. 4.33 but valid for the cycle-7: 1200 UTC August 30.

Figure 4.37: Similar to Fig. 4.34 but for NE-SW cross-section for cycle-7 at 1200 UTC Aug 30.

Figure 4.38: Similar to Fig. 4.35 but for cycle-7 at 1200 UTC Aug 30.
Figure 4.39: Similar to Fig. 4.33 but valid for the cycle-8: 2100 UTC August 30.

Figure 4.40: Similar to Fig. 4.34 but for NE-SW cross-section for cycle-8 at 2100 UTC Aug 30.

Figure 4.41: Similar to Fig. 4.35 but for cycle-8 at 2100 UTC Aug 30.

Figure 4.42: Similar to Fig. 4.33 but valid for the cycle-9: 2200 UTC August 30.
A similar analysis of calculating the mean absolute error from the 4DVar, first-guess and control is performed, but now they are compared with the surface winds observed by SFMR. The results for the mean absolute errors are presented in Fig. 4.45. The main feature to notice is that, in contrast to the flight-level results, the errors near the inner core region (0-50 km) are larger, especially for the first-guess and 4DVar. For the same region the 4DVar error is significant and similar to the first-guess error. These values, along with the mean error values found in the flight-level analysis characterize the overall impact of assimilating ADR wind data in this study.
4.4 Analysis of the vertical structure, primary circulation and multivariate response to the assimilated wind data.

In this section we investigate (1) the impact of assimilating ADR 3D winds observations in the vertical structure; (2) the primary circulation; and (3) the 4DVar multivariate response. In order to analyze the vertical structure the vertical cross-sections are sampled along the flight legs. The primary circulation of the TC is examined from the azimuthal tangential wind field. For both verification methods, the control, first-guess (FG), and 4DVar are compared with ADR observations. These analyses will clearly show the evolution of the wind speed during the period of RI phase. The multivariate response is evaluated similar to the analyses performed on Hurricane Ike. This involved the azimuthal mean of the temperature anomaly. The temperature anomaly is height-radius dependent and shows the relative warmness (or coolness) of a point relative to the mean state at that level. The following figures present the resulting analyses for several DA events.
Figures 4.46 and 4.47 shows the results for cycle-3 (1200 UTC Aug 29), prior to the onset of the RI event. At this time Earl was a weak category one hurricane. It is noted that the center at 8-10 km is not collocated with the 0-2 km center during this time (Fig 4.46). The tilt of the vortex can be attributed to the light to moderate shear present in the storm’s environment. The 4DVar analysis is able to simulate this feature along with the clear signal of a primary and secondary eyewall evident in the ADR azimuthal tangential wind observations (Fig 4.47a). In terms of the temperature perturbation analysis shown in Fig. 4.47b, the warm-core for the FG and the 4DVar are weaker than the control. This is expected given the stage where Earl was at the time. The 4DVar develops the warm-core through a slightly deeper vertical layer than the FG’s.

Overall, the results show that 4DVar always improves the FG and fit the observations. Additionally, the 4DVar is able to recover the strengthening and deepening of the vortex and development of the eyewall revealed by the observations. These features are clearly seen in Figs. 4.48-4.51. The FG suggests that even after the 4DVar adjusted the vortex size to better match the observations, the model wants to broaden the vortex during the 10-h of forecast. As expected, the control experiment always overestimates the intensity of the storm.
Figure 4.46: Vertical cross-section of wind speed along the flight leg (SW-NE cross-section) of the aircraft for the experiments and ADR wind observation, valid for cycle-3: 1200 UTC Aug 29.
Shortly after this period, Earl experienced RI that agrees with the time where the vortex is aligned (Fig. 4.48-4.51). These processes highlight the potential importance of the vortex alignment in RI. The ADR observation for cycle-6 (1100 UTC Aug 30) clearly illustrates this aspect. Figures 4.48 and 4.49 show that the vortex from the FG is still tilted. The 4DVar is consistent with the previous results and is able to correct this, closely fitting the observations. The control simulation still produces a stronger storm with a broader eyewall. The temperature perturbation analysis shows a small difference between the FG and the 4DVar. Both analyses show the 8 K anomaly between 6-8 km levels. However, the warm core is a little deeper in the 4DVar estimate, which is consistent with the stronger winds near the eyewall region. This is also true for the cycle-8 results (Fig. 4.51b). The analyses presented suggest that in addition to the statement that the FG is
also able to maintain some of the inner-core structures, the warm core structure remains fairly conserved.

Figure 4.48: Same as Fig 4.46 but valid for cycle-6: 1100 UTC Aug 30, (W-E cross-section).
Figure 4.49: Same as Fig. 4.47 but valid at cycle-6: 1100 UTC Aug 30.

The last example is at cycle-8 valid at 2100 UTC Aug 30 (Fig. 4.50 and 4.51). At this time the ADR wind data reveals a very tight eye with the strengthening and deepening of the vortex. In general the results show that the 4DVar once again clearly improve these components of the TC structure that resulted in more accurate forecasts.
Figure 4.50: Same as Fig 4.46 but valid for cycle-8: 2100 UTC Aug 30, (NW-SE cross-section).
An alternative approach to verify the storm structure is to investigate the impact of assimilating ADR wind data on the storm precipitation structure. The model-derived reflectivity at the lowest model level is compared qualitatively with radar reflectivity measured by the NWS WSR-88D San Juan, PR Radar. This is done comparing the observation with the FG, the 4DVar, and with a short 4DVar forecast valid at 0000 UTC August 31. Figure 4.52 shows the observed reflectivity valid at 2200 UTC August 30 and 0000 UTC August 31 and the model derived reflectivity. The comparison reveals that the 4DVar analysis is the most accurate in predicting the structure and details of the inner core region seen in the observed radar panel. The arrows in the figure show some of the features seen in both 4DVar and observation but missed in the FG panel; details such as the high reflectivity region near the SE quadrant and the small eye structure. In terms of the forecast, the 4DVar shows some features that are also similar to the radar observation.
These results suggest that the inner-core wind structure obtained by assimilating wind translate to an improvement in the precipitation as well.

Figure 4.52: Model derived radar reflectivity and the estimated by the NWS WSR-88D San Juan Radar valid at 2200 UTC August 30 and 0000 UTC August 31, for the first-guess (FG) and 4DVar.

4.5 Summary

In this chapter, results from the Hurricane Earl experiment were described. The data assimilation and forecasts phases were studied with the methodology developed for Hurricane Ike. However, only one configuration for the 4DVar was investigated. This was using 4-km for the DA horizontal resolution and the newly generated static background error covariance that included the storm vortex information. Overall the results showed that having continuous DA events estimate better long-term intensity of the storm. The initial conditions were adjusted every 12-h for the period between August 28 to September 2. However, it is also shown that for the period when the storm was
under the RI event, it became harder for 4DVar to correct its intensity. Results from the intensity and MSLP errors analysis showed that the 4DVar always had smaller errors than the no-DA forecasts, with the exception at the 72-96-h forecast; however, by this time the adjustments introduced by the DA are considered negligible. The slight increase in the 4DVar error for the first 6-h of forecasts indicated that although the DA improved the initial condition, the model was not able to maintained and changed it. It is also noted that despite the fact that the no-DA forecast had a very large error at the initial condition, the model tried to reduce the error in the succeeding hours. The results from the track forecast simulations confirmed that this parameter is not largely affected when assimilating ADR inner-core observations using our methodology.

Verification of the TC structures showed that the 4DVar analysis continuously improved the inner-core structure since it was able to reproduce the inner-wind maximum seen in the observations. Additionally, the model tried to maintain the small eye and bordering eyewall during the intervening forecasts, at least for some of the cases. In general, the 4DVar was able to fit closely the structure of the surface winds observations, but for some DA cycles it was not able to capture the peak wind. Results from the vertical cross-section analysis showed the advantages of assimilating 3D winds in 4DVar since it was able to simulate the deepening of the vortex during the RI event thus, fitting the observed storm.
Chapter 5: CONCLUSIONS

5.1 Overall Conclusions

This study examines the impact of assimilating inner-core Airborne Doppler radar wind observations in hurricanes Ike (2008) and Earl (2010). The WRF-4DVar Data Assimilation system is used in this work. The analysis of Hurricane Ike includes the period of 2100 UTC September to 1200 UTC September 13. This experiment follows a previous study where both 3DVar and 4DVar techniques were analyzed. The results showed positive impact on initial representation of Ike’s inner-core structure. These corrections led to some improvements in the short-term intensity forecast. However, some limitations in this work prevented the results to be accurate as expected. For instance, the horizontal resolution of 12-km used in the DA system was relatively coarse. Hence, for the ADR observation to match this resolution, the 3-km data had to be thinned to 15-km. Another shortfall was the background error covariance used, in which no vortex information was included. The first part of this project focuses on these two aspects and how they can be improved to potentially produce better results using the 4DVar technique. The improvements are: (1) increasing the horizontal resolution of DA from 12-km to 4-km and (2) constructing a background error covariance more suitable for this high-resolution DA approach.

The first case study was on Hurricane Ike. It includes two parts: (1) the DA phase in which ADR $u$ and $v$ wind components are assimilated over a period of 23-h from 2300 UTC September 9 to 2200 UTC September 10, and (2) the extended forecast phase which starts after the last DA event until the 1200 UTC September 13. Overall the results
showed that increasing the horizontal resolution from 12-km to 4-km in 4DVar system made the larger impact improving the inner-core structure of Ike. This can be partially attributed to the fact that at this resolution the convective scales features can be better captured, especially a clear double eyewall region. The control experiment in which no ADR was assimilated could not develop the inner structure. In contrast, it was found that small impacts in the analyses were produced by the 4DVar that used the newly generated (vortex-specific) background error covariance. Both 4DVar showed comparable results. No further improvements were achieved by the 4DVar with vortex-specific BE, in part because the background error covariance was derived from an ensemble of Hurricane Earl. Hurricane Earl had a significantly different structure compared to Ike. The difference between these two storm might have impacted the BE file, and eventually the results.

The improvements introduced by both the 4-km and vortex specific 4DVar analysis to the initial condition helped to produce a more accurate long-term intensity forecast (Figs. 3.21-3.22). The intensity (MWS) and track mean error analysis showed that these two experiments on average were more accurate for a longer time than the 12-km 4DVar. However, in terms of the pressure field, the 12-km 4DVar was more accurate than the other two simulations. This initial pressure difference between the models was shown to grow during the forecasts and the 12-km 4DVar storm developed a lower central pressure during the first 24-36 h of forecast, which was closer to the observed value. The results also showed that all models did not maintain the double wind maxima for a longer time. This double wind maximum observed in Ike prevented the outer winds
to contract and hence, to intensity as much as the models suggested. The control intensity forecast overestimated the storm intensity for the entire period.

It is important to mention that the intensity of Hurricane Ike was very difficult to predict. Most of the operational models failed to forecast the correct values, because they were not able to capture the double eyewall feature. The efforts made by using the 4DVar approach to better represent the observed storm were limited because of the complexity of this storm.

To validate the methodology used in the first part of this study, a second case study is evaluated. The selected case was Hurricane Earl (2010). In comparison to Ike, this storm had a very different inner-structure, such as not producing the long lasting double inner wind maximum structure. Additionally, Earl was a storm well sampled by the NOAA aircraft, providing excellent information about the inner structure. In this experiment only one 4DVar method was performed. In the experiment, we used the higher-resolution of 4-km in the DA domain and the newly generated and appropriate static background error covariance. A total of 10 DA cycles were performed for the period of August 28 to September 2. The purpose of this experiment was to investigate whether a continuous DA improves the inner-core structure and to determine the impact on the intensity forecast of the storm versus the forecast without any DA. The analyses obtained from the 4DVar served as initial condition for the forecasts that were initialized every 12 hours for the same period. These experiments were compared with a control forecast initialized at 0000 UTC Aug. 28 and with the no-DA forecasts each initialized at the same times as the 4DVar.
Results over the DA phase showed that the continuous DA cycles estimated better the long-term intensity of the storm, both MWS and MSLP parameters. This is consistent with the results found in the experiments on Hurricane Ike. The MWS and MSLP from the 4DVars were more accurate than the no-DA forecasts. However, the no-DA forecasts were able to produce the rapid intensification signal although the timing and intensity were not correct. These results suggest that the environment in Earl was already conducive for rapid intensification. Additionally, as the storm became more intense, more difficult was for 4DVar to capture the peak wind parameter. In terms of model error, the results revealed that the forecasts initialized with 4DVar analyses had a smaller error in the intensity comparison to the no-DA forecasts. It should be noted, however, that the errors in the no-DA forecast were largely reduced in the first 12 hours of forecast. The track error analysis shows that the assimilation of inner-core data does not largely affect the track forecast. Both experiments show similar errors, which is consistent with the results found in Ike experiment.

Verification of the storm structure revealed that the 4DVar continuously improved the inner-core structure, since it was able to produce the strengthening and deepening of the vortex and developing the observed eyewall at different stages. In contrast, the control forecast was not able to produce this structure. Results of the flight-level cross-section mean error demonstrated that on average the 4DVar error is very small (less than 5 ms\(^{-1}\)) while that in the control experiment exceeded 6 ms\(^{-1}\). This clearly verifies the advantages of assimilating inner-core wind data using 4DVar. The results of the surface wind structure error showed that the errors were slightly larger than the ones found in the flight-level analysis. The higher error in the 4DVar was found in the inner-core region
where the maximum winds are generally located. Although, this implies that for some cases the 4DVar was not able to capture the peak wind estimated by the SFMR or the best track, the verification of the structure demonstrated that the wind field structure was well represented. The ability of the 4DVar to represent some of the dynamical features of these storms demonstrated the advantage of assimilating inner-core high-resolution data, but also exposed the importance of having a good estimate of the outer region field. Another parameter that was not investigated in this study is the calculation of Integrated Kinetic Energy (IKE) (Powell and Reinhold, 2007). This analysis would provide an additional forecast verification method to better measure the destructive power of a storm considering how strong the winds are and the spatial coverage of these winds.

5.2 Weaknesses and Possible Improvements

As reviewed in the methodology chapter, data assimilation effectiveness also depends on how the background error covariance is represented. In this research, the background error covariance was calculated based on the TC storm-scale and storm-relative domain from an actual hurricane forecast. These have been considered very important features in order to have an appropriate BE covariance matrix (Gordon, 2011). The covariance matrix was computed using an ensemble of forecasts from Hurricane Earl (2010). Due to the limitation in the computational resources, a total of 10 ensemble members, for a 5-days forecast were used in the experiment. It is recognized that the amount of ensemble forecast used here might be small and an increase of the ensembles members could result in a better error statistics. Another approach to address this issue is
the hybrid variational/ensemble data assimilation technique because it does not demand a large ensemble size.

The background error covariance structure determines the propagation of observational information in the 4DVar analysis. The correlation length scale is often tuned in inner-core data assimilation. Analogous to the previous study (Gordon, 2011) the length scales for the newly calculated static background error covariance had to be tuned by a factor of 0.15 in order to get balanced and representative looking structures like an appropriate inner-wind maximum and a compact vortex structure. Although we do not know what the exact tuning factors should be, the results for both experiments showed that the 4DVar was able to reproduce the inner-core features such as the wind field structure and the small eye. With the tuned BE covariance, improved analyses from Doppler radar data assimilations were demonstrated.

In addition to the ensemble size and the tuned BE, the newly generated (vortex-BE) covariance was used in both experiments, Ike and Earl. This could be an issue because Earl had significantly different structure compared with Ike. For example, unlike Ike, Earl was more symmetric storm and overall produced a single eyewall. These differences impacted the BE file and ultimately the results of Ike. As discussed in chapter 3, the impacts because of the vortex-BE covariance in Ike experiment were small. Therefore, an appropriate covariance matrix derived from Ike is needed in order to further understand the difference between the two approaches.

Another limitation in this research is the short time window in which DA is performed. Each 4DVar event was made over a 1-h time window. It is well known that the 4DVar scheme is able to adjust the increments dynamically over the time-window.
Therefore, a longer time-window would produce even more dynamically dependent analysis increments. In addition, this would allow assimilating more ADR observations within the same time-window. However, the temporal coverage of the observation needs to be appropriate. Earl is a good candidate to perform this experiment because there are three or more consecutive ADR observations for certain periods.

As introduced in the methodology section, the computational cost of the 4DVar process can be large. Therefore, the solution of the 4DVar was considered minimized when a specific maximum of inner-loop iteration has been performed. In this research, we selected 35 inner-loop iterations. It was found that some of the cycles did not reached 35 iterations, especially in Earl’s experiment. This is ideal; it means that the criteria of minimizing the gradient were accomplished. However, in some cycles the 4DVar routine did reach the limit of 35. Reaching 35 means more iterations are needed because the minimization did not attained the minimum. Regardless of the weaknesses of the 4DVar performed in this work, the results showed large improvements in both analyses and forecasts due to DA.

Further and more robust developments of the DA systems are necessary given the encouraging results in this study and could potentially produce better results. More research focused in implementing the model error and observation error, better techniques of calculating BE, and working in the physics of the tangential linear and adjoint model are needed in the DA system. Although this study did not explicitly show the impact of the model error in the simulations there were clear indications of the model error playing an important role in the results. This was found to be true during the DA phase of both experiments. Despite the large improvement in the inner-core structure
produced by the assimilation of ADR wind data, these features dissipated very quickly during the intervening forecasts, mainly during Ike. The first-guesses continuously showed that the small eye was lost with strong wind speed gradient near the RMW. There is a possibility that the model’s propensity of developing this type of wind distribution is an intrinsic bias. It was found that in the Earl experiment the model error also come in special attention. The RMW analyses illustrated the tendency of the model of reducing the RMW from the forecasts. This suggests that the model prefer a specific level for the distribution of the maximum winds in the storm. The reason why the model behaves in a particular mode is still unknown and is beyond the scope of this study. However, more effort should be invested in order to understand how this issue could be addressed. This will improve the benefit of the different DA systems on producing better initial conditions that results in more accurate long-range forecasts.
REFERENCES


Gustafsson, N. 2007: Discussion on ‘4D-Var or EnKF?’.* Tellus, 59A*, 774-777.


