National Oceanic and Atmospheric Administration

Hurricane Forecast Improvement Program
Five-Year Strategic Plan

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HURRICANE FORECAST IMPROVEMENT PROGRAM FIVE-YEAR STRATEGIC PLAN

Hurricane Forecast Improvement Program Five-Year Strategic Plan

1 Introduction

This document represents the official Five-Year Strategic Plan of the Hurricane Forecast Improvement Program (HFIP) to achieve a 20% overall improvement in hurricane numerical forecast guidance provided by the National Centers for Environmental Prediction (NCEP) to the National Hurricane Center (NHC). This improvement in guidance is for both track and intensity. HFIP also includes goals for predicting rapid intensification and for extending forecast guidance out to seven days. In addition, this plan sets in place development to achieve a 50% improvement in both track and intensity within 10 years.

1.1 Background on HFIP

HFIP provides the basis for the National Oceanic and Atmospheric Administration (NOAA) and other agencies to coordinate hurricane research needed to significantly improve guidance for hurricane track, intensity, and storm surge forecasts. It also engages and aligns the inter-agency and larger scientific community efforts towards addressing the challenges posed to improve hurricane forecasts. The goals of the HFIP are to improve the accuracy and reliability of hurricane forecasts; to extend lead time for hurricane forecasts with increased certainty; and to increase confidence in hurricane forecasts. These efforts will require major investments in enhanced observational strategies, improved data assimilation in numerical model systems, and expanded forecast applications based on the high-resolution and ensemble-based numerical prediction systems.

The specific goals of the HFIP are to reduce the average errors of hurricane track and intensity forecasts by 20% within five years and 50% within 10 years with a forecast period out to seven days. In addition, the goals are to increase the probability of detection (POD) for rapid intensity change to 90% at Day 1 (decreasing linearly to 60% at Day 5), and to decrease the false alarm ratio (FAR) for rapid intensity change to 10% for Day 1 (increasing linearly to 30% at Day 5).

The benefits of HFIP will significantly improve NOAA's forecast services through improved hurricane forecast science and technology. Forecasts of higher accuracy and greater reliability (i.e., user confidence) are expected to lead to improved public response, including savings of life and property.

NOAA recognizes that addressing the broad scope of the research and technology challenges associated with improving hurricane forecasts requires interaction with, and support of, the larger research and academic community. It is hypothesized that these very ambitious goals of the HFIP can only be met using high-resolution (~5-15 km) global atmospheric forecasting numerical models run as an ensemble in combination with regional models at even higher resolution (~1-5 km). Demonstration of this hypothesis is very expensive computationally and requires access to resources currently available only at the few supercomputing centers in the country. The demonstrated value of high-resolution modeling is critical to justify the use of these computational resources for operational hurricane forecasts.

For FY10, the HFIP program consisted of about $24 million with $3 million dedicated to enhancing computer capacity available to the Program. About $10 million of the $24 million is part of the base funding for the Atlantic Ocean and Meteorology Laboratory (AOML) in Miami and the Environmental Modeling Center (EMC) at NCEP for hurricane model development. The remaining $11million in 2009 was distributed to various NOAA laboratories and centers (Earth System Research Lab (ESRL), Geophysical Fluid Dynamics Laboratory (GFDL), National Environmental Satellite, Data, and Information Service (NESDIS), and National Hurricane Center (NHC)). Funding was also provided to the National Center for Atmospheric Research (NCAR), the Naval Research Laboratory (NRL) in Monterey, and several universities (University of Wisconsin, Pennsylvania State University, Colorado State University, University of Arizona, and University of Rhode Island). Finally, $1 million was contributed to the National Oceanographic Partnership Program (NOPP) Announcement of Opportunity for competed proposals related to improving understanding and prediction of hurricanes. The funding to NOPP from HFIP was matched by funding from the Office of Naval Research (ONR). HFIP anticipates comparable levels of funding and a comparable distribution of funds throughout the five years of this Plan.

HFIP is primarily focused on techniques to improve the numerical model guidance provided by National Weather Service (NWS) operations to the NHC as part of the hurricane forecast process. HFIP is organized along two paths of development called Streams. Stream 1 assumes that the computing power available for operational hurricane forecast guidance will not exceed what is already planned by NOAA. The development for this stream has been in planning for several years by EMC. HFIP activities at the NOAA labs and centers will help accelerate this development.

HFIP Stream 2 does not put any restrictions on the increases in computing power available to NWS operations, and in fact, assumes resources will be found to greatly increase available computing power in operations above that planned for the next five years. The purpose of Stream 2, therefore, is to demonstrate that the application of advanced science and technology developed under the auspices of HFIP along with increased computing will lead to the expected improvements in accuracy and other aspects of forecast performance. Because the level of computing necessary to perform such a demonstration is so large, the Program is applying for resources outside NOAA in addition to seeking increased internal computing capability for the demonstration.

A major part of Stream 2 is a demonstration system, or Demo System, that is run in testing mode each hurricane season. The purpose of this system is to evaluate strengths and weaknesses of promising new technology. Demo System testing may reveal components of particular interest to operational forecasters. If resources do not permit implementation of these components in the operational infrastructure, the Demo System for the following season will emphasize those components and will provide specific output for NHC forecaster evaluation. We refer to this component of the Demo System as Stream 1.5. Table 1 outlines these various streams.

Roughly half of the HFIP funding is going toward Stream 2 development activities. In Stream 2, the best approach to improving the forecast hurricane track beyond four days is assumed to be the use of high resolution global models run as an ensemble. The logic behind this assumption is described below. For improvements in forecasts of hurricane intensity, especially in the one to four day time range, the best approach is likely to be the use of high-resolution regional models, also run as an ensemble. The global models are likely to be limited in resolution to about 10 km for at least the next five years due to computer limitations, especially when the models are run as an ensemble. The only way to achieve the very high resolution of about 1 km necessary for resolving the inner core of the hurricane is with regional models. It is generally assumed that the inner core must be resolved before consistently accurate hurricane intensity forecasts can be achieved. For both the regional and global models, statistical post processing of the model results is expected to significantly improve numerical guidance beyond results provided directly from model output.

To facilitate the transition of research to operations, HFIP has recognized the importance of having research and operations share the same code base and has co-sponsored the Developmental Testbed Center (DTC) to make available and support the Hurricane Weather Research and Forecasting (HWRF) model to the community. This support started in February 2010 with the DTC/EMC/Mesoscale Microscale Meteorology (MMM) Joint Hurricane Workshop and Weather Research and Forecasting (WRF) for Hurricanes Tutorial.

Table 1. The Two Stream Strategy

Stream 1	Development to directly improve the current operational global and regional hurricane models. Assumes computing available for for operations is the capability currently planned.
Stream 2	Assumes that operational computing can be substantially increased above current plans. Seeks computing resources from major supercomputing centers for testing and evaluation. Emphasis is on high-resolution global and regional models run as ensembles. The strategy will include a demonstration system (DEMO) run in real time each summer to test and evaluate promising new technology.
Stream 1.5	Stream 1.5 will be part of the summer demonstration system and will be forecaster defined. Components from Stream 2 that forecasters see as particularly promising in one year will be configured to run in real time the next year, with products made available to NHC.

1.2 High-Resolution Ensemble Approach

A single "deterministic" forecast by a particular numerical model has an inherent but unknown level of uncertainty. Any two model forecasts starting from infinitesimally different initial states will grow differently with time, the amount of difference depending upon the weather situation. If the forecast is reproduced many times, each time introducing small initial differences, the result is called an ensemble. The individual model forecasts of the ensemble can potentially provide information on the confidence one should place in a particular forecast. The correct forecast is frequently near the mean, median or mode of the ensemble, though other ensemble realizations have a finite probability of being correct. Because the various forecasts diverge with time, emergency managers should be able to make more effective decisions when provided with ensemble guidance rather than a single forecast.

These ensembles can be produced in a number of ways. An ensemble can be produced by simply changing the initial conditions of a single model slightly to form the various members of the ensemble. The physical parameterizations within a single model can also be altered and combined to form a different type of ensemble of slightly different models. Another type of ensemble combines the results from several model systems where the core, physics and initialization are all different. This multi-model ensemble is the one that currently provides the best operational forecast guidance for both track and intensity. Ensembles could also employ a mixture of the above methods.

High resolution is hypothesized to be necessary in these ensembles in order to adequately resolve the hurricane structure. This is important because the hurricane can alter the flow in which it is embedded and, in turn, this altered flow will impact the hurricane track and its intensity. Resolutions of 5-15 km are necessary to begin resolving structures resembling actual hurricanes in the forecast model. Ideally, each ensemble member will have this resolution, and as many members as possible will be computed to provide adequate estimates of the uncertainty.

Beyond about three days, forecast guidance must come from global ensembles since planetary-scale patterns interact with and influence the steering of the storm. After about three days, it has been shown that the evolution of the atmospheric flow at a given location depends on atmospheric features distributed globally. Therefore, forecasts extending out to 4-7 days require global forecast modeling.

The potential value of high-resolution global ensembles has been demonstrated in part through forecasts from international organizations such as the European Centre for Medium-Range Weather Forecasts (ECMWF). However, there is still much to be learned about high-resolution global modeling. The best way for the U.S. to make progress is to run the ensembles over enough cases such that statistical significance of the computed skill of the forecasts can be determined. Generally this requires at least that the high-resolution ensemble be run over the most active few months of the hurricane season and every forecast period from genesis to decay (with 2 to 3 years of cases being even better at capturing the full range of tropical cyclone characteristics associated with inter-annual changes in environment, e.g., associated with El Nino events). This is an enormous computing challenge, but it needs to be performed to demonstrate the value of the high-resolution forecast guidance over the guidance that is operationally available today.

Much the same can be said for regional ensembles, but here the emphasis shifts from track forecasts at longer forecast leads to intensity forecasts at medium forecast leads and rapid intensification at the shorter lead times. Much of the control of the intensity of the storm is thought to reside in the dynamics of the inner core region of the hurricane. If this is true, then the inner core must be resolved to account for these dynamics requiring a modeling resolution of at least 3-5 km. Ideally, regional high-resolution ensembles are nested within high-resolution global ensembles which provide an ensemble of lateral boundary conditions describing the influence of global flow patterns. Also, it is preferable to use similar advanced data assimilation approaches and model physics in the related ensembles.

2 The HFIP Baseline

To measure progress toward meeting Program goals, HFIP established a baseline against which results from experimental and operational HFIP model guidance will be measured. These HFIP Performance Goals Baselines were developed in a white paper authored by James Franklin dated 5 May 2009 and summarized here.

For both the track and intensity goals, a consensus (equally-weighted average) of operational guidance models was utilized and evaluated for the Atlantic Basin over the period 2006-2008. This three-year average was determined to be feasible and adequate. This short three-year period is adequate to determine the HFIP Performance Goal Baselines because there has been a significant reduction in track error in recent years, and because increased tropical cyclone activity in the Atlantic Basin in the last few years allows for more stable statistics over this short time period.

For track error, this consensus was a particularly good choice because the mean skill of the official NHC forecast is very close to that of the consensus. Consequently, a 20% improvement in any HFIP guidance over this baseline could reasonably be expected to translate to a 20% improvement in the official forecast. This would not be the case if an individual operational model were used as a baseline.

The track baseline was a consensus of GFSI, GFDI, UKMI, NGPI, HWFI, GFNI, and EMXI, (see list of acronyms in appendix B) which were computed whenever at least one of the consensus members was present. This is essentially the membership of NHC's current operational track consensus variable member (TVCN) model. Even though HWFI was only available in 2007-2008, the recommendation was to include the 2006 data set as well. The additional year of data will provide a more representative assessment of the current state of the forecast guidance. Evaluation of this consensus over 2006-2008 is given below as the HFIP Baseline for Track and Intensity (BASE). PeRsistence skill and Climatology baseline errors (PRCL) are also shown (PRCL) for comparison, as are the Official NHC Forecast (OFCL) errors. Forecast errors are in nautical miles.

Table 2. HFIP Track Performance Baseline (nautical miles)

VT (h)	N	OFCL	PRCL	BASE
0	818	7.4	7.7	7.8
12	741	29.4	44.5	30.0
24	663	49.6	93.3	49.8
36	586	69.9	150.9	69.5
48	518	91.2	212.2	89.6
72	411	135.0	317.2	132.0
96	313	173.0	396.5	175.2
120	247	218.6	473.0	221.9

For intensity, the consensus members were GHMI, HWFI, DSHP, and LGEM (note that GHMI is the GFDL model). The consensus was computed whenever at least one of these models was present. This is the same set of models used in the operational Intensity Consensus (ICON) (except that ICON is not computed unless all the member models are present). Evaluation of this consensus over 2006-2008 is given below, along with climatology/persistence and the official forecast. Forecast errors are in knots. The table shows that the intensity consensus is actually slightly better than the official forecast, at least beyond approximately 24 hours. In part, this is because this intensity consensus has only been operationally utilized for one year. NHC's operational practice of only making incremental changes to the official forecast, from forecast to forecast, may also contribute to the weaker performance of the intensity consensus.

Table 3. Proposed HFIP Intensity Performance Baseline (knots)

VT (h)	N	OFCL	PRCL	BASE
0	820	1.9	2.2	2.2
12	745	7.2	8.3	7.7
24	667	10.4	11.5	10.1
36	590	12.6	14.2	11.7
48	522	14.6	16.1	13.7
72	415	17.0	17.8	16.0
96	316	17.5	19.3	16.6
120	250	19.0	19.3	17.0

In both tables the column labeled BASE is the baseline to which HFIP will measure its progress in meeting its goals.

3 The HFIP Model Systems

Below we describe the various global and regional models that are currently part of HFIP. This is the current suite as of summer 2010. The mix of models used may change as the program progresses but the list below provides a good idea of the model resources available to the Program. The discussion below outlines some of the major components. There are others and all are listed in Tables 4 and 5.

3.1 The Global Models

- FIM—Refers to the Flow-following finite-volume Icosahedral Model. The FIM is an experimental global model that can be run at various resolutions and uses initial conditions from a number of sources. It has been built by the NOAA Earth System Research Laboratory (ESRL) is currently using a fixed ocean.

- GFS—Refers to the Global Forecast System. There are two versions of this model currently running in the demonstration system. This includes a version of the current operational model run at the NOAA National Centers for Environmental Prediction (NCEP) and an experimental version of that model.

- NMM—This Non-hydrostatic Mesoscale Model is a global version of the model noted below as part of the regional WRF models. It uses a latitude-longitude grid with a high latitude filter. It is being developed by the Environmental Modeling Center (EMC) of NCEP.

- CUBED SPHERE—Refers to a finite-volume element model where the grid points are mapped onto a cube. It is being developed at the Geophysical Fluid Dynamics Laboratory (GFDL)

- NOGAPS—Refers to the Navy Operational Global Atmospheric Prediction System. Currently a semi-Lagrangian version of NOGAPS is being developed, which will allow for efficient high-resolution forecasts.

Table 4. Specifications of the HFIP Global Models

Models	Horizontal resolution	Vertical levels	Cumulus Parameterization	Microphysics	PBL	Land Surface	Radiation	Initialization
FIM	20 km	64	From 2010GFS - Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	Noah LSM	GFDL/RRTM	ESRL EnKF
GFS	27 km	??	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	Noah LSM	GFDL scheme	ESRL EnKF
NMM-B	10 km (or 15 km)	64	Simplified Arakawa Schubert + Shallow Convection	Zhao	GFS PBL (stability dependent local/non-combination)	Noah LSM	RRTM	GSI
Cubed Sphere	25 km	32	Shallow only	Modified Lin, 6-class	Lock (AM2)	GFDL LM3	GFDL	nudging to NCEP analysis

NOGAPS	**41 km**	**42**	**Emanuel**	**N/A**	**NOGAPS**	**NOGAPS**	**Harshvardhan/ Fu-Liou**	**NAVDAS-AR**

3.2 The Regional Models

- WRF - The WRF is a modeling system with options for the dynamic core (ARW—Advanced Research WRF built by NCAR and NMM—Non-hydrostatic Mesoscale Model, built by EMC) and physics as well as initialization systems, post processing systems, and verification systems.

- NCEP Hurricane WRF (HWRF) - This model is based on the NMM dynamic core and has a movable, two-way nested grid capability for the 9 km inner nest. The coarse domain is 27 km resolution and covers a 75° x 75° region with 42 vertical layers. Advanced physics include atmosphere/ocean fluxes, coupling with the Princeton Ocean Model (POM) and the NCEP GFS boundary layer, and deep convection.

- Multi-Model Ensemble - This ensemble was organized by Florida State University in 2009 and included a total of seven models run by different organizations. Two of the members were the operational models GFDL at 7.5 km and HWRF at 9 km. GFDL is an older operational model still being run in parallel with the current operational model HWRF. HWRF is constructed from the NMM core of the WRF. Both the GFDL and HWRF models are coupled to the POM in the Atlantic Basin. A version of the HWRF was also run at 4 km resolution (HWR4) during the 2009 hurricane season. HWRF-x is an experimental version of the operational HWRF run by the Hurricane Research Division of the Office of Oceanic and Atmospheric Research (OAR). HWRF-x did not have an interactive ocean model associated with it but employ an interactive nest. HyHWRF is the HWRF model coupled to the Hybrid Coupled Ocean Model (HyCOM) and was run in parallel for the 2009 hurricane season for the Atlantic Basin.

- In addition to HWRF, two versions of the WRF ARW system were also run. The ARW system run by NCAR used a simplified one dimensional model of the ocean. It used two interactive nests within the outer regional model. FSU also ran a version of the ARW without an interactive ocean.

- The Coupled Ocean Atmosphere Mesoscale Prediction System – Tropical Cyclone (COAMPS-TC) is a Navy model run by NRL Monterey. It is a version of their COAMPS regional prediction system that is being run operationally and uses an interactive ocean.

- The Penn State Regional Ensemble is another version of the WRF ARW system similar to the NCAR WRF ARW. It used a static interactive inner nest but no interactive ocean. It was run as a 30-member ensemble.

Since 2009, many more regional models including various versions of the same basic models became available to HFIP. The full suite of models available in 2010 is outlined in Table 3. All are potential components of the 2010 multi-model and will be run in real-time. Some will have two seasons of retrospective data available for statistical post processing and for guidance to forecasters in choosing which models to emphasize. These are candidates to be part of Stream 1.5 (see Table 1) and are highlighted in yellow. The rest are part of Stream 2. The mix of models indicated in Table 5 may change from year to year for the duration of this Plan.

Table 5. Specifications of the HFIP Regional Models.

Models	Nesting / Horizontal Resolution (km)	Vertical Levels	Cumulus Parameterization	Microphysics	PBL	Land Surface	Radiation	Initial and Boundary Conditions	Initialization	Ocean Coupling
HWRF (OPS)	2 27/9	42	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS	GSI 3DVAR	POM
GFDL (OPS)	3 30/15/7.5	42	Arakawa Schubert	Ferrier	GFS Non-Local PBL	Slab Model	Schwarz-kopf-Fels Scheme	GFS	GFDL Synthetic Bogus Vortex	POM
HWRF IC	2 27/9	42	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS	GSI 3DVAR with inner core data	POM
HWRF 3	2 9/3	42	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS	GSI 3DVAR	POM
HWRF HYCOM	2 27/9	42	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS	GSI 3DVAR	HYCOM
HWRF-HRD EnKF DA	2 9/3	42	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS	EnKF with aircraft data	POM
HWRF NOAH LSM	2 27/9	42	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	NOAH LSM	GFDL Scheme	GFS	GSI 3DVAR	POM
GFDL Parallel	3 30/15/7.5	42	Arakawa Schubert	Ferrier	GFS Non-Local PBL	Slab Model	Schwarz-kopf-Fels Scheme	GFS	GFDL synthetic Bogus Vortex	POM
WRF ARW FSU	2 12/4	40	Simplified Arakawa Schubert	WSM5	YSU	5-Layer Thermal Diffusion soil Model	RRTM (longwave) / Dudhia (shortwave)	GFS (initial and boundary condition)	Initialized from GFS	none
WRF ARW (NCAR)	2 12/4	36	New Kain Fritsch (12 km only)	WSM5	YSU	5-Layer Thermal Diffusion soil Model	RRTM (longwave) / Dudhia (shortwave)	GFS	EnKF method in a 6-hour cycling mode	1-d ocean
WRF ARW Utah	3 27/9/3	31	Betts-Miller	Lin	MYJ	5-Layer Thermal Diffusion Scheme	RRTM	Dudhia	Vortex relocation & WRF 3DVAR	none
COAMPS-TC	3 45/15/5 (15/5 km following the storm)	40	Kain Fritsch on 45 and 15 km meshes	Explicit microphysics (5 class bulk scheme)	Navy 1.5 Order Closure	Slab with the NOAH LSM as an option	Harshvardhan	NOGAPS (could use GFS if desirable)	3D-Var data assimilation with synthetic observations	Option to run coupled with NCOM may be used depending on computational resources
Wisconsin Model	UW NMS (3D enstrophy/	3-4 90/45/9	52	Modified Emanuel	Explicit bulk microphysics	1.5 Order Closure	WRF vegetation/la	RRTM	GFS/GFDL	GFDL Synthetic

	entropy/KE conserving dynamics core)	**km 90/45/9/3 km**			**(cloud/rain/pristine/ aggregate/graupel)**		**nd surface/Andreas emulsion layer**			**Vortex**
Penn State ARW	**3 40.5/13.5/4.5 for ensemble forecast 1.5-km nest for control**	**35**	**Grell-Devenyi ensemble scheme (40.5 km only)**	**WSM 6-class graupel scheme**	**YSU**	**5-layer thermal diffusion scheme**	**RRTM (longwave) / Dudhia (shortwave)**	**GFS**	**EnKF with NOAA airborne radar**	**none**

3.3 Ocean/Wave Models

- POM—Princeton Ocean Model. Developed by GFDL and used operationally for the last decade.
- HyCOM—Hybrid Coordinate Ocean Model. Under development at various labs including EMC and will replace the POM as the operational ocean forecast system at NCEP in the next couple of years.
- WaveWatch III. Forecasts surface wave spectra using winds from atmospheric models. Various versions of this model have been operational for more than a decade.

3.4 Initialization Systems

A number of approaches are available to HFIP to create the initial state for the global and regional models:

- Grid point Statistical Interpolation (GSI). This is the initial state created for the current GFS operational model interpolated to the higher resolution grid. The GFS uses the initialization system, a three-dimensional variational approach (3DVAR), that has run operationally for years.
- NRL Atmospheric Variational Data Assimilation System (NAVDAS). This is the system used to provide the initial conditions to the Navy global model. The 3DVAR system (NAVDAS) was upgraded to 4DVAR (NAVDAS-AR) for the global system in September 2009.
- Ensemble Kalman Filter (EnKF). This is also an advanced assimilation approach (somewhat like 4DVAR) that uses an ensemble to create background error statistics for a Kalman Filter. While this approach is still in the experimental stage in the U.S. (though operational in Canada), it has shown considerable promise.
- Hybrid Variational-Ensemble Data Assimilation System (HVEDAS). This system combines aspects of the EnKF and 3D- or 4DVAR for example, using an ensemble of forecasts to estimate the co-variances at the start of a 4DVAR assimilation window. This technology is under development at NOAA/NCEP/EMC, NOAA/OAR/ESRL and NOAA/OAR/Atlantic Oceanographic and Meteorological Laboratory (AOML). It will not be ready for testing in the 2010 season but may be available for subsequent seasons. This hybrid approach is likely to define the operational global data assimilation system for NOAA in the five-year time frame.
- Besides the overall initial state of the global models provided by the data assimilation systems noted above, some of the global models (e.g. GFS) also use relocation processes during data assimilation to match the initial location in the model with the

observed location. Other models such as NOGAPS introduce a bogus vortex at the observed location and intensity.

- The initial state for the regional models is generally produced by downscaling the global models' analysis and forecasts. In addition, the Penn State Regional Ensemble model, the WRF/ARW/NCAR model uses an EnKF initialization system.
- The operational HWRF utilizes an advanced vortex initialization and assimilation cycle consisting of four major steps: 1) interpolate the global analysis fields from the GFS onto the operational HWRF model grid; 2) remove the GFS vortex from the global analysis; 3) add the HWRF vortex modified from the previous cycle's six-hour forecast (or use a synthetic bogus vortex for cold start); and 4) add satellite radiance and other observation data in the hurricane area (9 km inner domain). The major differences from the GFDL model initialization are steps 3) and 4).

4 HFIP Computer Resources

Success in achieving HFIP goals is heavily dependent upon considerable computer resources beyond that currently available to NCEP Operations. These additional computer resources will come from computers outside normal operational resources. These include those available through a proposal process (such as the Oak Ridge National Laboratory (ORNL) computers in Tennessee, The Texas Advanced Computing Center in Austin, Texas) those available through institutions participating in HFIP (NCAR, Navy, and GFDL) and major computing resources being developed through HFIP funding at ESRL in Boulder, Colorado (n-jet and t-jet in the Table 4). Table 6 shows the computing resources available to HFIP in 2010.

Table 6. 2010 HFIP Computer Resources

Computer	Available Cores	Processor Hours available Aug-Oct	Notes
n-jet	472	1 m-h	Reserved for small development jobs
t-jet	10,056	21 m-h	Entire machine available to HFIP
Jaguar (ORNL)	220,000	10 m-h	About half of our ORNL allocation will be available for the summer program
NCAR	4,608	0.2 m-h	MMM Allocation
GFDL			Cubed Sphere model be run on GFDL resources
Navy	640	1.4 m-h	Navy will run their models on the DoD High Performance Computing facility at the Navy DSRC at Stennis Space Center, Mississippi
NCEP			The operational HWRF and GFDL models will be run on the operational computer. Development versions of the operational models (GFD5, HWRF HYCOM, HWRF NOAH and HWRF DA) will be run on the NCEP development computer. HWRF3 and HWRF-HRD DA will be run on t-jet.
NOAA HPC	~200,000		NOAA is purchasing two very high performance computers - One at Oak Ridge and a second at Fairmont, WV. These are expected to be available to HFIP

			at least during the hurricane season

5 HFIP Teams

The HFIP program is guided with the advice of eight teams representing the various development areas needed by HFIP to achieve its goals. The work of the teams is ultimately conducted by various organizations that receive HFIP funding, but the overall plan is guided by the teams. Table 7 in Appendix A lists the eight teams and shows their leadership and the various organizations represented on each team.

This overall HFIP Strategic plan is constructed from individual plans developed by each team. Section 8 shows each of their plans and provides the details on how HFIP will achieve the more general plans outlined in the Section 7.

6 HFIP Challenges

HFIP has been working on the hurricane forecast improvement problem for about two years. As an initial spin-up to a separate program, HFIP spent the last year conducting testing and evaluation of various options. From this work, several challenges have been identified that HFIP must resolve before meeting its goals.

- Most model initialization times will not have the advantage of aircraft data. Exceptions will occur in the Western Atlantic but this challenge will hold true for almost all Pacific storms. Better use of available satellite data near the storm center is needed in these cases, particularly in reference to incorporation of data into the regional models. Satellite data also needs to be fully utilized in characterizing the storm environment, whether or not aircraft data are available.

- Improvement in the initial states of the regional models is absolutely essential to achieving progress in the rapid intensification goals. Emphasis is on rapid intensification in the first 24 hours and current models take that long to settle down from the shock of initialization.

- For storms with aircraft data (particularly radar data), expanded use of that data could be crucial for hurricane initialization and needs to be tested further. In addition, communication systems from the aircraft need upgrading so data from the aircraft can be made available to the models in real-time.

- Development and tuning of physics packages for hurricane models at high resolution is critical.

- Advanced data assimilation systems in both regional and global models appear to lead to substantial forecast improvement. These advanced assimilation systems should be entered into operations as soon as possible.

- It is becoming evident that intensity forecasting goals will be difficult to achieve with the use of raw numerical model output, even with the improved output from ensembles. Statistical post-processing of model and ensemble output and improved model data assimilation (such as addition of supplemental observations) have shown considerable promise and may be the key to meeting the intensity forecast improvement goals.

- Better products are needed to effectively convey ensemble information to forecasters.

- Emphasis on the coordination between HFIP modeling, observations and evaluation components is needed to determine observational requirements for the improvement of model initialization and physics packages.

The plan outlined below addresses the challenges to be met in achieving the proposed operational system for 2014 shown in Section 7.3.

7 Overall HFIP Strategic Plan

This section describes the overall plan for the Program with further information on how HFIP goals will be met. More detail on specific components of the Program is provided in the HFIP team plans available in Appendix A

7.1 Strategy

Track

Improved global modeling is needed to support hurricane track forecasting goals. This is especially true for the longer lead times, since a forecast at a particular location (after about 48 hours) is affected by systems distributed globally. The track in a regional model is very much affected by the track in the global model, which the regional model uses for boundary conditions. Therefore, primary emphasis on improving track forecasts will be placed on improvements in the global models.

Intensity

Intensity is controlled by processes both external and internal to the hurricane. The external processes are controlled by the large scale flow surrounding the hurricane. Improving forecasts of the external factors controlling intensity will require improved global models. The internal processes are controlled by convective processes occurring within the hurricane, particularly in or near the eyewall, and by interaction with the oceanic and atmospheric environments. Improvements in forecasting the internal factors controlling intensity must be tackled with very high-resolution definition of the hurricane in regional models.

Global models

Hurricanes alter the flow in which they are embedded, which in turn controls their track and intensity. To capture this environmental feedback, the global model must be run at a high resolution to adequately resolve the hurricane. It is generally thought that the hurricane is reasonably resolved at a horizontal resolution of 5 km. High-resolution modeling requires a large number of computer processors for real-time run operations. This degree of resolution for a global model running in real-time will not be possible for another 3-5 years, even with currently planned research supercomputers. Hence, the strategy is to use the finest resolution possible to begin to demonstrate the ability of global models to forecast hurricanes at long lead times. The goal is to develop global models to run at 10 km by the end of five years.

Regional Models

Much higher resolution is possible today with regional models. A single-model deterministic run at 3 km in real-time is possible now and 1 km may be possible operationally within five years. This resolution should be adequate to capture the convective processes occurring in or near the center of the storm, including processes coupled to the ocean. This, however, needs to be demonstrated. Our strategy is to use the regional models, coupled to high-resolution global models, to address the problem of improving forecasts of intensity.

Ensembles

A single deterministic run of a model is essentially one member of an ensemble as noted above. If the forecasts of tracks from all members of an ensemble are plotted from the initial position of the hurricane, the result is a diverging fan of tracks. A deterministic run could be any one of these members. At lead times beyond two days when the track spread has generally diverged significantly from the ensemble mean, the ensemble will provide the best information to forecast the most probable track. The same reasoning holds true for the forecasting of intensity. In five years, global ensembles with resolutions of 10-20 km should be available in real-time with enough members to give a good statistical distribution of forecast probability. Regional ensembles, which will also be used to forecast intensity, can be run at 4-5 km.

Statistical Post-Processing

Any variable from any model forecast will have some bias. With adequate runs of retrospective cases, this bias can be estimated. When that bias is removed, the forecasts usually are closer to reality than the raw forecast. For example, global models with resolutions of worse than 10 km will usually have a significant negative intensity bias because the hurricane is not adequately resolved. When this bias is removed the intensity forecasts are closer to reality. There are other statistical techniques that can extract certain predictors from the models (such as shear in the vicinity of the hurricane) as well as from various observations to make specific forecasts such as max wind speed. Statistical models constructed in this way currently provide the best intensity guidance to forecasters when compared with dynamical models. A major part of HFIP development will include developing these statistical methods.

Observations and Data Assimilation

Early results from the HFIP program pointed to the need for improving the current data assimilation systems, particularly as applied to initial conditions in hurricanes within regional models. Advanced data assimilations systems using 4DVAR, EnKF and their hybrid are currently in the planning process. These systems will need to take advantage of additional data sources as they become available from current or planned satellite systems, various aircraft observations, and both land-based and airborne radar. To solve the initialization problem in regional models, satellite data already used and planned for global applications needs to be applied at higher resolution in the vicinity of the hurricane. Much of the satellite data near the hurricane will contain clouds. Methods need to be developed to use radiance data in cloudy regions. All aircraft-derived data should be utilized and observing strategies must be synchronized to the availability of planes to maximize the value to model initialization. There may still be data gaps for both model initialization and direct forecaster use that will need to be addressed.

Ocean/Wave Models

Some of the models used in HFIP interact with active ocean models both one-dimensionally and three-dimensionally. Both the POM and HyCOM models are used. During the next five years, most atmosphere models with an interactive ocean will likely shift to use of the more complex HyCOM. Ensembles, particularly global ensembles, may use the one-dimensional parameterization of the impact of the hurricane on the ocean rather than a full three-dimensional model in consideration of computational costs.

7.2 Target Operational Prediction System for 2014

The milestones and deliverables outlined in Section 7.3 are designed to lead to the fielding of an operational prediction system by the end of 2014.

- 20-40 member ensembles: 10 km global and 3 km regional resolution
    - two global model cores/physics (~ FIM and NMM)
    - three regional model cores/physics (~ HWRF, AHW, COAMPS –TC)
- Statistical post-processing of both track and intensity from a 20-year reforecast from the various models (Rerun each year)

- At least one member of each model in the ensembles will be computed using a full three-dimensional ocean. Others may use parameterized ocean coupling.

- Both global and regional models will use a 4DVAR/ensemble hybrid system

- Regional models will use all available satellite and aircraft derived data for inner core initialization

    – Ensemble and model products that maximize value to forecasters will be emphasized

7.3 Milestones and Deliverables

This section provides a broad overview of the main deliverables and milestones for HFIP. Details on how the milestones and deliverables in this section will be achieved are available in the various team reports in Appendix A.

FY10

- Upgrade HWRF operational model (June) (includes improved physics). New higher resolution GFS system.
- Run COAMPS-TC in real-time in West, Central and East Pac
- Provide synthetic GOES satellite images from HWRF and GFS (GFS images to include Central and Western Pacific)
- Conduct DEMO experiment (Aug 1-Oct 30)
    - 30 km real-time global ensemble, 20 members
    - 6-10 member multi-member regional ensemble some with bias correction
    - 30 member regional ensemble
    - EnKF data assimilation (DA) using inner core observations and radar data in experimental HWRF
    - Stream 1.5 components (multi-model ensemble)
    - Testing of new products from multi-model ensemble and global ensemble for forecasters.
- Continued development of global models (FIM, Cubed Sphere, NMM, NOGAPS) and regional models (WRF, COAMPS-TC, Wisconsin model) and their ensembles
- Continued development of physics packages for both global and regional models
- Testing and development of alternative (to 3DVAR) DA (EnKF, 4DVAR, hybrid)
- Testing of HyCOM ocean model in HWRF

FY11

- Preliminary testing of new options for HWRF upgrade and diagnostic evaluation of various models
- Development of 15 years of retro forecasts by 30 km EnKF GFS system for statistical post-processing
- Development of new model products for forecasters (at least one per year)
- Retro testing of 30 km global ensemble for Stream 1.5
- HWRF operational model upgrade (June), including HyCOM ocean, improved physics, and initial vortex. Possibly include operational Central Pacific Hurricane HWRF runs.
- Provide synthetic polar orbiter satellite images from HWRF and GFS (GFS images to include Central and Western Pacific)
- Retro testing of regional model components of multi-model ensemble for Stream 1.5
- Conduct DEMO experiment (Aug 1-Oct 30)
    - 20 km real-time global ensemble (20 member)
    - 6-10 member multi-member regional ensemble with bias correction
    - 30 member regional ensemble—all storms with inner core data when available

    - High-resolution experimental HWRF with EnKF DA using inner core observations and radar data when available and improved use of satellite data at other times
    - Stream 1.5 components (multi-model ensemble, high-resolution global ensemble (30 km))
    - Testing of new products from regional multi-model ensemble and global ensemble for forecasters. Include input from all hurricane centers (NHC, Central Pacific Hurricane Center (CPHC), Joint Typhoon Warning Center (JTWC))
- Continued development of global models (FIM, Cubed Sphere, NMM, NOGAPS) and regional models (WRF, COAMPS-TC, Wisconsin model) and their ensembles
- Continued development of physics packages for both global and regional models
- Pre-implementation testing of new DA in operations (EnKF, 4DVAR, hybrid)

FY12

- Preliminary testing of new options for HWRF upgrade, diagnostic evaluation of various models
- Operational implementation of COAMPS-TC for all Pacific basins.
- Development of 15 years of retro forecasts by EnKF 20 km global model (GFS or alternative such as FIM) system for statistical post-processing
- Development of new model products for forecasters (at least one per year)
- Initial retro testing of 10 km FIM
- HWRF operational model upgrade (June), improved physics, and advanced data assimilation system
- Testing of new aircraft observation strategies for improved model initialization
- Retro testing of regional model components of multi-model ensemble for Stream 1.5
- Conduct DEMO experiment (Aug 1-Oct 30)
    - 15 km real-time global ensemble (20 member)
    - 6-10 member multi-member regional ensemble some with bias correction
    - High-resolution experimental HWRF with EnKF DA using inner core observations and radar data when available and improved use of satellite data at other times
    - Stream 1.5 components (multi-model ensemble, high-resolution global ensemble (20 km))
    - Testing of new products from regional multi-model ensemble and global ensemble for forecasters.
- Focus Development of Global models on one or two selected models (TBD) and regional models (WRF, COAMPS-TC, Wisconsin model) and their ensembles
- Continued development of physics packages for both global and regional models
- Pre-implementation testing of new DA in operations (EnKF, 4DVAR, hybrid)
- Pre-implementation testing of inner core data assimilation based vortex initialization

FY13

- Preliminary testing of new options for HWRF, COAMPS-TC upgrade, and diagnostic evaluation of various models
- Development of 15 years of retro forecasts by EnKF 15 km global model (GFS or alternative such as FIM) system for statistical post-processing.
- Development of new model products for forecasters (at least one per year)
- HWRF operational model upgrade (June) - improved physics and improvements to HWRF DA and vortex initialization
- Operational implementation of aircraft observation strategies for improved model initialization
- Retro testing of regional model components of multi-model ensemble for Stream 1.5
- Conduct DEMO experiment (Aug 1-Oct 30)
    - 10 km real-time global ensemble (20 member)
    - 6-10 member multi-member regional ensemble (some with bias correction)
    - Stream 1.5 components (multi-model ensemble, high-resolution global ensemble (20 km))
    - Testing of new products from regional multi-model ensemble and global ensemble for forecasters.
- Continued development of global models and regional models
- Continued development of physics packages for both global and regional models
- Operational implementation of new DA in operations (EnKF, 4DVAR or hybrid)
- Pre-implementation testing of high-resolution global ensemble (10-20 km)

FY14

- Preliminary testing of new options for HWRF, COAMPS-TC upgrade, and diagnostic evaluation of various models
- Implementation of high-resolution global ensemble (10-20 km)
- Development of new model products for forecasters (at least one per year)
- HWRF operational model upgrade (June) (improved physics and further improvements in HWRF data assimilation system)
- Implement multi-model regional ensemble
- Retro testing of regional model components of multi-model ensemble for Stream 1.5
- Conduct DEMO experiment (Aug 1-Oct 30)
    - Include components not yet feasible for routine operations such as regional and global ensembles at higher resolution
- Continued development of global models and regional models and their ensembles
- Continued development of physics packages for both global and regional models

8 Appendix A: Strategic Plans by Development Teams

8.1 HFIP Teams

Eight specialized HFIP development teams were in place in 2010. A listing of these teams is provided in Table 7.

Table 7. HFIP Development Teams

FY2010 Teams	**Team Leads and Member's Organization**
1. Global Model/Physics	*Stan Benjamin* (ESRL), *John Brown* (ESRL), AOML, NRL, GFDL, EMC, NRL
2. Regional Model/Physics	*Morris Bender* (GFDL), *Young Kwon* (EMC), AOML NRL, ESRL URI, Old Dominion Univ, NESL
3. Ensembles	*Zoltan Toth* (ESRL), *Carolyn Reynolds* (NRL), AOML, PSU, EMC, NHC, FSU
4. Data Assimilation/Vortex Initialization Team	*Jeff Whitaker* (ESRL), *Bill Lapenta* (EMC), AOML, NRL, CIRA, PSU
5. Verification Team	*Tim Marchok* (GFDL), Barb Brown (RAL), NRL, NESDIS/STAR, AOML, NHC, EMC, ESRL
6. Applications Development and Diagnostics	*Ed Rappapor*t (NHC), *Mark DeMaria* (NESDIS/STAR), EMC, NRL, HRD, RAL, ESRL, OU, AOML, FSU
7. Hurricane Observations	*Sim Aberson* (AOML), *Shay* (RSMAS), NHC, EMC, NESDIS/STAR, ESRL, URI, NRL, AOC, RAL
8. Ocean/Wave Models	*Hendrik Tolma*n (EMC), *Halliwell* (AOML), URI, ESRL, NRL, RSMAS

8.2 Team 1 Global Model/Physics

Team Overview

HFIP has defined specific goals related to improving prediction of tropical cyclones (TCs). These goals are focused on TC track and intensity forecasting, including better prediction of rapid intensification and extending skillful forecasts out to seven days lead-time. The Global Model/Physics Team develops and tests global models and their parameterizations of physical processes, and considers both operational and research models that have potential for operational implementation. We believe parameterizations of physical processes are a critical component for numerical TC prediction, and a large proportion of the Global Model/Physics Team effort will be given to adapting, improving and testing physical parameterizations.

During the past 25 years, global models have gone from playing at best a secondary role in TC prediction to becoming indispensible tools for the NHC and JTWC forecasters because the tropical cyclone genesis, intensity and track forecast problem is essentially a global forecast problem beyond 2-3 days, involving interactions of the tropical cyclone and its environment with baroclinic processes at higher latitudes in both hemispheres. Further, computing resources available to operational centers now allow horizontal model resolutions that permit a reasonable representation of the TC mesoscale vortex (~ 25 km), even for global models. Improving these models, and the parameterization of physical processes within them, is therefore directed toward improving overall model performance. Such improvement should also benefit TC prediction by regional models that may be nested within the global models.

Within this overall goal, four research and development thrusts involving global models are underway and are expected to continue for the duration of HFIP:

- Fundamental improvement in model **dynamical core**, **physics (including chemistry)** and **resolution**, with a primary long-range goal of developing an operational cloud-resolving global model having skill in TC genesis, intensification and track prediction
- Improvement in model initial conditions, including TCs
- Design of global ensembles used in TC prediction, including use of stochastic physics and diversity of physics suites
- Interactive coupling of atmosphere and ocean models for operational use

To move forward with the second and third of these goals, strong interaction is needed between the Global Model/Physics team and the Ensemble Systems Development and Data Assimilation/Vortex Initialization Teams. Much can be learned from the Regional Model/Physics Team as current and future global models approach the resolutions of current regional models. The Verification Team will, of course, play a crucial role in assessing Global Model/Physics Team progress.

Summary of Accomplishments to Date

Some of the specific accomplishments of the Global Model/Physics Team to date are as follows:

- Adapted the Flow-following finite-volume Icosahedral Model (FIM) and the Global Spectral Model (GSM) of NCEP's Global Forecast System (GFS) to run on the Texas Advanced Computing Center (TACC) Ranger system
- Devised and introduced a "tri-section" procedure for constructing Voronoi cells, allowing for more flexibility in the layout of the FIM icosahedral grid (horizontal grid spacing no longer has to change by a power of two to go to the next permissible higher resolution)
- In collaboration with the Data Assimilation Team, helped run the ESRL EnKF using a 60-member GSM at T382 resolution on a 6-h update cycle in real time for August and September 2009
- Again, in collaboration with the Data Assimilation Team, ran at TACC a 20-member FIM ensemble at G8 (30-km grid spacing) resolution once per day in real time for a few weeks in 2008 and approximately two months in 2009, including Hurricanes Ike (2008) and Bill (2009)
- Confirmed the expected result that the low bias in prediction of TC intensity forecast is reduced with higher resolution based on the near real-time TACC runs with 30, 15 and 10 km versions of FIM, all initialized with operational GFS initial conditions
- Determined that the intensification of TCs in FIM is concurrent with an increase of the fraction of precipitation occurring on the grid scale
- Experimented with the Simplified Arakawa Schubert deep convective scheme in the operational GFS to see how the fraction of convective to total precipitation and spurious spin-up of TC like disturbances in FIM forecasts is affected by changing the parameter (XKT2) that determines convective cloud top
- Successfully ran the GFDL Cubed-Sphere Model (CSM) at 25 km resolution for the 2005-2009 boreal TC seasons
- Upgraded CSM and introduced a dynamically balanced vortex initialization scheme for 2010 … makes CSM competitive with operational regional models in retrospective tests
- Progress on development of localized grid refinement in CSM toward localized grid-refinement to cloud-resolving scales in potential genesis regions
- Finished design and testing of a new shallow convective scheme and revised deep convective scheme in GFS; will be implemented into operations June 2010.
- Successfully transitioned T319L42 version of NOGAPS into operation on 18 May 2010

Focus Areas of Development

Focus areas of development will follow the four thrusts of Section A. In model development, the team sees rapid progress in design of high-resolution (10-15 km) hydrostatic and non-hydrostatic global models and notes that the European Centre for Medium-Range Weather Forecasting (ECMWF), with implementation of their operational T1279 upgrade, is not far from the limit of applicability of the hydrostatic approximation. Thus, development of an operational global model capable of cloud-resolving resolutions (3-4km horizontal grid spacing) is seen as a high, long-range priority. Among other things, this will permit realistic simulation of the inner core of the TC and improved ability to describe the effect of convective precipitation-driven downdrafts and of vertical shear of the horizontal wind on mesoscale organization of convection during formation. In the near term, operational constraints for global forecasts will continue to limit our ability to resolve such key processes. In the context of ensemble forecasting, this limitation is not expected to go away soon. Efforts will continue therefore on multiple areas of model physics parameterization, including deep convection. Although higher resolution models will permit explicit, rather than parameterized deep convection, they will require development of coupled or unified surface, boundary layer and shallow cumulus parameterizations.

As part of this effort, or perhaps parallel to it, a move should continue toward prediction of atmospheric aerosol (e.g., sea salt, Saharan dust) and its interaction with cloud nucleation in bulk (probably 2-moment (mixing ratio + number concentration of hydrometeor species) microphysics schemes). A FIM-chem model with in-line treatment of 16 aerosol types with radiation (but not microphysics) interaction started running in real-time in Spring 2010. Schemes with aerosol-microphysics interaction are under development currently for application in operational regional models. Of course, in order to make use of these advances in operations there will need to be a very large (by a factor of at least 10^3) increase in computer resources for operations.

It is clear from operational model performance that progress in initialization of the tropical cyclone vortex is desperately needed. Further, current 3DVAR analysis schemes don't appear to have the flexibility to handle both the larger scales of motion in the tropics and extratropics, and also incorporate the mesoscale structure of the TC vortex. The results of the past 2 years in which the FIM has been run at 30-10 km resolution with initial fields generated by the ESRL EnKF system using GFS are very promising. In concordance with results from other operational centers that have invested in this or 4DVAR approaches, FIM forecasts run with EnKF ensemble-mean initial conditions show improvements over identically configured FIM forecasts initialized from the operational GFS initialization in both TC track and intensity forecasts, in anomaly-correlation scores outside the tropics and for tropical upper-tropospheric winds.

Ensemble TC forecasts clearly have a critical role in providing guidance on track and intensity uncertainty. However, it is necessary that these ensembles produce forecasts that are truly random and draw from the universe of possibilities. The current GFS ensembles exhibit insufficient spread in track to be of optimal use. Improvement in this underdispersion will likely come with improved resolution of the ensembles, however, other options should be considered. Techniques such as stochastic parameterization, in which parameterization tendencies are randomly perturbed, or perturbed in such a way as to incorporate uncertainty from sub-grid processes that fluctuate on rapid time scales, need to be examined in the TC prediction context. Development and refinement of this or other techniques for better design of ensembles is expected also to be an ongoing, several-year effort with incremental improvements being made to operations as promising developments move into operations.

The necessity for coupled atmospheric-ocean models for TC application is now widely recognized for the regional application. As the global models run at higher resolution, the importance of such coupling in global models will become much more apparent. Development in this area is well underway at GFDL with the CSM, and has begun at ESRL with development of an icosahedral version of HYCOM that will be coupled to FIM.

Milestones and Deliverables

Specific milestones and deliverables are included below. Expected dates of completion are listed as "ongoing" for those items that the Global Model/Physics Team expects to be performing on an ongoing basis, whilst other items are divided into ranges of short term (1-2 years) or longer term (3-5 years).

Milestones:

1. Participate in annual DEMO forecasting exercises with CSM, FIM, GFS, and NOGAPS or their successors, as appropriate (Ongoing)
2. Annual upgrades to global models (including physics and ensemble design) that participate in annual DEMO forecasting exercises (Ongoing)
3. Evaluation of performance of FY10Q3 GFS physics in GFS and in FIM as part of 2010-11 DEMO forecasting exercises. Emphasis will be on TC demographics. (Short-term)
4. Evaluation of global model intensity forecasts by running, inside the global model, statistical-dynamical intensity models including: 1) Logistics Growth Equation Model (LGEM); and 2) the Coupled Hurricane Intensity Prediction System (CHIPS). The basic idea is to determine how much of intensity change in global models can be explained by model large-scale processes (Short term)
5. Incorporate advances made in TC initialization by the Vortex Initialization Team into global model initialization (Short term or ongoing)
6. Initialize FIM with FIM-based (not GFS-based as at present) EnKF developed by Ensemble Systems Development and Data Assimilation/Vortex Initialization Teams. Assess relative to GFS (GSI) initial conditions in DEMO forecasting exercises or retro experiments (Short-term).
7. Run 15-20 km FIM ensembles in real time as part of Demo forecast exercises, or retrospectively, if real-time resources not available (Short term)
8. Exploration of benefit of ensembles versus higher-resolution "deterministic" runs for deterministic track prediction (Short-term)
9. Preliminary design of ensembles incorporating stochastic physics or diverse physics suites (Short-term)
10. Evaluation of ensembles based on stochastic physics concepts (Long-term)

11. Explore potential of stretched-horizontal-grid versions of global models to make potentially operationally useful cloud-resolving forecasts over areas of special interest for TC genesis/intensity change at less computational expense than with uniform-grid global models (Long-term)
12. Explicit TC track and intensity forecasts by “cloud-resolving” global models (at first, in retrospective mode, later in DEMO forecasting exercises) (Long term)
13. Introduction of aerosol-microphysics and aerosol-radiation interaction into global model, test on retrospective cases of suspected Saharan dust interaction with nascent TC (Long-term)
13. Tests of FIM coupled with HYCOM on retrospective cases at G8 resolution (Medium-term)
14. FIM coupled with HYCOM running at least G8 resolution in annual DEMO forecasting exercises.

Deliverables:

Port of improved models/physics to operational centers for consideration for operational implementation

Report on new developments in models and physics in documents, publications and manuscripts for peer-reviewed publication

8.3 Team 2 Regional Model/Physics

Introduction

As noted above, it is expected that the most likely solution to the hurricane *intensity* forecast problem will be through the use of regional models run at high resolution (1-5 km) where the inner structure of the hurricane is resolved. Primary improvements in track forecasts will come from the global models as described previously. Since it is not feasible to run the global models at 1-5 km resolution operationally for at least the next 5 years, regional models will be used for intensity forecasts. The regional models have a clear separation between Streams 1 and 2 since stream 1 is for the operational models and the primary operational models currently are regional for hurricanes. The milestones and deliverables indicated below reflect this separation. Key focus areas for development include: resolution, numerics, cloud microphysics, coupled atmosphere-wave-ocean systems, and boundary layer schemes.

FY10-FY11

Stream 1

- Continue testing of NOAH LSM in HWRF for operational implementation in 2011. Evaluate and compare tracks, intensity and rainfall with slab LSM.
- Continue evaluation of HWRF coupling to HYCOM for possible 2011 operational implementation
- Evaluate local and the non-local boundary layer parameterization schemes in HWRF and COAMPS-TC
- Perform sensitivity of horizontal diffusion of HWRF in order to make possible improvement of storm size and wind-pressure relationship
- Investigate expansion of ocean coupling in HWRF to East/Central Pacific
- Improved formulation of lateral boundary conditions for HWRF to address the deviations in large-scale HWRF forecast fields. Consider testing GFDL method as well as other schemes.
- Development of movable triply-nested (27/9/3) version of HWRF; expand coupler for triply-nested grid configuration, transferring code to general WRF code repository
- Development of the coupled atmosphere-wave-ocean version of HWRF and COAMPS-TC with a new air-sea interface module, including wind-wave-current interaction physics and sea spray parameterization based on ocean state using coupled wave-ocean-atmosphere system
- Test and evaluate a triply-nested version of COAMPS-TC with 45/15/5 km or 36/12/4 km resolution. Test improved physical parameterizations in COAMPS-TC (new shallow convection, PBL, surface fluxes, microphysics, NOAH LSM). Coordinate advancements with HWRF team
- Release and provide support of HWRF-v3 system (including vortex initialization, POM, HYCOM and coupler) to the community (DTC, EMC, URI), facilitating the use of a common code base for research and operations.

Stream 2

- Develop a framework for research and operations collaboration in hurricane numerical forecasting in the NOAA Environmental Modeling System (NEMS) era
- Develop the capability of performing idealized simulations with HWRF and transition it to the community WRF code
- Use idealized framework for evaluation of various advanced micro-physics parameterization schemes in HWRF, AHW and COAMPS-TC
- Install Hebrew University bin micro-physics parameterization as an option in general WRF code repository and test in (27/9/3) version of HWRF and COAMPS-TC for calibration of improved bulk microphysical parameterization
- Coordinate strategy within modeling groups for evaluation and advancement of other advanced physics parameterizations and suites for HWRF, AHW and COAMPS-TC
- Document and evaluate the sensitivity of storm track, structure and intensity to increased vertical resolution within HWRF, AHW and COAMPS-TC
- Continue development of high-resolution (9:3:1) triply nested version of HWRFV3.2 and transferring code to general WRF code repository
- Extend the HWRF coupler for HYCOM and WAVEWATCH to work with AHW and support to community

FY12

Stream 1

- Continue development of the above-mentioned coupled atmosphere-wave-ocean version of HWRF and COAMPS-TC
- Continue evaluation of advanced microphysics schemes in HWRF, AHW and COAMPS-TC using real date cases, with improved calibration based on bin microphysics.
- Continue development of an improved formulation of the lateral boundary condition for HWRF
- Continue evaluation of the impact of increased vertical resolution within COAMPS-TC, AHW and HWRF, using both idealized and real data
- Continue to evaluate local and the non-local boundary layer parameterization schemes (or new advanced scheme) in HWRF, AHW and COAMPS-TC
- Begin testing triply-nested version of wave-ocean-atmosphere coupled version of HWRF and COAMPS-TC with new enhanced surface, boundary layer and microphysics, including new sea-spray parameterizations
- Continue support of HWRF to the community
- Evaluate AHW with full ocean/wave coupling and sea spray parameterization and compare to HWRF and COAMPS-TC

Stream 2

- Continue development of high-resolution, triply-nested, coupled version of HWRFV3 (9/3/1), with advanced bulk and bin microphysics, coupled wave-ocean-atmosphere system and with increased vertical resolutions

FY13

Stream 1

- Begin rigorous testing, over multiple seasons in Atlantic and Eastern Pacific, of wave-ocean-atmosphere coupled version of HWRF (27/9/3 km), with new sea-spray parameterization, advanced microphysics, improved surface parameterizations, and possibly improved boundary layer schemes
- Begin rigorous testing over multiple seasons in the Western Pacific, Atlantic and other basins, of the wave-ocean-atmosphere coupled version of COAMPS-TC (27/9/3 km) using high-resolution physics including advanced microphysics, boundary layer, and surface fluxes
- Coordinate results with HWRF team
- Run new version of HWRF and COAMPS-TC in parallel for 2013 hurricane season
- Continue support of HWRF to the community

Stream 2

- Continue development of high-resolution, triply-nested, coupled version of HWRFV3 (9/3/1), with advanced bulk and bin microphysics, coupled wave-ocean-atmosphere system and with increased vertical resolutions.
- Implement a semi-Lagrangian, positive definite, monotonic advection scheme for the scalar quantities including the microphysics within COAMPS-TC and test new physical parameterizations in COAMPS-TC (possibilities include new shallow convection, PBL, surface fluxes, microphysics).
- Coordinate advancements with HWRF team
- Test and compare the performance of the AHW advanced model to COAMPS-TC and HWRF
- HWRF development in NEMS framework

FY14

Streams 1 and 2

- Operational implementation of new (27/9/3) version of HWRF at EMC depending on availability of computer resources.
- Operational transition of a new fully coupled (air-sea-wave) COAMPS-TC to FNMOC, contingent on available computational resources

- Continue comparison of (27/9/3) version of HWRF with (9/3/1) version with bin microphysics
- Testing HWRF in NEMS framework
- Continue support of HWRF to the community
- Continue physics improvements in Stream 2 models and performing inter-comparisons with HWRF and COAMPS-TC

FY15

Streams 1 and 2

- Consider increased horizontal resolution of HWRF (e.g., 18/6/2) in accordance with changes to GFS resolution and availability of computer resources
- Continue testing HWRF in NEMS framework for possible implementation during the 2015 hurricane season
- Continue support of HWRF to the community

8.4 Team 3 Ensembles

Introduction

In the overall introduction, the use of ensembles was noted as the best prospect for improving track guidance out to seven days and intensity forecasts out to five days. The probability information contained in the ensemble can provide both probabilities for individual forecast members as well as additional guidance to forecasters on the most probable forecast. This is true for both the global and regional models.

Not only will ensembles help provide information on the most probable forecast but they will also be a central part of any future data assimilation system. More is noted in the section below on data assimilation.

From the recent HFIP sponsored experiments, the following are noted:

- Advanced data assimilation systems (EnKF, 4DVAR) very significantly improve global forecasts over the current operational 3DVAR "GSI" data assimilation system with the GFS model, especially for hurricane track. In summer 2009, experiments with an EnKF and a higher-resolution GFS ensemble yielded a steady improvement with forecast lead time (approximately 20% improvement at 4 days). Significant improvements were also found at NRL by switching from 4DVAR to 3DVAR.
- High-resolution ensemble systems (global and regional) are showing improvements in track and intensity as expected. By using both higher resolution in the GFS and a more advanced data assimilation system (EnKF in this case), the skill of the GFS system can be made to match that of the ECMWF (Fig. 1). It has not been established how much of this ability to match skills comes from the data assimilation system and how much comes from improved resolution, though both are probably important. Planned upgrades to the GEFS at NCEP, including increased resolution, stochastic perturbations, and changes to horizontal diffusion, show significant improvement in ensemble mean track forecasts. High-resolution global ensembles (30 km, 20 members) can be run in real-time on available computing resources. Higher resolution is definitely possible.
- The multi-model regional ensemble showed promise: Insufficient data was acquired last summer for a training phase to allow computation of a bias-removed ensemble. Continued running of the multi-model ensemble may allow more meaningful statistics of the system to be developed. This, however, will be difficult to achieve since all component models undergo significant changes due to model improvements. Later model improvements can reduce the value of statistics from earlier runs. Regardless, the ensemble provides useful statistics even in raw data output. For example, the ensemble mean provides estimates of position error comparable to the official forecast. The same is true for intensity statistics.

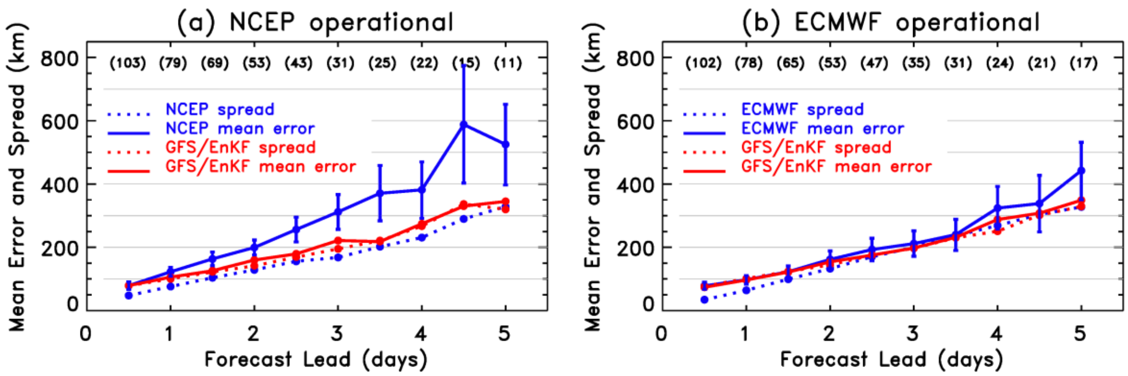


Figure 1. Comparison of GFS/EnKF ensemble mean track error (solid red) and ensemble spread (dashed red), with the ensemble mean track error and spread from other systems.

Goals for Hurricane Guidance Improvement Using Ensembles:

- Develop more reliable and useful automated probabilistic numerical guidance for hurricane track, intensity, structure, rainfall, storm surge, and other associated weather elements through improved ensemble forecasting systems and improved post-processing methods
- Work closely with HFIP data assimilation group on development and use of ensemble-based data assimilation techniques for initializing ensemble predictions
- Work with verification team on developing and using ensemble/probabilistic measures
- Work with Products Team to develop ensemble/probabilistic products

Milestones and Deliverables:

FY10

- Determination of the effect of global Ensemble Data Assimilation (EnsDA) relative to existing GSI/ET technique for hurricane forecast performance
- Determination of the effect of stochastic backscatter, stochastic parameterizations, and parameter variations on global ensemble forecasts of hurricanes
- Evaluation of uncoupled COAMPS-TC ensemble performance
- Delivery of initial conditions/lower boundary conditions to AOML for regional EnsDA/ensemble forecast experiments
- Single-model and multi-model ensemble weighting method for intensity forecasts
- Determination of effect of resolution in global EnsDA and forecasts
- Transition (if warranted) of deformation-based initial TC perturbations in the Navy Global Ensemble system
- Transition (if warranted) of higher resolution global ensemble into Navy operations
- Deliver baseline ensemble verification suite to verification team

FY11

- Evaluation of impact of improved TC initial perturbations (and implementation pending satisfactory results) into Navy global ensembles
- Evaluation of two-way (atmosphere-ocean) coupled COAMPS-TC ensembles
- Operational implementation of stochastic convection/backscatter into operational global models, if warranted from experiments
- Determination of whether fully coupled ocean model is required for hurricane global ensemble forecasts and whether simpler schemes are adequate replacements
- Operational implementation of global EnsDA system or EnsDA//4DVAR hybrid in a NOAA global model, if warranted by results

FY12

- Evaluation of NRL global ensemble tests with coupled model
- Evaluation of three-way (atmos-ocean-wave) coupled COAMPS-TC ensembles
- Reanalyze and reforecast data set appropriate to hurricane problem
- Determination of whether perturbed ocean conditions and/or perturbed ocean physics improves ensemble hurricane forecasts

FY13

- Experimental calibrated hurricane forecast products from global ensemble using reforecasts
- Evaluation and potential implementation of Navy global coupled ensembles
- Evaluation and potential implementation of COAMPS-TC ensembles as part of multi-model ensembles

8.5 Team 4 Data Assimilation/Vortex Initialization Team

Introduction

The purpose of data assimilation is to produce initial states (analyses) for numerical prediction that maximize the use of information contained in observations and prior model forecasts to produce the best possible predictions of hurricane track and intensity. Most data assimilation methods use observations to correct short-term model forecasts, and therefore the accuracy of the resulting analysis is not just a function of the data assimilation methodology, but the fidelity of the forecast model itself. Therefore, improvements in data assimilation are directly tied to improvements in the underlying forecast model, as well as the observing system. The fundamental goal of the HFIP data assimilation effort is to develop data assimilation systems that leverage improvements in forecast models and observing systems to produce the most accurate analyses possible. The accuracy of the analyses is measured by the quality of the resulting forecasts.

Results from Recent HFIP Experiments

The HFIP DA team has made significant progress in improving hurricane forecasts by using flow-dependent background error statistics derived from short-term ensemble forecasts using the Ensemble Kalman Filter (EnKF) technique, and by assimilating tropical cyclone central pressure observations.

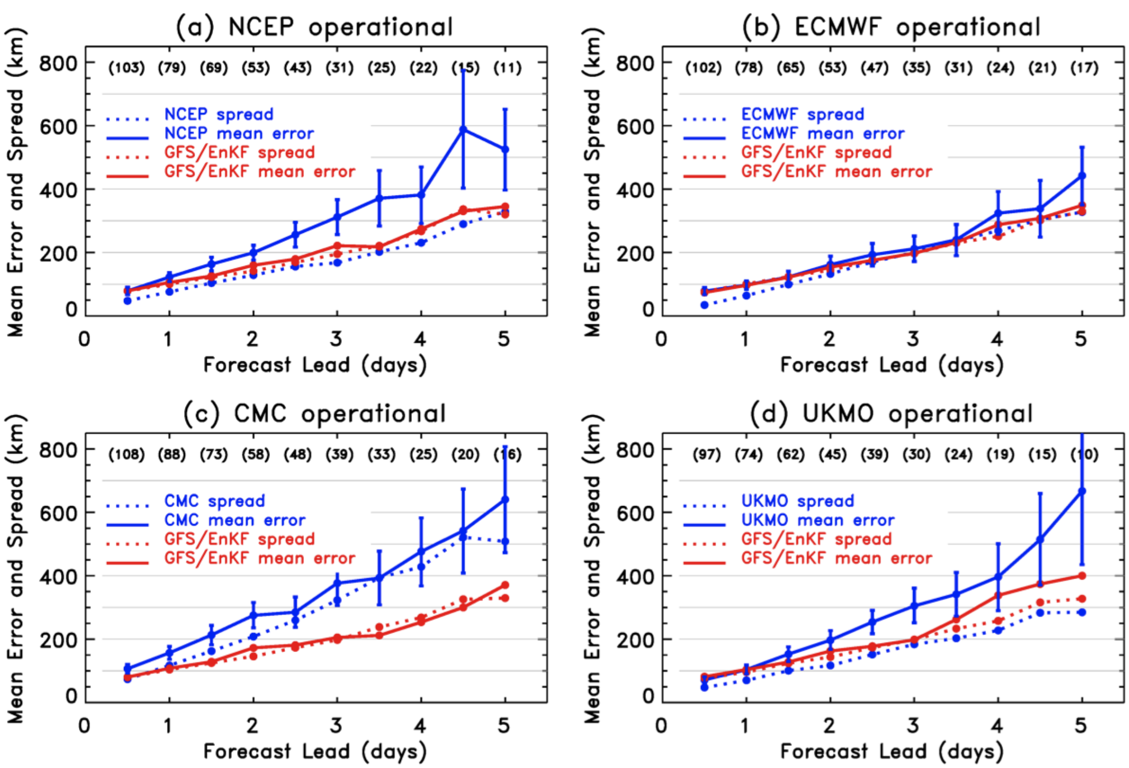


Figure 2. Homogeneous comparison of global average track forecast errors and average spread between the experimental GFS/EnKF and (a) the NCEP operational ensemble

system, (b) the ECMWF operational ensemble system, (c) the CMC operational ensemble system and (d) the UK Met Office operational ensemble system. Numbers in parentheses at the top of each panel indicate the sample size at a particular forecast lead, i.e., the number of matched paired forecasts between the GFS and the model in question. Dashed lines indicate spread, solid lines indicate error. Error bars indicate the 5th and 95th percentiles of a resampled block bootstrap distribution. For more details, see Hamill et al (2010).

Figure 2 shows the skill of experimental global hurricane track ensemble forecasts for 2009, initialized from an experimental EnKF system compared to forecasts from other operational centers. The EnKF-based forecasts, using the operational NOAA GFS, are as or more skillful than any operational forecasts issued worldwide. The variability of the hurricane tracks within EnKF-based ensemble (the dashed red line in Fig. 2) accurately reflects the uncertainty of the mean forecast, an important property for any probabilistic forecast system. Most of the progress to date results from the use of more accurate background-error statistics that reflect the dynamics in the vicinity of the hurricane vortex as well as the larger-scale environment in which the hurricane is embedded. Assimilation of tropical cyclone central pressure observations has also had a significant positive impact, and has now been implemented in the NCEP operational three-dimensional variational (3DVAR) analysis system for global forecasts. Work is underway to merge the experimental global EnKF with the existing NCEP operational variational (Var) data assimilation system, and this effort will culminate in the implementation of an operational NOAA hybrid Var/EnKF system within the next several years.

Goals for Hurricane Guidance Improvement from Data Assimilation

Advances in global data assimilation have put HFIP in a good position to meet the five-year goal of a 20% reduction in hurricane track forecast errors (Fig. 3), at least for days 2-5.

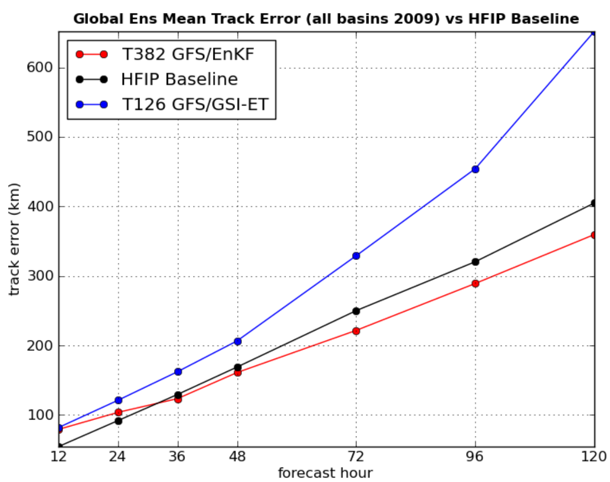


Figure 3. The HFIP baseline hurricane track error as a function of lead time (black), the operational NCEP ensemble mean hurricane track errors for the 2009 hurricane season in all basins (blue) and ensemble mean track errors from the experimental GFS-based EnKF

system for the same set of cases as the operational NCEP ensemble (red). The HFIP baseline is based on consensus forecast errors for 2006-2008 in the Atlantic basin only.

Meeting the 5-year goals for track forecast error for day 2 and beyond should be achieved with continued improvement of the global hybrid Var/EnKF system, with an focus on better treatment of sampling and model error (along with continued improvements in the global forecast model). Making progress at shorter lead times, and for the intensity forecast, has been more difficult. Progress in these areas will require high-resolution models that can accurately simulate inner-core processes, and data assimilation systems that can make effective use of prior forecast information from these high-resolution models as well as inner core observations, such as airborne radars, dropsondes and satellite radiances. There have been some notable successes, such as Hurricane Humberto in 2007 (Fig. 4).

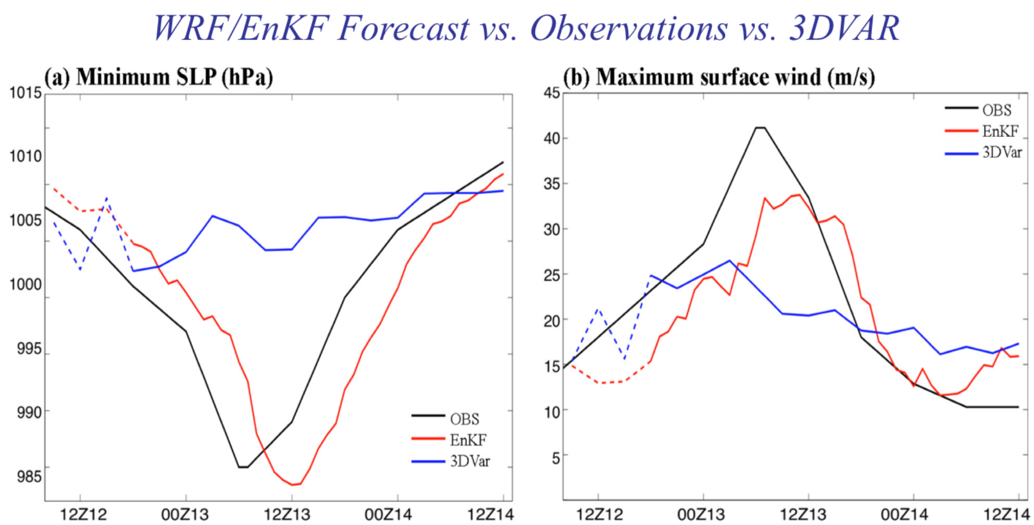


Figure 4. The observed and forecast intensity of Hurricane Humberto (2007). The red curve is for forecasts initialized by an EnKF and the blue curve is for forecasts initialized by a 3DVAR system. Both systems assimilated Doppler radar winds, but the 3DVAR system did not use flow-dependent background error covariances. For more details, see Sippel and Zhang (2010).

However, a focused effort to accelerate the integration of the high-resolution regional models into the hybrid Var/EnKF system currently being tested for global applications is needed. Current generation prediction systems suffer from a "spin-down" problem - when inner-core observations are assimilated in intense tropical cyclones, the forecast model is not able to retain the analyzed vortex structure, resulting in a transient decay of the forecast cyclone. This is partly a result of model deficiencies (our current models, even when run at convection-permitting resolutions, are often not able to represent structures we observe), and partly a result of deficiencies in our data assimilation systems (which do not yet represent the statistics of forecast and observation errors accurately enough in the inner core of intense tropical cyclones). As previously mentioned these two problems are not independent, since in a four-dimensional data assimilation system such as an EnKF the structures for the background error are predicted by the model itself.

In order to meet the HFIP goals for intensity forecasts, as well as 0-2 day track forecasts, a focused effort is needed to:

- Merge global and regional EnKF-based data assimilation efforts around the hybrid Var/EnKF system being developed jointly at NCEP, ESRL and NASA, so that a single system can be used by all research groups for both global and regional applications. This will allow for better collaboration and more effective use of resources, more consistent boundary conditions for regional models, a more direct way of measuring progress, and a smoother transition to NOAA operations.
- Develop better methods for accounting for ‘representivity errors’ (the component of observed variability that cannot be represented by the forecast model) .
- Develop better methods for treating the error associated with estimating background-error covariances with a small ensemble. Current methods are not flow dependent, and do not account for the specific nature of sampling errors in the vicinity of hurricane vortices.
- Make better use of satellite observations, particularly in cloud affected regions around tropical cyclones.
- Develop better methods for evaluating and identifying model errors which result from physical parameterizations (in collaboration with other HFIP teams).
- Improve the physical parameterizations in forecast models so that they can more accurately simulate the structures observed within tropical cyclones. This will directly affect the ability of data assimilation systems to accurately represent background forecast error statistics, which will in turn lead to more effective use of inner-core observations to initialize hurricane forecasts.
- Develop representations of model uncertainty through the use of stochastic physics parameterizations. Given that models will have significant errors in the vicinity of tropical cyclones in the foreseeable future, it is crucial to better account for the model uncertainty component of the background error statistics needed for data assimilation.

Milestones and Deliverables

FY2010:

- Test the global Var/EnKF data assimilation system in near-real time for the 2010 hurricane system and evaluate its performance relative to operational global prediction systems.

- Test the assimilation of inner core aircraft observations in a regional EnKF system based on HWRF.

FY2011:

- A hybrid Var/EnKF based system for global ensemble hurricane prediction is delivered to NCEP/EMC for initial pre-implementation testing.

- The EnKF component of this system is adapted for use with the regional WRF model (both HWRF and WRF-ARW versions).

- A stochastic physics parameterization is tested within the context of the global ensemble prediction system.

- Test the assimilation of radiances in cloudy regions around tropical cyclones.

- Test COAMPS-TC using EnKF and compare track and intensity results with 3DVAR.

FY2012:

- Parallel testing of the Var/EnKF system at NCEP for the global application.

- Test new methods for accounting for model uncertainty in the data assimilation system.

- The integrated regional/global Var/EnKF system is tested with all observations assimilated in NCEP operations, plus inner core observations.

- Continue testing and evaluation of COAMPS-TC using EnKF and 4DVAR assimilation methods that are under development.

FY2013

- The Var/EnKF system is implemented in NCEP operations for global applications.

- Testing regional Var/EnKF system continues. The value-added by regional models is rigorously assessed.

- Implementation and testing in real time of advanced assimilation (EnKF or 4D-Var) using the COAMPS-TC system.

8.6 Team 5 Verification

Introduction

The two fundamental tasks of the Verification Team are the performance of model verification analyses and the development and/or adoption of new verification techniques. The verification approaches can be divided into two categories: "benchmark" verification analyses that are targeted specifically at the metrics for the main HFIP goals, and then all other verification studies that may be performed for a variety of model development and evaluation purposes.

The primary focus of the Verification Team is on the benchmark verification analyses and related activities, such as contributing to the organization and coordination of real-time and retrospective runs, with the objectives of: (1) providing reports to management on the progress of the models towards the HFIP goals, and (2) providing forecasters and other decision-makers with the statistics they need to understand model biases and also make informed decisions on potential transitioning of a model to operations.

As resources allow, the Verification Team will also work on other verifications and related activities. These activities may include: performance of verifications for metrics that are not part of the main HFIP goals, the development of new verification techniques, and the distribution of verification software to the community.

Recent Results

In order to help HFIP achieve its ambitious forecast goals, the Verification Team is performing verification analyses using available software, and is also developing software to aid in the verification of new parameters. The following list details some of the Team's accomplishments in these areas to date.

- Performed an extensive evaluation of forecasts from models that participated in the FY09 HFIP High-Resolution Hurricane test and provided a comprehensive report to HFIP management and participants (see Fig. 5).
- Established baseline track and intensity standards for both the Atlantic and Eastern Pacific Ocean basins that will be used to measure future progress in model forecast performance (see Fig. 6).
- Upgraded track and intensity verification software to extend verification analyses out to 7 days.
- Implemented verification software at NCAR for independent testing and evaluation of forecast performance.
- Collected data from 2009 Demonstration.
- Developed testing plan for retrospective evaluations, and worked with modeling groups to implement the plan.
- Developed initial version of software for verifying surface wind structure forecasts.

- Developed initial version of software for verifying tropical cyclone rainfall forecasts.
- Developed initial version of software for verifying forecasts of rapid intensity change.
- Developed initial version of software for verifying run-to-run consistency in model forecasts.

Focus Areas of Development

In order to help HFIP achieve its five-year 20% improvement goals, the Verification Team will focus primarily on these four areas:

- Contribute to the planning and coordination of HFIP hurricane model tests for retrospective tests and annual DEMO forecast exercises to ensure representative samples will be collected that can be used for meaningful model evaluations.
- Perform model verification analyses for annual DEMO exercises and retrospective studies and provide results to the community on-line and in summary reports.
- Develop, test, and implement new tools for evaluation of hurricane forecasts, including tools for cyclone tracking, as well as tools for the verification of ensemble forecasts and forecasts of TC genesis and TC rainfall. Provide mature tools to the community.
- Provide in-depth evaluations of collected hurricane datasets (e.g., HRH test; HWRF) to provide more insight into results from these studies. For cases in which the verification results indicate that more in-depth analysis is needed, coordinate with the HFIP Applications and Development Diagnostics (ADD) Team to collaborate and share datasets, software and results.

Milestones and Deliverables

Specific milestones and deliverables are included below. Expected dates of completion are listed as "ongoing" for those items that the Verification Team will be performing on an annual basis, while other items are divided into ranges of short-term (1-2 years) or longer-term (3-5 years).

Plan and Coordinate Tests

- Plan and coordinate annual retrospective reruns for evaluation of representative samples of forecasts and storms (ongoing).
- Contribute to the planning and coordination of the annual DEMO forecasting projects (ongoing).

Deliverables:
Planning documents and timelines

Perform Model Verification Analyses

- Perform independent, statistically valid model verification analyses for the annual DEMO and retrospective projects and prepare reports for HFIP management and participants (ongoing).
- Create a testing and evaluation environment on the HFIP computing platform that will be used for evaluation of HFIP model forecasts; facilitate running and testing of models on this platform (1-2 years).
- Perform in-depth evaluations of hurricane datasets collected from the High-Resolution Hurricane (HRH) test, retrospective and demonstration project forecasts. For cases in which the verification results indicate that more in-depth analysis is needed, coordinate with the HFIP ADD Team to collaborate and share datasets, software and results (ongoing).

Deliverables:

- Report on performance of HFIP forecasts in documents and presentations.

Development of New Tools for Evaluation of Hurricane Forecasts

- Develop Climatology and Persistence (CLIPER) and Decay-Statistical Hurricane Intensity Forecast (SHIFOR) models that extend out to seven days in order to provide a skill benchmark for 7-day forecasts (1-2 years).
- Develop software to detect TC genesis and track new storms. Develop accompanying evaluation system to assess the performance of model genesis forecasts (1-2 years).
- Develop a portable version of the Marchok, Rogers & Tuleya TC rainfall validation software. Test and implement additional (spatial) methods for evaluation of TC rainfall (1-2 years).
- Develop tools for evaluation of forecast consistency (1-2 years).
- Develop tools for evaluation of wind structure. Initially (1-2 years), this will be focused primarily on the two-dimensional surface wind structure. In the longer term (3-5 years), this will include three-dimensional wind structure down to the vortex scale.
- Develop, implement, and enhance tools for evaluation of TC ensemble forecasts (1-2 and 3-5 years).
- Develop tools for validating forecast-critical ocean parameters (3-5 years).
- Develop tools for validating model forecasts of the thermodynamic phase of the storm (e.g., tropical, subtropical, extratropical; 3-5 years).
- Develop a set of TC forecast evaluation tools that can be distributed to the community. Enhance the toolset as new tools are developed (1-2 and 3-5 years).
- Perform statistical studies to develop improved, more efficient, comprehensive approaches for testing and evaluation of hurricane forecast performance for use in the transition from research to operations (1-2 years).
- Develop tools for determining the independence of forecast track and intensity errors for the individual models as well as members of model ensembles (1-2 years).

- Develop software to include significance tests and add error bars to hurricane track and intensity forecast error statistics. Make this software available for use by the various HFIP teams and the operational modeling and forecasting centers (1-2 years).

Deliverables:

- New forecast verification tools available to the community.

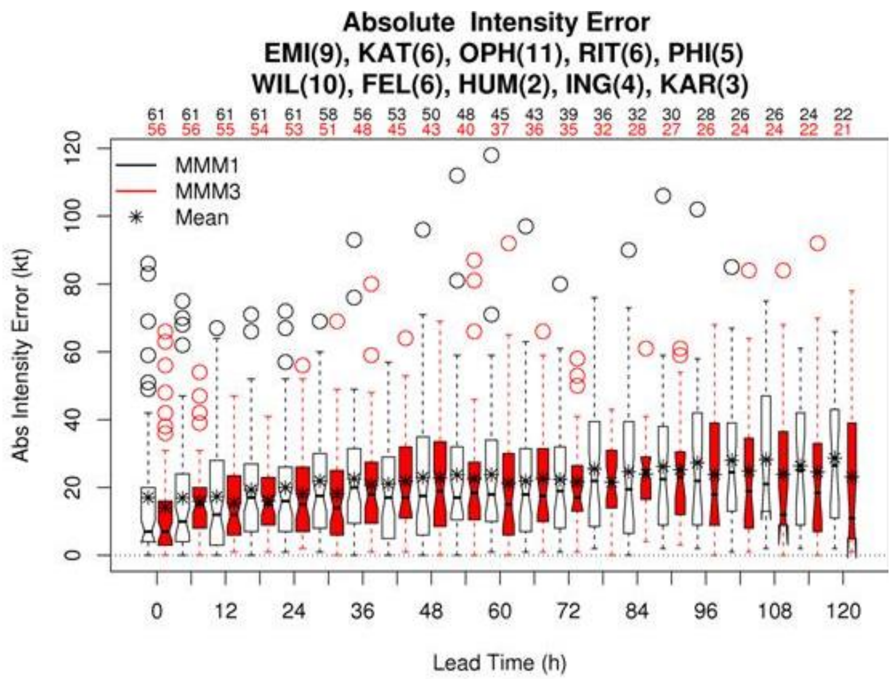


Figure 5. Example of results from the HRH test, showing distributions of intensity errors for the MMM models. See report (http://www.dtcenter.org/plots/hrh_test/HRH_Report_30Sept.pdf).

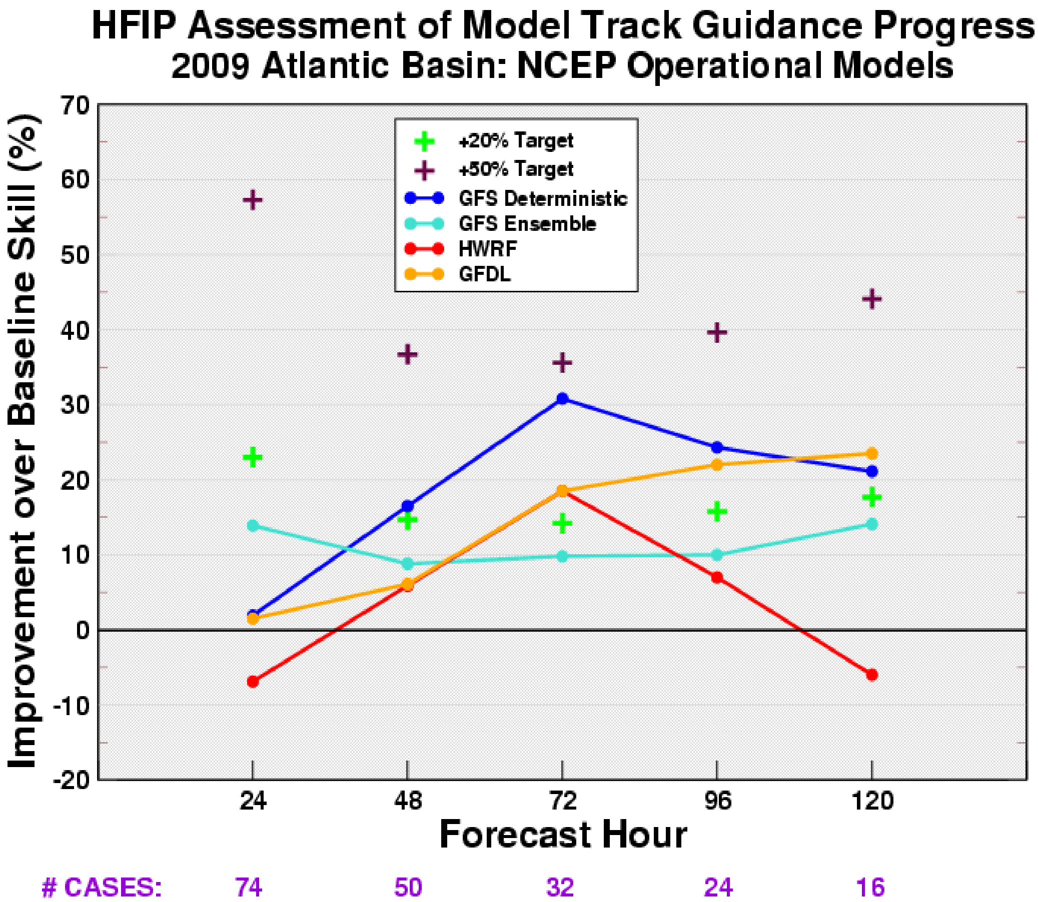


Figure 6. Comparison of operational model performance for hurricane track forecasts in 2009 to HFIP targets.

8.7 Team 6 Model Output Applications and Model Diagnostics

Introduction

The Applications Development and Diagnostics Team (ADD) will develop applications of the HFIP numerical model forecasts, including deterministic and ensemble runs. These applications include (1) advanced diagnostic techniques to better understand model performance and to provide guidance for model improvement to other HFIP teams, and (2) post-processing applications that optimize use of HFIP advances by operational forecast offices (e.g., National Hurricane Center), and can lead to greater effectiveness of end-user products. While these two activities are closely linked, it is useful to describe them separately.

Current Status

Diagnostic Work

An initial diagnostics workshop was held in May of 2009 (see http://rammb.cira.colostate.edu/research/tropical_cyclones/hfip/workshop_2009/) to help establish the scope of the diagnostics effort. It included regional and global models and both operational models such as HWRF, COAMPS-TC and GFDL and experimental models such as HWRFx, ARW and FIM that are run as part of the annual HFIP model demonstration. It also includes the analysis of single deterministic runs of these models and ensemble forecasts, as well as the atmosphere and ocean components of the coupled regional models.

The main purpose of the diagnostic effort is to identify sources of model biases and errors so that the models can be improved. The diagnostic studies range from the calculation of fairly simple large-scale parameters such as vertical wind shear and steering flow for statistical analysis, to more in-depth analysis such as energetic and potential vorticity budgets.

Another aspect of the diagnostics effort is the incorporation of observations. These include aircraft data, such as airborne radar observations for use in evaluation of the statistical properties of the model-generated convection, and satellite observations. Procedures are under development for using model forecast fields as input to radiative transfer algorithms to generate synthetic satellite observations that can be compared with the real satellite data. This will aid model evaluations in regions such as near the cloud top or below the ocean surface, where in situ data are not usually available.

An example of the use of satellite data for model evaluation is shown in Fig. 7. The top panel shows the Oceanic Heat Content (OHC) from the HyCOM ocean model, which is part of an experimental version of the coupled HWRF system. The 72-hr HyCOM forecast of OHC is from a case for Hurricane Ike. The bottom panel shows the OHC estimated from satellite altimetry and sea surface temperature data. This type of comparison will help to establish the reliability of the coupled ocean forecasts and provide guidance for improvements.

Another function of the diagnostics effort is to provide a means to collect model output from the operational and demonstration forecast systems at common locations for later analysis by the participating groups. The DTC/TCMT has taken on this role. In the first year, three tiers of data were identified. Tier 1 includes the tracks and intensity estimates from the various models in the Automated Tropical Cyclone Forecast (ATCF) system format, which can be used for model inter-comparison and basic verification studies. Tier 2 data includes subsets of model fields for basic diagnostic studies, and tier 3 includes the full model fields. The tier 3 data are too large to be housed at a common location, but specific forecasts can be made available as needed.

Applications Development Work

The applications development component of the work serves three user groups: Hurricane Specialists (forecasters) at the NHC, other HFIP teams, and "end users" comprising mainly emergency managers, the media and the public.

Forecasters can access numerical guidance products from several operational global and regional models on display systems like the NCEP Advanced Weather Interactive Processing System (N-AWIPS), AWIPS, the ATCF system and the web. Data and display options are very limited at this time, however, for viewing the information of some models (e.g., ensembles) in certain configurations (e.g., high-resolution data; cross-sections) and for observing some key features (e.g., inner core and convective-scale/mesoscale structures).

To help guide the applications development, forecasters provided the ADD team with a prioritized list of new or enhanced guidance products to improve model utility. Table 8 shows the highest priority items from the full listing. A part-time contractor hired in late 2009 has already started work on some of the forecasters' requirements in Table 8. Fig. 7 shows preliminary examples of products generated from model forecasts. Another goal of HFIP is to extend tropical cyclone forecasts from five to seven days. Work has begun to modify the ATCF system to accommodate the longer forecasts, as shown in Fig. 9. One of the more challenging aspects of application development is the utilization of ensemble forecasts. An ensemble product development workshop was held in April, 2010 (see http://www.ral.ucar.edu/jnt/tcmt/events/2010/hfip_ensemble_workshop) to provide guidance for these activities. Preliminary work has begun to modify the ATCF to display large numbers of forecasts from ensemble modeling systems. Fig. 10 shows an example of this capability for storm tracks generated from NHC's existing statistically-based wind probability model.

Focus Areas for the Next Five Years

Diagnostics

In the short term, the emphasis will be the determination of a standard set of basic large-scale diagnostics for the operational and experimental models that will be run during the next hurricane season. The use of standard procedures will allow for model inter-comparison. Preliminary versions of the synthetic satellite imagery will also be developed, including infrared (IR) and microwave channels. Development of more advanced diagnostic techniques will begin and will include the incorporation of aircraft data for comparison. Diagnostics for the ocean component of coupled models will also be developed, including incorporation of satellite-derived ocean parameters such as OHC, and in situ ocean profiles where available. The establishment of the model output distribution capabilities that were started in 2009 will be expanded. Diagnostics for a regional model ensemble will build on preliminary results from 2009. Work will also begin on embedding statistically-based intensity forecast models within global modeling systems.

Similar to the application development described below, the longer-range plans will evolve as experience is gained after each hurricane season, and through interactions with other HFIP teams. The initial diagnostic efforts described above will evolve over the next five years to include more sophisticated techniques, including methods specifically designed to understand the behavior of physical parameterizations such as cloud microphysics and the boundary layer. These studies will need to include observed quantities such as vertical velocity and hydrometeor measurements from aircraft and particle size estimates from satellite algorithms. On the storm scale, Lorenz-type energetic studies modified to include non-hydrostatic effects and angular momentum budgets will be performed to better understand model evolution. Also in the longer term, adjoint techniques will be applied to better understand model sensitivities to initial conditions and parameters used in physical parameterizations. The synthetic satellite data techniques will also be refined, with the possibility of developing more general methods for visible channels with more accurate representations of cloud scattering.

Enhanced Diagnostics and Coordination

To augment the general diagnostics plan, the DTC can provide an organizational framework to support a dedicated and ongoing diagnostics effort for continuous and effective feedback to the model developers of HWRF, COAMPS-TC and the AHW. This effort would require several full-time dedicated people investigating different aspects of model behavior. The investigation should include review of past seasons to establish model climatology and help provide feedback on potential upgrades on model performance to model developers.

In support of this effort for HWRF, the DTC is developing a parallel EMC testing environment so that proposed annual upgrades to the HWRF system can be effectively evaluated on model performance. This represents preseason preliminary diagnostics requiring close coordination with HWRF model developers. The constancy of this effort is particularly time critical to assess impending upgrades as the operational HWRF evolves each year with upgrades to the system prior to the start of hurricane season. For both operational and research models, it is also imperative to assess ongoing model

improvements and assess potential new enhancements that would impact model performance. Over the course of several years, it is likely that new benchmarks for performance will have to re-established with the operational HWRF system, as well as the research models at NRL and MMM. As the COAMPS-TC nears transition to operations, careful benchmarking of model performance will be imperative.
This effort will require substantial coordination between the different levels of diagnostics. The enhanced effort will depend on the delivery of time critical studies of preliminary diagnostics as described above in order to target specific case studies. Also, model climatology will be altered with various system upgrades, and will need to be addressed in benchmarking efforts. The intent of this effort is to provide feedback to support time critical model developments especially as model complexity increases. Specific scientists will need to be identified to work on these various levels. This is critical to properly manage this effort. This expertise and described capability is required to deliver useful and timely diagnostic information.

Application Development

In the short term, the emphasis of the application development will be on the first few items from Table 8. Work will also begin on applications recommended at the ensemble product development workshop. These include new displays that combine track and intensity information from ensembles, and that couple dynamical ensemble model output with statistically based products. In the longer term, the applications development will be an iterative process that will depend on experience gained with experimental applications and display, the evolution of the operational display capabilities at NHC (for example, the transition from N-AWIPS to AWIPS-II), improvements in the operational and HFIP demonstration modeling systems, and interactions with other HFIP teams. Also in the longer term, NHC's probabilistic products, currently using statistical methods for estimating uncertainty, will be reviewed for potential replacement by similar products based on ensembles. Results from a separate HFIP effort intended to identify new or enhanced NHC products for end users will be folded into ADD in future years.

Milestones and Deliverables

Listed below are milestones and deliverables, along with estimated completion dates, through 2014 for the diagnostic and application development efforts. Similar to the tropical cyclone forecasts themselves, the longer-range items have greater uncertainty.

Diagnostics

- Aug 2010 - First version of synthetic satellite imagery from tropical cyclone models
- Aug 2010 – Establishment of first generation HFIP data service
- Sep 2010 – Common large-scale diagnostic dataset from NCEP and Navy operational models (HWRF, COAMPS-TC, GFDL, GFS) and selected set of HFIP demo models

- Sep 2010 – Initial capability to use aircraft data in diagnostic studies
- Sep 2010 – Initial capability to embed statistical intensity models in the FIM global model forecasts
- 2011 – First capability for routine ocean model diagnostic capabilities
- 2011 – Evaluation of large-scale diagnostic study from 2010 season, provision of feedback to modeling groups, adjustment of diagnostics as needed
- 2011 – Upgraded HFIP model/data service
- 2012 – Generalization of diagnostics with focus on physical parameterizations
- 2012 – Lorenz-type energetic analysis
- 2013 – Angular momentum studies
- 2013 – Refinement of synthetic satellite imagery, better treatment of visible channels
- 2014 - Adjoint-based sensitivity studies
- 2014 – Mature system for utilization of all available in situ data for diagnostics, including in situ, aircraft, satellite and oceanic measurements

Application Development

- Aug 2010 – First version of at least two forecaster applications for NHC
- Sept 2010 – Prototype version of web-based ATCF to enhance HFIP-NHC interaction
- 2011 – First ensemble product for NHC forecasters
- 2011 – Mutual product development with other HFIP teams
- 2012 - New or prototype products for each of the 14 forecaster requirements listed currently
- 2012 – First test of replacing statistical input with ensemble input to NHC probabilistic products several operational ensemble model products
- 2013 – Completion or re-evaluation of the set of 14 forecaster products in Table 8
- 2013 – Development of new set of forecaster priorities based on experience from previous hurricane seasons and new HFIP developments
- 2014 – Adaptation of more sophisticated diagnostic applications to real time environment
- 2014 – 3 to 5 new or enhanced NHC public products.

Table 8. NHC Product Development Priorities as of Fall 2009.

- Shear analysis for user-specified layers
- User-selectable (e.g., point and click) vertical cross sections of any field or combination of fields
- Genesis probabilities derived from global model ensembles and possibly high-resolution pre-TC models (capability to record probabilistic information in ATCF)
- Magnitude and location of maximum 1-minute sustained surface (10 m) wind speed for each minute of integration (for operations and diagnostics); full surface wind field at hour intervals
- Probability distribution of intensity change (including rapid intensification)
- Guidance on the best locations for additional observations, e.g., supplemental soundings, G-IV dropsondes, C-130 data
- Ensemble-based probabilistic guidance for track, intensity, wind structure, storm surge, rainfall, as well as support for existing products.
- Structural analyses using the mass and motion forecast fields to help diagnose tropical, subtropical and extratropical stages (e.g., phase space)
- Capability to make model comparisons (contemporary and sequential runs of any combination of models)
- Global model tropical cyclone formation index/indicator and verification methods
- Model originated simulated radar/microwave imagery
- Center locations at multiple vertical levels and depiction of vertical coherence
- Ensemble mean track (high priority; a near-default output)
- Surface map of accumulated forecast rainfall

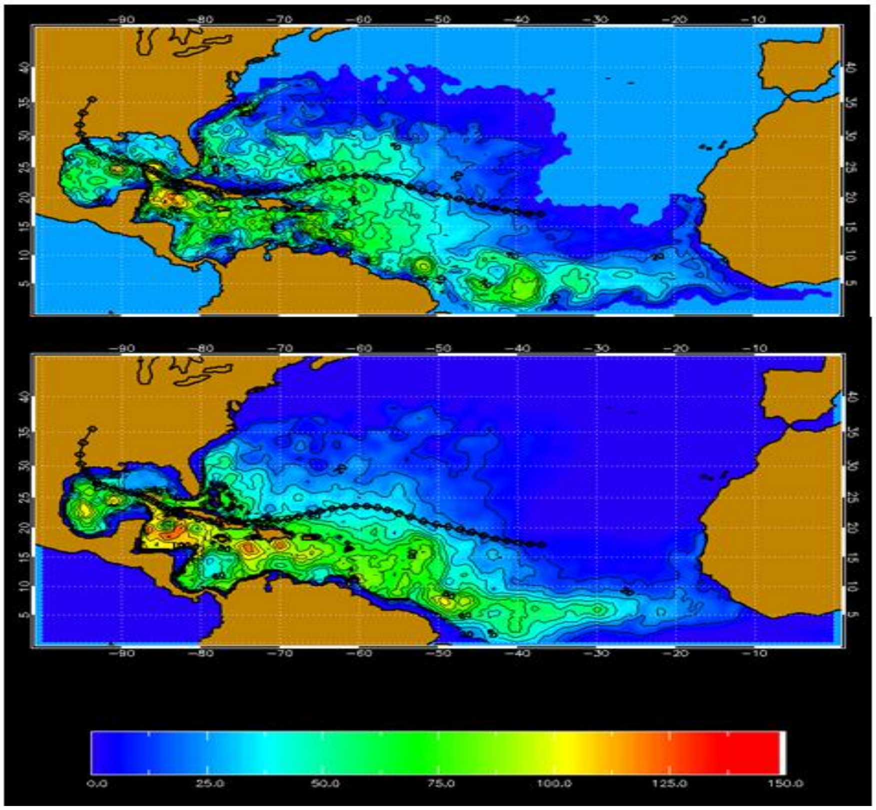
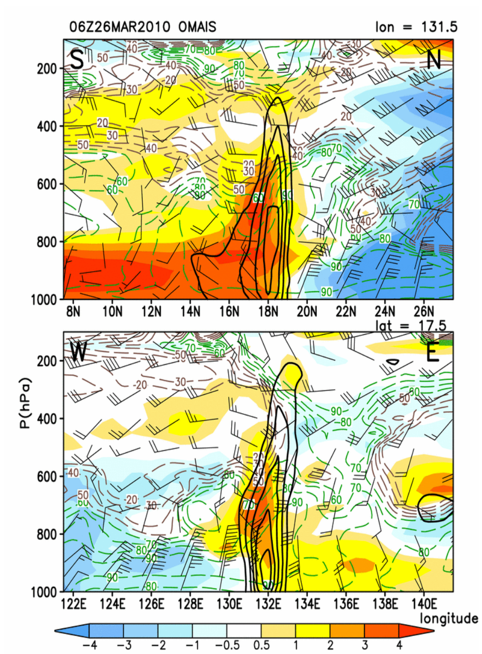


Figure 7. Oceanic Heat Content (OHC, kJ/cm^2) from a 72 h forecast of the experimental HyCOM-HWRF modeling system for Hurricane Ike initialized at 00 UTC on 8 September 2008 (upper panel) and the corresponding OHC fields from a satellite retrieval (lower panel). The full track of Hurricane Ike is also shown. Ike was just east of Cuba at the model initialization time.



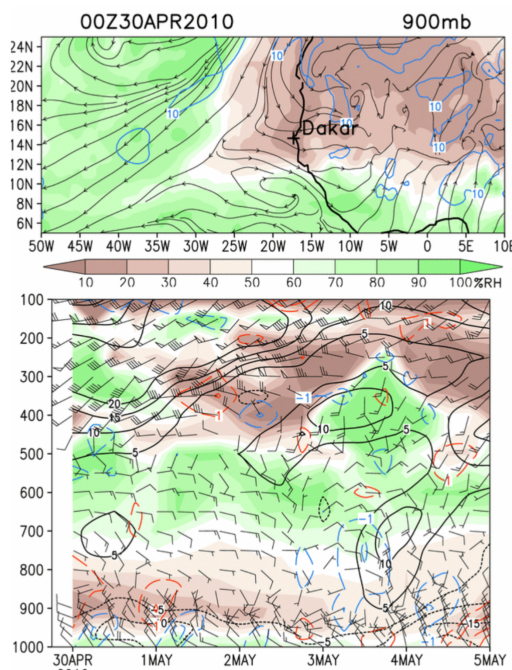


Figure 8. Examples of prototype forecast products generated from model output. The left panel shows a vertical cross section through tropical cyclone Omais and the right panel shows a wind and moisture display from model-simulated soundings (included a Hovmoller format for Dakar).

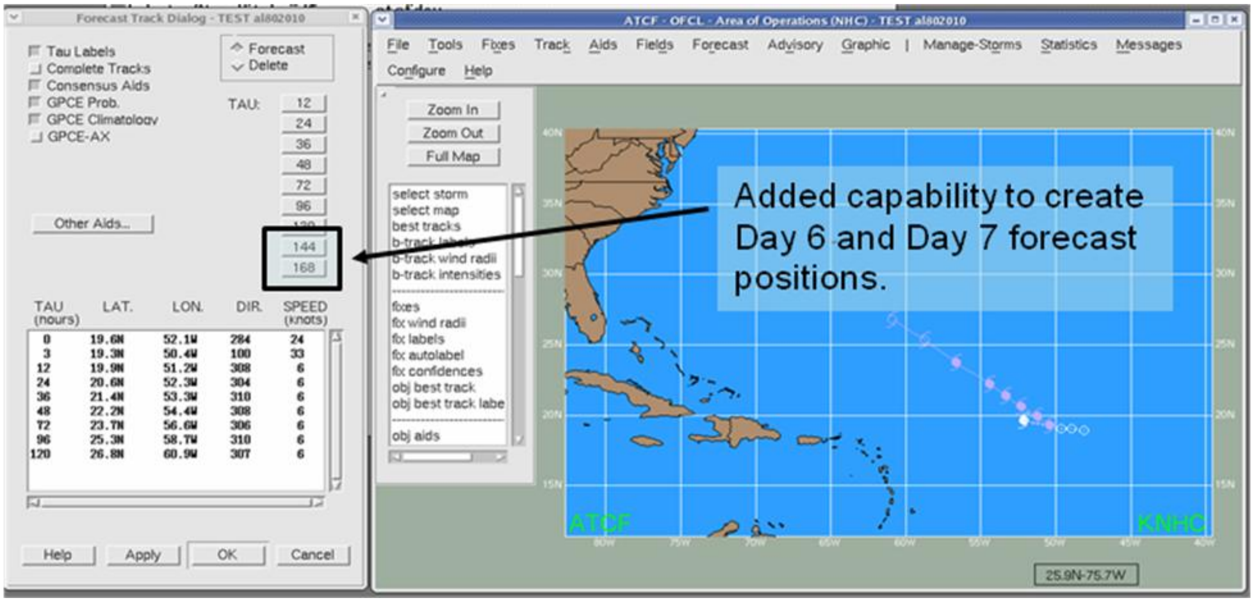


Figure 9. Capability for hurricane forecasters to generate 6- and 7-day forecasts under development as part of combined HFIP and Joint Hurricane Testbed (JHT) effort.

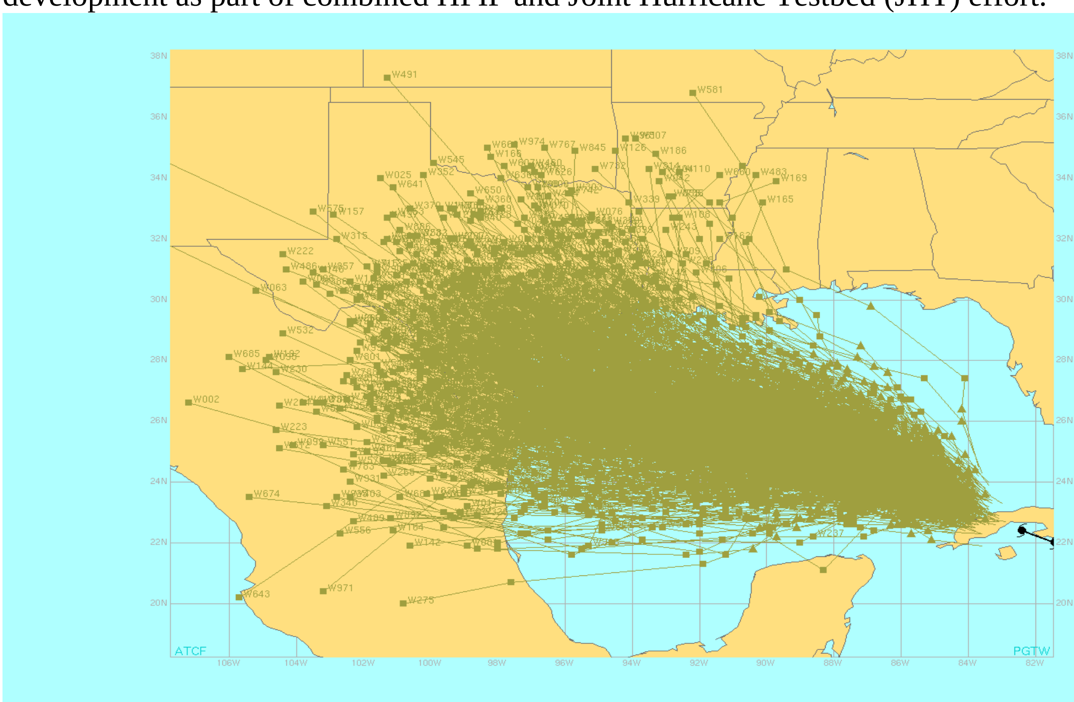


Figure 10. New capability for hurricane forecasters to display tracks of one thousand or more ensemble members as part of combined HFIP and JHT effort.

8.8 Team 7 Obtaining and Using Observations for Hurricane Forecasting

Current State of the Science

Data are currently gathered in the tropical cyclone vortex and its environment with land- and ocean-based platforms, airborne platforms, and satellites. These data are the basis for all tropical cyclone analyses and forecasts by operational centers. They are also used by the research community for data assimilation and physics studies, and to improve understanding and analysis of the ocean and for forecast verification. Some deficiencies in the current platforms have been identified:

- Automated Surface Observing System (ASOS) stations provide much of the ground-based observations in and near the United States. These stations frequently lose power and stop transmitting observations during tropical cyclone events.
- Mesonets and other portable observing platforms are frequently deployed to impacted regions during landfall events. However, many do not have the ability to transmit data in real time.
- Many nations in the region have operational ground-based Doppler radar data. The raw data are unavailable to operations and researchers in real time, though some products are generally available.
- Current position and intensity observations and analyses are made on a regular basis. The probable accuracy of these observations are not reported, but are necessary for the observations to be assimilated into numerical models.
- Sea spray observations are necessary for physics and ocean interaction studies. A W-band radar would provide these observations once installed on aircraft.
- Sea spray and surface flux observations are necessary for physics and ocean interaction studies. Instruments for these observations can be deployed on small aircraft, such as a Twin Otter, for low-wind situations, or large aircraft, such as a P-3, in high-wind situations.
- Surface stress and latent and sensible heat fluxes and momentum fluxes observations are scarce. Additional observations could be made by Unmanned Aerial Vehicles (UAVs) or by towed vehicles.
- High time-resolution wind speed, temperature, and moisture profiles are necessary for understanding of turbulent fluxes. These can be obtained by UAVs. The wind speed measurements can be taken by Doppler wind lidar.
- Cloud particle size distributions and number concentrations, and aerosol size distributions and chemical properties are necessary for understanding the cloud physics of tropical cyclones. Some measurements are available, but more are needed. Microphysics probes and the W-band radar would add to these observations.

Goals for Improvement to Hurricane Guidance:

Much of the improvement to numerical guidance can be accomplished by improving the data assimilation to produce improved analyses, by improving the physics of the models themselves, and by improving the verification techniques. The observation team is committed to improving data availability, filling data deficiencies, and improving instrumentation to provide data needed for operations, data assimilation, air-sea interaction, physics and verification of tropical cyclone models.

Milestones and Deliverables:

The observations team is committed to improving instrumentation and communications to provide the data that other teams need to accomplish their goals. This will be in conjunction with the NOAA Hurricane Field Program for airborne instrumentation, and in collaboration with other bodies for ground- and ocean-based observing systems and satellites.

8.9 Team 8 Ocean/Wave Coupling

Introduction

Because the ocean is the source of the thermal energy required to sustain hurricanes, it is critically important for coupled forecast models to correctly reproduce the thermal flux from ocean to atmosphere. Wind waves on the ocean surface provide major challenges to modeling the surface boundary layers of the atmosphere and the ocean along with the exchanges between them. Accurate modeling of air-sea exchanges requires dynamic modeling of the atmosphere, ocean, and wind waves along with the relevant dynamic coupling among these subsystems. In this, the need for accurate ocean initialization has been shown to play a critical role. Recent studies have shown that hurricane intensity prediction is very sensitive to stress and flux parameterizations that explicitly take into account wave induced stresses and effects of sea spray. Recent work at URI indicates that effects of wave-current interactions on surface wave dramatically impact stress balances and air-sea fluxes in all quadrants of a hurricane. Adequate modeling of effects of sea spray on surface fluxes requires explicit estimates of wave parameters, including wave breaking statistics and is thus most beneficial in a three-way coupled atmosphere-wave-ocean system.

The goal of the Coupled Ocean/Wave Modeling Team is to improve hurricane intensity forecasting by realistically and explicitly modeling interactions between the ocean and the atmosphere. This will result in state-of-the-art coupled systems that are uniquely positioned to address such coupling issues not only in hurricanes, but also in general atmospheric conditions for improving numerical weather forecasts. Assessing the capability and potential of coupled forecast systems will require continuous interaction between this team and others, particularly the observations team and both the global and regional modeling teams. Observations are critical for evaluating and improving the ocean, atmosphere, and wave models and the coupling among them, Modelers should have real-time input to observing strategy and quality-controlled observations should be made available to modelers as quickly as possible.

Focus Areas of Development

The key areas of development are:

- Develop new coupled forecast models for operational implementation
    - Continue evaluation of the existing HYCOM-HWRF coupled forecast model
    - Port the existing coupled HWRF to the East Pacific region
    - Develop the new HYCOM-HWRF-WWIII coupled forecast model and commence testing during 2011
    - Continue the development and testing of the COAMPS-TC coupled forecast model
- Evaluate and improve air-sea flux parameterizations
- Evaluate and improve ocean model performance in response to hurricane forcing

- Improve ocean model initialization for coupled hurricane forecasting

Accomplishments to Date

The coupled HWRF-HYCOM system was tested in parallel during real-time operations at NCEP during the 2009 Atlantic hurricane season. For the pre-op testing during 2010, key upgrades were included, specifically improved physics and resolution in the GFS model within which HWRF-HYCOM is nested, and improved stress representation in HWRF. The HWRF-HYCOM has been accepted for 2011 baseline evaluation. Additional progress at NCEP involves improvements to the RTOFS-Atlantic Ocean model within which HYCOM is nested. NCEP will adopt the existing 0.08° global HYCOM model from the Naval Research Laboratory to replace the existing RTOFS-Atlantic system during 2011. Transition to a global model will permit porting HWRF-HYCOM to the East Pacific region with tests expected to begin during late 2011. Development of the new HWRF-HYCOM-WWIII coupled forecast model (Figure 11) continues at NCEP. The framework for this three-component model already exists in the GFDL model and tests of this model will begin during 2011. This model will be an important testbed for the ongoing improvements in ocean model performance and air-sea flux parameterizations being conducted by our team.

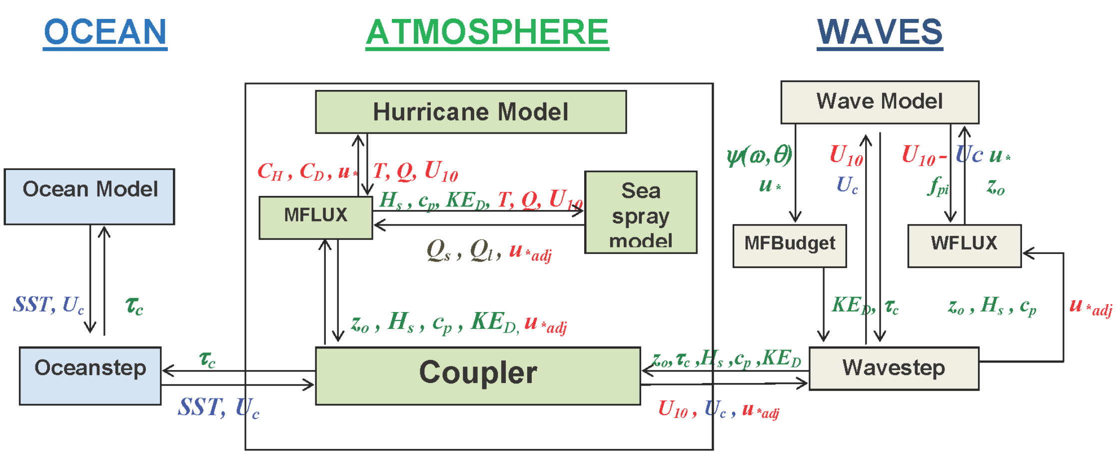


Figure 11. Schematic diagram of the HYCOM-HWRF-WWIII model developed through a collaboration between NOAA/EMC and URI that will be tested during 2011.

Two-way coupling with the NCOM ocean model has been implemented in the COAMPS-TC forecast model. Other improvements to this model include upgrading the ocean data assimilation system to 3DVAR NCODA, improved storm tracker, precipitation output on the moving nests, and total liquid water output. Tests have been performed on 2009 storms. An example of the impact of coupling on forecasts of Hurricane Bill (2009) is presented in Figure 12. There is a small improvement in track error and a huge improvement in intensity effort, particularly after 24 hours. Although this particular case is clearly not representative of the average impact that ocean coupling will have on hurricane intensity forecasts, it illustrates that the impact may be large in at least a small percentage of cases. Further research into this impact and its dependence on storm parameters such as strength and propagation speed is important and will be conducted by our team.

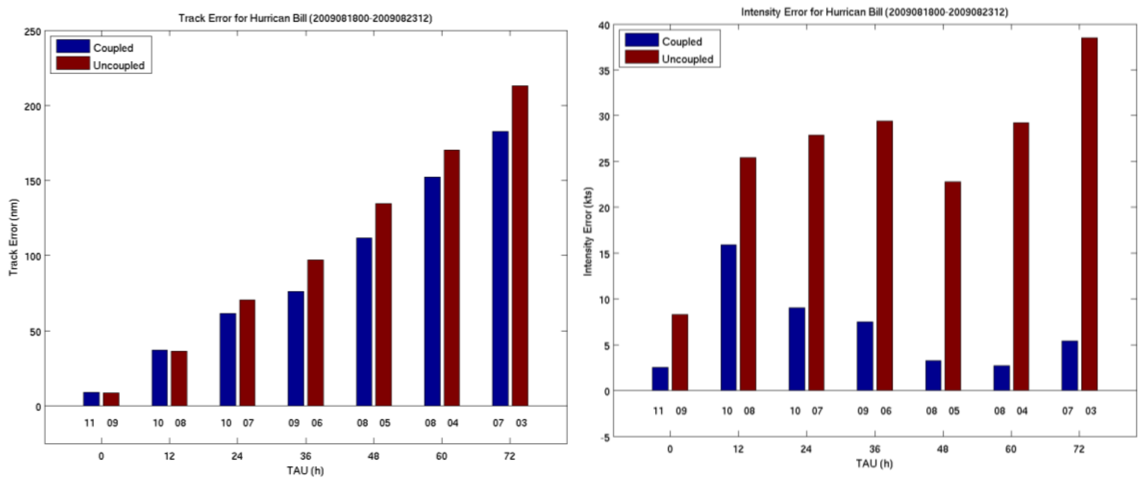


Figure 12. Hurricane Bill (2009), track and intensity forecast to 72hr, produced by COAMPS-TC produced by the uncoupled (red) and coupled (blue) versions of the model.

Key progress in improving air-sea interaction parameters has involved ongoing development of the URI Air-Sea Interface Model (ASIM) and improvement in sea-spray parameterizations conducted by NOAA/ESRL and URI. The ASIM model contains explicit wind-wave-current interaction effects and is fully implemented in GFDL model. It will be included as part of the HWRF-HYCOM-WWIII model to be tested next year. The sea-spray parameterization research has produced the following results: As the wind speed increases, the droplet size increases and the overall wind speed in the surface layer above the level of sea-spray generation increases. This indicates that the increase of droplet size due to the increase of wind speed enhances the vertical mixing. This is consistent with observations and results from previous numerical model simulations of the microphysical characteristics of sea spray in the atmospheric boundary layer. These sea spray effects act to reduce the friction velocity and increase the overall enthalpy flux in the storm inner core.

Efforts to improve ocean model performance under hurricane forcing are ongoing at several institutions:

- AOML and RSMAS (uncoupled HYCOM)
- AOML (HYCOM-HWRFx)
- NCEP/EMC (HWRF with POM & HYCOM)
- NRL-Monterey (COAMPS-TC with NCOM ocean)
- URI (POM & HYCOM)

The use of multiple ocean models in the evaluation efforts by our team is a positive situation given that no existing ocean model is an optimal choice for all situations. Sensitivity of results to ocean model choice is an important consideration. In this spirit, URI (R. Yablonsky) led a collaborative joint evaluation of POM and HYCOM revealing that although each model generally performs well, they both have strengths and weaknesses and neither model was an overall clear-cut “winner” in all situations. This model comparison was idealized in many respects, with models forced by idealized wind stress only and the forecast SST cooling compared to cooling predicted by the buoy-based climatological SHIPS statistical algorithm of Cione and Uhlhorn. This idealized comparison provides an important baseline for performing ongoing model evaluations and comparisons as continued improvements are made to ocean models.

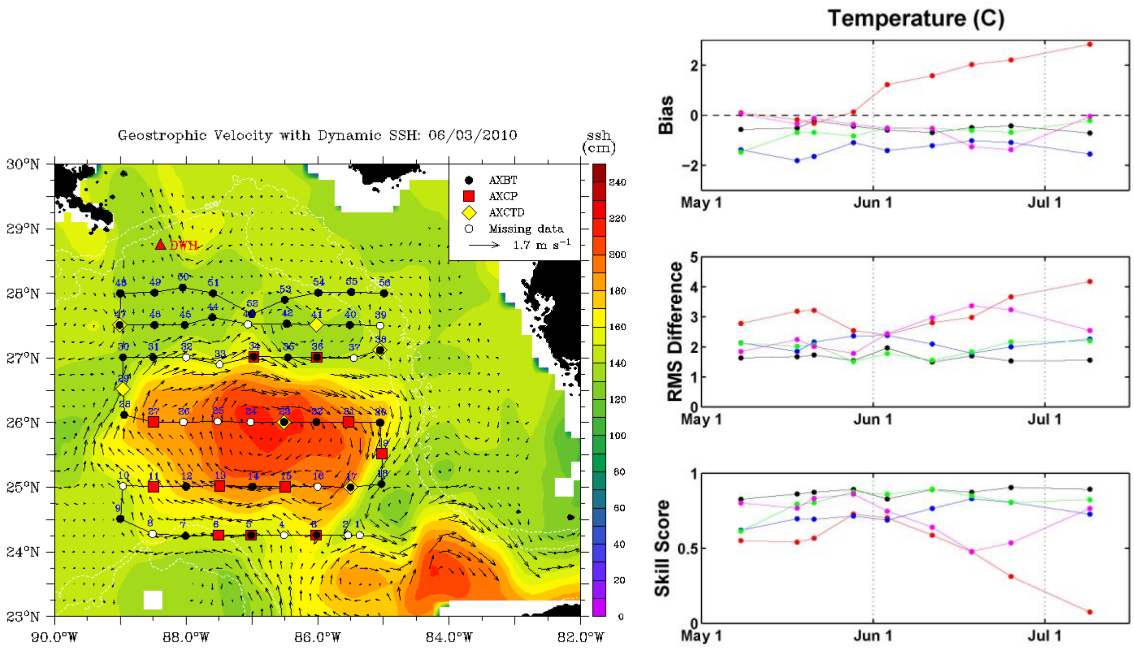


Figure 13. Upper-ocean profiles sampled by a NOAA P3 aircraft on 3 June 2010 in response to the DeepWater Horizon oil spill (left). Error evaluation of temperature profiles over the upper 360 m between five ocean models and P3 profiles for the nine P3 flights conducted during 2010 (right). Models include GOM HYCOM (black), global HYCOM (green), IASNFS (blue), RTOFS (red), and NOAA NGOM (magenta). The P3 observations provide an unprecedented opportunity to evaluate existing data assimilative ocean models for initializing the ocean component of hurricane forecast models.

AOML/RSMAS ocean model evaluation efforts have determined that SST forecast accuracy under hurricane forcing is very sensitive to ocean model initialization. Improvement of ocean model initialization is therefore an important goal of our team. The Deepwater Horizon oil spill motivated an intensive observational effort in the Gulf of Mexico that will provide an unprecedented dataset to evaluate data-assimilative ocean analysis products for use in ocean model initialization. These observations include NOAA P3 AXBT, AXCTD, and AXCP profiles designed for synoptic ocean sampling (Figure 13). Nine flights were conducted between 8 May and 9 July 2010 and a final flight was conducted on 9 September. Error analysis between existing operational data assimilative ocean analysis products and the P3 profiles (Figure 13) demonstrate that these extensive observations will enable a more detailed joint evaluation of these products that heretofore possible. This evaluation effort will be continued and will include other observations such as special oil spill cruises, surface drifters, and Minerals

Management Service moored measurements. Research on improved ocean data assimilation techniques and observing system design studies that can potentially improve ocean model initialization is ongoing at AOML.

Milestones and Deliverables

Year 2 (2010) activities

- Operational implementation of global 1/12° global HYCOM at NCEP.
- Develop nesting capabilities in global model for Pacific coupled HWRF-HYCOM system.
- Adding ocean data assimilation to operational HWRF-HYCOM model runs.
- Fine tuning of HWRF-HYCOM model by optimizing of present coupling approaches; focus on both overall model performance for hurricane track and intensity, and on performance with respect to ocean response.
- Further improvement of ocean model performance and ocean model initialization
- Further development of stress and sea spray parameterizations.
- Development of coupling methods in experimental HWRF-HYCOM-WW3 model.
- Quantify impact of ocean coupling in forecast models
- Incorporate WW3 and SWAN into COAMPS-TC to enable the three-way coupling capability.
- Test and evaluate several wind-wave-current coupling parameterizations for historical cases of various coupled systems.

Year 3 (2011) activities

- Continuation of year 2 activities.
- Systematic testing on large number of historic cases of three-way coupled system in EMC’s operational environment in preparation of a possible 2012 operational implementation (possibly to be accelerated with appropriate computer resources).
- Increased focus on landfall issues (shallow water ocean and wave issues).
- Test the impact of NCODA ocean data assimilation for TC structure and intensity forecast.
- Develop and evaluate wave data assimilation in coupled COAMPS-TC.
- Test and evaluate the impact of targeted ocean observations.

Years 4-7

- Continue incremental improvements to the coupled HWRF system at NCEP as outlined above.
- Coupling focus to shift to coastal issues for land falling hurricanes.
- Implement HYCOM as an different ocean circulation model option into the three-way coupled COAMPS-TC
- Test and evaluate the sensitivity of using different ocean circulation and wave models to TC structure and intensity forecasts for historical cases.
- Possible inclusion of surge and hydraulogical models to coupled system at NCEP and NRL.

9 Appendix B: List of Acronyms

9.1 Organization Acronyms

AOC—Aircraft Operations Center, NOAA
AOML—Atlantic Oceanographic and Meteorological Laboratory, OAR/NOAA
CPHC-Central Pacific Hurricane Center
DTC—Developmental Testbed Center
ECMWF—European Center for Medium Range Weather Forecasting
EMC—Environmental Modeling Center, NCEP/NOAA
ESRL—Earth Sciences Research Laboratory, OAR/NOAA
FSU—Florida State University
GFDL—Geophysical Fluid Dynamics Laboratory, OAR/NOAA
HFIP—Hurricane Forecast Improvement Program
HRD-Hurricane Research Division
JTWC-Joint Typhoon Warning Center
MMM—Mesoscale Microscale Meteorology Division NCAR
NCAR—National Center for Atmospheric Research
NCEP—National Centers for Environmental Modeling, NWS/NOAA
NESDIS—National Environmental Satellite Data Information Service, NOAA
NHC—National Hurricane Center, NWS/NOAA
NOAA—National Oceanic and Atmospheric Administration
NOPP-- National Oceanographic Partnership Program
NRL—Naval Research Laboratory, Monterey
NWS—National Weather Service, NOAA
OAR—Ocean and Atmospheric Research, NOAA
ODU—Old Dominion University
ORNL-Oak Ridge National Laboratory
OST—Office of Science and Technology, NWS/NOAA
OU-University of Oklahoma
RAL—Research Applications Laboratory, NCAR
RSMAS—Rosenstiel School of Marine and Atmospheric Science, University of Miami
URI—University of Rhode Island

9.2 NHC Model Acronyms

BASE—HFIP Baseline for track and intensity
COAMPS-TC - Coupled Ocean Atmosphere Mesoscale Prediction System – Tropical Cyclone
DSHP—Decay Statistical Hurricane Intensity Prediction Scheme
EXMI—Previous cycle of ECMWF, adjusted
GFSI—Previous cycle of GFS, adjusted
GFDI— Previous cycle of GFDL, adjusted
GFNI— Previous cycle of GFDN, adjusted
GHMI— Previous cycle of GFDL, adjusted w/variable offset
HWFI— Previous cycle of HWRF, adjusted
ICON—Intensity consensus

LGEM—Logistic growth equation model
NGPI— Previous cycle of NGPS, adjusted
OFCL—Official NHC Forecast
PRCL—PeRsistence skill and CLimatology baseline errors
TVCN—Track consensus, variable members
UKMI— Previous cycle of UKM, adjusted

9.3 Other Acronyms

3DVAR—3 Dimensional VARiational data assimilation
4DVAR—3 Dimensional VARiational data assimilation
AHW-Advanced Hurricane Research WRF
ARW—Advanced Research WRF core of WRF
ATCF-Automated Tropical Cyclone Forecast system
CSM-Cubed-Sphere Model
COAMPS-TC-Coupled Ocean Atmosphere Mesoscale Prediction System-Tropical Cyclone
DA—Data Assimilation
EnKF—Ensemble Kalman Filter data assimilation
EnsDA-Ensemble Data Assimilation
FIM—Flow following Icosahedral Model
GFDL Model—Operational GFDL forecast model
GFS—Global Forecast System
GSI—Grid point Statistical Interpolation data assimilation
HyCOM—Hybrid Coordinate Ocean Model
HVEDAS—Hybrid Variational-Ensemble Data Assimilation System
HWRF—Hurricane WRF
HWRF-HRD DA-HWRF-HRD Variational Data Assimilation System
N-AWIPS-NCEP Advanced Weather Interactive Processing System
NAVDAS—NAVy Data Assimilation System
NMM—Non-Hydrostatic Mesoscale Model core of WRF
NOAH LSM-NCEP, Oregon State University, Air Force, Office of Hydrologic Development Land-Surface Model
PBL-Planetary Boundary Layer
POM—Princeton Ocean Model
WRF—Weather Research and Forecasting model