2008

Superensemble Forecasts of Hurricane Track and Intensity Using a Suite of Mesoscale Models

Melanie A. Kramer

FLORIDA STATE UNIVERSITY

COLLEGE OF ARTS AND SCIENCES

SUPERENSEMBLE FORECASTS OF HURRICANE TRACK AND INTENSITY USING A SUITE OF MESOSCALE MODELS

By

MELANIE A. KRAMER

A Thesis submitted to the
Department of Meteorology
in partial fulfillment of the
requirements for the degree of
Master of Science

Degree Awarded:
Summer Semester, 2008

The members of the Committee approve the Thesis of Melanie A. Kramer defended on May 23, 2008.

T.N. Krishnamurti
Professor Directing Thesis

Robert Hart
Committee Member

Paul Ruscher
Committee Member

The Office of Graduate Studies has verified and approved the above named committee members.

ACKNOWLEDGEMENTS

I would like to acknowledge my major professor, Dr. T.N. Krishnamurti, for all of his instruction and guidance. The many meetings with my other committee members, Dr. Robert Hart and Dr. Paul Ruscher, provided new and beneficial insight into different aspects of this project, for which I am most grateful. Their comments helped me to learn a great deal about modeling and kept me interested in studying hurricanes. Thanks to the Krishnamurti lab, specifically Mrinal Biswas, Dr. Sandeep Pattnaik, Dr. Arindam Chakraborty, and Dr. Lydia Stefanova for the countless hours of instruction and assistance in this research process, for which I am greatly indebted. Thank you also to the many who have gone before me helping me in writing, formatting, and getting through. Lastly thank you to all who supported me and helped me to remember that science can and will always be fun.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AVHRR	Advanced Very High Resolution Radiometer
DSHP	Decay-Statistical Hurricane Intensity Prediction Scheme
EMC	Environmental Modeling Center
FSSE	Florida State Superensemble
FSU	Florida State University
GFDL	Geophysical Fluid Dynamics Laboratory model
GFS	Global Forecast System
GFSI	GFS interpolated 12 hours
HWRF	Hurricane Weather Research and Forecasting model
LBAR	Limited Area Sine Transformation Barotropic Model
MAE	Mean Absolute Error
MM5	Fifth-Generation NCAR/Penn State Mesoscale Model
MPI	Maximum Potential Intensity
MRF	Medium Range Forecast Scheme
NCEP	National Center for Environmental Prediction
NCEP FNL	NCEP Final Analysis
NHC	National Hurricane Center
NWP	Numerical Weather Prediction
OBSV	Observed or "Best Track"
OFCI	Official six-hourly interpolated model
PBL	Planetary Boundary Layer
PERS	Persistence model
POM	Princeton Ocean Model
RMS	Root Mean Square

RMSE	Root Mean Square Error
RRTM	Rapid Radiative Transfer Model
SAS	Simplified Arakawa Schubert
SHF5	SHIFOR intensity five day model
SHIFOR	Statistical Hurricane Intensity Forecast model
SHIPS	Statistical Hurricane Intensity Prediction Scheme
UTC	Universal Standard Time
WRF	Weather Research and Forecasting model
WRFA	Weather Research and Forecasting Advanced Research WRF model
WRF-ARW	Weather Research and Forecasting Advanced Research WRF model
WRFB	Weather Research and Forecasting model
WRFSI	WRF Standard Initialization
WSM6	WRF Single Moment 6-class microphysics scheme
YSU	Yonsei University PBL Scheme

ABSTRACT

The tropical cyclone superensemble has provided skillful forecasts for Atlantic tropical cyclone activity for several years. Until very recently, the tropical cyclone superensemble had only been run using a suite of large scale models. Using large scale models within the Florida State Superensemble produced noticeable improvement over each of the respective member models with respect to track and intensity forecasting. The more recent development of operational tropical cyclone mesoscale models led to the development of the mesoscale tropical cyclone Florida State Superensemble, which is utilized for this study. This study uses a combination of four different mesoscale models. One model is currently being run operationally for the National Hurricane Center and the other three models are in-house models run at Florida State University. This research includes most of the tropical cyclones that occurred during the 2004, 2005, and 2006 Atlantic hurricane seasons. There are twenty six storms available for study during that period and most storms have a 0000 UTC and 1200 UTC initialization. This provides the Florida State Superensemble with fifty-seven forecast cases. For each storm the Florida State Superensemble issues track, minimum sea level pressure, and maximum wind forecasts out to seventy-two hours at six hourly intervals. These tracks and intensities are compared to the "best track" analysis as determined by the National Hurricane Center. The results show that the tropical cyclone Florida State Superensemble can provide accurate forecasts when using a suite of mesoscale models, though increased work needs to go into improving the accuracy of the member models, which on average have slightly higher errors than the similarly run Florida State Superensemble with large scale member models. This study quantifies the errors of the Florida State Superensemble, ensemble mean, and the respective mesoscale models, compares them to the large scale models, and

examines several ways that the mesoscale tropical cyclone Florida State Superensemble can be enhanced for future work.

CHAPTER ONE

INTRODUCTION

1.1 Background and Thesis Objectives

There are many challenges involved in tropical cyclone forecasting. Large scale forecasting models have attempted to ease some of these challenges; yet, these forecasting models tend to miss some of the smaller scale features within the storm that are so crucial to understanding hurricane structure, track, and intensification mechanisms. Recently, much work has gone into combating these problems by developing finer resolution tropical cyclone mesoscale models, specifically the Geophysical Fluid Dynamics Laboratory (GFDL) model (Kurihara et al. 1993, 1995, 1998; Bender 1993, 2007) and the Hurricane Weather Research and Forecasting (HWRF) model (Surgi 2004, 2006). These higher resolution models have been fine tuned with advanced ocean/atmosphere coupling, improved physics packages, and more realistic vortex initialization. With these advancements HWRF and GFDL have shown to be able to better define and depict the evolution of a tropical cyclone in time along with the tropical cyclone structure's at those times, which has resulted in marked improvements in tropical cyclone forecasts for track and intensity.

Even with all of those advancements many times large errors still remain within a forecast. Tropical cyclones may traverse very erratic paths (Gordon in 1994). These storms may undergo rapid intensification (Wilma in 2005), rapid weakening (Lili in 2002), or maintain the same intensity for extended periods of time (Ophelia in 2005). Trying to forecast those types of situations has proven difficult and much more work still remains to be done to improve these forecasts. These improvements in forecasting tropical cyclones appear to be all the more necessary as more and more people living along the Atlantic coast rely on tropical cyclone forecasts during hurricane season.

The Florida State Superensemble (FSSE) model has shown notable improvement in tropical cyclone forecasting. Over the past several years, this model has issued forecasts superior to many other models, including the official National Hurricane Center (NHC), for both tropical cyclone track and intensity. FSSE forecasts have been made for the Atlantic Ocean, Western Pacific Ocean, and Eastern Pacific Ocean. Within the Atlantic Ocean FSSE forecasts have been made for real-time operational purposes; however, the work within the other two oceanic basins has primarily been confined to the research field, though FSSE forecasts are currently issued for the tropical cyclones in the Eastern Pacific Ocean. Continued work is being done to further improve the FSSE, by taking some of the more newly developed mesoscale models such as GFDL and HWRF and incorporating them into the FSSE framework, in the Atlantic Ocean, with the hope of seeing continued improvement to tropical cyclone forecasts. These improvements in the FSSE forecasts may then be utilized to improve the FSSE forecasts in other oceanic basins.

1.2 Previous Work

A great degree of research has been done on FSSE tropical cyclone forecasts using large scale models and the possible implications for real-time operational tropical cyclone forecasting. Williford (2002) performed some of the first work on tropical cyclone forecasting using the FSSE for the Atlantic basin for the 1998 to 2001 hurricane seasons and showed the FSSE was able to produce more accurate forecasts than other models used within it. Though he noted that there was still more work to be done with tropical cyclone intensity forecasting and suggested that the inclusion of mesoscale models into the FSSE in place of large scale models, may achieve better results for tropical cyclone intensity forecasting. Vijaya Kumar et al. (2003) helped to transition the FSSE from only being studied for Atlantic Ocean tropical cyclones to using it to forecast tropical cyclones in the Western Pacific Ocean. He applied the FSSE model to storms that developed within the Western Pacific basin for the years 1998, 1999, and 2000 and was able to show remarkable results for both tropical cyclone track and intensity forecasts with the FSSE having the lowest errors overall. This work demonstrated that the FSSE model could easily be used to forecast tropical cyclones in other basins and still consistently achieve more accurate results than the other models. Szymczak (2004) brought the FSSE research back into the Atlantic Basin using a slightly different version of the FSSE called the synthetic superensemble. The synthetic superensemble is different from the original FSSE in that the original FSSE uses a statistical linear regression technique of forecasts from various models to construct an optimal consensus forecast; the synthetic superensemble forecasts are generated by altering the original model track and that alteration is done by placing a best fit line through different model track forecasts and then perturbing those best fit lines with Fourier curves of varying harmonics producing several different tracks from one model (Szymczak 2004). The synthetic superensemble includes the synthetic and original versions of the models within it. This new version of the superensemble was run for tropical cyclones within the Canadian Maritime Provinces in 2001, 2002, and 2003 Atlantic hurricane season. Szymczak (2004) demonstrated that the synthetic superensemble can be another useful tool for making track forecasts, since it was consistently able to do better than the other models in that study. Jordan (2005) expanded the FSSE even further to study storms of the 2004 hurricane season occurring within the Eastern Pacific Ocean Basin. His work presented various methods for constructing a FSSE forecast by using a variety of training sets and testing which set would provide the most skillful track and intensity results. His results showed differing levels of accuracy within all the models, including the FSSE, depending on the training set used. His work emphasized that further research needs to be done to determine how to reduce the inconsistencies presented within the individual models and how to best construct an FSSE training dataset.

In addition to that research, much work has also been done to improve the models used within the FSSE, specifically with model initialization. Correct numerical model initialization has been shown to be key in producing a good forecast (Emanuel et al. 2004). It is difficult to have the correct model initialization with tropical cyclones because unless a vortex is inserted into the model at the initial time the model will need time to spin up the vortex. This spin-up time can be 12 hours or more, leading to large errors as the forecast extends out in time especially when the observed storm is very strong at the beginning of the forecast. Lord (1991) proposed the idea of vortex bogusing during the model initialization which involves inserting a vortex into the model to compensate for the model spin up problem. Kurihara et al. (1993) began employing that technique within the framework of the GFDL model with the initial results from that study showing great promise towards future use of the vortex bogusing technique for model initialization of tropical cyclones. This technique was refined several times within the GFDL model (Kurihara et al. 1995, Bender et al. 2007). The HWRF model (Surgi 2004, 2006) further improved upon the vortex bogusing technique used by GFDL, with the inclusion of Doppler radar data to help initialize the tropical cyclone structure. These changes in the HWRF model resulted in significant improvements to the tropical cyclone forecasts, especially the three dimensional model representation of the storm.

However, even with these model changes official intensity forecasts have shown little change in the amount of error over the last fifteen years (Franklin 2006) with Fig. 1.1 and 1.2 depict the changes of three models (OFCL, GFDI, FSSE) over the last ten years for intensity and track. There have been many attempts to reduce these errors, with the most promise currently being seen with statistical models. The Statistical Hurricane Intensity Prediction Scheme (SHIPS) developed in 1994 by DeMaria and Kaplan has aided in reducing these errors by the use of a standard multiple regression technique that includes various climatological, persistence, and synoptic predictors. Some of these predictors include the difference between the current tropical cyclone intensity and its maximum potential intensity (MPI), 200 hPa temperature, and the tropical cyclone intensity change over the last 12 hours. These predictors are used to help generate the regression equations utilized in making tropical cyclone forecasts for SHIPS. This model has shown potential for future forecast intensity error reduction but more work remains to be done with the model as sometimes large errors still remain in the model forecast. The SHIPS model will be further discussed in Chapter two. The quantification and removal of inherent systematic biases within a model is important to produce a downward shift in intensity errors. Earlier work using the FSSE has shown that removal of these biases results in a substantial error reduction that can be seen with both tropical cyclone track and intensity forecasts.

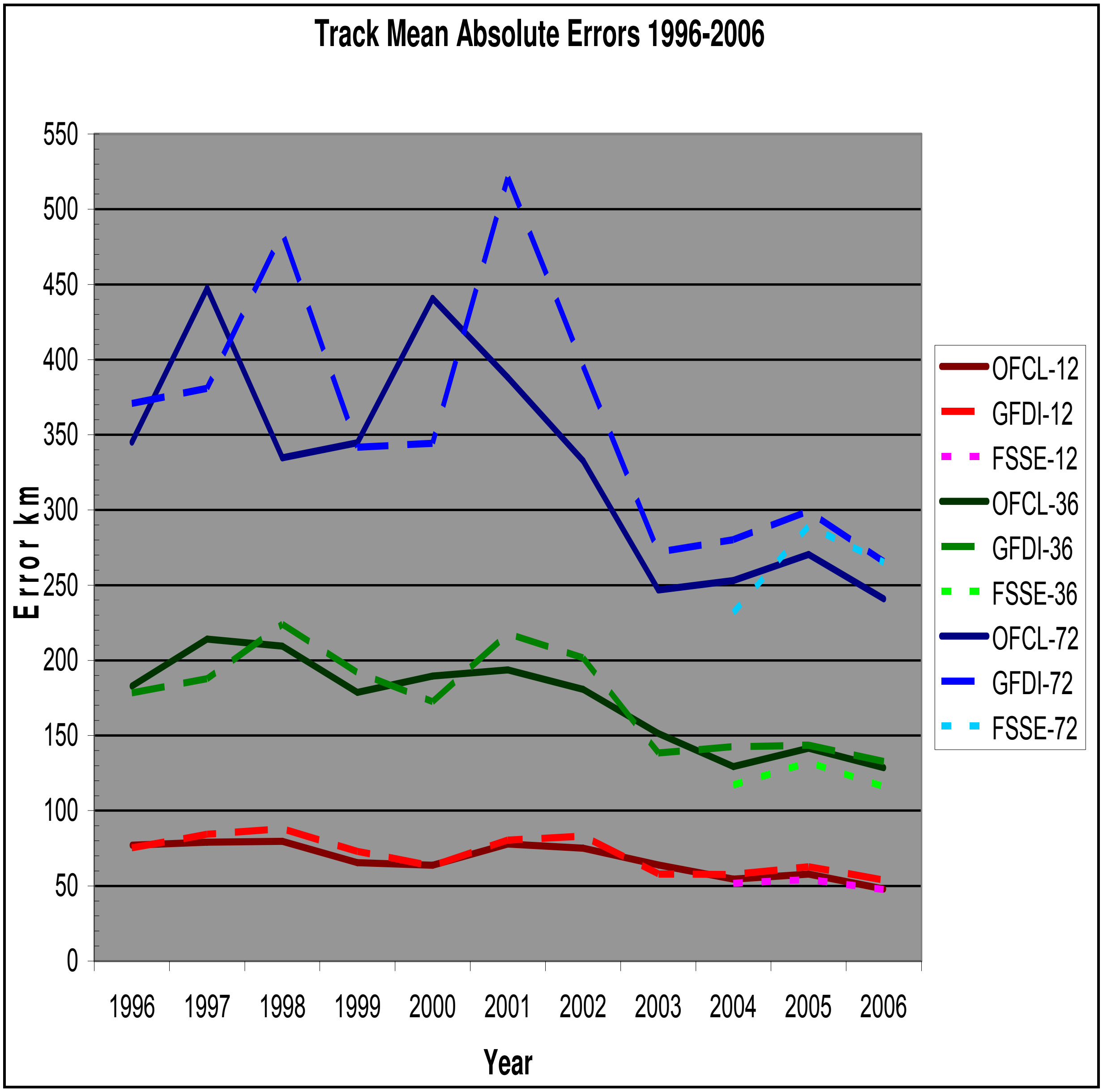

Figure 1.1 Track mean absolute errors, in kilometers, for 1996 to 2006 for the OFCL (solid, dark), GFDI (long dash, medium), and FSSE (short dash, light). The red group is the 12 hour errors; the green group is the 36 hour errors; and the blue group is the 72 hour errors. The FSSE information was only available starting in 2004. Courtesy of the National Hurricane Center.

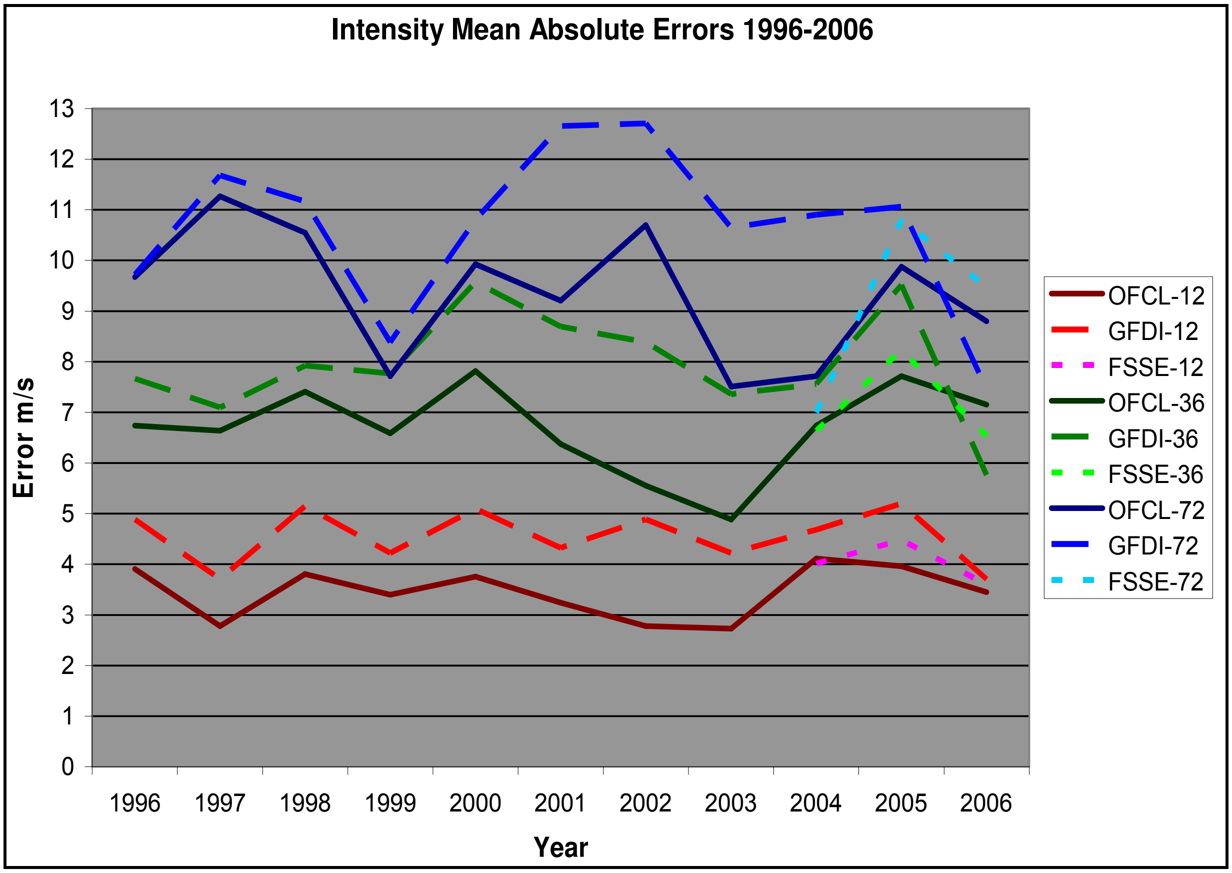

Figure 1.2 Maximum wind speed mean absolute errors, in ms^{-1}, for 1996 to 2006 for the OFCL (solid, dark), GFDI (long dash, medium), and FSSE (short dash, light). The red group is the 12 hour errors; the green group is the 36 hour errors; and the blue group is the 72 hour errors. The FSSE information was only available starting in 2004. Courtesy of the National Hurricane Center.

1.3 Organization of Thesis

Chapter two will present the history and description of the Florida State Superensemble, discuss the models used for this particular research, and describe the methodology used for this study. Chapter three will present and discuss error calculation methodology along with the overall errors averaged over all the years examined in this study. Chapter four will present and discuss the average errors for each year. Chapter five will present a brief synoptic discussion of some select storms from this study along with the errors associated with those storms. Chapter five will also present a comparison of overall errors for large scale models and mesoscale models. Conclusions and ideas for future work will follow in Chapter six.

CHAPTER TWO

SUPERENSEMBLE METHODOLOGY

2.1 History of the Florida State Superensemble

Goerss (2000) found that a simple ensemble of several models consistently performed better than each of the models within the ensemble. Each model within the simple ensemble was given an equal weight with poorer performing models received the same weight as the better performing models. A slightly different version of that simple ensemble is the bias corrected ensemble. The bias corrected ensemble removes the relative biases of each of the member models but still gives equal weights to all the models. Note that a member model simply refers to one of the models used in the ensemble. If a model typically had a $5ms^{-1}$ overestimation bias for the maximum surface wind speed, this bias would be removed in this new ensemble. The Florida State Superensemble was developed in 1998, by T.N. Krishnamurti as a tool for improving upon both the simple ensemble mean of models and the bias corrected ensemble. This model was different from both the simple ensemble and the bias corrected ensemble because the individual member models in addition to being bias corrected are not each assigned equal weights and are weighted according to their level of accuracy and reliability. This weighting tends to create forecasts that are shifted more toward the better performing models and away from the poorer performing models. Work done by Krishnamurti et al. (1999) solidified that idea by examining forecasts for precipitation, hurricane track and intensity, and 850 hPa winds. Those forecasts produced using the FSSE were shown to consistently be superior to both the ensemble mean and the individual models used within the FSSE.

With the success of this early work the superensemble was expanded to include global numerical weather prediction (NWP) for both precipitation and climate forecasting (Krishnamurti 2000a, 2000b). With respect to global precipitation, 850 hPa winds, and hurricane track and intensity forecasts from the 1998 season, the FSSE produced forecasts that showed considerably lower errors than both the ensemble mean and the other respective models. Williford et al. (2002 and 2003) expanded upon those 1998 hurricane forecasts to further refine the FSSE and help produce a model that could be run for real-time operational purposes.

After this extensive research, the FSSE began to be run using a real-time approach for the 1999 Atlantic hurricane season. The results from that season showed that the FSSE had notable skill over all of the other models. The track forecasts displayed some of the most error reduction especially later in the forecast, as shown by Fig. 2.1. The ability of the FSSE to consistently produce a forecast with lower overall

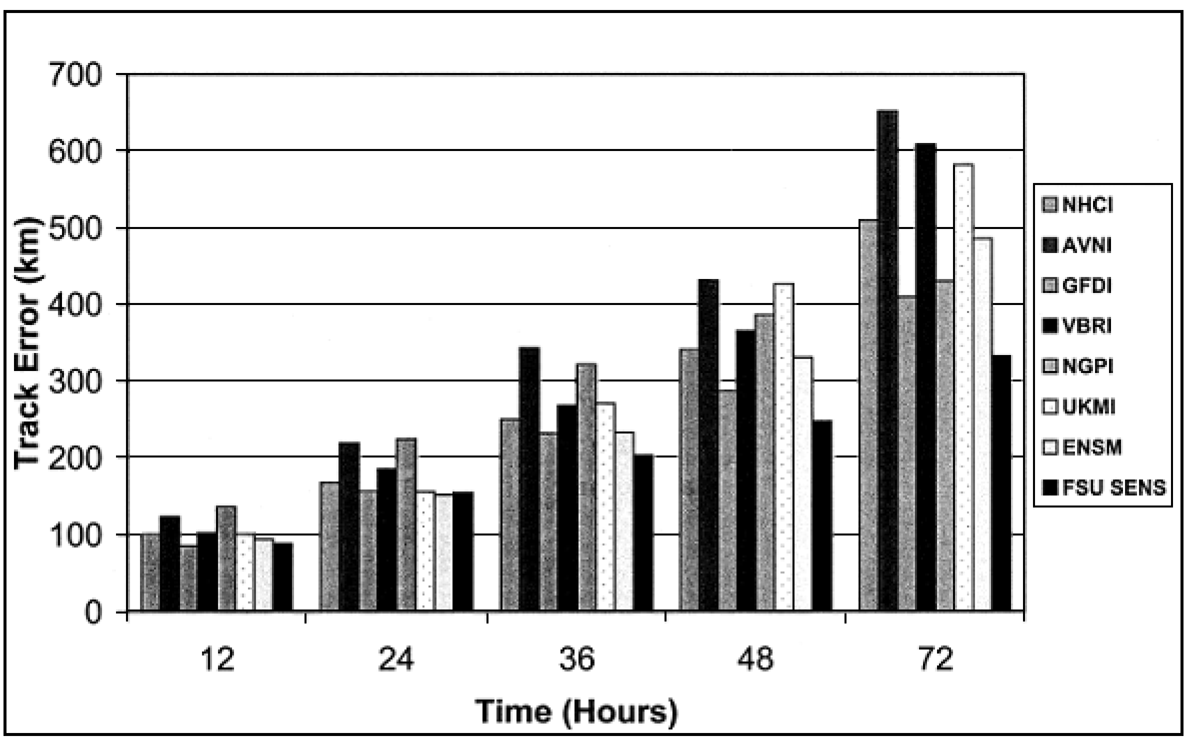

Figure 2.1 The magnitude of track errors, in kilometers, for the 1999 Atlantic Hurricane season, for the FSSE, as compared to the ensemble mean and the respective member models. For each time period on the right the columns correspond to the legend top to bottom. From Williford et al. (2003).

errors than the other models helped to transition this model from simply a research model to a real-time operationally run model, with it being run operationally for the National Hurricane Center in beginning in 2003.

2.2 Description of the Florida State Superensemble

The FSSE, as stated earlier, is an advancement upon a simple ensemble of models. A simple ensemble takes the average of all models for a given value with each model receiving the same weight as the other models.

$$\text{Ensemble}\,(t) = \sum_{i-i}^{n}\left(\frac{1}{n}F_i(t)\right) \tag{1}$$

F_i is the forecast value (e.g. temperature, maximum wind speed, longitude) for the i^{th} model, the summation of the forecast values is performed over all the available models one to n and then divided by the number of models within the ensemble. With this method the poorly performing models are given the same weight as the models that perform well. If one or two models model perform significantly worse than the other models the ensemble will reflect that, producing a more degraded forecast, than if those poorly performing models were not included in the ensemble.

A spin-off of this is the bias corrected ensemble forecast. The bias corrected ensemble technique is similar to ensemble but it is different in the sense that it attempts to correct for some of the bias within a model.

$$\text{Bias Corrected Ensemble}\,(t) = \sum_{i-i}^{n}\left(\frac{1}{n}(F_i(t) - \overline{F}_i)\right) \tag{2}$$

$\overline{F}_i$ is the average value for a particular model. For this research $\overline{F}_i$ and F_i are incremental values. They refer to the difference between a value at one forecast hour and a value at the successive forecast hour (e.g. difference between zero hour maximum wind speed and six hour maximum wind speed). Following that, $\overline{F}_i$ would be the average increment over a specified number of model cases. $\overline{F}_i$ is determined from a set of cases, in what is called a training set, further discussed in Section 2.5. From the training set the incremental values are examined for each case and averaged over the total number of cases within that training set. By performing this subtraction the bias correction is attempting to remove any of the systematic bias that remains within the model. Yet, like the simple ensemble, all the models are still given equal weighting.

The superensemble expands upon the bias corrected ensemble by weighting the different models.

$$S(t) = \overline{O} + \sum_{i=1}^{n} a_i (F_i(t) - \overline{F}_i) \quad (3)$$

S(t) is the superensemble incremental value for each forecast time. The $\overline{O}$ is the observed incremental value of the observed data over the entire training set. The a_i is the regression coefficient for each model (Williford 2002). These coefficients are calculated by using the multiple linear regression technique. The respective model forecasts are regressed to the observed state in an attempt to minimize the spread between the two. This minimization is achieved by using the minimization function J:

$$J = \sum_{t=0}^{\text{length}} (S(t) - O(t))^2 \quad (4)$$

$S(t)$ Is the value of the superensemble in time; and $O(t)$ is the value of observed in time. The length refers to the length of the training set (Williford 2002). This minimization is done using a matrix format and is represented by A • x = b such that:

$$\|b - Ax\|^2 \to 0 \quad (5)$$

Performing this calculation determines the different model coefficients, a_i, which will go into the superensemble shown in equation three (Williford 2002).

Each model is assigned a different coefficient with more reliable models normally having a higher coefficient others (Stefanova and Krishnamurti 2002). Based on the study done by Stefanova and Krishnamurti (2002) the smallest regression coefficients tend to correspond to the largest root mean square (RMS) errors and the largest regression coefficients tend to correspond to the smallest RMS errors. Thus, better performing models should receive higher coefficients than more poorly performing models. This is not always the case because sometimes some of the individual member models perform erratically, making the determination a proper regression coefficient difficult. In order for the coefficients to be representative of what is going on in the model forecast, the model behavior in the forecast phase must be consistent with the model behavior in the training phase. A representation of the generation of an FSSE forecast is shown in Fig 2.2.

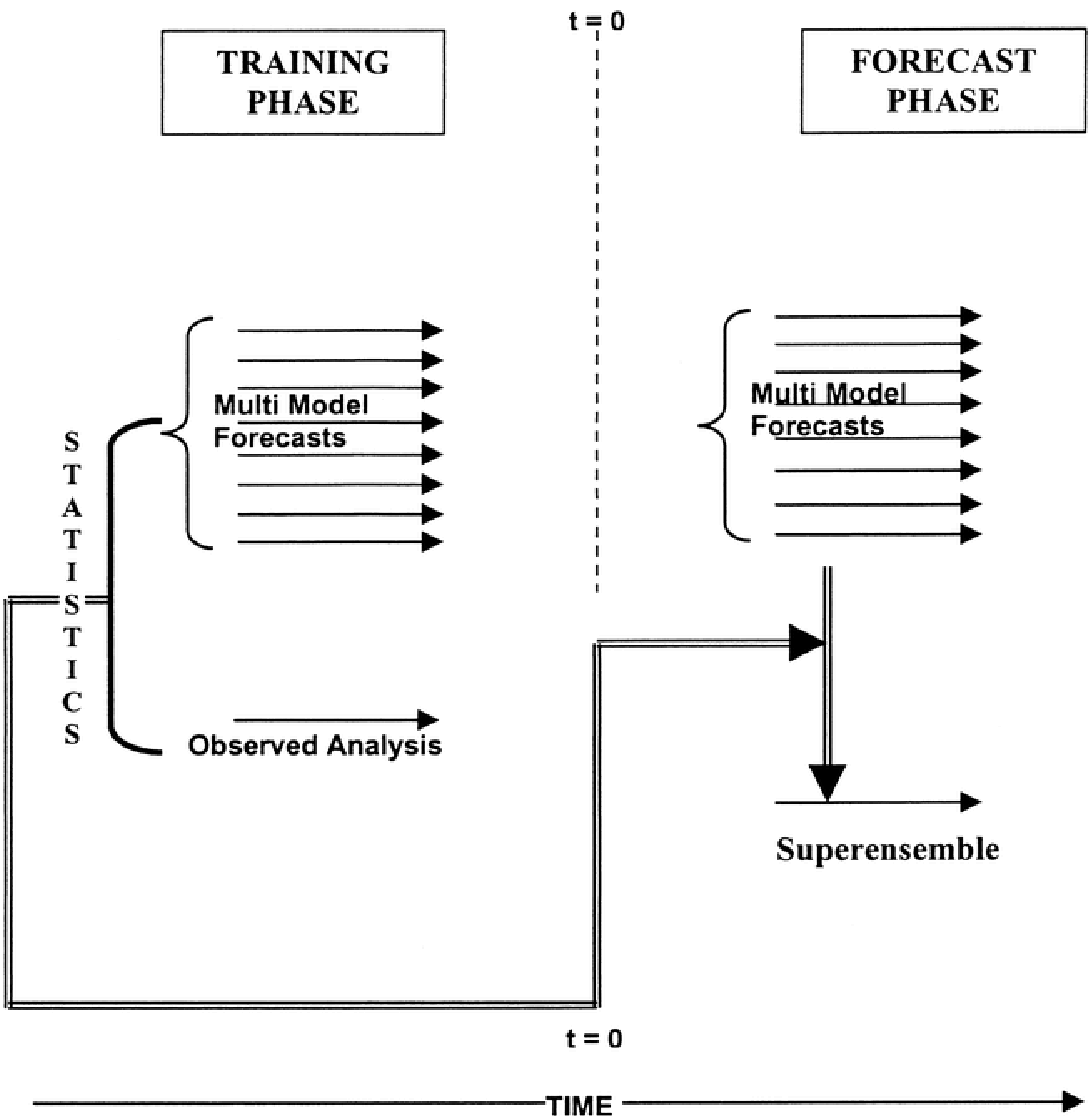

Figure 2.2 A schematic of a FSSE forecast in time, with the regression coefficients calculated in the training phase being applied to the generation of an FSSE forecast in the forecast phase. From Krishnamurti et al (2001).

2.3 Model Description

The version of the FSSE run for this research contains four mesoscale models and the official “best track” analysis. The official “best track” analysis is a post season analysis that is issued by the NHC for every tropical cyclone that forms within the season. This analysis includes the storm date, latitude and longitude positions, maximum sustained wind speed (in knots, converted to ms^{-1} for this study), and minimum central pressure (in hectopascals). This information is available for every six hours at 0000, 0600, 1200, 1800 UTC. This analysis differs somewhat from the initial advisories issued by the NHC in their real-time forecasts. Occasionally, in real-time, there may be multiple center fix positions and intensities given for storm at a one time from the different models and observations available making exact determination of the center and storm intensity difficult. Post-season reanalysis smoothes the positions and intensities by reexamining all the available data for each storm and creates a track and intensity profile that is more representative of the storm. Within this study the “best track” is assumed to be the observed position. To calculate the various regression coefficients and perform error analysis the individual models are compared to the observed (OBSV) data. In real-time operational use of the FSSE the real-time observed positions are used as the OBSV and the “best track” is not used.

There are four models that comprise the suite of mesoscale models used within the FSSE. Three of the models; the Weather Research and Forecasting Advanced Research WRF model (WRF-ARW, WRFA in this study), the Weather Research and Forecasting model (WRF, WRFB in this study), and the Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) were run at Florida State University (FSU), specifically for this study. The fourth model included in the suite of models, HWRF, was run at the National Center for Environmental Prediction (NCEP) specifically for research purposes. Two versions of the WRF model are chosen as that model is currently undergoing changes and improvements whereas the MM5 model is slowly becoming obsolete. To maintain continuity within each model the model parameters (e.g. physics options, model resolution, domain size, and other characteristics) are kept constant over the entire time of study. However, the initial conditions in the three FSU run models are not consistent from year to year. This was done because an important component of the FSSE is that a member model should not undergo any major model changes within its period of study (Williford 2002). That allows for more continuity in model behavior and the FSSE being better able to derive model behavior for the entire period of study.

The GFDL model, previously mentioned, was initially considered for inclusion in the suite of mesoscale models used for this research. However, preliminary examination of the GFDL data revealed large changes in model behavior from season to season. As the goal of this research is to keep the model parameters constant from season to season to allow for model continuity, the GFDL model was removed from the suite of mesoscale models.

2.3.1 WRFA:

The WRFA is a mesoscale model that was run at FSU. This model has a resolution of nine km with 31 vertical sigma levels. The resolution of this model, along with the other two FSU run models, was based on the resolution used in the HWRF model. The model was run at 0000 UTC and 1200 UTC for each storm in this study and produced three hourly output out to 72 hours. The model domain, for Hurricane Ivan 2004, covers a large portion of the Gulf of Mexico south into the Caribbean Sea and east into the Atlantic, as shown by Fig. 2.3. The domain for each storm varies in spatial extent and the size of the domain is determined by the smallest domain that will capture the entire 72 hour forecast of the storm used for that case. Thus one storm will have a different domain size and location than another storm. Issues with computational power and storage prevented the domain size from being large. This model has two schemes for radiation a longwave scheme and a shortwave scheme. The longwave scheme used the Rapid Radiative Transfer Model (RRTM) from Mlawer et al. (1997) which was found to be better for estimating downward longwave radiation at high latitudes (Iacono et al. 2000) which prior to that were typically underestimated (Wild et al. 2001). The shortwave radiation scheme run in the model was the Dudhia scheme (Dudhia 1989 and Grell et al. 1994). For surface physics this model used the Monin-Obukhov (Janjic) scheme (Monin and Obukhov 1954). The five layer thermal diffusion model was run for the land surface (Skamarock et al. 2005). The Mellor-Yamada-Janjic Turbulent Kinetic

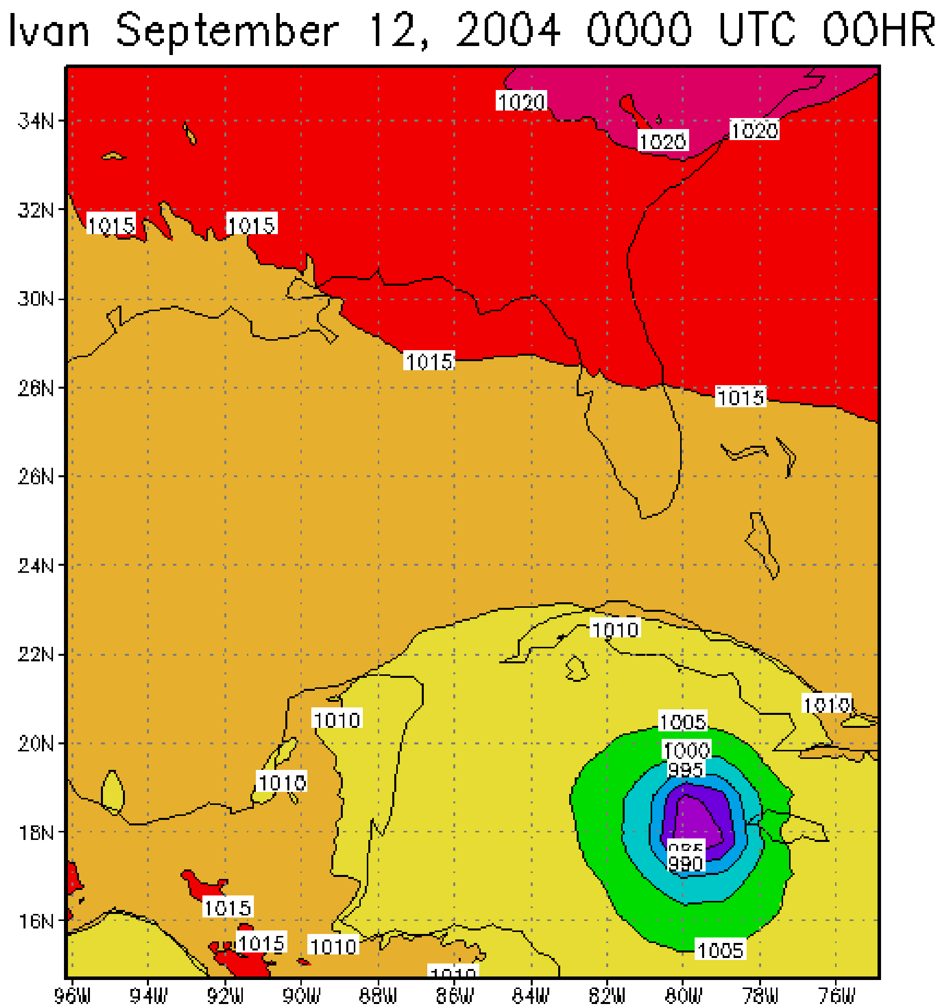

Figure 2.3 Model domain coverage of WRFA for Hurricane Ivan on September 12, 2004 at 0000 UTC 00 hr showing sea level pressure.

Energy Scheme, for local mixing, was used (Janjic 1994) to represent the planetary boundary layer (PBL). This scheme explicitly defines turbulent quantities using a conservation of turbulent kinetic energy (Misenis et al. 2006). There was a choice of several schemes to use for the implicit convection in the WRFA model; the Betts-Miller-Janjic scheme (Betts and Miller 1993 and Janjic 1994) was chosen due to its ability to better handle tropical convection within a tropical cyclone. This scheme also worked very well with the explicit moisture scheme, WRF 6-class graupel scheme (WSM6) (Hong et al. 2004 and Hong and Lim 2006). The WSM6 allows for the inclusion of graupel as a water species, which can lead to a greater intensification of a given system as compared to no inclusion of graupel in the model (Hong and Lim 2006). The WRFA model was initialized with initial and boundary conditions from NCEP FNL (final) analysis. The boundary conditions were updated every six hours.

2.3.2 WRFB:

The WRFB model is very similar to the WRFA model. This model has the same horizontal and vertical resolution, domain coverage, radiation schemes, surface physics scheme, and implicit convection scheme. The model was also run at 0000 UTC and 1200 UTC with a three hour timestep and a 72 hour forecast length. Unlike the WRFA, the WRFB used the Yonsei University PBL scheme (YSU) (Noh et al. 2003) which is an advancement of the Medium Range Forecast Scheme (MRF) (Hong and Pan 1996 and Skamarock et al. 2005). This new scheme also includes countergradient fluxes, PBL height estimation for convective PBL, and a different handling of entrainment being handled explicitly rather than implicitly (Hacker and Rostkier Edelstein 2007). The height of the planetary boundary layer is dependent upon the Bulk Richardson number, unlike the Mellor-Yamada-Janjic PBL scheme in which the height of the PBL is defined by the turbulent kinetic energy (Misenis et al. 2006). The WRFB did not use the WSM6 explicit moisture scheme instead it used the Ferrier scheme (Ferrier 1994). The Ferrier scheme was designed to incorporate many of the basic microphysical processes found in more complex storms while using less computational resources (Bender et al. 2007) and the scheme was found to work well with the Betts-Miller-Janjic implicit convection scheme. The WRFB model also used the NCEP FNL analysis for the initial and boundary conditions in the model. The boundary conditions were updated every six hours. The physics schemes chosen to be run in both the WRFA and WRFB models are chosen based on previous experience with mesoscale tropical cyclone modeling (Pattnaik 2008, personal communication).

2.3.3 MM5:

The MM5 model version 3.7.1 was also run at FSU. This model was run at 0000 UTC and 1200 UTC producing three hourly output out to 72 hours. The model has a horizontal resolution of nine km with 23 vertical sigma levels and a higher vertical resolution within the planetary boundary layer. The domain coverage of the model very closely matched that of the WRFA and WRFB models. Small differences in the overall domain coverage, as demonstrated by Fig. 2.4, are a result of the different model configurations between the WRF and MM5. The size of the domain was determined in

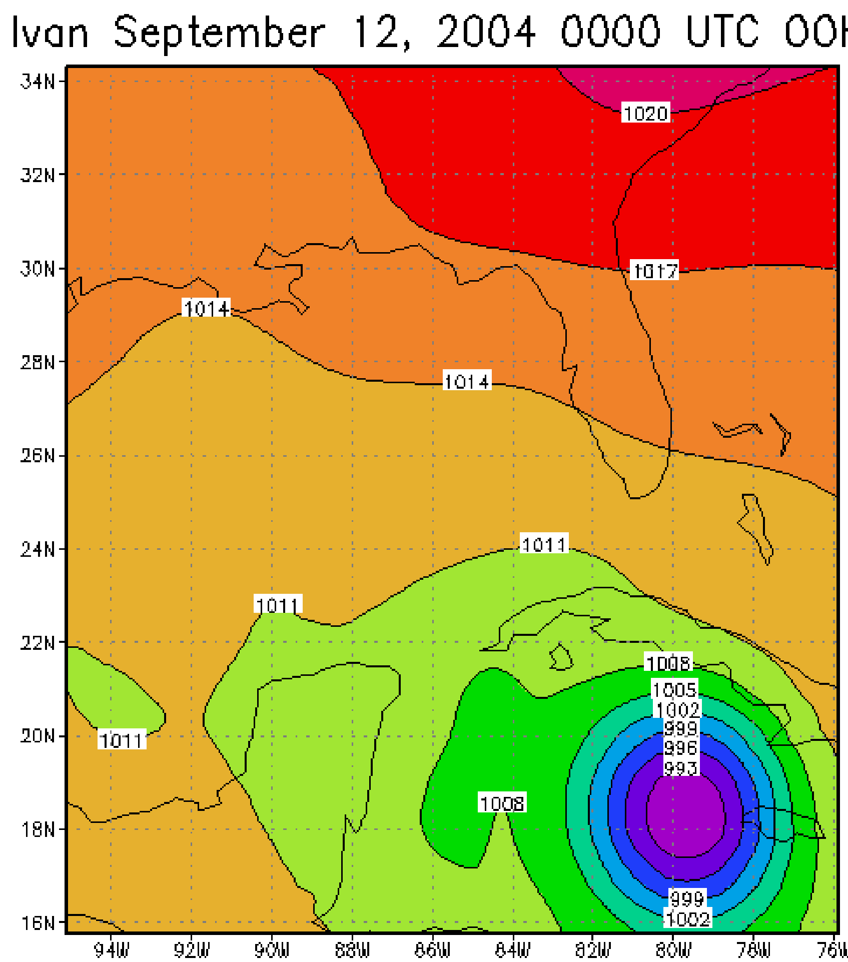

Figure 2.4 Model domain coverage of MM5 for Hurricane Ivan on September 12, 2004 at 0000 UTC 00 hr showing sea level pressure.

the same manner as the WRFA and WRFB models. For the radiation within the model the cloud-radiation scheme from Dudhia (1989) was included. To parameterize the surface layer the multilayer soil temperature model (Dudhia 1996) was run in the model.

This particular surface layer model was able to improve upon prior treatment of ground temperatures (Dudhia 1996). For processes going on within the planetary boundary layer the PBL scheme developed by Blackadar (Blackadar 1976, 1979) was included in the model. This scheme was found to be to be able to explicitly simulate the vertical development of the boundary layer (Zhang et al. 1999), which is very important in tropical cyclones. Like the WRFA and WRFB the MM5 also had several different implicit convection schemes to choose from. The Betts-Miller scheme (Betts and Miller 1986) was chosen as that worked well with the Goddard microphysics scheme (Tao et al. 1989 and Lin et al. 1983) which was used for the explicit moisture scheme; and, Baik et al. (1990) and Puri and Miller (1991) found some success with using the Betts-Miller scheme to simulate a tropical cyclone. Like the WRFA and WRFB the MM5 model was also initialized with NCEP FNL analysis for the initial and boundary conditions. The boundary conditions were updated every six hours.

2.3.4 HWRF:

The HWRF model was run at NCEP, this being the only model used in the mesoscale FSSE that was not run at FSU. This model only began being run in an operational setting in 2007, though development of the model started in 2003 at the NWS/NCEP Environmental Modeling Center (EMC). The outermost grid of the HWRF model has a 27 km resolution that is 75 degrees by 75 degrees. The innermost grid has a nine km resolution and 42 vertical levels at seven degrees by seven degrees. All of the data obtained from this model is from the innermost grid of the model. Fig 2.5 shows a sample of the innermost domain for the HWRF model. Like the other models, the domain coverage changes for each storm. This model was also available at 0000 UTC and 1200 UTC with six hourly output out to 96 hours. However, for this study only data out to 72 hours was used. This model used a vortex initialization similar to the vortex bogusing technique used in the GFDL model. The GSI 3D-VAR Assimilation of Doppler radar was implemented for the vortex bogusing as a potential improvement over the currently used GFDL technique. This technique allows for vortex relocation and intensity adjustment to better match the actual tropical cyclone conditions.

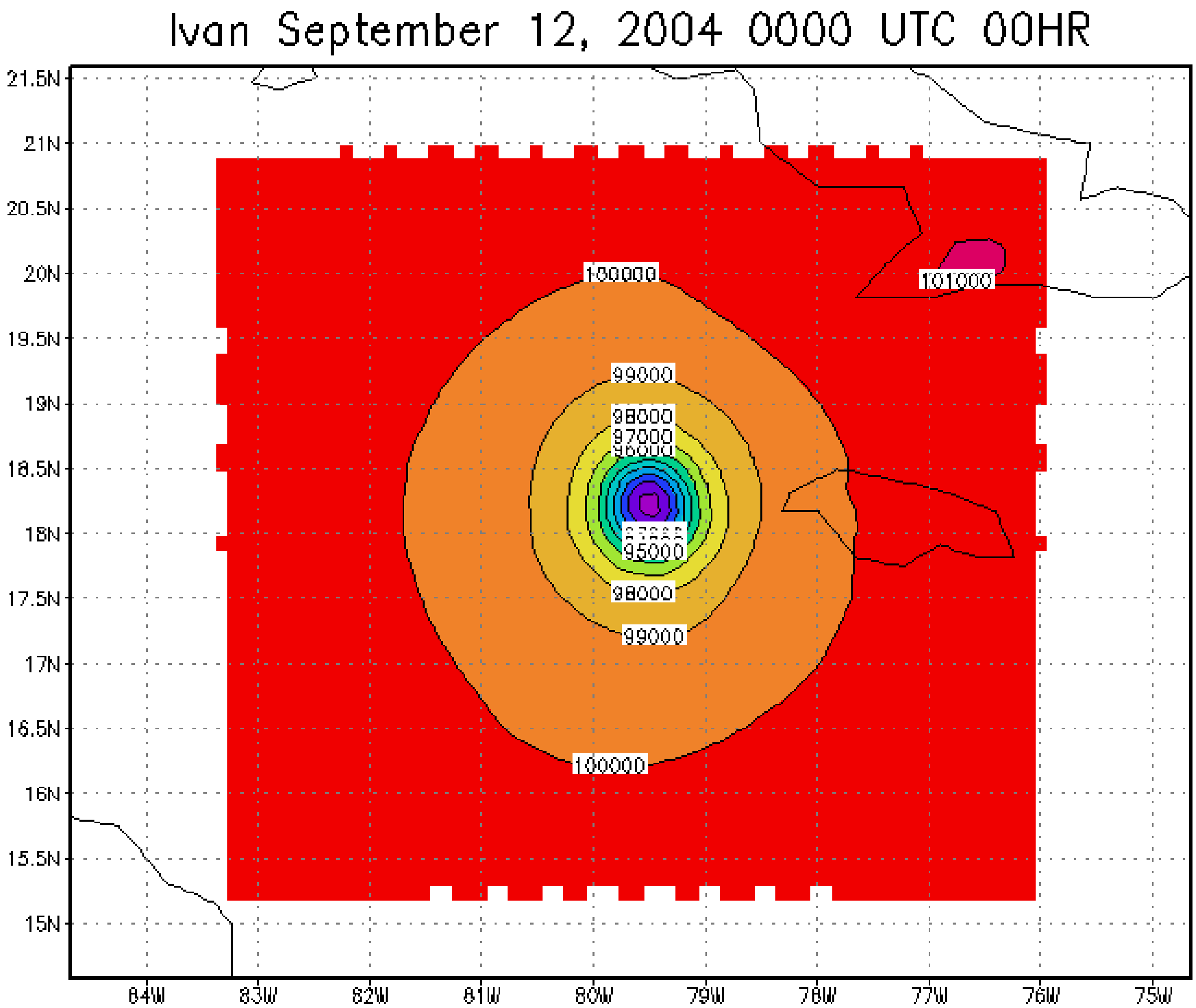

Figure 2.5 Model domain coverage of HWRF for Hurricane Ivan on September 12, 2004 at 0000 UTC 00 hr showing sea level pressure.

Unlike the WRFA, WRFB, and the MM5 the HWRF model is a coupled two-way double nested model with a moving nest. The MM5, WRFA, and WRFB do not have vortex initialization, coupling, or a moving nest as incorporation of those into a model requires considerable computation power and storage not available for this study. The atmospheric component of the HWRF model was coupled with the Princeton Ocean Model (POM) (Blumberg and Mellor 1987), which allows for the inclusion of the loop current initialization and the evolution of the SST field. To initialize for the static, land surface, and parent domain the WRF Standard Initialization (WRFSI) was run to produce initial and boundary conditions for the model. HWRF uses a non-hydrostatic system of equations on a rotated latitude longitude Arakawa-E grid. The other mesoscale models used here use the simple sigma coordinate in the vertical; whereas the HWRF model uses the pressure hybrid coordinate (Simmons and Burridge 1981). The GFS/GFDL surface, boundary layer physics, and GFDL/GFS radiation options were incorporated for some of the physics options. The Simplified Arakawa Schubert (SAS) was used for the convection scheme (Arakawa and Schubert 1974, Grell 1993), and similar to the WRFB the Ferrier microphysics scheme was used. All HWRF model information is available from Tuleya and Gopalakrishnan (2006) and the HWRF website at [http://www.emc.ncep.noaa.gov/HWRF/index.html]. The description of the experimentation methods, years and storms studied for this work will be discussed in Section 2.5.

2.4 Large Scale Model Description:

Mesoscale modeling is a relatively immature science for tropical cyclone forecasting. Mesoscale models were developed, in part, to better resolve changes within tropical cyclones that can lead to intensity change as their older counterparts large scale models had difficulty resolving some of the small scale features within tropical cyclones. With the development of more operational tropical cyclone mesoscale models it is important to compare them to the previously developed large scale models to see if they can demonstrate any improvement over the large scale models. Part of that comparison is performed by running mesoscale models in the FSSE and comparing it to the FSSE run with large models. The description of the experimentation done to compare the two will be described in Section 2.5.

Prior to this study, the FSSE had only used large scale models to study tropical cyclone track and intensity. This study provided the perfect opportunity to compare error values and characteristics for the large scale models and mesoscale models. Table 2.1 provides a list and brief description of all the large scale models used within this model to perform this comparison.

Table 2.1 List of Large Scale Models with a brief description about each model

Large Scale Models	Brief Description
OFCI	Human forecast from the NHC, six hourly interpolated
CLP5	Five-day statistical track model run at NHC
SHF5	Five-day statistical intensity model run at NHC
A98E	Statistical dynamical models run at NHC
A9UK	Statistical dynamical models run at NHC
A90E	Statistical dynamical models run at NHC
PERS	00Z/12Z OFCL forecast kept constant in time
CLIP	Three-day statistical track model run at NHC
GFDI	Six hourly interpolated multi-layer regional dynamical model
GFSI	12 hourly interpolated multi-layer global dynamical model
DSHP	Statistical intensity model with a land decay component
DSHI	Linear interpolated DSHP model

2.4.1 OFCI, PERS:

The Official six hourly interpolated model (OFCI) is a forecast issued by the NHC with a six hourly interpolation based on a collaboration of all the NHC forecasters (Rhome 2008). The NHC forecasts are typically issued at 0300 UTC, 0900 UTC, 1500 UTC, 2100 UTC. This interpolation was necessary as forecasts pertaining to the current forecast hour were not yet available and it was performed using the previously issued forecast and adjusted to the current position and intensity of the storm. This same technique was also used on the GFDI and GFSI models, both of which are discussed later in this section. The Persistence model (PERS) takes the 00 hour official forecast (OFCL) and keeps that forecast constant in time out to 72 hours. (i.e. the 72 hour persistence forecast is the same as the 00 hour persistence forecast) The persistence forecast is used in this study as a benchmark of skill only for intensity. OFCL pressure forecasts for SLP are not available for the times necessary so the forecast advisories from three hours prior to each model forecast are used to create the

PERS SLP forecast. The 0000 UTC model forecast uses the pressure reported from the 2100 UTC forecast advisory (previous day forecast) and the 1200 UTC model forecast uses the pressure reported from the 0900 UTC (same day) forecast advisory. Everything else about the SLP PERS forecast is the same.

2.4.2 A90E, A98E, A9UK:

The A90E, A98E, and A9UK are statistical dynamical models run at NHC. These models reflect the statistical relationships between storm behavior and predictors obtained from dynamical models such as deep-layer-mean Global Forecasting System (GFS) geopotential height fields averaged over 1000-100 hPa (Rhome 2008). These models were run at 0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC and produced 12 hourly output of only track forecasts.

2.4.3 GFSI:

The GFSI is a global spectral model that is six hourly interpolated. This model has 35 km resolution for forecasts out to 180 hours and 80 km for forecasts from 181 hours to 384 hours and had 64 vertical levels with a hybrid sigma-pressure vertical coordinate system (Simmons and Burridge 1981). The SAS convective parameterization scheme was used for the convective parameterization (Arakawa Schubert 1974, Grell 1993). To represent the PBL the first order closure method was implemented. The initial conditions for the model came from the 3D-VAR Gridpoint Statistical Interpolation, and the vortex from the initialization was relocated to the NHC position for each forecast. This model was developed and maintained by EMC of NCEP and was run at 0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC and producing 12 hourly output (Rhome 2008).

2.4.4 SHF5:

The SHF5 is a statistical tropical cyclone intensity model run at the NHC and used as a baseline for forecast skill measurement (Jarvinen and Neumann 1979); this model does not produce track forecasts. This model was developed from data that describes the past history of tropical cyclones to create a set of multiple linear regression equations for prediction (Knaff et al. 2003) with the historical track and intensity information coming from the “best track” database. Some of the predictors used to develop the multiple linear regression equations were storm date, zonal speed, and 12 hour change in intensity. These forecast equations were allowed to evolve in time. This model received no input about the atmospheric state and for operational and research work is considered a no-skill forecast model for intensity forecasting. SHF5 forecasts were issued at 0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC and produced 12 hourly output; five day forecasts started in 2003 (Knaff et al. 2003).

2.4.5 CLIP, CLP5:

The Climatology and Persistence model (CLIP) is a statistical tropical cyclone track model developed by Neumann (1972) and later extended to produce five day output (CLP5) by Aberson (1998). Like the SHF5, this model is also used as baseline for forecast skill measurement. This model is based on a climatology and persistence of tropical cyclones with that information being used to develop the regression equations for prediction. Several predictors used within this model to generate the regression equations were direction of motion, initial intensity, and current and past movement during the past 12 to 24 hours. This model also received no input about the state of the atmosphere and for operational and research work is considered a no-skill forecast model for track forecasting. These forecasts were issued at 0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC and produced 12 hourly output not including a 60 hour forecast. The CLIP and CLP5 do not produce any intensity forecasts.

2.4.6 GFDL:

The GFDL (with the six hourly interpolated GFDI being used in this study) is a primitive equation multiply nested movable mesh grid (MMM) model. The model issued three hourly forecasts out to 126 hours at 0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC. The domain is one degree for the outermost domain and .166 degree for the innermost domain as shown by Fig. 2.6 and it has 42 vertical sigma levels. The domain and number of nests underwent a few changes with the addition of a third nest in 2005 that had had an approximate horizontal resolution of nine km and that new nest was placed inside the previous innermost nest. This new inner nest is confined to a five degree by five degree box, shown in Fig. 2.6.

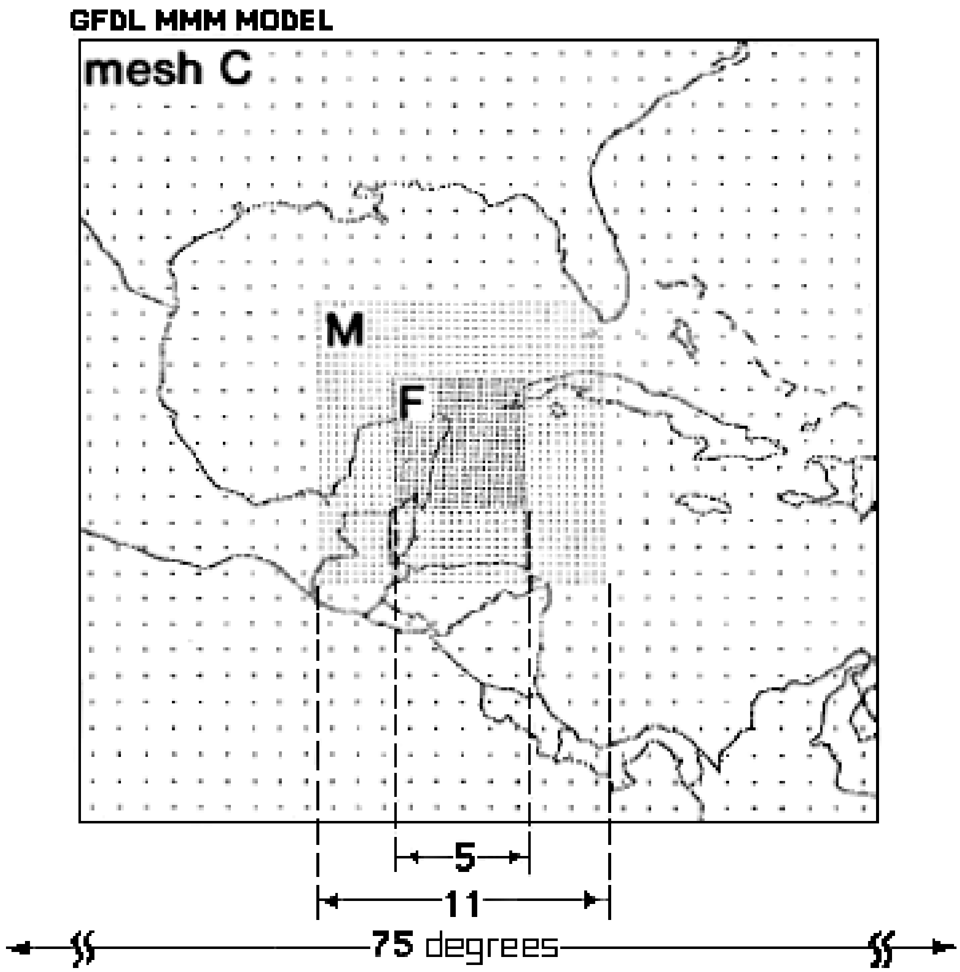

Figure 2.6 Sample model domain coverage of GFDL, showing the three nests with the outermost nest (mesh C) having .166 degree resolution and the innermost nest (mesh F) having a .083 degree resolution within a five by five degree domain (resolution and domain of current configuration used in this study). From Kurihara et al. (1998).

Within the model the diffusion parameter included the Smagorinsky nonlinear viscosity scheme (1963) in the horizontal and Troen and Mahrt (1986) scheme in the vertical. For surface fluxes the Monin-Obukhov framework was incorporated into the model with sea surface temperatures (SST) used for the ocean and the land surface temperature prediction used for land surface (Monin and Obukhov 1954). The cumulus parameterization used the SAS scheme (Arakawa Schubert 1974, Grell 1993). The radiation scheme had an infrared component and a solar component with the infrared component based on the Schwarzkopf-Fels scheme (1991) and the solar component based on the Lacis-Hansen scheme (Lacis and Hansen 1974). The GFDL model was initialized with environmental fields from NCEP Global Analysis. The initial NCEP specified vortex was not used and instead vortex initialization was performed to more closely represent the storm structure, position, and intensity. The vortex initialization incorporated information from the National Hurricane Center and a separate model integration performed using the technique discussed by Kurihara et al. (1998).

The vortex was initialized by first removing the initial vortex from NCEP FNL from the environmental field. The vortex was removed by specifying a domain around the cyclone and filtering out the hurricane component of the storm within that domain. The new environmental field then became:

$$\text{(environmental field)} = \text{(basic field)} + \text{(nonhurricane component)} \qquad (6)$$

The basic field is original environmental field specified by NCEP and the nonhurricane component is the nonhurricane features within the vortex removal domain. After the removal of the vortex, a symmetric vortex was generated separately based on a time integration of an asymmetric version of the hurricane prediction model starting with a motionless condition (Kurihara et al. 1995). During the time integration the tangential wind component was gradually forced towards a specified target profile based on information from NHC storm observations. A storm beta (β) gyre was generated through the time integration of a simplified vorticity equation (Ross and Kurihara 1992). The generated symmetric vortex and asymmetric wind were placed at the observed position and merged with the environmental fields and then readjusted to the mass field for continuity. The vortex removal, spin up, and initialization underwent several improvements in 2005. There were other smaller changes made to the model and its vortex initialization technique, all of which can be found in Bender et al. (2007).

In 2001 the GFDL became a coupled atmospheric ocean model with the inclusion of the POM into the GFDL model framework. The POM is a three dimensional primitive equation model with thermohaline dynamics, σ vertical coordinates, and a free surface (Blumberg and Mellor 1987). The ocean model had approximately 18.5 km horizontal resolution and was ocean bottom following. The POM used a Second-Order Turbulence Closure Scheme (Mellor and Yamada 1982) to better represent surface mixed layer dynamics. There were 21 vertical levels in the Gulf of Mexico and 23 vertical levels in the Western Atlantic. To initialize the POM real-time global analysis from NCEP was used and this analysis was combined with available buoy and ship data and weekly SST averages from the Advanced Very High Resolution Radiometer (AVHRR). Additional information about the Princeton Ocean Model can be found in Blumberg and Mellor (1987) and Mellor (1998).

2.4.7 DSHP:

The Decay-Statistical Hurricane Intensity Prediction Scheme (DSHP) is a statistical-dynamical model that is run at the NHC, primarily used for real-time intensity forecasts, however, for this particular study both its track and intensity forecasts are used. This model used a multiple linear regression technique with climatological, persistence, and synoptic predictors (DeMaria and Kaplan 1994) to produce the track and intensity forecasts. The original track forecasts for DSHP came from the Limited Area Sine Transform Barotropic Model (LBAR); starting in 1999 the DSHP model replaced those track forecasts with the track forecasts from the OFCL. The original DSHP was simply the Statistical Hurricane Intensity Prediction Scheme model (SHIPS) as the decay component of the model had not yet been developed.

The decay component was developed because early work shows that tropical cyclones tend to behave very differently once they make landfall primarily due to the reduced latent heat and surface fluxes into the storm (Miller 1964, Ooyama 1969, Rosenthal 1971, and Tuleya et al. 1984). In an attempt to quantify how that behavior affects tropical cyclone wind speed with time, much work was done to try and determine a wind decay pattern for a tropical cyclone after landfall (Hubert 1955, Malkin 1959, Schwerdt et al. 1979, and Ho et al. 1987). Much of this earlier research took the approach of investigating the decrease in the pressure gradient between the tropical cyclone center and the surrounding environment. Kaplan and DeMaria (1995) followed up that work with the development of a simplified inland decay model. This work would later be used in the SHIPS model to improve intensity forecasting after a storm has made landfall (DeMaria et al. 2005).

Their work was only based on landfalling tropical storms that had made landfall from the southern east Texas coast up to the Delmarva Peninsula. They did this due to the fact that the Northeast United States typically has much different terrain from the rest of the Eastern United States coast. DeMaria and Kaplan (1995) assumed that tropical cyclone winds decay at a rate proportional to their landfall intensity. They developed a simple equation to account for the decay of tropical cyclone surface winds with time after landfall:

$$\frac{dV}{dt} = -\alpha V \tag{7}$$

V refers to the mean sustained surface wind; t is the time after landfall; and α is a decay constant. This model was incorporated into the SHIPS model 2000 and would be turned on during landfall and then later turned off if the model re-emerged out into open waters (DeMaria et al. 2005).

The DSHP is simply an amended version of the SHIPS model; they have the same forecasts over open water. They work similarly to the CLIP and SHF5 model in regards to having a set of predictors that help to develop a multiple linear regression equation to use for prediction. Until recently this model had many of the same predictors as CLIP and SHF5 models. Several of the new predictors are weekly averaged sea surface temperatures, included in 1996, brightness temperatures from GOES, and oceanic heat content information from satellite altimetry (DeMaria et al. 2005). DeMaria et al. (2005) found noticeable improvement with the incorporation of the new predictors and the empirical inland decay model. Like the CLP5 model, this model was originally only run out to three days, but, as of 2001 the SHIPS and DSHP were extended to five days. This model was run at 0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC and produced 12 hourly output. The DSHI model is simply a linear interpolated version of the DSHP model, different from the other interpolated models and has 12 hourly output at hours alternating to the DSHP model. This model is only used for comparison of error statistics.

2.5 Description of FSSE Experiments

This study is focused on tropical cyclones that occurred within the Atlantic basin during the 2004, 2005, and 2006 hurricane seasons, with Table 2.2 listing the specific tropical cyclones included in this study. Each storm included in this study is forecast out to 72 hours at 0000 UTC and 1200 UTC for a particular storm day producing an average of two cases for each storm. Frances, Ivan, and Katrina each have four cases, encompassing two days, and Chris only has a 1200 UTC case. The specific storms and

Table 2.2 List of years, storms, and storm specific dates used in this research.

2004 Hurricane Season		2005 Hurricane Season		2006 Hurricane Season	
Charley	August 10	Dennis	July 7	Chris	August 1 (1200 UTC only)
Danielle	August 15	Emily	July 15	Debby	August 22
Frances	September 1	Harvey	August 3	Ernesto	August 27
Frances	September 2	Irene	August 13	Gordon	September 13
Gaston	August 28	Katrina	August 26	Helene	September 17
Ivan	September 12	Katrina	August 27	Isaac	September 30
Ivan	September 13	Maria	September 4		
Jeanne	September 24	Nate	September 6		
Karl	September 18	Ophelia	September 8		
Lisa	September 25	Philippe	September 18		
		Rita	September 21		
		Stan	October 2		
		Wilma	October 22		

dates chosen are based off available HWRF data provided for this study. Several of these storms do not have a full 72 hour forecast due to storm decay within one of the models. If a storm decays earlier than 72 hours in one model every other model forecast for that same case is shortened to that same length for continuity within this study. Each forecast for every storm, whether 0000 UTC or 1200 UTC, is representative of one case within this study. There are 57 total cases available from the storms.

With this number of cases there were two possible ways to formulate the training set for running the FSSE using the real-time operation approach or the cross validation approach. Using the real-time operational approach Hurricane Frances of 2004 would have only the storms that occurred prior to it included in its training set (Charley, Danielle, and Gaston in this case). Other storms would use the same approach to construct their training sets. This approach would produce very small training sets for storms early in this study and much larger training sets for storms later in the study. Hurricane Charley of 2004 has no storms available before it in this study and thus would not have a training set and could not be forecast using the real-time approach. To forecast Charley using the real-time method 2003 model data would need to be included in this study.

Very small training sets do not adequately allow the FSSE to derive model characteristics and biases. To combat that problem another method of formulating the training data sets for the FSSE was investigated. This other approach is known as the cross-validation approach. This approach involves creating a training set that includes all the tropical cyclones available within the study with the exclusion of the case being forecasted. For example, the training set for Hurricane Ophelia in 2005 at 0000 UTC would include all storms prior to Ophelia at 0000 UTC and all storms after Ophelia 0000 UTC and with the 1200 UTC storm data for Ophelia being included in the training set. Every other storm would have their training set constructed in a similar manner. Each case for each storm would have the same training set size as the other storms in the study. Tropical cyclones early in the period of research would have a much larger training set with the cross validation approach than the real-time approach. In addition to that, the two different methods of constructing a training set will not produce the same error statistics and will likely vary quite significantly depending on the years and storms examined.

Williford (2002) used 75 or more cases within each training set for his examination of the 1998 to 2001 Atlantic hurricane seasons. His primary method of experimentation involved utilizing the cross-validation approach to construct his training sets. That was chosen to keep model characteristics constant within each training set as several of the models had undergone major model changes in the previous year. Jordan (2005) chose to use the real-time approach for his work and with the large number of cases available each storm forecast had a sufficiently large training set. He used anywhere from 130 to upwards of 900 cases to construct training sets for his research. This approach is most realistic for operational use. The cross-validation approach is utilized in this study to allow for storms early in the period of study to be forecasted along with storms later in the period. Each storm would have a reasonable training set size of 56 cases for the FSSE to determine model characteristics and biases.

This study examines both track and intensity forecasts for tropical cyclones, with the intensity forecasts being measured by both the minimum pressure within the storm (SLP), in hPa, and the maximum 10 meter sustained wind speed, in ms^{-1}. For each particular storm, at every six hours up to 72 hours, the track and intensity values are obtained from a tracking program which is based on sea level pressure for determination of the storm center and 10 meter wind speed which is used for determination of the maximum 10 meter wind speed in the storm. The sea level pressure field provides the minimum sea level pressure within the storm and it also provides the position of the storm. The 10 meter wind speed field provides the maximum 10 meter wind speed within the storm. Forecast outputs are utilized to obtain the track and intensity values. This method of visual inspection was used only on the HWRF, WRFA, MM5, and WRFB models, except for the HWRF forecasts of Hurricane Isaac, which were obtained from already created text files with the track and intensity information. Also the 0000 UTC forecast for Hurricane Stan of 2005 utilized the atmospheric version HWRF not the air/ocean coupled version, due to data availability issues. All other model datasets (large scale models and “best track”) already have the track and intensity variables available in the format required for the FSSE study, thus no visual inspection is needed to retrieve the data. Many of the large scale models did not have SLP forecasts available for the entire period of study and thus large scale model forecasts of SLP are not done.

These experiments are broken up into two parts. The first part involves running the FSSE with HWRF, WRFA, MM5, and WRFB to generate a mesoscale FSSE forecast. This forecast is then compared to the PERS model, OBSV model, the DSHP and DSHI models, and lastly the CLIP model. The second part of the experimentation involved comparing the FSSE mesoscale model runs with some FSSE large scale model runs. Model data with track, and intensity was already available for large scale models. The large scale models are unavailable for several cases and only provided 47 total cases out of the original 57 to work with. The FSSE is then run with the OFCI, CLP5, SHF5, A98E, A9UK, A90E, GFDI, and GFSI to produce a large scale FSSE forecast. Most of the models did not produce both track and intensity forecasts, thus only certain models are used to produce FSSE track forecasts and only certain models are used to produce FSSE intensity forecasts, shown in Table 2.3. The large scale FSSE model forecasts are then compared to the mesoscale FSSE forecasts. The results and model comparisons will be discussed in Section 5.6.

Table 2.3 List of large scale models used for producing track forecasts and large scale models used for producing intensity (maximum wind) forecasts.

Large Scale Track Models	Large Scale Intensity Models
OFCI	OFCI
GFSI	GFSI
GFDI	GFDI
CLP5	SHF5
A90E	
A9UK	
A98E	

CHAPTER THREE

OVERALL RESULTS AND ERROR METHODOLOGY

3.1 Error Calculation Methodology

This section presents all the methods used for error calculation and the overall errors of this study. The errors for each year will be discussed in Chapter four and some select individual case errors and synoptic discussion will be discussed in Chapter five. The comparison of large scale model errors to mesoscale model errors will also be presented in Chapter five. Each model forecast is compared to the observations and errors are calculated using several methods of error calculation. The errors calculated are Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and individual model biases. Only a few select MAE plots will be shown. Note that errors will be shown for CLIP, PERS, DSHP, and DSHI but those models are not included as member models within the FSSE when the FSSE is run. Also not all model forecast errors are available at all forecast hours. The CLIP model only has error statistics for the 12hr, 24hr, 36hr, 48hr, and 72hr forecast. The DSHP and DSHI have forecasts at alternating forecast hours.

MAE is one of the simplest ways to show relative error for a given case or set of cases and is calculated using the formula:

$$\text{Mean Absolute Error} = \frac{1}{n}\sum_{k=1}^{n}\left|y_k - o_k\right| \qquad (8)$$

The n refers to the number of samples in the calculation, with one being errors for only one case, and 57 being the errors averaged over all of the cases in this study. The y is the model value for intensity and the o is the observed value for intensity (Wilks 1995).

The subscript k refers to the case being examined (e.g. case one k equals 1 case 57 k equals 57). Track errors cannot be computed in the same way due to the values being compared are different points of latitude and longitude on a sphere. The Great Circle Distance Formula, or Haversine Formula, (Sinnott 1984) currently represents the best way to calculate distances between two points on a sphere {lat1, lon1} and {lat2, lon2}.

$$d = 2 * \mathrm{asin} + \sqrt{\left[\sin\left(\frac{\mathrm{lat1} - \mathrm{lat2}}{2}\right)\right]^2 + \cos(\mathrm{lat1}) * \cos(\mathrm{lat2}) * \left[\sin\left(\frac{\mathrm{lon1} - \mathrm{lon2}}{2}\right)\right]^2} \qquad (9)$$

The d refers to the distance between the two points. This formula is not valid if one or both of the points is located at the North or South Pole; however, this problem does not affect any storms in the dataset. For both of the above error equations lower values indicate a more accurate forecast.

The RMSE error calculations are more sensitive to large errors in the dataset (Wilks 1995). The RMSE function is simply the square root of the mean square error.

$$\text{Root Mean Square Error} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(y_k - o_k)^2} \qquad (10)$$

RMSE will be used in this study as the error units are the same as the error units for MAE (Wilks 1995). Similar to MAE, the lower the RMS errors the more accurate the model.

To examine for overestimation of intensity or underestimation of intensity a simple straight subtraction is done using the following formula:

$$-(\text{Model Bias}) = (y - o) \qquad (11)$$

For SLP negative error values represent an underestimation of the minimum sea level pressure of the storm and positive error values represent an overestimation of the minimum sea level pressure of the storm. For 10 meter maximum wind speed negative values correspond to an overestimation of the maximum wind speed in the storm and positive values correspond to an underestimation of the maximum wind speed in the storm. This calculation allows one to see the particular bias a model has from one storm to the next with regards to intensity. This formula is only used to calculate the biases for one case and not for overall error determination. A model bias of zero indicates a perfect forecast.

3.2 Overall Errors

To compute the overall RMS errors the individual errors have been calculated for each of the 57 cases in this study and averaged. In this chapter, the overall RMS errors of the track, SLP, and maximum 10 meter maximum wind speed will be presented and discussed. The 10 meter maximum wind speed will be referred to as the maximum wind speed for the rest of this study. The track error results do not include the PERS model errors due to the fact that the PERS errors are typically an order of magnitude larger than the errors for the other models and the persistence model used in this study is not a useful benchmark of accuracy due to the storm being fixed in space for the entire 72 hour forecast.

FSSE is able to show some improvement in track forecasting over all the models for most of the forecast. It has the lowest errors at hours 6, 18, and beyond 18, Fig. 3.1.

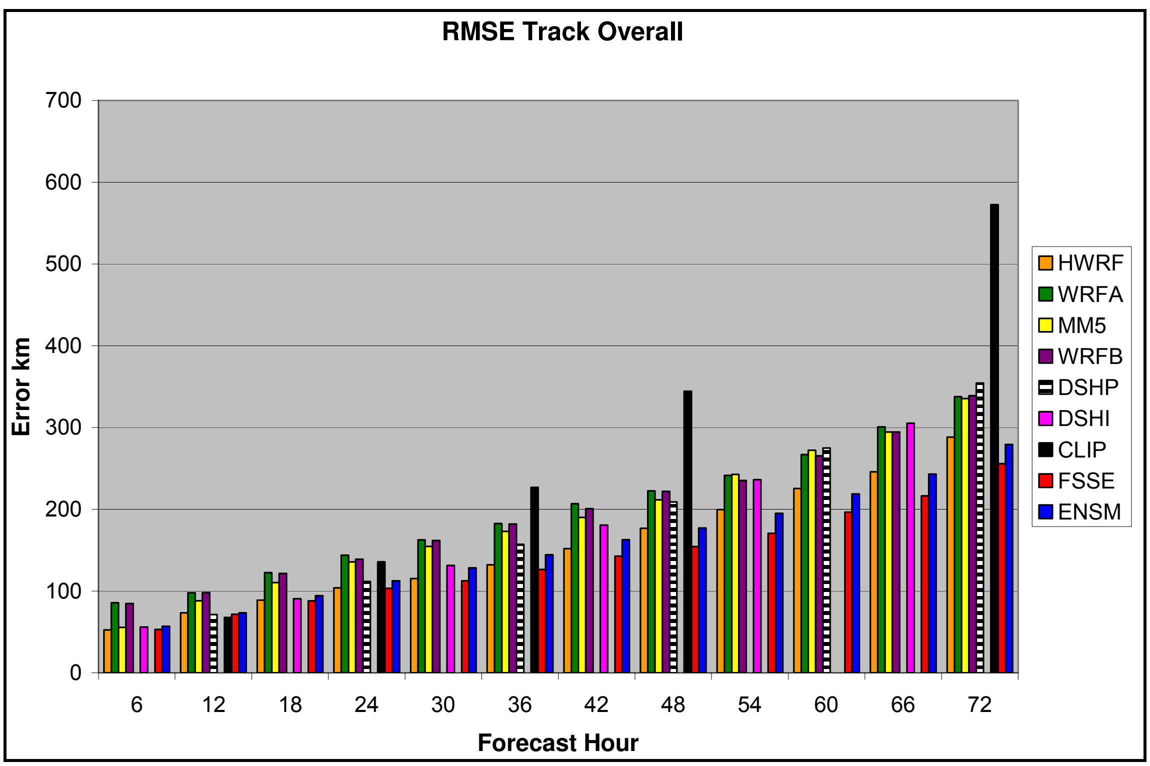

Figure 3.1 The RMSE, in kilometers, for all the track cases. The FSSE is in red and the Ensemble Mean is in blue. This includes the DSHP (horizontal stripes), DSHI (magenta).

At 12 hours the CLIP forecast has the lowest errors, however the FSSE errors are only slightly higher than it. The DSHP track forecast comes from the OFCL forecast and the ability of the FSSE to beat that for much of the forecast time is impressive. WRFA and WRFB have some of the most trouble with the model spin up at the early hours, with their errors being noticeably larger than the other models. The lack of information about the atmospheric state within the CLIP model dramatically degrades this model's forecasts in time, especially after 42 hours. This degradation of the forecast demonstrates how important information about the atmospheric state is in the issuance of two and three day forecasts.

SLP forecasts are not available for all models in this study, specifically DSHP, CLIP, and DSHI. The SLP errors for all of the other models will be shown. Forecasting the correct intensity in time is, in part, largely dependent on the model initialization as stated in the introduction (Emanuel 2004). HWRF uses many advanced techniques for model initialization, specifically vortex bogusing using information from Doppler radar. This vortex bogusing helps to address some of the problems that exist when a model is forced to generate its own vortex. As none of the models run at FSU use vortex bogusing in their initialization, noticeable differences are present early in the forecast period for those models as compared to HWRF, clearly seen in Fig. 3.2. Though even with vortex bogusing exact replication of the real storm atmosphere in a model at the initial time is impossible as many atmospheric processes are not fully understood and as a result errors exist in the model initialization causing there to be large errors early on in the forecast. The HWRF, PERS, and FSSE have noticeably smaller errors than WRFA, WRFB, and MM5, in the early forecast hours. The models have a hard time with the PERS forecast. The FSSE is still able to do quite well up to 48 hours, even with the large errors of several of the member models, with it having the lowest errors of all the models. As short term forecasts become increasingly more important for the issuance of watches and warnings, the FSSE's ability to succeed over other models early on shows that it can be a useful tool in forecasting for the critical forecast times. Past 48 hours the models tend to produce more erratic SLP forecasts, with respect to the observed, from one storm to the next with only moderate continuity between the different storms. As a result, correct weighting and removal of the model bias for the

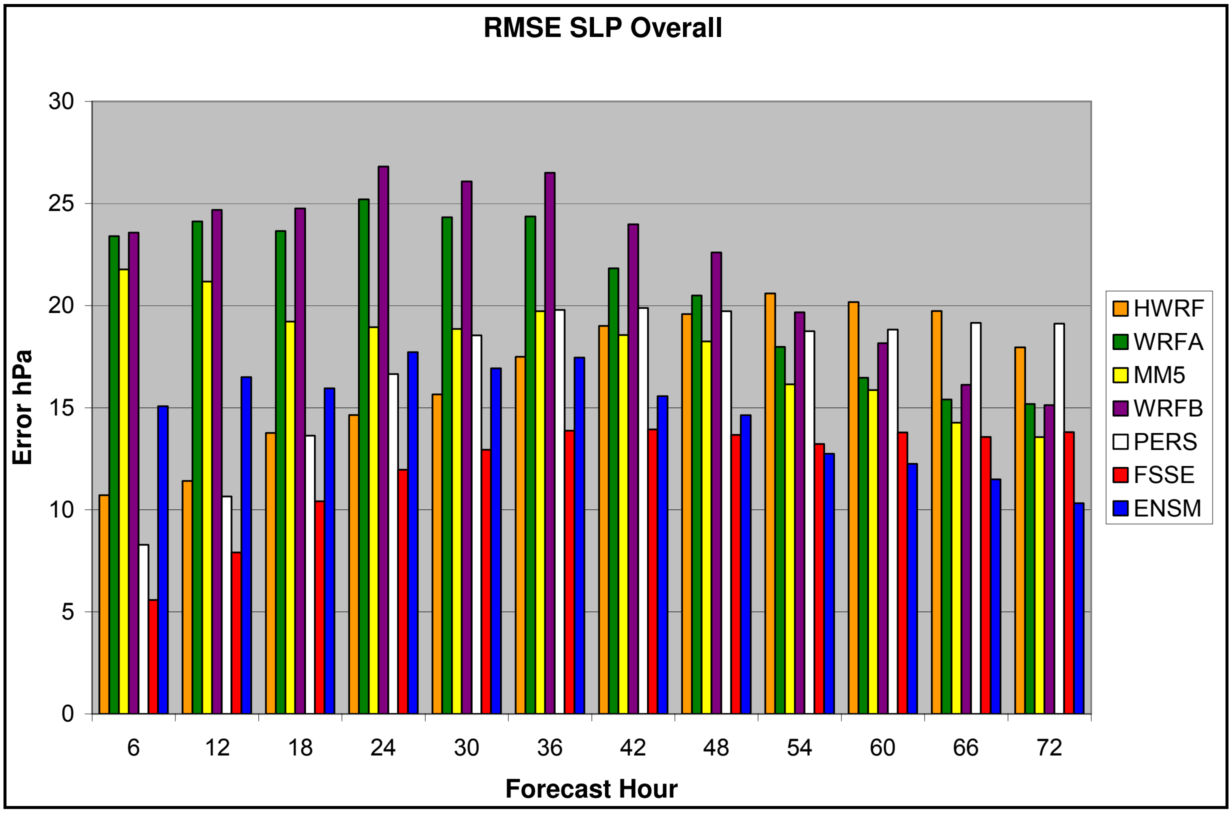

Figure 3.2 The RMSE, in hPa, for all SLP cases. Persistence is in white.

FSSE is a bit more difficult at these later hours. Increasing the size of the training sets, with the inclusion of more cases in the study, would possibly provide the FSSE with a better idea of the model behavior at the later forecast hours.

The forecasts for tropical cyclone intensity, for maximum wind speed, are challenging. Similar to SLP forecasts model initialization is very important where inaccurate initialization can produce large intensity errors that will perpetuate well into the forecast. Many of the storms included in this study are of hurricane strength for a significant portion of their forecast. This presents a problem for the models run at FSU as they typically tend to underestimate the maximum wind speed of the storm throughout their forecast. Though as the storm develops within those models the errors usually decrease as seen in Fig. 3.3. However some of that reduction in error may be due to the fact that as some of the observed storms weaken in time they approach the model forecast storms which are generally weaker. Early on the FSSE is able to show

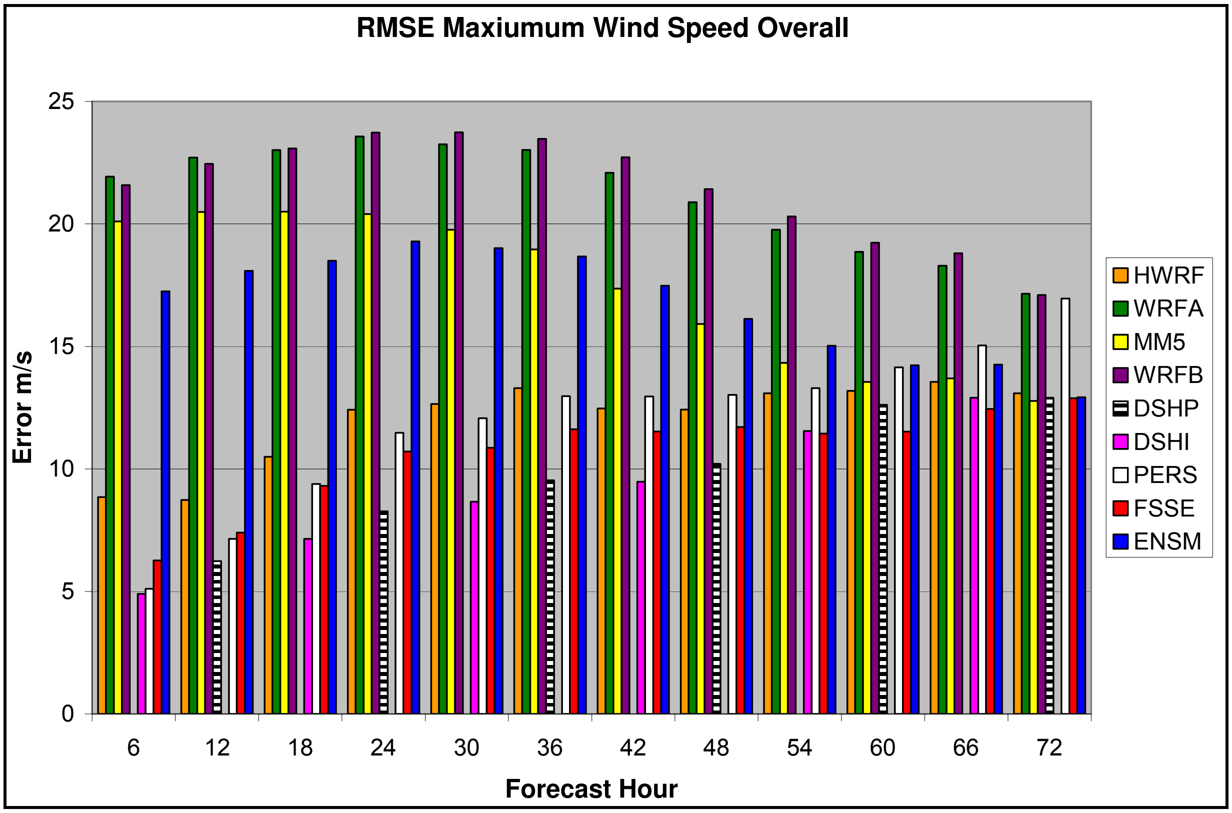

Figure 3.3 The RMSE, in ms^{-1}, for maximum wind speed.

improvement over the member models and the ensemble mean (ENSM). There are several storms that early on in their forecast prove troublesome for all the models where the persistence forecast exactly matches the observations (Frances, Ivan, Harvey, Irene, and Debby). The DSHP model is a very difficult model to beat and recent enhancements to the model (e.g. GOES data) appear to give the edge early on in the forecast (DeMaria 2005).

The differences between the PERS errors for maximum wind speed and for the SLP are likely attributed to many different things. Both the PERS SLP and maximum wind speed values are obtained from the OFCL forecast information; however differences exist between how the two values are obtained at the NHC. There are likely differences in how the SLP and wind speed values are rounded, how the observational data is extrapolated to determine the actual intensity values, and differences in how the two intensity fields are sampled. Those differences can amount to the PERS model having different results for the two different intensity fields.

3.3 Discussion

Overall the DSHP, HWRF, and FSSE have the lowest errors for SLP, maximum wind speed, and track. FSSE is able to successfully remove a large amount of the bias that remains within some of the mesoscale models; but there is increasing difficulty in error removal at later forecast hours as the models typically do not have a consistent bias or pattern at those times. Later in the forecast the observed storms frequently change their track pattern or intensity pattern and the models having great difficulty responding to those changes. Many of the mesoscale models in this study frequently forecast a lengthened period of either slow and modest intensification or continual moderate to rapid intensification and do not undergo the several phases of moderate weakening and/or strengthening seen in the observations. The observations show that a majority of the storms in this study do not follow the typical model behavior and often have one or two phases of intensification and weakening with some of the observed storms also making landfall. The model parameters need further refinement to properly depict the observed storm behavior and better assist in forecasting the changes in intensity.

There are several storms that are very intense tropical cyclones at the beginning of their forecast with some of those storms undergoing a slow weakening phase with time. For those storms the common member model behavior for the models run at FSU involves spinning up the storm in the first several hours of the forecast and then intensification in time with the MM5 having a more rapid rate of intensification than the WRFA and WRFB. As a result, those three models produce large forecast errors as the intensity changes in the model do not match the intensity pattern of the actual storm. However, those models do not always have large forecast errors and are better able to forecast weaker storms.

The FSSE shows some fairly consistent skill in error removal even with all of the problems present in the member models. The FSSE results do demonstrate, however, that in order for it to better capture the storm behavior later on in the forecast period the member models have to be more consistent in capturing the actual behavior of a storm. Other studies have shown that with the inclusion of more cases in a training set the FSSE is able to determine forecast biases that are more representative of the overall model behavior and more accurately capture storm behavior (Krishnamurti et al. 2006). Additional explanations for model errors will be presented in Chapter four and Chapter five.

CHAPTER FOUR

YEARLY ERROR RESULTS

4.1 2004 Errors

The 2004 Atlantic Hurricane Season was one of the most devastating seasons on record (Franklin et al. 2006). Florida was affected by four of the strongest storms of the season (Charley, Frances, Ivan, and Jeanne). This study examines those storms plus several other storms. For these few, some of the models show slightly lower errors for track than seen in the overall error plot, Fig. 4.1, but they prove a bit troublesome for the models with the models having trouble forecasting the lower pressures and higher wind speeds. The FSSE has its lowest errors out to about 48 hours after which fluctuating model behavior proves difficult for the FSSE to overcome.

The 2004 storms are easier to forecast as many of them propagate westward due to the high pressure in place over the eastern United States and the western Atlantic Ocean (Franklin et al. 2006) with the FSSE doing quite well compared to some of its member models. The HWRF captures the track forecasts with highest degree of accuracy and overall has the lowest track errors for the entire season seen in Fig. 4.1. Specifically HWRF is more accurate for the Frances and Karl cases (not shown); but FSSE's forecasts are also accurate with it doing slightly better for Ivan (discussed in Chapter five). Even though the HWRF produces the lowest errors at each forecast hour the FSSE is very close to and competitive with it. Closer examination of the FSSE forecasts reveals that the HWRF frequently receives the highest weight for track helping to improve the FSSE forecast.

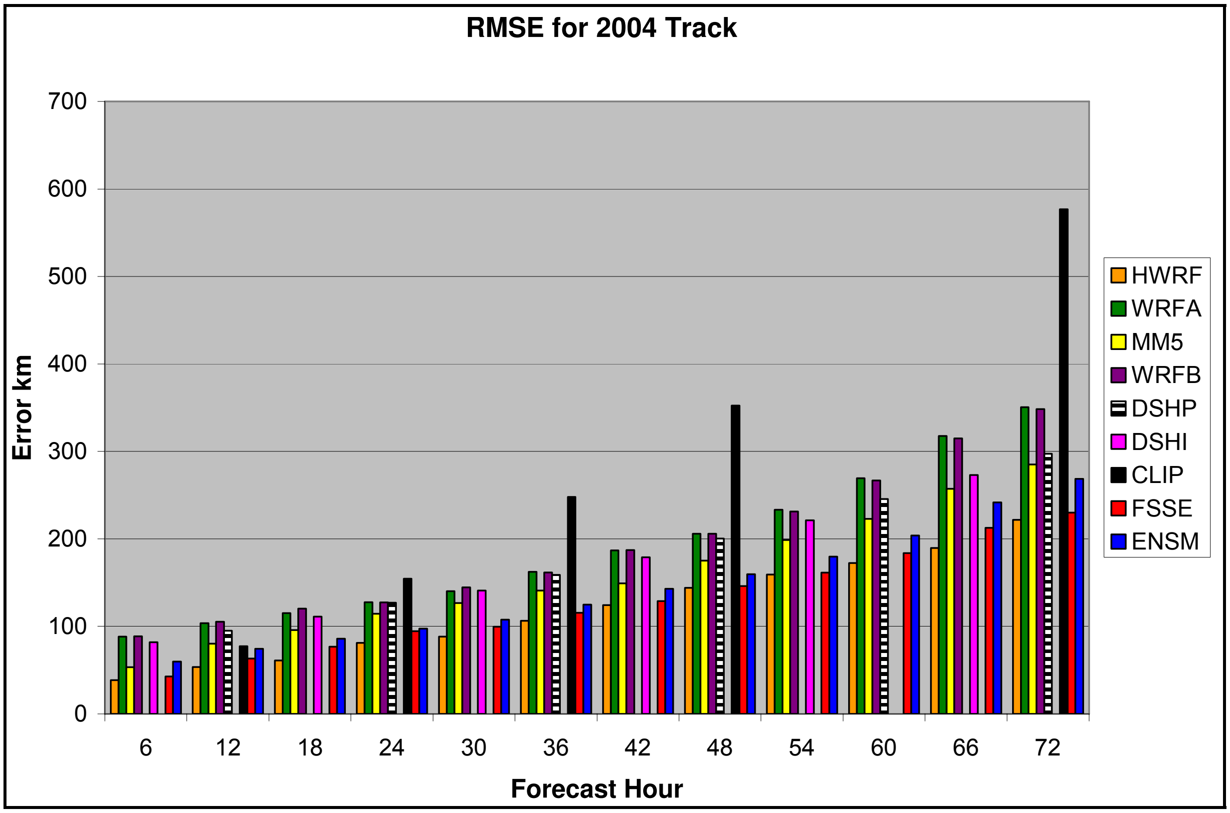

Figure 4.1 The RMSE, in kilometers, for 2004.

The SLP forecasts are a bit more difficult for all the models to forecast, especially the HWRF model, with that model having the highest errors after 36 hours. The large errors seen in the HWRF model can be partially attributed to its overintensification of several storms. Another reason for some of the models having such high errors is that several of the storms in 2004 are major hurricanes during the very beginning of their forecast (e.g. Ivan) and the models have a difficult time generating the proper initial intensity of the strong storms, with the average errors for all of the member models being 20 hPa and higher and in some instances over 35 hPa. As will be shown in Chapter five the HWRF and FSSE closely matched the initial intensity of that storm. The FSSE is able to produce the lowest errors out to 48 hours, Fig. 4.2, but afterwards is unable to beat the ENSM. Quite often the FSSE forecast storms begin to weaken after about 36 hours, not always realistic of observations. Future work may help to explain that. The strengthening that occurs later in the forecast in some of the observed

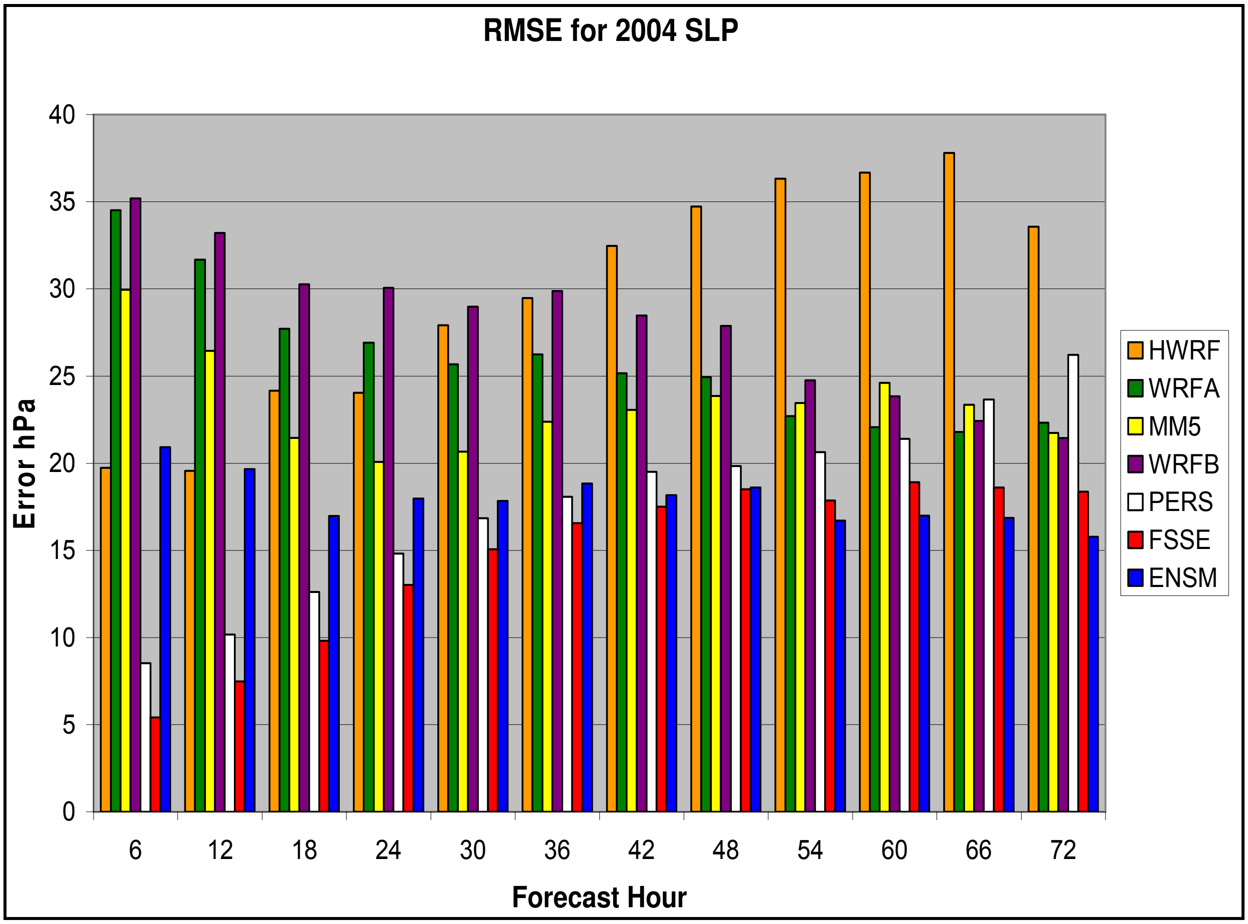

Figure 4.2 The RMSE, in hPa, intensity for SLP for 2004.

storms is not adequately captured by all of the member models increasing their errors. Though the storms that weaken with time during the later half of the forecast help to reduce the errors of the WRFA and WRFB as they would normally underestimate the intensity. The MM5 behaved slightly differently and, similar to the HWRF, frequently would overintensify the storms as seen with Charley in Fig. 4.3. A possible reason for the ENSM doing better later in the forecast, as see in Fig. 4.2 and 4.3, is that the WRFA and WRFB drastically underestimate the SLP several times and the MM5 and HWRF overestimate the SLP producing and ENSM forecast between the two groups that is slightly closer to the OBSV than the FSSE.

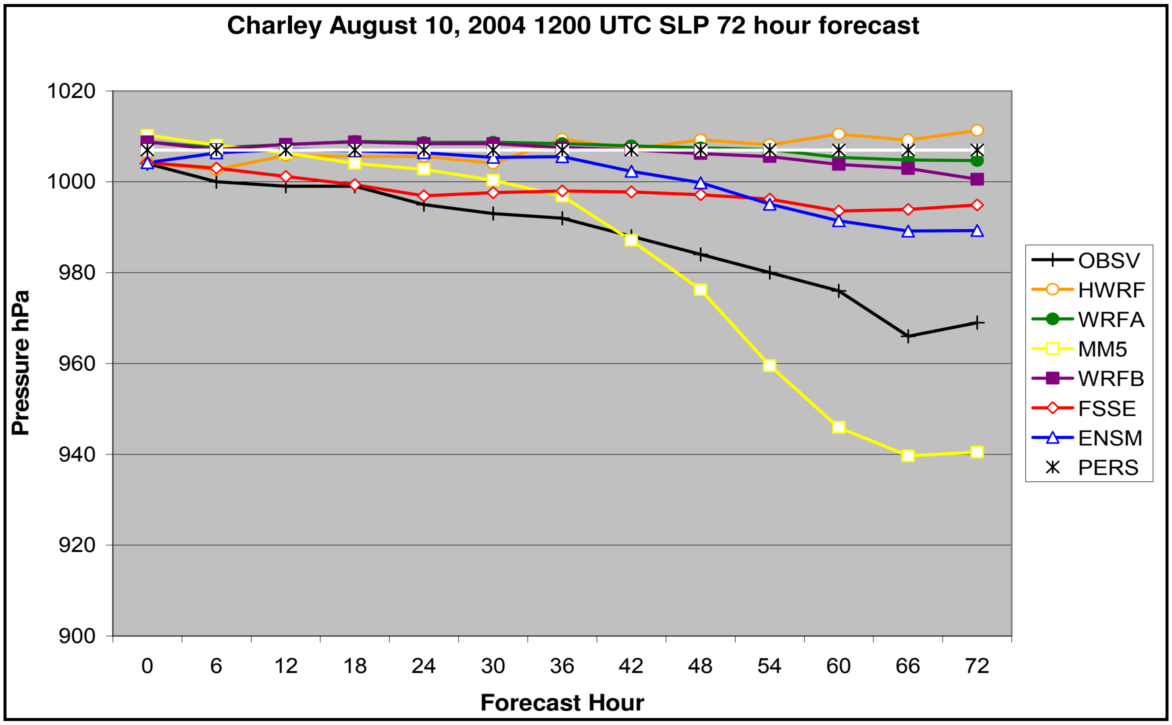

Figure 4.3 The SLP forecast, in hPa, for Charley on August 10, 2004 at 1200 UTC, showing the deepening of the forecast tropical cyclone in the MM5 model, which intern pulls the ENSM closer to the OBSV. The OBSV is in black, the FSSE is in red, and the ENSM is in blue.

The maximum wind speed forecasts appear to be a bit more difficult for the FSSE to forecast than SLP. Up until 66 hours the FSSE is able to beat all of the member models but unable to beat the DSHP model. The DSHP produces a more accurate intensity forecast for wind speed, seen in Fig. 4.4. Those low errors are aided by that models close approximation of the intensification of Charley. With that same storm, the MM5 is also able to capture the intensification fairly well and in doing so pulls the ENSM closer to the observed maximum wind speed giving the ENSM lower errors at 72 hours. The MM5's ability to capture Hurricane Charley's intensification, Fig. 4.5, and the weakening of Hurricane Frances (not shown) later in the forecast period help to give it the edge over the FSSE at 66 and 72 hours. Despite the difficulty the FSSE has later in the forecast, its errors are quite comparable to the DSHP model the first 18 hours of the forecast, and much less than the MM5, WRFA, and WRFB throughout the forecast.

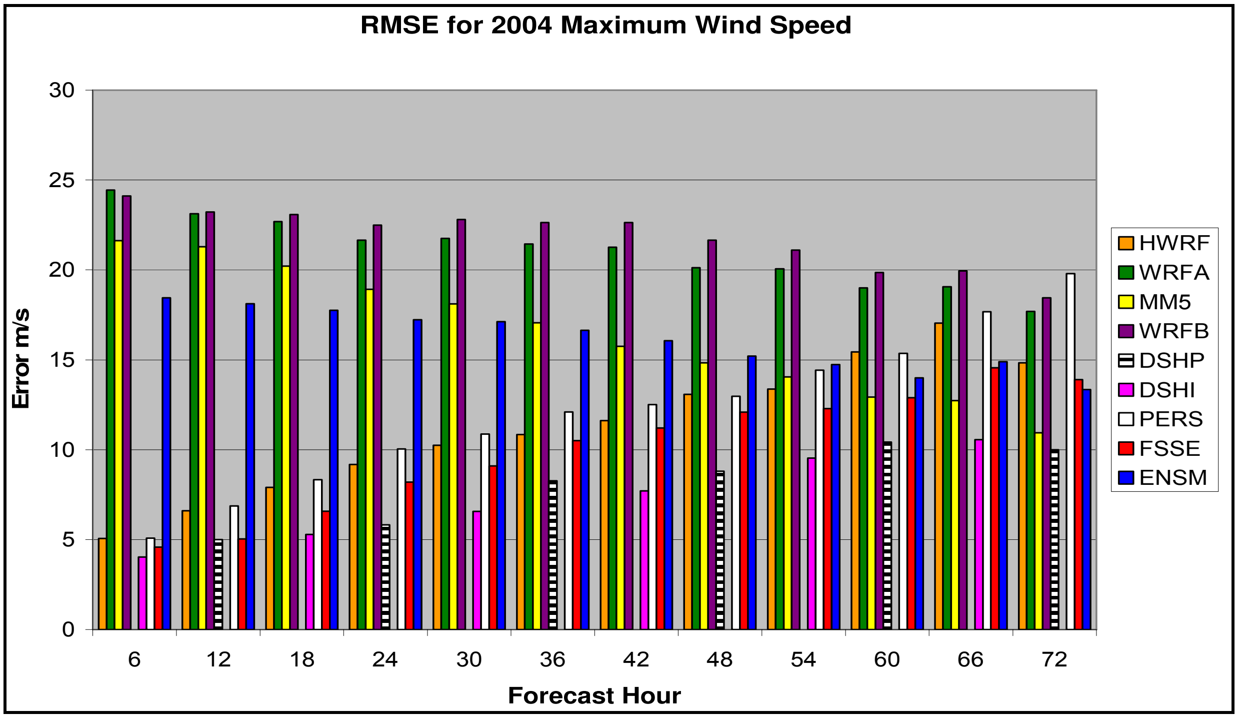

Figure 4.4 The RMSE, in ms^{-1}, for maximum wind speed for 2004.

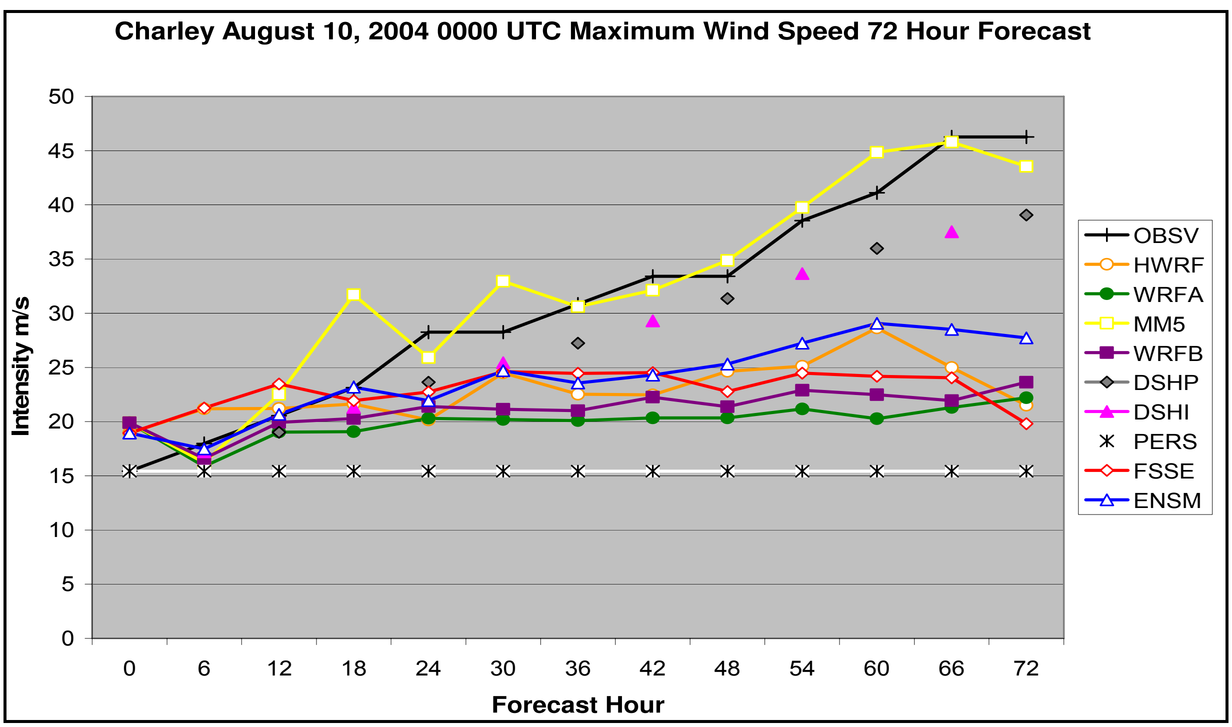

Figure 4.5 The maximum wind speed forecast for Charley, in ms^{-1}, on August 10, 2004 at 0000 UTC showing the MM5 model's ability to capture the intensification of Charley.

4.2 2005 Errors

The 2005 Atlantic Hurricane Season is the most active season on record. This season set many records including for the number of hurricanes and the number of storms reaching category five strength (Beven et al. 2008). A majority of the cases in this study are from the 2005 season. There are a few commonalities between the 2005 and 2004 season most notably the atmospheric flow pattern in 2005 was quite similar to the one in place in 2004 with there being anomalous ridging occurring in the middle troposphere over the eastern United States (Beven et al. 2008). In both instances that tended to produce more westwardly propagating storms than normal.

The pattern of error for the 2005 track shows approximately the same magnitude of RMS error for all 72 hours of the forecast as compared to the 2004 errors, Fig. 4.6.

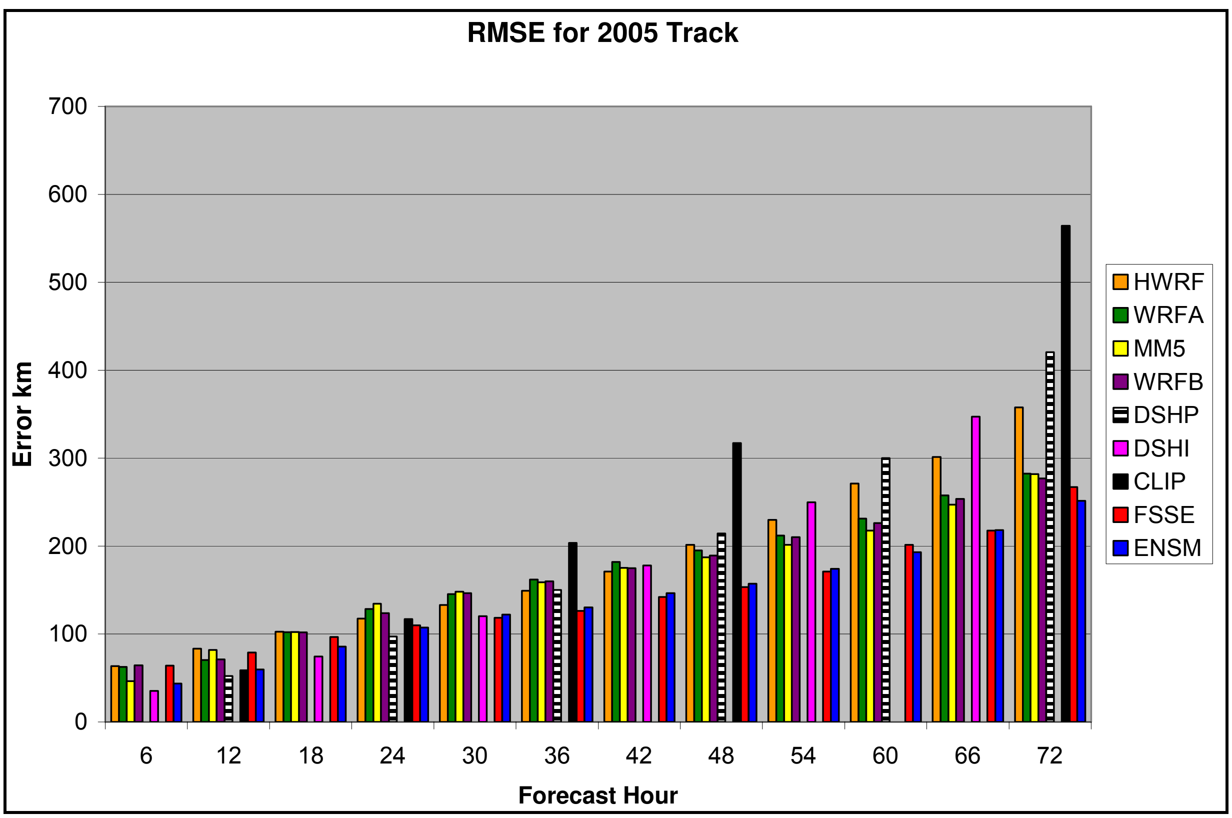

Figure 4.6 The RMSE, in kilometers, for 2005.

The FSSE does well with respect to the member models, but struggles to outdo the ENSM, the DSHP, and CLIP though only early on for CLIP. The reason for this is mostly due to FSSE's forecasts of Harvey and Katrina (not shown), in which both cases erratic model behavior (with respect to other model storm forecasts) is detrimental to the FSSE forecast. Many of the member models had a difficult time forecasting those two tropical cyclones, especially Katrina, as most of the member models forecast the storm to hit the western panhandle of Florida. HWRF's forecast is much closer to the observed position of Katrina affecting the Louisiana Gulf Coast region. The FSSE's forecasts for Katrina are closer to the MM5, WRFA, and WRFB models. The ENSM has a slight edge over the FSSE with this storm as HWRF is much farther to the west pulling the ENSM closer to the OBSV. Future work decomposing the storm motion may provide a better idea of what influenced the storms motion.

The SLP intensity forecasting for the 2005 storms are not as easy for the FSSE as the track forecasting as the model struggles to beat some of its member models after 42 hours, Fig. 4.7. The MM5 model's problem of overintensification gives it the slight

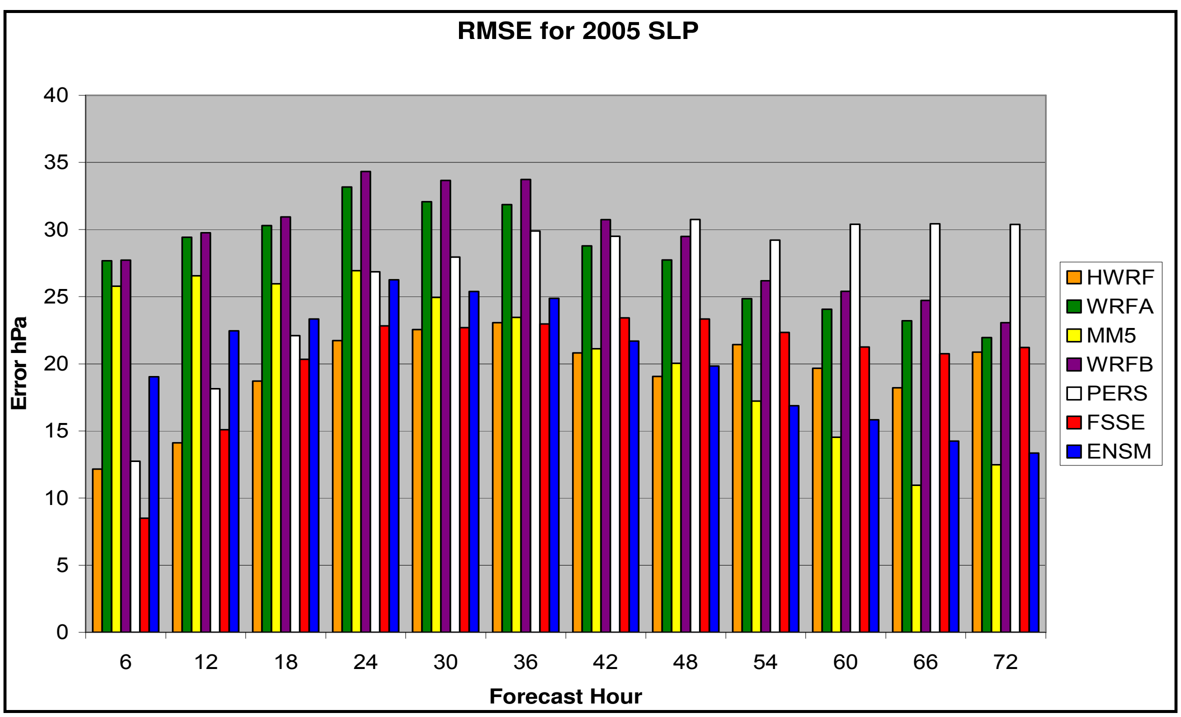

Figure 4.7 The RMSE, in hPa, intensity for SLP for 2005.

edge over the FSSE later in the forecast time, though several times the FSSE is more on target with the SLP later in the forecast than it is. Some of the MM5 forecasts, such as Fig. 4.8, assisted in the reduction of errors of the ENSM as it is pulled away from the other models by the MM5 model and closer to the OBSV. Unlike the MM5, the WRFA and WRFB have a much harder time intensifying the storms. Those models generally have more modest changes in intensity with time usually maintaining one set pattern of intensification per case, yet very rarely does an observed storm maintain one pattern of intensification or weakening for an entire 72 hour period. The pattern of intensity change in most models may partially be a result of the model parameters not correctly simulating inner storm and surrounding environmental changes. Despite that, the FSSE is still able to make accurate forecasts early on, seen in Fig. 4.8 for six to 36 hour period. If the member models were better able to replicate the intensity changes seen in the observed at the later hours the FSSE would likely be able to more accurately correct for the model biases and issue an improved forecast.

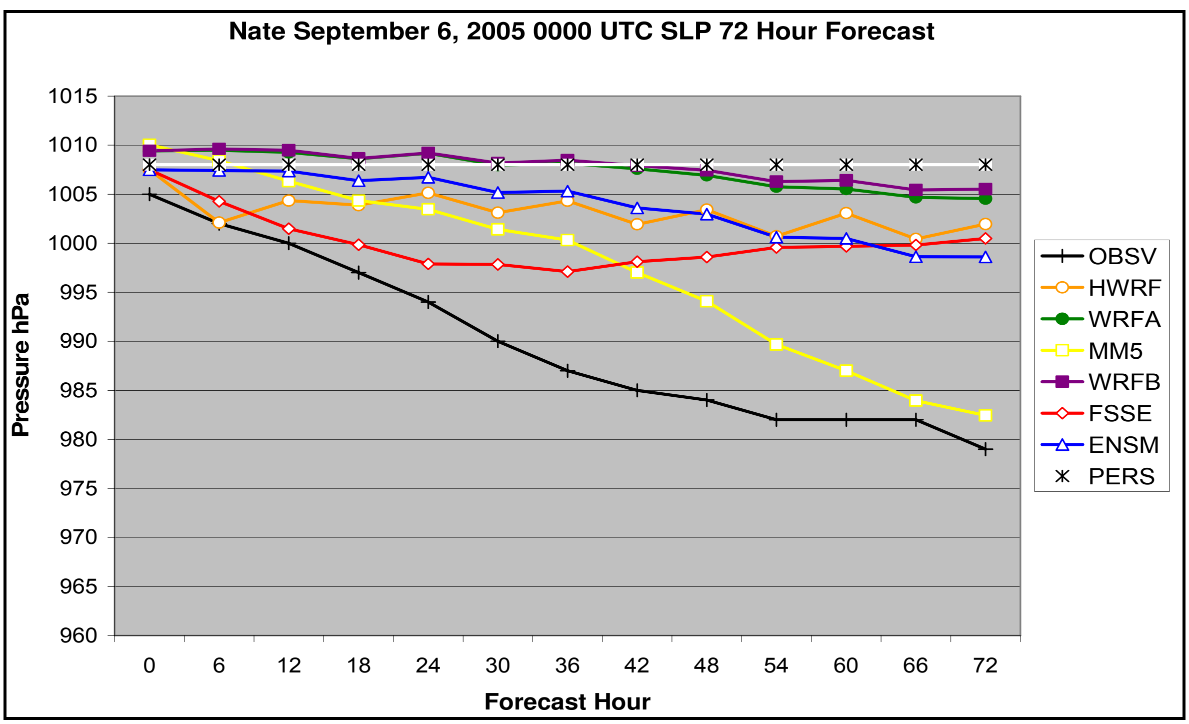

Figure 4.8 The SLP forecast, in hPa, for Hurricane Nate on September 6, 2005 at 0000 UTC. After 42 hours the MM5 is best able to capture the continuing intensification of the storm.

The maximum wind speed forecasts are a bit easier for the FSSE to forecast, however like the 2004 season the DSHP model has more accurate forecasts than the FSSE though this time only up to 48 hours, Fig. 4.9. The FSSE shows skill over DSHP at later hours as the DSHP has problems with overintensification of Hurricane's Philippe and Stan (not shown) and has a problem of weakening some storms at the wrong time such as Hurricane Katrina and Hurricane Wilma (both not shown). The PERS forecast does quite well early on primarily due to the fact that Tropical Storm Harvey, Hurricane Irene, and Hurricane Katrina all have several hours of steady state wind conditions exactly matching the observations and those cases help to reduce the overall errors giving PERS the edge over all the models at six hours and over many of the models up to 24 hours. PERS, however, is not a realistic forecast as in most cases tropical cyclones frequently change intensity throughout their lifecycle. Though, it does demonstrate that the models are usually unable to simulate the steady state behavior of tropical cyclones.

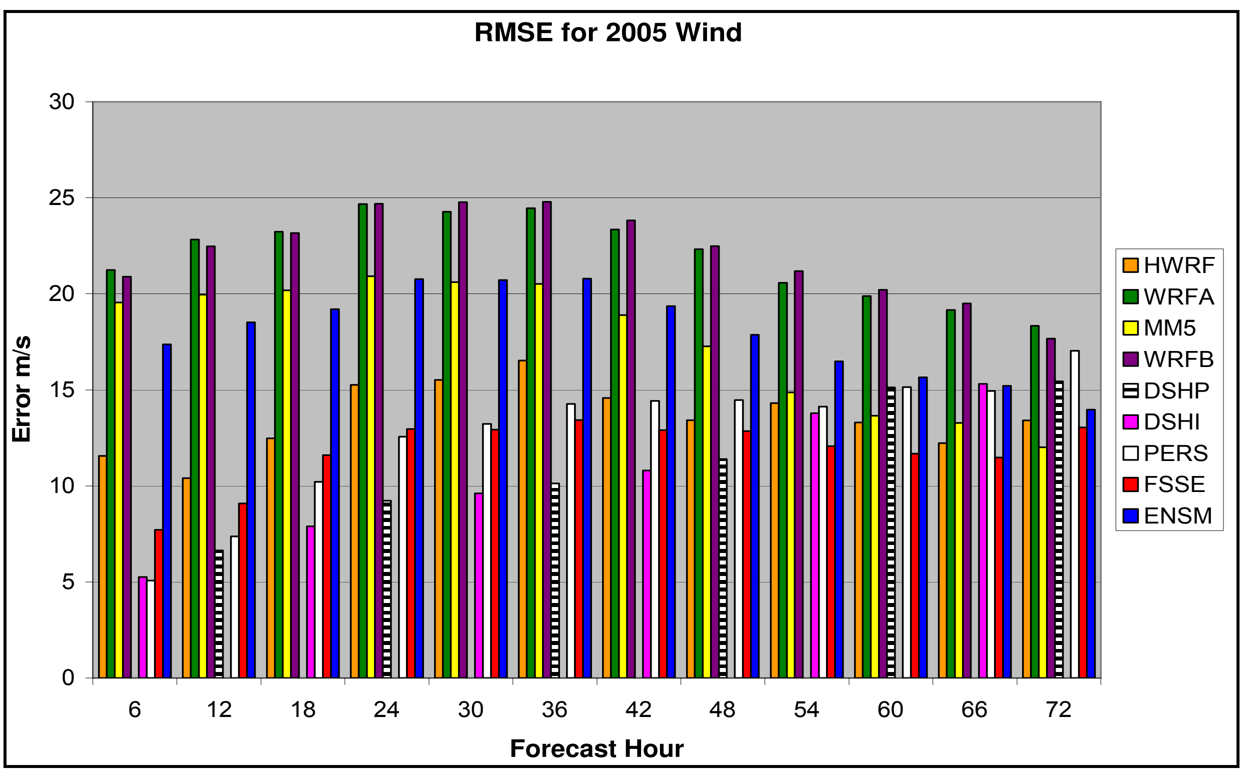

Figure 4.9 The RMSE, in ms^{-1}, for maximum wind speed in 2005.

4.3 2006 Errors

The 2006 Atlantic Hurricane Season was the least active season of all the seasons examined in this study. Hurricane Isaac, the last storm of the season to develop only lasted until October 2 giving an early end to the hurricane season only succeeded, after 1966, by 1983 and 1993 seasons which both ended on September 30 (Franklin and Brown 2008). Overall the 2006 hurricane season produced much weaker storms with only two of the storms becoming major hurricanes (Franklin and Brown 2008). These weaker storms help make the 2006 season one of the most successful seasons for all the models, including the FSSE, as SLP and maximum wind speed errors are lower than the other two years.

The 2006 track forecasts are not as good for the FSSE as in 2004; but it does very well with respect to the WRFA, WRFB, and MM5, Fig. 4.10. The 2006 season has several recurving tropical cyclones (not all shown here), a noticeable difference from the

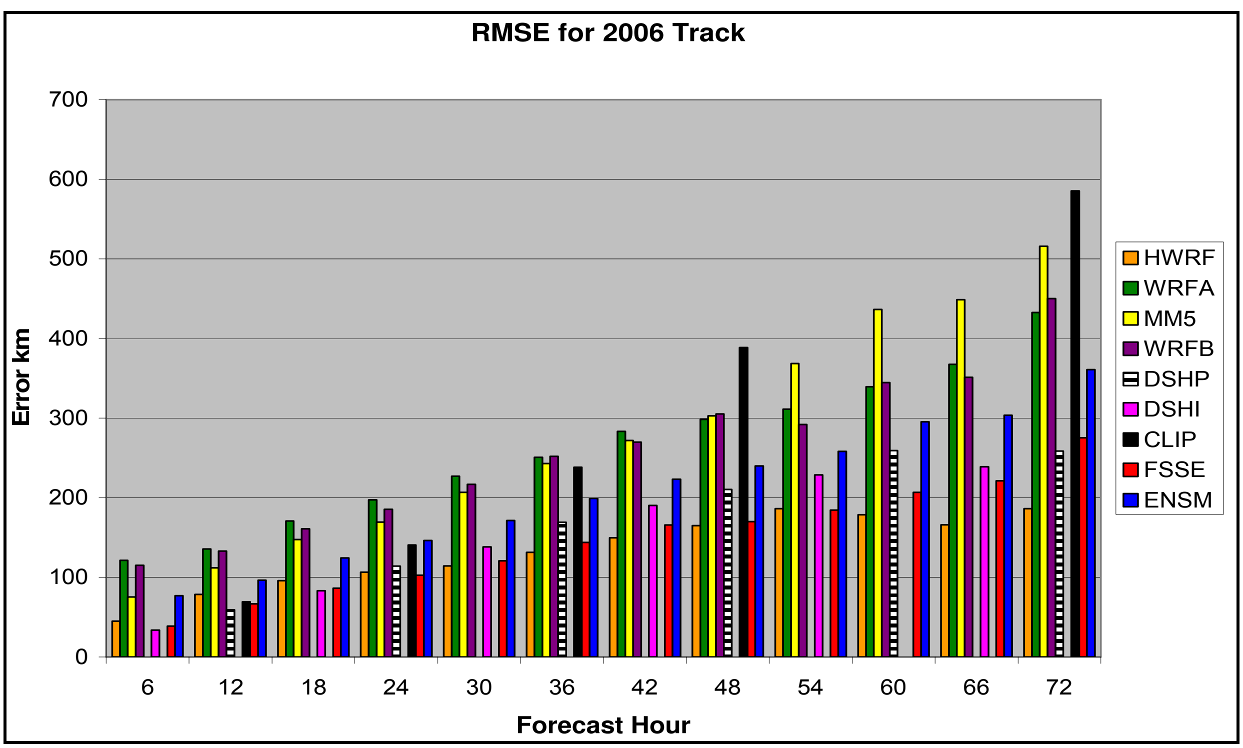

Figure 4.10 The RMSE, in kilometers, for track forecasts of 2006.

2004 and 2005 seasons, which have primarily westward moving storms. The WRFA, MM5, and WRFB have a harder time with the 2006 storms as the RMS track error magnitudes are higher for 2006 than 2004 and 2005. The WRFA, WRFB, and MM5 have a particularly difficult time with Hurricane Ernesto, Hurricane Gordon, and Hurricane Helene pulling the ENSM farther away from observations and giving the FSSE the edge (Ernesto not shown, Helene and Gordon shown in Chapter five). None of the models forecast Ernesto to hit Florida and four of the models have Ernesto hitting Jamaica. The exact reasons for this are difficult to explain and further examination of the model gridded fields may explain their behavior. CLIP errors are quite large at the later forecast hours and the forecasts of Hurricane Isaac proves most troublesome for this model as it is unable to correctly simulate the forward motion of the storm.

The FSSE does better with the 2006 SLP forecasts as a majority of its forecasts have lower RMS errors than the other models Fig. 4.11. Also the magnitudes of the RMS error are less than 2004 and 2005, having no overall errors larger than 14 hPa.

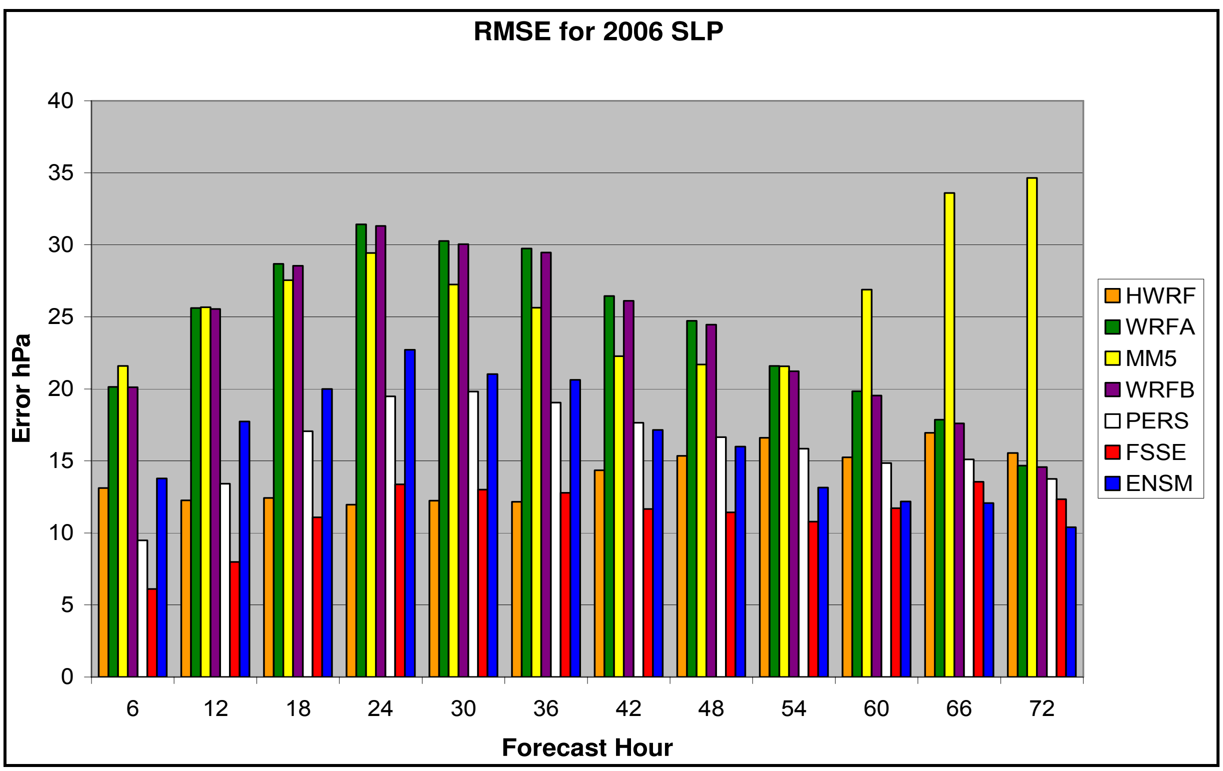

Figure 4.11 The RMSE, in hPa, intensity for SLP for 2006.

The MM5, WRFA, and WRFB have six hour RMS errors that are on average five hPa lower than 2004 and 2005. The weaker initial intensities (e.g. Tropical Storm Debby) are much easier for the model to capture resulting in lower errors. These weak intensities occasionally pull the ENSM farther from the observed (e.g. Gordon) giving the FSSE an edge over the ENSM.

The FSSE performs well for maximum wind speed forecasting with it having the least error out of all the models a majority of the time, Fig. 4.12, and lower overall errors than the 2004 and 2005. The MM5 has several problems with overintensification at later hours (Tropical Storm Chris and Hurricane Ernesto) resulting in the large errors seen for its 66 and 72 hour forecasts. The weakening of Hurricane Ernesto and

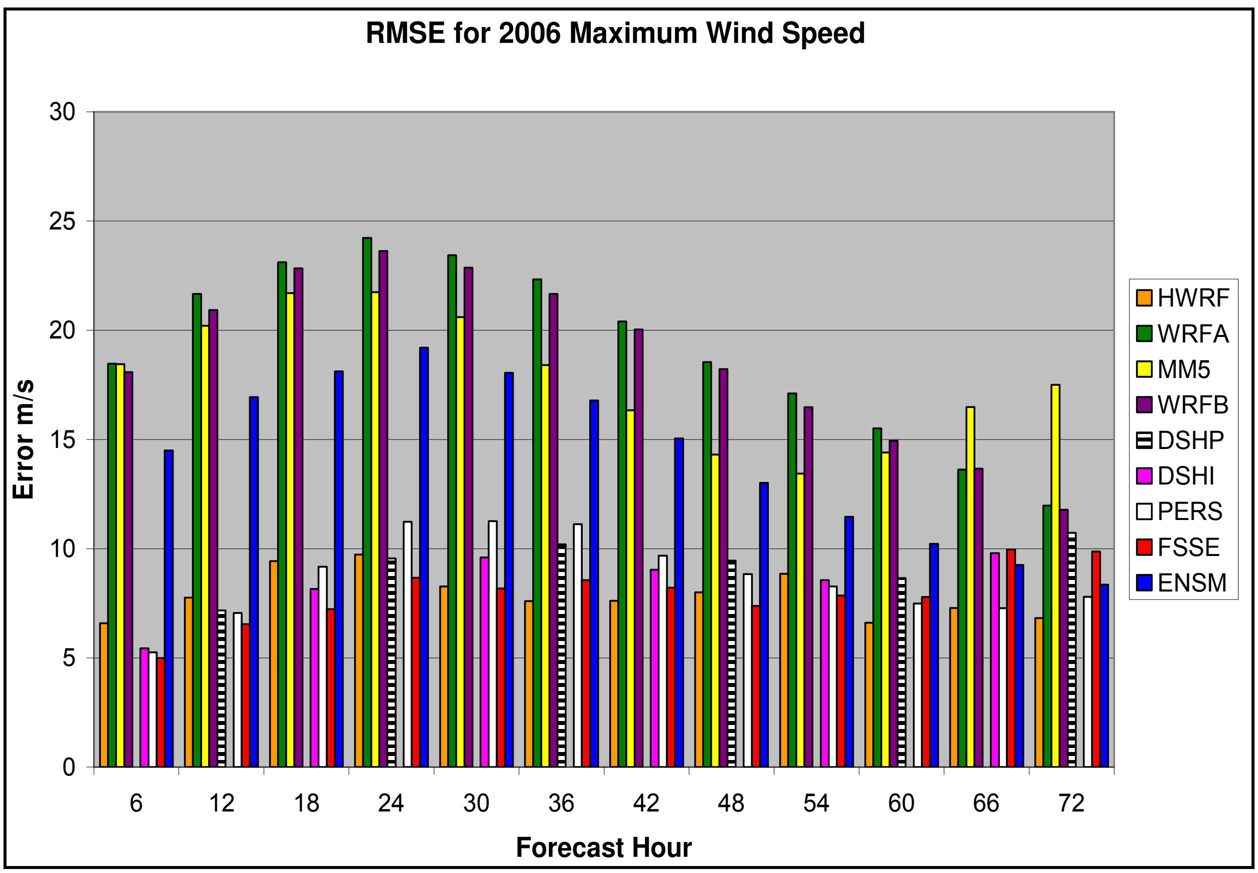

Figure 4.12 The RMSE, in ms^{-1}, for maximum wind speed in 2006.

Hurricane Helene is better approximated by the HWRF. PERS had an edge over the FSSE at the later forecast hours as Hurricane Helene's observed steady state conditions exactly matched the PERS forecast. At the later forecast hours the member models are somewhat divided on forecasted maximum wind speed of the storm making the FSSE forecasting a bit difficult. There is usually one outlier in those instances that helps to push the ENSM a bit closer to the OBSV.

4.4 Discussion

Careful examination of the different storms reveals much fluctuation in model behavior from storm to storm and year to year. For most of the 2006 hurricane season the MM5, WRFA, and WRFB tend to forecast the hurricane well eastward of the observed track. That same trend does not occur in the other two years and storms such as Hurricane's Gaston, Nate, Ophelia, Philippe, and Stan make discerning a model track biases more difficult for the FSSE.

A tropical cyclone's track is largely dependent upon the surrounding environmental steering. The layers of the atmosphere affecting the motion are dependent on the tropical cyclone intensity with very intense hurricanes generally being steered by a higher and thicker layer of the atmosphere than weak tropical storms (Velden 1993). The intensity of a storm is dependent upon the interactions between internal storm dynamics, such as eyewall replacement cycles and rainbands, and external storm dynamics, such as environmental shear, upper level flow pattern, and trough interaction. The interplay of those two factors within a storm is not fully understood and fluctuates from storm to storm and with the storm's lifecycle. Simply because one process is dominant in intensity modification at a certain time does not mean another process cannot be working in the background to also alter the intensity of a storm. To better predict storm motion it is essential to understand the relative role these process play in modulating the tropical cyclones track.

Just as scientists struggle to forecast and understand such processes models have even greater difficulty forecasting them. If models cannot correctly forecast the different mechanisms for intensity change than it cannot be expected that they will achieve the correct storm intensity (though they may). This makes accurate forecasting difficult and it makes it harder for the FSSE to provide the best bias correction at all times. To attempt to solve that problem, it may be necessary to further determine how different models intensify or weaken storms and construct training sets and tropical cyclone forecasts based on those relationships.

Another way to improve the intensity forecasts may be to fine tune the physics schemes used within the model and making sure they are applicable for the scales being studied, as some of the currently used cumulus parameterization schemes or explicit moisture schemes for mesoscale models seem to be more appropriate for coarser resolution models. The resolutions of the currently run models may also need to be reduced (to one or two km) to be better able to resolve more realistic clouds. However, one to two kilometer resolution requires a lot of computational power and storage, which for operational purposes is not always available though models of that scale are currently being developed and their inclusion in the FSSE may improve its track and intensity forecasts. Several more explanations for model behavior will be presented at the end of Chapter five.

CHAPTER FIVE

INDIVIDUAL STORMS AND MODEL DISCUSSION

5.1 Overview

In this section some select storms will be examined in detail. The evolution of the storm within the models and in the observed will be shown with track maps, the SLP forecasts, maximum wind speed forecasts, the errors and biases of those storms, and a synoptic discussion about each storm. Except for Ivan only one forecast will be presented and discussed per storm.

One of the original goals of this study was to compare the mesoscale FSSE results to some large scale FSSE results to determine if the inclusion of higher resolution mesoscale models in the FSSE yields an improvement in track and intensity forecasts of tropical cyclones. This section will present and compare the RMS errors of the mesoscale and large scale FSSE to determine if the use of mesoscale models does lead to more accurate forecasts. Following that analysis some additional sources of member model error will be discussed to provide an idea of the current limitations that still exist with this work and how those models and the FSSE can be improved.

5.2 Hurricane Ivan

Hurricane Ivan was a long-lived Cape-Verde hurricane that developed well to the east of the Lesser Antilles and became one of the more unusual storms of the 2004 hurricane season (Stewart 2005). Hurricane Ivan developed at about 1800 UTC on

September 2, 2004 approximately 4000 km east-southeast of the Lesser Antilles and then began to move west. On September 6 Ivan underwent a period of rapid intensification, making it the southernmost major hurricane on record at that point (Stewart 2005). It then weakened, possibly as a result of dry air intrusion, but soon after underwent another period of rapid intensification (Stewart 2005). By September 8 Ivan was moving southwest of Grenada and entering into the Caribbean Sea. While in the Caribbean Sea, Ivan went through several weakening and intensifying phases and brushed the island of Jamaica. On September 12, beginning of the Ivan forecast for this study, the storm passed south of Grand Cayman Island having recently deepened to a pressure of 910 hPa. Ivan was able to maintain category five strength as it entered into the Gulf of Mexico and at approximately 0650 UTC on September 16 Ivan made landfall near Pine Beach, Alabama. It continued to move northeast up into the United States midatlantic region re-emerging at the Delmarva Peninsula on September 18. After Ivan re-emerged into the Atlantic Ocean it began to move southward and eventually crossed over the southern tip of Florida on September 21. Ivan made landfall for the second time on September 24 at 0200 UTC near Holly Beach, LA. Ivan caused significant damage in Grenada, Grand Cayman Island, the Panhandle of Florida, and Southern Alabama (Stewart 2005). Only September 12 at 1200 UTC and September 13 at 1200 UTC 72 hour forecast periods of Ivan will be examined here.

The model track forecasts for Ivan are reasonably close to the observed the first half of each forecast though there are some larger deviations later in the forecast time, Fig. 5.1, most notably with the DSHP model. The FSSE does quite well and the track forecast of September 12 at 1200 UTC and nearly matches the observations. Most of the other models are in good agreement with each other the first 30 hours of the forecast, except for the DSHP and MM5 which have Ivan veering off towards Panama City, Florida. The corresponding track errors show FSSE having the lowest errors for all of the forecast hours except at 6 hours, Fig. 5.2 with at other hours it having significantly lower than errors for the other models, especially DSHP, WRFA, MM5, and WRFB. As Ivan continued to approach land forecasting the track became a bit more difficult as

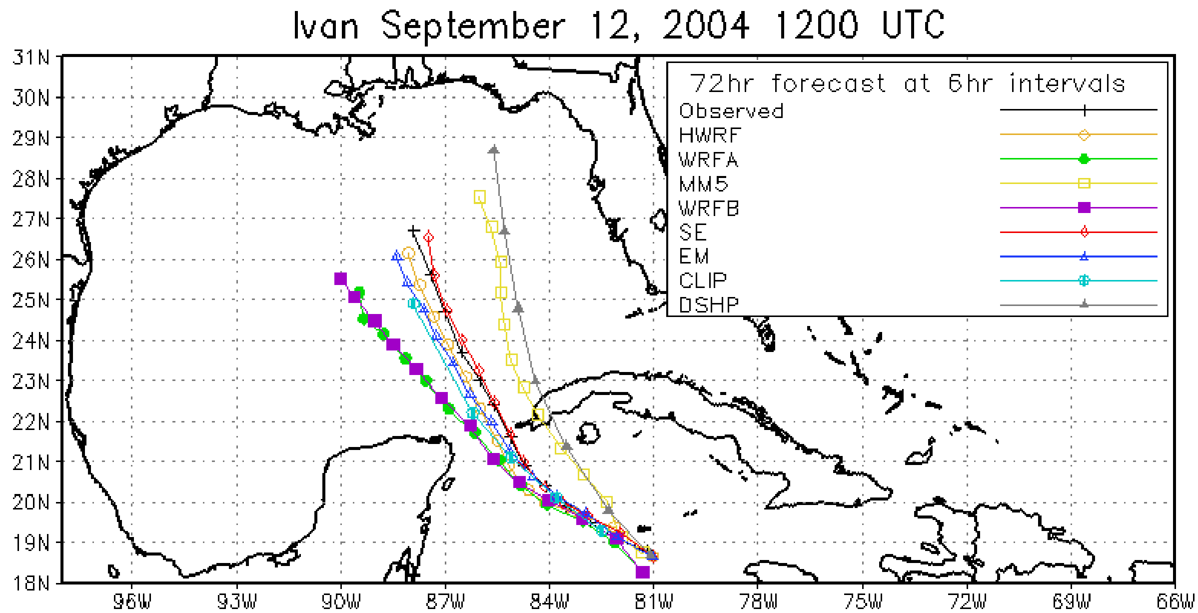

Figure 5.1 The 72 hour track forecasts for Hurricane Ivan on September 12, 2004 at 1200 UTC. The OBSV is the black line with plus signs and the FSSE is the red line with diamonds.

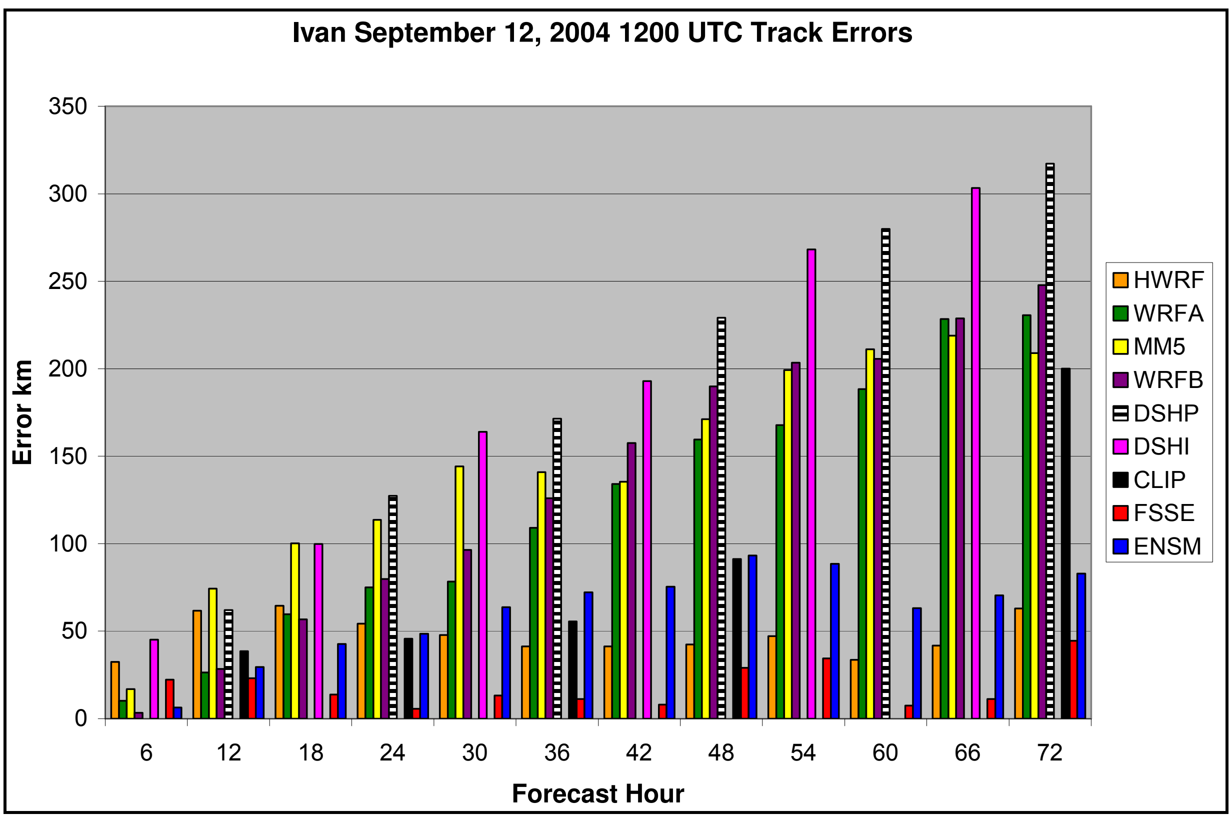

Figure 5.2 Track errors out to 72 hours, in kilometers, for Hurricane Ivan on September 12, 2004 at 1200 UTC.

several of the models incorrectly forecast the forward speed and landfall location, Fig. 5.3. FSSE does reasonably well up to 60 hours after which it begins to forecast Ivan to hit Pensacola. The HWRF and MM5 also experience a similar problem and have Ivan slightly east of the observations at the end of the forecast.

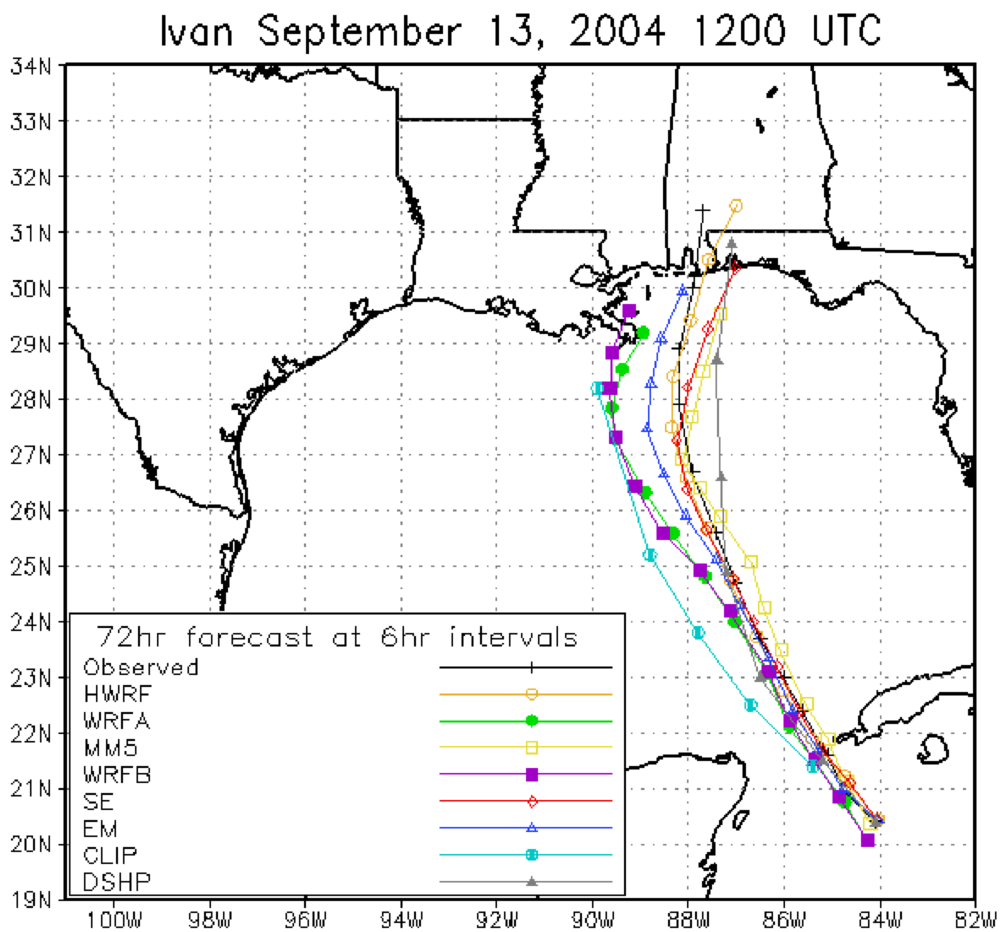

Figure 5.3 The 72 hour track forecasts for Hurricane Ivan on September 13, 2004 at 1200 UTC.

SLP forecasts are not nearly as good for some of the models as their track forecasts as some of their initial SLP values are over 60 hPa weaker than the observed and they have a difficult time getting the intensification and weakening phases correct in both time and duration, Fig. 5.4. The FSSE shows a fairly steady pattern early on with a

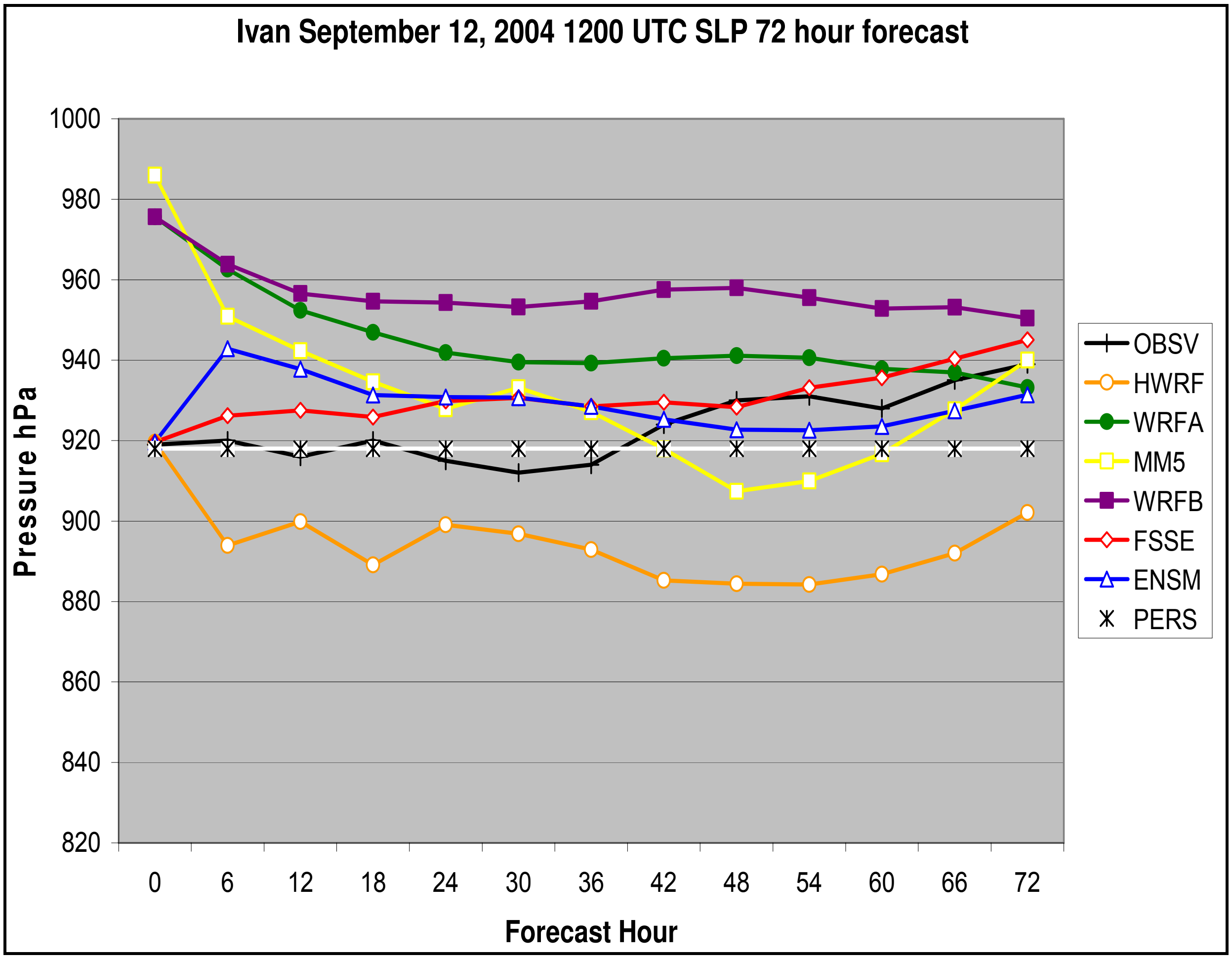

Figure 5.4 SLP 72 hour forecast, in hPa, for Hurricane Ivan on September 12, 2004 at 1200 UTC.

weakening trend at the end that partly matches up with the timing of the last weakening phase of Ivan. WRFA and WRFB struggle to properly develop the storm whereas HWRF overdevelops the storm, deepening Ivan to pressures close to 885 hPa. Note the large pressure drop in the HWRF model during the first six hours of the forecast and how there is no corresponding change in the wind field, Fig. 5.5, demonstrating that the model may be out of balance early in the forecast. This change in pressure within the model is part of the geostrophic adjustment process to bring the model back into balance. Commonly when the radius of maximum winds is much smaller than the rossby radius of deformation the pressure field adjusts to the wind field and not the reverse. There are also large pressure changes observed in the MM5 model in the first

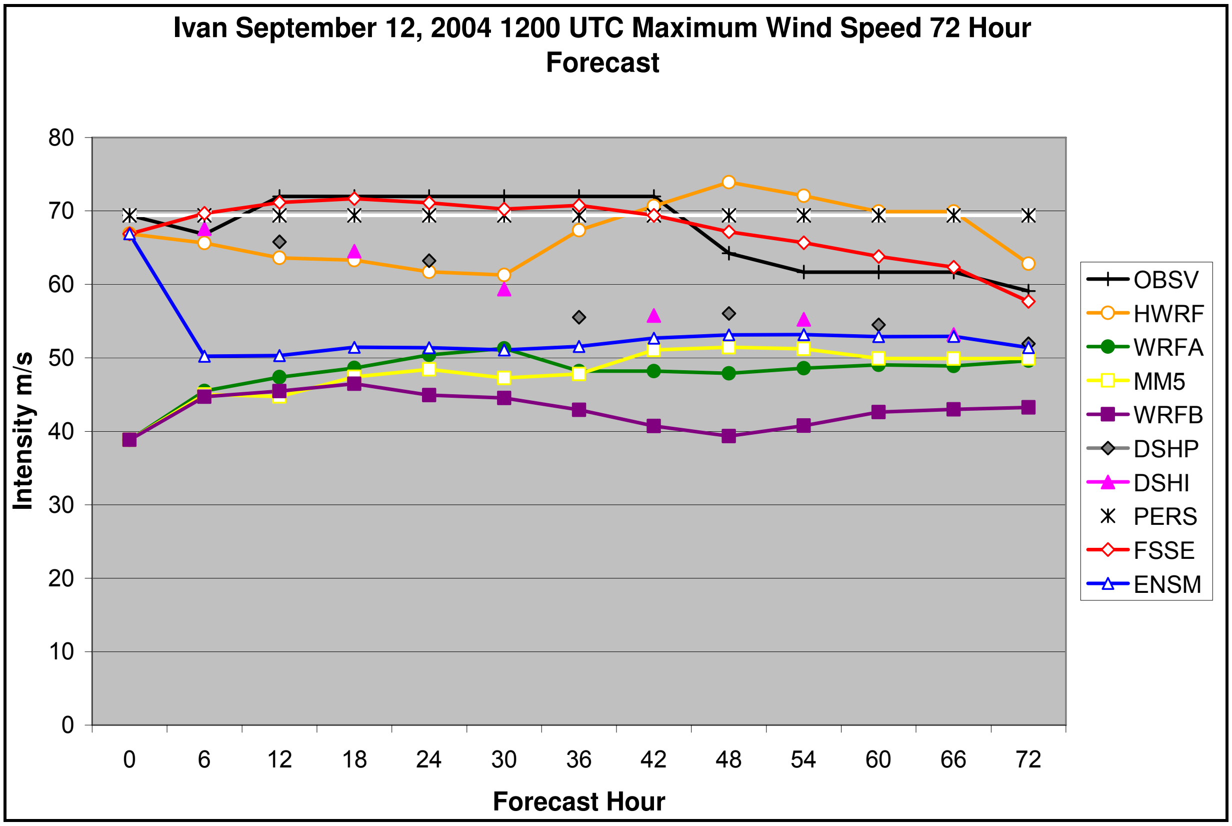

Figure 5.5 The 72 hour forecast maximum wind speed, in ms^{-1}, for Hurricane Ivan on September 12, 2004 at 1200 UTC.

six hours of its forecast, Fig. 5.4, however in those instances the wind field and pressure field change correspondingly, not one adjust to the other. The reasons behind MM5's pressure changes may be more a result of the physics options chosen than the model being out of balance. Previous work by Braun and Tao (2000) examined various PBL parameterizations in simulations of Hurricane Bob (1991) and the model parameters recommended from their work were used to run the MM5. Closer examination of their work reveals that Ivan is a much more intense storm than Bob and thus the model parameters they chose may not be best for stronger storms like Ivan. The SLP errors show the FSSE has some of the lowest errors after 42 hours, Fig. 5.6 but the PERS model does better early on. HWRF errors are on average 30 hPa different from the observations, and the WRFB is the only model to underestimate the SLP the entire length of the forecast.

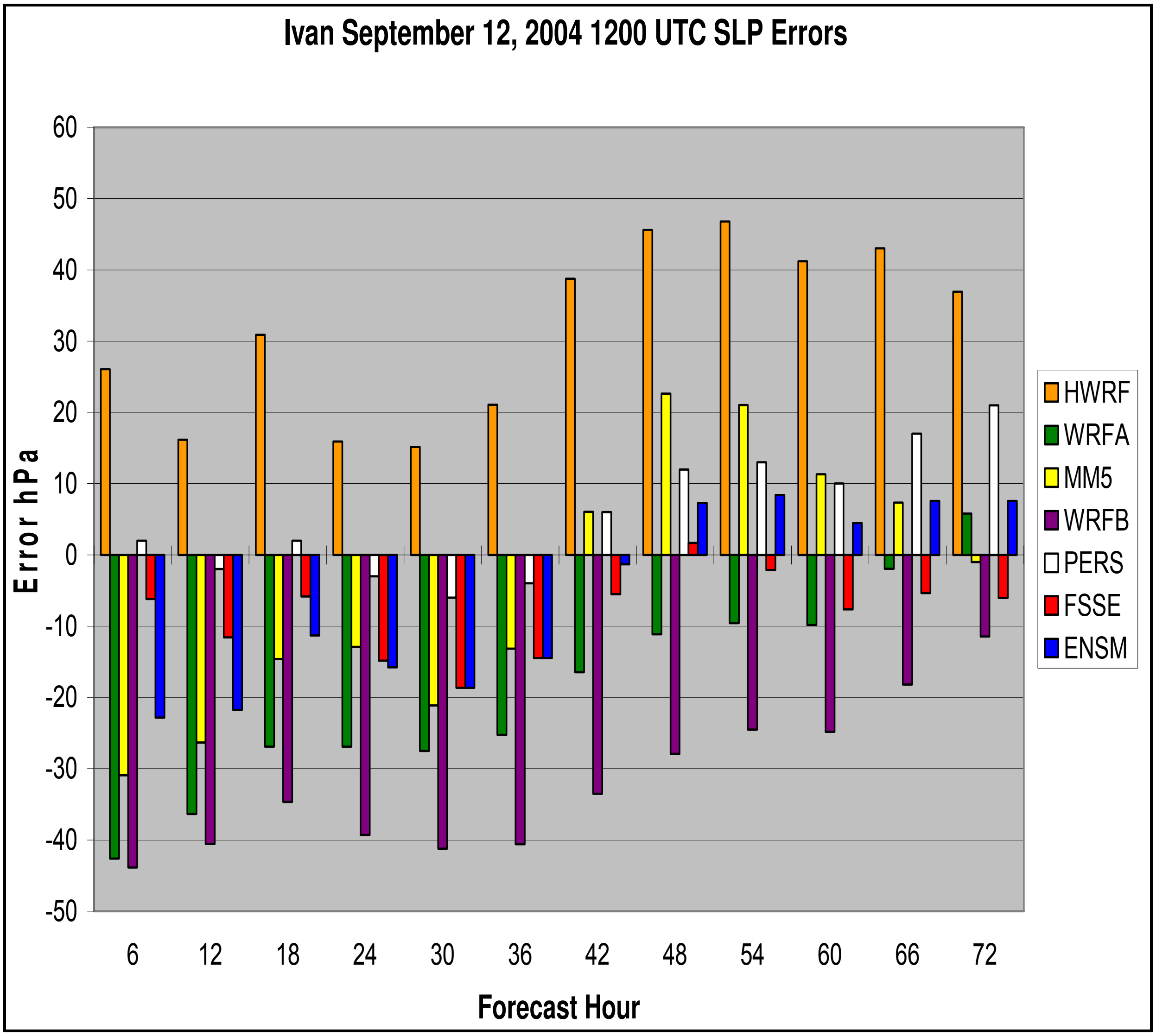

Figure 5.6 SLP errors out to 72 hours, in hPa, for Hurricane Ivan on September 12, 2004 at 1200 UTC.

The FSSE has more success with the maximum wind speed forecasts for Ivan and is fairly close to the observed throughout the first half of the forecast with a bit more deviation later on in the forecast. The HWRF model exhibits a rather odd trend of having an overintensification of the SLP throughout the duration of the forecast but having an underestimation of the maximum wind speed for the first half of the forecast, Fig. 5.5. This may partially be explained by the models initial pressure adjustment to the wind field in its attempt to get back into balance as discussed earlier, though further work needs to be done to fully understand the differences between the two fields. The maximum wind speed is reasonably well forecast by the FSSE with most of the other models underestimating the maximum wind speed of the storm particularly during the first half of the forecast. Fig 5.7 magnifies this underestimation showing error values which are occasionally in excess of 25 ms^{-1}; the FSSE has a much lower average of less than 2 ms^{-1}, half of the magnitude of the best model.

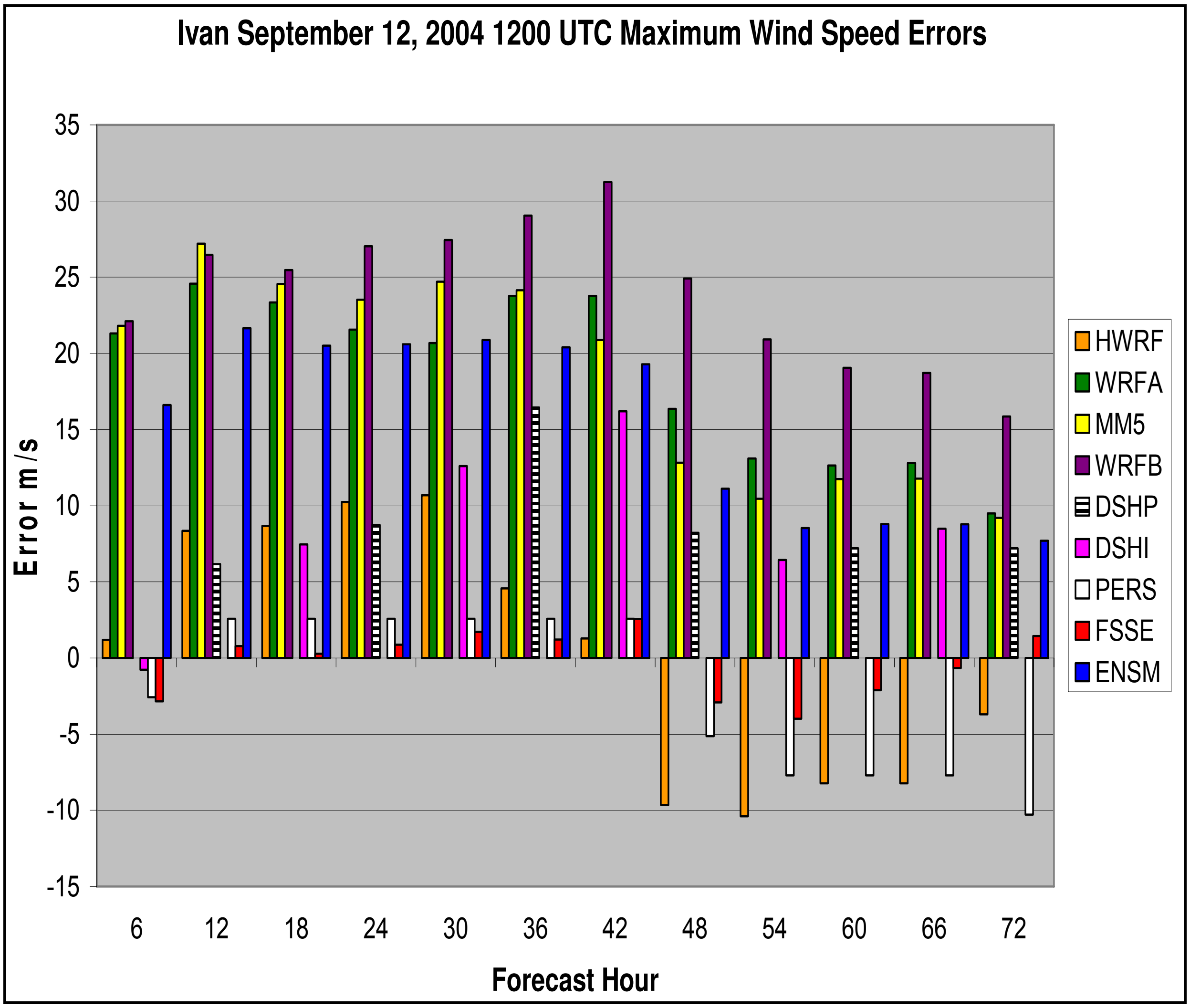

Figure 5.7 Maximum wind speed errors out to 72 hours, in ms^{-1}, for Hurricane Ivan on September 12, 2004 at 1200 UTC.

5.3 Hurricane Gordon

Hurricane Gordon was a mid-Atlantic tropical cyclone that affected the Azores and wreaked havoc on parts of Western Europe as an extratropical cyclone (Blake 2006). Gordon developed on September 10, 2006 at about 1800 UTC approximately 870 km east-northeast of the Leeward Islands. After some initial intensification early on Gordon moved northwest and then north starting on September 13, the beginning of the Gordon forecast in this study. During that time of northward motion Gordon was rapidly intensifying and managed to become a major hurricane, though thankfully was well out to sea. Soon after Gordon began to slow down and weaken but with the help of a developing high pressure system to the east was pushed northeastward on September 17 (Blake 2006). As the storm continued accelerating to the northeast it continued to weaken a result of increasing shear and lower SST's (Blake 2006). Gordon moved over the Azores around 0900 UTC on September 20 and later that day interaction with a cold front helped it to transition from a tropical cyclone to an extratropical cyclone (Blake 2006). Gordon was able to maintain hurricane strength as it approached the Iberian Peninsula and the British Isles, with much of those areas experiencing heavy rains and strong winds until the storm dissipated over the British Isles (Blake 2006). Only the September 13 0000 UTC 72 hour forecast period for Gordon will be examined here.

The track forecasts for Gordon are a bit more difficult for the models than they were for Ivan as they tend to accelerate the storm somewhat more than observed and most of the tracks are well west of the observations, especially at the later forecast hours. The FSSE and HWRF have more success with their forecasts being much less to the west than the other models though they too had a higher forward speed than the observed, Fig. 5.8. The MM5 has a smaller low embedded within it (just south of its main circulation) helping to steer the storm closer to Bermuda and away from the observations. That secondary low feature is not seen in the other models. Next to HWRF, FSSE has some of the lowest track errors, generally less than 100 kilometers even at 60 hours, Fig. 5.9.

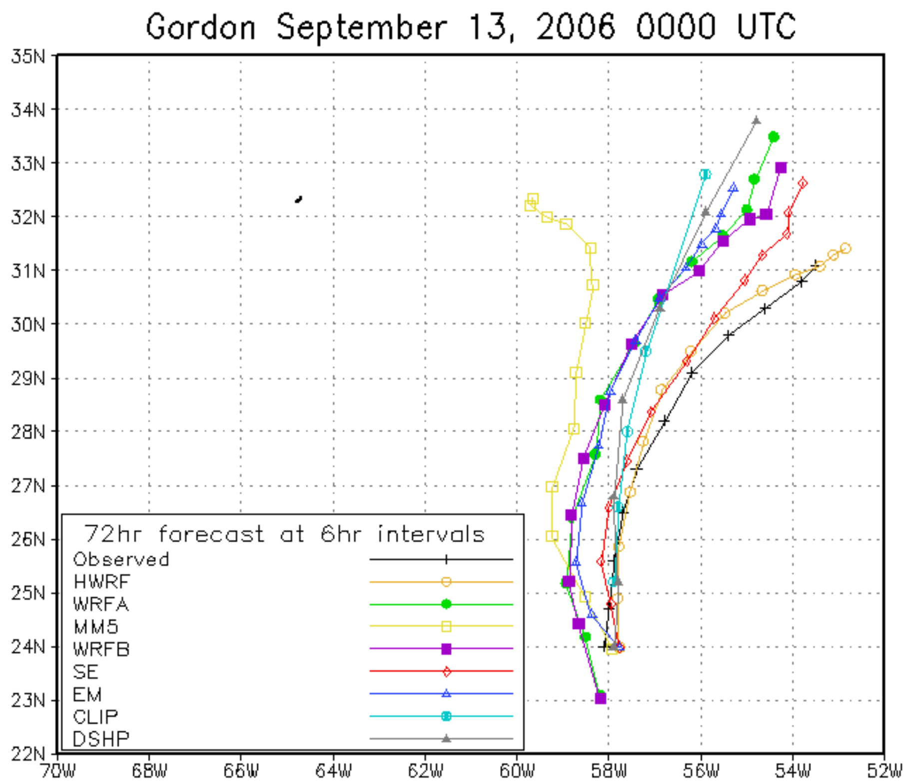

Figure 5.8 The 72 hour track forecasts for Hurricane Gordon on September 13, 2006 at 0000 UTC.

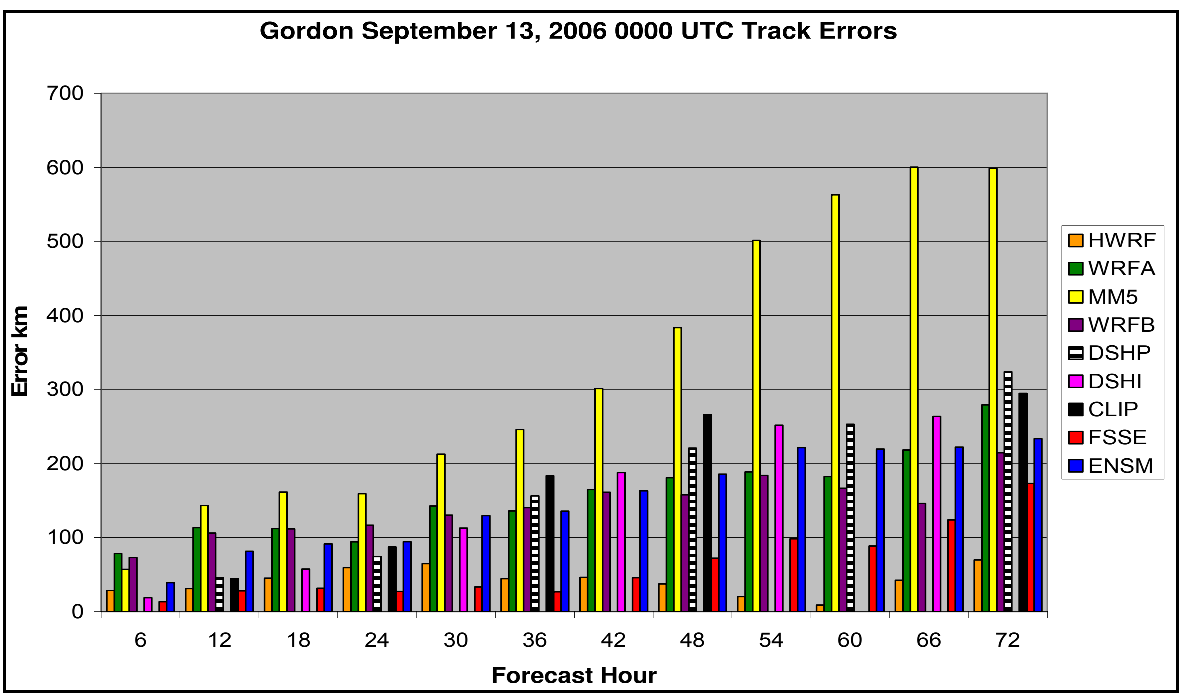

Figure 5.9 Track errors out to 72 hours, in kilometers, for Hurricane Gordon on September 13, 2006 at 0000 UTC.

Oddly the WRFA and WRFB overestimate the initial SLP of Gordon, but they quickly began to weaken the tropical cyclone, Fig. 5.10. There are multiple instances of the model forecasted cyclones weakening initially but the weakening that occurs in this case is more than triple the second highest rate of .86 hPa/hr. The FSSE shows a slightly similar intensity trend as compared to the observations, however produces a much weaker tropical cyclone. HWRF better approximates the SLP of the storm, yet forecasts a short period of weakening not noticed in the observations. The MM5 has a fairly constant SLP in time with only some slight weakening occurring and the WRFA and WRFB behave similarly to the MM5 after their initial weakening. The errors associated with this forecast, Fig. 5.11, show that aside from the HWRF model the FSSE is able to beat all the other models in all but the 72 hour forecast.

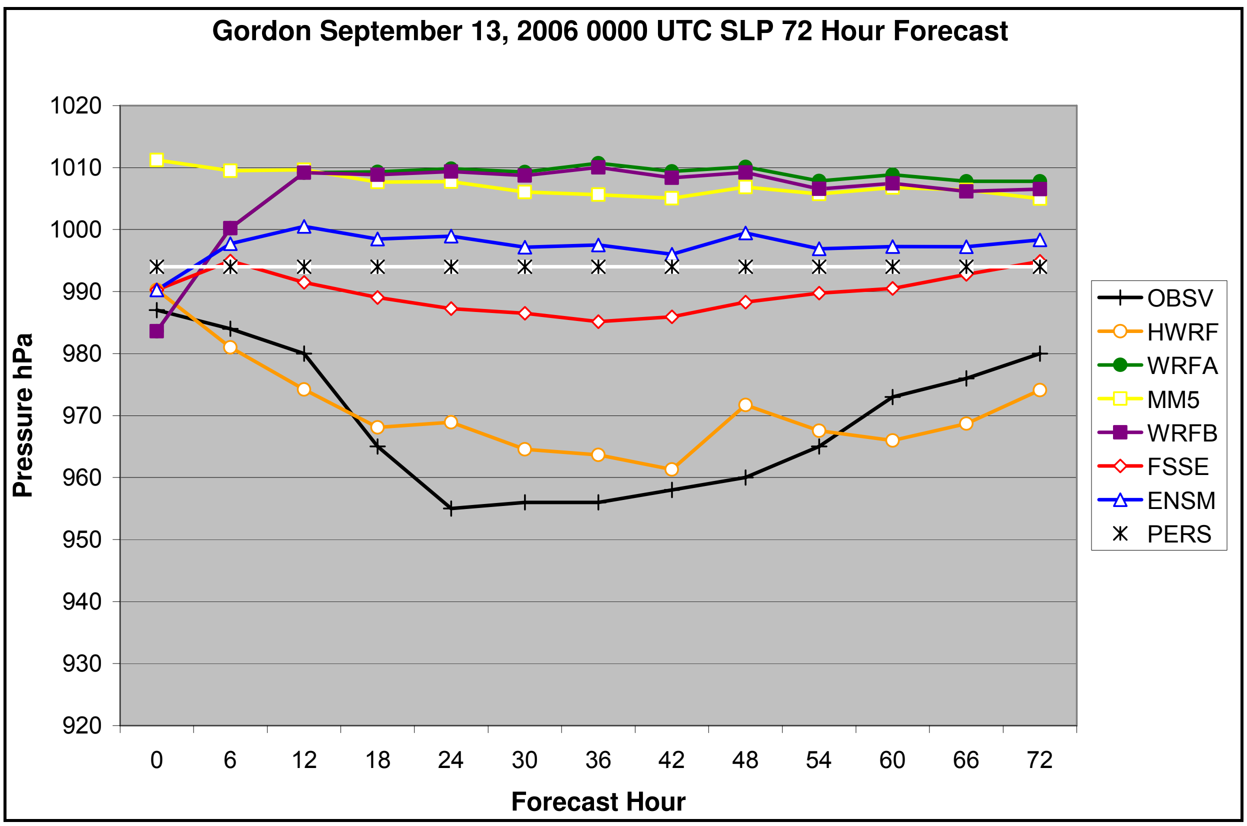

Figure 5.10 SLP 72 hour forecast, in hPa, for Hurricane Gordon for September 13, 2006 at 0000 UTC.

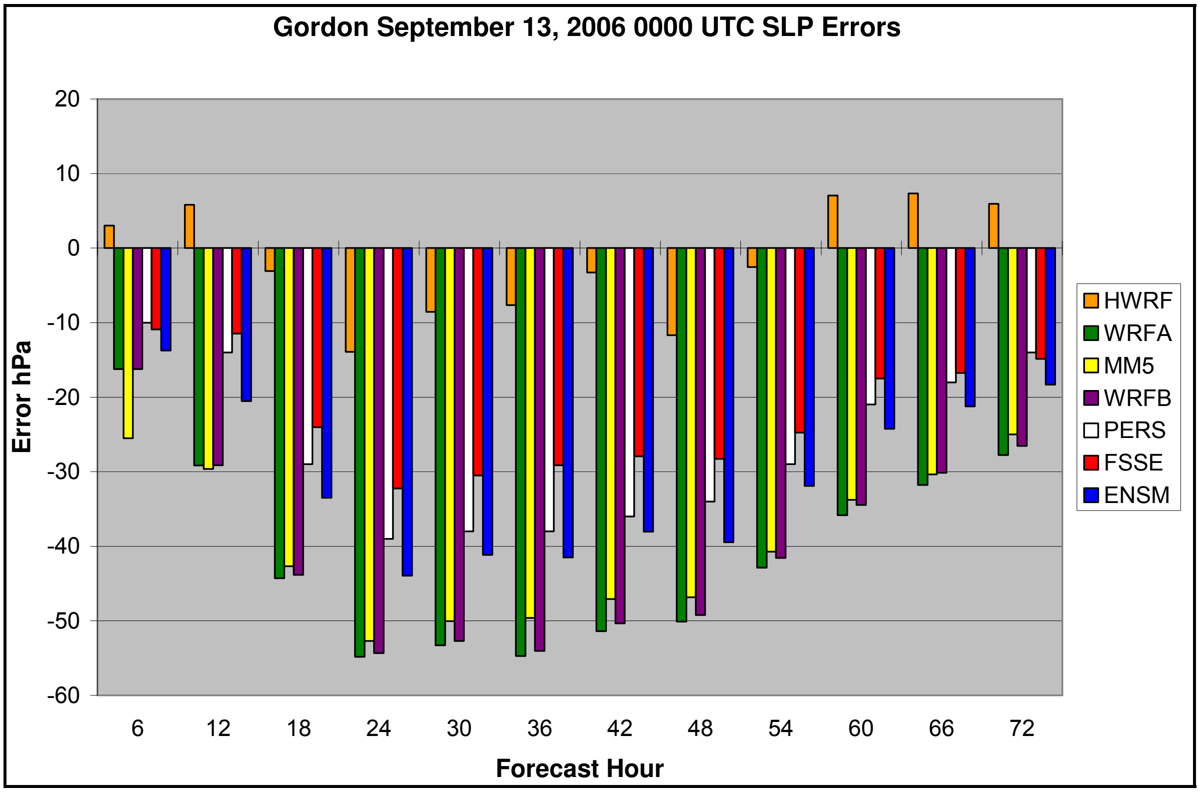

Figure 5.11 SLP errors out to 72 hours, in hPa, for Hurricane Gordon on September 13, 2006 at 0000 UTC.

The HWRF issues a more accurate forecast of SLP for Gordon than the other models, but the FSSE has a more accurate forecast of the wind speed; however the DSHP model better approximates the strongest wind speeds of Gordon. Notice that the first 12 hours and last 12 hours of the forecast are best forecast by the FSSE, Fig. 5.12. The FSSE is able to forecast the timing of the intensification and weakening of Gordon but struggles with the rate of intensification and weakening. The DSHP model forecasted winds are too strong during the first 12 hours and the last 12 hours. The three models run at FSU show a decrease in wind speed the first 12 hours but a modest increase the remainder of the forecast with none of those models forecasting wind speeds above tropical storm force, causing the huge RMS errors seeing in Fig. 5.13. The FSSE has low errors throughout the forecast and the lowest errors for the 6, 12, 60, 66 and 72 hour forecasts.

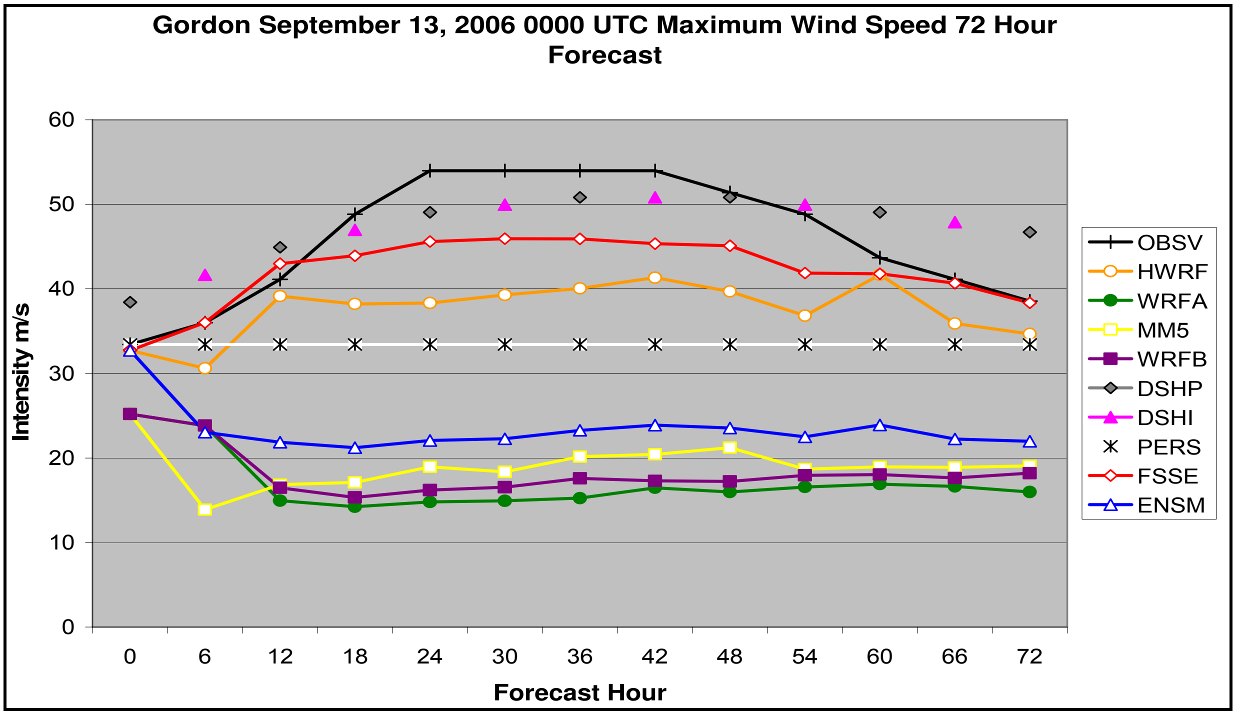

Figure 5.12 Maximum wind speed 72 hour forecast, in ms^{-1}, for Hurricane Gordon on September 13, 2006 at 0000 UTC.

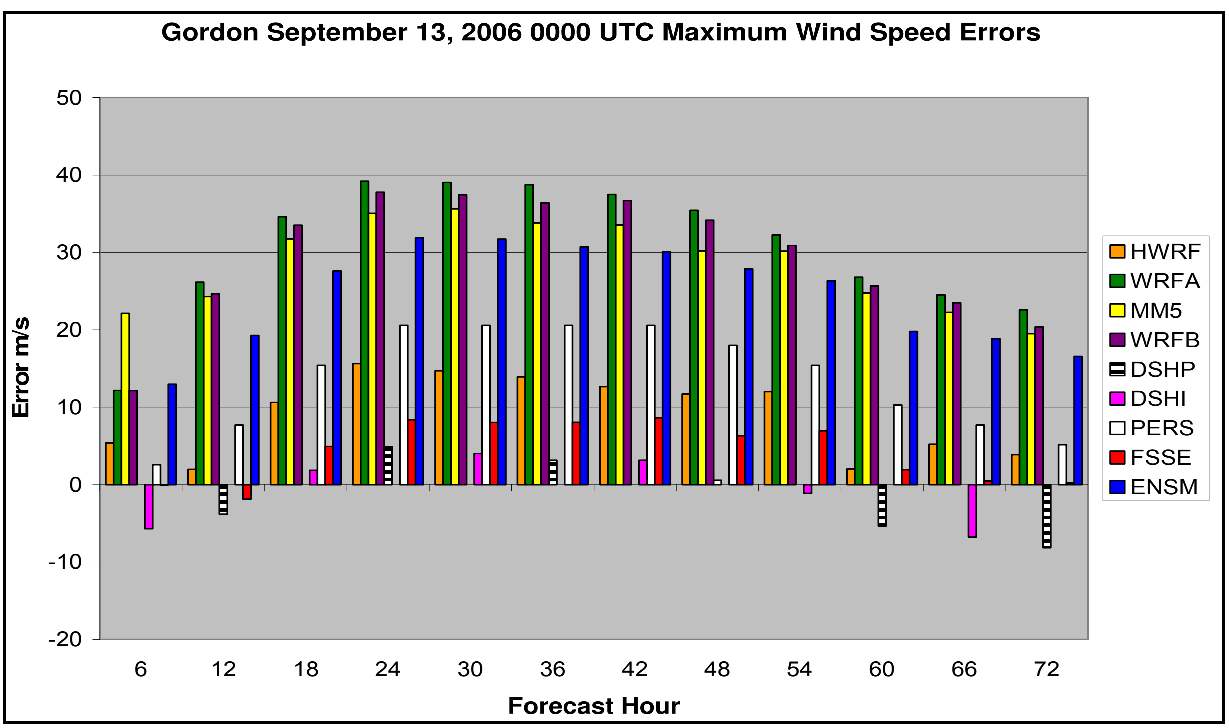

Figure 5.13 The maximum wind speed errors out to 72 hours, in ms^{-1}, for Hurricane Gordon on September 13, 2006 at 0000 UTC.

5.4 Hurricane Helene

Hurricane Helene was a long lived Cape Verde hurricane, like Hurricane Ivan, but stayed well out to see until the very end of the forecast where it then dissipated near Scotland (Brown 2006). Helene developed on September 12, 2006 at approximately 1200 UTC from a rather vigorous tropical wave that came off the coast of Africa (Brown 2006). At that time the storm was located roughly 370 km south-southeast of the Cape Verde Islands. Helene continued to move west-northwest becoming a hurricane on September 16 about 1850 km east of the Leeward Islands. The weakening of the subtropical ridge associated with Hurricane Gordon caused Helene to begin to move more to the northwest which was then accompanied by a general decrease in the forward speed of the storm, this all beginning on September 17, the start of the Helene forecast in this study (Brown 2006). Helene was still strengthening at this point and managed to strengthen to a category three hurricane. As Gordon continued to move out of the area a narrow mid-to-upper-level ridge began to build to the north of Helene at the same time as a deep-layer trough was moving off the east coast of the United States helping to steer Helene northward (Brown 2006). The shear ahead of this trough helped to weaken Helene back down to a category one hurricane and the storm began to head to the northeast towards Northern Europe; soon after it underwent extratropical transition (Brown 2006). Helene passed very close to the western coast of Ireland, on September 27, and then merged with an extratropical low that was located over the north Atlantic. Only the September 17 1200 UTC 72 hour forecast period will be examined here.

Many of the models had the general idea of Helene’s motion; however they forecast the storm to travel well south of the actual motion. The biggest departure of the models from observations occurs between 18 hours and 42 hours into the forecast, Fig. 5.14. Both the FSSE and the MM5 show what appears to be a more northward turn at the end, bringing them somewhat closer to the observations. Out of all the models shown the CLIP model has some of the highest errors as it fails to capture the storms correct recurvature and actually has the storm accelerate north-northwestward. The lack of information about the atmospheric state, within the CLIP model, may help to

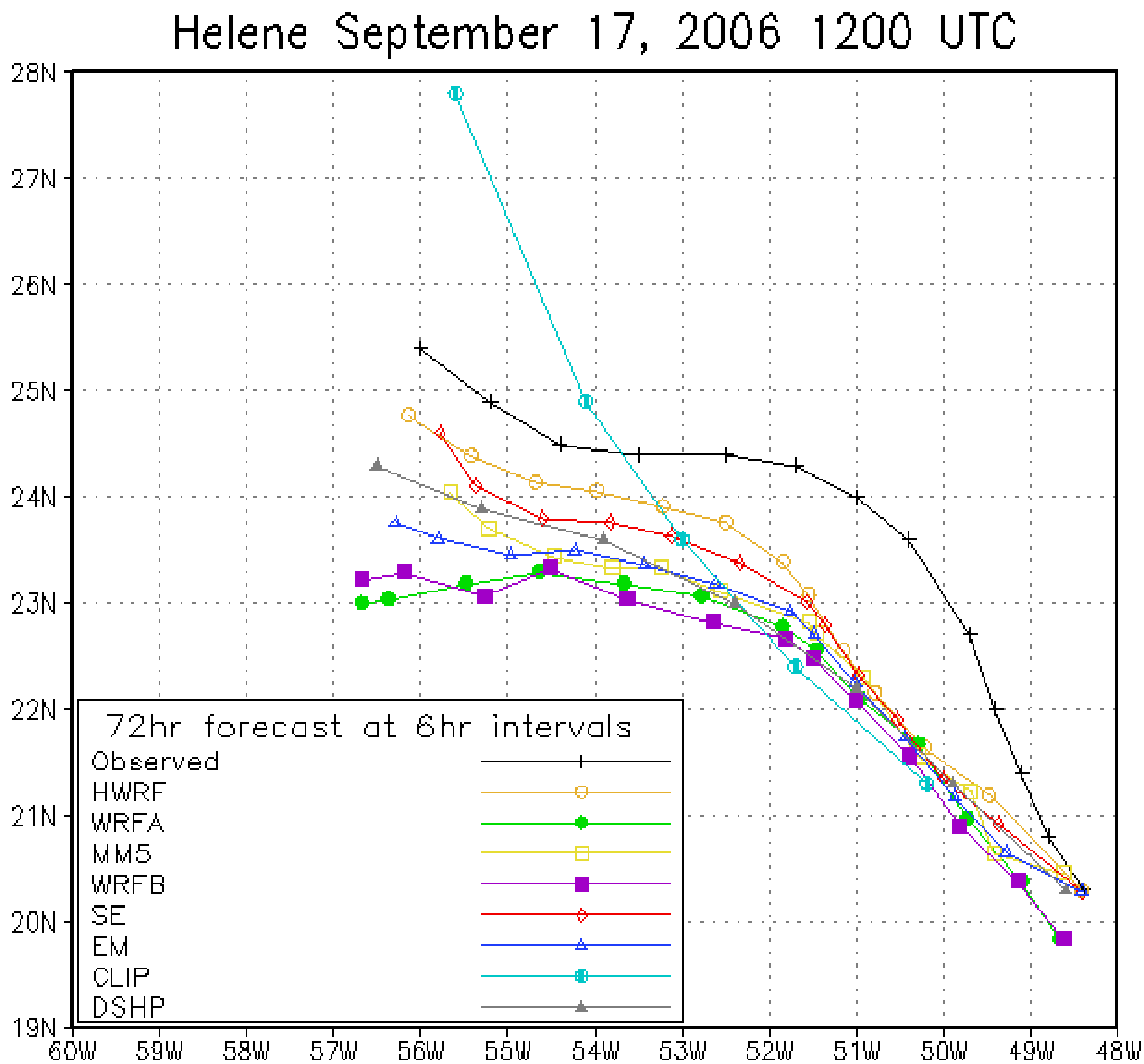

Figure 5.14 The 72 hour track forecasts for Hurricane Helene on September 17, 2006 at 1200 UTC.

explain the large errors in the track. Model errors at six hours for all the models excluding DSHI, Fig. 5.15, are higher than the model errors for Ivan and Gordon. Both the FSSE and the HWRF model show a decrease in errors with time, unlike Gordon, and forecast errors at 72 hours of less than 100 km.

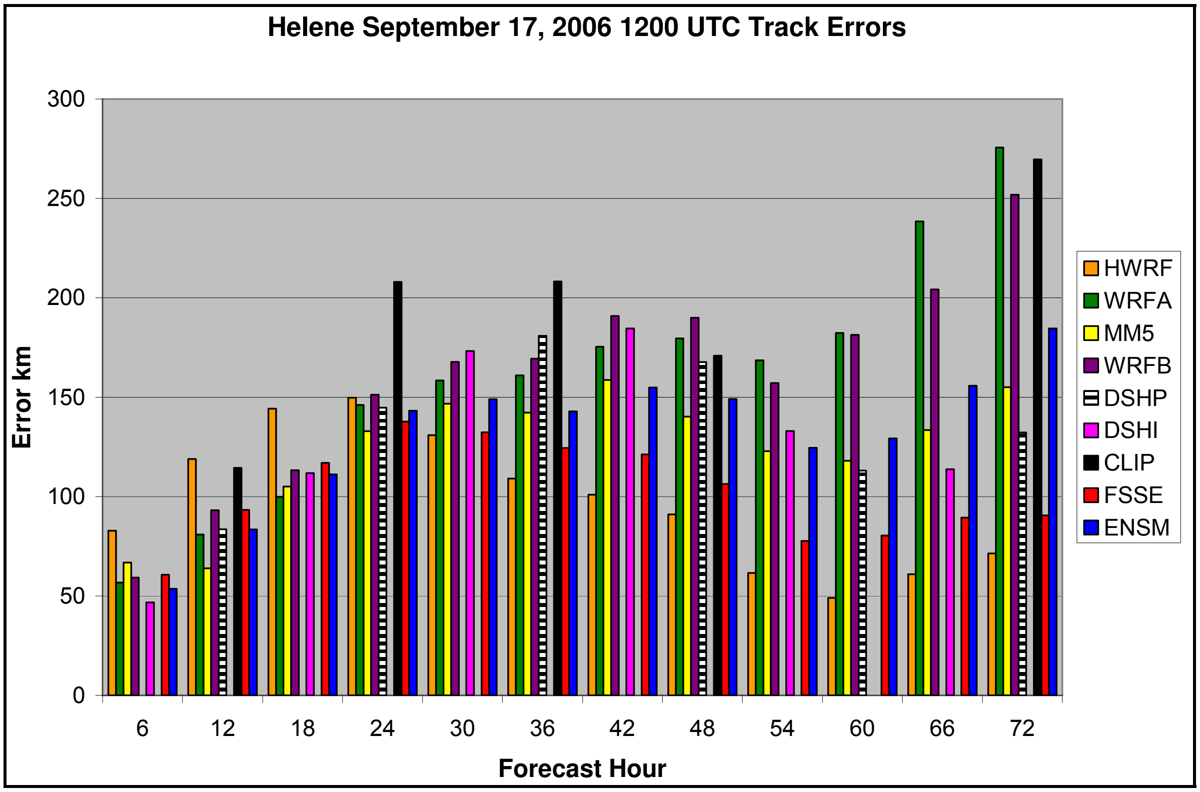

Figure 5.15 Track errors out to 72 hours, in kilometers, for Hurricane Helene on September 17, 2006 at 1200 UTC.

Unlike the track forecast the FSSE forecast of SLP is more representative of the observed trend of SLP than the HWRF models. The HWRF model grossly overestimates the SLP of Helene like with Gordon. Even though HWRF significantly overintensifies the storm the overall trend of SLP is comparable to the observations. The MM5, WRFA, and WRFB forecast a much weaker storm with a gradual strengthening for the entire duration of the forecast. In reality the storm strengthens initially and then has a fairly constant SLP. MM5 strengthens Helene enough so that the end of the forecast the SLP of the storm is much more representative of the observations than the WRFB and WRFA, Fig. 5.16. The general trend with the models, except for the FSSE and HWRF, is for a reduction in the errors with time with the FSSE and HWRF having fairly consistent errors. The reduction of errors in some of the models, Fig. 5.17, is a result of the weakening of Helene after 18 hours allowing the observed conditions to more closely match up with the weaker model storm forecasts.

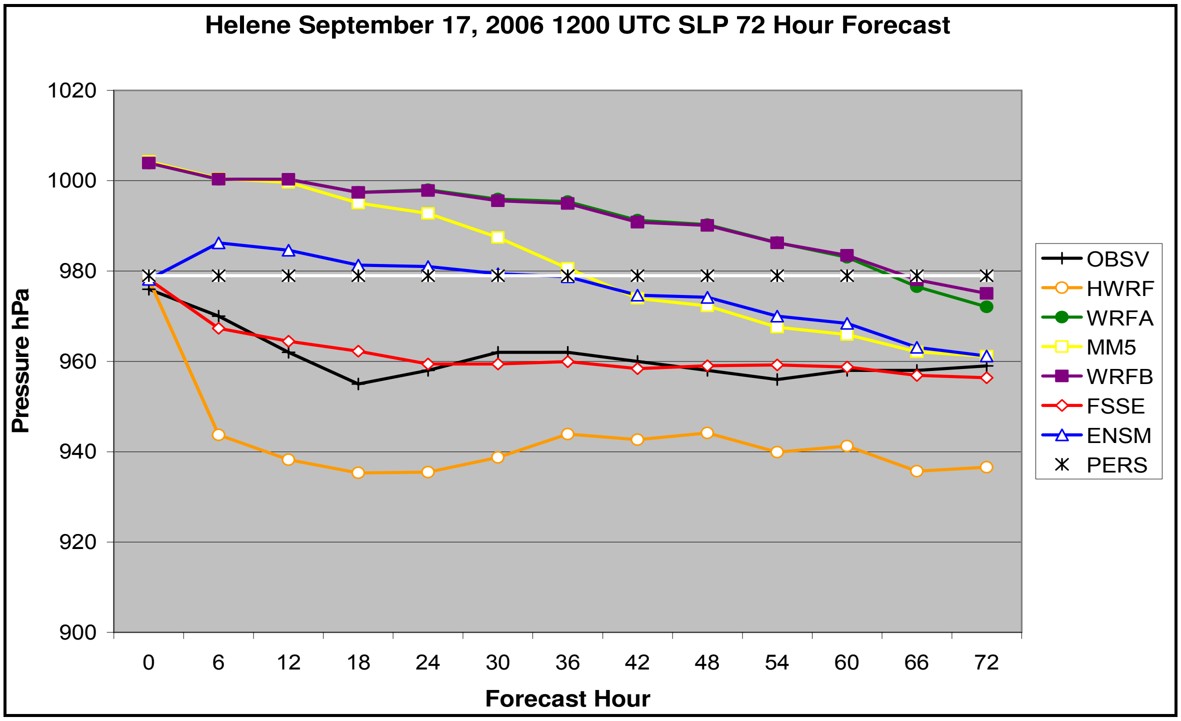

Figure 5.16 SLP 72 hour forecast, in hPa, for Hurricane Helene on September 17, 2006 at 1200 UTC.

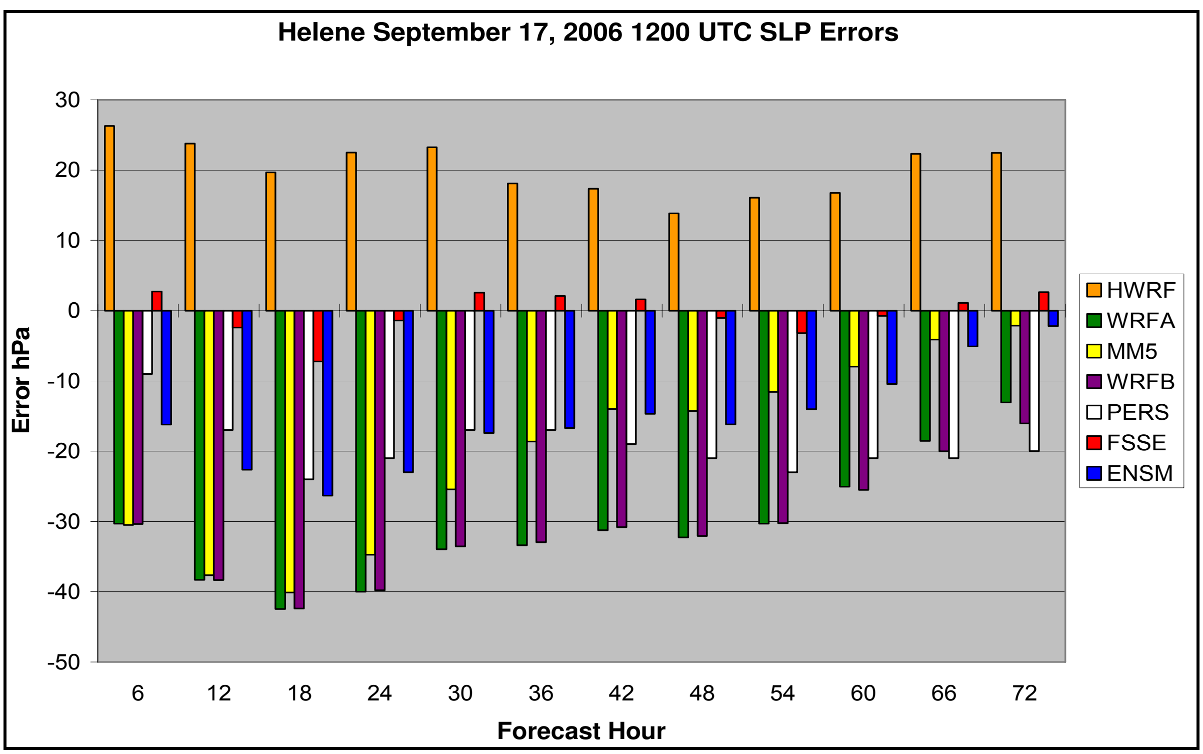

Figure 5.17 SLP errors out to 72 hours, in hPa, for Hurricane Helene on September 17, 2006 at 1200 UTC.

Similar to other storms in this study, HWRF overintensifies the storm in regards to SLP but then underintensifies the storm in regards to the maximum wind speed (e.g. Ivan, Jeanne, Karl, Dennis, and Ernesto). The FSSE does a good job of representing the trend of the maximum winds, however the intensification initially is not rapid enough to match observations and its slight intensification near the end of the forecast does not match the observed steady state conditions, Fig. 5.18. The steady state conditions are well captured by the FSSE during the 30 to 48 hour period as is the slight weakening that occurs thereafter, but in both instances the FSSE is a bit stronger than observed. DSHP does not intensify the storm enough and HWRF has several instances of model intensification and decay not noticed in the observations. Both the WRFA and WRFB models slowly intensify the storm with time, similar to their SLP forecasts, with a more rapid intensification occurring after 54 hours. Overall the FSSE is very competitive with the HWRF and DSHP models, yet none of the models are able to beat PERS the last 18 hours of the forecast, Fig. 5.19, with observations having the same maximum wind speed as the PERS forecast.

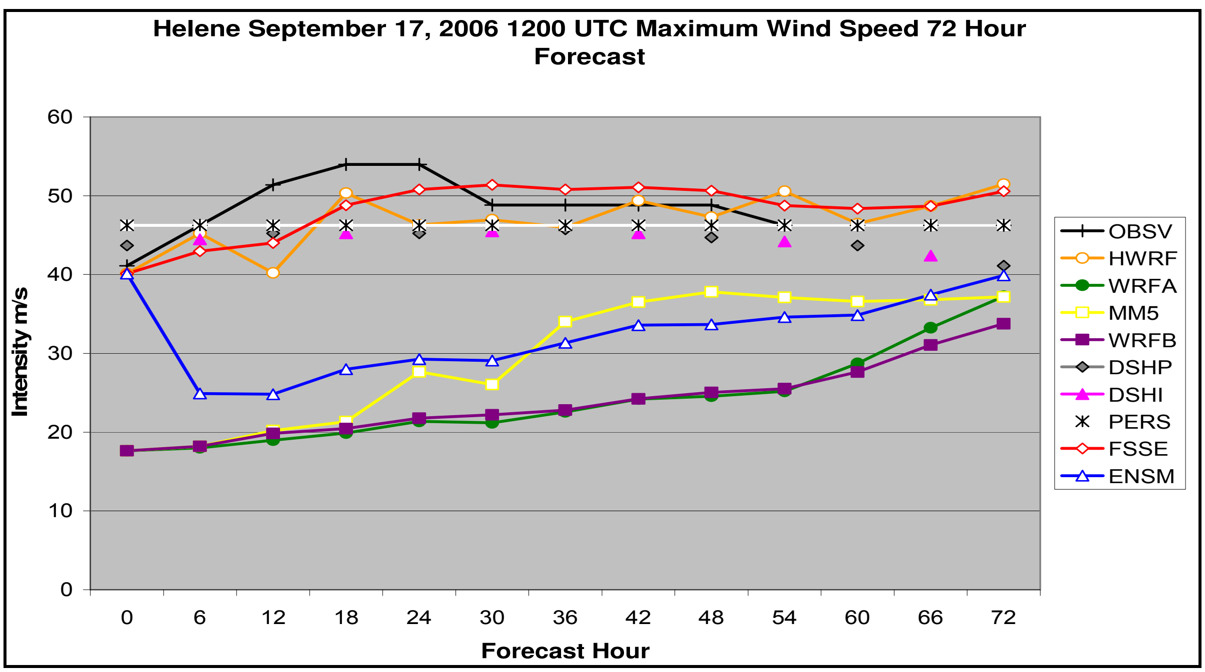

Figure 5.18 Maximum wind speed 72 hour forecast, in ms^{-1}, for Hurricane Helene on September 17, 2006 at 1200 UTC.

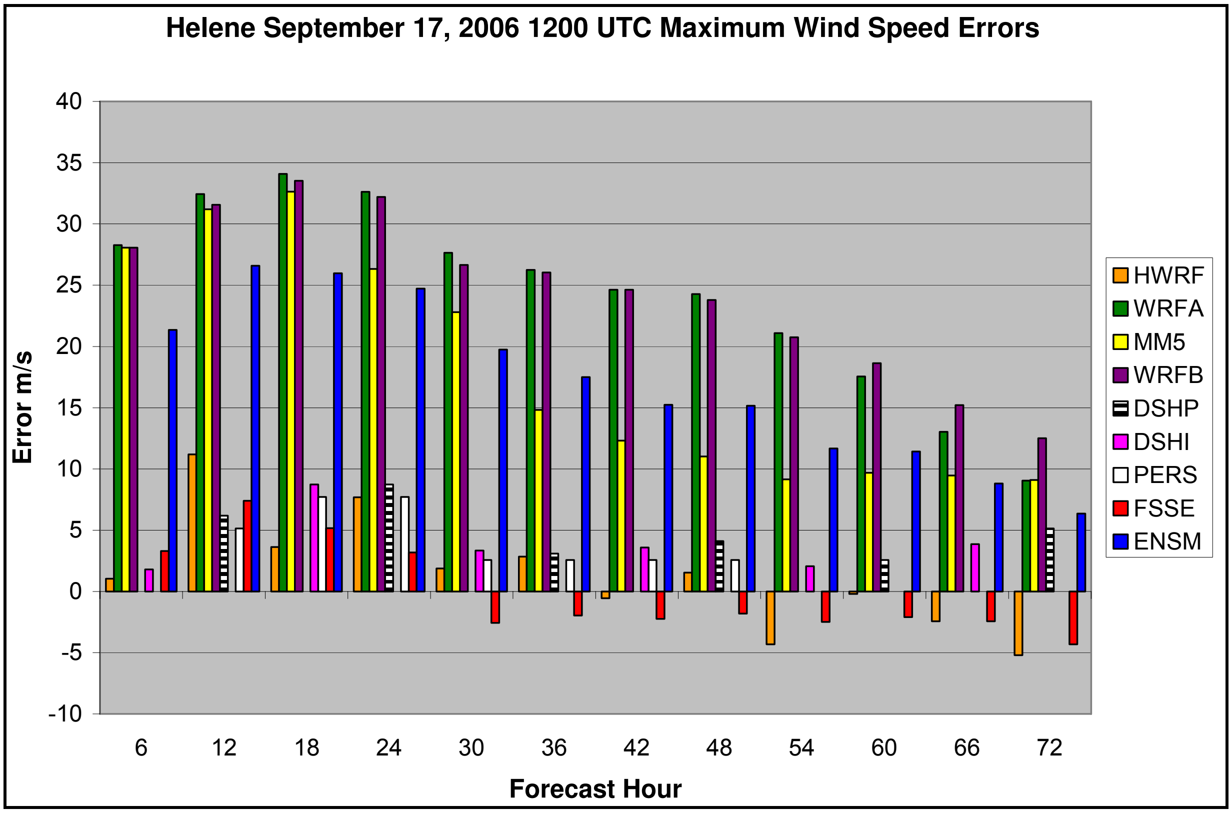

Figure 5.19 Maximum wind speed errors out to 72 hours, in ms^{-1}, for Hurricane Helene on September 17, 2006 1200 UTC.

5.5 Hurricane Isaac

Hurricane Isaac was a weak hurricane that developed over the central Atlantic Ocean and brought tropical storm force winds to Newfoundland (Mainelli 2006). Isaac developed on September 27, 2006 at 1800 UTC, from a tropical wave that came off the coast of Africa almost a week before (Mainelli 2006). Isaac continued to move to the northwest towards Bermuda, with its closest approach to the island being about 450 km east. As Isaac continued to move northwestward it began to interact with some cooler SST's and have inflow of dry air into the core (Mainelli 2006). Isaac was still a fairly weak tropical storm at that point but continued to strength, becoming a hurricane on September 30, the beginning of the Isaac forecast in this study. Shortly thereafter, Isaac began to recurve around a subtropical ridge that had developed to its east and continued on a more northeasterly track. As the storm moved northeastward it began to encounter some cooler SST's and southwesterly shear helping to weaken it (Mainelli 2006). The storm continued to trek to the northeast bringing tropical storm force winds to Newfoundland on October 2 (Mainelli 2006) and soon after began to transition into an extratropical cyclone later merging with a larger extratropical low on October 3 (Mainelli 2006). Only the September 30 1200 UTC 72 hour forecast period for Isaac will be examined here.

All of the models, except for CLIP, are sufficiently able to capture the recurvature of the storm; however none of the models, except for DSHP, are able to properly pick up on the forward speed of Isaac. CLIP had the hardest time with this as the storm in this model only traverses about 40 percent of the total distance traversed by the actual storm, Fig. 5.20. The MM5 and WRFB have the storm slightly recurving at the end of

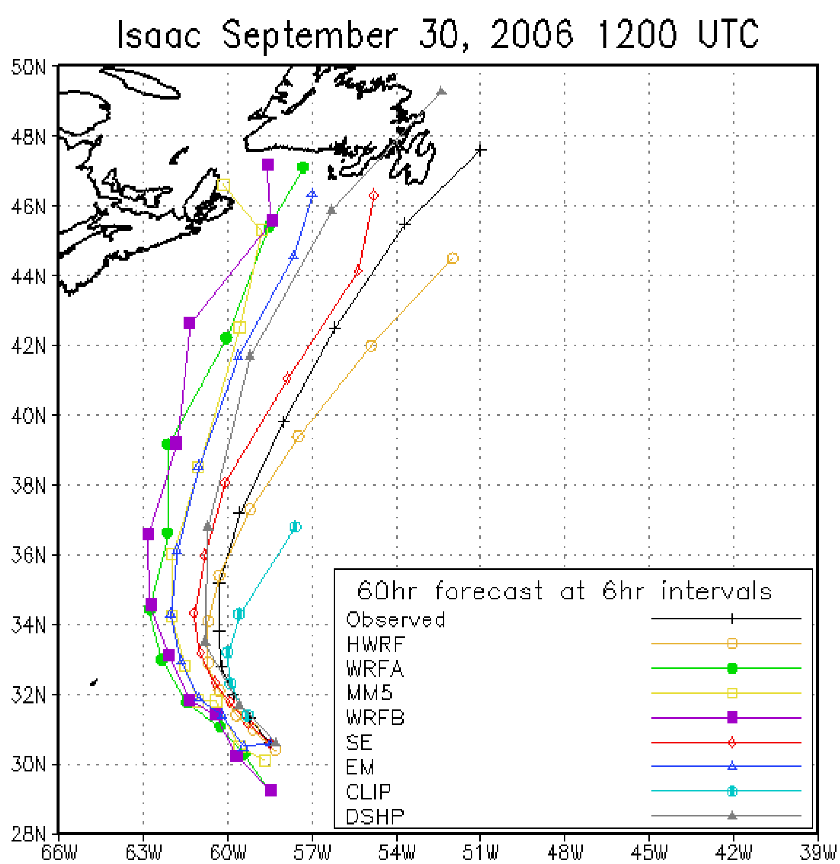

Figure 5.20 The 60 hour track forecasts for Hurricane Isaac on September 30, 2006 at 1200 UTC.

the forecast in the opposite direction towards the Gulf of the St. Lawrence River where as the actual storm center almost brushes Newfoundland. The FSSE also recurves towards the west at the end of the forecast, but not as much as the other two models. The size of the model domains does not allow for adequate evaluation as to why the storms moved westward at the end. The track errors for this storm are considerably larger than the other three storms, due to the model storms lagging the observations by a considerable amount, Fig. 5.21. Isaac has only a 60 hour forecast for this case because the storm dissipates at hour 66 in the forecast in a couple of the models

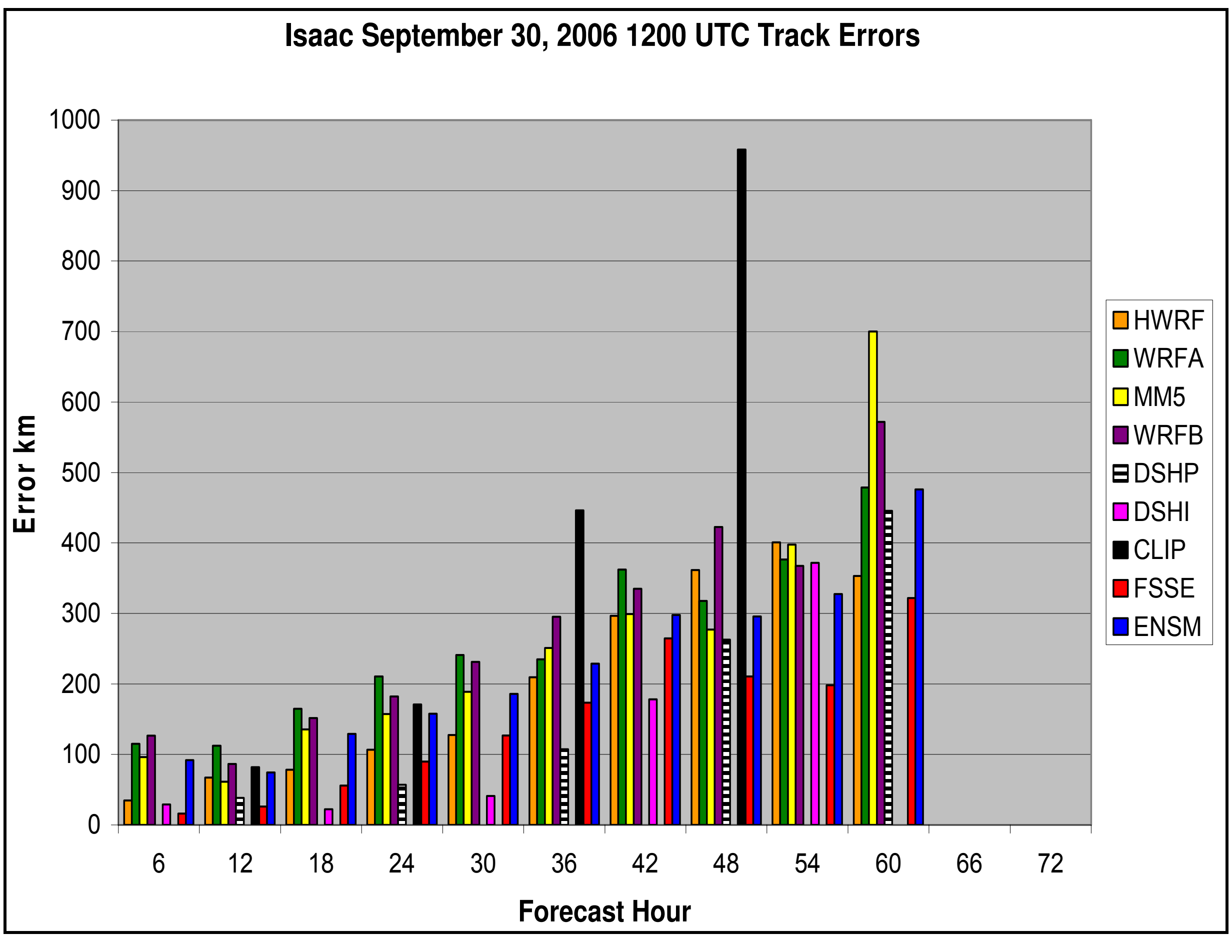

Figure 5.21 Track errors out to 60 hours, in kilometers, for Hurricane Isaac on September 30, 2006 at 1200 UTC.

resulting in an early termination of the forecast. The model errors for CLIP are almost an order of magnitude higher than the other storms at 48 hours and due to the rapid forward motion of Isaac CLIP model errors double with each successive forecast.

Many of the models are largely unable to capture the initial intensification or the weakening after that occurs in Isaac with the SLP forecasts of most of the models having an initial weakening with a slow modest deepening in time, the opposite of the observed, Fig. 5.22. All the models do show a slight weakening the last six hours of the

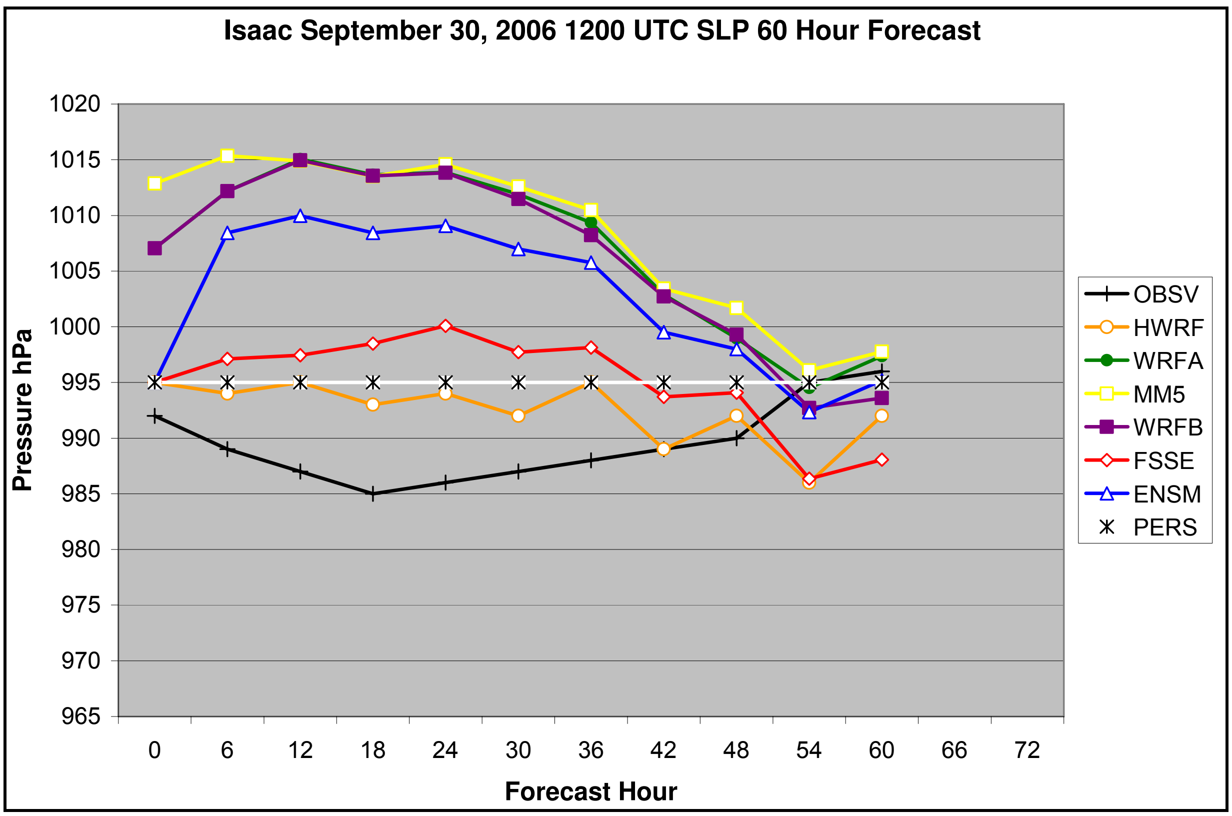

Figure 5.22 SLP 60 hour forecast, in hPa, for Hurricane Isaac on September 30, 2006 at 1200 UTC.

forecast matching with the observed conditions. With the models overall errors being lowest for this period, Fig 5.23. The FSSE and HWRF have less error overall than the other models, however as the HWRF SLP forecasts vary widely from storm to storm it makes it difficult for the FSSE to determine the best biases and weights for that model.

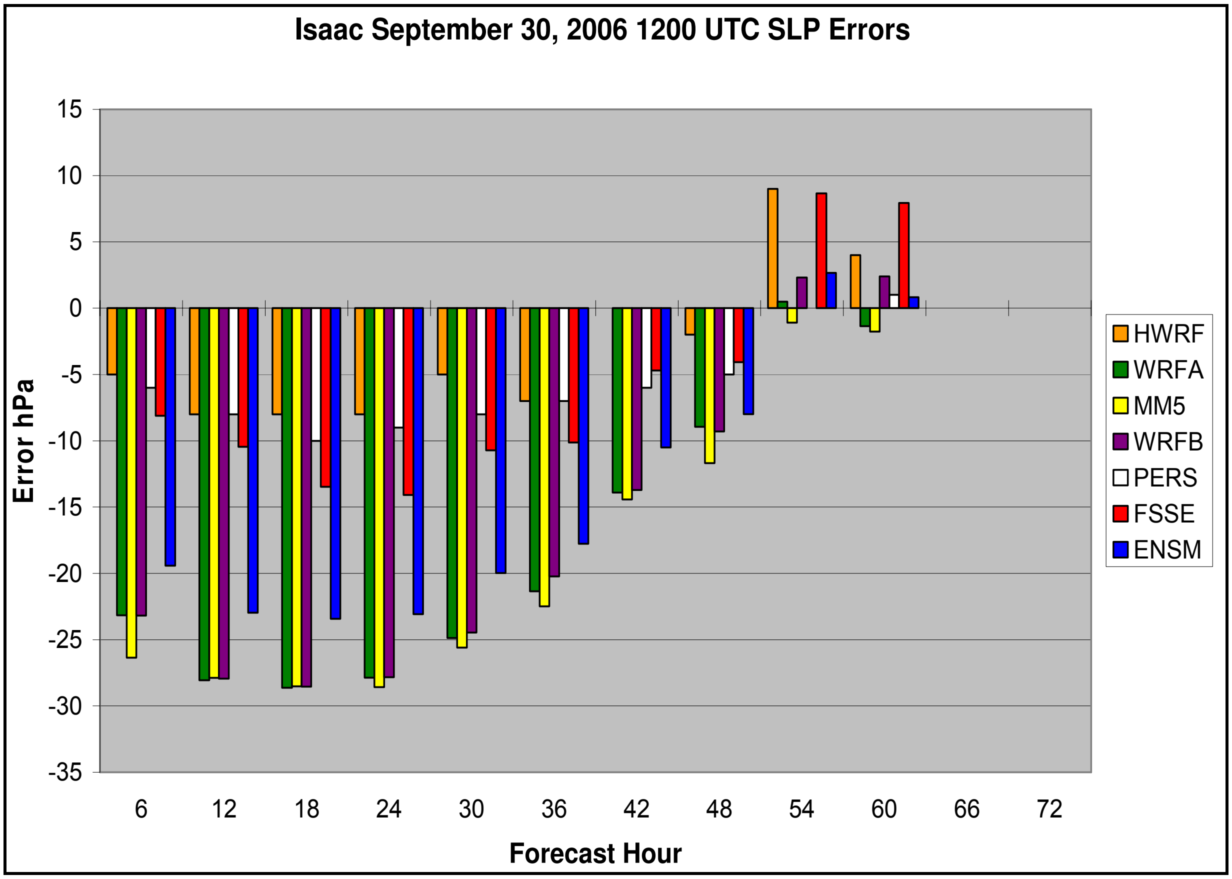

Figure 5.23 SLP errors out to 60 hours, in hPa, for Hurricane Isaac on September 30, 2006 at 1200 UTC.

The FSSE has a slightly easier time forecasting Ivan's maximum wind speed though it intensifies the storm at a slower rate than actuality and weakens the storm more rapidly than observed, Fig. 5.24. The HWRF has small periods of intensification and weakening not observed in the actual storm. Isaac begins weakening 18 hours into the forecast but none of the models are able to represent that decrease correctly. The WRFA, WRFB, and MM5 underestimate the magnitude of the maximum wind only forecasting weak tropical depression to tropical storm force winds when in reality the storm was actually a weak hurricane. They also forecast a continual intensification of

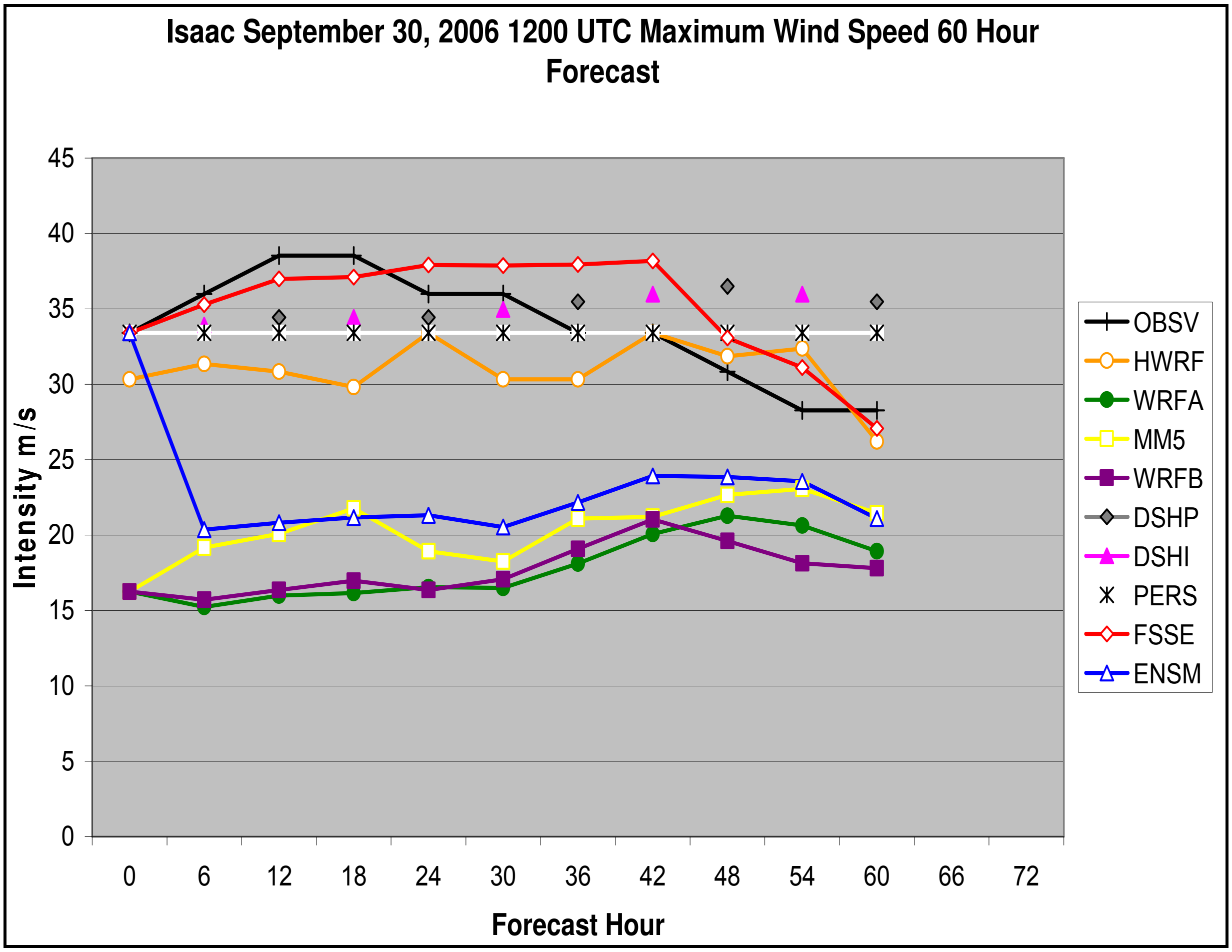

Figure 5.24 The maximum wind speed 60 hour forecast, in ms^{-1}, for Hurricane Isaac on September 30, 2006 at 1200 UTC.

wind speed with time, causing a reduction of errors in time, Fig. 5.25. About half the time the FSSE has the lowest errors and sometimes the errors are significantly less than those of the other models.

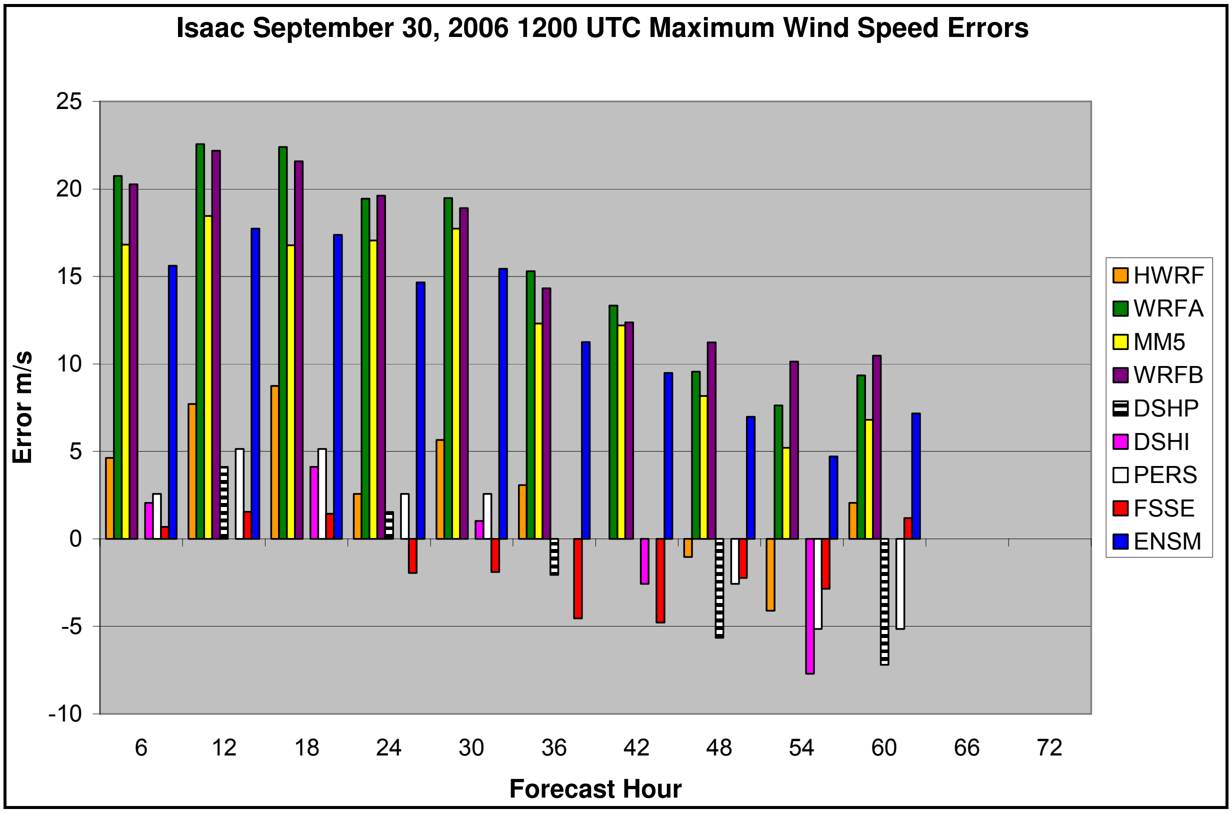

Figure 5.25 Maximum wind speed errors out to 60 hours, in ms^{-1}, for Hurricane Isaac on September 30, 2006 1200 UTC.

5.6 FSSE Mesoscale and Large Scale Model Run Comparisons

One of the final components of this study is the comparison of the FSSE run with a suite of large scale models to the FSSE run with a suite of mesoscale models, as prior to this the FSSE had only been run with large scale models when issuing tropical cyclone forecasts. It is important to compare these two methods of running the FSSE to see if the new mesoscale FSSE can improve upon the large scale FSSE. Only 47 of the original 57 cases are used for this part of the study as those are the only cases that have available large scale data for the models I chose. Both the large scale FSSE and the mesoscale FSSE are run for the exact same cases. However, a different set of large scale models is used for the large scale FSSE track forecasts than the intensity forecasts. Table 2.3 showed which large scale models provide track forecasts and which provide intensity forecasts. All of the mesoscale models provided are used to issue the track and intensity forecasts. It is important to note that when the large scale FSSE was previously run in a real-time operational setting different models may have been used than are currently being used here. Not all of the models used for that work are available for the entire time of this study. This particular section will only compare the overall track and maximum wind speed forecast RMS errors at 12 hourly intervals as large scale model data is only available at those times. The resolution and initializations are different between the two sets of models, despite that this experiment still provides an idea of how some mesoscale models perform with respect to the large scale models.

Track forecasts show overall improvement with the use of mesoscale models in the FSSE, though at 12 hours many of the member models struggle with storm location and strength and as a result the large scale FSSE has lower errors. The models used in the large scale FSSE run are initialized with a storm position very close to or exactly matching the observed position. Most of the mesoscale model initializations do not reposition their initialized storm to the observed position or provide the storm the same intensity as the observations. This will likely produce higher errors in the forecast than if vortex relocation been done. That lack of vortex initialization for many of the member models hurt the mesoscale FSSE and as a result it is unsuccessful at producing a more accurate forecast than the large scale FSSE for track forecasts at 12 and 24 hours, Fig. 5.26.

Similarly the mesoscale FSSE struggles to forecast intensity as many of the models included in the mesoscale FSSE have a hard time with the initial intensity of the storm. The WRFA, MM5, and WRFB tend to underpredict the initial storm intensity; the HWRF occasionally has rather large and unrealistic changes in SLP. The large scale models also struggle with intensity as they are not always able to weaken the storms at the same rate as the observations and sometimes actually strengthen a storm when it is weakening. That helps to cause the in higher errors in the later forecast hours, higher than the mesoscale FSSE, Fig. 5.27. The mesoscale FSSE also tends to have lower errors at the later forecast hours as the errors of the mesoscale models tend to decrease in time.

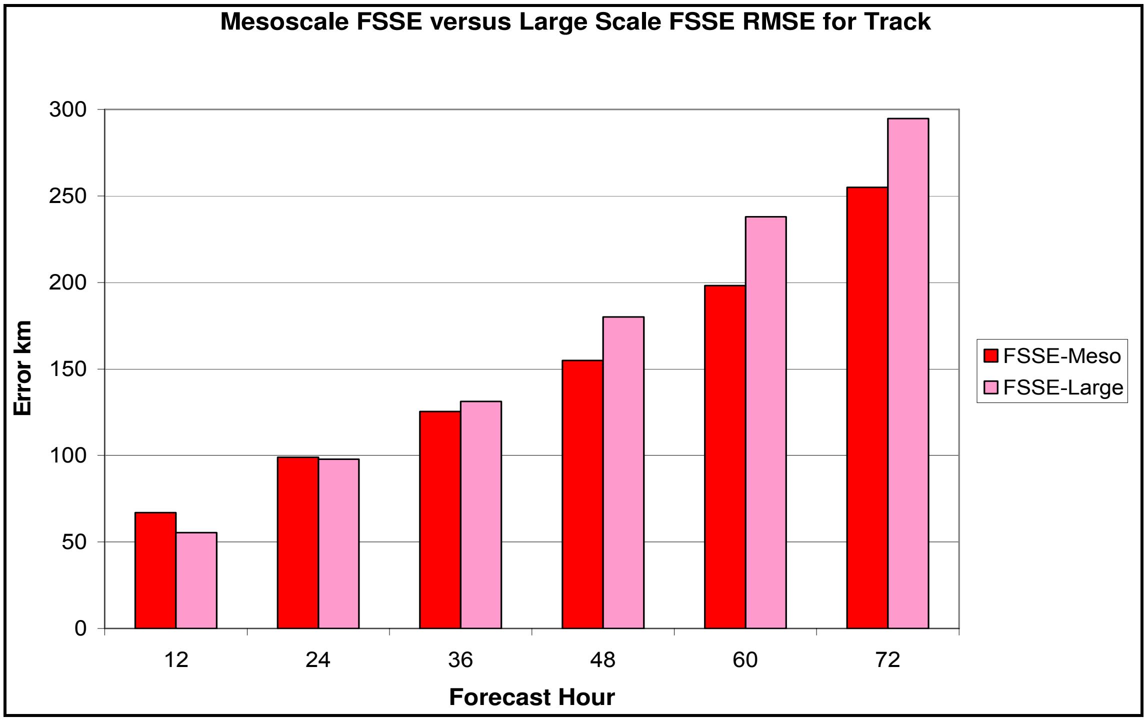

Figure 5.26 The RMSE errors for the mesoscale FSSE (red) versus the large scale FSSE (pink) for track, in kilometers.

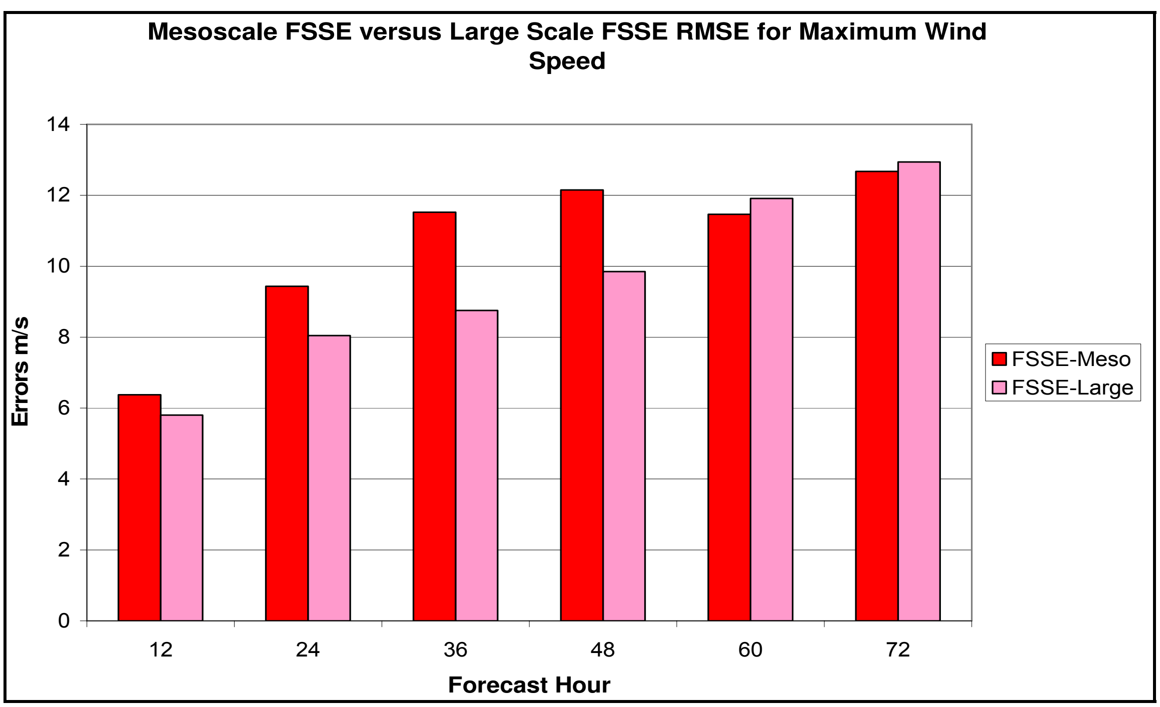

Figure 5.27 The RMSE errors for the mesoscale FSSE (red) versus the large scale FSSE (pink) for maximum wind speed, in ms^{-1}.

The improvements using the mesoscale FSSE are small and not always noticeable for the entire 72 hours for track and intensity forecasts. This may be a result of the mesoscale models not having the parameters needed to better simulate tropical cyclones. Further refinement of the model parameters may lead to improvements in mesoscale model forecasts and then improvements in the FSSE. A comparison of the gridded fields from the mesoscale models and the large scale models may shed some additional light onto the differences between them and help to further determine which changes need to be made to the mesoscale models to see improvements in their forecasts.

5.7 Limitations of Tropical Cyclone Modeling

In the previous sections many different results were presented and discussed with several theories presented as to the reasoning behind the model behavior and model errors. Additional explanation of possible reasons for the model errors will be presented here. Understanding exactly why models perform as they do is not very easily explained as the model parameters chosen (e.g. cumulus parameterization and PBL parameterization) to run in one model may produce a drastically different forecast if used in another model making determination of the best parameters a long and arduous process and even if the best parameters are chosen they may not produce an accurate representation of the storm structure within the model. Higher accuracy of the models would likely further increase the accuracy of the FSSE bias removal and weighting and also reduce the errors of the FSSE forecasts.

In improving the models it is important to make sure that things such as latent heat fluxes, sensible heat fluxes, and the sea state are properly represented within the model storms, as those things are very important within tropical cyclones, especially latent heat flux as that is an important source of energy for the models. In addition to properly representing the fluxes and sea state it is important to have them properly "communicate" with the other layers of the model atmosphere so that things such as temperature change within one layer will cause the proper and corresponding change within another layer.

The limitations in tropical cyclone modeling are not always directly related to how a model can or cannot forecast something but more so related to the lack of understanding of all of the tropical cyclone intensification, weakening, and genesis mechanisms. There are many theories as to what may cause tropical cyclogenesis and the later organization of convection: from shear to curvature dynamics, barotropic instability, combined instability, potential vorticity conservation, non-conservation of potential vorticity, psi-chi interactions, to the advection of earth's angular momentum (Molinari et al 1998, Ramaswamy 2003, Bell and Keyser 1993, and Krishnamurti et al. 2005) but none of those theories has shown to be the sole contributor to tropical cyclogenesis or the organization of convection. The lack of observational data about tropical cyclogenesis makes determination of that difficult as observations are key to determining which processes do or do not contribute to a tropical cyclones development and organization. The lack of observational data is also a hindrance to the forecaster's ability to understand how a storm intensifies and weakens. Many ideas of processes involved in storm intensification and weakening exist; concentric eyewall cycles, trough interaction, warm pools in the ocean, and eye-eyewall mixing; however the true magnitude of involvement of each of those processes in the intensification process is not fully understood. The difficulty in producing more observational data, to get that understanding, is that many of the observational instruments are unable to sample at a fine enough resolution to depict the different atmospheric processes that are occurring within a storm or in having that fine resolution are unable to sample multiple locations at one time.

The current direction of modeling is towards more atmospheric-ocean coupled mesoscale models for tropical cyclone forecasting with increased use of data assimilation. With new research and observations these models can be fine tuned to produce some of the most accurate tropical cyclone forecasts. These new models will be a great asset to the FSSE. Further refinement of the HWRF and GFDL combined with the newer coupled models will hopefully produce the FSSE model's best intensity forecasts.

CHAPTER SIX

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The FSSE has been shown here to be a useful tool for error reduction in tropical cyclone intensity and track forecasting; but proved to be highly dependent upon the models used within it. The error results may have been radically different had the FSSE used different mesoscale member models than the ones used here. The models need to have a relatively high degree of accuracy and/or reliability in order to be the most useful to the FSSE. Given reliable models, the FSSE is able to capitalize on them, determine their relative biases, remove those biases, and issue accurate forecasts fairly consistently In this case, however, many of the models in this study are not extremely reliable and have varying biases from storm to storm and year to year. Intensity biases (both SLP and maximum wind speed) for Ivan, which started off as a category five hurricane at the beginning of this forecast, are very high for a few of the models, yet the biases are much lower for weaker storms such as Debby (2006) and Stan (2005). That makes it difficult for the FSSE to determine the correct biases. Though the track biases in this study are more reliable the FSSE performed reasonably well for track.

Aside from the first six hour track forecast of the period the FSSE was able to beat all of the other member models, not including HWRF. Katrina proved to be a difficult storm for almost all the models to forecast, as they had the storm farther east than actuality, especially early on in the forecast. Part of the difficulty the models have is their initialized model conditions do not adequately match what is occurring in the real atmosphere. The HWRF was at an advantage as it was the only model with vortex bogusing. The vortex spin up time put the other models at a lag behind the HWRF model with regards to intensification and less so with track. That spin-up time and combined with the lack of model initialization proves to be a problem also for SLP and maximum wind speed forecasts as the WRFA, WRFB, and MM5 have very high RMS errors early on in the forecast. Despite that the FSSE does fairly well early on in the SLP forecast, up to about 48 hours, where increasing model irregularities prove to be problematic for the FSSE as the ENSM has slightly lower RMS errors at those times. The HWRF has relatively high SLP RMS errors later in the forecast time primarily due to the problem the model has with overintensification. The problem was also occasionally present during the first six hours of the forecast as the HWRF was attempting to correct for being out of balance. Further work needs to be done to better understand why the HWRF is out of balance. The low errors that the PERS model has demonstrate that models struggle with forecasting steady state conditions for intensity. The reduction of maximum wind speed RMS errors with time, for the WRFA, WRFB, and MM5 were a bit deceiving as it gave the impression that those models have a better handle on tropical cyclones intensity later in the forecast. However, this reduction of errors was primarily due the fact that some of the observed storms weakened with time bringing them closer to the underestimation of the models.

In terms of yearly errors, in 2004 the FSSE performed quite well and was very competitive with the HWRF model. It performed slightly better with SLP forecasts for the first half of the forecast but the problem MM5 had with overintensification tended to help push the ENSM closer to the observed. The FSSE did not perform as well for maximum wind speed forecasts, with the DSHP model having slightly more accurate forecasts. However, the FSSE, DSHP, and HWRF did the best job of approximating the trends in the maximum wind speed relative to the observed, though the exact timing of the intensification and/or weakening events did not always match the observations. The 2005 storms are a bit harder for the models to forecast and forecasting the storm tracks proved to be quite difficult for a few storms (Harvey, Nate, Stan) with the model forecasts, especially HWRF, differing considerably from observations. HWRF did better for SLP forecasting but the MM5 model's problem of continual intensification combined with the HWRF improvement gave both of those models a slight edge over the FSSE at the later forecast hours. The FSSE did slightly better for the maximum wind speed forecasts having the some of the lowest RMS errors the last half of the forecast. Ernesto of 2006 was a quite difficult forecast for some of the models as four of the models (MM5, WRFA, WRFB, and ENSM) had the storm hitting Jamaica, when the storm actually hit Cuba. The FSSE and HWRF were much closer to the observations; yet neither model had the storm making landfall in southern Florida. The FSSE errors were quite low for the SLP forecasts having the lowest RMS errors the majority of the forecast hours. The FSSE forecasts were not as good for the maximum wind speed with it having a hard time in the second half of the forecast beating the HWRF and PERS models.

Examination of the track and intensity pattern for several storms helped to shed light on some of the problems in the models forecasts of tropical cyclone track and intensity. Examining the RMS errors highlight things such as a models struggle with recurvature or with the timing of intensification. Examination of specific storms allowed for an even better depiction of model strengths and weaknesses. Hurricane's Ivan, Gordon, Helene, and Isaac actual forecasts and the forecast errors were examined to determine the magnitude of the difference between the models and the observations and to help determine what specific aspects of a tropical cyclone forecast do the models struggle with. The models struggled with the initialization of Ivan, having a hard time initializing the model vortex to match the category five in the observations. The models had more of a difficult time forecasting the correct track of Gordon with MM5 veering off into an entirely different direction. Helene's track forecasts were better but only the FSSE is really able to capture the SLP pattern of this storm. FSSE also did well for the track forecast of Isaac, though the timing of the weakening of the maximum winds was off by almost a day. These storm forecasts showed that the models had a hard time with the exact timing of intensification and weakening but were better able to approximate the storm tracks. The storm tracks frequently followed the same pattern as the observations but were a bit off in the actual location (e.g. capturing the recurvature and forward speed but being too far west).

The last component of this research compared the previously run large scale FSSE to the current mesoscale FSSE to see if the use of mesoscale models would provide any enhancement to tropical cyclone forecasts. The mesoscale models had a better handle on track forecasting after 24 hours as the large scale models were aided early on by vortex initialization. The lack of large scale gridded data did not allow for a more in-depth examination into the reasons behind the track differences later on in the forecast. Intensity forecasting proved to still be a large problem for the mesoscale models with the large scale FSSE having a slight edge over the FSSE. Further refinement of the various model parameters may lead to improvements in the mesoscale model intensity forecasts. That refinement needs to be coupled with scientists developing a greater understanding of hurricane dynamics from how a storm intensifies, why a storm intensifies, to how tropical cyclogenesis occurs. The improvement in the understanding of hurricane dynamics will hopefully lead to the development of more coupled models that better approximate what is occurring in the real atmosphere. Much work still remains to be done but studies such as this provide insight into what scientists need to further examine to see a decrease in forecast errors. Work also remains to be done with the mesoscale FSSE but the current work demonstrates that the FSSE can be a useful tool for short term forecasts and increased error reduction can be achieved with the FSSE through improvements in the individual member model forecasts.

6.2 Future Work

Additional work has already started on improving the mesoscale FSSE; preliminary results from Krishnamurti et al. (paper in preparation) has shown with the inclusion of the DSHP and GFDL models into this study's suite of mesoscale models the FSSE shows a decrease in the FSSE mean absolute errors as compared to without them in the FSSE model suite. This decrease in errors is seen occasionally for track and at all but 72 hours for intensity, Fig. 6.1 and 6.2. Only 12 hour forecasts are available for the DSHP model and thus only errors from those times will be examined.

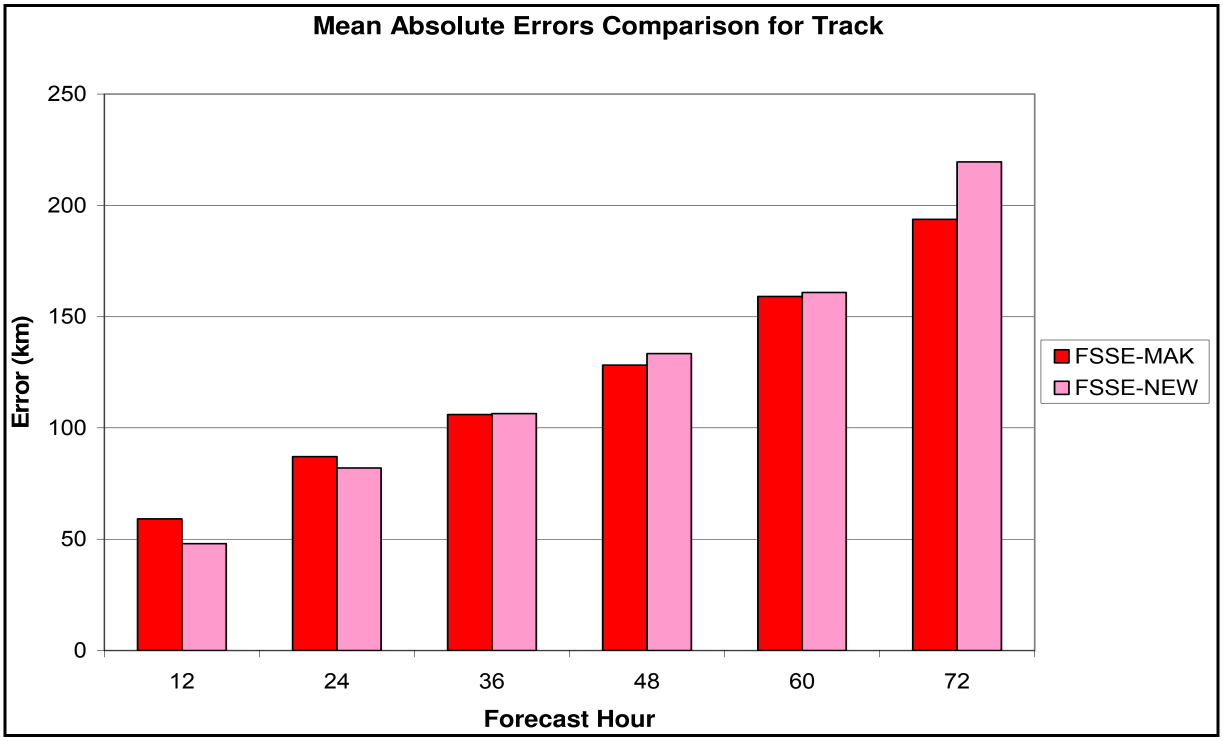

Figure 6.1 The mean absolute errors, in kilometers, for the FSSE in this study (red) and the FSSE in the new work by Krishnamurti et al. (paper in preparation) (pink) for track.

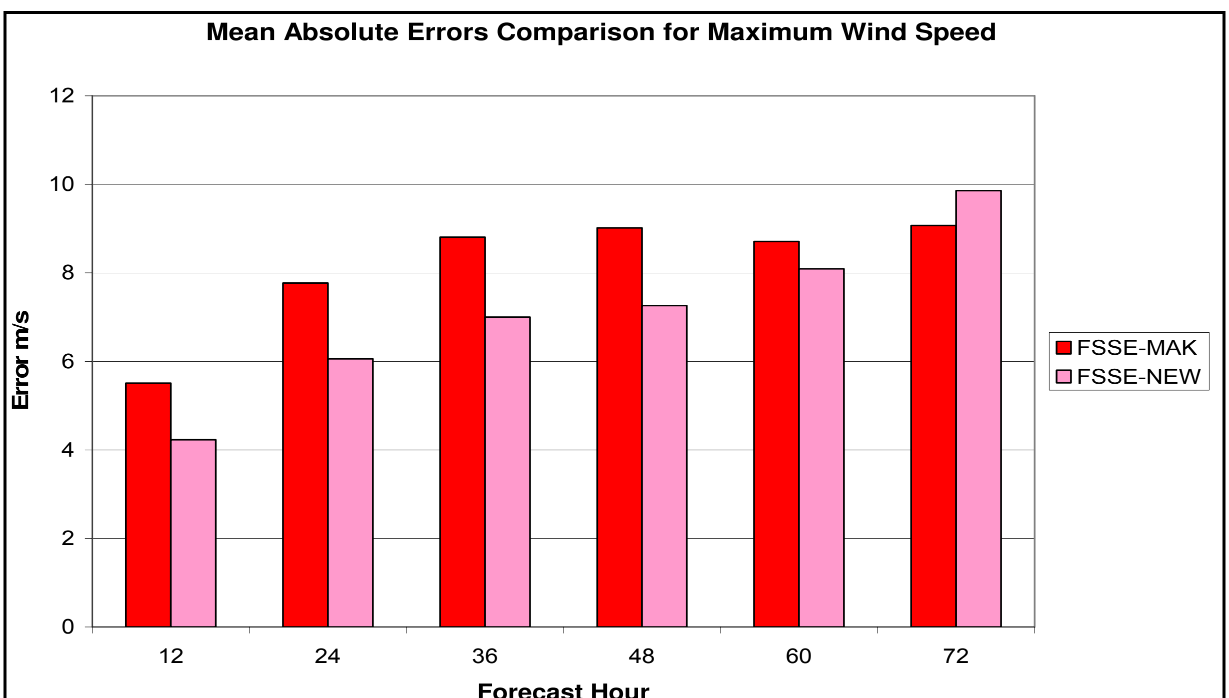

Figure 6.2 The mean absolute errors, in ms^{-1}, for the FSSE in this study (red) and the FSSE in the new work by Krishnamurti et al. (paper in preparation) (pink) for maximum wind speed.

To examine for a relationship between track and intensity in the models the correlation between track RMS errors and intensity RMS errors, both SLP and maximum wind speed errors should be examined. Preliminary work has been done to examine this, however, is still in preparation and not shown. Further examination of these correlations may provide a better idea of how the use of different models and/or model parameters produces radically different model behavior.

Another variable to look at is the pressure tendency of the models to see how realistic those are in comparison to observations. Occasionally the models produced large unrealistic changes to the intensity, a cursory examination of the pressure tendency for the first six hours of the forecast, Fig. 6.3, demonstrates this fact. The HWRF and MM5 models have almost double the rate of vortex deepening during this

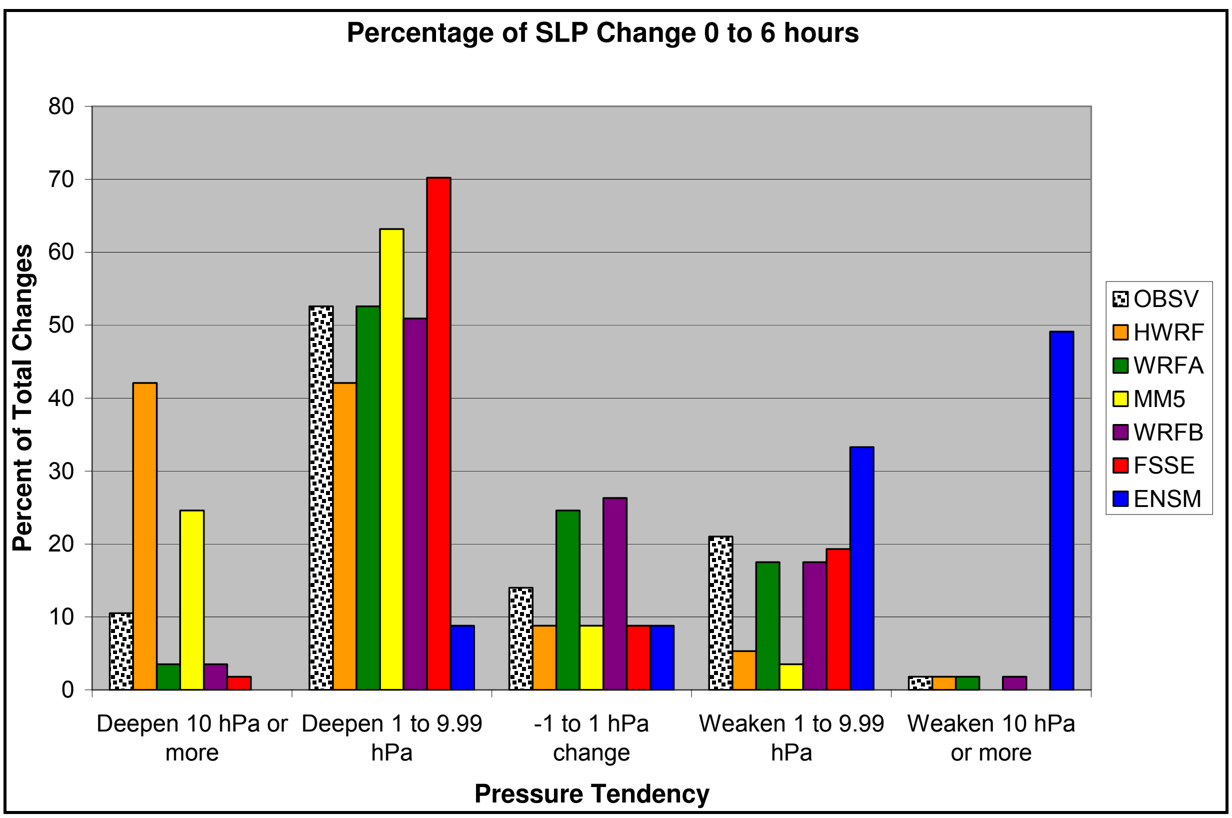

Figure 6.3 The percentage of cases that had a pressure tendency within each predefined bin. Example, approximately 11 percent of the total observed cases undergo a pressure drop of 10 hPa or more during the first six hours.

time, with over 42 percent of the HWRF models total cases having a drop in pressure of 10 hPa or more as compared to approximately 11 percent of the observed storms having that same pressure change. Future work could examine the pressure tendency at other hours, specifically near the end of the forecast as model SLP RMS errors tended to be lowest at that time.

There still remains a great deal to be done in quantifying models' strengths and weaknesses with respect to tropical cyclogenesis mechanisms, intensification mechanisms, and decay mechanisms. Different physics schemes (e.g. PBL parameterizations) have been tested, in previous work, to see which schemes work best for tropical cyclone forecasting. However, a greater degree of quantification still remains in determining at what specific instances in a tropical cyclones lifecycle the different physics schemes struggle the most and at what model resolutions do they work best. It is also important to understand why they are struggling and what particular aspects about the model parameters chosen had lead to problems in representation of a vortex. Increasing the horizontal and vertical resolution may assist in the vortex representation.

Another way to help evaluate the models is to compare the model forecasts to a different type of persistence forecast than used here. The persistence forecast used here kept the storm fixed in space undergoing no changes in location and intensity throughout the entire forecast. That method is a great way to examine model intensity forecasts, but not the best way to examine model track forecasts. To provide a more realistic persistence it may be useful to have a constant change of position and intensity over the entire forecast period (i.e. 5 ms^{-1} increase in wind speed every six hours with continual motion of 3 ms^{-1} to the northwest), giving another way to assess model skill.

These other avenues of explanation of model weaknesses are important, but it is also quite important to validate these results. The H*Wind product (Powell et al. 1998) may prove to a useful tool for performing such validation. To properly represent the ocean's feedback into the storm more coupled models need to be developed. Increasing use of data assimilation procedures in these new models will also likely help to improve the model forecasts. The FSSE will prove to be a useful tool in removal of any remaining model biases in the new models and will hopefully help to produce increasingly more accurate tropical cyclone forecasts.

REFERENCES

Aberson, S. D., 1998: Five-day tropical cyclone track forecasts in the North Atlantic basin. *Wea. Forecasting,* **13**, 1050-1056.

Arakawa A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment, Part I. *J. Atmos. Sci.*, **31**, 674-704.

Baik, J. J., M. DeMaria, and S. Raman, 1990: Tropical cyclone simulations with the Betts convective adjustment scheme. Part II: Sensitivity experiments. *Mon. Wea. Rev.,* **118**, 529-541.

Bell, G., and D. Keyser, 1993: Shear and Curvature Vorticity and Potential Vorticity Interchanges: Interpretation and Application to a Cutoff Cyclone Event, *Mon. Wea. Rev*., **121**, 76-102.

Bender M., and I. Ginis, 2000: Real-case simulations of hurricane–ocean interaction using a high-resolution coupled model: Effects on hurricane intensity. *Mon. Wea. Rev*., **128**, 917-946.

Bender, M. A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The Operational GFDL Coupled Hurricane-Ocean Prediction System and a Summary of Its Performance. *Mon. Wea. Rev*., **135**, 3965-3989.

Bender, M. A., R. Ross, R. Tuleya, and Y. Kurihara, 1993: Improvements in Tropical Cyclone Track and Intensity Forecasts using the GFDL Initialization System. *Mon. Wea. Rev*., **121**, 2046-2061.

Betts, A. K., and M. J. Miller, 1986: A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, ATEX and arctic air-mass data sets. *Quart. J. Roy. Meteor. Soc.,* **112**, 693-709.

Betts A. K., and M. J. Miller, 1993: The Betts–Miller scheme. *The Representation of Cumulus Convection in Numerical Models, Meteor. Monogr.,* No. 46, K. A. Emanuel and D. J. Raymond, Eds., Amer. Meteor. Soc., 107-121.

Beven, J. L., L. A. Avila, E. S. Blake, D. P. Brown, J. L. Franklin, R. D. Knabb, R. J. Pasch, J. R. Rhome, and S. R. Stewart, 2008: Atlantic Hurricane Season of 2005. *Mon. Wea. Rev.*, **136**, 1109-1173.

Black P. G., 1983: Ocean temperature changes induced by tropical cyclones. Ph.D. dissertation, Pennsylvania State University, 278 pp.

Blackadar A. K, 1976: Modeling the nocturnal boundary layer. Preprints, *Third Symp. on Atmospheric Turbulence and Air Quality,* Raleigh, NC, Amer. Meteor. Soc., 46-49.

Blackadar A. K, 1979: High resolution models of the planetary boundary layer. *Advances in Environmental Science and Engineering,* J. Pfafflin and E. Ziegler, Eds., Vol. 1, Gordon and Breach, 50-85.

Blake, E. S., 2006. Tropical Cyclone Report: Hurricane Gordon, 10-20 September 2006. 15 pp. [Available online at http://www.nhc.noaa.gov/2006atlan.shtml.]

Blumberg A. F., and G. L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model. *Three-Dimensional Coastal Ocean Models*, N. Heaps, Ed., Amer. Geophys. Union, 1-16.

Braun S. A., and W.-K. Tao, 2000: Sensitivity of high-resolution simulations of Hurricane Bob (1991) to planetary boundary layer parameterizations. *Mon. Wea. Rev.*, **128**, 3941-3961.

Brown, D. P., 2006: Tropical Cyclone Report: Hurricane Helene, 12-24 September 2006. 12 pp. [Available online at http://www.nhc.noaa.gov/2006atlan.shtml.]

Davis C., and L. F. Bosart, 2002: Numerical simulations of the genesis of Hurricane Diana (1984). Part II: Sensitivity of track and intensity prediction. *Mon. Wea. Rev.*, **130**, 1100-1124.

DeMaria M., and J. Kaplan, 1994: A Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin. *Wea. Forecasting*, **9**, 209-220.

DeMaria M., and J. Kaplan, 1999: An updated Statistical Hurricane Intensity Prediction Scheme for the Atlantic and eastern North Pacific basins. *Wea. Forecasting*, **14**, 326-337.

DeMaria M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531-543.

De Veaux, R. D., P. F. Velleman, and D. E. Bock, 2006: *Intro Stats*. 2nd ed. Pearson Education, Inc., 677 pp.

Dudhia J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.*, **46**, 3077-3107.

Dudhia J., 1996: A multi-layer soil temperature model for MM5. Preprints, *Sixth PSU/NCAR Mesoscale Model Users' Workshop,* Boulder, CO, NCAR/MMM, 49-50. [Available from NCAR, P.O. Box 3000, Boulder, CO 80307–3000.].

Ek M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarplay, 2003: Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *J. Geophys. Res*, **108**, 8851, doi:10.1029/2002JD003296.

EMC, cited 2008: HWRF The Hurricane Weather Research and Forecasting System. [Available online at http://www.emc.ncep.noaa.gov/HWRF/index.html.]

Emanuel K., C. DesAutels, C. Holloway, and R. Korty, 2004: Environmental control of tropical cyclone intensity. *J. Atmos. Sci.*, **61**, 843-858.

Ferrier B. S., 1994: A double-moment multiple-phase four-class bulk ice scheme. Part I: Description. *J. Atmos. Sci.*, **51**, 249-280.

Franklin, J. L., 2007: 2006 National Hurricane Center Forecast Verification Report. 57pp.

Franklin, J. L., and D. P. Brown, 2008: Atlantic hurricane season of 2006. *Mon. Wea. Rev.*, **136**, 1174-1200.

Franklin J. L., R. J. Pasch, L. A. Avila, J. L. Beven II, M. B. Lawrence, S. R. Stewart, and E. S. Blake, 2006: Atlantic hurricane season of 2004. *Mon. Wea. Rev.*, **134**, 981-1025.

Ginis I., and Kh. Zh. Dikinov, 1989: Modeling of the Typhoon Virginia (1978) forcing on the ocean. *Sov. Meteor. Hydrol. Engl. Transl*, **7**, 53-60.

Goerss, J.S., 2000: Tropical cyclone track forecasts using an ensemble of dynamical models. *Mon. Wea. Rev.*, **128**, 1187-1193.

Grell G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.*, **121**, 764-787.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: A description of the fifth generation Penn State/NCAR mesoscale model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 138 pp. [Available from NCAR Information Support Services, P.O. Box 3000, Boulder, CO 80307.].

Hacker, J. P., and D. Rostkier-Edelstein, 2007: PBL State Estimation with Surface Observations, a Column Model, and an Ensemble Filter. *Mon. Wea. Rev.*, **135**, 2958-2972.

Ho F. P, J. C Su, K. L Hanevich, R. J Smith, and F. P Richards, 1987: Hurricane climatology for the Atlantic and Gulf Coasts of the United States. NOAA Tech. Rep. NWS 38, 195 pp. [Available from NWS/NOAA, U.S. Dept. of Commerce, 8060 13th St., Silver Spring, MD 20910.].

Hong S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.*, **124**, 2322-2339.

Hong S.-Y., J. Dudhia, and S.-H. Chen, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Wea. Rev.*, **132**, 103-120.

Hong S.-Y., and J.-O. Lim, 2006: The WRF single-moment 6-class microphysics scheme (WSM6). *J. Korean Meteor. Soc.*, **42**, 129-151.

Hubert L. F., 1955: Frictional filling of hurricanes. *Bull. Amer. Meteor. Soc.*, **36**, 440-445.

Iacono M. J., E. J. Mlawer, S. A. Clough, and J. J. Morcrette, 2000: Impact of an improved longwave radiation model, RRTM, on the energy budget and thermodynamic properties of the NCAR community climate model, CCM3. *J. Geophys. Res*, **105**, 14873-14890.

Janjic Z. I., 1994: The step-mountain eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 928-945.

Jarvinen, B. R., and C. J. Neumann, 1979: Statistical forecasts of tropical cyclone intensity. NWS NHC-10, NOAA Tech. Memo., 22 pp. [Available from National Center for Environmental Prediction, Camp Springs, MD 20746.].

Jordan, Mark R., 2005: Using the Superensemble Method to Improve Eastern Pacific Tropical cyclone Forecasting. Master's Thesis, The Florida State University, Tallahassee, FL 32306, 75 pp.

Kain J. S., and J. M. Fritsch, 1993: Convective parameterization for mesoscale models: The Kain–Fritsch scheme. *The Representation of Cumulus Convection in Numerical Models, Meteor. Monogr.,* No. 46, Amer. Meteor. Soc., 165-177.

Kaplan J., and M. DeMaria, 1995: A simple empirical model for predicting the decay of tropical cyclone winds after landfall. *J. Appl. Meteor.*, **34**, 2499-2512.

Knaff J. A., M. DeMaria, C. R. Sampson, and J. M. Gross, 2003: Statistical 5-day tropical cyclone intensity forecasts derived from climatology and persistence. *Wea. Forecasting*, **18**, 80-92.

Krishnamurti, T. N., and Coauthors, 2001: Real-time multianalysis-multimodel superensemble forecasts of precipitation using TRMM and SSM/I products. *Mon. Wea. Rev.*, **129**, 2861-2883.

Krishnamurti, T. N., C. Kishtawal, T. LaRow, D. Bachiochi, Z. Zhang, C. Williford, S. Gadgil, and S. Surendran, 1999: Improved skills for weather and seasonal climate forecasts for multimodel superensemble. *Science*, **285**, 1548-1550.

Krishnamurti, T. N., C.M. Kishtawal, Z. Zhang, T. LaRow, D. Bachiochi, E. Williford, S. Gadgil, and S. Surendran, 2000a: Multimodel ensemble forecasts for weather and seasonal climate. *J. Climate*, **13**, 4196-4216.

Krishnamurti, T. N., C. Kishtawal, D. Shin, and C. Williford, 2000b: Improving tropical cyclone precipitation forecasts from a multianalysis superensemble. *J. Climate*, **13**, 4217-4227.

Krishnamurti, T. N., J. Sanjay, T. S. V. Vijaya Kumar, A. J. O'Shay, R. J. Pasch, 2005: On the weakening of Hurricane Lili, October 2002. *Tellus*, **57**, 65-83.

Krishnamurti, T. N., M. K. Biswas, R. G. Ellingson, P. Ruscher, and B. P. Mackey, 2006: Performance of the realtime FSU Superensemble for hurricane forecasts during 2004, 2005. FSU Report 2006-07, 42 pp.

Kumar T. S. V., T. N. Krishnamurti, M. Fiorino, and M. Nagata, 2003: Multimodel superensemble forecasting of tropical cyclones in the Pacific. *Mon. Wea. Rev.*, **131**, 574-583.

Kurihara, Y., M. Bender, and R. Ross, 1993: An Initialization Scheme of Hurricane Models by Vortex Specification. *Mon. Wea. Rev.*, **121**, 2030-2045.

Kurihara, Y., M. Bender, R. Tuleya, and R. Ross, 1995: Improvements in the GFDL Hurricane Prediction System and a Summary of Its Performance. *Mon. Wea. Rev.*, **123**, 2791-2801.

Kurihara, Y., R. Tuleya, and M. Bender, 1998: The GFDL Hurricane Prediction System and Its Performance in the 1995 Hurricane Season. *Mon. Wea. Rev.*, **126**, 1306-1322.

Lackmann G. M., and R. M. Yablonsky, 2004: The importance of the precipitation mass sink in tropical cyclones and other heavily precipitating systems. *J. Atmos. Sci.*, **61**, 1674-1692.

Lacis A. A., and J. E. Hansen, 1974: A parameterization for the absorption of solar radiation in the Earth's atmosphere. *J. Atmos. Sci.*, **31**, 118-133.

Lin, B. R. R. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor.,* **22**, 1065-1092.

Lord, S. J., 1991: A bogussing system for vortex circulations in the National Meteorological global forecast model. Preprints, *19th Conf. on Hurricanes and Tropical Meteorology,* Miami, FL, Amer. Meteor. Soc., 328-330.

Mainelli, M., 2006: Tropical Cyclone Report: Hurricane Isaac, 27 September- 02 October 2006. 11 pp. [Available online at http://www.nhc.noaa.gov/2006atlan.shtml.]

Malkin, W., 1959: Filling and intensity changes in hurricanes over land. National Hurricane Research Project Rep., 18 pp.

Mellor, G. L., 1998: User's guide for a three-dimensional, primitive equation, numerical ocean model. Program in Atmospheric and Oceanic Sciences, Princeton University, 35 pp. [Available online at http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/.].

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.*, **20**, 851-875.

Miller, B. I., 1964: A study of the filling of Hurricane Donna (1960) over land. *Mon. Wea. Rev.,* **92**, 389-406.

Misenis, C., X. M. Hu, S. Krishnan, Y. Zhang, and J. Fast, 2006: Sensitivity of WRF/Chem Predictions to Meteorological Schemes. Proceedings, 86th Annual AMS Conference/14th Joint Conference on the Applications of Air Pollution Meteorology, Atlanta, Georgia, Amer. Meteor. Soc., CD-ROM, P1.8.

Mitchell K., Coauthors, 2004a: The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *J. Geophys. Res*, **109**, D07S90, doi:10.1029/2003JD003823.

Mlawer E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102**(D14), 16663-16682.

Molinari, J., S. Skubis, D. Vollaro, F. Alsheimer, and H.E. Willoughby, 1998: Potential Vorticity Analysis of Tropical Cyclone Intensification. Journal of Atmospheric Science, **55**, 2632-2644.

Monin, A.S. and Obukhov, A.M., 1954: Osnovnye zakonomernosti turbulentnogo peremesivanija v prizemnom sloe atmosfery. Trudy geofiz. inst. *AN SSSR*, **24**, 163-187.

Neumann, C. J., 1972: An alternate to the Hurran (hurricane analog) tropical cyclone forecasting system. NOAA Tech. Memo. NWS SR-62, 23 pp. [Available from NTIS, Technology Administration, U.S. Dept. of Commerce, Springfield, VA 22161.].

Noh Y., W. G. Cheon, S.-Y. Hong, and S. Raasch, 2003: Improvement of the K-profile model for the planetary boundary layer based on large eddy simulation data. *Bound.-Layer Meteor.*, **107**, 401-427.

Ooyama, K. V., 1969: Numerical simulation of the life cycle of tropical cyclones. *J. Atmos. Sci.,* **26**, 3-40.

Powell M. D., S. H. Houston, L. R. Amat, and N. Morisseau-Leroy, 1998: The HRD real-time hurricane wind analysis system. *J. Wind Eng. Ind. Aerodyn.*, **77-78**, 53-64.

Price, J. F., 1981: Upper ocean response to a hurricane. *J. Phys. Oceanogr.,* **11**, 153-175.

Puri, K., and M. J. Miller, 1990: Sensitivity of ECMWF analyses-forecasts of tropical cyclones to cumulus parameterization. *Mon. Wea. Rev.,* **118**, 1709-1741.

Ramaswamy, Leela, 2003: Role of Diabatic Potential Vorticity during Hurricane Genesis. Master's Thesis, The Florida State University, Tallahassee, FL 32306, 98 pp.

Rhome, J. R., cited 2008: Technical Summary of the National Hurricane Center Track and Intensity Models. [http://www.nhc.noaa.gov/modelsummary.shtml.]

Rosenthal, S. L., 1971: The response of a tropical cyclone model to variations in boundary layer parameters, initial conditions, lateral boundary conditions, and domain size. *Mon. Wea. Rev.,* **99**, 767-777.

Ross, R. J., and Y. Kurihara, 1992: A Simplified Scheme to Simulate Asymmetries due to the Beta Effect in Barotropic Vortices. *J. Atmos. Sci.*, **49**, 1620-1628.

Schubert W. H., J. J. Hack, P. L. Silva Dias, and S. R. Fulton, 1980: Geostrophic adjustment in an axisymmetric vortex. *J. Atmos. Sci.*, **37**, 1464-1484.

Schwarzkopf, M. D., and S. B. Fels, 1991: The simplified exchange method revisited: An accurate, rapid method for computation of infrared cooling rates and fluxes. *J. Geophys. Res.*, **96**, 9075-9096.

Schwerdt R. W., F. P. Ho, and R. R. Watkins, 1979: Meteorological criteria for standard project hurricane and probable maximum hurricane wind fields—Gulf and East Coasts of the United States. NOAA Tech. Rep. NWS 23, 317 pp. [Available from National Hurricane/Tropical Prediction Center Library, 11691 S.W. 117th St., Miami, FL 33165-2149.].

Simmons A. J., and D. M. Burridge, 1981: An energy and angular-momentum conserving vertical finite-difference scheme and hybrid vertical coordinates. *Mon. Wea. Rev.*, **109**, 758-766.

Sinnott, R.W., 1984: Virtues of the Haversine. *Sky and Telescope*, **68**, 159.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang and J. G. Powers, 2005: A Description of the Advanced Research WRF Version 2, NCAR Tech Note, NCAR/TN–468+STR, 88 pp. [Available from UCAR Communications, P.O. Box 3000, Boulder, CO, 80307]. Available on-line at: http://box.mmm.ucar.edu/wrf/users/docs/arw_v2.pdf)

Smagorinsky, J., 1963: General circulation experiments with primitive equations. I. The basic experiment. *Mon. Wea. Rev.*, **91**, 99-164.

Stefanova L., and T. N. Krishnamurti, 2002: Interpretation of seasonal climate forecast using Brier Skill Score, the Florida State University superensemble, and the AMIP-I dataset. *J. Climate*, **15**, 537-544.

Stewart, S. R., 2005. Tropical Cyclone Report: Hurricane Ivan, 2-24 September 2004. 44 pp. [Available online at http://www.nhc.noaa.gov/2004ivan.shtml?.]

Surgi, N., 2004: The development of the WRF for Hurricanes (HWRF) at the National Centers for Environmental Prediction (NCEP). Preprints, *20th Conf on Weather Analysis and Forecasting/16th Conf. on Numerical Weather Prediction*, Seattle, Washington, Amer. Meteor. Soc., CD-ROM, 12.9.

Surgi, N., 2006: The Hurricane WRF (HWRF): Addressing our Nation's next generation hurricane forecast problems. Preprints, *27th Conf. on Hurricanes and Tropical Meteorology*, Monterey, California, Amer. Meteor. Soc., CD-ROM, 7A.2.

Szymczak, H. L., 2004: Skill of Synthetic Hurricane Forecasts for the Canadian Maritime Provinces. Master's Thesis, The Florida State University, Tallahassee, FL 32306, 87 pp.

Tao W.-K., and J. Simpson, 1989: Modeling study of a tropical squall-type convective line. *J. Atmos. Sci.*, **46**, 177-202.

Tao W.-K., S. Lang, J. Simpson, and R. Adler, 1993a: Retrieval algorithms for estimating the vertical profiles of latent heat release: Their applications for TRMM. *J. Meteor. Soc. Japan*, **71**, 685-700.

Troen I., and L. Mahrt, 1986: A simple model of the atmospheric boundary layer: Sensitivity to surface evaporation. *Bound.-Layer Meteor.*, **37**, 129-148.

Tuleya, R. E., M. A. Bender, and Y. Kurihara, 1984: A simulation study of the landfall of tropical cyclones using a movable nested-grid model. *Mon. Wea. Rev.,* **112**, 124-136.

Tuleya, R. E. and S. G. Gopalakrishnan, cited 2008: Hurricane Model Transitions to Operations at NCEP/EMC. [http://www.nhc.noaa.gov/jht/midterm/JHT05_Tuleya_midyear.pdf.]

Velden, C.S., 1993: The relationship between tropical cyclone motion, intensity, and the vertical extent of the environmental steering layer in the Atlantic basin. Preprints, *20th Conf. Hurr. Trop. Meteor.*, San Antonio, Texas, Amer. Meteor. Soc., 31-34.

Waliser D. E., J. A. Ridout, S. Xie, and M. Zhang, 2002: Variational objective analysis for atmospheric field programs: A model assessment. *J. Atmos. Sci.*, **59**, 3436-3456.

Wild M., A. Ohmura, H. Gilgen, J.-J. Morcrette, and A. Slingo, 2001: Evaluation of downward longwave radiation in general circulation models. *J. Climate*, **14**, 3227-3239.

Wilks, D. S., 1995: Forecast Verification. *Statistical Methods in the Atmospheric Sciences*, R. Dmowska and J. R. Holton, Eds., Academic Press, 233-283.

Williford, C. E., 2002: Real-time Superensemble Tropical Cyclone Prediction. Ph.D. Dissertation, The Florida State University, Tallahassee, FL 32306, 144 pp.

Williford, C.E., T.N. Krishnamurti, R.C. Torres, S. Cocke, Z. Christidis, and T.S.V. Vijaya Kumar, 2003: Real-time multimodel Superensemble forecasts of Atlantic tropical systems of 1999. *Mon. Wea. Rev.*, **131**, 1878-1894.

Wu C.-C., K.-H. Chou, Y. Wang, and Y.-H. Kuo, 2006: Tropical cyclone initialization and prediction based on four-dimensional variational data assimilation. *J. Atmos. Sci.*, **63**, 2383-2395.

Zhang D.-L., Y. Liu, and M. K. Yau, 1999: Surface winds at landfall of Hurricane Andrew (1992)—A reply. *Mon. Wea. Rev.*, **127**, 1711-1721.

BIOGRAPHICAL SKETCH

Melanie Kramer was born in Allentown, Pennsylvania on August 4, 1983. She attended Emmaus High School where she graduated with honors in 2002. She went on to attend college at The State University of New York at Albany in Albany, New York to pursue her bachelor's degree. While attending school in Albany, Melanie became a member of the American Meteorological Society, National Society of Collegiate Scholars and Phi Beta Kappa. She was an intern at the National Weather Service in Albany during the summer of 2005. She graduated magna cum laude with her Bachelor of Science degree in Atmospheric Science with a minor in Mathematics in 2006. She began her research studies under the direction of Dr. Krishnamurti in the fall of 2006. In 2007, she was inducted into the Golden Key Honor Society and in 2008 was inducted into Chi Epsilon Pi. Her research interests involve the improving the understanding of the physical processes that lead to hurricane intensification and the application of that to hurricane forecasting. Melanie is also a lifetime member of Girl Scouts of America.