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Skill of Synthetic Superensemble Hurricane Forecasts for the Canadian Maritime Provinces

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COLLEGE OF ARTS AND SCIENCES

**SKILL OF SYNTHETIC SUPERENSEMBLE HURRICANE
FORECASTS FOR THE CANADIAN MARITIME PROVINCES**

By

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I would like to dedicate my work to my parents, Tom and Linda Szymczak, for their unending love and support throughout my long academic career.

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LIST OF ABBREVIATIONS AND SYMBOLS

ACE	Accumulated Cyclone Energy
AMSU	Advanced Microwave Sounding Unit
ATCF	Automated Tropical Cyclone Forecasting data stream
AVN	Aviation Global Model of the NCEP
BAM	Beta and Advection Model
CHC	Canadian Hurricane Centre
CLIPER	Climatology and Persistence Statistical Model
EMC	NCEP's Environmental Modeling Center
EOF	Empirical Orthogonal Function
FSU	The Florida State University
GEM	Canadian Meteorological Centre's Global Environmental Multi-Scale Model
GFDL	Geophysical Fluid Dynamics Laboratory, Princeton
GFS	Global Forecasting System of the NCEP
GUNA	Consensus Model consisting of GFDL, UKMT, NOGAPS, and AVN/GFS models
GUNS	Consensus Model consisting of GFDL, UKMT, and NOGAPS models
HURDAT	Atlantic basin hurricane database
MMM	Multiple-Mesh Grid Point Regional Model
MRF	Medium Range Forecasts
NAVDAS	U.S. Navy Atmospheric Variational Data Assimilation System

NCDC	National Climate Data Center
NCEP	National Center for Environmental Prediction
NHC	NOAA's National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
POM	Princeton Ocean Model
SENS	The Florida State University Superensemble
T126	Triangular Spectral Truncation, 126 waves
UKMT	United Kingdom Meteorological Office Model
UTC	Universal Time Coordinate

ABSTRACT

The impact of tropical cyclones on Canadian Provinces is an important issue. From 1994 to 2003, fifty-five tropical cyclones entered the Canadian Hurricane Centre (CHC) Response Zone, or ~42% of all named Atlantic tropical cyclones in this ten-year period, and 2003 was the fourth consecutive year for a tropical cyclone to make landfall in Canada. The CHC forecasts all tropical cyclones that enter the CHC Response Zone and assumes the lead in forecasting once the cyclone enters the CHC Area of Forecast Responsibility. This study acknowledges the challenges of forecasting such tropical cyclones at extratropical latitudes. If a tropical cyclone has been declared extratropical, global models may no longer use vortex bogussing to carry the cyclone, and even if it is modeled, large model errors often result. The purpose of this study is to develop a new version of the FSU hurricane superensemble with greater skill in tracking tropical cyclones, especially at extratropical latitudes. This has been achieved from the development of the synthetic superensemble.

The synthetic superensemble is similar to the multi-model superensemble that is used operationally at FSU. The operational superensemble is a statistical linear regression technique that uses real-time forecasts provided by several hurricane models to construct an optimal consensus forecast. The synthetic superensemble differs from the operational version in that it uses a larger set of member models, including the regular member models, synthetic versions of these models, and the operational superensemble and its synthetic version. Synthetic member model forecast tracks are produced by a simple alteration of the original model track. The alteration consists of producing a linear best-fit line through a hurricane track and applying a Fourier curve to the linear best-fit line to artificially generate a new track shape.

This synthetic superensemble is being used here to forecast hurricane tracks from the 2001, 2002, and 2003 hurricane seasons. The synthetic superensemble produced forecasts with generally less track error than its member models, the operational superensemble, and the ensemble mean. It also performed exceptionally well for several major Canadian storms

including Hurricane Juan of 2003 where the synthetic superensemble outperformed the Official forecast and the operational superensemble by 425-480 km at the longest forecast hour. Forecasting challenges for each season are discussed and it was found that the synthetic superensemble produced forecasts with greatest skill in the 2003 season when there were few major changes made to member models and when member models performed at their best. Overall, this research shows that the synthetic superensemble performs consistently well and would be an asset to operational hurricane track forecasting.

CHAPTER 1

INTRODUCTION

1.1 Canadian Maritime Tropical Cyclones

Many people think of Atlantic hurricanes as being a problem for the Caribbean, the Gulf of Mexico, and the eastern United States. Few realize the impact of tropical cyclones on Canada and her provinces. In fact, in the ten-year period spanning 1994-2003, 55 tropical cyclones entered the Canadian Hurricane Centre's (CHC) Response Zone (see Figure 1.1); this is ~42% of all named Atlantic tropical cyclones in this period (<http://www.atl.ec.gc.ca/weather/hurricane>). Additionally, 2003 was the fourth consecutive year for a landfalling tropical cyclone in Canada.

The majority of Canadian tropical cyclones affect Newfoundland, Labrador and the Maritime Provinces of Canada, which include New Brunswick, Nova Scotia, and Prince Edward Island (see Figure 1.2). Most of the tropical cyclones that affect Canada are of tropical origin. These tropical cyclones generally form on the southern side of the Bermuda High roughly between Florida and the Cape Verde Islands. Movement of these storms is first westward to southwestward and then eastward and poleward as recurvature takes place (Galbraith 1980). An example of this type of storm is Hurricane Fabian of 2003 (see Figure 1.3). Another type of tropical cyclone that can affect the Canadian Maritime Provinces is one that has origins as a subtropical cyclone as in Hurricane Gustav of 2002 (see Figure 1.4).

Tropical cyclones are able to reach as far north as the Canadian provinces due, in part, to the Gulf Stream. The Gulf Stream is a warm water current that originates in the Gulf of Mexico, flows past the eastern United States towards Newfoundland, and then flows to the east towards Europe as the North Atlantic Drift. The Gulf Stream extends farther north in late summer and early fall as sea surface temperatures in the Atlantic Ocean increase (Ahrens 1994). This northward extent of warm water allows tropical cyclones to track farther north without losing their warm water energy source.

Figure 1.1: Canadian Hurricane Centre's Response Zone and Area of Forecast Responsibility.
Image courtesy of the CHC: [http:// www.atl.ec.gc.ca/weather/hurricane/](http://www.atl.ec.gc.ca/weather/hurricane/)

Figure 1.2: Canadian Provinces affected by Atlantic tropical cyclones

Many tropical cyclones affect provinces farther inland such as Ontario and Quebec. An example would be Hurricane Isabel of 2003 (see Figure 1.5). These tropical cyclones usually make landfall in the United States and are mainly rain events for the Canadian provinces, although they can still be quite destructive. A famous example of this type of tropical cyclone would be Hurricane Hazel of 1954. Hurricane Hazel made landfall in Cape Fear, NC as a

Figure 1.3: Hurricane Fabian track
27 August – 8 September 2003

Figure 1.4: Hurricane Gustav track
8-12 September 2002

Figure 1.5: Hurricane Isabel track, 6-19 September 2003

category four hurricane in mid-October. After Hazel moved inland, she continued to move northward. While most hurricanes rapidly decrease in intensity after moving inland, Hazel maintained a great deal of strength due to a constructive interaction with a negatively tilted trough (Knox 1955). As Hazel approached southern Ontario, it merged with a strong cold front. This combination brought eight inches of rain to Brampton, Ontario (just west of Toronto) and allowed the Humber River level to rise 20-30 feet. Hazel was responsible for 81 deaths in Canada, 75 of these due to drowning (Bowyer et al. 2004). Figure 1.6 shows the locations of all hurricane-strength tropical cyclones that have made landfall in Canada from 1851-2003.

Figure 1.6: Map of Hurricane landfall points in the Canadian Provinces from 1851-2003. Image courtesy of Ketch (2004).

Many tropical cyclones are no longer purely tropical as they reach Canada. Most storms lose their true tropical characteristics north of 40°N latitude. These storms are either undergoing extratropical transition or are already considered extratropical. The National Hurricane Center (NHC) defines an extratropical cyclone as a cyclone that has lost its tropical characteristics due to “a conversion of the cyclone’s primary energy source from the release of latent heat of condensation to baroclinic (the temperature contrast between warm and cold air masses) processes” (<http://www.nhc.noaa.gov>). It has been found that ~42% of all Atlantic tropical cyclones were classified by the NHC as transitioning. Transition most often occurs in the months of September and October. Even though these transitioning cyclones are over cooler water, 51% of them will be stronger than their pretransition intensity. This strengthening most often results from an increase in available potential energy, thus making the atmosphere more conducive to baroclinic growth (Hart and Evans 2001).

Just because a cyclone is no longer purely tropical does not make it any less threatening. An extratropical cyclone has a very asymmetric appearance, unlike a tropical cyclone, which is typically symmetric. This means that wind and precipitation distributions are no longer concentrated about the circulation center of a tropical cyclone, but have evolved into broad asymmetric distributions and have expanded in area (Jones et al. 2003a). This allows for a significant increase in the radii of gale (17 m/s) and hurricane force (34 m/s) winds in an extratropical or transitioning cyclone. Once a tropical cyclone has completed extratropical transition, its radius of influence can increase from roughly 111 km to 300 km (Hart and Evans 2001). The asymmetry of the extratropical cyclone means that the heaviest precipitation will occur to the left of the cyclone track (Attalah and Bosart 2003). This means that a transitioning cyclone can have devastating effects on Canada. Not only will a larger portion be hit by hurricane or gale force winds, but the heaviest area of precipitation can be directly over land, even if the extratropical cyclone does not make landfall.

1.2 Objective of Thesis

The World Meteorological Organization has mandated the NHC with the forecasting of Atlantic basin tropical cyclones. In addition to the NHC, the CHC begins to track any tropical cyclone that enters the CHC Response Zone. The CHC is a division of the Canadian Department of the Environment. They have a mandate to conduct research and forecast tropical cyclones that impact Canada's land and marine response zone. Once a tropical cyclone enters the CHC Area of Forecast Responsibility (see Figure 1.1), the CHC assumes the lead in forecasting the storm. The CHC's Area of Forecast Responsibility lies along the Canada–United States border and extends 200 nautical miles into Canadian waters (<http://www.atl.ec.gc.ca/weather/hurricane>). Research at the CHC is directed towards transitioning tropical cyclones, extratropical cyclones, and cyclones merging with frontal systems. Even though the CHC and NHC are separate agencies, they often rely on each other for model data and forecast discussions. Forecasters at the CHC use the Canadian Meteorological Centre's Global Environmental Multi-Scale (GEM) model, a dynamical numerical weather model, in addition to a suite of dynamical and statistical models produced in the United States and Europe to forecast storms.

Forecasters at the CHC face many forecast challenges. When a tropical cyclone moves into the mid-latitudes and begins to undergo transition, dynamic models have their largest errors (Jones et al. 2003b). Further, problems arise when a tropical cyclone is declared extratropical by the NHC. When this happens, tropical cyclone modeling centers stop modeling the storm. Therefore, forecasters at the CHC lose the majority of their guidance. At this time, dynamical models, most of which use vortex bogussing, are no longer given vortex information for the model to simulate a tropical cyclone. Vortex bogussing is important to a hurricane model because tropical cyclones are often poorly resolved in operational analyses due to limited observations and coarse model resolution. A bogus vortex is a representation of a tropical vortex based on observed winds and tropical cyclone wind profiles. Vortex bogussing is used for initial conditions of high resolution hurricane models (Glickman 2000). These cyclones may still retain some tropical characteristics, which will make the system even more difficult to model. Unfortunately, this may all happen at a time when the CHC needs to issue land and marine warnings (Peter Bowyer, CHC, personal communication).

The objective of this thesis is to develop a new version of the Florida State University (FSU) hurricane superensemble with greater skill in tracking tropical cyclones, especially at extratropical latitudes. This is achieved by the development of a synthetic superensemble that uses synthetic versions of dynamic and statistical models, their original counterparts, and the real-time superensemble as inputs. Greater model skill can lead to greater lead-time for hurricane and tropical storm warnings in both Canada and the United States.

The motivation for this study essentially came from the success of a synthetic superensemble for seasonal climate prediction demonstrated by Yun et al. (2004). It was noted that a space-time smoothed version of a member model forecast could be used as a proxy forecast member model. Model physics such as deep convection and initial state uncertainties seem to lead to time evolution of variables that carry high frequencies in space and time. It was felt that smoothing of such forecasts could provide additional proxy models without degradation of useful information. Yun et al. used empirical orthogonal functions (EOF) in space and principal components of a time series to generate these synthetic models. In the context of hurricane tracks the only avenue available was a time smoothing. It was decided to try out such a smoothing using a least squares regression based on truncated Fourier smoothing. A first test on a Hurricane Erin (2001) forecast track showed promise, hence it was decided to use this approach to smoothing.

1.3 Organization of Thesis

This thesis is divided into six chapters. The methodology of the original and synthetic FSU hurricane superensemble along with the real-time application will be described in the next chapter along with a description of superensemble member models. Chapters 3 and 4 describe the tropical systems that affected Canada in the 2001 and 2002 hurricane seasons, respectively, and the skill of the synthetic superensemble for each season is discussed. Chapter 5 describes how the synthetic superensemble can be implemented into real-time forecasting and how this method was applied to Hurricane Juan and the rest of the 2003 hurricane season. Finally, Chapter 6 is a review of the study and provides concluding remarks.

CHAPTER 2

METHODOLOGY OF THE MULTI-MODEL SUPERENSEMBLE

2.1 Overview

In 1998, Dr. T.N. Krishnamurti developed a multi-model statistical superensemble technique. The superensemble was developed by using past forecasts from a variety of numerical models. These forecasts are used to derive statistics on the past performance of each multi-model member. The statistics were used to construct an objective consensus superensemble forecast with higher skill than each of the multi-model forecasts (Krishnamurti et al. 1999).

The superensemble method was developed in response to the success of an ensemble approach to forecasting. The ensemble approach typically consists of an ensemble mean, a simple average of all model forecasts, or a bias-removed ensemble mean in which the bias of each model is individually removed. In both of these approaches, each model is equally weighted. Goerss (2000) showed that using an ensemble mean of top dynamical tropical prediction models— GFDL, the UK Met Office global model (UKMT), and NOGAPS— often produces a better forecast than each individual member model. This method has no bias correction. Dr. Krishnamurti's method of multi-model superensemble forecasting has been known to produce results superior to any single model forecast. The approach has been applied to numerical weather and seasonal climate prediction (Krishnamurti et al. 2000a), precipitation forecasts (Krishnamurti et al. 2000b), and to tropical cyclone prediction in both the Atlantic (Williford 2002, Williford et al. 2003) and Pacific (Vijaya Kumar et al. 2003) basins with much success. The technique of tropical cyclone superensemble prediction is described in the following section.

2.2 Superensemble Description

The multi-model superensemble was initially designed to improve hurricane forecasts in the Atlantic Ocean. The superensemble is an objective consensus forecast; it combines individual multi-model forecasts to produce one optimal forecast. The superensemble differs from an ensemble mean in that it is not a simple average of model forecasts, but is a weighted average of model forecasts where individual biases of member models is collectively removed. The superensemble assigns different weights to each member model based on their past performance. This is achieved by using a multiple linear regression technique that regresses the member model forecasts against the observed counterpart (Krishnamurti et al. 1999, Williford 2002). This method acts to reduce the importance of past poor performing models and enhance better performing models.

A superensemble calculation consists of two phases: a training and forecast phase. The training phase consists of past forecasts from member models and the corresponding observations. During the training period, multi-model variables (latitude, longitude, intensity) at each forecast hour are regressed against the corresponding observed values. This regression consists of a least squares minimization of the differences of the member models and observed path. With this method, the regression coefficients, or weights a_i , are computed for each variable at the specific time period by minimizing the function J (Equation 1) where $S(t)$ is the predicted value of the superensemble, $O(t)$ is the observed state, and $length$ refers to the length of training (Krishnamurti et al. 2000a, Vijaya Kumar et al. 2003, Williford et al. 2003).

$$J = \sum_{t=0}^{length} (S(t) - O(t))^2 \quad (1)$$

In order to produce an optimum forecast, a significant amount of training data is needed. The training phase should include at least 75 past forecast cases. It has been found that training data taken from the past hurricane season (or past two seasons) plus data just collected from the current season's storms is optimum. A major challenge in piecing together a training data set is that many of the dynamical models go through changes or updates each season. The ideal setup would be to freeze each member model. In the past, models that had gone through significant changes from the previous season were thrown out of the current season's forecast. However, the

dynamical models go through changes so often and are considered the backbone of the superensemble, so they are no longer removed from real-time operations.

In the forecast phase, the superensemble forecast is constructed using statistics calculated in the training phase and the current multi-model forecasts. The predicted value of the superensemble, $S(t)$ is calculated using Equation 2.

$$S(t) = \bar{O} + \sum_{i=1}^N a_i (F_i(t) - \bar{F}_i) \quad (2)$$

In this equation, $\bar{O}$ is the mean of the observed value found in the training phase, N is the number of model members, a_i is the regression weight for model i , $F_i(t)$ is the latitude/longitude/intensity forecast of model i , $\bar{F}_i$ is the latitudinal/longitudinal/intensity mean of all forecasts made by model i over the training period, and $(F_i(t) - \bar{F}_i)$ is the forecast anomaly value for model i . The last term in Equation 1 accounts for bias removal when the sum is added to $\bar{O}$ (Williford 2002). $S(t)$ can either be a forecast value or an increment added to the previous forecast value; this depends on whether the values of $F_i(t)$ and $\bar{F}_i$ are forecast values or forecast increments. The superensemble approach used in this study is incremental. Using this approach, once a value of $S(t)$ is found for each variable (latitude, longitude, intensity) at each forecast hour t , it is added to the superensemble forecast at the previous time. Williford (2002) found that the incremental technique was better because it allowed the latest positions and intensities to be incorporated as the initial forecast information. A walk-through of one superensemble forecast for Hurricane Juan can be found in Chapter 2.5.

2.3 The Real-Time Hurricane Superensemble

The superensemble was first used to forecast the 1998 Atlantic hurricane season. These forecasts were produced experimentally in early 1999. Due to excessive model changes between 1997 and 1998, a cross-validation approach was used, meaning that the training data set consisted of 1998 hurricane season data excluding the specific storm that was being predicted. Results from this season indicated that the superensemble forecasts were superior to all other models and the NHC Official forecast.

Because of promising results for the 1998 season, the superensemble was run operationally for the 1999 hurricane season. For this season, training data consisted exclusively of 1998 model data. A superensemble forecast is run about one hour after synoptic time. The first model forecasts that are available are interpolated versions of each model, and therefore, it is these versions that are included in the real-time forecast. Again in 1999, the superensemble outperformed member models and reduced three-day errors by 82 km compared to the best model, GFDL (Williford 2002). Because of the success of the 1999 hurricane season, the FSU hurricane superensemble has been operational each season since.

The superensemble is run operationally once the NHC has declared a system to be of at least tropical storm strength. Superensemble forecast inputs are obtained via the ATCF (Automated Tropical Cyclone Forecasting system) model stream and are then sent to the NHC for use by their forecasters. Prior to the 2003 season, forecasts were produced twice daily at 00 and 12 UTC, but now they are produced four times daily at 00, 06, 12, and 18 UTC. Superensemble member models vary by season and operational forecaster. Since 2002, the four main dynamical models, GFS, GFDL, UKMT, and NOGAPS, and the NHC Official forecasts have all been included as part of the operational superensemble. These models will be described more fully in Chapter 2.6.

2.4 The Synthetic Superensemble

The synthetic superensemble uses basically the same technique and coding as in the operational superensemble, the only changes are in the member models. The synthetic superensemble consists of the regular member model input, synthetic versions of these models, and the operational FSU hurricane superensemble and its synthetic version. The synthetic superensemble, therefore, can have two times plus two the number of models as does the operational superensemble. This technique is similar to a bootstrapping technique, in that it increases the model input to the superensemble and it provides more variance in order to produce a more accurate forecast.

Synthetic model forecasts are produced by a simple alteration of the original model forecast. This alteration is achieved by first applying a linear trend to a model forecast. This produces a linear best-fit line through a nonlinear hurricane track. Then, a Fourier curve is

applied to the best-fit line to artificially generate a new track shape. Three synthetic forecasts are produced for each model using a one, two, or three harmonic Fourier curve, each producing a different geometry. Applying more than a three harmonic Fourier curve to model tracks was found to decrease the skill of the forecast. Please see the Appendix for more information on the synthetic superensemble. Table 2.1 shows a 120-hour superensemble forecast produced operationally for Hurricane Fabian in 2003 along with one, two, and three harmonic synthetic forecasts generated using the synthetic method described above. Figure 2.1 graphically shows the difference in the four forecasts.

Once synthetic model data has been produced for both the training and forecast phases, the superensemble can be run once again with the synthetic data included. Many versions of the synthetic superensemble were run for the 2001 and 2002 hurricane seasons. It was found that the synthetic superensemble that contained all member models of the operational superensemble, the synthetic versions of these models, and the operational superensemble and its synthetic version produced forecasts with the greatest skill. Also, a specific combination of harmonics was chosen for each forecast hour that was found to maximize the synthetic superensemble skill. The method for finding this combination is discussed in Chapter 3.

The synthetic superensemble is capable of being produced on a real-time basis. Since the synthetic superensemble requires input from the real-time superensemble, it cannot be produced exactly at synoptic time. However, it takes only a little more computing time to produce synthetic model versions and rerun the superensemble with synthetic data. Because this additional time is needed, the synthetic superensemble can be run with model data initialized from the current synoptic time instead of the interpolated versions of these models used in the real-time superensemble. These model versions are more skillful, but come in via ATCF data stream four-to-five hours after synoptic time.

Table 2.1: A comparison between the real-time FSU superensemble and its three synthetic components for a 120-hour forecast of Hurricane Fabian

	Latitude				Longitude			
Hour	Real-Time SENS	One Harmonic	Two Harmonics	Three Harmonics	Real-Time SENS	One Harmonic	Two Harmonics	Three Harmonics
0	20.90	20.22	20.57	20.49	61.30	61.28	61.01	61.65
12	21.91	22.02	21.89	21.80	62.74	61.54	62.57	62.50
24	23.01	23.41	22.97	23.08	64.00	63.05	64.07	63.46
36	24.44	24.70	24.50	24.54	65.22	65.14	64.86	65.20
48	26.34	26.23	26.53	26.40	66.20	66.95	65.71	66.18
60	28.61	28.26	28.67	28.70	66.77	67.69	67.07	66.52
72	31.26	30.88	30.88	30.99	66.62	66.96	67.74	67.52
84	33.73	33.97	33.55	33.48	65.68	64.87	66.06	66.70
96	36.85	37.25	36.95	36.86	63.23	61.99	62.08	62.01
108	40.07	40.37	40.57	40.68	59.38	59.18	58.06	57.45
120	43.48	43.05	43.17	43.20	54.02	57.27	57.05	57.43

Figure 2.1: A graphical representation of the comparison between the real-time FSU superensemble and its three synthetic components for a 120-hour forecast of Hurricane Fabian

2.5 Walking through a Synthetic Superensemble Forecast

To illustrate the basic mathematics behind the superensemble and the synthetic superensemble, a sample walk-through calculation is performed for a 72-hour forecast of Hurricane Juan (see Tables 2.2-2.4). Eight models are used for this sample calculation: the GFS model, the GUNS consensus model, the NOGAPS model, the real-time superensemble, and the synthetic versions of these four models. The forecast is produced in five steps and is a combination of each model's regression coefficient (a_i), forecast anomaly value or normalized difference ($F_i(t) - \overline{F_i}$), and the observed mean of all storms contained in the training data set ($\overline{O}$).

It is important to remember that the calculated coefficients are not based on forecast data sets from Hurricane Juan, only from 2002 and 2003 storms prior to Hurricane Juan. Model coefficients, derived from past model behavior, range from negative to positive values and some are very close to zero. These weights end up producing a superensemble forecast that is closest to the observed position (see Table 2.4). It can be seen that the forecast latitude and longitude are determined separately and an incremental approach is taken wherein the calculated latitude/longitude increment is added to the 60-hr forecast value to produce a 72-hour forecast. Overall, the synthetic superensemble outperforms all member models. An average of the eight models is also calculated to show that the synthetic superensemble has a smaller forecast error than an ensemble mean of the eight member models.

2.6 Superensemble Member Models

In this study, the nine member models used as input into the superensemble were based on the member models used in the real-time forecasting of the 2002 hurricane season. In real-time, hurricane track and intensity forecasts are received via the ATCF data stream from the NHC at the four synoptic times: 00, 06, 12, and 18 UTC. This data stream contains models from NCEP, GFDL, NOGAPS, the UK Met Office, statistical and in-house NHC models, and the Official NHC forecast. Member models contain a combination of consensus, dynamical, statistical, and beta and advection models. By far the biggest contribution to the superensemble

Table 2.2: 72-hour synthetic superensemble walk-through calculation of Hurricane Juan's latitude. Forecast valid 29 September 2003 at 12 UTC.

Model	Regression Coefficient a_i	Forecast Anomaly $(F_i(t) - \overline{F_i})$	$a_i(F_i(t) - \overline{F_i})$	SENS Forecast Increment $\overline{O} + \sum_{i=1}^N a_i(F_i(t) - \overline{F_i})$	Forecast Latitude (60 hr position + increment)	Forecast Error (latitude)
GFS	-0.09	5.99	-0.54	0.68 + 5.10 = 5.78	50.70	0.9
GUNS	0.05	5.15	0.26		50.00	0.2
NOGAPS	0.21	7.15	1.50		52.70	2.9
Real-Time SENS	0.28	4.53	1.27		49.50	-0.3
Synthetic GFS	0.19	6.46	1.23		51.58	1.78
Synthetic GUNS	0.00018	3.97	0.00072		49.15	-0.65
Synthetic NOGAPS	0.23	5.07	1.17		51.05	1.25
Synthetic R-T SENS	0.05	4.15	0.21		48.14	-1.66
			$\Sigma = 5.10$			
Ensemble Mean	60 hour forecast position = 44.38				50.35	0.55
Synthetic SENS	60 hour forecast position = 44.45				50.23	0.43
Observed	60 hour position = 42.80				49.80	-

Table 2.3: 72-hour synthetic superensemble walk-through calculation of hurricane Juan's longitude. Forecast valid 29 September 2003 at 12 UTC.

Model	Regression Coefficient a_i	Forecast Anomaly $(F_i(t) - \overline{F_i})$	$a_i(F_i(t) - \overline{F_i})$	SENS Forecast Increment $\overline{O} + \sum_{i=1}^N a_i(F_i(t) - \overline{F_i})$	Forecast Longitude (60 hr position + increment)	Forecast Error (longitude)
GFS	0.20	-4.28	-0.86	0.17 + -2.73 = -2.56	61.50	-0.9
GUNS	0.17	-2.37	-0.40		60.90	-1.5
NOGAPS	0.14	-2.39	-0.33		62.20	-0.2
Real-Time SENS	0.15	-2.29	-0.34		60.90	-1.5
Synthetic GFS	0.09	-4.46	-0.40		60.27	-2.13
Synthetic GUNS	0.18	-1.39	-0.25		61.63	-0.77
Synthetic NOGAPS	-0.04	-1.08	0.04		63.45	1.05
Synthetic R-T SENS	0.09	-2.07	-0.19		60.30	-2.1
			$\Sigma = -2.73$			
Ensemble Mean	60 hour forecast position = 63.75				61.39	-1.01
Synthetic SENS	60 hour forecast position = 63.99				61.43	-0.97
Observed	60 hour position = 63.90				62.40	-

Table 2.4: Overall forecast track error for a 72-hour forecast of Hurricane Juan valid 29 September 2003 at 12 UTC.

Model	72 – Hour Forecast Error (km)
GFS	118.73
GUNS	109.66
NOGAPS	322.61
Real-Time Superensemble	112.97
Synthetic GFS	248.23
Synthetic GUNS	91.16
Synthetic NOGAPS	157.57
Synthetic Real-Time Superensemble	239.80
Ensemble Mean	94.48
SYNTHETIC SUPERENSEMBLE	88.65

comes from the NHC Official forecast and the four dynamical models. Following is a brief description of the nine superensemble member models:

1. Official – model id 01

The NHC operational forecast: The “Official” forecast

The NHC issues an “Official” forecast for all operationally designated tropical and subtropical cyclones in the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. This forecast is a subjective consensus forecast produced by forecasters at the NHC in Miami, FL. These forecasts are issued one to one-and-a-half hours after synoptic time so that the most up-to-date data and model outputs are available. Before the 2003 season, the forecasts went out to 72 hours. In 2003, four and five day forecasts, previously experimental, were released operationally. This forecast is important to the superensemble because of its consistency and accuracy.

2. AVN/GFS – model id 15

The AVN model is NCEP’s global model for Medium Range Forecasts (MRF). In 2002 AVN and MRF runs were consolidated into a four-times daily Global Forecast System (GFS). This primitive equation model had a resolution of T126 with 28 vertical sigma levels (Kanamitsu et al. 1991). In 2002, resolution was increased to T254 with 64 vertical sigma levels (EMC Staff 2003). This model became a dominant forecasting tool in 2000 when there was a significant change in the way the model initialized the hurricane vortex (Liu et al. 2000). The GFS model is additionally important because its analysis and forecast fields are used as input to other track models, including the GFDL model. GFS forecasts are received out to 120 hours. The GFS model does not use vortex bogussing in model initialization.

3. NOGAPS – model id 26

NOGAPS, the U.S. Navy’s Operational Global Atmospheric Prediction System, is a dynamical primitive equation model. This model currently has a resolution of T239 with 30 sigma levels (Hogan and Clune 2003). Forecasts are produced every six hours at synoptic time and out to 144 hours. The NOGAPS model does use vortex bogussing in the initialization of the model. This model is currently undergoing changes involving NAVDAS

data assimilation of AMSU data becoming operational in the 2004 season (Goerss, personal communication 2004). More information on the NOGAPS model is described in Hogan and Rosmond (1991) and Goerss and Jeffries (1994).

4. UKMT – model id 27

UKMT is a global forecast model run by the United Kingdom Meteorological Office. This model is a grid point model with a resolution of 432 columns and 325 rows. This model also relies on vortex bogussing in its initialization. The NHC began receiving the model's forecasts operationally in 1996 and it has since become an important dynamical model. In August 2002, there was a major upgrade to the UK Met Office's global and mesoscale models. The Met Office implemented a new Unified Global Model that consists of a reformulation of the model's dynamics and a new physics package. This new version has shown improvements in the prediction of tropical cyclones (for more information see Milton et al. 2003). The UK Met Office's forecasts are now produced four times daily.

5. GFDL – model id 63

The GFDL model is a triple-nested moveable mesh primitive equation model run by NCEP's Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, NJ. This model is an outgrowth of the Multiple-Mesh Grid Point Regional Model (MMM), which was developed as a research model (Kurihara et al. 1998). GFDL is run with input analyses from NCEP'S GFS model. In 2001, the GFDL model was coupled with a high resolution version of the Princeton Ocean Model (POM) to improve intensity forecasts (Bender et al. 2002). Other changes have been made since 2001 including an increase in resolution to $\frac{1}{2}^\circ$ for the outer grid and 42 vertical levels. This model differs from the GFS model in that it relies on vortex bogussing in the initialization of the model. This model was first used as an operational hurricane prediction model in 1995 and forecasts are currently produced 4-times daily. For more information on this model see Bender et al. (2004).

6. GUNS – model id 21

GUNS is a simple ensemble mean of three dynamical models: GFDL, UKMT, and NOGAPS. Goerss (2000) found that a consensus forecast could be more accurate than the

forecasts of any of the individual models. Forecast positions for GUNS are determined by simply averaging the forecast positions from the three aforementioned models whenever positions for all three are available. GUNS has been used operationally by the NHC since 2000. Another consensus forecast, GUNA, an ensemble mean of GFDL, UKMT, NOGAPS, and AVN/GFS, is also widely used by the NHC since 2001. For more information on this ensemble technique see Goerss (2000).

7&8. BAMM/BAMD – model ids 22 and 23

Beta and Advection Model (BAM)

The BAM model is a dynamical-statistical model that follows a trajectory from the pressure-weighted vertically-averaged horizontal wind from the GFS model. The trajectory includes a correction term to account for the beta-effect of the storm– a differential in planetary vorticity advection that causes hurricanes to move westward and northward. The BAM model is run three times: with shallow (850-700 hPa), medium (850-400 hPa), and deep (850-200 hPa) winds. Only the medium and deep wind runs, BAMM and BAMD, are used as input to the superensemble. For a full description of the BAM models see Marks (1992).

9. NHC90 – model id 31

NHC90 is a statistical-dynamical track forecast model. It uses geopotential height predictors from GFS and output from CLIPER to produce a track forecast for each GFS run. CLIPER is a statistical model based on climatology and persistence and is used to evaluate a forecast's skill. NHC90 is produced at synoptic forecast times using the GFS global analysis and forecast from 6 hours previous. A newer version of this model, NHC98, uses a blend of three track estimates. For more information on this model see Neumann and McAdie (1991).

CHAPTER 3

SKILL OF THE SYNTHETIC SUPERENSEMBLE FOR CANADIAN TROPICAL SYSTEMS OF THE 2001 HURRICANE SEASON

3.1 The 2001 Atlantic Hurricane Season

The 2001 hurricane season spanned from Tropical Storm Allison on 5 June to late season Hurricane Olga on 4 December 2001 (see Table 3.1). The season was slightly above normal with 15 named storms, 9 hurricanes, and 4 major hurricanes (at or above category three on the Saffir-Simpson Hurricane Scale). This was more than predicted by the Climate Prediction Center at NOAA: 9-12 named storms, 6-8 hurricanes with 2-4 major hurricanes (<http://www.cpc.ncep.noaa.gov>). Tropical Storms Allison and Barry and Hurricane Gabrielle all made landfall in the United States. Karen made landfall in Nova Scotia as a tropical storm.

Six tropical systems entered the CHC Response Zone in 2001 (see Figure 3.1). Canada was hit hardest in the month span from the end of August to the end of September when four named storms all passed through Atlantic Canada, two of which had a significant effect on the Canadian Maritimes. Hurricane Gabrielle brought massive amounts of rain to Newfoundland causing extreme flooding and prompting the mayor of St. John's to declare Gabrielle "the worst storm in 100 years (<http://www.atl.ec.gc.ca/weather/hurricane/storm01.html>).” Karen was the only storm to make landfall in the Maritimes; it was an unusual storm in that it possessed highly tropical characteristics in such high latitudes (Bowyer et al. 2004). In the following paragraphs each of the six systems affecting the Canadian Maritimes is discussed.

Table 3.1: Named Atlantic tropical cyclone statistics for the 2001 hurricane season

Storm Name	Dates	Max Wind (knots)	Saffir-Simpson Category
Tropical Storm Allison	5 – 17 June	50	
Tropical Storm Barry	2 – 7 August	60	
Tropical Storm Chantal	14 – 22 August	60	
Tropical Storm Dean	22 – 28 August	60	
Hurricane Erin	1 – 15 September	105	Category 3
Hurricane Felix	7 – 18 September	100	Category 3
Hurricane Gabrielle	11 – 19 September	70	Category 1
Hurricane Humberto	21 – 27 September	90	Category 2
Hurricane Iris	4 – 9 October	125	Category 4
Tropical Storm Jerry	6 – 8 October	45	
Hurricane Karen	12 – 15 October	70	Category 1
Tropical Storm Lorenzo	27 – 31 October	35	
Hurricane Michelle	29 October – 5 November	120	Category 4
Hurricane Noel	4 – 6 November	65	Category 1
Hurricane Olga	24 November – 4 December	80	Category 1

Figure 3.1: Atlantic tropical cyclone tracks for 2001 storms that entered the CHC Response Zone denoted by the black line

Tropical Storm Dean

Dean formed as a tropical wave off the African coast. On 22 August 2001, Dean developed a surface center and tropical storm force winds while in the Caribbean Sea. Dean traveled through the U.S. Virgin Islands, lost its closed circulation, and was downgraded to a tropical wave on 23 August. As the wave moved northward, convection began to redevelop and Dean was upgraded back to a tropical storm and reached its maximum intensity of 60 knots on 27 August (Beven et al. 2003). Dean entered the CHC Response Zone on 27 August, 240 n mi south of Sable Island. Storm and gale warnings were issued for much of the southern Canadian marine forecast areas, but no warnings were issued over land. As Dean moved northward it weakened due to cool waters in the southern Grand Banks, the center became less defined, and the convective bands less organized. In the afternoon of 28 August, Dean lost tropical characteristics and later dissipated as it encountered a frontal low. Maximum winds reported in Canadian waters were 60 knots. Newfoundland experienced heavy rainfall, but no damages resulted (Bowyer et al. 2004).

Hurricane Erin

Erin developed from an African wave on 30 August 2001. On 1 September the system strengthened into a tropical storm with the establishment of a closed circulation. Due to strong vertical shear, Erin weakened into an area of disturbed weather on 5 September. The next day, the system headed northward and a surface circulation redeveloped; Erin was upgraded to a tropical storm north of the Leeward Islands. On 8 September, Erin reached its peak intensity, 968 mb and 105 knots, 90 n mi east of Bermuda making it a category 3 hurricane. Then, a mid-upper level trough off eastern Canada accelerated Erin northeastward (Beven et al. 2003).

On 11 September, Hurricane Erin entered the CHC Response Zone. Maritime Canadian weather centers issued gale and later hurricane warnings for marine areas north and northeast of Newfoundland. On 14 September, Hurricane Erin passed to the southeast of Cape Race, Newfoundland and hurricane force winds passed over the waters south of Newfoundland, but Erin did not make landfall. Maximum winds were estimated at 90 knots over water and 50 knots over land. Newfoundland was hit worst by rain, first by a quasi-stationary front late on 13 September, then from Erin on 14 September, which brought 75-125 mm of rain. Erin lost tropical characteristics as it continued north and eventually merged with cyclonic flow over eastern Greenland on 17 September (Beven et al. 2003, Bowyer et al. 2004).

Hurricane Gabrielle

Gabrielle formed as a tropical depression on 11 September 2001 when a trough east of the southeastern United States moved across Florida and merged with a surface low over the Gulf of Mexico, becoming an organized system. The storm moved in a loop over the Gulf of Mexico and strengthened to become Tropical Storm Gabrielle. A mid-level trough pushed Gabrielle northeastward as it made landfall 14 September in Venice, Florida. Gabrielle affected Florida with 100-175 mm of rain and 18 tornadoes before strengthening to a category one hurricane northwest of Bermuda. Gabrielle continued to move northeastward weakening to tropical storm status as its center lost deep convection (Beven et al. 2003).

Gabrielle became extratropical as it reached the CHC Response Zone on 19 September. Even though Gabrielle was considered extratropical, it still retained some tropical characteristics and had a central pressure of 975 mb as it crossed the Grand Banks and affected southern Newfoundland. Gabrielle had a large radius of gale and storm-force winds that brought gusts upwards of 100 knots. The Avalon Peninsula got the brunt of the rain and experienced extensive flood damage. In Newfoundland, Cape Race recorded 162 mm of rain and St. John's recorded upwards of 120 mm. After Gabrielle passed through Newfoundland, it merged with an extratropical low over the north Atlantic (Beven et al. 2003, Bowyer et al. 2004).

Hurricane Humberto

Humberto formed in the subtropical Atlantic Ocean from a trough extending southwestward from Gabrielle and an upper-level low passing west over the trough. The storm became organized, developed a circulation center by 21 September, and was upgraded to Tropical Storm Humberto the next day. Humberto then turned north-northwestward and strengthened to a category 2 hurricane. Humberto encountered vertical shear, but picked up speed and strength as it entered warmer waters. While 175 n mi south-southwest of Sable Island, Nova Scotia, it reached a peak intensity of 90 knots and 970 mb on 26 September. Hurricane Humberto had few effects on Canada as it entered the CHC Response Zone to the east of the Maritime Provinces. Few warnings were issued due to Humberto being such a compact system. Humberto dissipated well to the east of Canadian waters on 27 September as an open trough (Beven et al. 2003, Bowyer et al. 2004).

Hurricane Karen

Karen originated in the subtropical Atlantic Ocean from a stalled cold front southeast of Bermuda on 10 October 2001 and became an extratropical low. As the system moved north, it acquired warm-core characteristics and on 12 October became Subtropical Storm One 30 n mi south of Bermuda. As it moved northward past Bermuda, it began to slow down and increase in organization. On 13 October after deep convection had developed and an eye appeared in satellite imagery, the system became Tropical Storm Karen and strengthened to a category one hurricane later that day. Maximum intensity occurred at 70 knots 350 n mi south of Nova Scotia. Karen moved northward very erratically, speeding up then slowing down until making landfall near Western Head, Nova Scotia on 15 October as a tropical storm. The maximum winds reported were gusts of 52 knots at MacNabs Island with sustained winds of 38 knots. Wave heights reached over five meters in Halifax Harbour. Storm and gale warnings were issued for the marine areas south of Nova Scotia. Because the storm was moving rapidly over land and rainbands were concentrated to the west of the storm, rainfall amounts didn't exceed 45 mm. After making landfall, Karen lost all deep convection and became an extratropical low-pressure system (Beven et al. 2003, Bowyer et al 2004).

Hurricane Noel

Noel developed from a non-tropical occluded low that formed early on 2 November 2001. The system was classified as a subtropical cyclone 775 n mi south of Cape Race, Newfoundland. By 5 November, Noel had developed a warm core and was classified as a category one hurricane with wind speeds of 65 knots. Twelve hours later, Noel weakened to a tropical storm due to westerly wind shear. Noel entered the CHC Response Zone as a system with both tropical and non-tropical characteristics. Noel brought rain and flooding to southeast Newfoundland and strong rain and winds to the eastern Grand Banks. Late on 6 November, Noel lost all convection and became extratropical 285 n mi southeast of Newfoundland (Beven et al. 2003, Bowyer et al. 2004).

Non-Canadian Tropical Cyclones

There were also several significant tropical cyclones that did not affect Canadian Provinces in 2001. Felix developed in the tropical Atlantic from an African tropical wave on 7 September. Felix reached a maximum intensity of 100 knots, making it a major hurricane; Felix dissipated on 19 September without affecting land. Iris developed in the tropical Atlantic from

an African easterly wave on 4 October. Iris reached its maximum intensity of 125 knots just before making landfall in Belize on 9 October. Iris was responsible for severe destruction and 31 deaths in Belize. Michelle also developed from an African easterly wave on 29 October along the Nicaraguan coast. Michelle was at its peak category four intensity when it struck Cuba; Michelle was the strongest hurricane to hit Cuba since 1952. Michelle's path of destruction reached from Central America to the Bahamas. Olga was a late season tropical cyclone that developed in the subtropical Atlantic on 24 November and strengthened to a category one hurricane. Olga dissipated on 4 December, four days after the official end to the Atlantic hurricane season (Beven et al. 2003).

3.2 Skill of the Synthetic Superensemble for the 2001 Season

For the 2001 hurricane season, a training data set was compiled using member model forecasts from the 2000 and 2001 hurricane seasons. A cross-validation approach was utilized due to model changes between seasons. This meant that the training data set was different for each storm. Training data consisted of 209 to 223 cases, where a case consists of one forecast; 120 of these cases came from the 2000 hurricane season. This training data set was found to produce optimum forecasts. Skill was degraded when only year 2000 forecast cases were used or when year 1999 forecasts were added to training. Synthetic superensemble member models consisted of the nine models discussed in Chapter 2.6, the synthetic values of these models, and the real-time superensemble and its synthetic version. It was mentioned in Chapter 2 that three versions of the synthetic superensemble are produced: one, two, and three harmonic versions. The final synthetic superensemble represents an optimum combination of these forecasts. The combination was decided using 2001 and 2002 season-end statistics. For a shorter forecast, a higher harmonic will produce too many high frequency waves, so a lower harmonic is optimum. For a longer forecast, a greater amount of high frequency waves is desired as the forecast error increases, so a higher harmonic works best. The optimum combination calls for forecast hours 12-48 and hour 96 to use the one harmonic forecast, hours 60-72 to use the two harmonic forecast, and hours 84 and 108-120 to use the three harmonic forecast. For the 2001 hurricane season, there were 103 synthetic superensemble forecast cases at 12 hours, 89 cases at 24 hours, 66 cases at 48 hours, 44 cases at 72 hours, 29 cases at 96 hours, and 10 cases at 120 hours.

Track errors from the 2001 hurricane season are shown in Figure 3.2. Forecast error is determined by the great-circle distance between each forecast position at each forecast hour and its corresponding best track position. The best track positions are found in the HURDAT file, which contains the final official estimates of tropical cyclone position and maximum one-minute sustained winds ten meters above the surface as determined in post-storm analysis at the NHC. Up to 60 hours, the synthetic superensemble has the lowest track error. Past this point, AVN is the dominant model, with either the synthetic superensemble or the ensemble mean with the second smallest error. The worst performers were the NHC90 statistical model and the GUNS ensemble mean, which had large errors past 72 hours. A break down of selected track errors can be found in Table 3.2.

Figure 3.2: 2001 Atlantic tropical cyclone RMS track errors. Number of cases: 103, 89, 77, 66, 55, 44, 35, 29, 22, and 10.

Table 3.2: 2001 selected Atlantic tropical cyclone track error statistics. RMS error units are in *km*

MODEL	TRACK ERROR (<i>km</i>)					
Forecast Hour	12	24	48	72	96	120
Best-Model (AVN)	78.56	132.37	221.72	305.09	331.40	321.71
Real-Time SENS	101.32	186.89	340.45	495.36	669.86	913.78
Ensemble Mean	77.90	132.38	250.04	354.16	427.93	478.58
Synthetic SENS	67.94	120.80	221.56	351.91	510.20	487.36

It is of interest to note the difference between the synthetic superensemble and the ensemble mean. This ensemble mean is a straight average of all synthetic superensemble member models; it has no bias removal. The synthetic superensemble outperforms the ensemble mean up to 84 hours; however, the only noticeable difference past 84 hours is at 96 hours and 108 hours. The synthetic superensemble also outperforms the real-time superensemble at each forecast hour. The real-time superensemble seems to perform badly compared to the member models, it is of note that its member models are interpolated model versions: they are not the same member models listed here and, because they are interpolated, they have larger errors than the synthetic superensemble member models. Real-time superensemble results are the same as those depicted in Williford (2002). It is also of note that season-end statistics only include 2001 season named storms with five or more real-time superensemble forecast cases. These statistics exclude the following storms: Allison, Dean, Jerry, Karen, and Noel.

One of the most significant Canadian storms of the 2001 hurricane season was Hurricane Gabrielle, dubbed “the worst storm in 100 years” by the mayor of St. Johns, Newfoundland. Synthetic superensemble forecasts for this storm were superb. The synthetic superensemble outperformed all member models up to 108 hours at which point the AVN and BAMM models were superior. Figure 3.3 shows track errors for Hurricane Gabrielle and Table 3.3 provides selected track errors. A 60-hour Gabrielle forecast can be seen in Figure 3.4. The synthetic superensemble also performed well for the Canadian hurricanes Erin and Humberto; it was a top

performer at many forecast hours. Forecast tracks from these two storms can be seen in Figures 3.5 and 3.6.

Neumann (1981) found that track forecast errors generated by the Atlantic CLIPER statistical model can be taken as a measure of forecast difficulty and can be used to determine forecast skill. CLIPER is a statistical model that is based on climatology and persistence. It consists of prediction equations that relate future displacements of a tropical cyclone to a specific set of predictors. These predictors include: initial and previous 12-hour positions, initial and previous 12-hour storm motion vectors, day number of the year, and the estimated maximum surface wind (DeMaria et al. 1990). Because this model only takes climatology and persistence into account, it is said to have no skill and any model forecast more accurate than the CLIPER model is said to be skillful. Large CLIPER track errors are indicative of a storm that is difficult to forecast. CLIPER errors become large as systems recurve and become caught up in the westerlies; this causes forward speed to increase and makes tracks difficult to predict (McAdie and Lawrence 2000).

Figure 3.3: Hurricane Gabrielle Atlantic tropical cyclone RMS track errors. Number of cases: 11, 10, 9, 8, 7, 6, 4, 3, 3, and 2.

Table 3.3: Hurricane Gabrielle selected Atlantic tropical cyclone track error statistics.
RMS error units are in *km*

MODEL	TRACK ERROR (<i>km</i>)					
Forecast Hour	12	24	48	72	96	120
Best-Model (AVN)	67.68	123.01	330.88	467.95	470.54	450.92
Real-Time SENS	151.24	272.23	509.43	705.53	1034.59	1500.43
Ensemble Mean	96.17	164.45	361.86	523.94	583.94	777.83
Synthetic SENS	58.48	90.93	252.66	432.22	301.76	695.95

Figure 3.4: Hurricane Gabrielle 60-hour forecast for 16 September 2001 at 12 UTC. The thick red line indicates the synthetic superensemble

Figure 3.5: Hurricane Erin 60-hour forecast for 12 September 2001 at 12 UTC.

Figure 3.6: Hurricane Humberto 72-hour forecast for 24 September 2001 at 12 UTC.

In 2001, average official track errors were small, being 5-17% less than the previous ten-year average and 26-51% less than CLIPER errors. This decrease in error can be attributed to an improvement in numerical guidance (Beven et al. 2003). Table 3.4 compares CLIPER errors to select models and Figure 3.7 depicts the forecast skill for year 2001 Atlantic tropical cyclone tracks. The synthetic superensemble was found to have, on average, ~92% less error than CLIPER while the best model, AVN, was found to have ~86% less error than CLIPER up to 72 hours.

3.3 2001 Season Summary

The 2001 hurricane season had 15 named storms, 9 of those becoming hurricanes and 4 of those major hurricanes. This is very similar to the 2000 hurricane season, which had 15 named storms, 8 of those becoming hurricanes and 3 of those major hurricanes. Both of these seasons were climatologically above the average of 10 named storms, 6 hurricanes, and 2 major hurricanes (Franklin et al. 2001, Beven et al. 2003). This is not where the similarities between the two seasons end. In both 2000 and 2001, much of the tropical cyclone activity occurred in subtropical regions north of 25° N. In 2000, four of the season's cyclones were subtropical for a portion of their life cycle and two of the three major hurricanes reached their peak intensity in the subtropical Atlantic where the environment was more favorable than the tropical Atlantic throughout most of the season (Franklin et al. 2001). Similarly in 2001, six named storms formed north of 25° N from non-tropical weather systems, and four tropical cyclones were classified as subtropical during a portion of their life cycle. In fact, in 2001 there were no hurricanes south of 23° N latitude (Beven et al. 2003). These similarities between seasons strongly benefited the 2001 superensemble forecasts. When hurricanes follow related patterns, the training data set will be similar to the current season's forecast data set. The superensemble is able to account for past model behavior in the training and compensate in the forecast phase. This similarity between seasons is likely the major reason for the success of the synthetic superensemble in the 2001 hurricane season.

Table 3.4: 2001 CLIPER track errors in comparison to the AVN model and the synthetic superensemble. RMS error units are in *km*

MODELS	FORECAST HOUR				
	12	24	36	48	72
CLIPER	104.44	232.71	344.90	456.46	672.78
Best-Model (AVN)	78.56	132.37	177.40	221.72	305.89
Synthetic SENS	68.01	120.27	160.48	221.56	351.91

Figure 3.7: Relative forecast skill for 2001 Atlantic tropical cyclone tracks. Errors are relative to CLIPER in percentage

A major challenge to the 2001 season involves the AVN model. This model went through vast improvements in the 2000 and 2001 hurricane seasons. In 2000, there was a change made in the way the AVN model initialized the hurricane vortex (Liu et al. 2000). This change greatly improved track forecasts for the AVN model. However, this model was unavailable via the ATCF data stream through the 2001 season so it was not included as a member model for the real-time superensemble until the 2002 season. It is thought that the real-time superensemble forecasts would have greatly improved had AVN been a member model. This would have additionally benefited the synthetic superensemble, because the real-time superensemble is a member model. Also, in 2001 there were several changes to the AVN model including significant changes in data assimilation and physical parameterization (Moorthi et al. 2001). These changes resulted in the AVN outperforming all member models and the synthetic superensemble past 60 hours for the 2001 season. Had this model performed as well in 2000 as it did in 2001, its weighted coefficient would have been higher and the model would have had a more significant impact on the synthetic superensemble.

CHAPTER 4

SKILL OF THE SYNTHETIC SUPERENSEMBLE FOR CANADIAN TROPICAL SYSTEMS OF THE 2002 HURRICANE SEASON

4.1 The 2002 Atlantic Hurricane Season

The 2002 hurricane season spanned from Tropical Storm Arthur on 14 July 2002 to Tropical Depression Fourteen ending on 16 October 2002 (see Table 4.1). Gustav became the first hurricane of the Atlantic season on 11 September, which made it the latest date for the Atlantic's first hurricane since 1944. The season was below normal with twelve named storms, four hurricanes, and two major hurricanes. In this season, nine of the twelve named systems originated at subtropical latitudes. Seven tropical cyclones made landfall in the United States and one in Canada. Hurricanes Isidore, Kyle and Lili brought extensive damage to the United States with combined damage costs around \$1 billion. Gustav brought severe damage to Newfoundland in Canada. Also, Hurricane Kyle lasted for 22 days making it the third-longest lived Atlantic tropical cyclone (Pasch et al. 2004b).

Five systems passed into the CHC Response Zone in 2002 (see Figure 4.1). Three of these storms were tropical in nature, while the other two were extratropical as they passed into the Response Zone. Hurricane Gustav made landfall in Nova Scotia as a category one hurricane, the first hurricane to do so since Michael in 2000. Overall, the Canadian season was weak with Gustav being the only significant tropical storm in the Maritimes. In the following paragraphs each of the five systems affecting the Canadian Maritimes is discussed (Bowyer et al. 2004).

Table 4.1: Named Atlantic tropical cyclone statistics for the 2002 hurricane season

Storm Name	Dates	Max Wind (knots)	Saffir-Simpson Category
Tropical Storm Arthur	14 – 16 July	50	
Tropical Storm Bertha	4 – 9 August	35	
Tropical Storm Cristobal	5 – 8 August	45	
Tropical Storm Dolly	29 August – 4 September	50	
Tropical Storm Edouard	1 – 6 September	55	
Tropical Storm Fay	5 – 8 September	50	
Hurricane Gustav	8 – 12 September	85	Category 2
Tropical Storm Hanna	12 – 15 September	50	
Hurricane Isidore	14 – 27 September	110	Category 3
Tropical Storm Josephine	17 – 19 September	50	
Hurricane Kyle	20 September – 12 October	75	Category 1
Hurricane Lili	21 September – 4 October	125	Category 4

Figure 4.1: Atlantic tropical cyclone tracks for 2002 storms that entered the CHC Response Zone denoted by the black line.

Tropical Storm Arthur

Arthur originated from a decaying frontal zone in the Gulf of Mexico on 9 July 2002 and traveled through the southeastern United States. As the storm moved off the Carolina coast, its circulation became organized and was upgraded to a tropical depression 40 n mi southwest of Cape Hatteras, North Carolina. A cut off low from the Canadian Maritimes caused the storm to strengthen and accelerate east-northeastward. Arthur reached tropical storm status on 15 July with maximum winds of 50 knots 350 n mi south of Nova Scotia. Arthur became extratropical as it tracked through Canadian waters and moved over Newfoundland with winds around 45 knots; rainfall was not significant. On 17 July, Arthur became a low-pressure system (Bowyer et al. 2004, Pasch et al. 2004b).

Hurricane Gustav

Gustav developed from an amplifying upper level trough located between the Bahamas and Bermuda. On 7 September a surface low formed and convection became organized so it was upgraded to a subtropical depression 440 n mi south-southeast of Cape Hatteras, NC. This system strengthened slowly, becoming Subtropical Storm Gustav on 8 September as it moved west-northwestward; on 10 September it turned northward and acquired enough convection over the center to become a tropical storm. The center passed near Cape Hatteras, encountered an approaching trough, accelerated northeastward and intensified further. On 11 September, Gustav was upgraded into a category one hurricane with a maximum intensity of 85 knots (Pasch et al. 2004b).

On 12 September, Gustav made landfall on the southern coast of Cape Breton, Nova Scotia. By the time the storm exited Nova Scotia and headed toward Newfoundland it was classified as a strong extratropical storm. All Maritime Provinces and Maine experienced rain, heavy wind, and localized flooding. Even though Gustav moved quickly over land, several areas of Nova Scotia accumulated more than 100 mm of rain. Winds reached around 54 knots in Nova Scotia and 59 knots in Newfoundland, while Prince Edward Island and New Brunswick accrued more wind-related damages. Gustav eventually dissipated over the Labrador Sea on 15 September (Bowyer et al. 2004, Pasch et al. 2004b).

Hurricane Isidore

Isidore formed from a tropical wave on 9 September; on 14 September the system was classified as a tropical depression near the Venezuelan coast. Development was hindered by

land interaction and it was downgraded to a tropical wave. As the system entered the western Caribbean, a closed circulation was re-established and the storm reached tropical depression status. The next day, the system was upgraded to Tropical Storm Isidore as it passed west of Jamaica. Isidore became a category one hurricane on 19 September before making landfall in western Cuba. The next day Isidore reached its maximum intensity of 110 knots and 934 mb just before making landfall on the Yucatan Peninsula where it weakened to a minimal tropical storm. Next Isidore made landfall just west of Grand Isle, Louisiana with winds at 55 knots before weakening to a tropical depression while moving northward through the United States. On 27 September, Isidore became extratropical over Pennsylvania and merged with a frontal zone. Isidore passed through New Brunswick, Canada on 28 September and was a rain event for southern Ontario, Quebec, and portions of the Canadian Maritimes (Bowyer et al. 2004, Pasch et al. 2004b).

Tropical Storm Josephine

Josephine developed from a weak low-pressure system 750 n mi east of Bermuda on 16 September 2002. The system slowly moved westward as it developed deep convection and a low-level circulation to become Tropical Storm Josephine on 18 September. It then accelerated northeastward ahead of a deep-layer trough. Josephine entered the southeastern part of the CHC Response Zone on 19 September, but stayed more than 200 n mi away from Canadian forecast areas. The system lost tropical characteristics later that day and merged with a larger extratropical frontal system (Bowyer et al. 2004, Pasch et al. 2004b).

Hurricane Kyle

Kyle formed in the North Atlantic Ocean from a non-tropical mid-level trough that caused the development of a stationary low-pressure system east-southeast of Bermuda. Surface winds associated with the system increased on 20 September 2002 so that the system was classified as Subtropical Storm Kyle 680 n mi east of Bermuda the next day. Deep convection strengthened Kyle's center as it began to acquire warm-core characteristics so that on 22 September Kyle became a tropical storm. Kyle drifted southeastward intensifying steadily and on 25 September it was classified a category one hurricane. Kyle's peak intensity was 75 knots, which it maintained for 24 hours until encountering vertical wind shear. Kyle weakened to below tropical storm strength on 30 September, but again hit tropical storm strength several times in October. Kyle made landfall in McClellanville, SC and Long Beach, NC on 11 October

as a tropical storm and Surf City, NC on 12 October as a tropical depression. Kyle then exited North Carolina at Nags Head. Kyle entered the extreme southern region of the CHC Response Zone on 12 September as an extratropical cyclone; all rain and wind associated with Kyle remained outside offshore Maritime waters (Pasch et al. 2004b).

Non-Canadian Tropical Cyclones

There were significant tropical cyclones that had no effect on Canadian provinces in 2002. Tropical Storms Bertha, Edouard, Fay, and Hanna all made landfall in the U.S. Bertha, Fay, and Hanna made landfall on the Gulf Coast, while Edouard made landfall in Ormond Beach, FL. Hurricane Lili originated from a tropical wave over the tropical Atlantic Ocean on 21 September. Lili made landfall in Cuba as a category two hurricane and on the Louisiana coast as a category one storm. Lili caused extensive damages from the Windward Islands to Louisiana (Pasch et al. 2004b).

4.2 Skill of the Synthetic Superensemble for the 2002 Season

The 2002 synthetic superensemble training data set was compiled using member model forecasts from the 2001 and 2002 hurricane seasons. Again, a cross-validation approach was used. This was necessary due to excessive model changes. There were changes in each of the four main dynamic hurricane models: AVN/GFS, GFDL, NOGAPS, and the UK Met Office global model. Despite changes, all four of these models are important contributions to the superensemble and were included in both real-time and synthetic superensemble forecasting. This season, training consisted of 188 to 171 cases, 109 of these from the 2001 hurricane season. Synthetic superensemble member models were the same as those used for the 2001 season and are discussed in Chapter 2.6. For the 2002 hurricane season, there were 77 cases at 12 hours, 76 cases at 24 hours, 71 cases at 48 hours, 63 cases at 72 hours, 54 cases at 96 hours, and 25 cases at 120 hours. In 2002, there are a larger number of cases at later forecast hours than there were in 2001 due to long-lived Hurricane Kyle.

Track errors from the 2002 hurricane season are shown in Figure 4.2. Again this season, only named storms with five or more real-time superensemble cases were included in season-end statistics. Therefore, the following storms were excluded: Arthur, Bertha, Cristobal, Fay, Hanna, and Josephine. This season, the synthetic superensemble is the best model up to 36 hours. From

Figure 4.2: 2002 Atlantic tropical cyclone RMS track errors. Number of cases: 77, 76, 75, 71, 67, 63, 59, 54, 49, and 25.

36 to 96 hours, the NOGAPS and GUNS models usually outperformed the synthetic superensemble. At 120 hours, the synthetic superensemble is outperformed by GUNS and all dynamical models with the exception of the GFDL model. The synthetic superensemble outperformed the real-time superensemble at each forecast hour except at 108 and 120 hours, and it outperformed the ensemble mean up to 96 hours. The best member models were NOGAPS and the GUNS consensus model, both of which performed poorly in 2001. The worst member models for 2002 were both BAM models and NHC90. It is of note that the best model in 2001, AVN/GFS, was not a top performer in 2002 and only slightly beat the synthetic superensemble at five days. A breakdown of selected track errors can be found in Table 4.2.

Table 4.2: 2002 selected Atlantic tropical cyclone track error statistics. RMS error units are in *km*

MODEL	TRACK ERROR (<i>km</i>)					
Forecast Hour	12	24	48	72	96	120
Best Model (NOGAPS)	98.05	134.13	244.66	346.07	525.24	786.86
Real-Time SENS	90.07	140.74	269.69	405.96	605.66	842.14
Ensemble Mean	87.26	125.77	240.19	369.54	555.72	851.08
Synthetic SENS	68.99	120.82	241.51	360.00	568.57	882.10

In 2002, Hurricane Gustav made landfall in Nova Scotia. For this storm, the synthetic superensemble performed well, but was often outperformed by the GUNS, NOGAPS, and UK Met Office models. Track statistics can be found in Figure 4.3 and a sample 72-hour Gustav forecast in Figure 4.4. The synthetic superensemble also performed extremely well for Hurricane Isidore (see Figure 4.5). It was often the best model and was only outperformed by NOGAPS and GUNS at later hours (see Table 4.3). Figure 4.6 shows how all models, except for NOGAPS, predicted landfall to the west of where it was actually observed. Of these models, the synthetic superensemble is furthest to the right. The model also performed well for Hurricane Lili, which had no effect on Canadian Provinces. A sample Lili forecast can be seen in Figure 4.7.

As was mentioned in Chapter 3.2, the CLIPER model can be used to determine the skill of a forecast. In 2002, model errors were 28-48% less than CLIPER and 15-33% less than the 10-year previous average CLIPER (Pasch et al. 2004b). Table 4.4 compares CLIPER errors to select models and Figure 4.8 depicts the forecast skill for 2002 Atlantic tropical cyclone tracks. The synthetic superensemble was found to have, on average, ~111% less error than CLIPER, while the best model, NOGAPS, was found to have ~100% less error than CLIPER (keep in mind that the CLIPER model is only run out to 72 hours).

Figure 4.3: Hurricane Gustav Atlantic tropical cyclone RMS track errors. Number of cases: 6, 6, 6, 6, 6, 6, 6, 5, and 4.

Figure 4.4: Hurricane Gustav 72-hour forecast for 10 September 2002 at 00 UTC. The thick red line indicates the synthetic superensemble.

Figure 4.5: Hurricane Isidore Atlantic tropical cyclone RMS track errors. Number of cases: 16, 16, 16, 15, 14, 13, 12, 11, 10, and 9.

Table 4.3: Hurricane Isidore selected Atlantic tropical cyclone track error statistics. RMS error units are in *km*

MODEL	TRACK ERROR (<i>km</i>)					
Forecast Hour	12	24	48	72	96	120
Best-Model (NOGAPS)	65.51	84.52	148.94	257.65	367.41	412.17
Real-Time SENS	74.81	114.45	253.84	417.71	701.67	825.15
Ensemble Mean	74.36	83.38	209.38	359.01	567.27	763.16
Synthetic SENS	52.97	84.00	157.89	268.17	484.68	723.54

Figure 4.6: Hurricane Isidore 84-hour forecast for 23 September 2002 at 12 UTC.

Figure 4.7: Hurricane Lili 120-hour forecast for 29 September 2002 at 00 UTC.

Table 4.4: 2002 CLIPER track errors in comparison to the NOGAPS model and the synthetic superensemble. RMS error units are in *km*

MODELS	TRACK ERROR (<i>km</i>)				
Forecast Hour	12	24	36	48	72
CLIPER	119.11	238.94	381.02	549.44	902.48
Best-Model (NOGAPS)	98.05	134.13	177.29	244.66	346.07
Synthetic SENS	69.03	121.53	179.42	238.27	372.74

Figure 4.8: Relative forecast skill for 2002 Atlantic tropical cyclone tracks. Errors are relative to CLIPER in percentage

4.3 2002 Season Summary

In 2002, there were 12 named tropical systems, two more than the climatological average. However, only four of these 12 reached hurricane strength, two less than the climatological average. Because many of the named systems were weak and short-lived, the accumulated cyclone energy (ACE) for 2002 was lower than average and so the season was considered less active than normal. ACE is defined as the sum of the squares of the wind speed of all named tropical systems. This decrease in activity can be attributed to a moderate El Niño and above normal shear over the Caribbean and tropical Atlantic (Pasch et al. 2004b). As in 2001, most tropical cyclones in 2002 originated in subtropical latitudes. However, in 2001, most activity took place in the subtropical Atlantic, while in 2002, much of the tropical cyclone activity took place in the Gulf of Mexico.

The differences between the two seasons had some impact on the performance of the superensemble in 2002. However, the main forecasting issue for the 2002 synthetic superensemble forecasts has to do with changes made to the dynamical models. These changes resulted in models that performed differently, and the superensemble is not able to fully compensate for this in training. It would be ideal to freeze a model before it has been changed for use in the superensemble, but this is not possible. This is the main reason why a cross-validation approach was utilized for the 2001 and 2002 seasons. The consistency of the synthetic superensemble should also be noted. In 2001, AVN/GFS was the best performing member model. In 2002, however, GFS was not one of the best performing member models. In 2001, the NOGAPS and GUNS models were two of the worst member model performers, and they were the two best in 2002. The synthetic superensemble has performed consistently well over both seasons.

Another major challenge to the 2002 season was Hurricane Kyle. Kyle lasted 22 days and comprised ~30% of season-end statistics. Kyle was an extremely difficult storm to forecast. All models except GFDL had track errors of over 1000 km at five days. The reason for such large forecast errors was weak steering currents that embedded Kyle causing the storm to drift erratically over the open Atlantic (Pasch et al. 2004b). Figure 4.9 depicts a 120-hr forecast for Kyle. One can easily see high variability in the models and large errors in track position. Kyle had such an impact that Pasch et al. (2004b) noted that while the average official 72-hr track forecast was 200 n mi, 60% of the errors are greater than 200 n mi.

Figure 4.9: Hurricane Kyle 120-hour forecast for 30 September 2002 at 12 UTC.

CHAPTER 5

SKILL OF THE SYNTHETIC SUPERENSEMBLE IN A REAL-TIME SETTING FOR HURRICANE JUAN AND THE 2003 HURRICANE SEASON

5.1 The 2003 Atlantic Hurricane Season

The 2003 hurricane season spanned from Tropical Storm Ana on 30 April to Tropical Storm Peter on 11 December 2003 (see Table 5.1). This season was above normal with 16 named storms, seven hurricanes, and three major hurricanes. The 2003 season was exceptionally long with Tropical Storm Ana forming six weeks before the traditional start of the Atlantic hurricane season and Tropical Storms Odette and Peter forming in December after the traditional end of the Atlantic hurricane season. Unlike the two previous seasons, most of year 2003 storms originated in tropical latitudes below 25° N. Six tropical systems impacted the United States in 2003 and two hurricanes made landfall. Hurricane Claudette made landfall in Texas as a category one hurricane; Hurricane Isabel made landfall in North Carolina as a category two storm. Isabel was also the first hurricane since Mitch in 1998 to reach category five intensity (NCDC 2003).

Five systems passed into the CHC Response Zone in 2003: Hurricanes Danny, Fabian, Isabel, Juan, and Kate (see Figure 5.1). All five of these storms were tropical in nature as they entered the Response Zone, and three became extratropical while in the Response Zone. Additionally Hurricane Juan made landfall in Halifax, Nova Scotia as a category two hurricane and became the strongest hurricane in modern history to impact Halifax. Isabel was also a

Table 5.1: Named Atlantic tropical cyclone statistics for the 2003 hurricane season

Storm Name	Dates	Max Wind (knots)	Saffir-Simpson Category
Tropical Storm Ana	20 – 24 April	50	
Tropical Storm Bill	29 June – 2 July	50	
Hurricane Claudette	8 – 17 July	80	Category 1
Hurricane Danny	16 – 21 July	65	Category 1
Hurricane Erika	14 – 17 August	65	Category 1
Hurricane Fabian	27 August – 8 September	125	Category 4
Tropical Storm Grace	30 August – 2 September	35	
Tropical Storm Henri	3 – 8 September	50	
Hurricane Isabel	6 – 19 September	145	Category 5
Hurricane Juan	24 – 29 September	90	Category 2
Hurricane Kate	26 September – 7 October	110	Category 3
Tropical Storm Larry	1 – 6 October	55	
Tropical Storm Mindy	10 – 14 October	40	
Tropical Storm Nicholas	13 – 23 October	60	
Tropical Storm Odette	4 – 7 December	55	
Tropical Storm Peter	7 – 11 December	60

Figure 5.1: Atlantic tropical cyclone tracks for 2003 storms that entered the CHC Response Zone denoted by the black line

significant storm to Canada. It was the most intense media event to date for the CHC due to a news story predicting Isabel to be a repeat of Hurricane Hazel (1954). In the following paragraphs, each of the five systems affecting the Canadian Provinces is discussed (Bowyer et al. 2004).

Hurricane Danny

Danny formed from a tropical wave on 9 July 2003. The system quickly became disorganized, but regained thunderstorm activity and organization to become a tropical depression on 16 July 550 n mi east of Bermuda. Even though the storm was located at high latitudes, it began to strengthen and became a tropical storm on 17 July, and it intensified into a category one hurricane just inside the CHC Response Zone on 19 July. Because of Danny's high latitude location, it became embedded within a higher than average surrounding environmental pressure field. As Danny moved eastward, it encountered moderate shear and cooler sea surface temperatures causing it to weaken into a remnant low on 21 July. Danny had no direct effects to land (Stewart 2003, Bowyer et al. 2004).

Hurricane Fabian

Fabian originated from a strong easterly wave near the Cape Verde Islands. The storm quickly strengthened into a tropical depression on 27 August and a hurricane on 30 August. Fabian traveled through a favorable environment and was able to reach category four intensity and maintain major hurricane status for almost one week. Fabian was initially steered by deep easterlies south of the subtropical ridge, but recurved as it approached a large, mid-tropospheric trough. Fabian passed over Bermuda with an intensity of 100 knots on 5 September and was reported to be the worst hurricane since 1926 in Bermuda (Pasch et al. 2004a). Fabian entered the CHC Response Zone on 7 September as a category one hurricane. The storm moved through the southeastern Grand Banks bringing significant wave heights in excess of 20 m. Fabian lost tropical characteristics on 8 September, 700 n mi east-northeast of Cape Race, Newfoundland (Bowyer et al. 2004).

Hurricane Isabel

Isabel also formed from a tropical wave off the African coast. As the wave moved westward, convection increased and the disturbance became Tropical Storm Isabel on 6 September. The next day Isabel turned west-northwestward and strengthened into a hurricane. As Isabel began to turn westward under the Bermuda High, it strengthened into a category five

hurricane and was able to maintain an intensity of 130-140 knots for five days. On 15 September, Isabel turned west-northwestward and began to weaken due to increased vertical shear. Isabel made landfall near Drum Inlet, NC as a category two hurricane. Isabel weakened to a tropical storm over Virginia and became extratropical as it entered the Canadian province of Ontario (Beven and Cobb 2004).

Isabel caused an extreme storm surge along coastal North Carolina, Virginia, and Maryland. Precipitation from the storm was greatest over Virginia at 4-7 inches, and flooding ensued due to unusually high precipitation in the months leading up to Isabel. Highest winds were reported near Cape Hatteras with gusts of 85 knots and a sustained wind of 69 knots (Beven and Cobb 2004). Isabel brought tropical storm force winds and flooding to Southern Ontario. Additionally, Isabel brought about intense media attention due to a 14 September news story warning that conditions were “ripe” for Isabel to be a repeat of Hurricane Hazel (see Chapter 1.1) (Bowyer et al. 2004).

Hurricane Juan

Juan’s origins consisted of a large tropical wave and an area of low pressure that moved off the African coast on 14 September 2003 and traveled westward across the Atlantic. The system was still disorganized when it began to interact with a large upper-level low associated with Hurricane Isabel’s outflow. Next, the system became involved with a frontal zone and gained some extratropical characteristics. On 24 September, deep convection had increased enough for the system to attain tropical depression strength. Two days later, the cyclone had developed an eye and was upgraded to Hurricane Juan. Juan moved northward then northwestward as it gradually intensified to a peak intensity of 90 knots on 27 September just before entering the CHC Response Zone. At this point, Juan again turned northward, sped up, and made landfall near Halifax, Nova Scotia on 27 September with sustained winds of 85 knots and gusts of 125 knots, or category two strength. Initially Juan was classified as a category one hurricane at landfall, but after reanalysis the storm upgraded to just above category two strength. Hurricane Juan retained tropical characteristics and hurricane strength as it moved over Nova Scotia and Prince Edward Island. On 29 September Juan was absorbed by an extratropical low and dissipated. A close-up of Hurricane Juan’s track is shown in Figure 5.2 (Avila 2004, Bowyer et al. 2004).

Figure 5.2: Hurricane Juan track (red), 24-29 September 2003. The black line denotes the CHC Response Zone.

Juan was a very unique storm. It is not rare for a hurricane to strike Nova Scotia, but they usually are barely hurricane strength as they strike. Based on Canadian hurricane records, a storm as strong as Juan occurs once every fifty years in Nova Scotia. So, the main question is, why was Hurricane Juan so strong at landfall? First of all, Juan occurred at the end of September when surface waters are at their warmest (see Chapter 1.1). However, surface waters are still quite cool along the Scotian Slope. The reason Juan did not weaken much over these cooler waters involves the speed of the storm. Juan significantly accelerated south of Nova Scotia so its rapid forward motion counteracted the slight weakening as far as wind speeds were concerned. Also, because of the forward speed increase, Juan spent less time over the cooler waters (Fogarty 2003a). Juan's increase in forward speed did have some positive impacts: it allowed for the storm to quickly move over land, thereby significantly reducing precipitation. Rainfall amounts were in the vicinity of 38 mm (1.5 inches) (Bowyer et al. 2004).

The majority of Juan's damages came from high winds and storm surge. The strong force of Juan's winds caused extensive portions of forests to be flattened. Because Juan was

starting extratropical transition at landfall, hurricane force winds were confined to the east side of the storm and almost all wind damage occurred east of Juan's track (Fogarty 2003b). Due to the straight northward track of Juan, the storm surge was exceptionally high (6.5 ft) and established a new record water level at Halifax. A straight track sets up extremely high waves (significant wave heights were ~29.5 feet) and the northward track allowed for a strong surge. Usually the storm surge will peak at the time of landfall, while the highest waves lag the storm, but because Juan was moving so quickly, the two arrived at about the same time. This extreme storm surge contributed to beach erosion and extensive flooding of the Halifax waterfront. Twice daily high tides in Halifax Harbour also added to additional flooding (Bowyer 2003).

Hurricane Juan has become the most widely destructive tropical cyclone to hit the Canadian Maritimes in over one century. Bowyer et al. (2004) write that an estimated 100 million trees were lost in Nova Scotia. The storm also claimed eight deaths, four direct and four indirect. Several hundred thousand Nova Scotians were without power for up to two weeks and several dozen marinas and boats were destroyed. Conservative estimates place Juan's damages in the \$150,000 million dollar range (Bowyer et al. 2004). In April of 2004, it was announced that Environment Canada had succeeded in its request for the World Meteorological Organization to officially retire the name "Juan" from its rotating list of hurricane names. This marked the first time that Canada has requested the retirement of a hurricane name (Environment Canada 2004).

Hurricane Kate

Kate also originated as a tropical wave and became a tropical storm on 27 September 900 n mi west-southwest of the Cape Verde Islands. Despite moderate shear, Kate briefly reached hurricane strength while moving north-northeastward. Kate took a hairpin turn, began to move west-southwestward into a more favorable environment, and regained hurricane strength. Kate reached its maximum intensity of 110 knots on 4 October while centered 565 n mi east-southeast of Bermuda. Kate entered the CHC Response Zone on 7 October and was at tropical storm strength as it moved through the southeastern and northern Grand Banks. Along with a stalled frontal system, Kate brought almost four inches of rain to southeastern Newfoundland. Kate became extratropical by 8 October (Pasch and Molleda 2003, Bowyer et al. 2004).

Non-Canadian Tropical Cyclones

There were several significant tropical cyclones that had no effect on Canadian Provinces in 2003. Four tropical storms developed in the Gulf of Mexico and made landfall in the United States. Tropical storm Bill came ashore in southeast Louisiana with 52 knot winds and caused significant rainfall in several southern states. Erika crossed into Mexico and then Texas as a tropical storm with 60 knot winds. Tropical storm Grace also made landfall in Texas as a weak tropical storm. Henri reached tropical storm status, but made landfall in Florida as a tropical depression. Only two hurricanes impacted the United States: Claudette and Isabel. Hurricane Claudette was the first hurricane of the 2003 season. It formed in the Caribbean Sea and became a hurricane in the Gulf of Mexico. Claudette made landfall in Texas as a category one hurricane (NCDC 2003).

5.2 Skill of the Synthetic Superensemble for the 2003 Season and Hurricane Juan

In 2003, a cross-validation approach was not utilized in forecasting the season's storms. This was done in order to discern whether or not the synthetic superensemble would do well in a real-time setting. The 2003 training set consisted of the entire 2001 hurricane season, the 2002 hurricane season minus Hurricane Kyle (due to large model errors), and all 2003 tropical cyclone model data collected prior to the date of the storm being forecasted. Training consisted of 174 cases for Claudette to 392 cases for Odette; 109 of these came from the 2001 hurricane season and 62 came from the 2002 hurricane season. Synthetic superensemble member models were the same used from the 2001 and 2002 seasons and are discussed in Chapter 2.6. For the 2003 hurricane season, there were 119 cases at 12 hours, 111 cases at 24 hours, 94 cases at 48 hours, 76 cases at 72 hours, 61 cases at 96 hours, and 50 cases at 120 hours. There are a large number of cases at 120 hours due to several long-lived tropical systems in 2003. It is of note that the real-time superensemble was run every six hours during major storms in 2003. The synthetic superensemble, however, was only run at 00 and 12 UTC. Data from the other two forecast times at 06 and 18 UTC were only used for training purposes. It was possible to run the real-time superensemble every six hours in 2003 because all member models used were produced at all four synoptic hours.

Track errors from the 2003 hurricane season are shown in Figure 5.3. Again in 2003, only named storms with five or more real-time superensemble cases were included in season-end statistics. The following storms were excluded: Ana, Bill, Erika, Grace, Henri, Mindy, and Peter. This season, the synthetic superensemble is the best model up to 84 hours. Past this point, the synthetic superensemble is often outperformed by GFS, GFDL, GUNS, or the Official forecast. This season was the first in which the NHC publicly released forecasts beyond three days. Prior to 2003, the four and five day forecasts were only produced experimentally and remained in-house. The real-time superensemble also performed very well in 2003, outperforming the synthetic superensemble past 84 hours. The synthetic superensemble also outperformed the ensemble mean out to 96 hours. The best member models in 2003 were the official forecast and the GFDL model. Again, the worst member models for 2003 were the BAMD and NHC90 models. It is of note that the best performers in 2001 (AVN or GFS) and 2002 (NOGAPS) are not top performers in 2003. The synthetic superensemble outperformed the GFS up to 96 hours and NOGAPS up to 108 hours. A breakdown of selected track errors can be found in Table 5.2.

Two long-lived storms made up much of the 2003 season statistics. Hurricanes Isabel and Fabian accounted for 39% of 12-hour and 56% of 120-hour synthetic superensemble forecasts. The synthetic superensemble performed very well for both of these storms. A Fabian forecast is depicted in Figure 5.4 and an Isabel forecast is depicted in Figure 5.5.

In 2003, Juan made landfall in Nova Scotia as a destructive category two hurricane. Because Juan was short-lived, the superensemble only produced forecasts out to 84 hours. The synthetic superensemble performed very well for this storm and was extremely accurate concerning Juan's landfall position near Halifax, Nova Scotia and in Prince Edward Island. Track statistics for Hurricane Juan can be found in Figure 5.6 and Table 5.3 shows selected track errors for Juan. The synthetic superensemble outperformed the best member model, the official forecast, at all forecast hours except 72 hours and outperformed the real-time superensemble at all forecast hours except 60 hours. The GFS and GFDL models in addition to the ensemble mean also performed well for Hurricane Juan, often outperforming the synthetic superensemble in early forecast hours. A 72-hour Juan forecast can be found in Figure 5.7.

Figure 5.3: 2003 Atlantic tropical cyclone RMS track errors. Number of cases: 119, 111, 103, 94, 85, 76, 68, 61, 55, and 50.

Table 5.2: 2003 selected Atlantic tropical cyclone track error statistics. RMS error units are in *km*.

MODEL	TRACK ERROR (<i>km</i>)					
Forecast Hour	12	24	48	72	96	120
Best-Model (Official)	67.61	121.13	241.23	285.57	353.37	450.16
Real-Time SENS	64.86	116.39	210.88	273.49	352.71	452.57
Ensemble Mean	69.17	108.03	211.83	335.43	458.20	614.08
Synthetic SENS	57.86	101.15	181.37	247.13	445.96	663.41

Figure 5.4: Hurricane Fabian 72-hour forecast for 5 September 2003 at 00 UTC.

Figure 5.5: Hurricane Isabel 96-hour forecast for 14 September 2003 at 12 UTC.

Figure 5.6: Hurricane Juan Atlantic tropical cyclone RMS track errors. Number of cases: 7, 6, 5, 4, 3, 2, and 1.

Table 5.3: Hurricane Juan selected Atlantic tropical cyclone track error statistics. RMS error units are in *km*.

MODEL	TRACK ERROR (<i>km</i>)						
Forecast Hour	12	24	36	48	60	72	84
Best-Model (Official)	78.83	131.70	152.90	209.42	205.96	53.96	450.19
Real-Time SENS	64.13	124.78	176.67	192.06	132.94	238.64	506.50
Ensemble Mean	62.6	77.82	108.69	99.78	97.67	87.01	257.26
Synthetic SENS	62.47	98.94	147.89	155.90	168.65	127.11	23.52

Figure 5.7: Hurricane Juan 72-hour forecast for 26 September 2003 at 12 UTC.

Again for 2003, the CLIPER model was used to determine forecast skill. Table 5.4 compares CLIPER errors to select models and Figure 5.8 depicts the model forecast skill for year 2003 Atlantic tropical cyclone tracks. The synthetic superensemble was found to have, on average, ~140% less error than CLIPER while the best model, the official forecast, was found to have ~322% less error than CLIPER. Forecast skill for Hurricane Juan was also calculated. Table 5.5 compares Juan's CLIPER errors to select models while Figure 5.9 depicts the model forecast skill for Hurricane Juan. The synthetic superensemble was found to have, on average, ~330% less error than CLIPER while the official forecast had ~506% less error than CLIPER. A comparison of Tables 5.4 and 5.5 shows that CLIPER errors for Hurricane Juan were much higher than average CLIPER errors for the entire 2003 season; at 72 hours CLIPER errors for Juan were ~30% bigger than 2003 season errors. This shows that Juan was more difficult to forecast than many other year 2003 tropical cyclones.

Table 5.4: 2003 CLIPER track errors in comparison to the Official forecast and the synthetic superensemble. RMS error units are in *km*.

MODELS	TRACK ERROR (<i>km</i>)				
Forecast Hour	12	24	36	48	72
CLIPER	95.27	216.28	350.51	482.88	738.10
Best-Model (Official)	78.83	131.70	152.90	209.42	53.96
Synthetic SENS	57.96	101.18	138.27	180.05	245.25

Figure 5.8: Relative forecast skill for 2003 Atlantic tropical cyclone tracks. Errors are relative to CLIPER in percentage.

Table 5.5: Hurricane Juan CLIPER track errors in comparison to the Official forecast and the synthetic superensemble. RMS error units are in *km*.

MODELS	TRACK ERROR (<i>km</i>)				
Forecast Hour	12	24	36	48	72
CLIPER	122.16	344.16	536.16	641.12	1056.95
Best-Model (Official)	78.83	131.70	152.90	209.42	53.96
Synthetic SENS	62.47	98.94	147.89	155.90	127.11

Figure 5.9: Relative forecast skill for Hurricane Juan's storm track. Errors are relative to CLIPER in percentage.

5.3 2003 Season Summary

In 2003, there were 16 named tropical systems, four above the climatological average; seven hurricanes, one above the average; and three major hurricanes, one above the average. Not only was 2003 a year of increased activity, but it was a long season with one tropical cyclone forming before the official start of the hurricane season (1 June) and two forming after the official end of the season (30 November). This season was different from the previous three in that much of the activity took place at tropical latitudes. Additionally, 2003 was a big year for Canada with Hurricane Juan making landfall as a category two hurricane near Halifax, Nova Scotia.

The 2003 hurricane season saw improved superensemble forecasts. A comparison between all three seasons examined in this study shows that the 2003 synthetic superensemble produced more accurate forecasts than in 2001 and 2002 at all forecast hours except 120 hours where the 2001 season had a more accurate average. This decrease in error came from three different sources. First, the size of the training data set was significantly increased for 2003; the training data set was anywhere from three to 204 cases larger by the end of the season compared to the 2002 season. Training was increased not only because cases were taken from both 2001 and 2002 seasons, but also because the real-time superensemble began to produce forecasts four-times daily. With four forecasts per day, the 2003 training data was just about doubled. This will greatly enhance training for the 2004 season when there will be two seasons of four-times-daily forecasts. Another positive impact to 2003 forecasts was the inclusion of four and five day official forecasts. This forecast is very important to the superensemble because it is the only subjective forecast and it is produced by experienced hurricane forecasters. Once the four and five day official forecasts were incorporated into 2003 training, long-term superensemble forecasts seemed to improve. This is evidenced in Hurricane Isabel's average five-day synthetic superensemble forecast track error of only 290 km. The final reason 2003 synthetic superensemble forecast errors were lower than the previous two seasons is the relative lack of significant model changes. It was seen in 2002 statistics that a lot of model changes could seriously affect a superensemble forecast. From 2002 to 2003 there were few significant changes to the four main dynamical models and, therefore, an improved superensemble forecast.

Another reason that the synthetic superensemble forecasts were improved in 2003 has to do with the difficulty of the season. The CLIPER model can be used to determine the forecast difficulty for a storm or a season. Figure 5.10 compares CLIPER errors for each season. It can be seen that 2002 was the most difficult season to forecast and the 2001 and 2003 seasons were the least difficult to forecast.

Figure 5.10: Average CLIPER errors for each season studied: 2001, 2002, and 2003

CHAPTER 6

SUMMARY AND CONCLUSIONS

The purpose of this study was to develop a new version of The Florida State University hurricane superensemble with greater skill in forecasting tropical cyclones, especially at extratropical latitudes. The FSU hurricane superensemble was implemented in real-time during the 1999 hurricane season and has been a top-performing model each season since. In this work, a synthetic superensemble was developed and tested for the 2001, 2002 and 2003 hurricane seasons to see whether there would be improvement over the real-time superensemble and its member models.

In 2001 and 2002, a cross-validation approach to training was utilized, whereby training data consisted of the previous season's data and the current season's data (minus the storm being forecasted). In 2001, the synthetic superensemble had the lowest track error up to 60 hours, outperformed the real-time superensemble at each forecast hour, and outperformed the ensemble mean up to 84 hours. In 2002, the synthetic superensemble had the lowest track error up to 36 hours, outperformed the real-time superensemble at all hours except 120, and outperformed the ensemble mean up to 96 hours. A different approach was taken to forecast the 2003 hurricane season; cross-validation was not used in order to discern whether the synthetic superensemble would do well in a real-time setting. In 2003, the synthetic superensemble was the best model up to 84 hours, outperformed the real-time superensemble up to 84 hours, and outperformed the ensemble mean out to 96 hours. Also in 2003, Hurricane Juan made landfall near Halifax, Nova Scotia and became the strongest hurricane in modern history to impact Halifax. The synthetic superensemble performed very well for this storm and was extremely accurate concerning Juan's landfall position in Nova Scotia.

The synthetic superensemble is not always the best performing model at every forecast hour, but it has proven to be the most consistently good model of all three seasons in this study. In 2001, the AVN/GFS model was the best superensemble member model, superior to the synthetic superensemble at 72 hours and beyond. But in 2002, the AVN/GFS model was not a top performer, while the NOGAPS and GUNS models were. NOGAPS and GUNS were not top performers in 2001, however. In fact, GUNS was one of the worst performing member models of the 2001 season. In 2003, the Official forecast was the best performing member model. The GFDL model also performed well in 2003 and 2002, but performed poorly in 2001. Overall, the synthetic superensemble was the most consistently accurate model. The NHC90 statistical model and BAM models were the worst performers over the three seasons. However, when these models were removed as member models, the synthetic superensemble forecast skill was degraded. Therefore, for the synthetic superensemble to have the greatest amount of skill, there needs to be a large variation in member model track forecasts.

In this study, forecast skill was determined by the CLIPER model. Because this model is only run out to 72 hours, skill relative to CLIPER is determined only to this point. In 2001, the synthetic superensemble had an average error ~92% less than CLIPER; in 2002, it had ~111% less error; and in 2003, the synthetic superensemble had ~330% less error than CLIPER. Even though the synthetic superensemble had less error relative to CLIPER in 2002 than in 2001, the synthetic superensemble performed better in 2001 because of large errors at later forecast hours in 2002. It can be seen, by using the CLIPER model, that 2002 was the most difficult season to forecast and 2001 was the least difficult. The 2002 season was difficult to forecast mainly because of the slow, meandering track of Hurricane Kyle. The 2001 season would be the easiest to forecast due to its similarities to the 2000 hurricane season. It is assumed, that the synthetic superensemble had the best forecasts in the 2003 mainly due to the increased skill in its member models. The exceptional synthetic superensemble forecasts for the 2003 season show that the model has the ability to produce forecasts better than its member models and better than the operational superensemble in a real-time setting

There are several potential major challenges in producing useful tropical cyclone track forecasts over the extratropical latitudes near Canada. Improving these forecasts is important to Canadians as the year 2003 marked the fourth consecutive year that a tropical cyclone had made landfall in a Canadian Maritime Province. The main challenge is major changes to the dynamics

or physics of member models. The synthetic superensemble performs best when there are little to no changes in the dynamics or physics of member models (as in the 2003 season) and performs worse when there are major changes (as in the 2002 season). Also, the synthetic superensemble cannot run without the majority of its member models. When the NHC declares a storm to be extratropical and tropical modeling centers stop modeling the storm, the superensemble cannot continue producing forecasts. It is often at this point that the CHC needs the guidance, because the cyclone is close to Canadian land. One solution would be to add the Canadian GEM model to the superensemble member models once the storm enters the CHC Response Zone. The other solution lies with the NHC and tropical modeling centers. Modelers need to realize that many cyclones still contain tropical characteristics even after they have been declared to be extratropical, and global models cannot resolve these storms as well as tropical cyclone models. Modeling centers need to continue to run their models with vortex bogussing to be able to resolve the cyclone. This change will be the most useful to CHC forecasters who rely on this information when a cyclone affects their land and marine areas.

APPENDIX

THE SYNTHETIC SUPERENSEMBLE

Yun et al. (2004) proposed a method for constructing a space-time forecast that was based on smoothing using empirical orthogonal functions (EOF) in space and principle components (PC) in time (PC time series). A similar notion is being used in this study for the temporal smoothing of predicted hurricane tracks using Fourier components.

Given six hourly forecast positions (X_i , $i = 1, 21$) i.e. hours (0, 6, 12, 18, 24, 30, 36, 42, 48, 54, 60, 66, 72, 78, 84, 90, 96, 102, 108, 114, 120) a Fourier decomposition of X_i , limited to a few wave numbers, provides a smoothed track that can be expressed by Equations 2-4

$$\begin{aligned} X_0 &= \text{wave number zero} \\ &= \text{constant} \end{aligned}$$

$$\begin{aligned} X_1 &= \text{wave number one} \\ &= A_1 \sin(t) + B_1 \cos(t) \end{aligned} \tag{2}$$

$$\begin{aligned} X_2 &= \text{wave number two} \\ &= A_2 \sin(2t) + B_2 \cos(2t) \end{aligned} \tag{3}$$

$$\begin{aligned} X_3 &= \text{wave number three} \\ &= A_3 \sin(3t) + B_3 \cos(3t) \end{aligned} \tag{4}$$

where A_i and B_i are the amplitudes of the sine and cosine functions; they are found by a method of least squares. When six hourly positions were not available, they were linearly interpolated

using twelve hour positions. Using a method of least squares and using all of the available data sets, the Fourier smoothed track was constructed for each forecast.

These Fourier smoothed tracks for all the models during the training and the forecast phase of the superensemble constitute half of the synthetic superensemble forecast track data sets. These data sets were next subjected to the construction of the overall superensemble that included the unsmoothed and the smoothed data sets together.

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BIOGRAPHICAL SKETCH

Heather Lynn Szymczak was born on June 24, 1980 in Toledo, Ohio and has since lived in Temperance, Michigan. Heather attended high school at Notre Dame Academy in Toledo, Ohio where she excelled in academics and swimming. In June 1998 Heather graduated with honors. Heather then moved to South Carolina where she attended Coastal Carolina University and double majored in Marine Science and Biology. She was active at Coastal Carolina as a peer mentor, an orientation leader, a member of the Dean of Science Advisory Board, and was initiated into Phi Sigma Sigma National Pan Hellenic Sorority and Sigma Zeta Math and Science Honor Society. In May 2002, Heather received her Bachelors of Science and graduated Magna Cum Laude from Coastal Carolina University.

While living in South Carolina, Heather had the opportunity to experience several hurricanes, including Hurricane Floyd in 1999. These experiences provoked an interest in tropical meteorology and she decided to further her education in this field. She was accepted into the Masters of Science program in Meteorology at The Florida State University and was invited to work under Dr. T.N. Krishnamurti to study hurricane modeling. She has traveled to Halifax, Nova Scotia, Seattle, Washington, and Sedona, Arizona as part of her studies. Since attending Florida State, Heather has joined the American Meteorology Society and become a member of Chi Epsilon Pi Meteorology Honor Society.