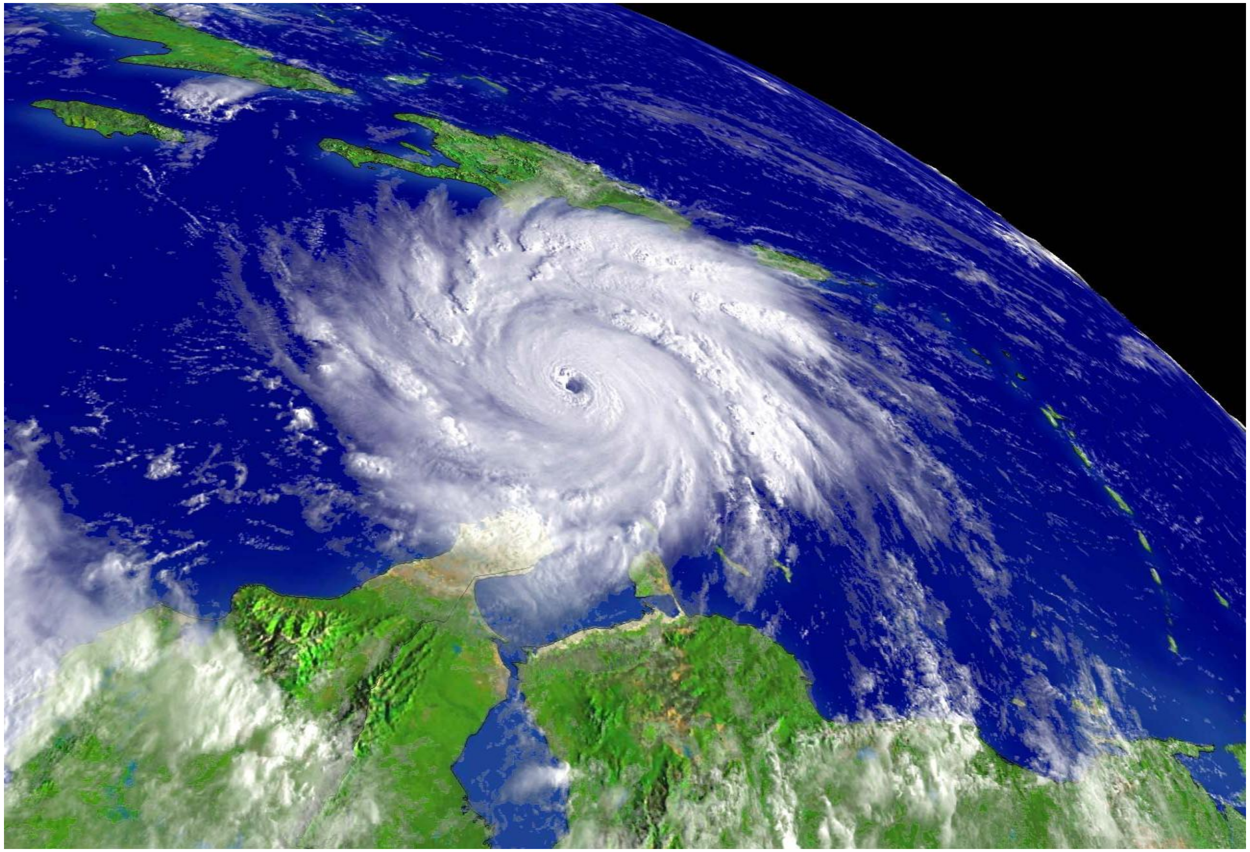
Challenges Facing Numerical Prediction of Hurricanes

Morris A. Bender (GFDL/NOAA)



2011 WRF Tutorial, Boulder, Co

Tuesday, April 26th, 2011

Outline

1.) Overview of Numerical Modeling of Hurricanes

2.) Overview of Present Forecast Skill

3.) Power of the Consensus Technique

4.) GFDL Forecast System: Research to Operations

5.) Where we go from here: 2011 and Beyond

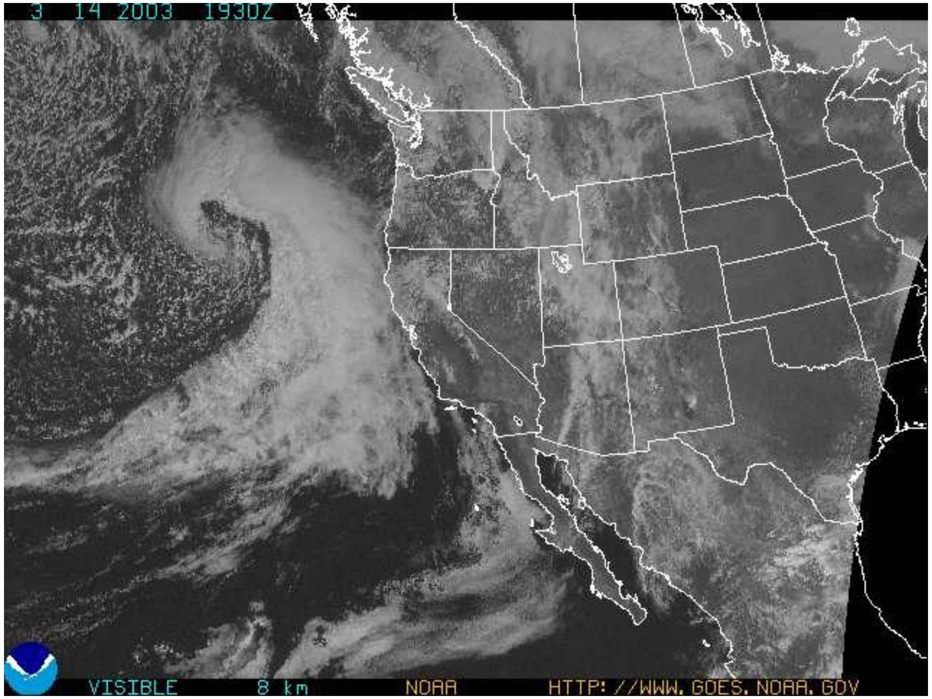
6.) Summary and Concluding Thoughts

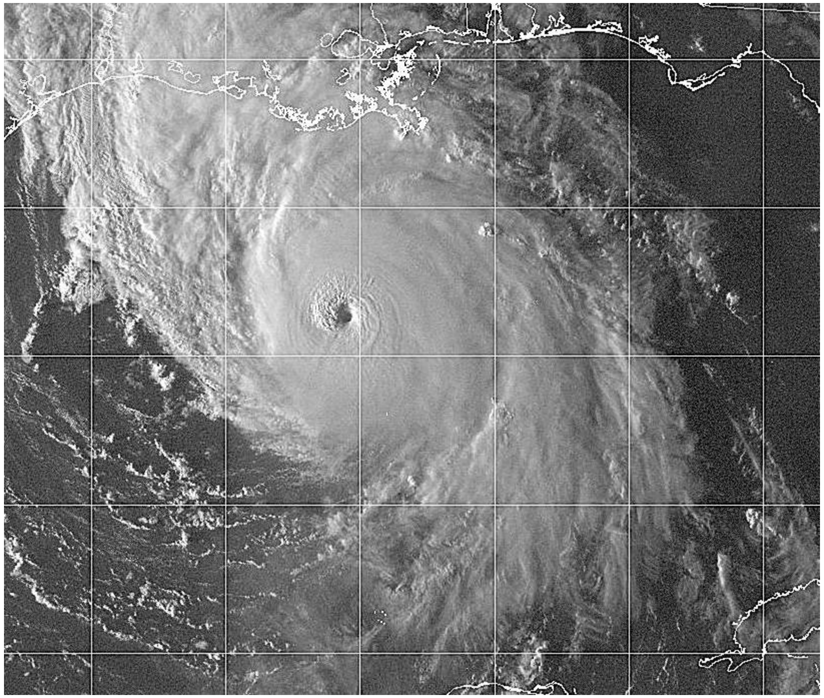
Tropical cyclone model vs. Extra-tropical model

- Specifically for tropical cyclone
- Focus on one system
- Locally forced (latent heating)
- Limited data often available in tropics over oceans
- Spans scales from cumulus through synoptic

- Variety of weather systems (fronts, cyclones, etc)
- Linear instability (baroclinic, barotropic)
- Relevant data more available
- Cumulus scale less important

Extra-tropical vs. tropical





Research vs. Operational

- instability mechanism, ideal development (e.g. Ooyama,1969)
- Steering/interaction (Kasahara,1959,Fiorino&Elsberry,1989)
- Identified importance of surface energy source
- Gradual transition from modeling essential axi-symmetric structure to more complete 3-D spiral bands, asymmetric outflow, eye (Anthes,Kurihara,Jones,1970's)

- Barotropic (track)
  - Sanbar (Sanders,Burpee ,1968)
  - Vicbar (DeMaria et.al., 1992)
- Trajectory (track)
  - Bamm, Bamd (1980s)

Other storm phenomena not modeled (e.g. intensification, decay?)

Uncertain mechanisms, too computationally intensive

- Early 3-D
  - MFM (Hovermale)
  - QLM (Mathur)

Application of Hurricane models to real-time forecasting: Track and intensity prediction. How well are we presently doing ?

Overview of Current Operational Hurricane Modeling. Accessing of Present Forecast Skill

What types of models predict TC motion?

Climatological / Statistical: CLIPER (CLImatology and PERsistence model). Used as a benchmark of skill for more complex models.

Advection models and barotropic dynamical models: BAM (Beta and Advection Model), LBAR. These assume either no storm structure (BAM) or a simplified storm structure (LBAR) and assume simplified, mean steering flows.

Baroclinic dynamical models: Global models (NCEP/GFS, UKMET, Navy/NOGAPS, ECMWF); Regional mesoscale models (GFDL, HWRF). Provide for the explicit, 3-D evolution of the atmospheric flow and structure of the storm.

Operational Dynamical Computer Models Used For Hurricane Track and Intensity Forecasting

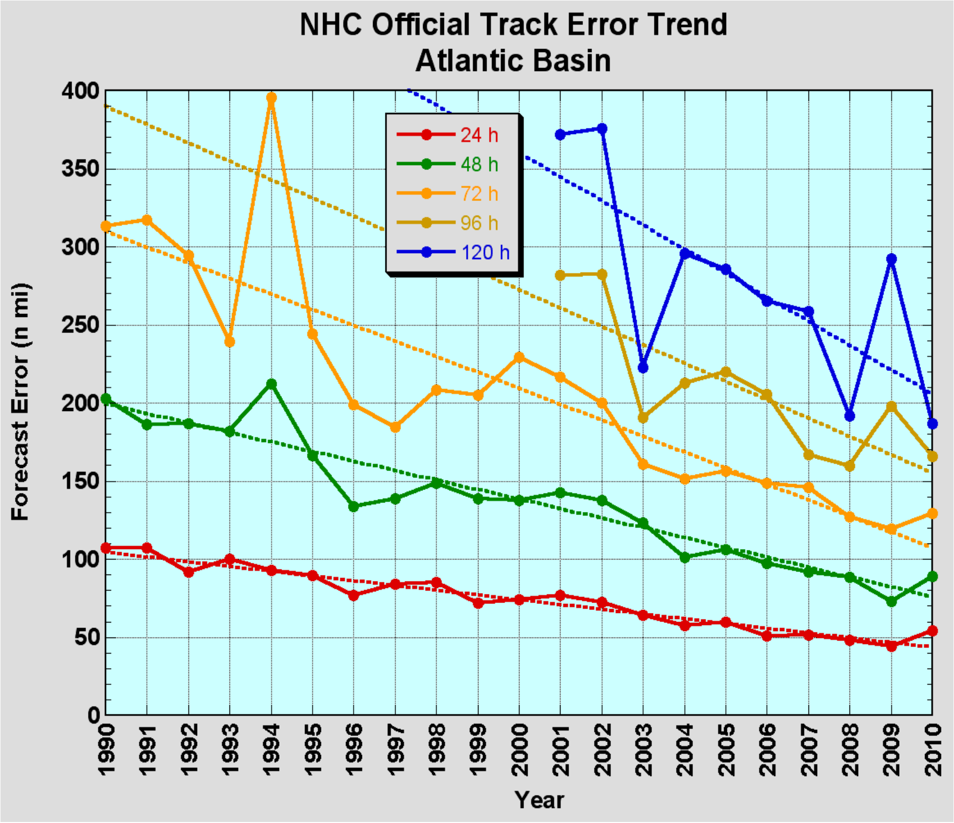
Each Provides a Forecast out to at least 120 hours

- GFS (Global model run by US Nat'l Weather Service)
- GFDL (Limited Area Movable Mesh Model that uses the GFS Model for its Boundary Condition, 1995)
- Hurricane-WRF (HWRF: Limited Area Movable Mesh Non-hydrostatic Model that uses the GFS Model for its Boundary Condition, 2006)
- NOGAPS (Global model run by the US Navy)
- GFDN (Limited Area Movable Mesh Model that uses the NOGPAS Model for its Boundary Condition, 1996)
- UKMET (Global model run by British Met Office)
- ECMWF (Global model run by European Center for Medium Range Weather Forecasting)

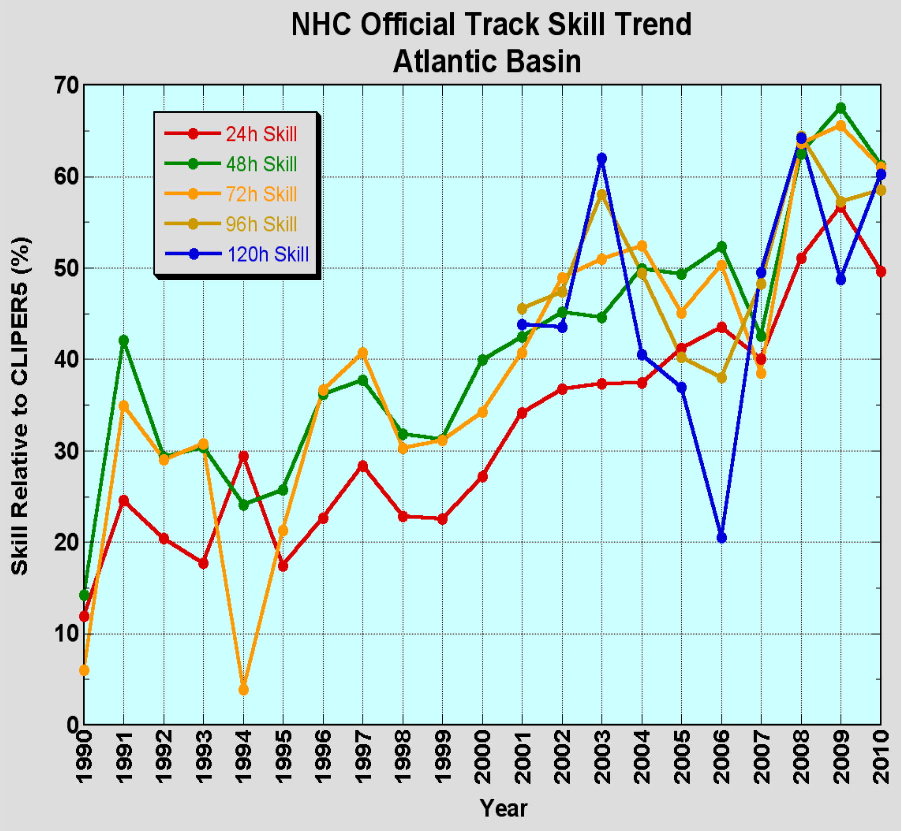
Atlantic Track Error Trends

Remarkable progress achived during past 15 years

Atlantic Mean Track Error



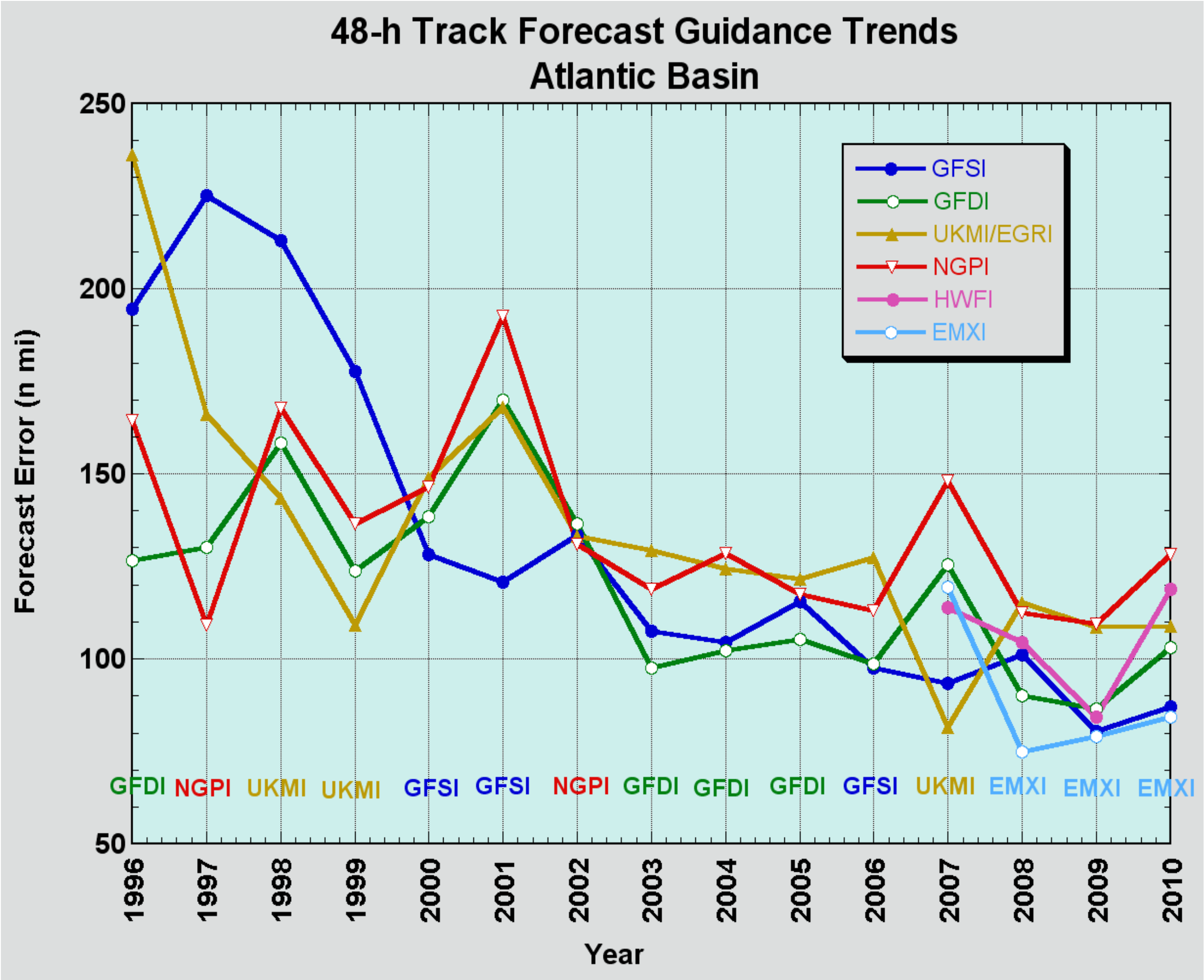
Atlantic Track Skill



Since 1990, track errors have decreased by about 60%. Current five-day error is as large as the 3-day error was just 10 years ago.

Improved track prediction attributed to much improved dynamic track guidance

Atlantic Track Model Skill Trends

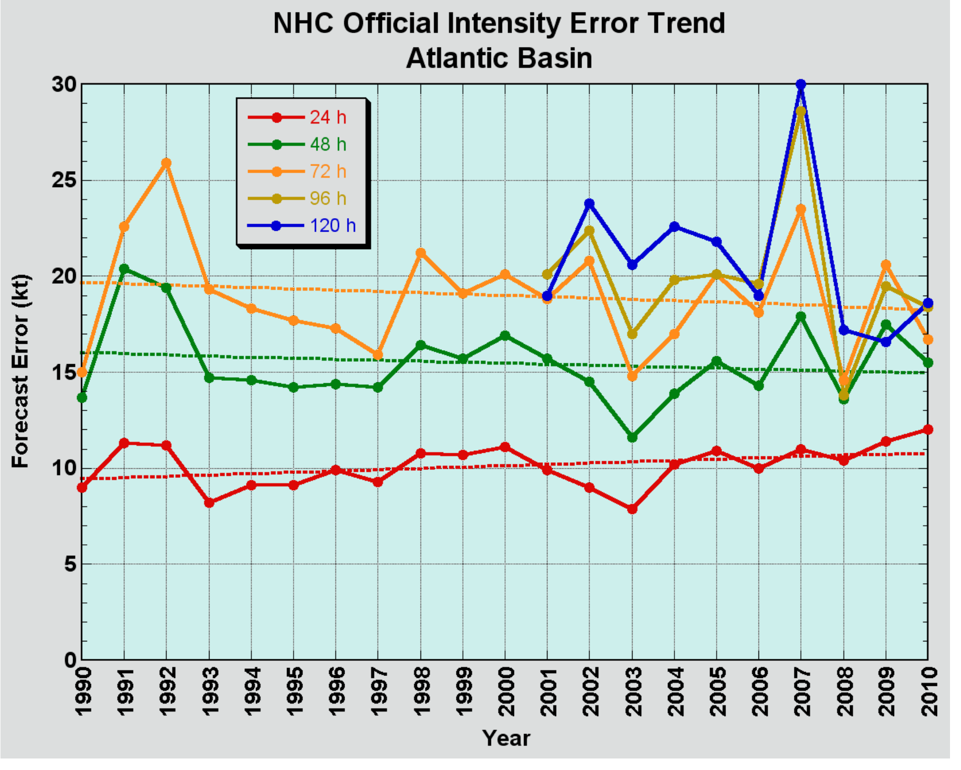


Compliments of

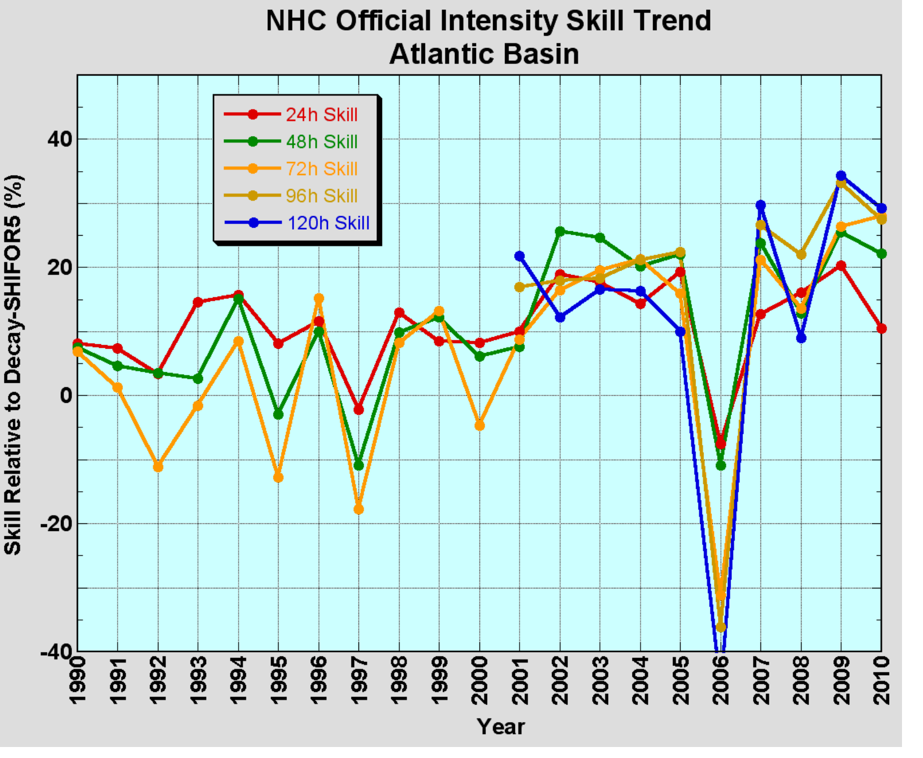
James Franklin

(NHC)

Atlantic Intensity Error Trends



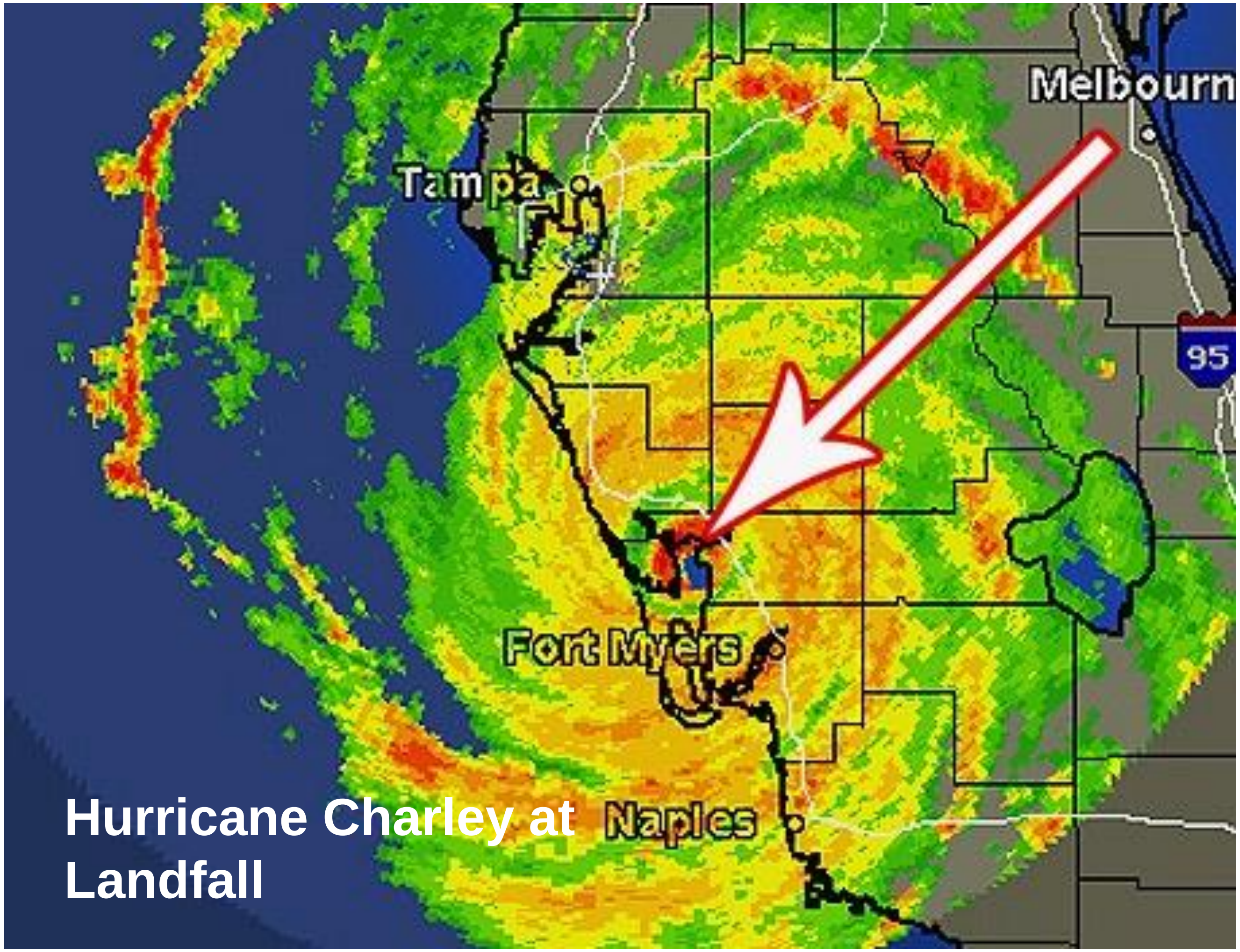
Atlantic Intensity Skill Trends



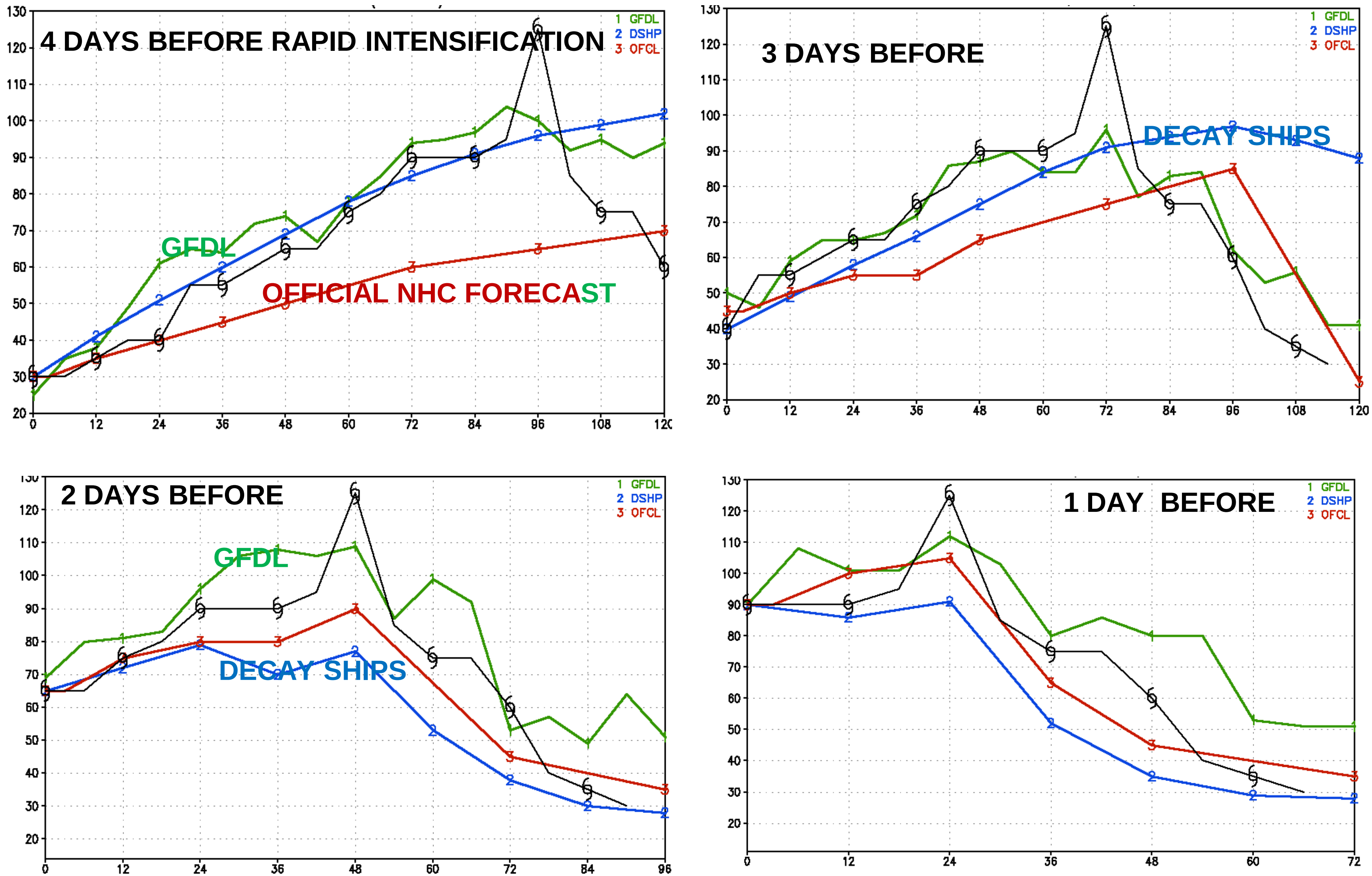
Despite Improved Track prediction:

No progress with intensity prediction !!!

FORECASTING OF RAPID INTENSIFICATION EVENTS REMAINS A GREAT CHALLENGE TO REDUCE ERRORS IN INTENSITY PREDICTION SKILL



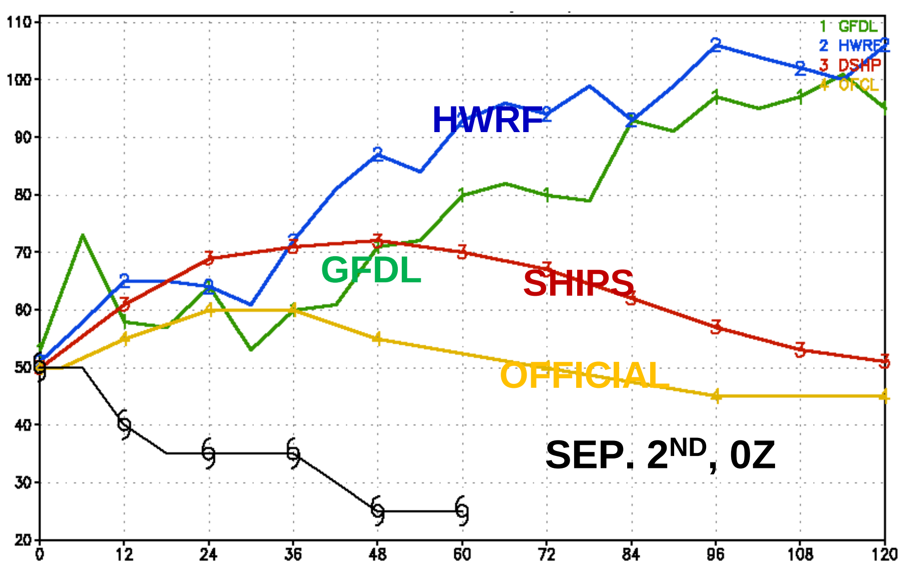
CHARLEY (2004): AN EXAMPLE OF UNDER-PREDICTION OF RAPID INTENSIFICATION

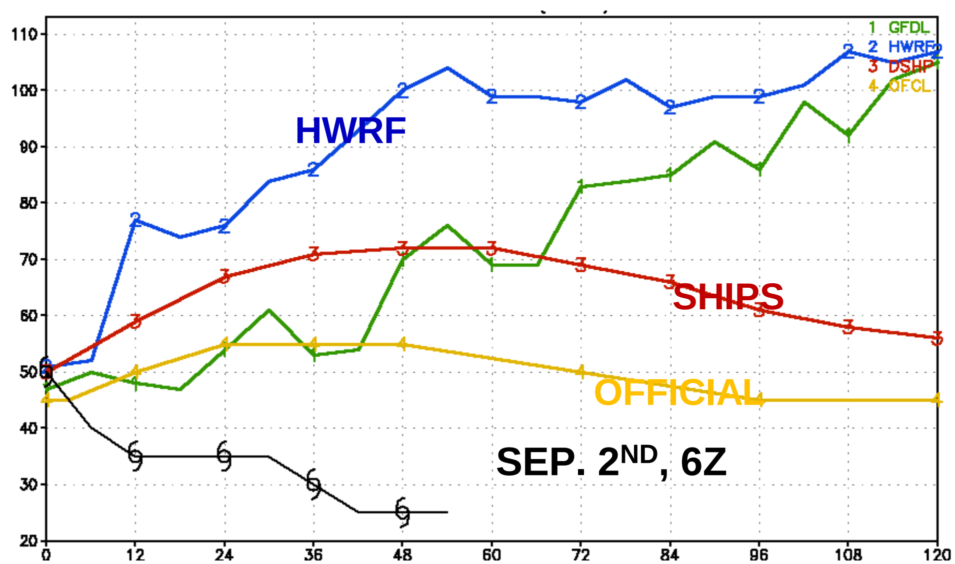


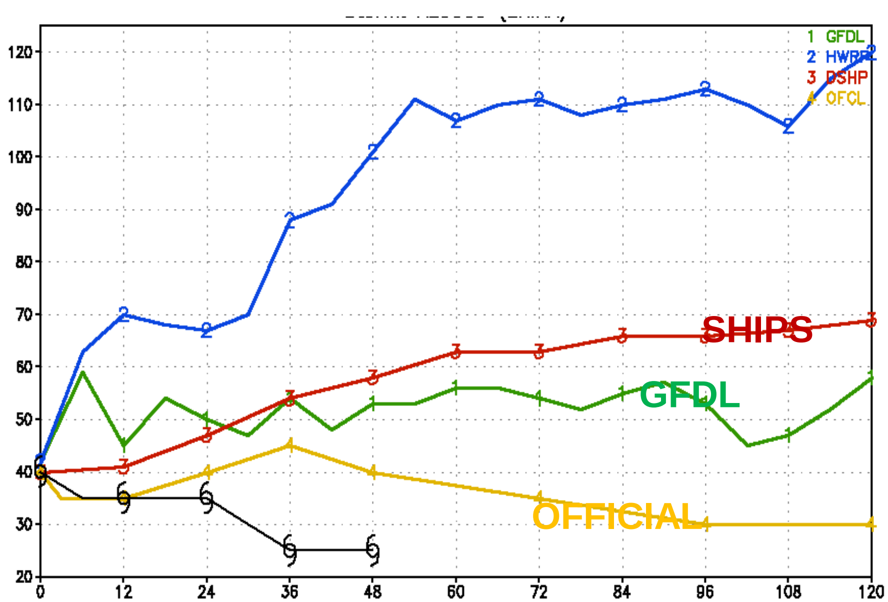
MUCH OF OUR <u>LARGEST ERRORS</u> IN INTENSITY PREDICTION WITH REGIONAL DYNAMIC MODELS IS DUE TO INABILITY TO PROPERLY REPRESENT IMPACTS OF ENVIRONMENTAL WIND SHEAR ON TROPICAL CYCLONES

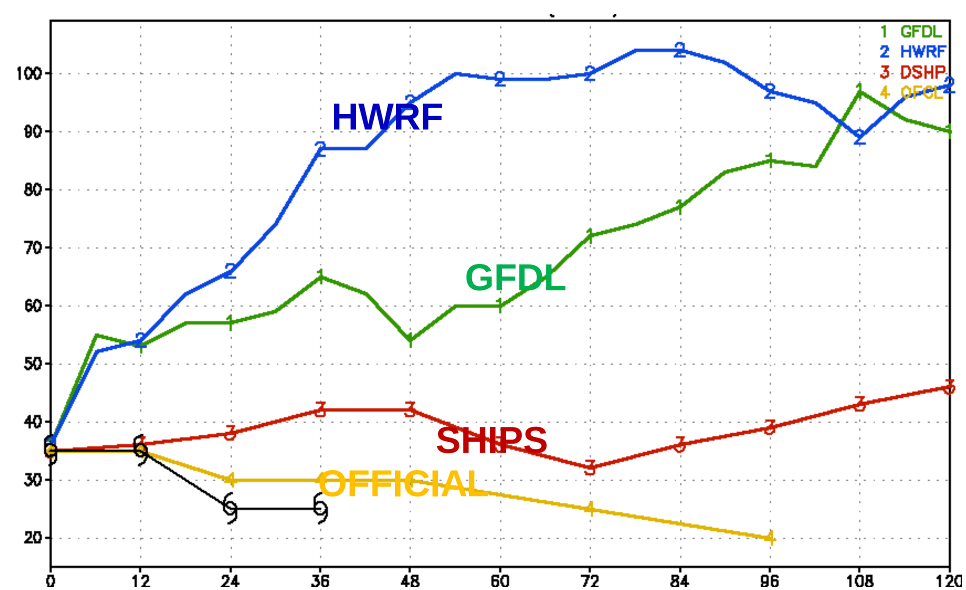
A COMBINATION OF INADEQUATE PHYSICS AND IMPROPER REPRESENTATION OF INITIAL VORTEX STRUCTURE

ERICA (2009): OVER INTENSIFICATION IN SHEARED ENVIRONMENT





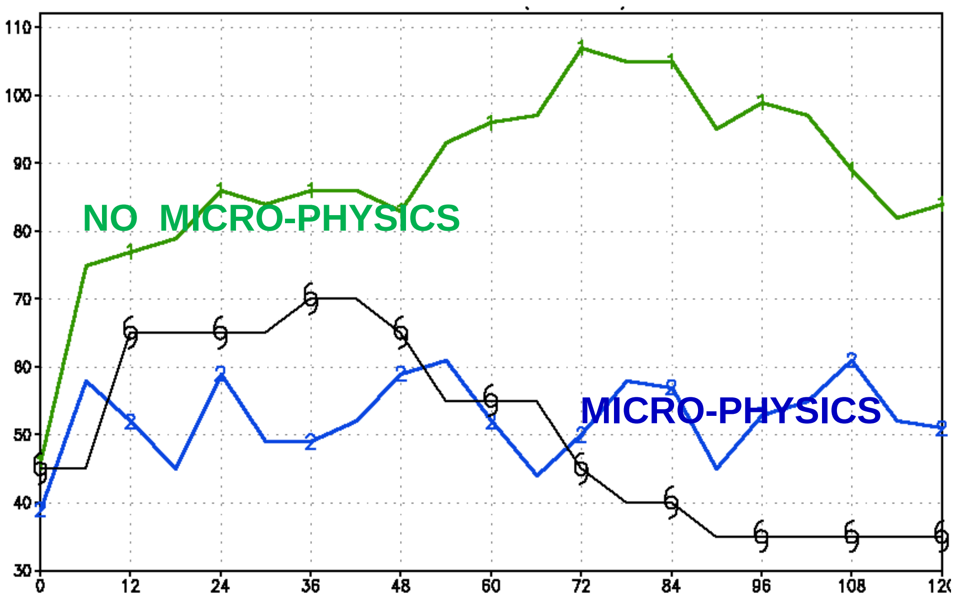


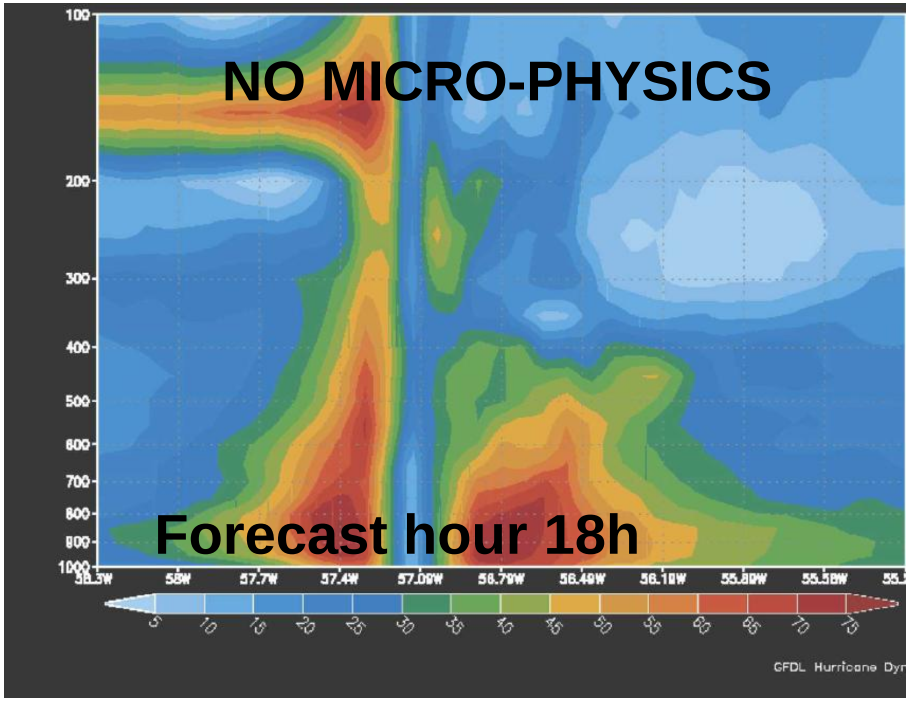


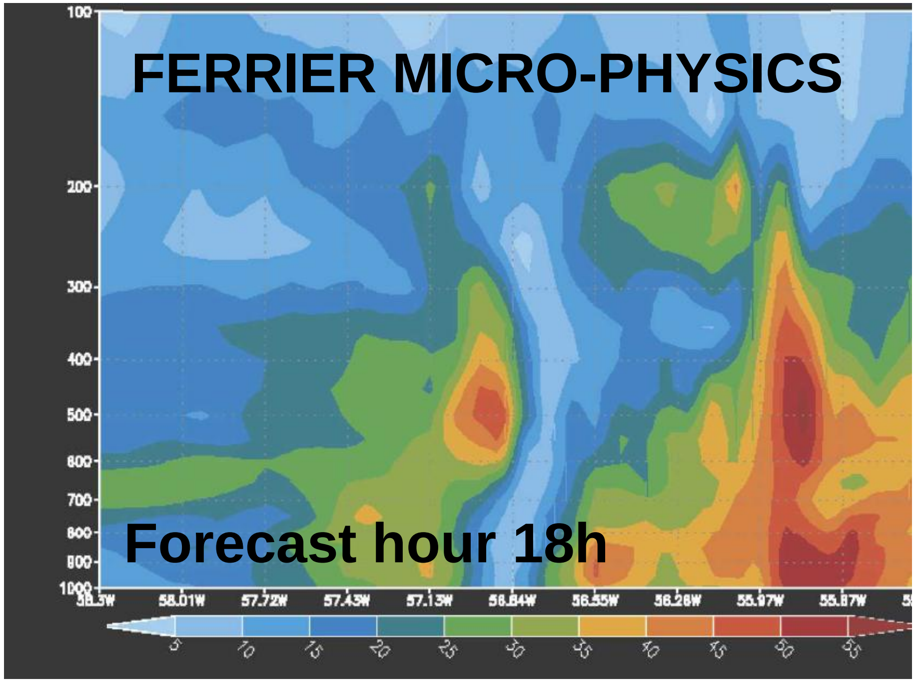
EXAMPLE OF MAJOR IMPACT OF PHYSICS IN STRONGLY SHEARED ENVIRONMENT

HURRICANE PHILIPPE (2005)

Initial Time: September 18th, 12z

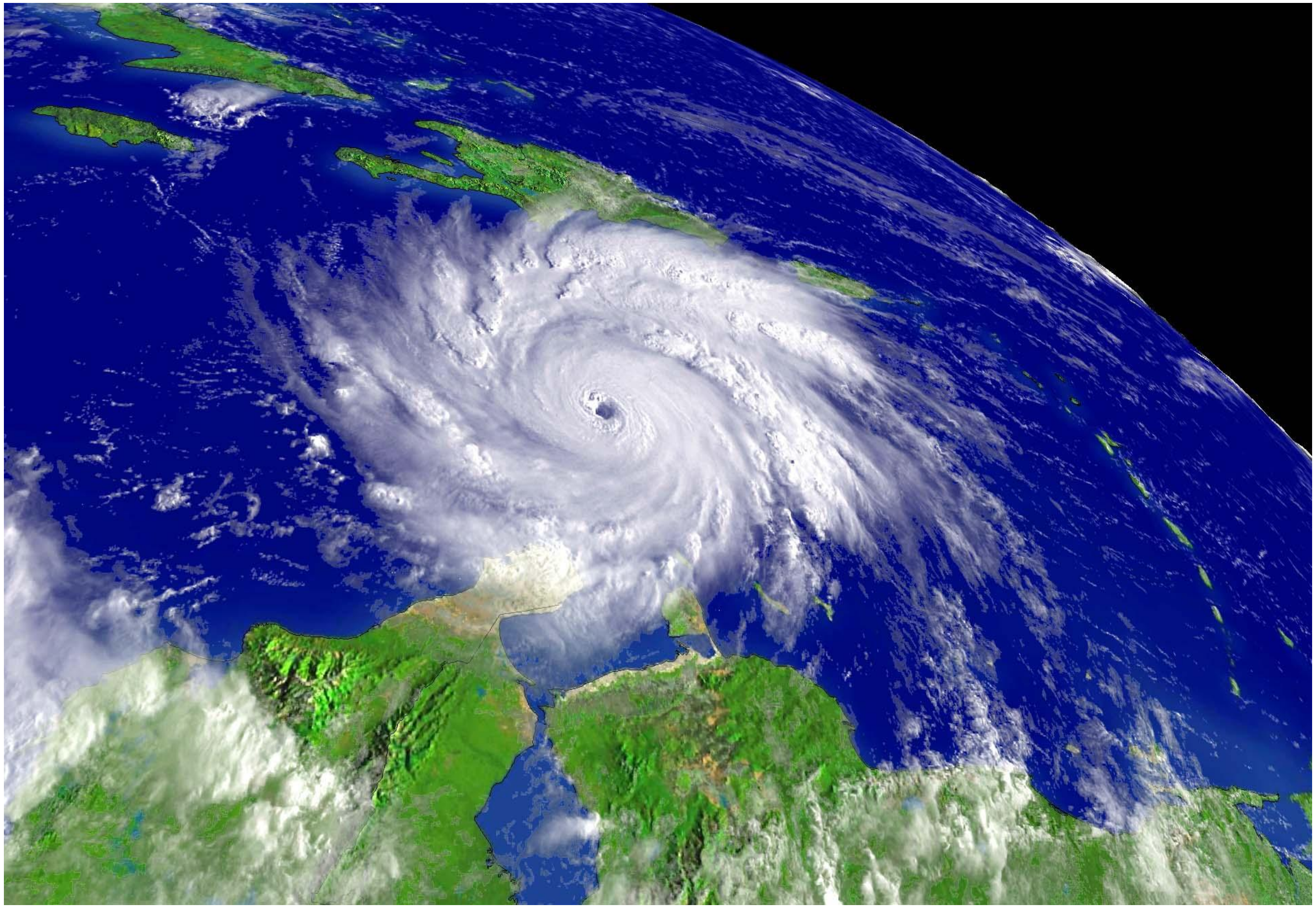






Power of the Consensus Technique

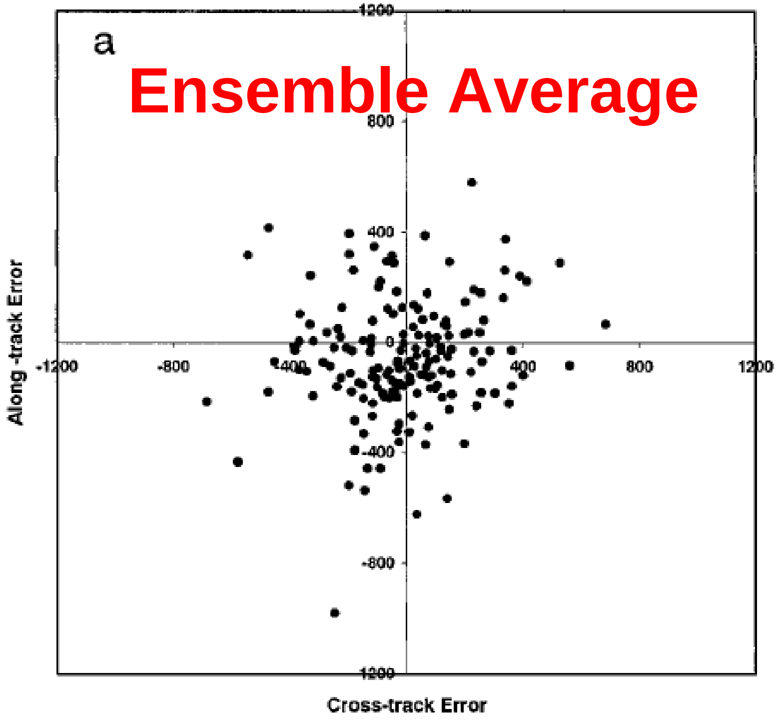
A major contributor to reduced track error

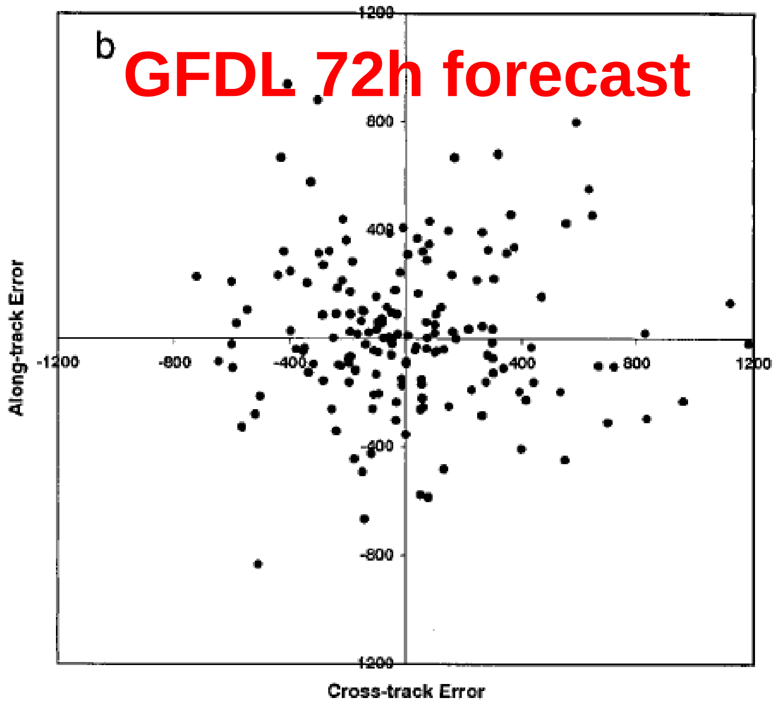


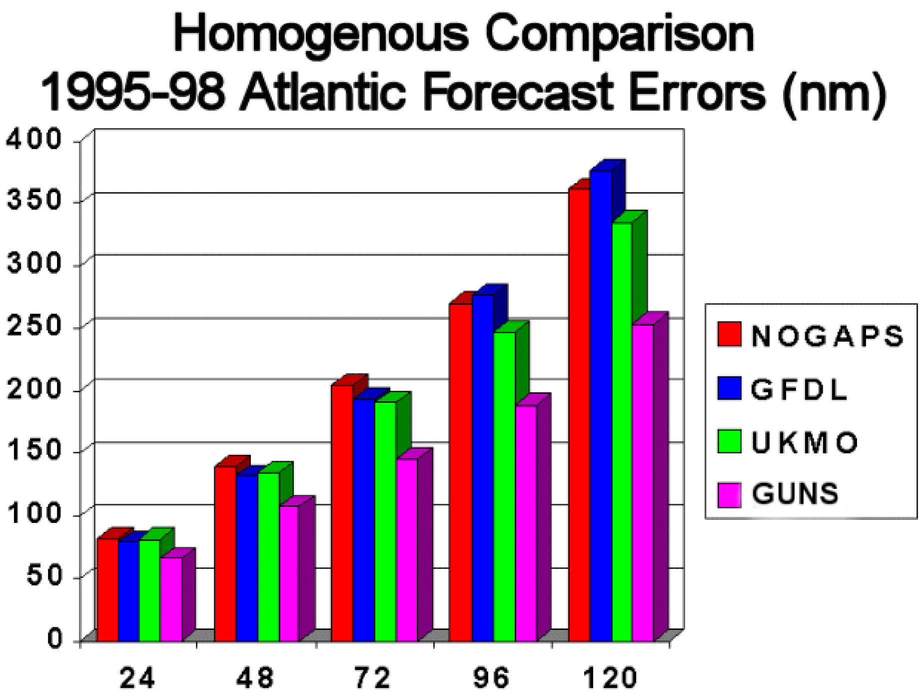
Tropical Cyclone Track Forecasts Using an Ensemble of Dynamical Models

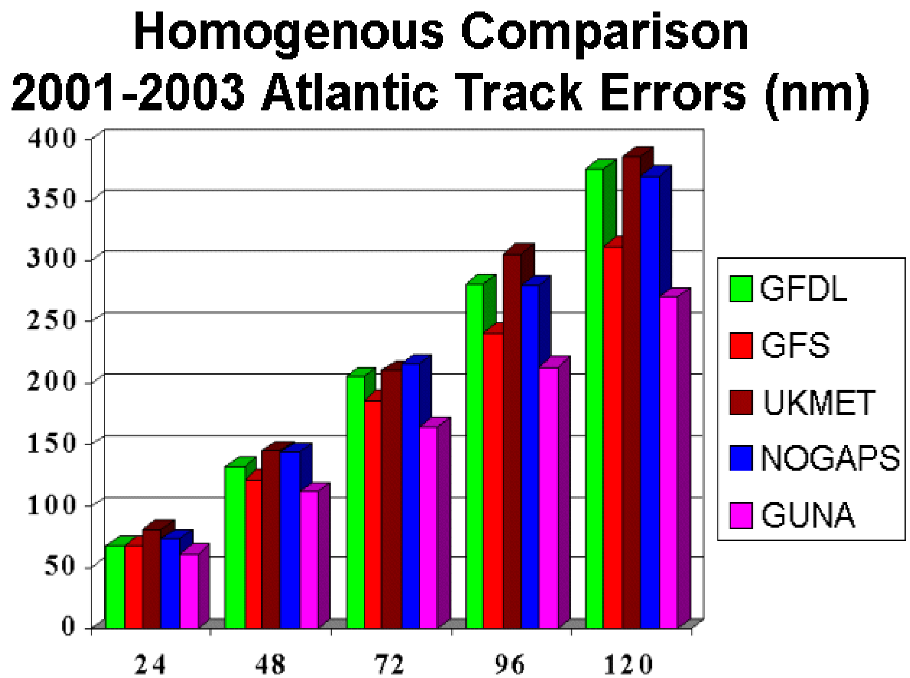
JAMES S. GOERSS

The relative independence of the tropical cyclone track forecasts produced by regional and global numerical weather prediction models suggests that a simple ensemble average or consensus forecast derived from a combination of these models may be more accurate, on average, than the forecasts of the individual models. Forecast

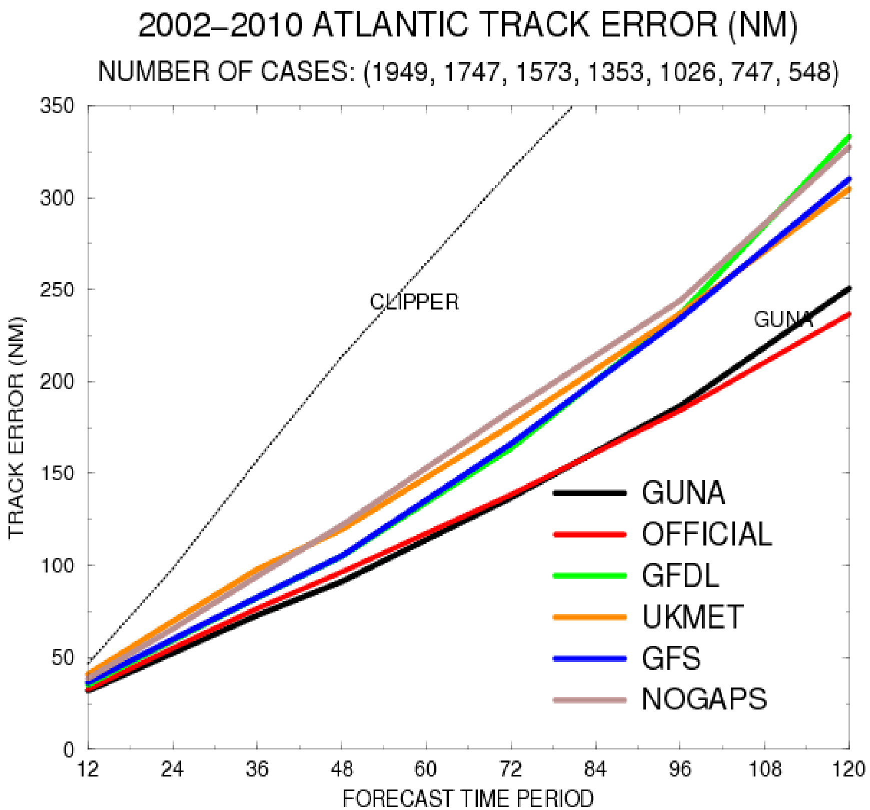


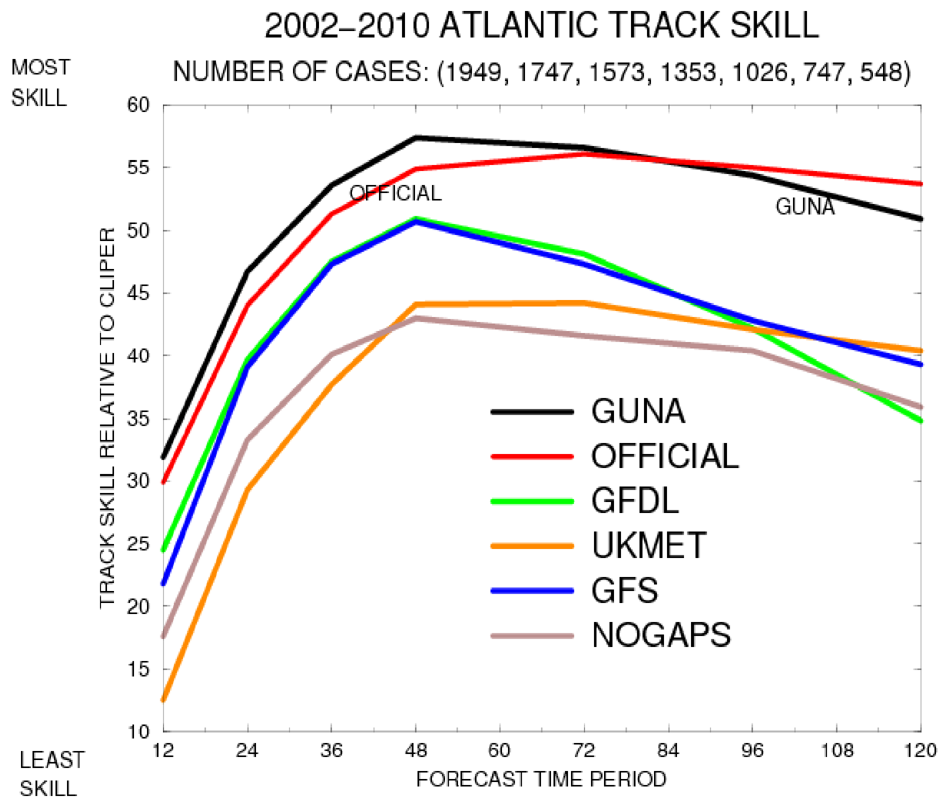



Homogenous Comparison
1995-98 Atlantic Forecast Errors (nm)
400
350
300
250
200
150
100
50
0
24
48
72
96
120
NOGAPS
GFDL
UKMO
GUNS


Homogenous Comparison
2001-2003 Atlantic Track Errors (nm)
400
350
300
250
200
150
100
50
0
24
48
72
96
120
GFDL
GFS
UKMET
NOGAPS
GUNA

EVALUATION OF THE CONSENSUS MODEL GUNA FOR THE PAST 9 ATLANTIC HURRICANE SEASONS

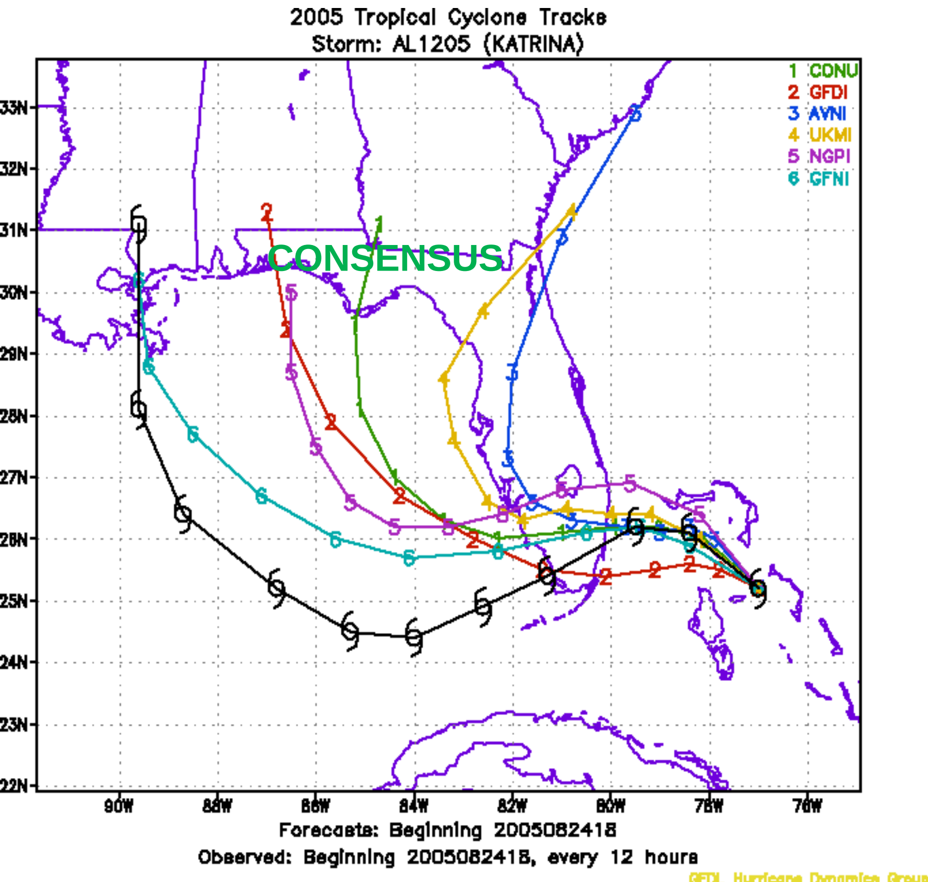




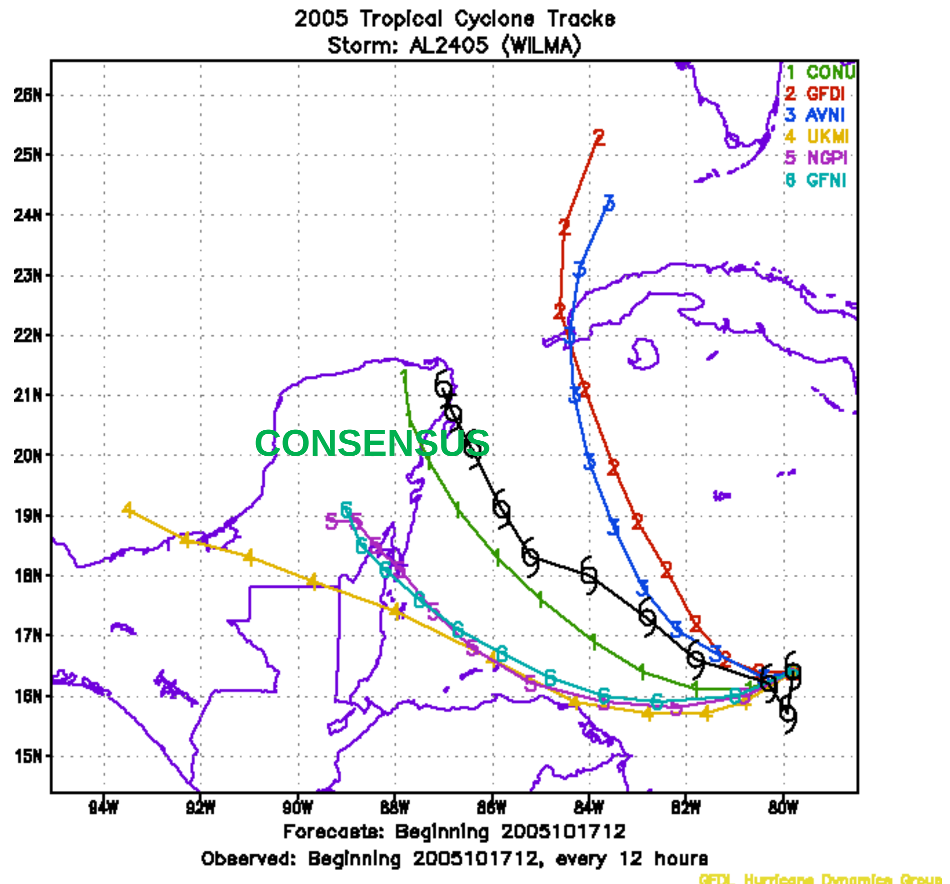
With large Spread between Model Forecasts

Consensus Usually Provides the Best Forecast

KATRINA (August 28th, 18z)

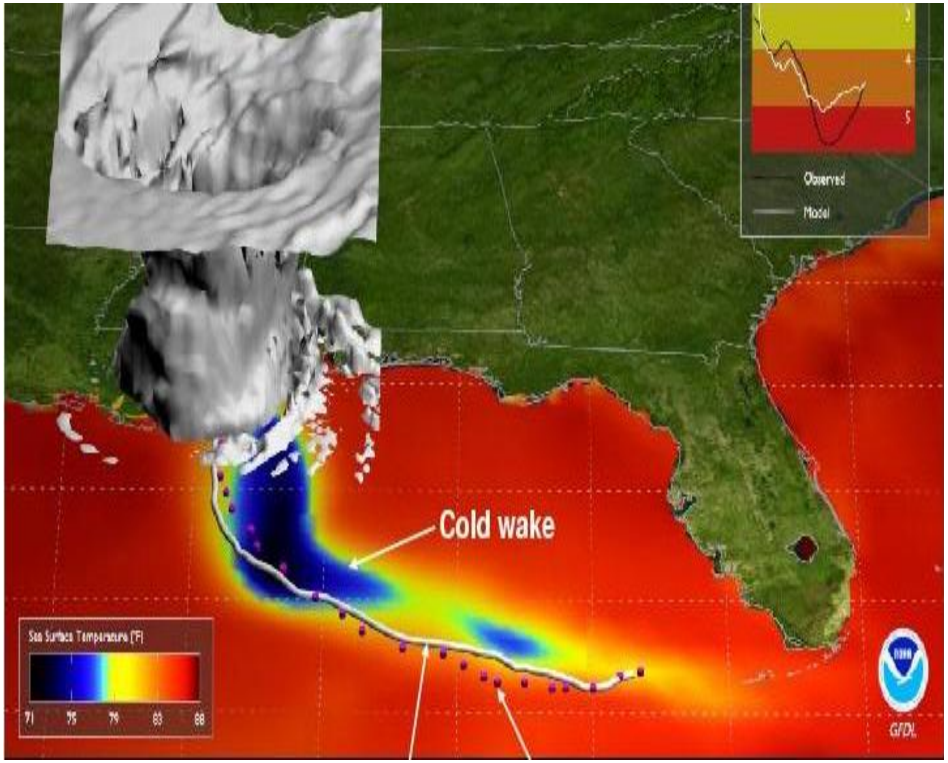


WILMA (October 17th, 12z)



GFDL Story

NOAA's Example of a Successful transition of Research to Operations



What can we learn from this example to help us continue to improve dynamic hurricane models in the future

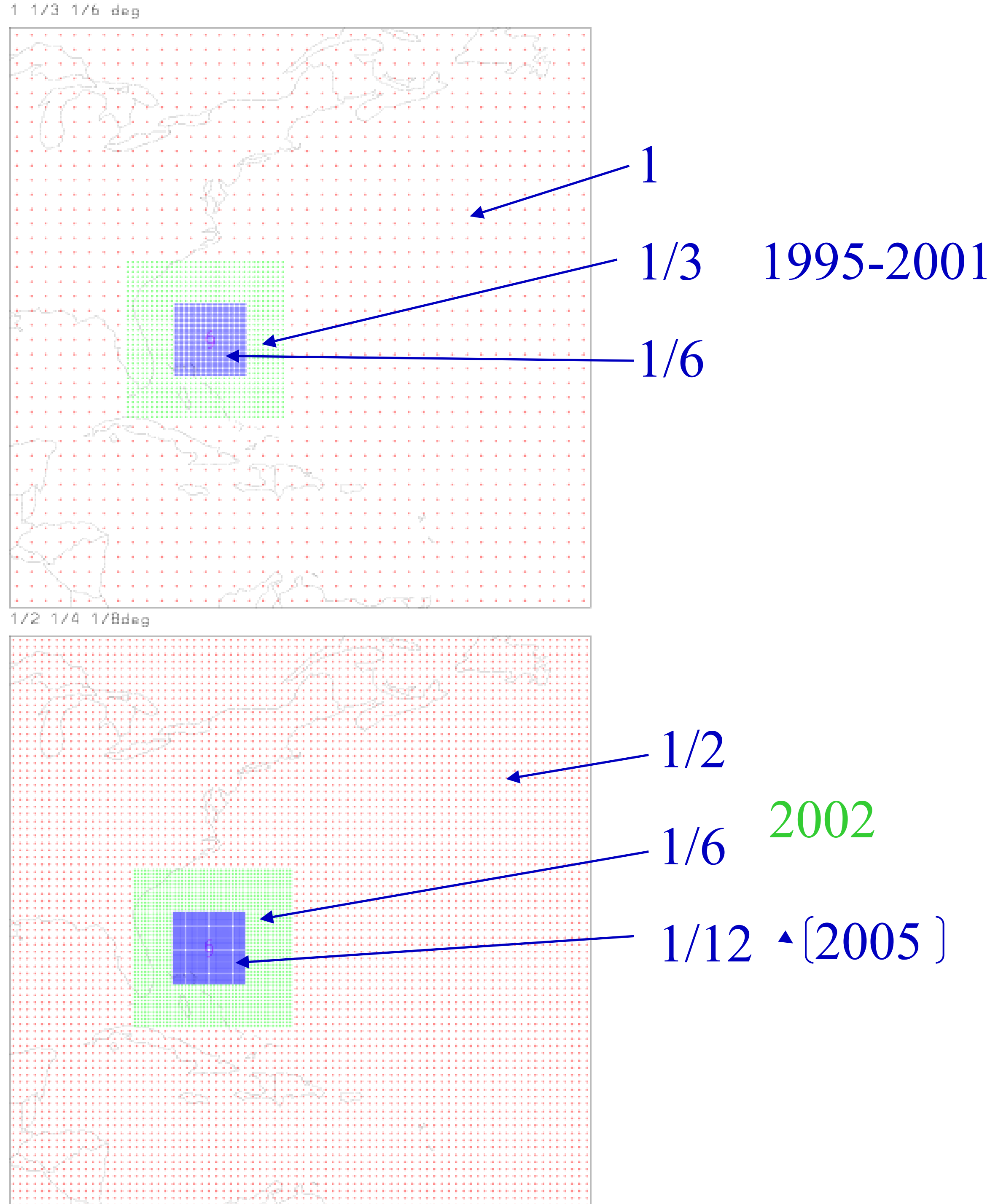
The Success of the GFDL Hurricane Program began with the vision of two men

Yoshio Kurihara and GFDL's Founder Joe Smagorinsky

History of the GFDL Hurricane Model

1970	Hurricane group formed at GFDL to perform research
1976/79	A new movable nested hurricane model developed
1987/90	Accelerated development of hurricane prediction system
1992/93	Test of prediction system in semi-operational mode at GFDL (Andrew, Iniki, Emily)
1994	Transfer of GFDL system to NCEP to run on Cray c90
1995	GFDL model becomes operational at NCEP
1996	GFDL model becomes operational for Navy
1999-	GFDL continues to provide support to NCEP & Navy
2001	GFDL-POM coupled system becomes fully operational
2003, 2006, 2011	GFDL major physics upgrades continue

GFDL Nested Meshes

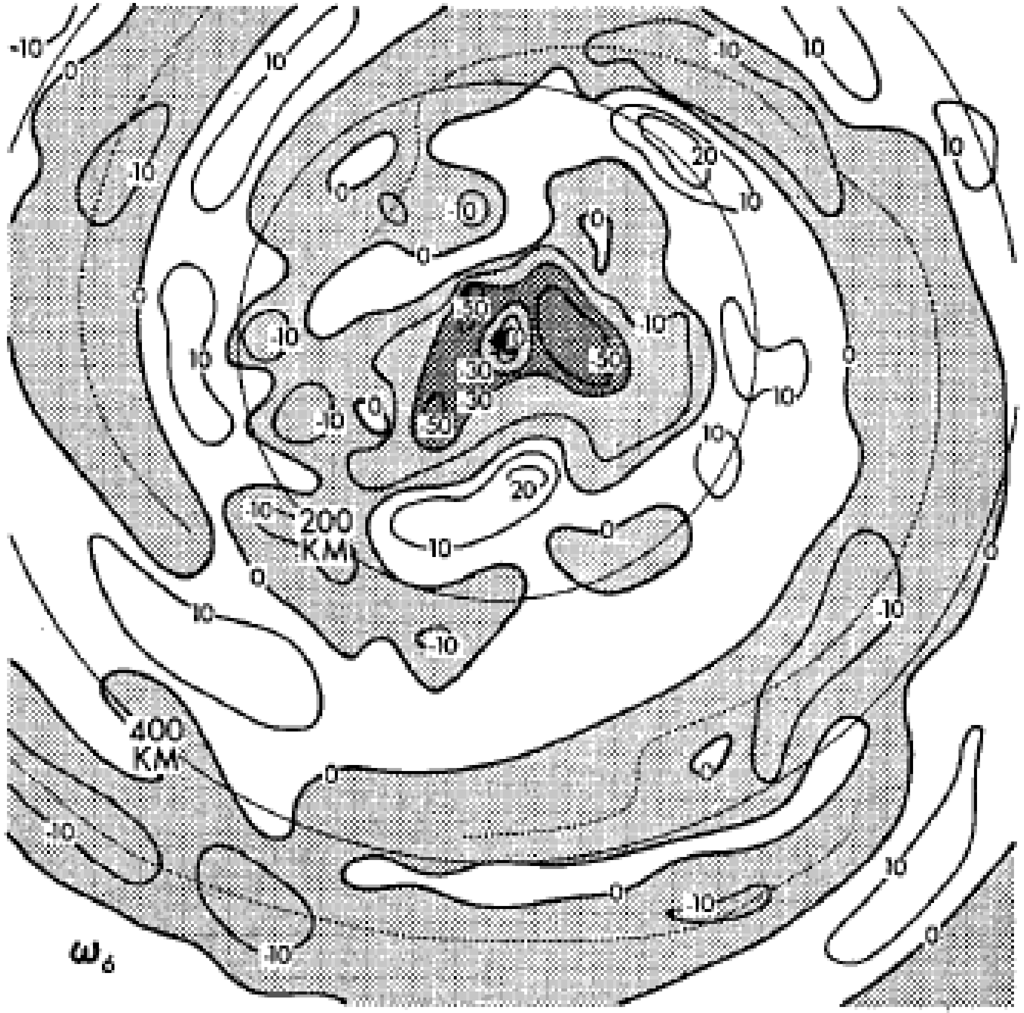


Emphasis in 70s and early 80s on Basic Research:

Improved understanding of hurricane structure, decay after landfall, hurricane genesis, and impacts of topography on hurricane motion (and other basic research topics)

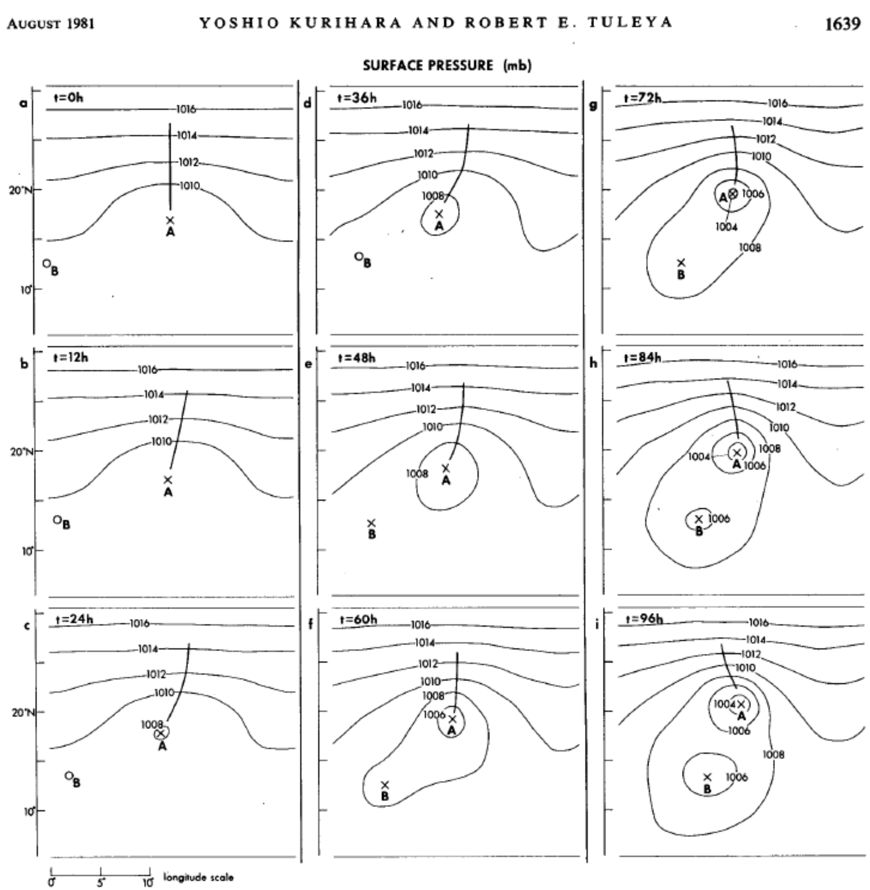
Early 3-D model (hurricane in a box!)

Kurihara, Y., and R. E. Tuleya, 1974 . JAS

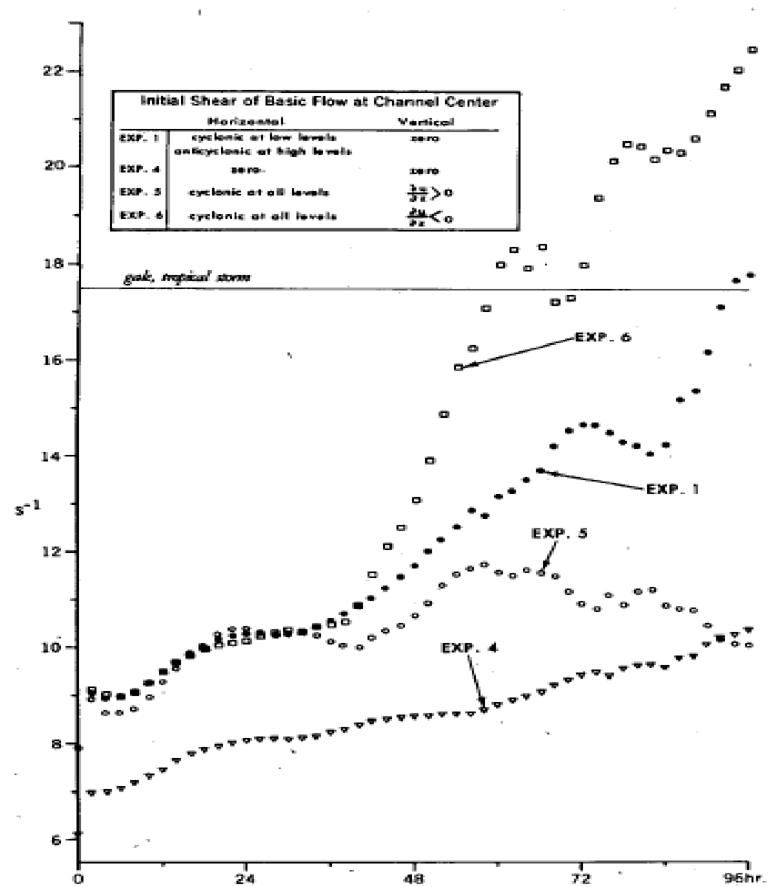


TC genesis-impact of environment

Kurihara, Y., and R. E. Tuleya, 1981, MWR



Wave → TC

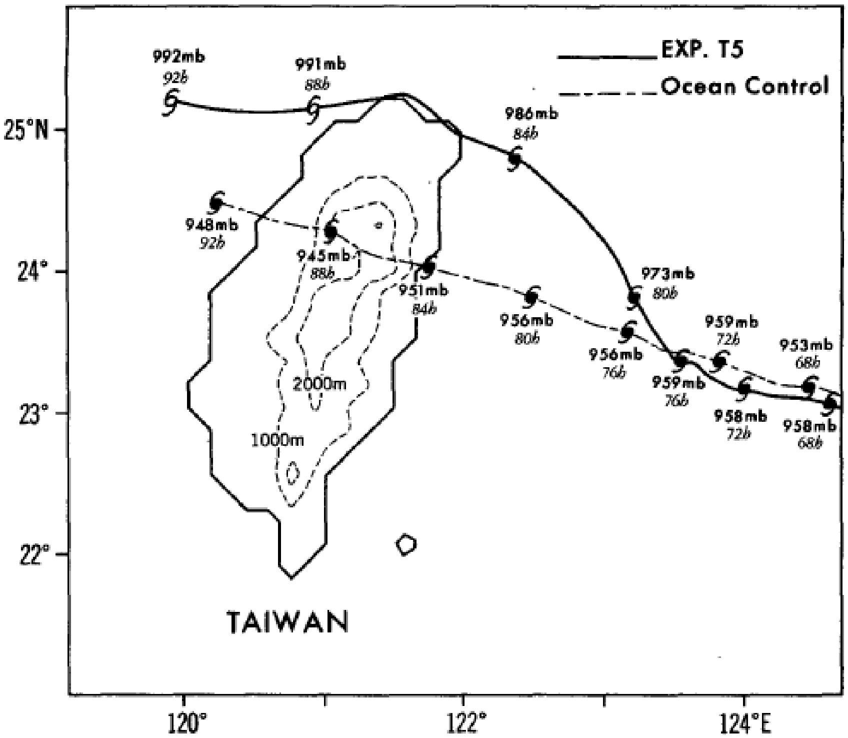


Effect of shear

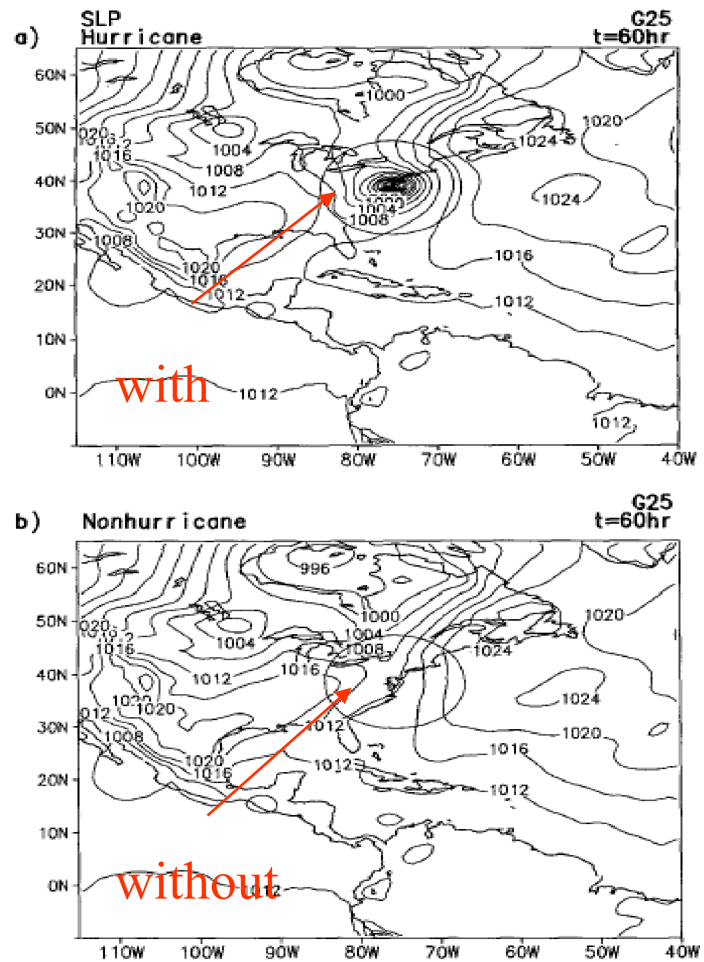
Impacts on and by TC

Bender,M.A, R.E. Tuleya and Y. Kurihara, 1987,MWR

Ross, R. J., and Y. Kurihara, 1995,MWR



Topographical impact

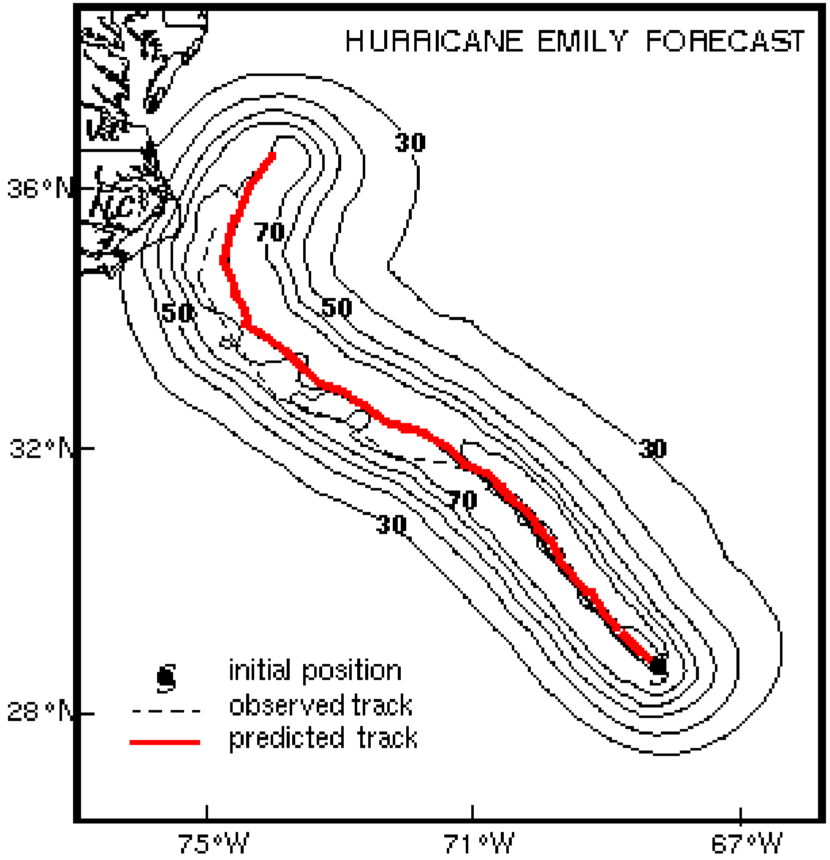


TC's impact on coastal front

TRANSITION OF BASIC RESEARCH TO OPERATIONS:

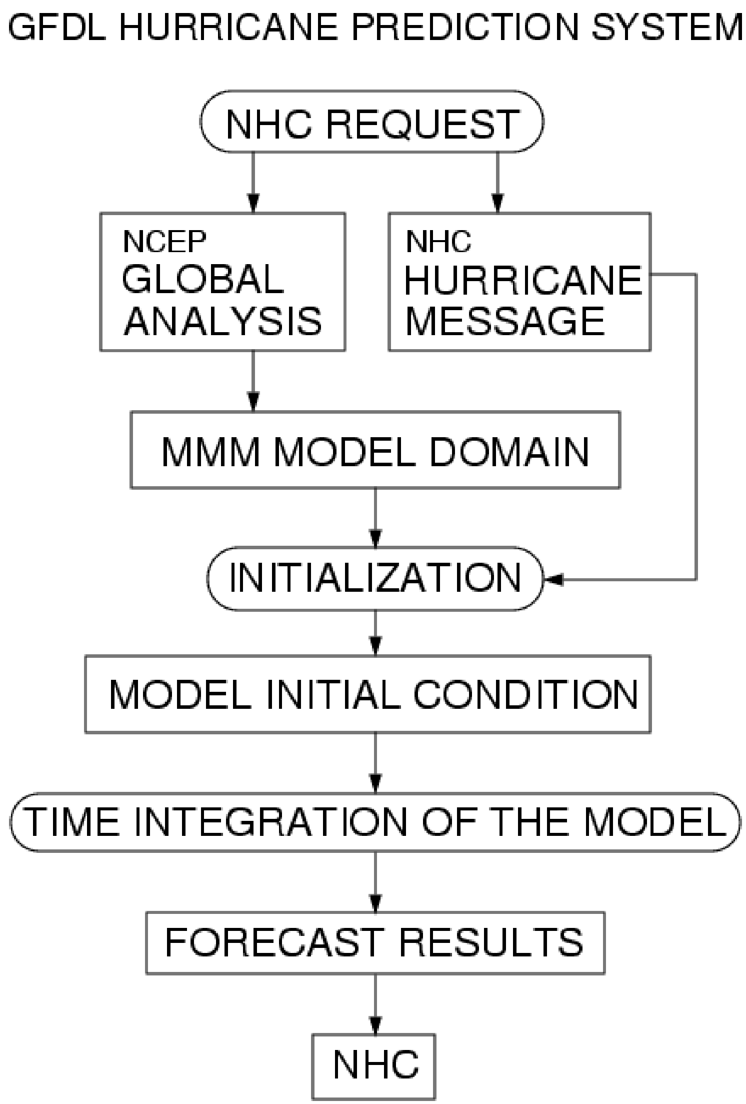
Late 90s Began an Accelerated development of new hurricane prediction system for potential operational use.

Involved a multi-year effort



After development of improved physics, new lateral boundary condition and vortex initialization near real time forecasts began in 1992 at GFDL on limited number of storms, in near real time.

1993: Example of GFDL product made available in near real time (+10 hours)

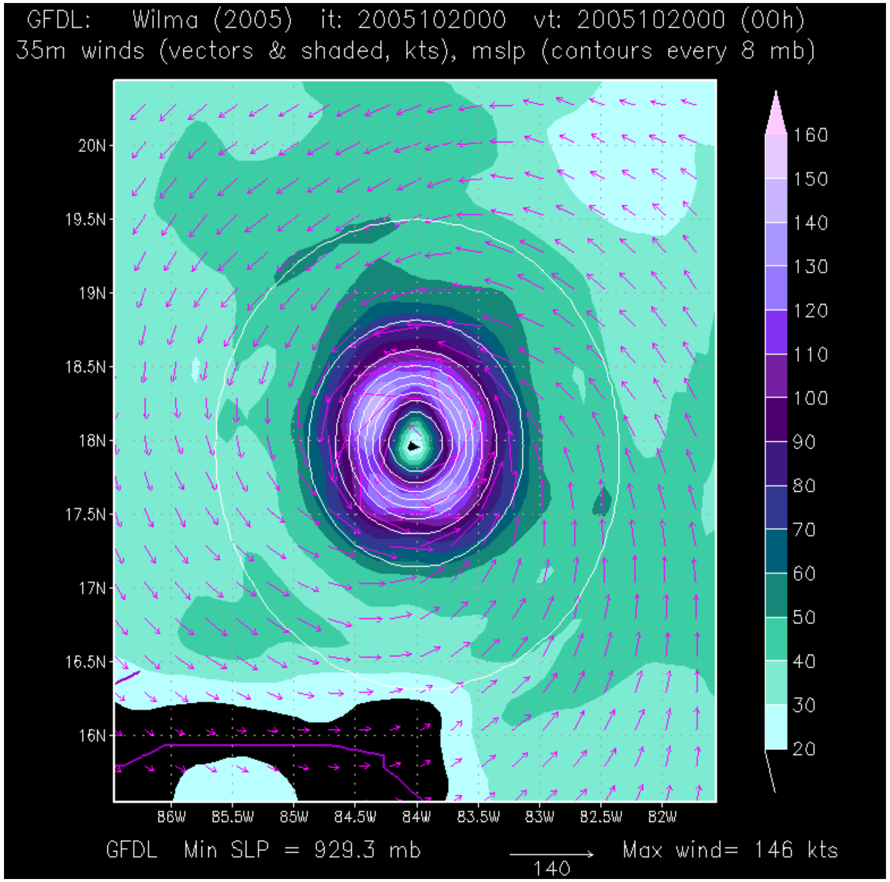


~ 1 hour wallclock

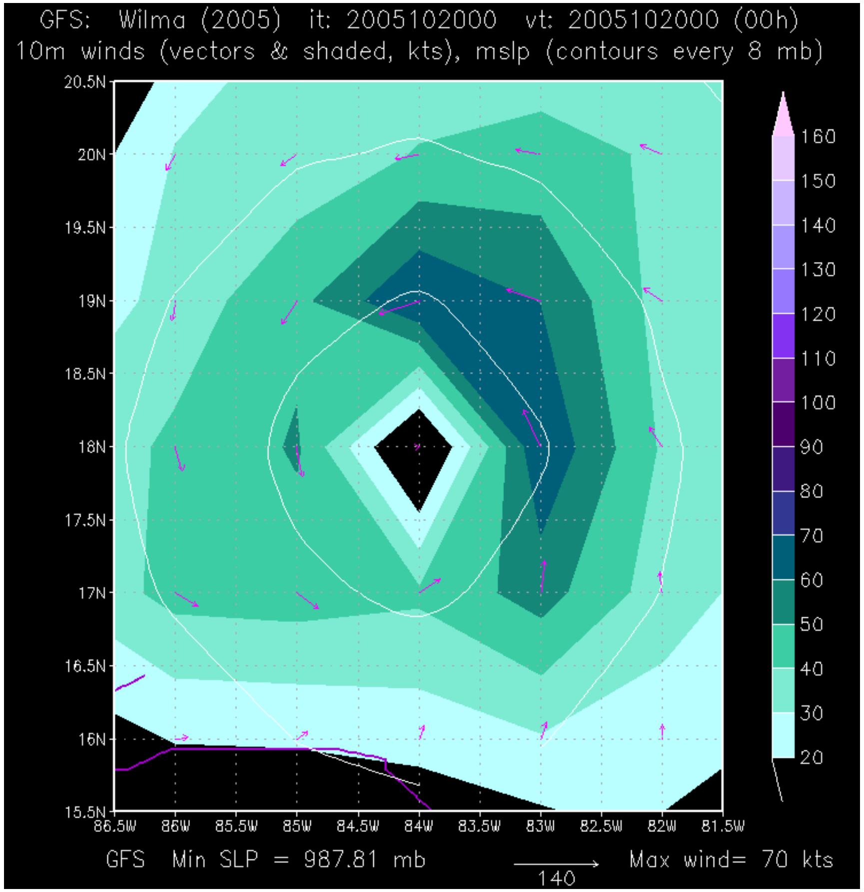
Same time constraint remains both for the GFDL and HWRF

Global models too coarse for intensity prediction: Why new vortex initialization technique was required to be developed

GFDL: max resolution = 1/12 deg (~9 km)

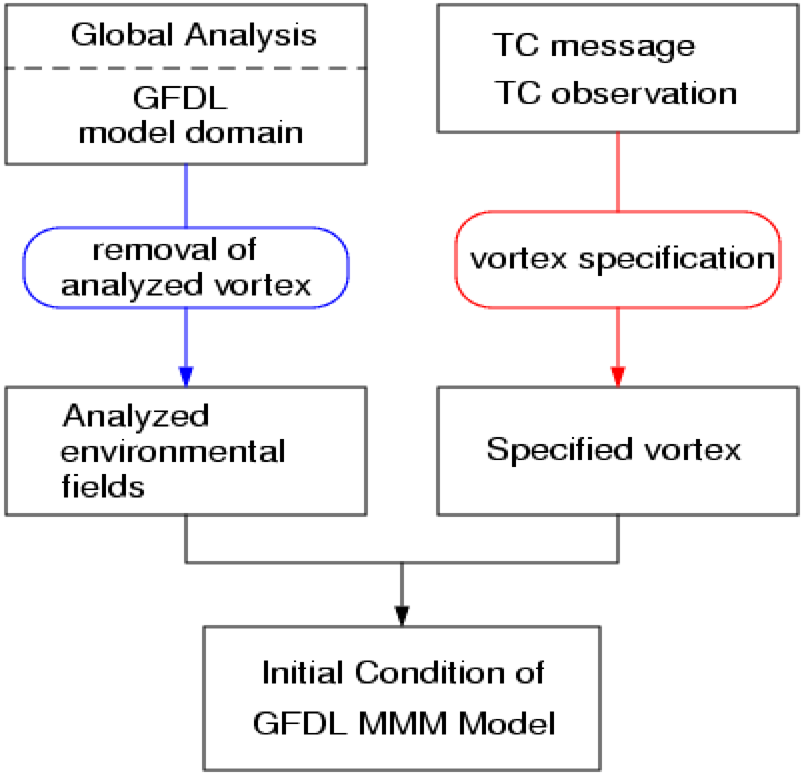


GFS: resolution approx 0.4 deg (~44 km)



At this time (00 UTC 20 October 2005), Wilma was observed to have a minimum sea level pressure of 892 mb and maximum winds of 140 knots. The GFDL hurricane model and the GFS global model present starkly different initial representations of the storm structure.

Initial Condition of the GFDL Hurricane Model



Strategy in Scheme's Development

1. Goal was to develop a vortex initialization that accurately represented the tropical cyclone.
2. Structure of vortex should be dynamically and thermodynamically consistent.
3. Coherence of moisture field to other variables
4. Specified vortex should accurately represent observed storm size and intensity
5. Specified vortex should be compatible with resolution and physics of prediction model
6. 2.) Initialization should minimize change to the Global analysis

1.) REMOVAL OF VORTEX FROM GLOBAL ANALYSIS USING GFDL FILTER TECHNIQUE (*Kurihara et al. 1993 &1995)*. FILTERING STRENGTH MADE A FUNCTION OF HEIGHT IN 2002.

2.) COMPUTATION OF ENVIRONMENTAL FIELD.

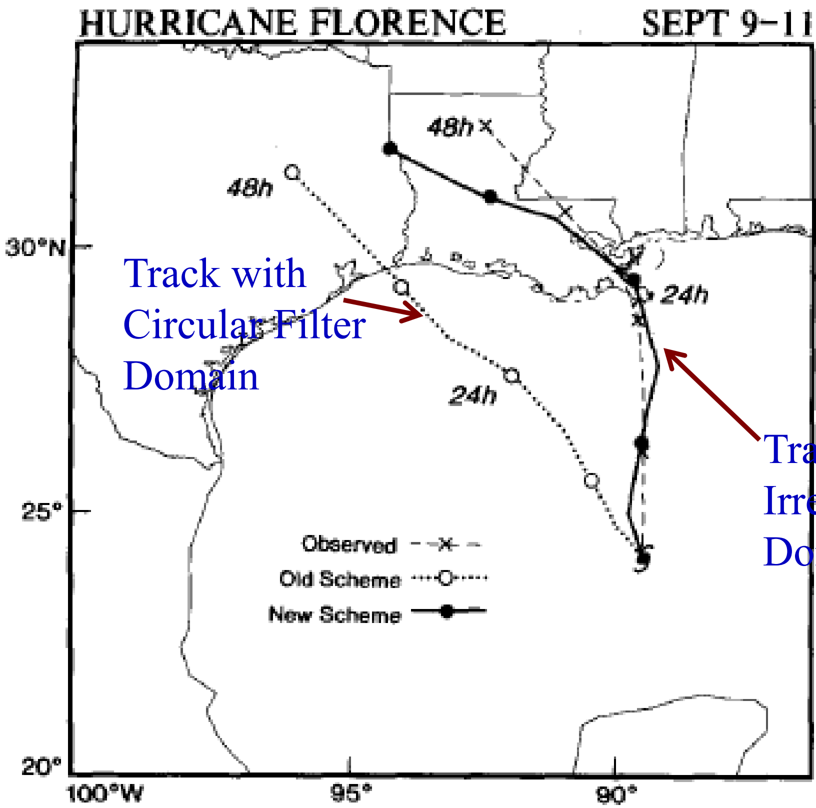
$$(h_{\text{Environmental Field}} = h_{\text{Basic Field}} + (h_{\text{Disturbance Field}} - h_{\text{Global Vortex}})$$

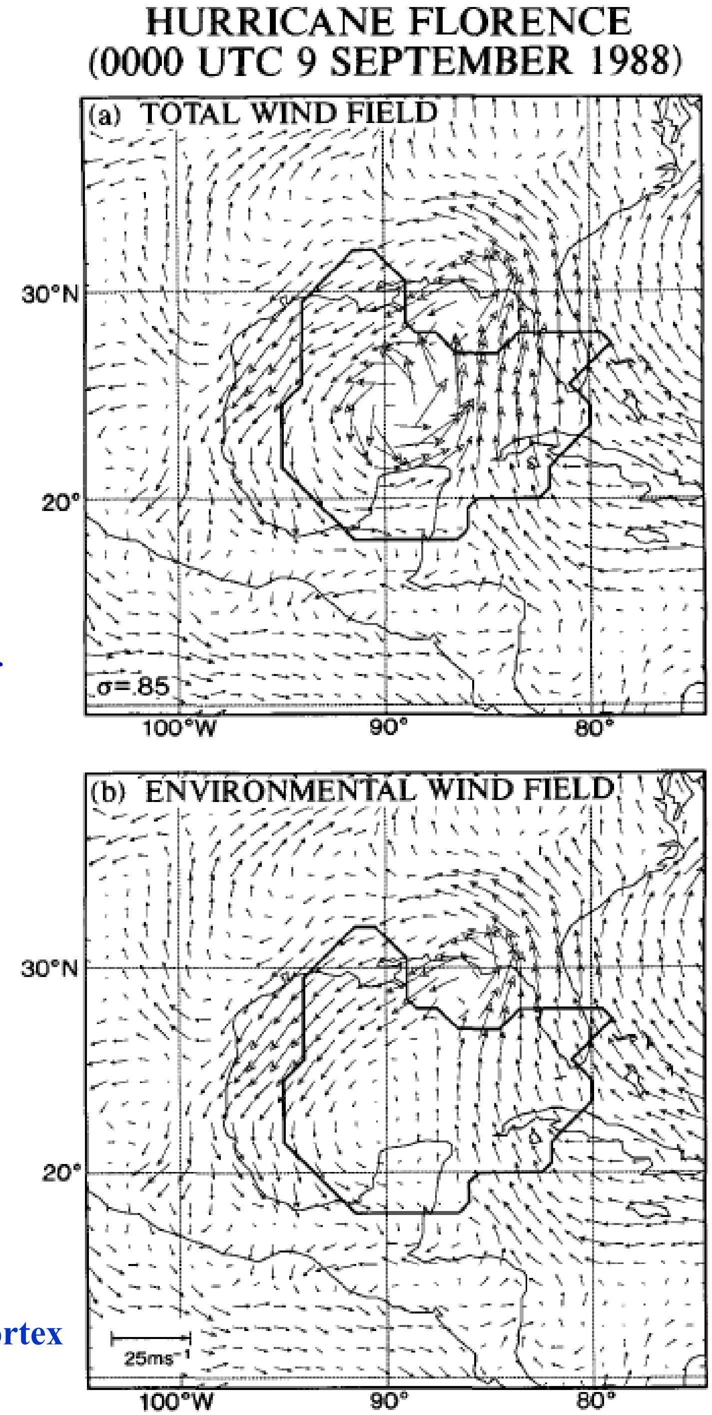
3.) SPIN-UP OF AXI-SYMMETRIC INTEGRATION OF PREDICTION MODEL. TANGENTIAL WIND FIELD GRADUALLY FORCED TOWARD OBSERVED STORM STRUCTURE.

4.) COMPUTATION OF STORM ASYMMETRIES DETERMINED FROM VORTEX FIELDS IN PREVIOUS FORECAST CYCLE (*Bender et al.* 2007).

5.) INSERTION OF SYMMETRIC AND ASYMMETRIC VORTEX INTO ENVIRONMENTAL FIELDS AT OBSERVED POSITION (WIND, MASS AND MOISTURE). INITIALLY, MASS FIELD WAS REBALANCED USING REVERSE BALANCE EQUATIONS. BUT STEP WAS FOUND TO BE UNNECESSARY (2004) SINCE VORTEX INCREMENT WAS WELL BALANCED.

Positive impact of improved filter domain on hurricane track



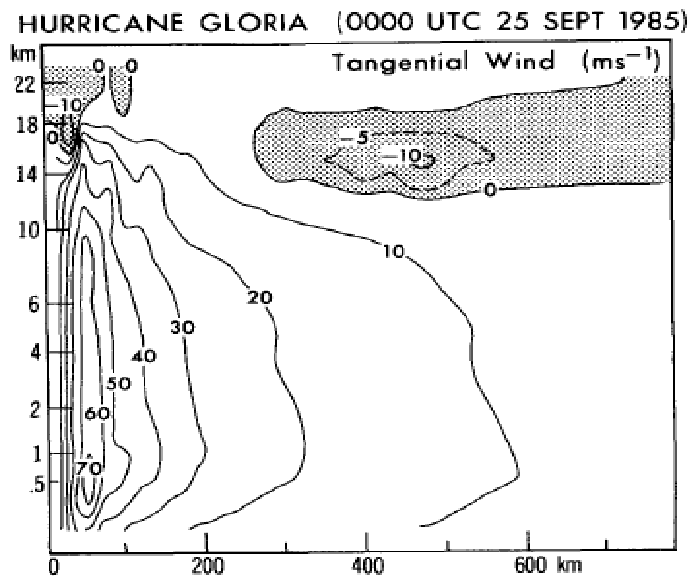


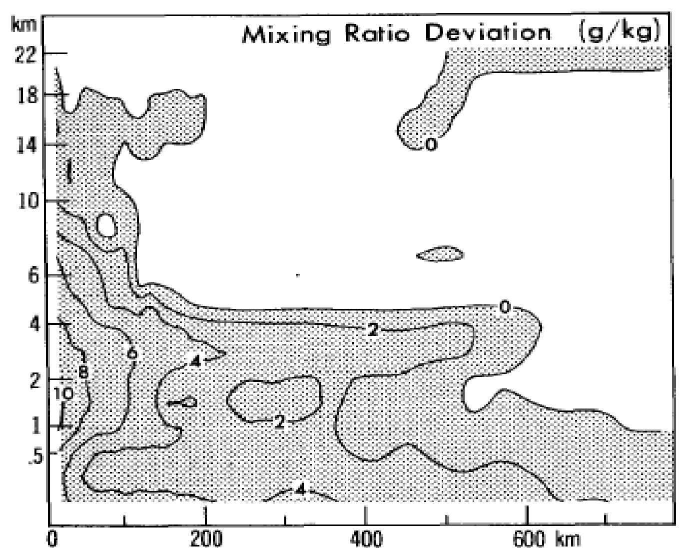
Definitions:

$h_{\text{Environmental Field}} = h_{\text{Basic Field}} + (h_{\text{Disturbance Field}} - h_{\text{global vortex}}$

$h_{\text{Disturbance Field}} = h_{\text{non-hurricane disturb.}} + h_{\text{global vortex}}$

Initialization of the moisture field obtained from the deviation of the water vapor mixing ratio from the environmental state





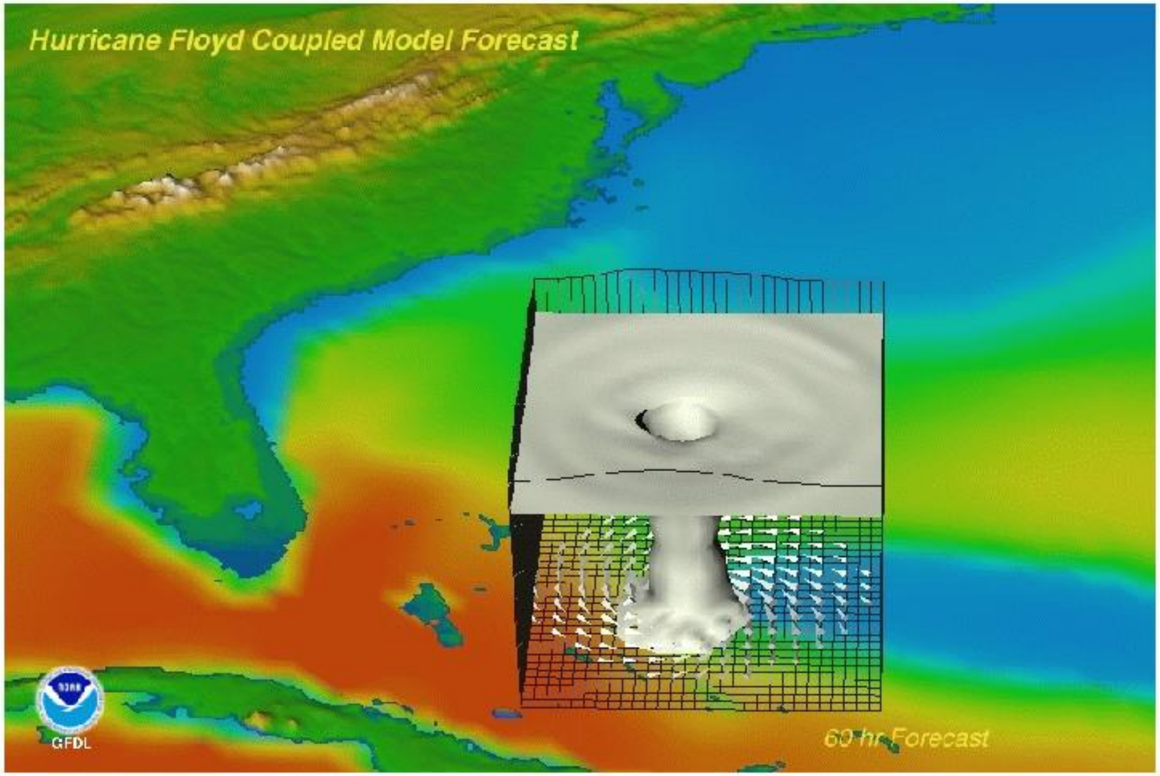
Our approach works well in favorable environment of weak wind shear. <u>Major shortcoming if strong environmental wind shear is present</u>

Why need to develop regional DA System to tackle impacts of environmental wind shear

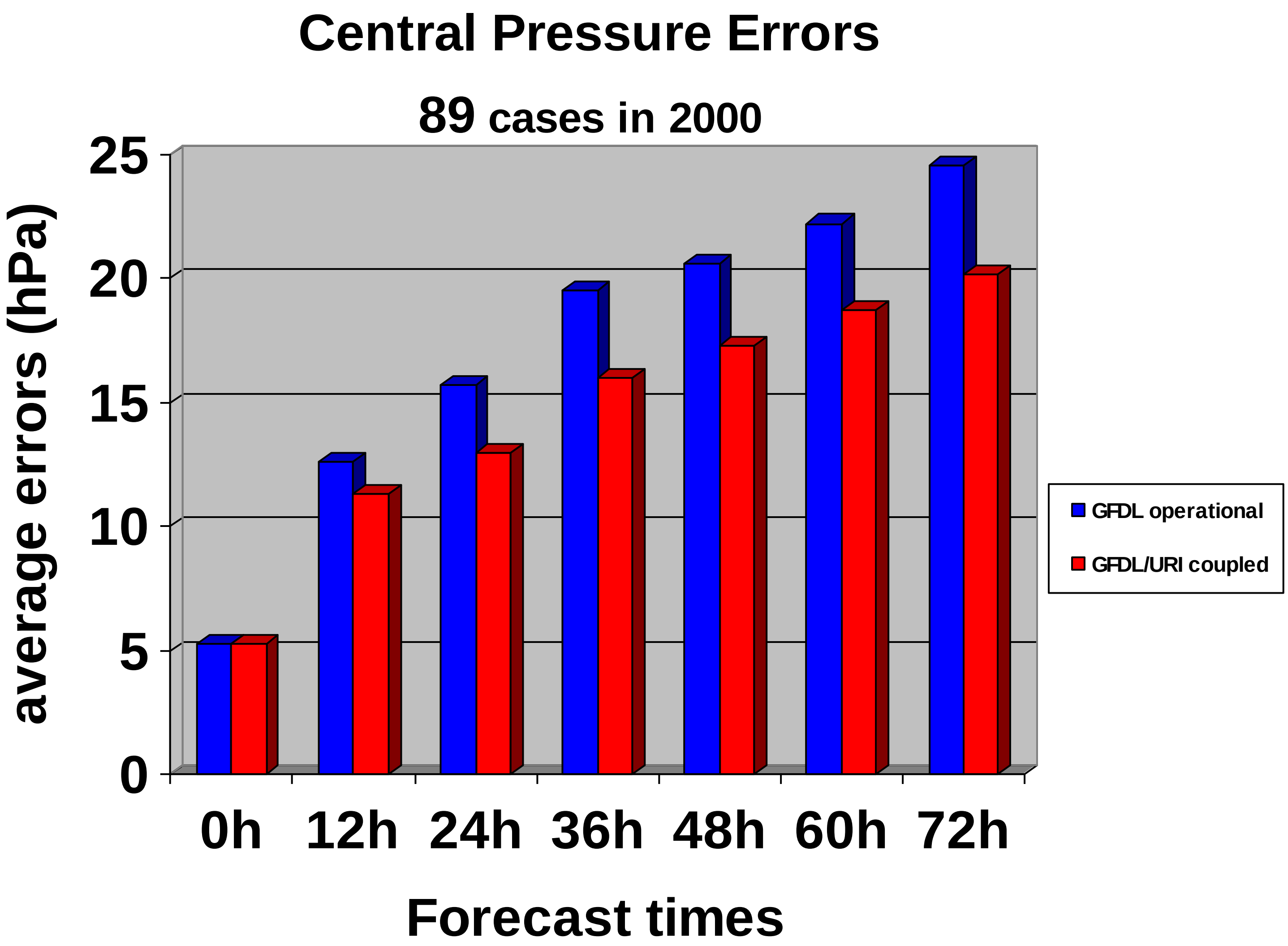
Our approach yields a reasonable and model consistent moisture field if initial vortex is vertically structured

Multi-year close collaboration between GFDL and Scientists at the University of Rhode Island (URI) was essential to develop the first fully atmosphere-ocean coupled system for hurricane operational forecasting

(Coupled System Made Operational in 2001)

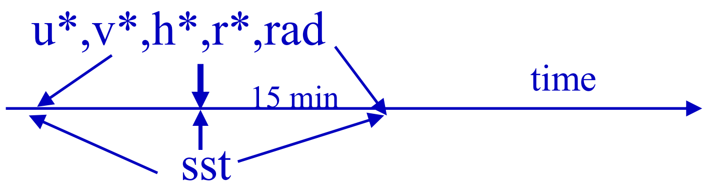


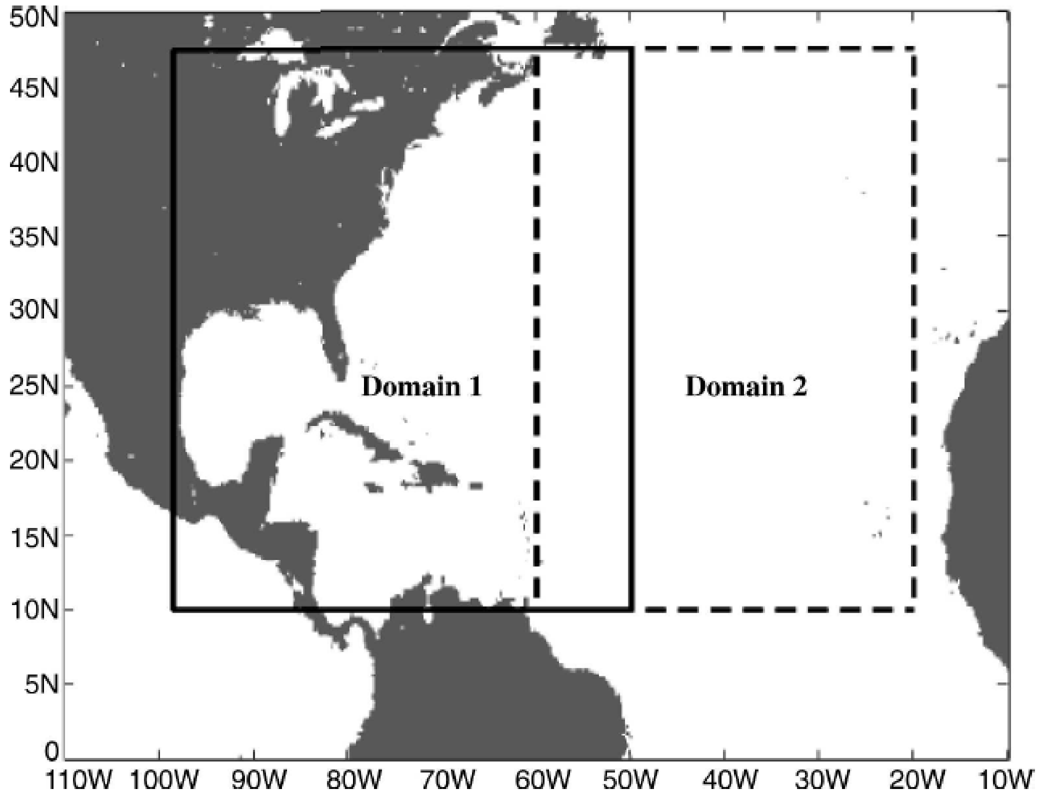
Example of where close collaborations between NOAA and the Academic community paid off !!
(essential for accelerated improvements in future as well)


Central Pressure Errors
89 cases in 2000
average errors (hPa)
25
20
15
10
5
0
0h
12h
24h
36h
48h
60h
72h
Forecast times
GFDL operational
GFDL/URI coupled

Ocean Model (POM)

1/6º uniform, 23 sigma levels





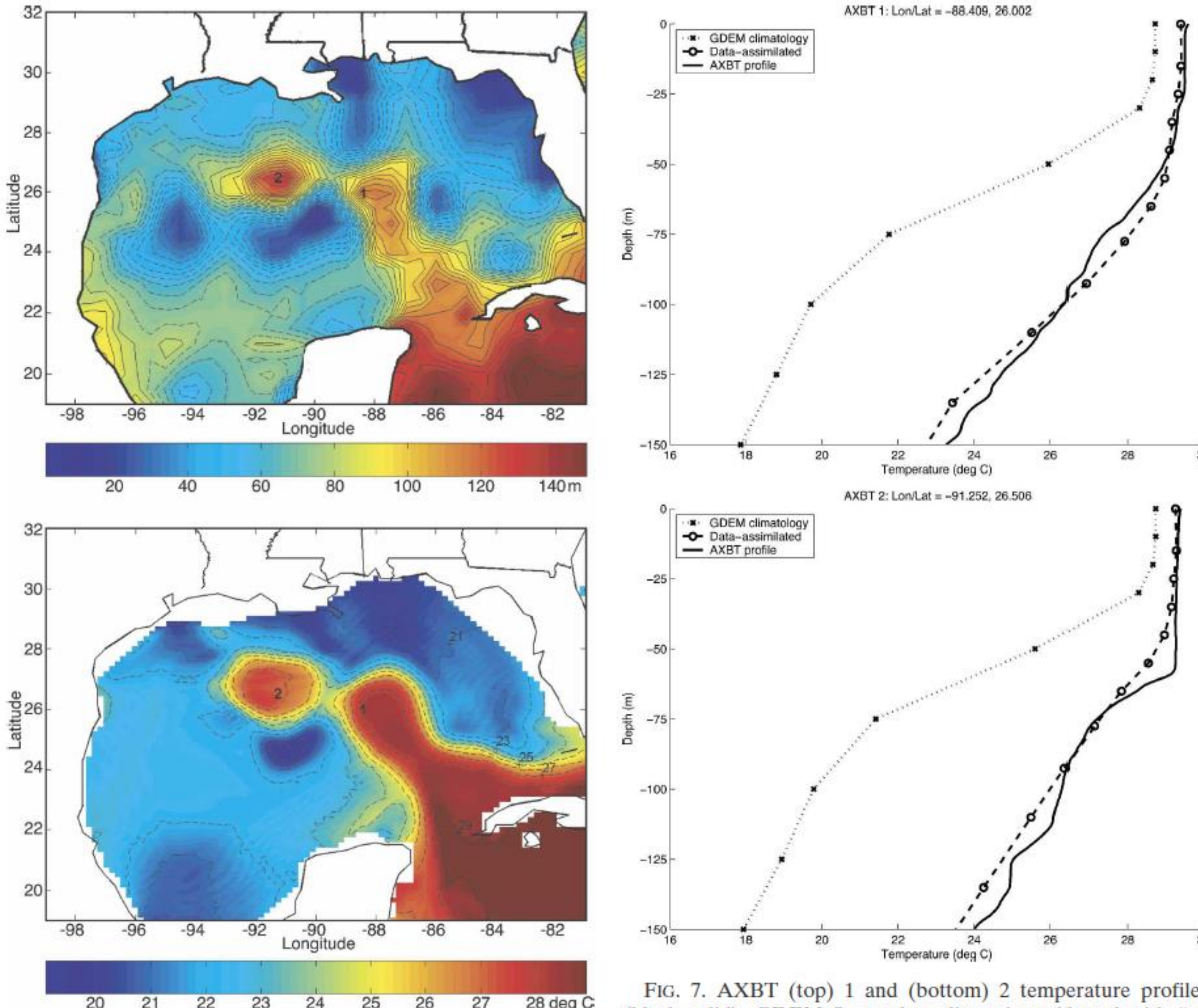
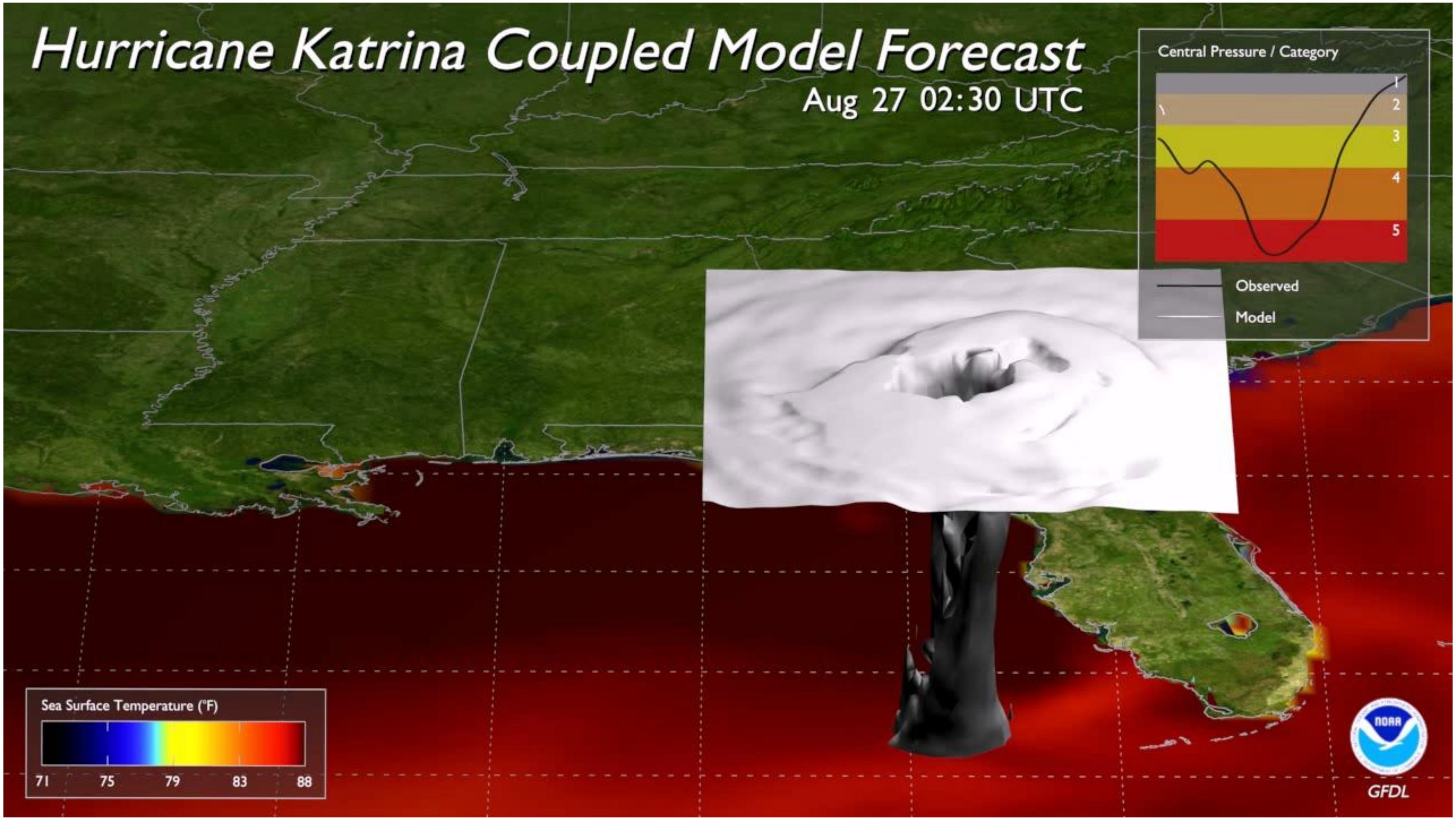


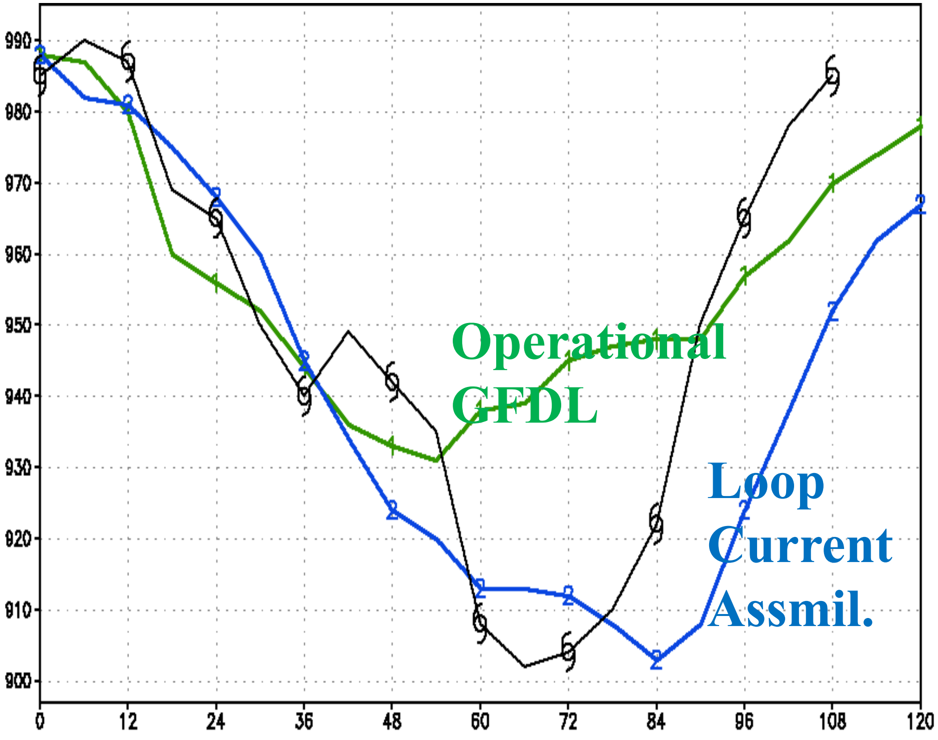
FIG. 7. AXBT (top) 1 and (bottom) 2 temperature profiles (black solid), GDEM September climatology (dotted with "x"

Example of impact of loop current in rapid intensification of Hurricane Katrina

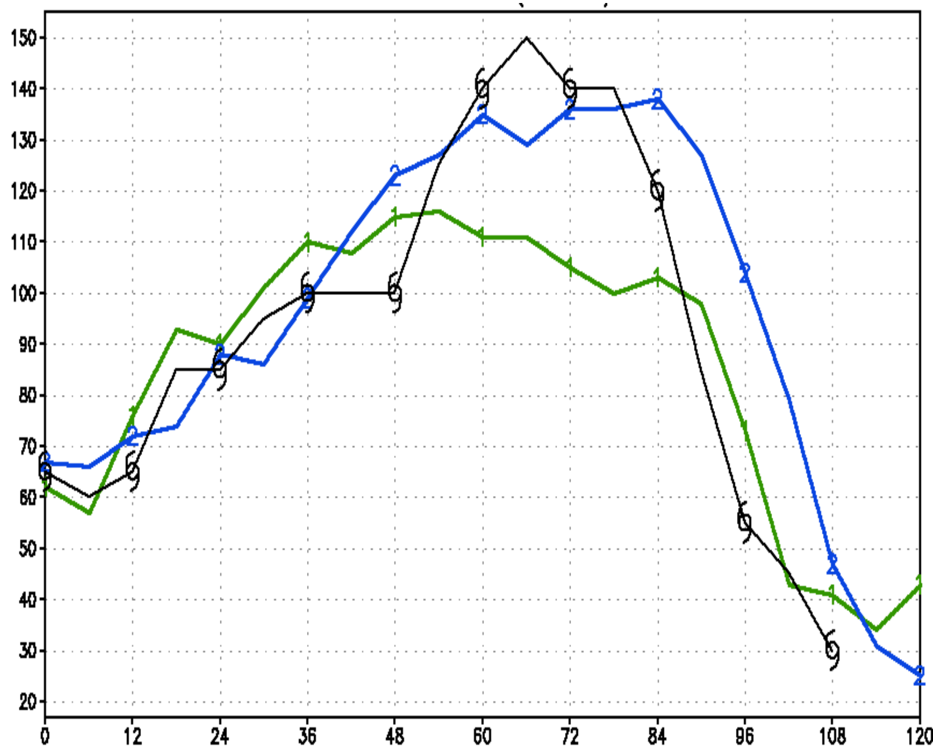


Improved Intensity Prediction with new loop current assimilation

Hurricane Katrina (Initial time: 1200 UTC 26th August



Min. Sea-level Pressure (hPa)



Max. Surface winds (knots)

New in 2002:

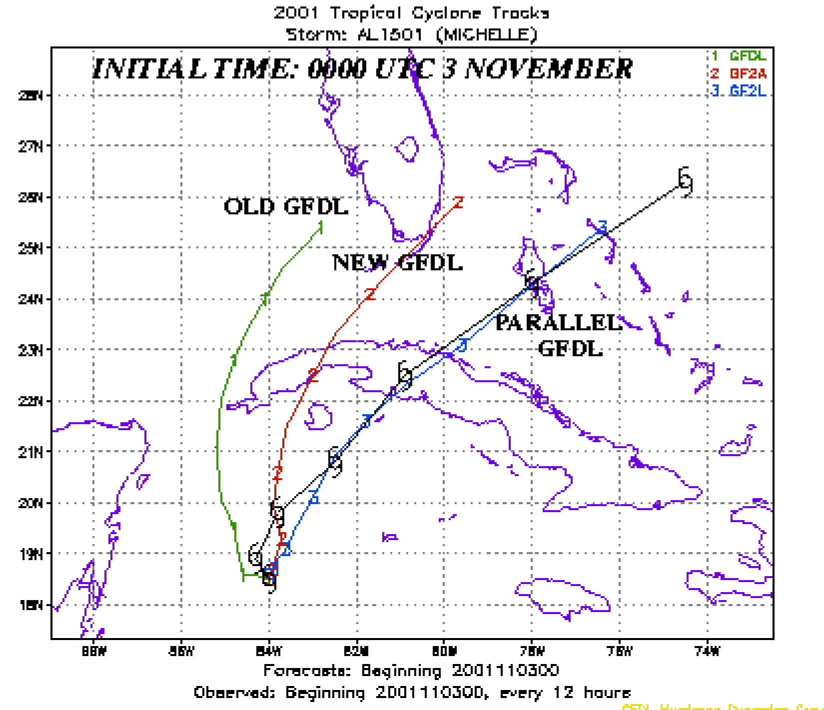
2 nests $\frac{1}{2}^{\circ}$, $1/6^{\circ}$

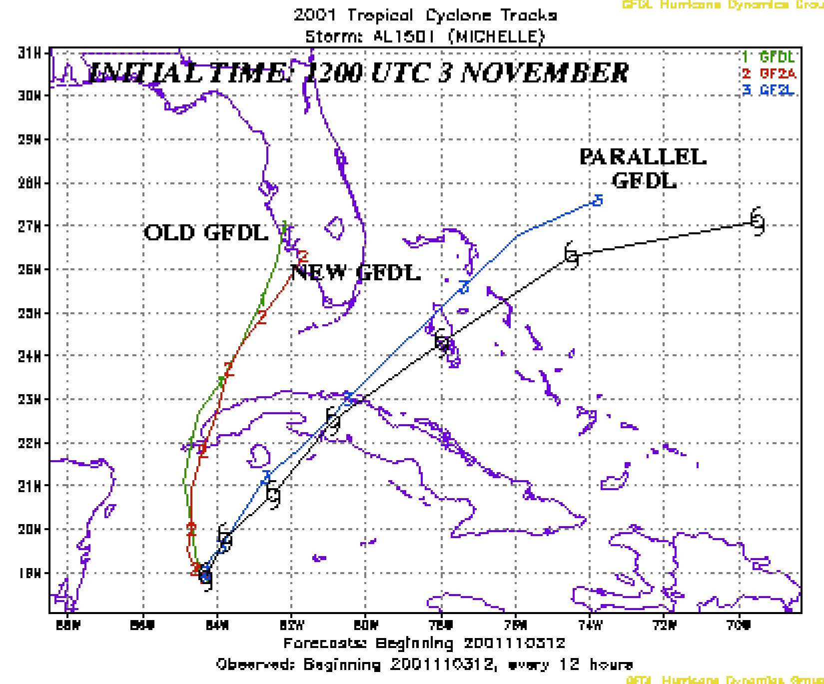
Filtering problem fixed…

New in 2003:

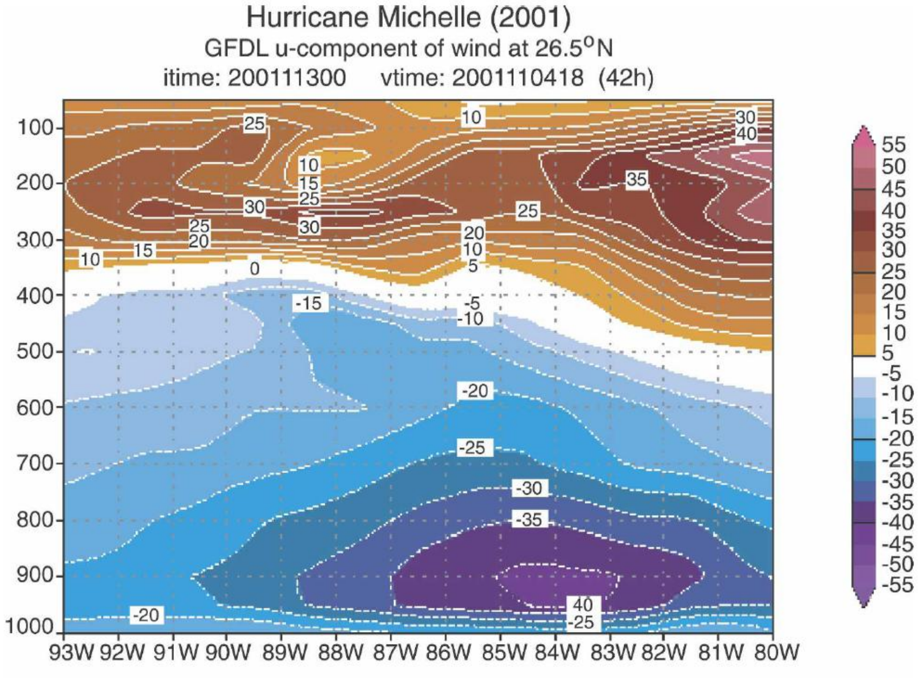
Replacement of convective Parameterization with GFS Simplified Arakawa Schubert scheme lead to better prediction of environmental field

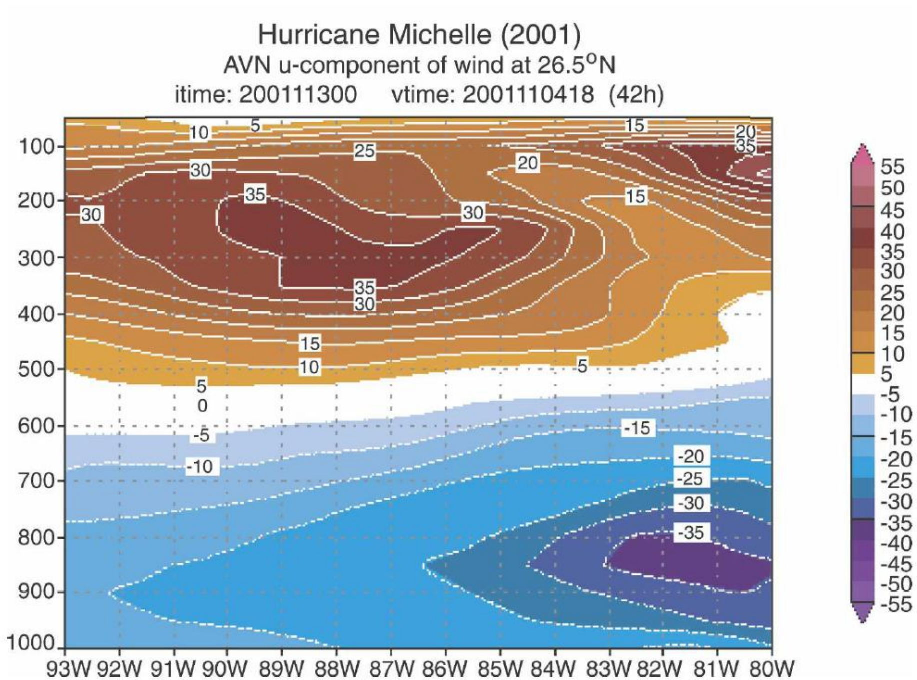
HURRICANE MICHELLE



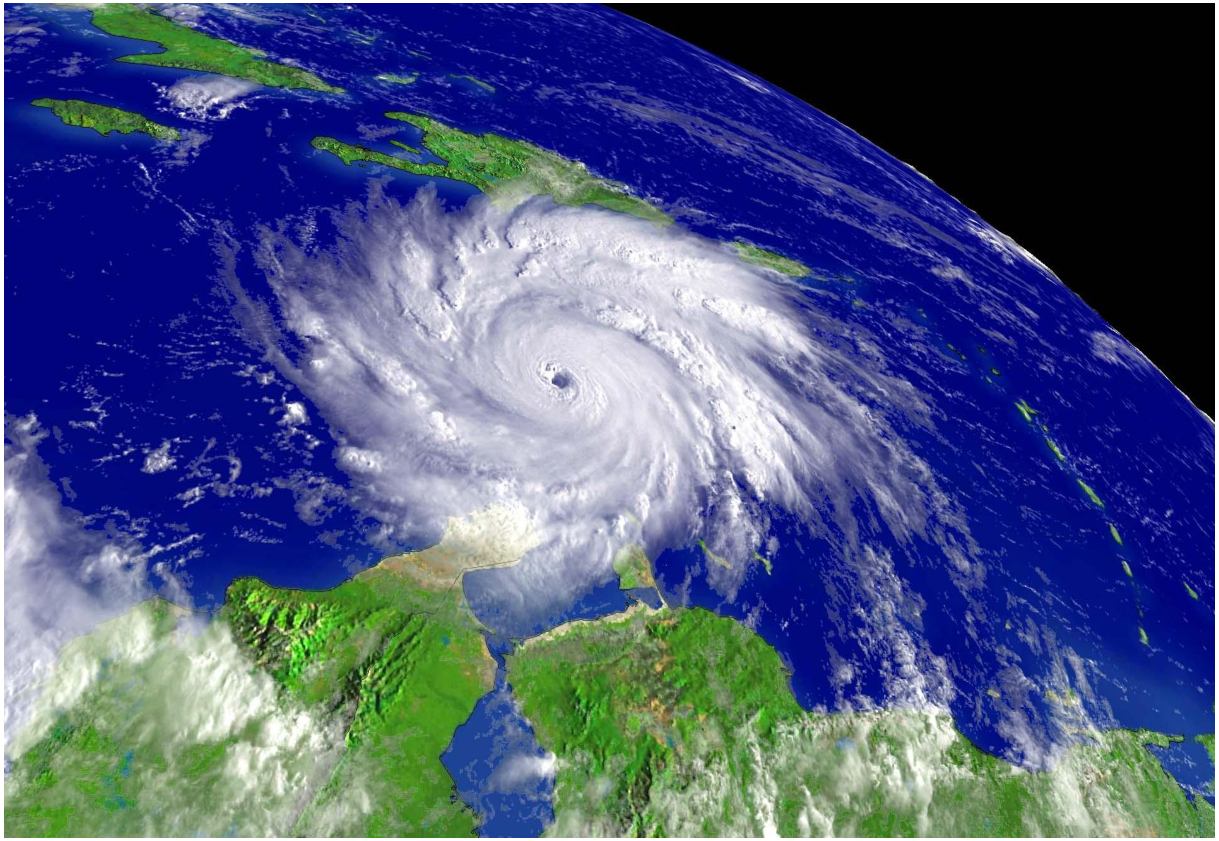


Old Convective Parameterization produced too strong Easterlies up to 400 hPa



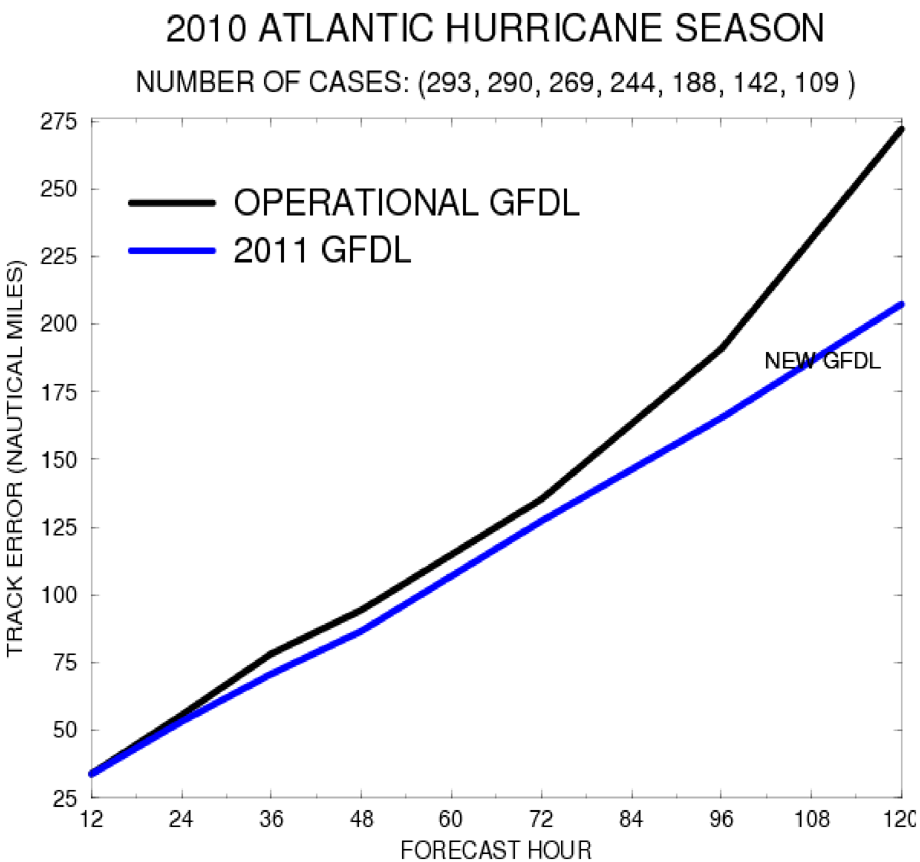


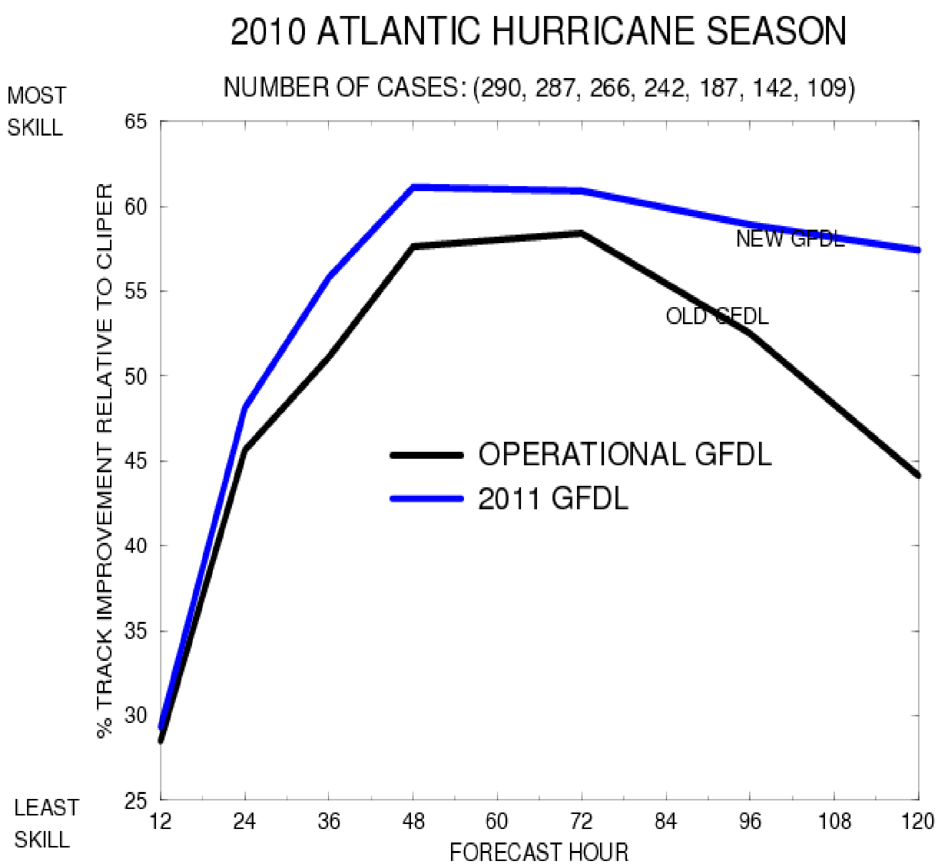
2011 Hurricane Model Upgrade



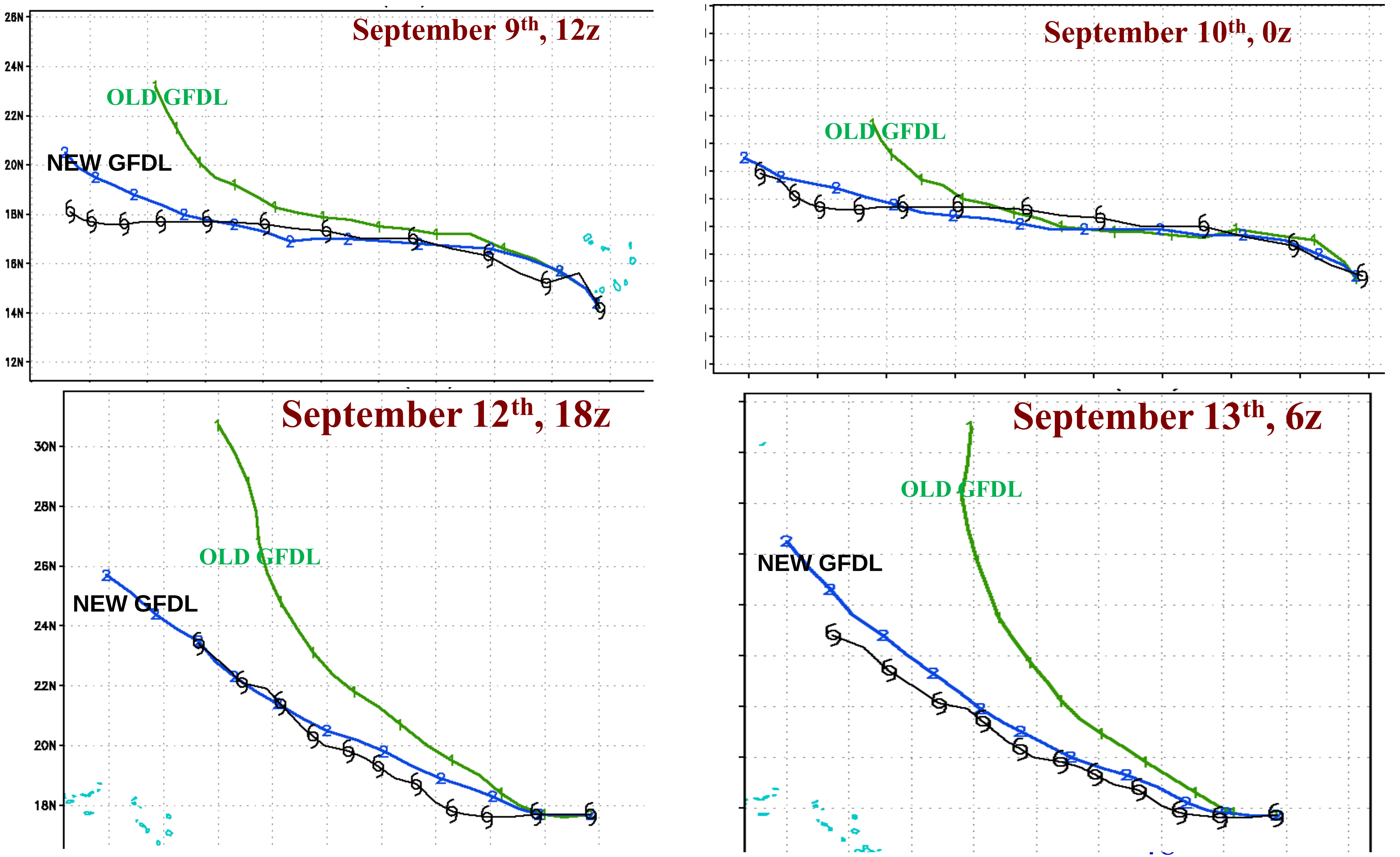
Decision to unfreeze GFDL Model in 2011 offered promising improvements for track prediction for upcoming season

Improvements in track for operational GFDL and HWRF primarily due to new GFS deep convection scheme

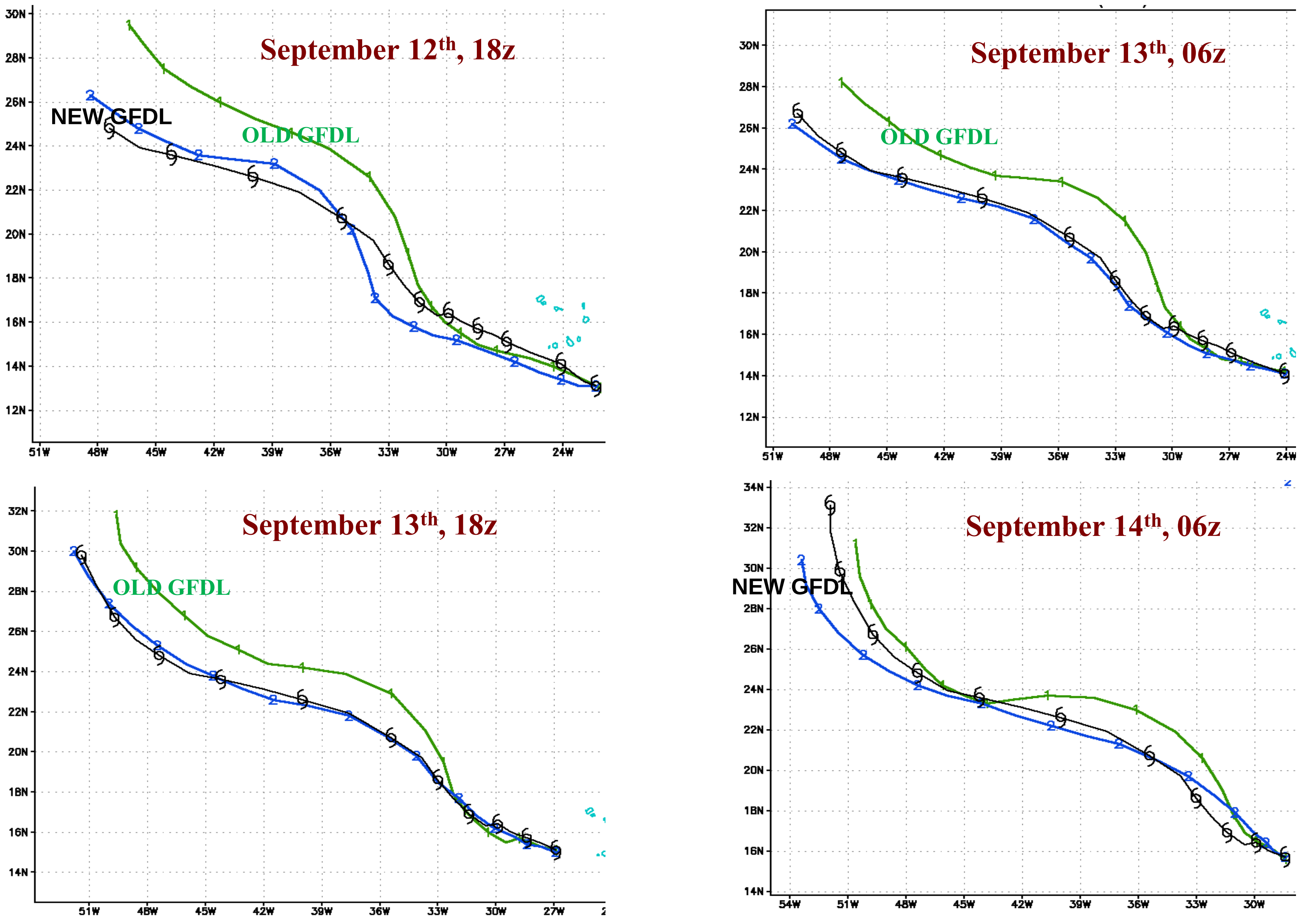




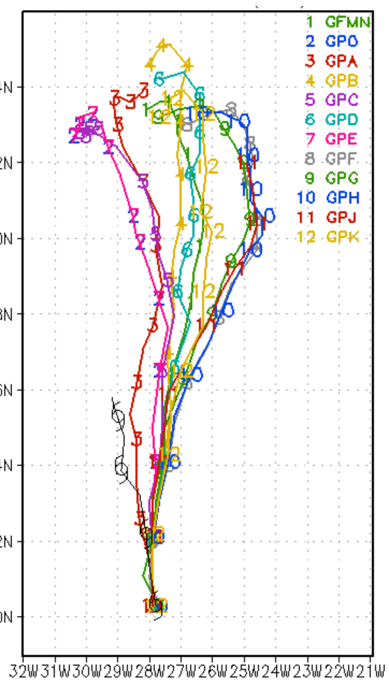
New Deep Convection produced stronger Subtropical Ridge and reduced north bias for Hurricane Igor



Hurricane Julia

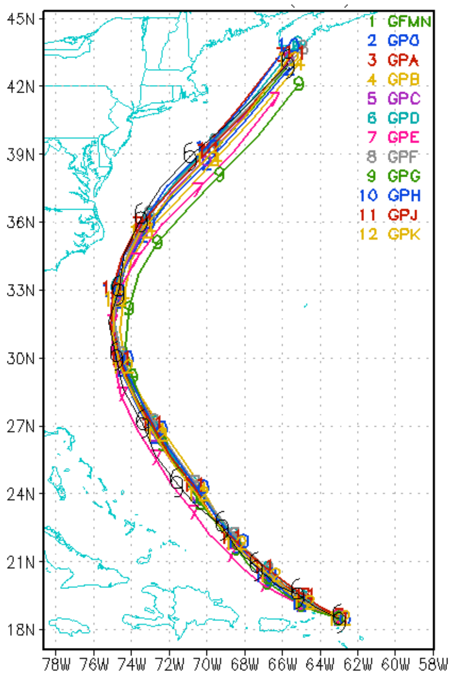


Use of GFDL Hurricane Model Ensemble to evaluate forecast spread

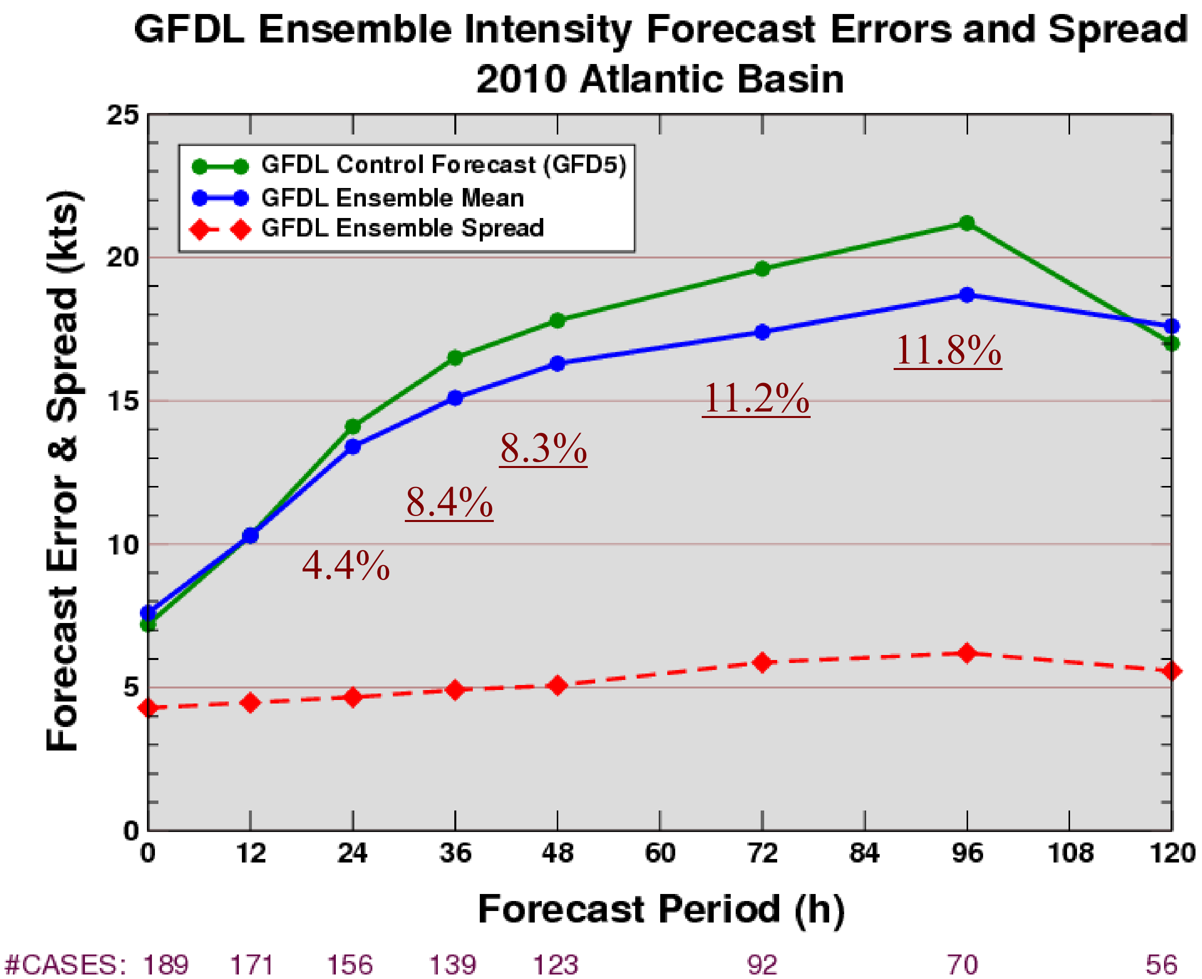


In 2010 test of GFDL Ensemble system the initial storm structure was perturbed, by increasing/decreasing storm size and radius relating to storm structure.

In 2011 version tunable parameters in physics will also be modified within reasonable limits.



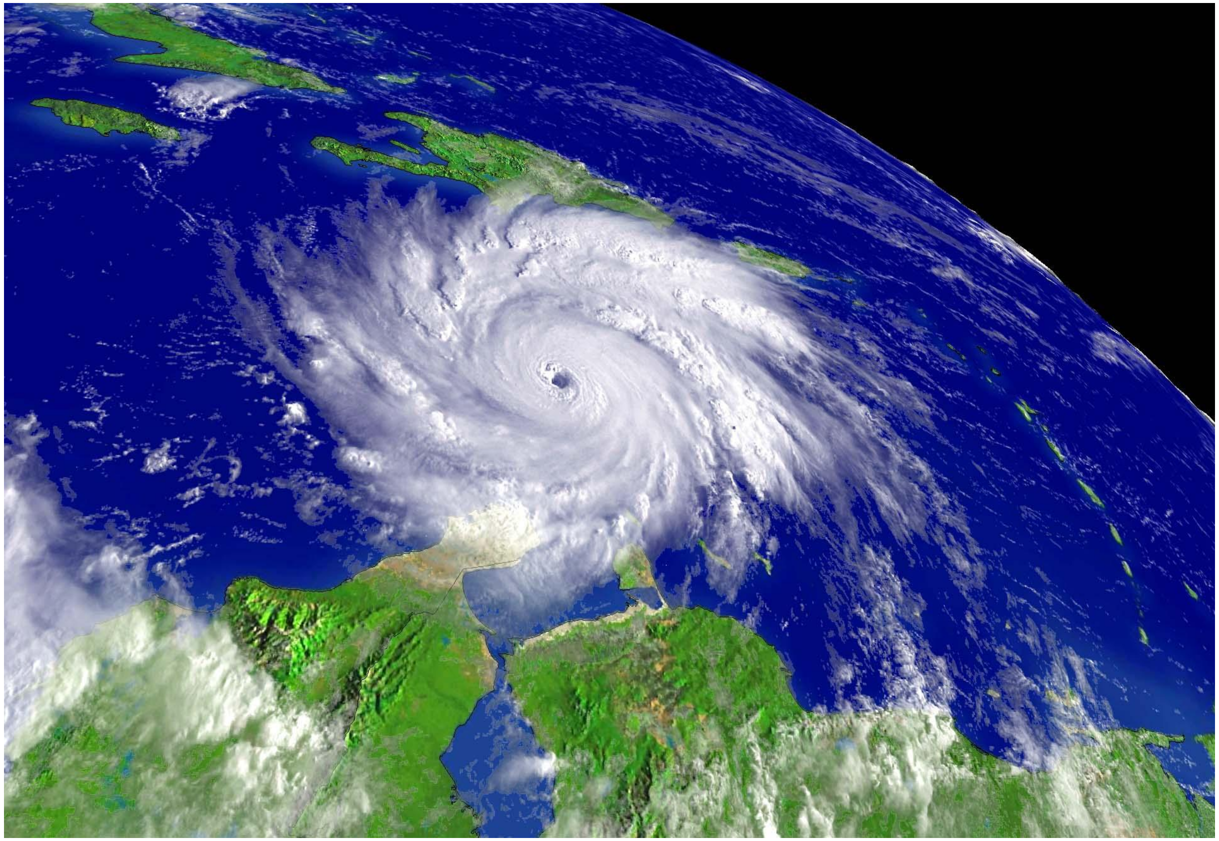
Intensity Results



Statistically significant improvements of the ensemble mean over the control are seen through the middle of the forecast period.

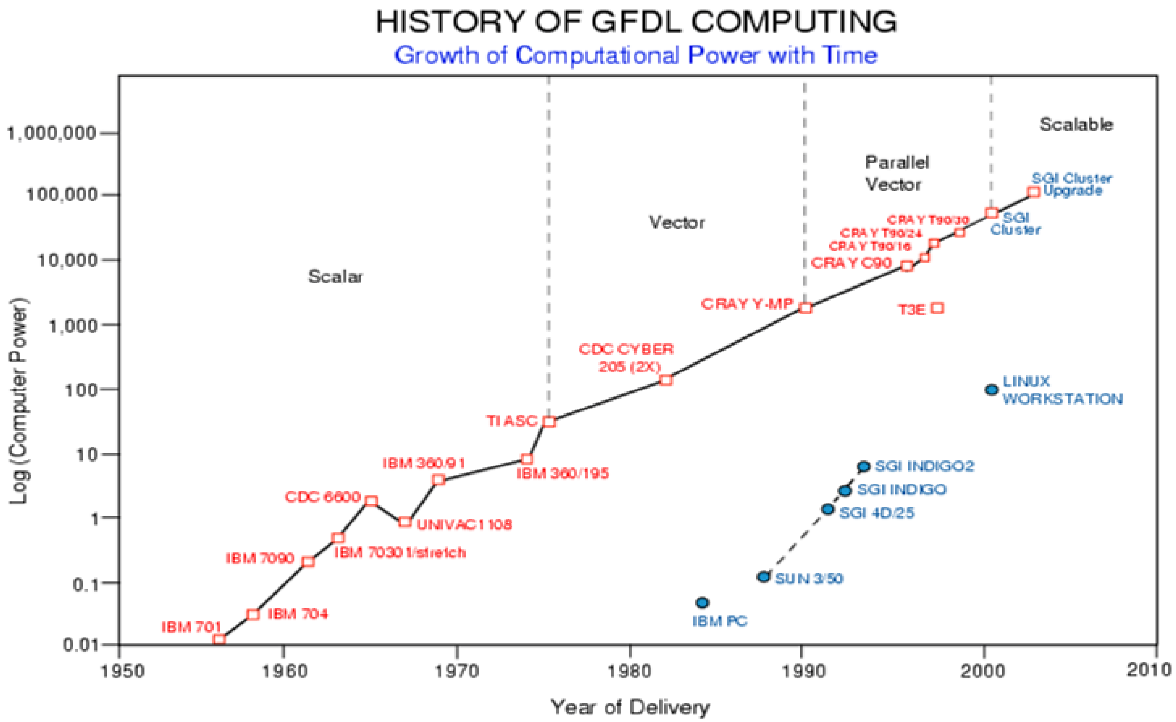
However, the spread results indicate an underdispersive ensemble

Where to go from here to maximize continued model improvements



Amazing exponential increase in computing power over past 50 years will continue in the future, enabling more resolution.

But do we have the adequate physics and correct vortex structure to take advantage of this



HFIP providing the basis for NOAA and other agencies to coordinate hurricane research needed to significantly improve guidance for hurricane prediction.

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, 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% in ten years with a forecast period out to 7 days. 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.

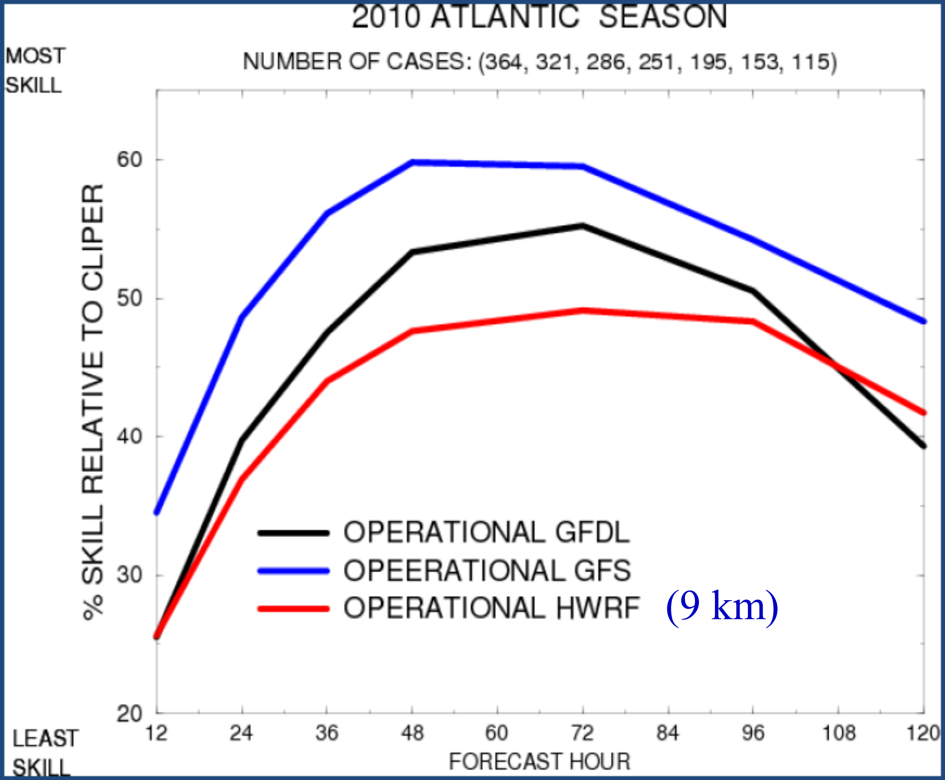
HFIP 2010
regional models run in near real time

***Participating Regional models*:**

– **HWRF (Operational)**	**9km**
– **GFDL (Operational)**	**7.5km**
– **HWRF-x (AOML)**	**3km**
– **WRF/ARW/NCAR**	**1.3km**
– **WRF/ARW/FSU**	**4km**
– **COAMPS-TC**	**5km**

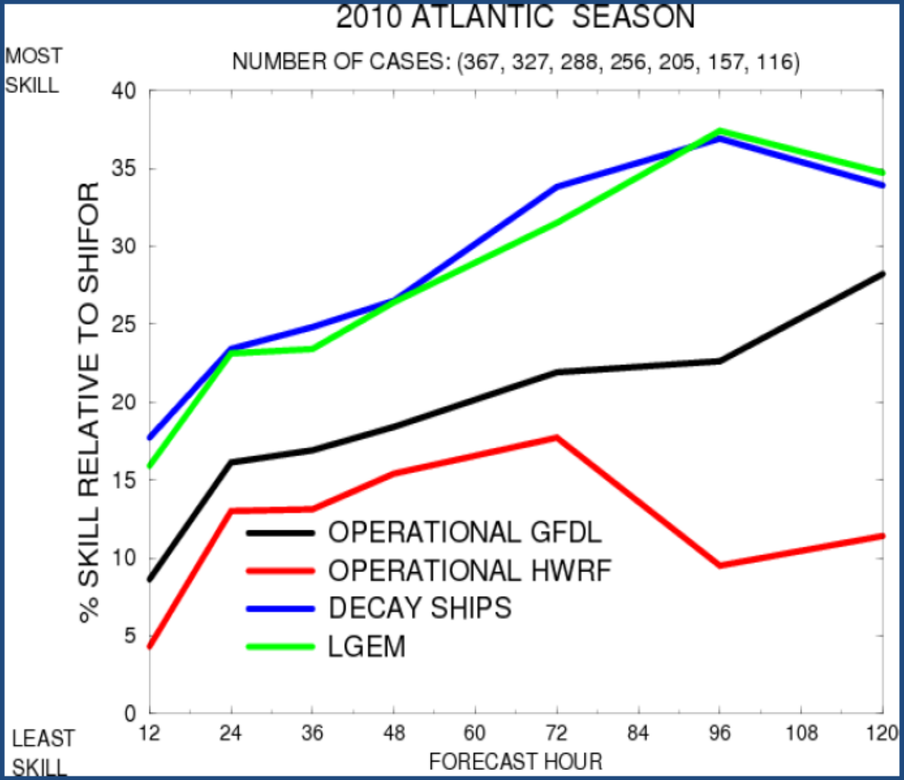
2010 Operational Verifications

NORMALIZED TRACK ERROR



GFS global model showed more skill for Track at Every Time Level (HWRF very poor performance in Tomas significantly affected its overall seasonal performance)

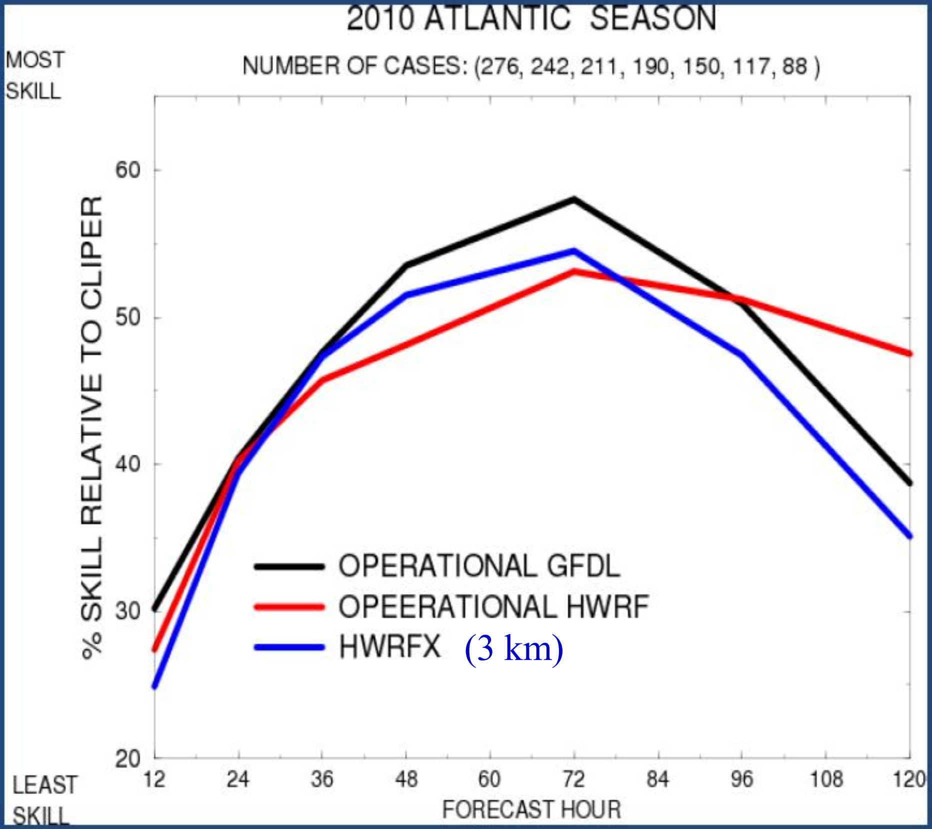
NORMALIZED INTENSITY ERROR



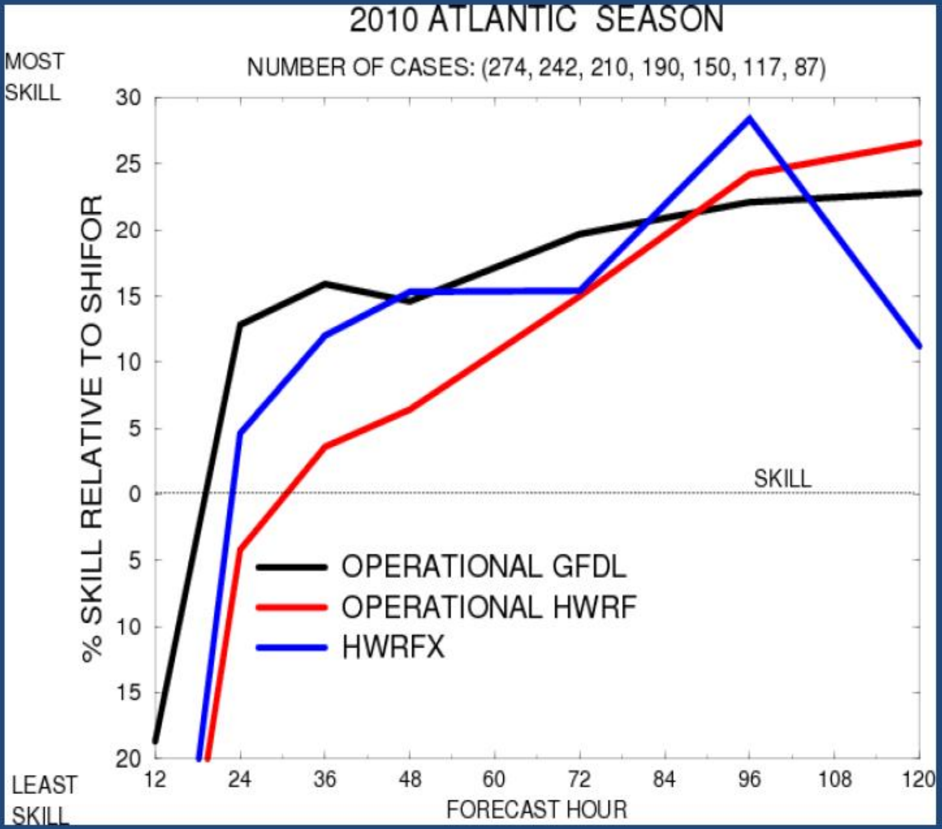
Operational Regional Models Still not as good as the statistical models for Intensity.
HWRF had significant negative bias

Late model Verification of HWRFx vs. Regional Operational Models

NORMALIZED TRACK ERROR



NORMALIZED INTENSITY ERROR

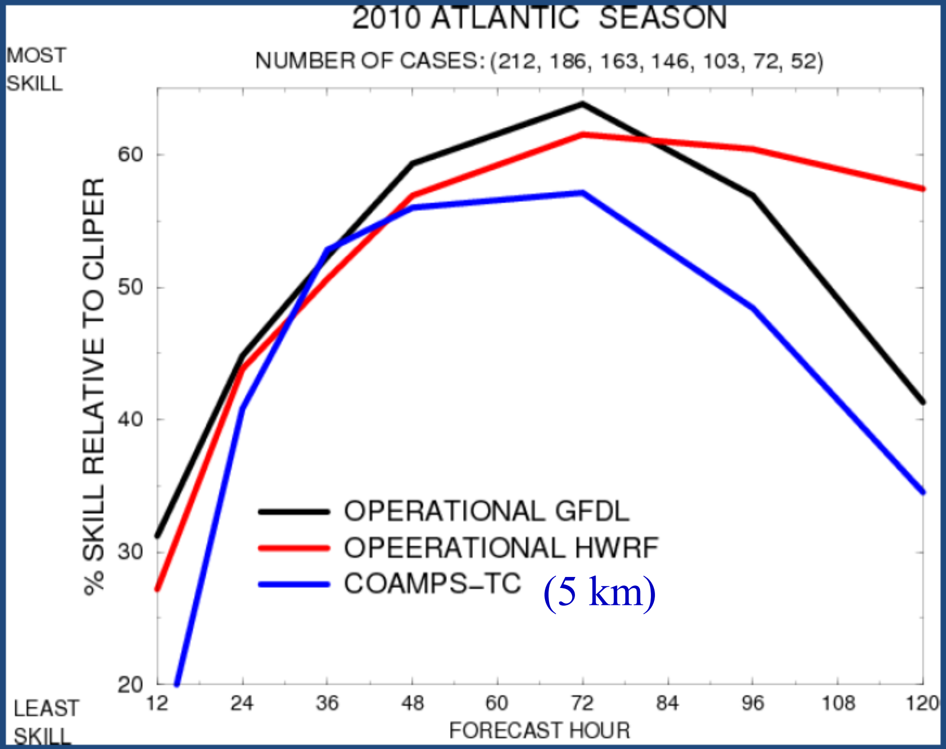


HWRFx Neutral or Inferior for Track

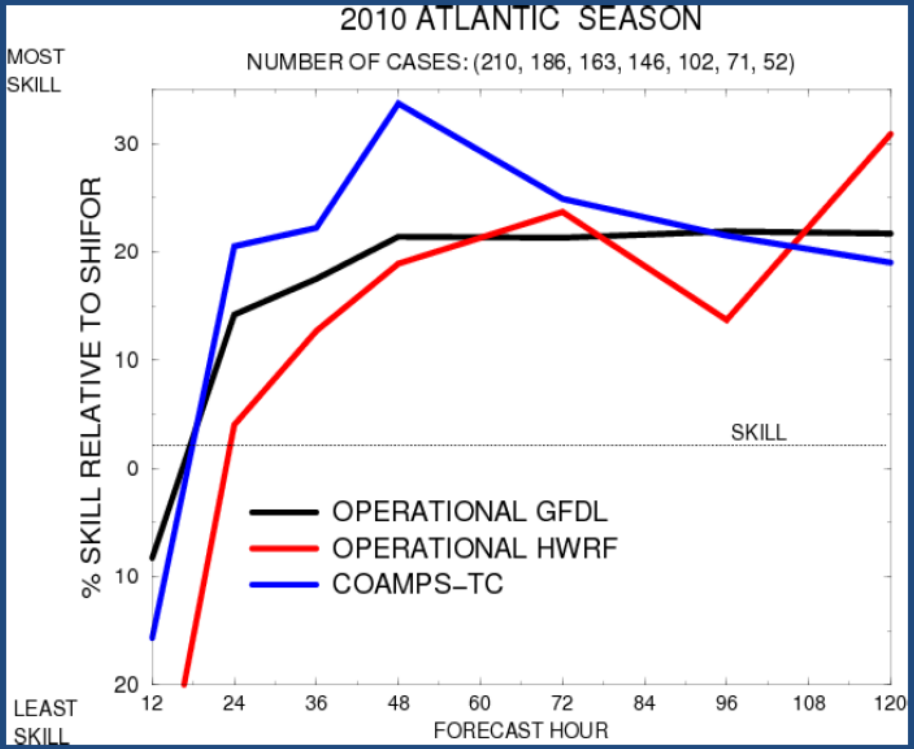
HWRFx Slightly Improved Intensity

Late model Verification of COAMPS-TC vs. Regional Operational Models

NORMALIZED TRACK ERROR



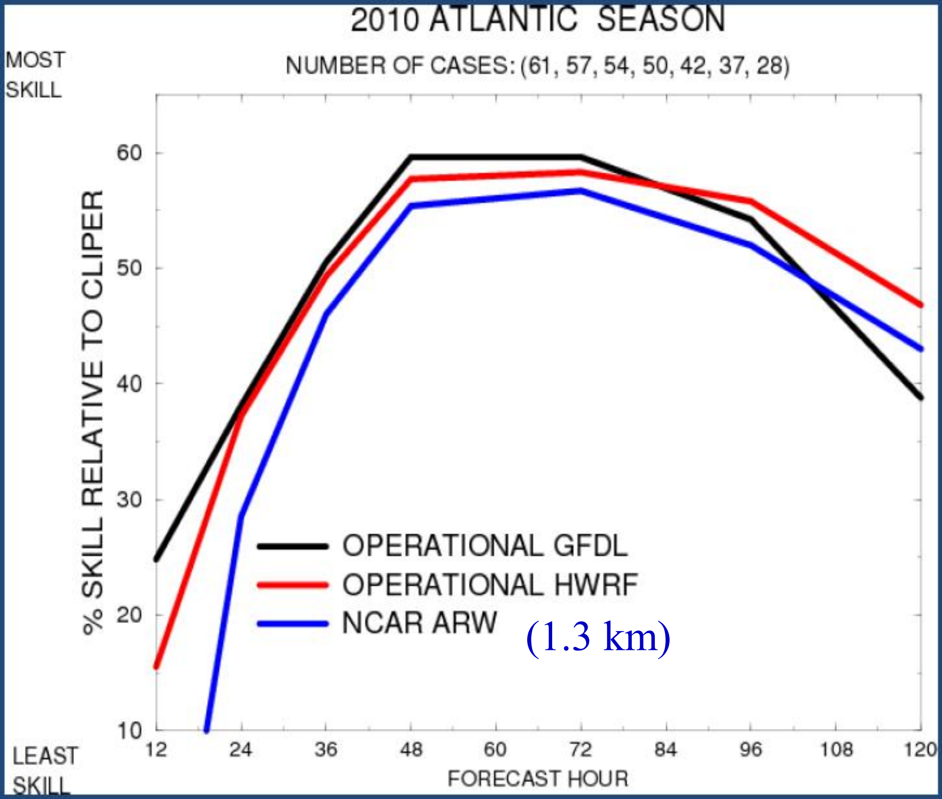
NORMALIZED INTENSITY ERROR



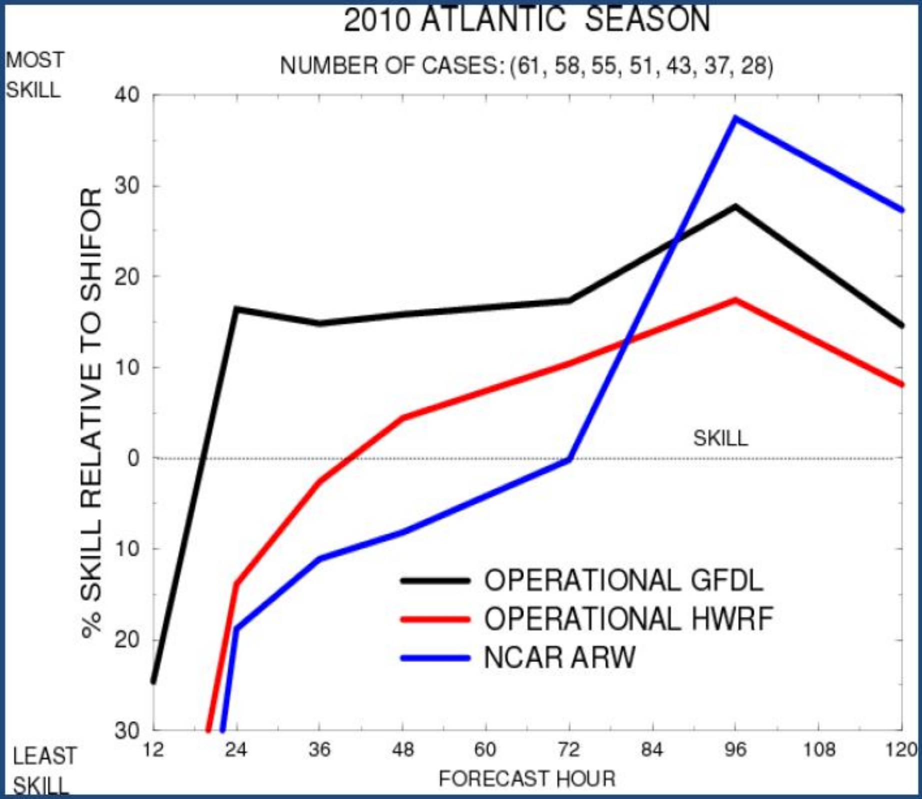
Most Skillful of the Regional Models for Intensity through 2 Days

Late model Verification of NCAR ARW vs. Regional Operational Models
(very limited data set for meaningful comparison)

NORMALIZED TRACK ERROR



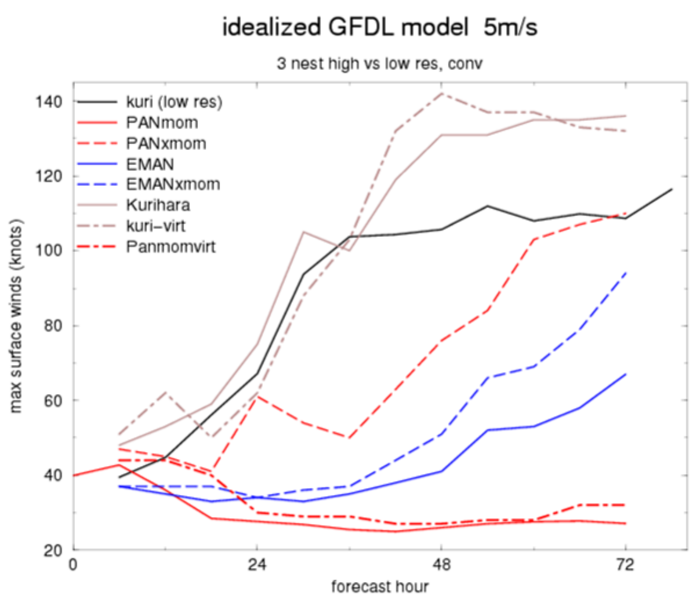
NORMALIZED INTENSITY ERROR



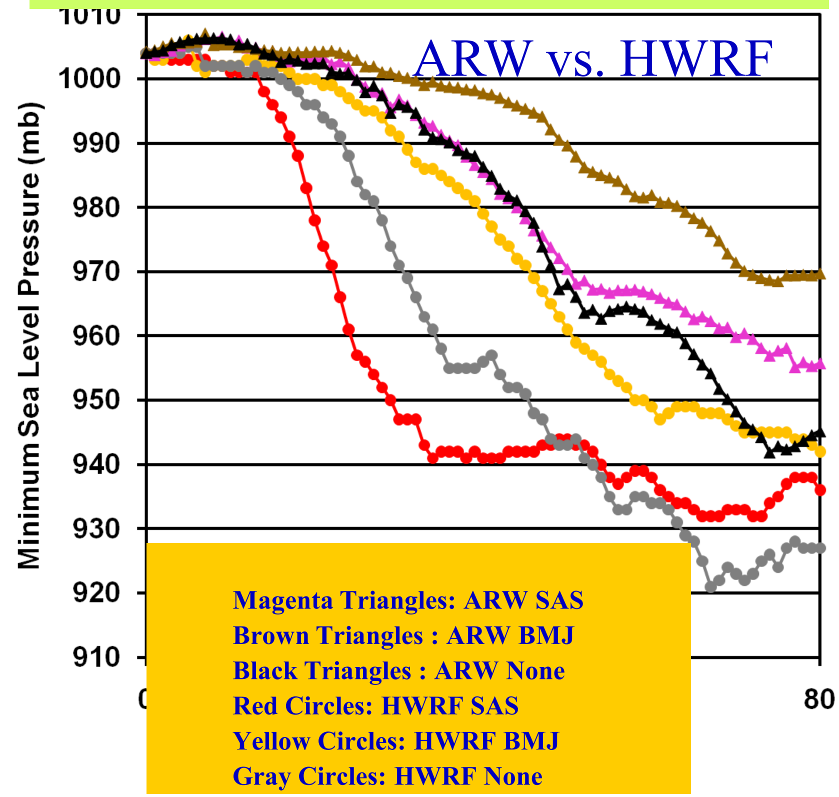
HOW PREDICTABLE ARE CHANGES TO INTENSITY ?
Does large sensitivity to small changes in physics suggest problem is inherently unpredictable, <u>or that we do not have the proper physics to properly simulated mechanisms responsible for intensity changes.</u>

Sensitivity to Convective Parameterization

Max. Surface winds (knots)

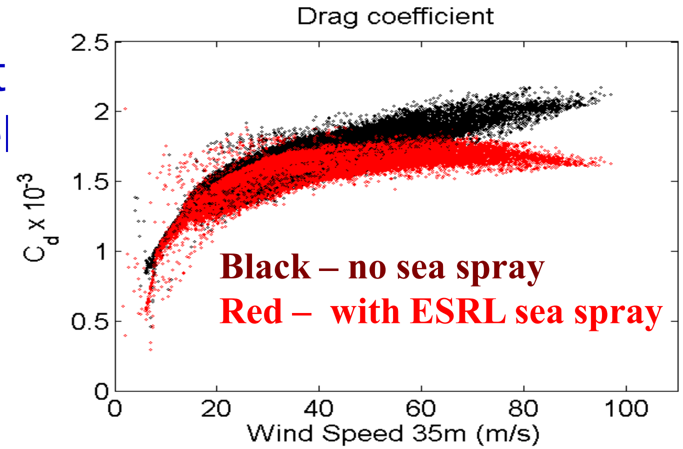


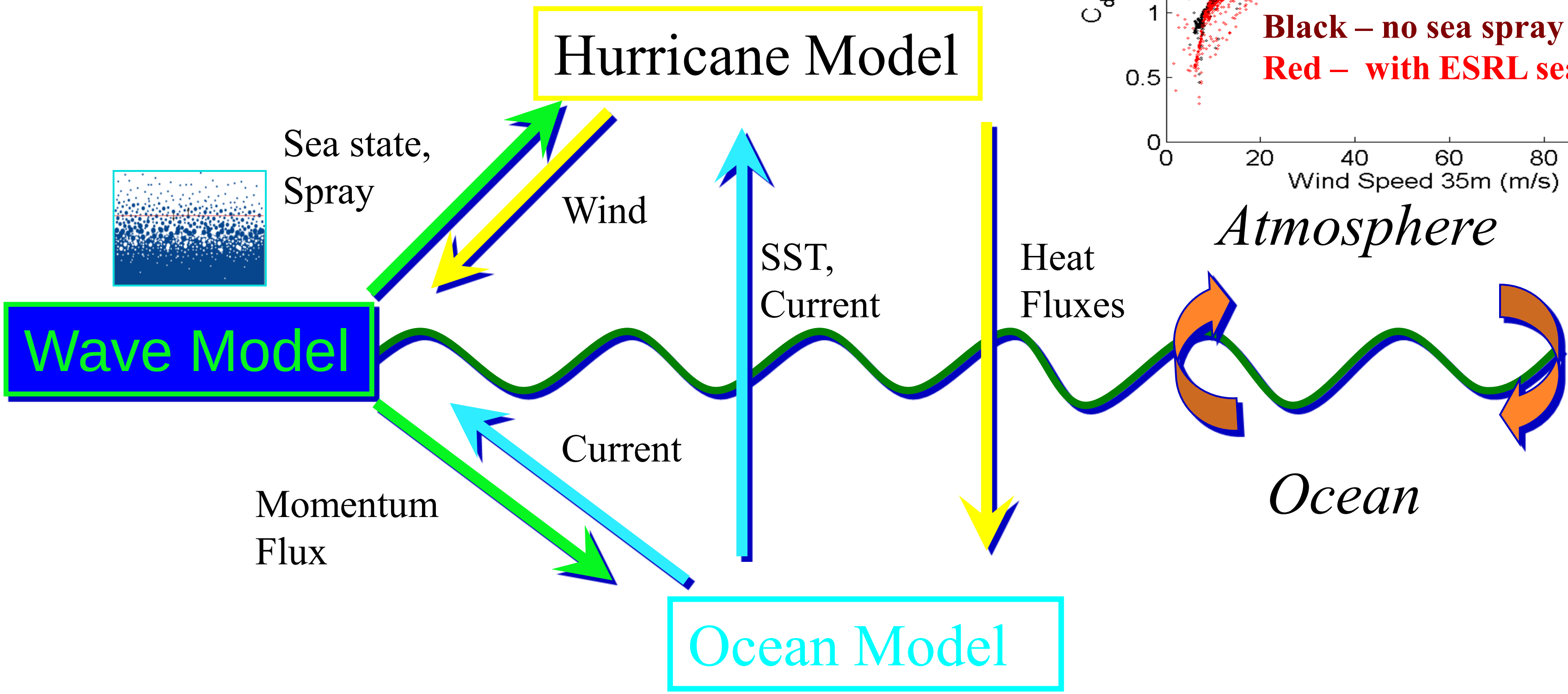
Min. Sea-level Pressure (mb)



Does this Demonstrate Need for New Level of Sophistication in Physics and DA Valid in Hurricane Conditions

Effect of Sea Spray on Drag Coefficient in GFDL Hurricane-Wave-Ocean Model





- Includes effects of wind-wave-current interaction and sea spray
- Allows for different algorithms of sea-state and sea-spray parameterization

Current HFIP development foci

1. Development of the Hybrid data assimilation system using a blend of GSI and EnKF. This system will be used for both regional and global models.
2. Further develop the ability to assimilate all aircraft derived data from the inner core.
3. Incorporate as much satellite data as possible taken around the hurricane core and its environment. The satellite data may further improve intensity forecasts over that provided by the aircraft data and will be necessary for those initializations (the majority) for which no aircraft data is available
4. Develop and test ensemble systems
5. Create output products from ensemble systems that help forecasters to use ensemble information to improve the official forecast
6. Emphasize development of statistical post processing systems using both ensemble and deterministic model information
7. Continue testing various physics options in both global and regional models

Summary of Lessons From Talk

•HFIP Regional Model Development is at a Crucial Crossroads to achieve its goals within 5 years to significantly improve intensity skill.

•Along with very promising development of new regional DA :
There should be a careful and focused effort to develop physics that will correctly represented hurricane inner core physics processes that can be adequately resolved at high resolutions. (upcoming physics workshop)

•Still need to devote resources to find out what is the minimum horizontal resolution needed to adequately resolve the hurricane inner core (1km, 2km, 3km ??)

•Collaboration between the academic community and NOAA will be essential to help achieve needed physics improvements.

•Closer collaboration is also needed between observational and model development teams to improve physics (e.g., surface, micro-physics)