



# Advancements to the Operational HWRF Modeling System at EMC

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**WRF for Hurricanes Tutorial, Science Day, DTC, Boulder, CO.  
Tuesday April 26, 2011**

# Overview of the Operational HWRF

## The HWRF Team

- **Vijay Tallapragada (Team Lead)**
  - Model development, T&E, operational support, verification and diagnostics
- **Robert Tuleya\***
  - Physics and Product Development
- **Qingfu Liu**
  - Vortex initialization and Physics
- **Young Kwon**
  - Physics and model development
- **Zhan Zhang**
  - Ensembles, pre-implementation testing
- **Sam Trahan**
  - Code management, product automation, software support, pre-implementation testing
- **Eric Aligo\***
  - Microphysics, radiation, model diagnostics
- **Janna O'Connor**
  - Graphics, website maintenance, organization of weekly meetings

- **MMAB Collaborators**
  - Hyun-Sook Kim
  - James Sims
  - Hae-Cheol Kim
  - Dan Iredell
- **DA Collaborators**
  - John Derber
  - Mingjing Tong
  - In-Hyuk Kwon
  - Emily Liu (JCSDA/HFIP)
- **GCWMB Collaborators**
  - Hua-Lu Pan
  - Dmitry Sheinin
  - Fanglin Yang
- **MMB Collaborators**
  - Dusan Jovic, Tom Black
  - Matt Pyle, Brad Ferrier
- **Ensemble Team**
  - Jiyayi Peng
- **Land Surface**
  - Yihua Wu
- **NHC**
  - Wallace Hogsett

Special Recognition to established DTC, AOML, TPC and HFIP partnerships

\* Works from ODU; \* New Hire

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## HWRF Atmosphere

- Movable, two-way nested vortex following grid
- 9km inner domain and 27km outer domain, 42 vertical layers
- Advanced physics from GFDL/GFS
- Advanced vortex initialization with GSI/3DVAR

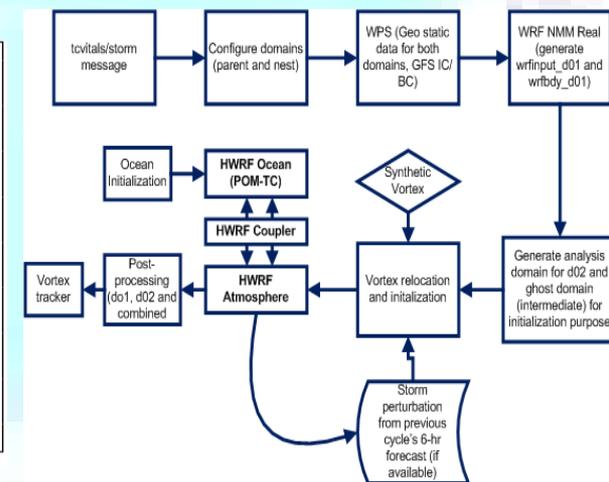
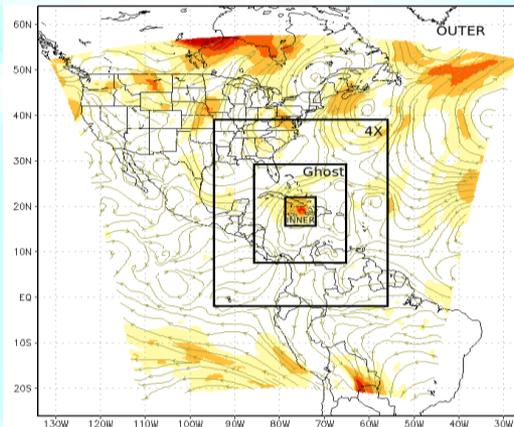
## HWRF Ocean

- Coupled to Princeton Ocean Model (POM) in the Atlantic Basin
- Feature based initialization of loop current and warm/cold core rings, cold wake specification during spin-up phase

## Operational HWRF products

- Numerical guidance on 6-hrly hurricane track and intensity for as many as five storms (both Atlantic and Eastern Pacific)
- High-resolution swaths (hourly, 10<sup>th</sup> of a degree) for wind and precipitation along the projected storm path
- Simulated GOES synthetic satellite imagery (IR, VIS and WV) and radar reflectivity

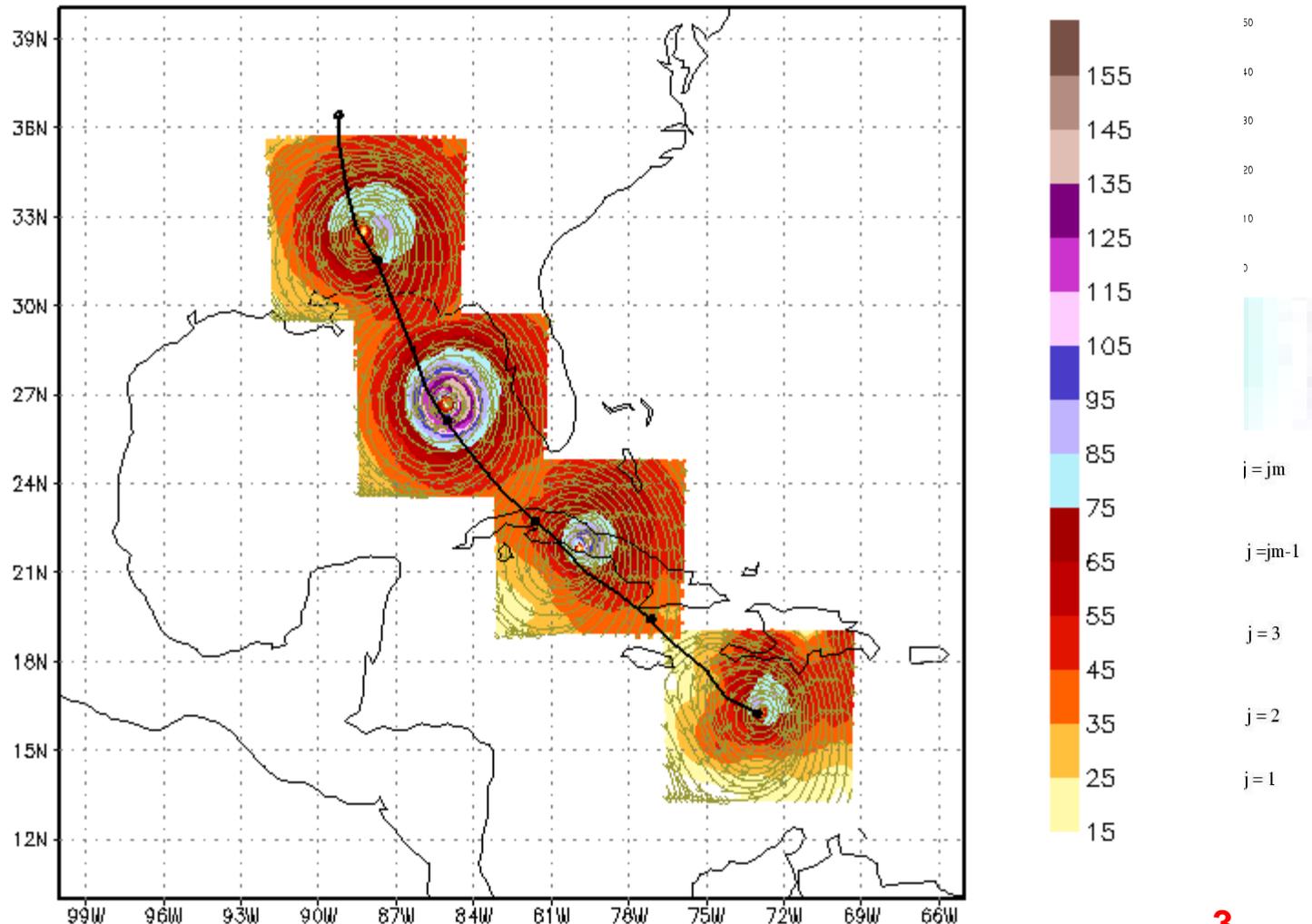
- Four years into operations, since 2007



# Design of movable nest

Plot of grid and subgrids

JUL 07, 2005 00Z: 120-hr HWRP Forecast, Hurricane Dennis  
(Winds at 850 hPa)



# Why the HWRF?

The HWRF is a next generation forecast system. It is an advancement over the GFDL in the following ways:

- In order to address intensity problem, we need higher resolution of hurricane core circulation to resolve more details of the storm structure. The hurricane circulation is driven by non-hydrostatic motions.
- HWRF is a non-hydrostatic model. GFDL is not.
- Also, the HWRF has its own analyses of the hurricane core. HWRF makes use of the operational data assimilation for the core initialization. This will allow the use of observations to help define the storm strength and structure. (GFDL does not have a vortex analyses and uses a bogusging technique for storm initialization)

# Evolution of HWRF

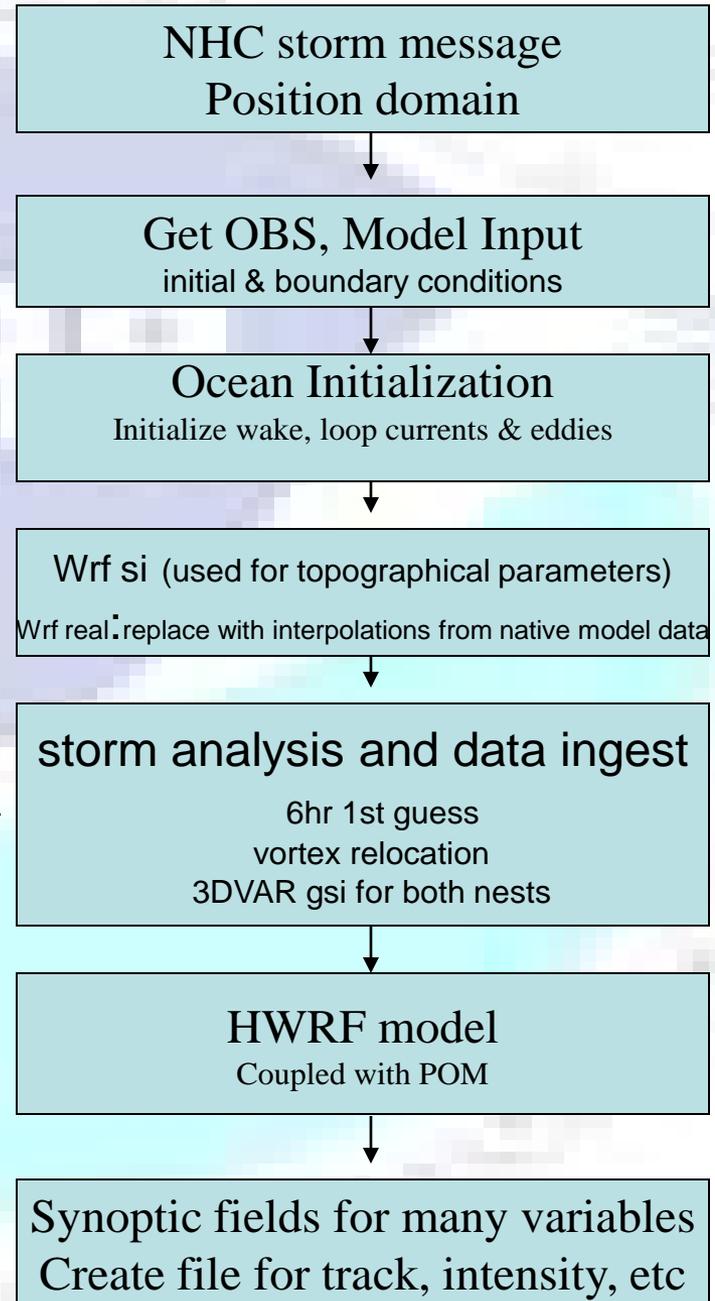
- **Initial implementation in 2007 hurricane season**
  - Model design and development of movable nested grid started in 2002
  - Initial HWRF workshop at NSF in 2004
  - 28 different configurations tested individually (each with about 200 simulations) before initial implementation
  - Extensive 3-season (2004-2006) pre-implementation testing of HWRF for all storms in the Atlantic and Eastern Pacific basins
- **Vortex initialization upgrades in 2008**
  - Address intensity bias for weaker systems, modifications to storm balance
- **Infrastructure upgrade and transition to P6 in 2009**
  - Capability enhancements to allow coupling to HyCOM and Wave Watch-III
  - Script enhancements (identical scripts for NCO operations and EMC parallels)
- **Physics and initialization upgrades in 2010 to improve the forecast skill.**
  - New baseline version with several bug fixes
  - Modified surface physics formulation and use of Gravity Wave Drag parameterization
  - Addition of satellite radiance data assimilation in the hurricane environment
  - Focus on reducing intensity bias

# HWRF

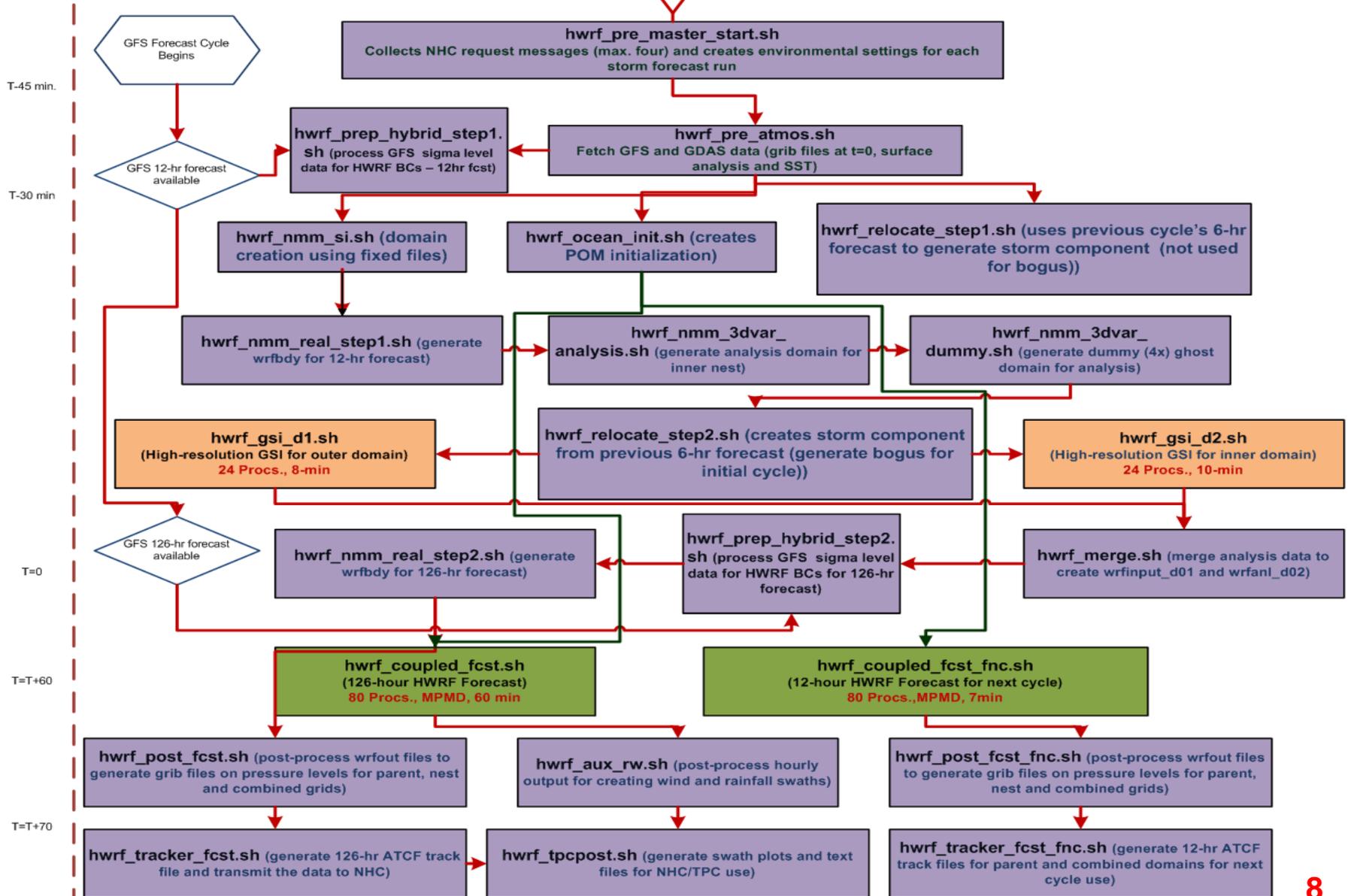
# GFDL

|                             |                          |                                    |
|-----------------------------|--------------------------|------------------------------------|
| Grid configuration          | 2-nests (coincident)     | 3-nests(not coincident)            |
| Nesting                     | Force-feedback           | Interaction thru intra-nest fluxes |
| Ocean coupling              | POM (Atlantic only)      | POM                                |
| Convective parameterization | SAS                      | SAS                                |
| Explicit condensation       | Ferrier                  | Ferrier                            |
| Boundary layer              | GFS non-local            | GFS non-local                      |
| Surface layer               | GFDL ..(Moon et. al.)    | GFDL ..(Moon et. al.)              |
| Land surface model          | GFDL slab                | GFDL slab                          |
| Dissipative heating         | Based on D-L Zhang       | Based on M-Y TKE 2.5               |
| Radiation                   | GFDL (cloud differences) | GFDL <b>6</b>                      |

# HWRF Operational Hurricane Forecast System



# NCEP Operational HWRF-POM Coupled Modeling System for Hurricane Forecasts



# Hurricane Forecast System Requirements Document for T20

Requirements document co-written between EMC and NHC for transition to NCEP operations of a new candidate hurricane model...or for annual or periodic upgrades to an existing operational hurricane model for transition to NCEP operations.

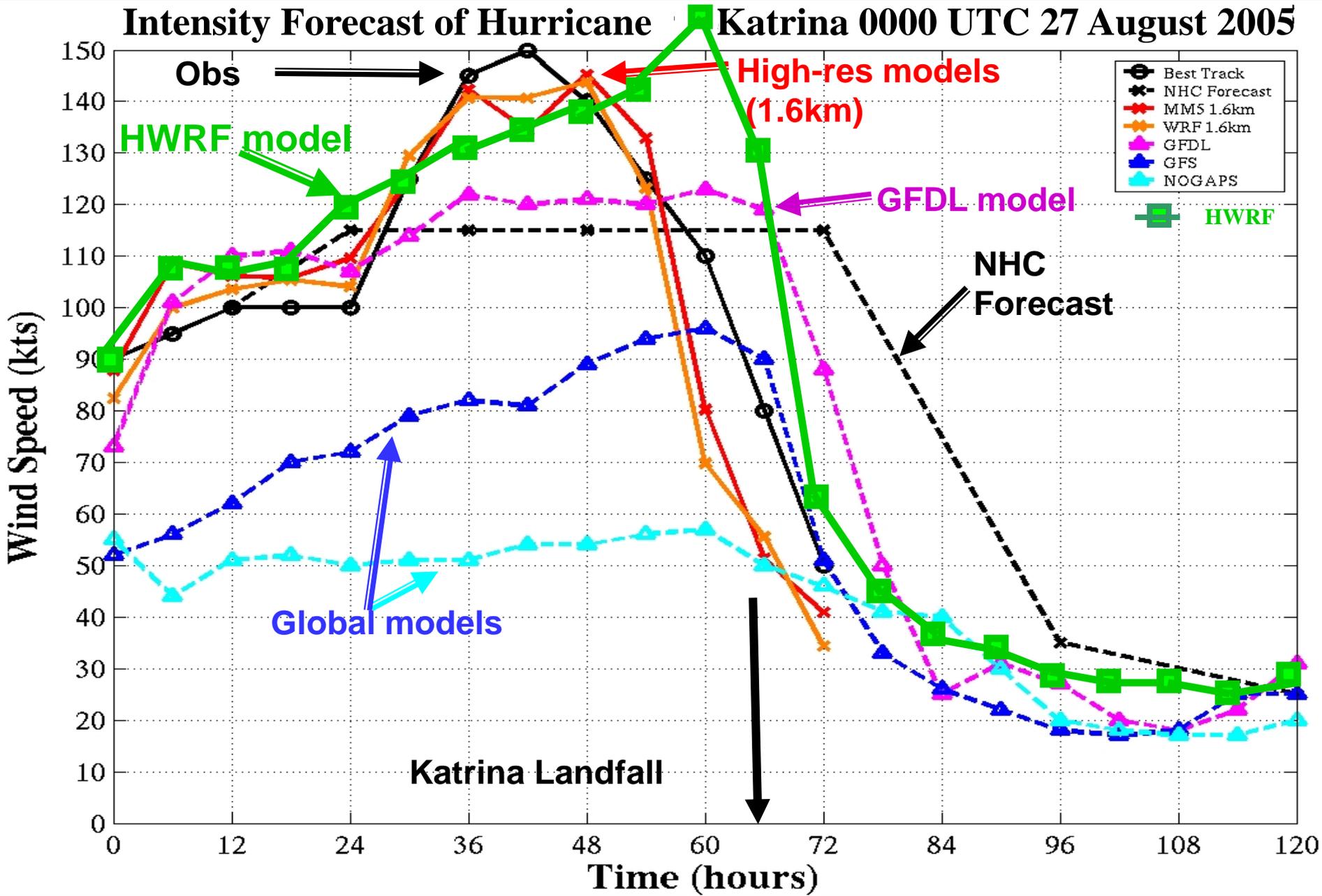
**Sets standards for:**

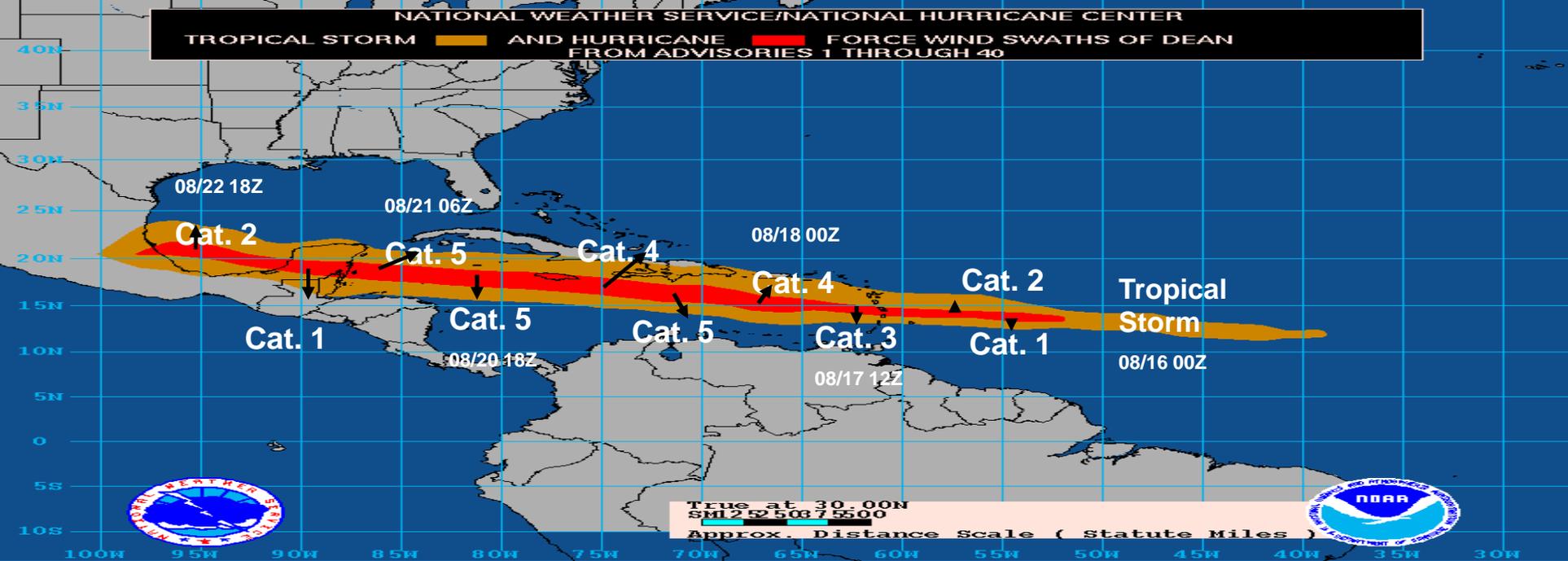
**Performance testing – case load, evaluation criteria**

**System functionality – initialization, coupling**

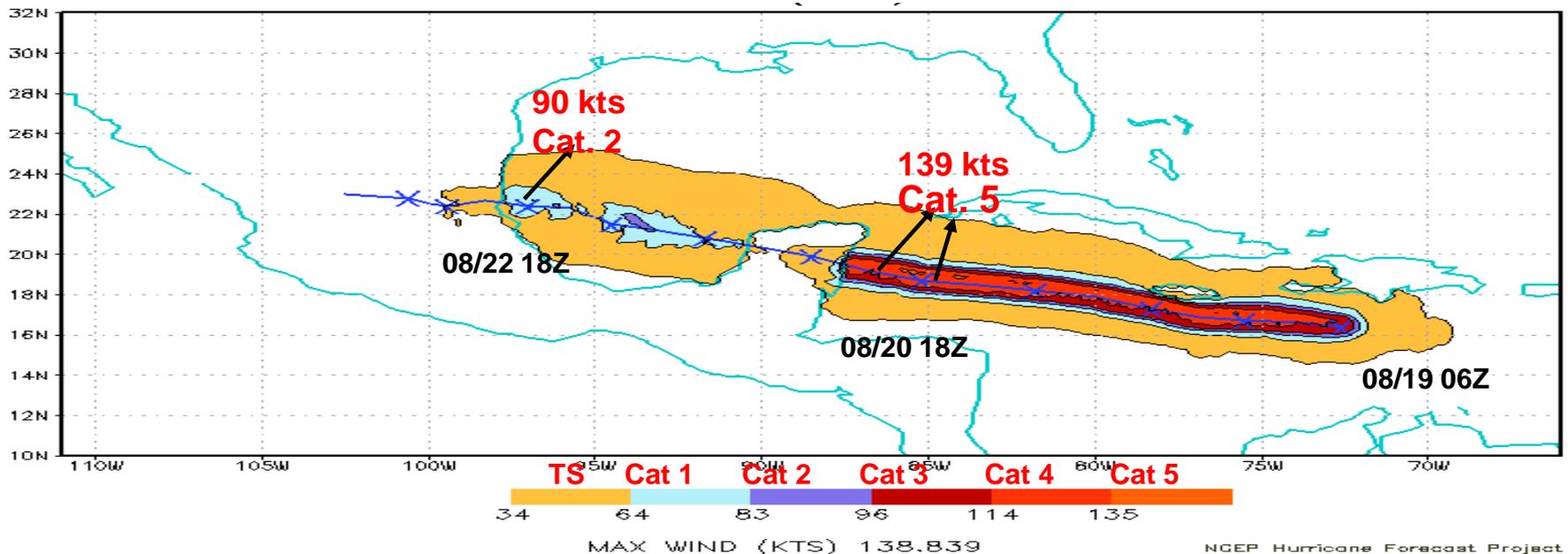
**Computational performance**

Research model forecasts of storm intensity for Hurricane Katrina  
showing benefit of high (1.6km) resolution (S. Chen)





## Hurricane Dean 5 day forecasts of maximum winds starting from 8/19/06Z



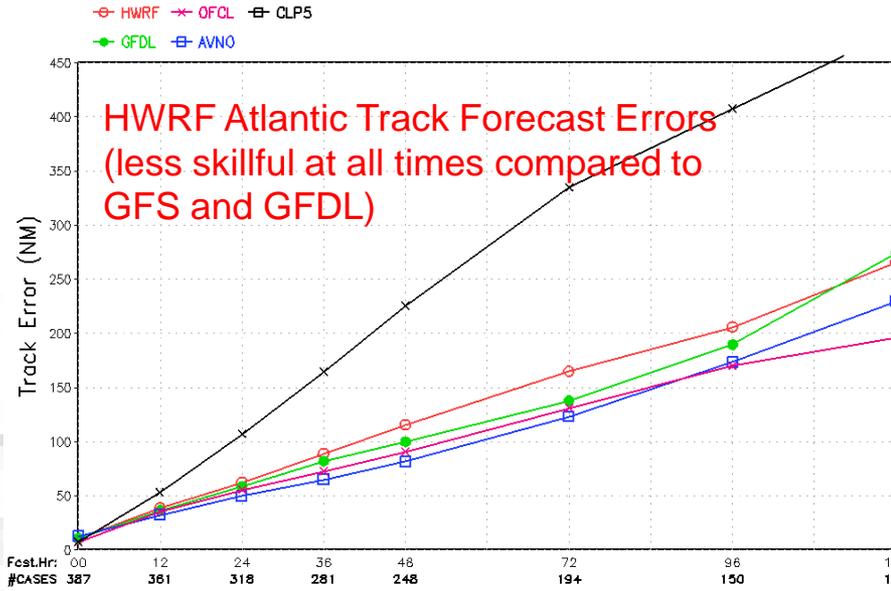
# 2010 HWRF operational configuration

- **Based on WRF NMM Dynamic Core V2.0**
  - Movable, two-way nested vortex following grid
  - 9km inner domain (6 x 6° domain) and 27km outer (75 x 75° domain)
  - 42 vertical layers
- **Advanced physics (tested in GFDL and GFS)**
- **Advanced vortex initialization that uses GSI 3D-var assimilation**
- **Coupled to Princeton Ocean Model (POM) with feature based initialization of loop current and warm/cold core rings and cold wake specification**
- **Upgrades/changes to the operational FY2009 HWRF configuration to improve the forecast skill:**
  - **New baseline version with several bug fixes for radiation, land surface temperature and non-hydrostatic advection of vertical velocity**
  - **Modified surface physics formulation based on observed profiles of drag coefficients for momentum and heat fluxes**
  - **Gravity Wave Drag parameterization**
  - **Addition of satellite radiance data assimilation in the hurricane environment**
- **Additional operational products**
  - **Simulated GOES synthetic satellite imagery (IR, VIS and WV) and radar reflectivity**
  - **MLD and OHC from POM and operational archival of ocean output**
  - **Operational capability to run 5<sup>th</sup> storm**

# Performance of the Operational HWRf for 2010 ATL hurricane season

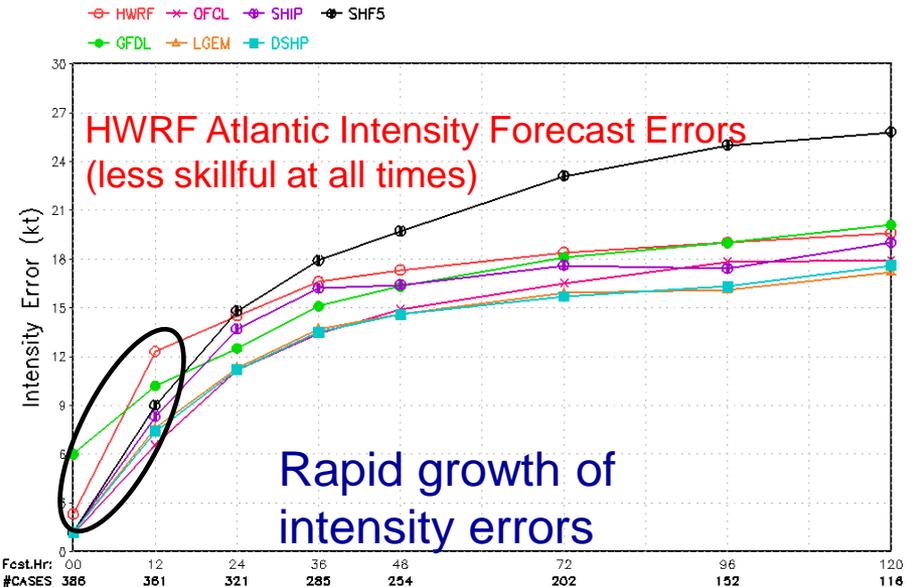
Average Track Errors (NM)

Operational Statistics Plots – ALL 2010 ATLANTIC through TOMAS21L



Average Intensity Errors (kt)

Operational Statistics Plots – ALL 2010 ATLANTIC through TOMAS21L

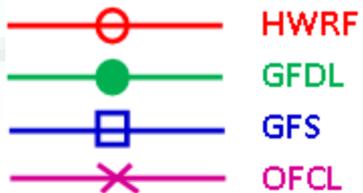
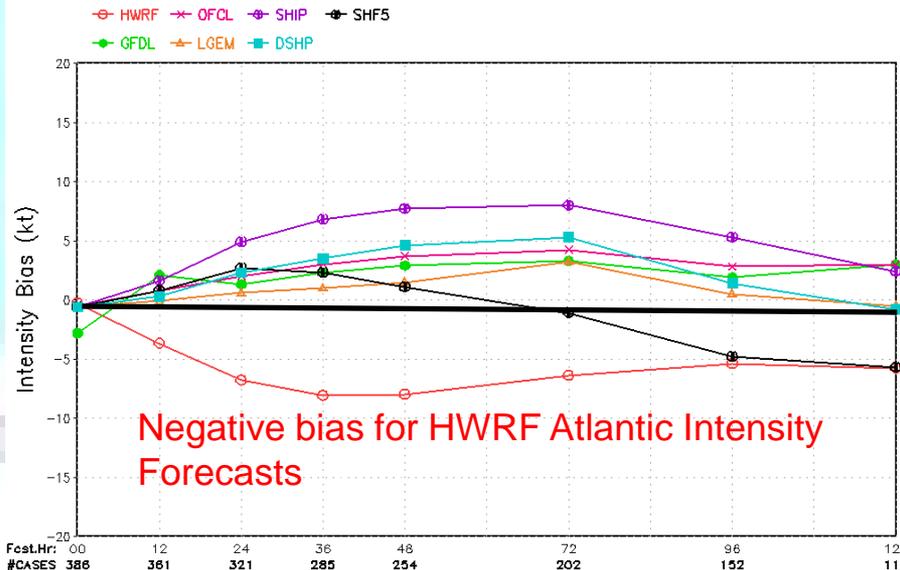


NCEP Hurricane Forecast Project

NCEP Hurricane Forecast Project

Intensity Bias (kt)

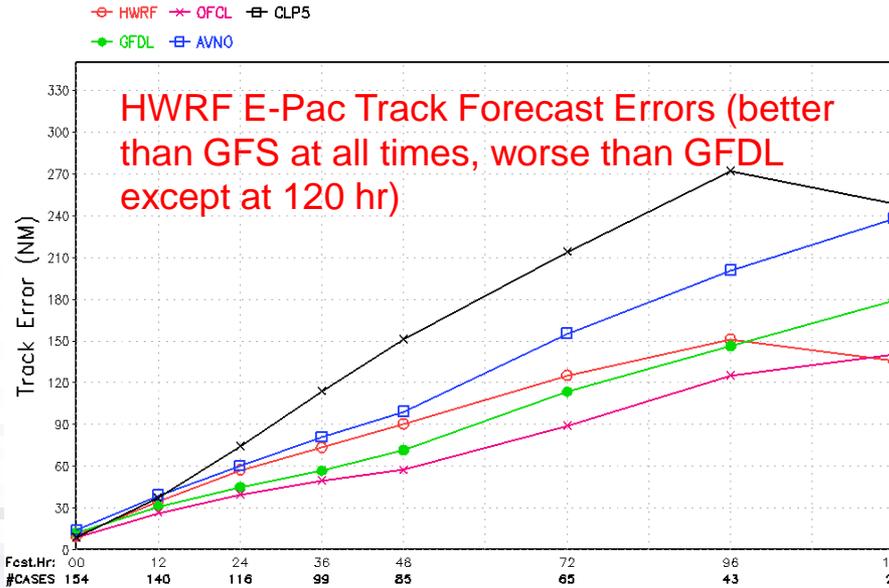
Operational Statistics Plots – ALL 2010 ATLANTIC through TOMAS21L



# Performance of the Operational HWRF for 2010 EPAC hurricane season

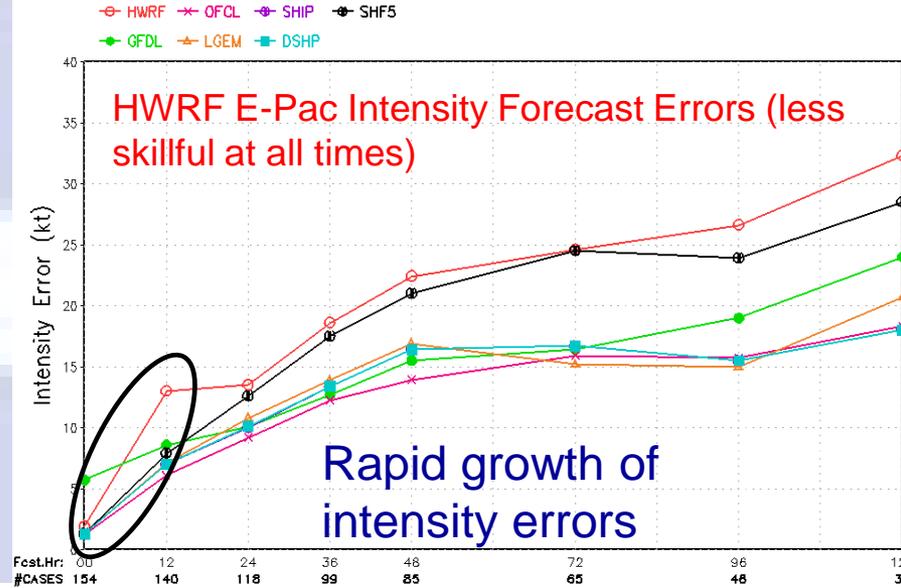
Average Track Errors (NM)

Operational Statistics Plots – ALL 2010 EASTPAC through GEORGETTE12E



Average Intensity Errors (kt)

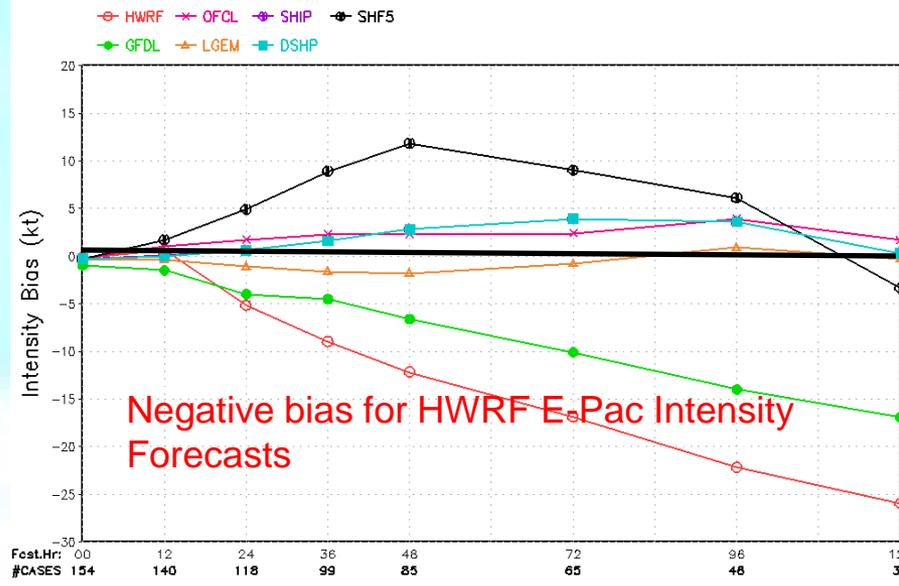
Operational Statistics Plots – ALL 2010 EASTPAC through GEORGETTE12E



NCEP Hurricane Forecast Project

NCEP Hurricane Forecast Project

Operational Statistics Plots – ALL 2010 EASTPAC through GEORGETTE12E

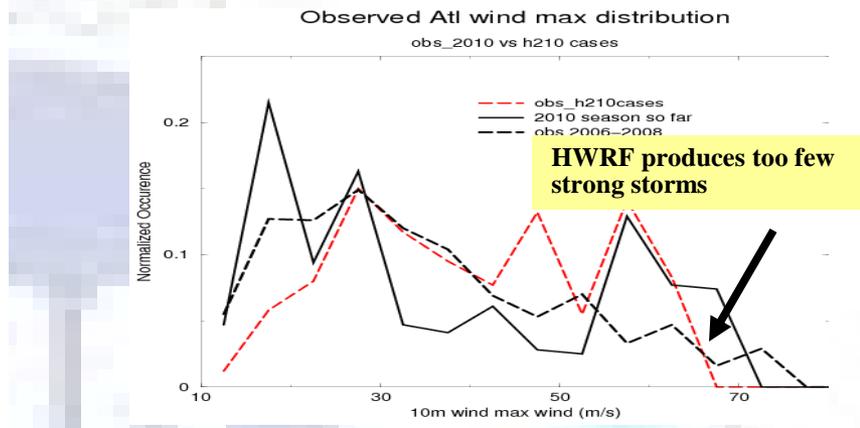
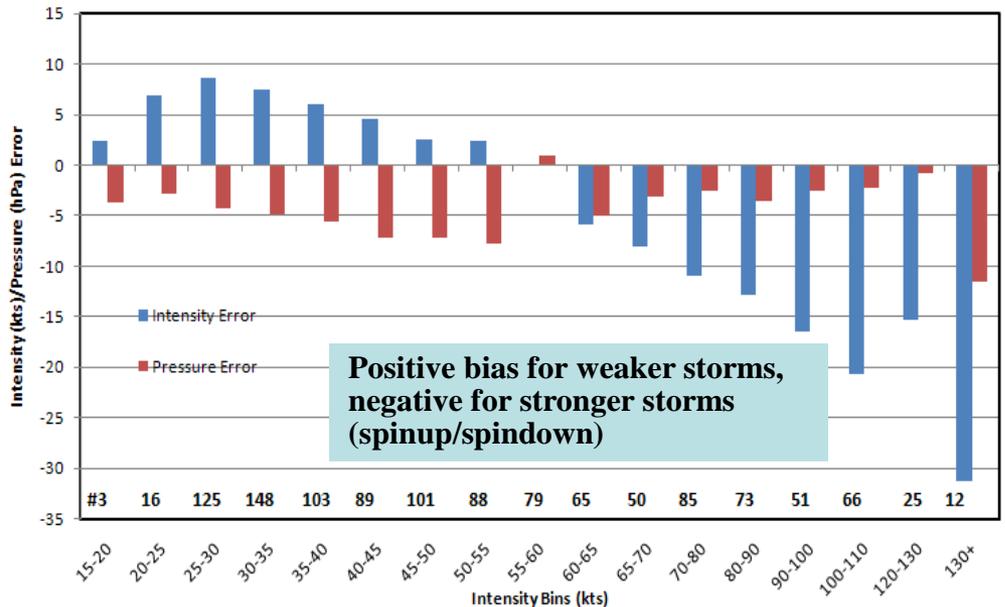


- HWRF
- GFDL
- GFS
- × OFCL

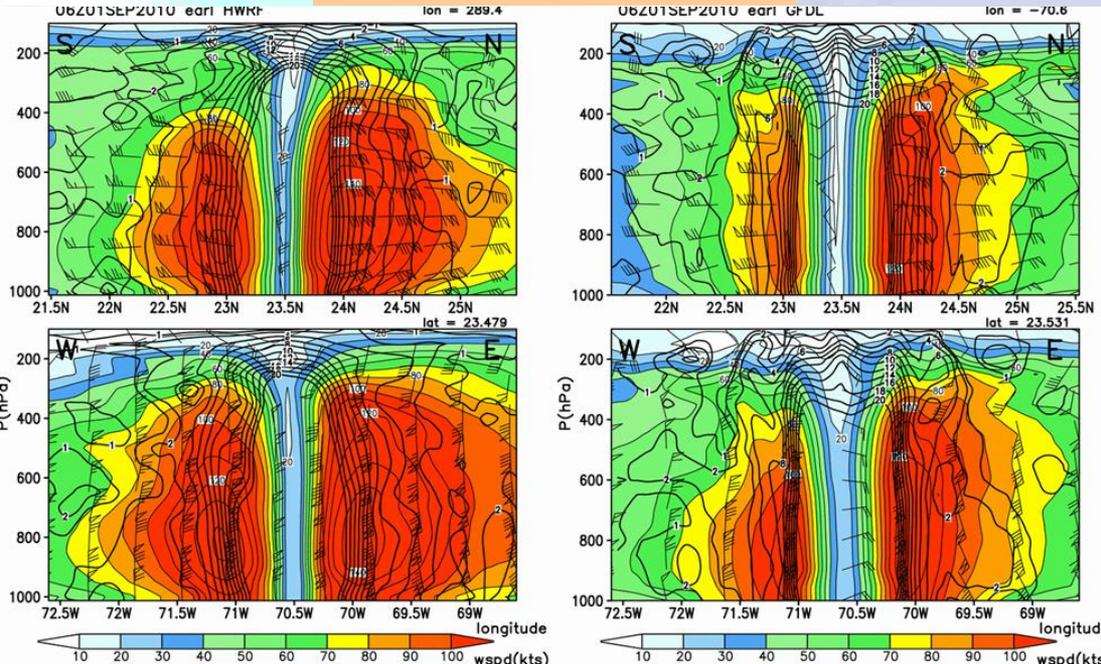
NCEP Hurricane Forecast Project

# HWRf 6-hr Forecast Errors of Intensity (kts) and Pressure (hPa)

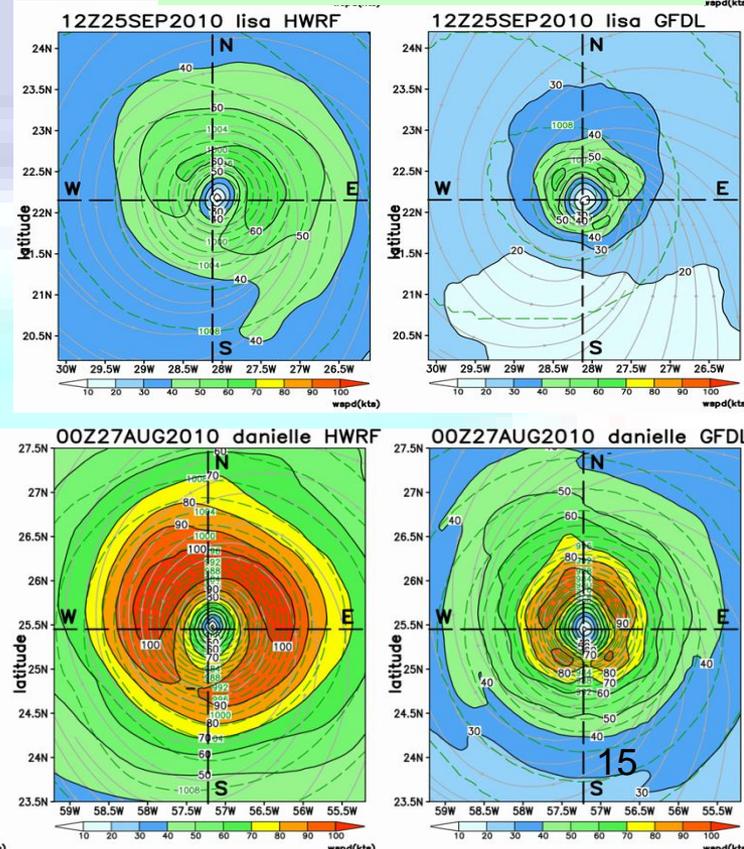
# Vortex Initialization Issues/Challenges



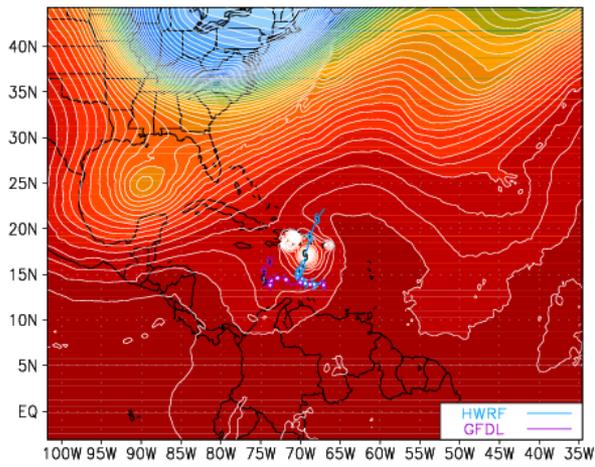
## Broad initial vertical structure



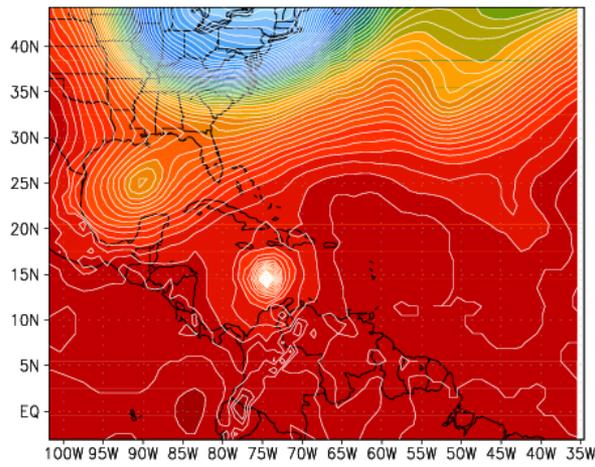
## Insufficient vortex size correction



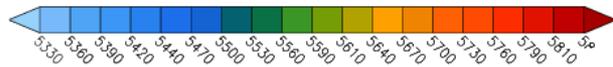
HWRF



GFDL

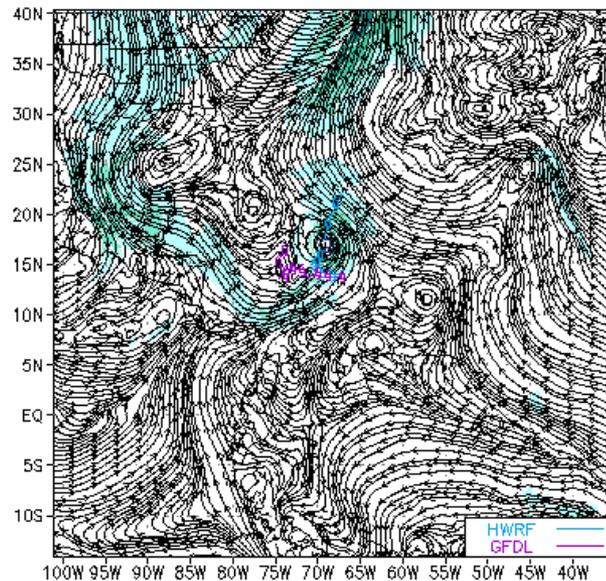


**Issues with nest -  
topography  
interaction and  
feedback**

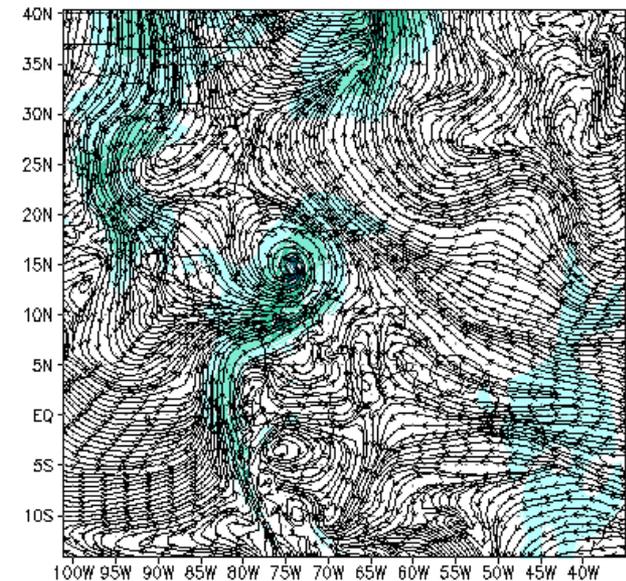


**Issues with evolution  
of large-scale flow**

HWRF



GFDL



# HWRF Simulated-GOES Images

HWRF PROD IGOR 11I Combine Simulated GOES IR TB (K)      HWRF PROD IGOR 11I Combine Simulated GOES IR TB (K)

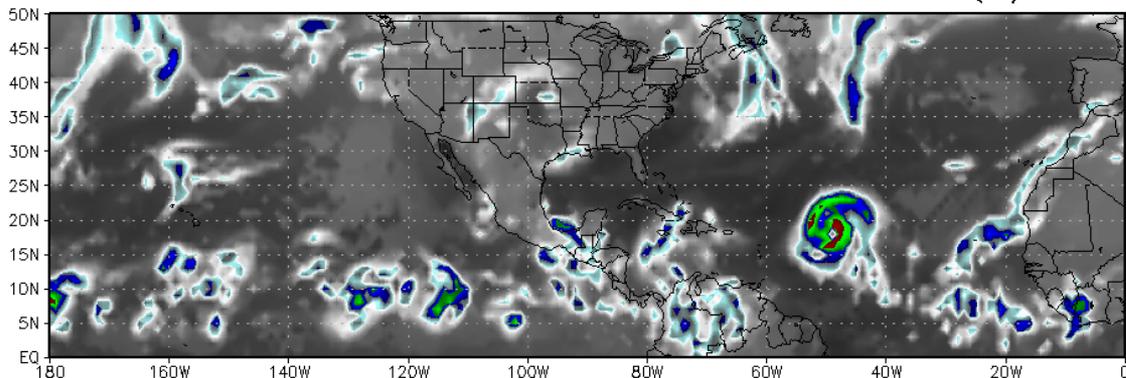
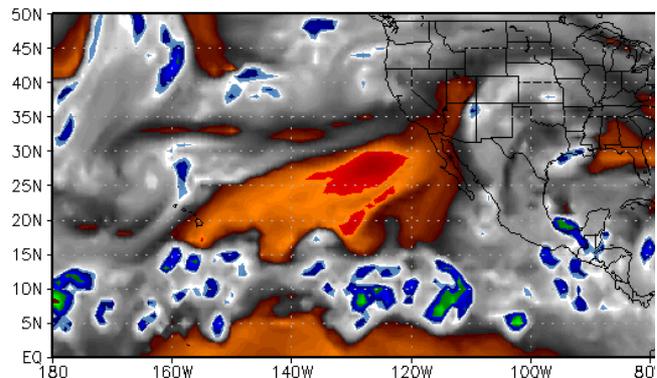


INIT 2010091218Z for 18 h FCST

INIT 2010091218Z for 18 h FCST VALID 2010091312Z

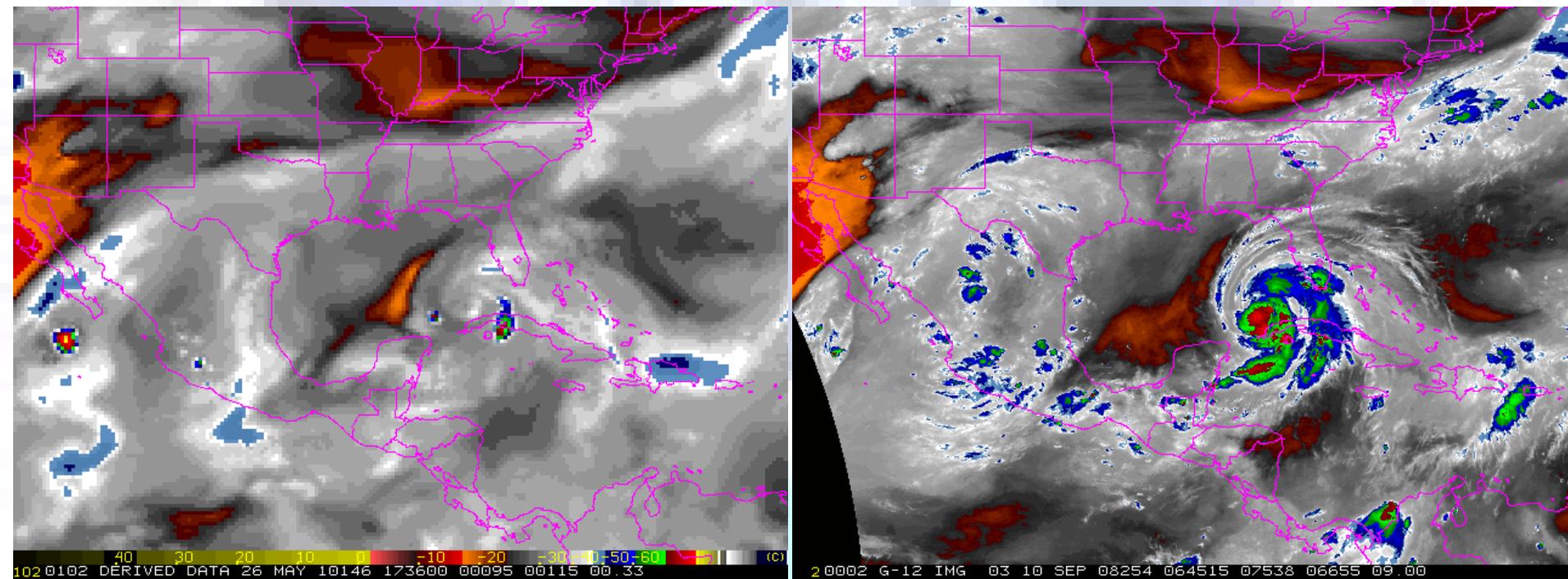
GFS PROD IGOR 11I Simula

GFS PROD IGOR 11I Simulated GOES IR TB (K)



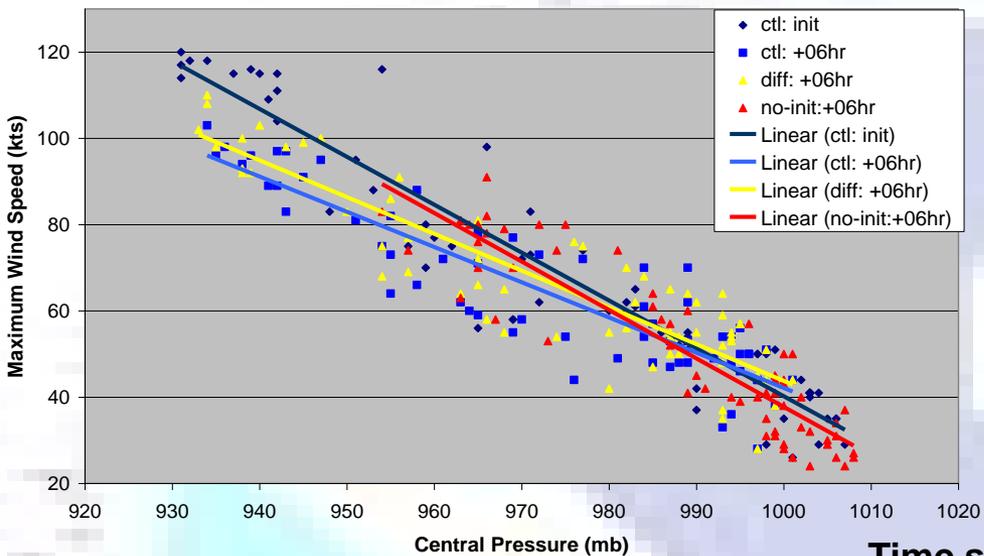
**Band 3 Loop Simulated**

**Band 3 Loop Real**



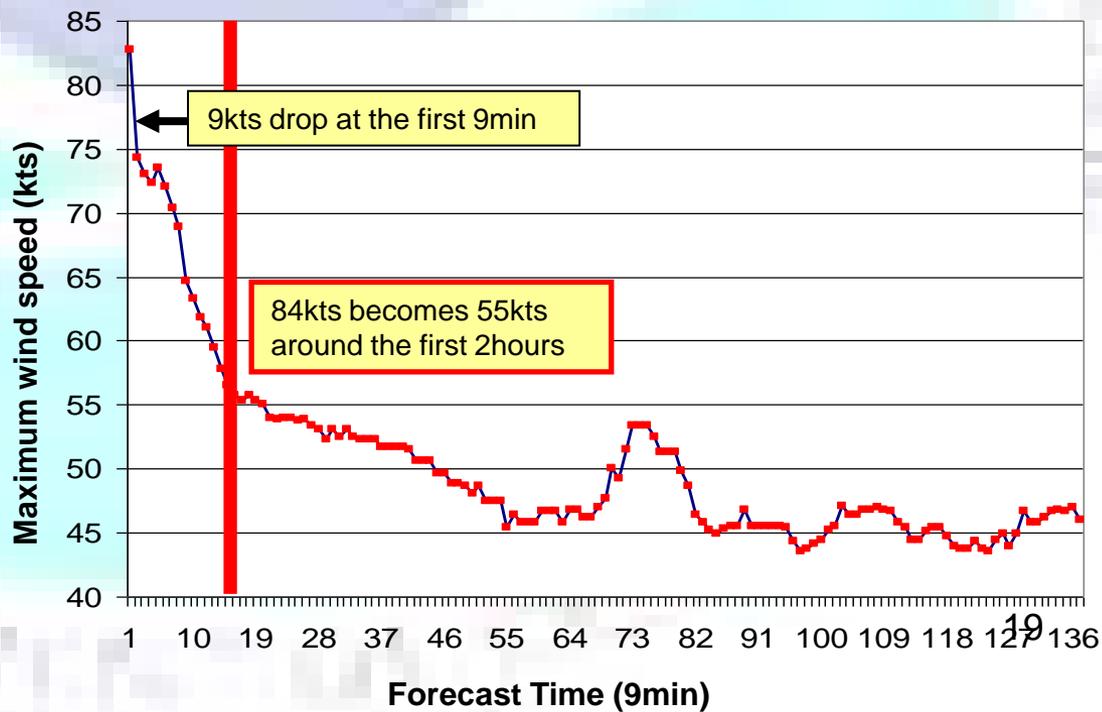
**Convection and moisture transport in HWRF  
– systematic dryness**

**Max Wind vs central Pressure at 6hr forecast**  
Hurricane Alex and Earl



## W-P Relationship

**Time series of max. wind speed (Celia: 2010062218)**



**Rapid weakening of strong storms**

# HWRF Upgrades FY2011 (05/24/2011)

## Model Upgrades (Atmosphere)

- Upgrade dynamical core to NMM community version V3.2 (EMC-DTC Collaboration)
- New GFS Deep Convection, Improved surface physics, and new FY2011 GSI/GFS IC/BC (EMC-GFDL Collaboration)

## Vortex initialization upgrades

- Improved storm size correction based on radius of 34 kt winds or ROCI and dynamical mass-wind consistency of the initial vortex (EMC-HRD collaboration)
- Modification of synthetic storm and its application in the initialization (vortex cycling)
- Upgrade HWRF GSI to V2.5 (community code)

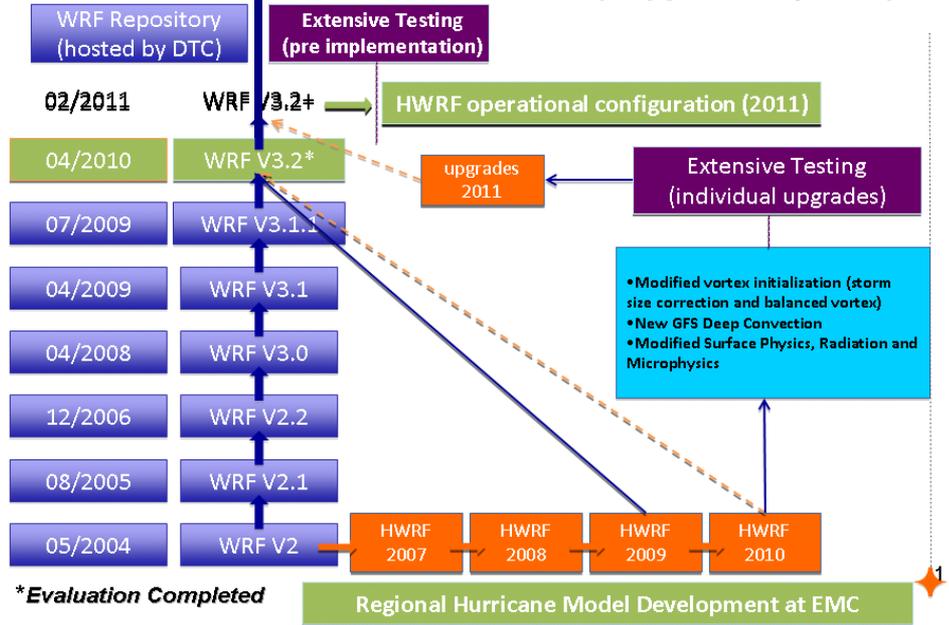
## Ocean Upgrades

- Coupling to HYCOM Ocean Model (\*Withdrawn from 2011 implementation plans, will be tested in parallel)

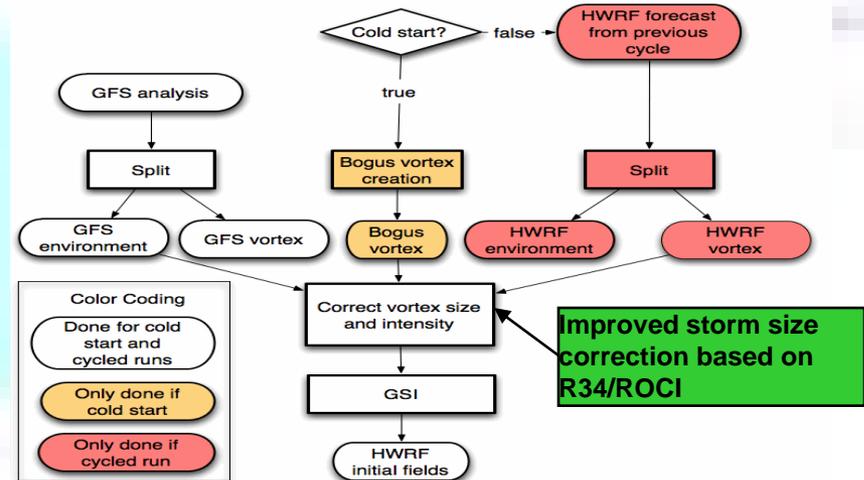
## Operational HWRF product enhancements

- Satellite angle corrections for simulated GOES WV and IR imagery, additional simulated microwave products
- New enhanced HWRF website for product display and navigation
- High-frequency output (3 hourly) and additional derived variables for diagnostics (EMC-NHC-CIRA Collaboration)

## FY2011 Operational HWRF Baseline Configuration (Supported by DTC)

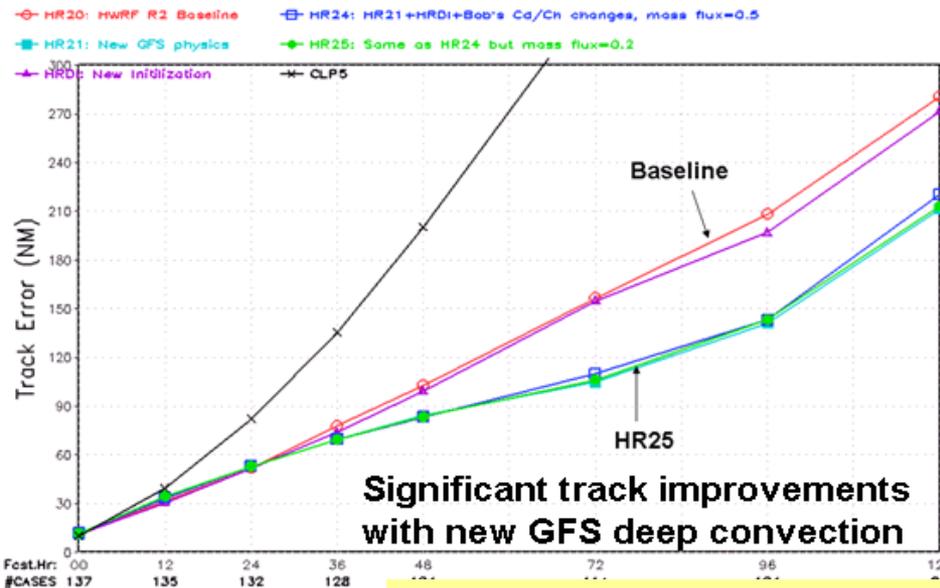


## HWRF Operational Initialization (with GSI)



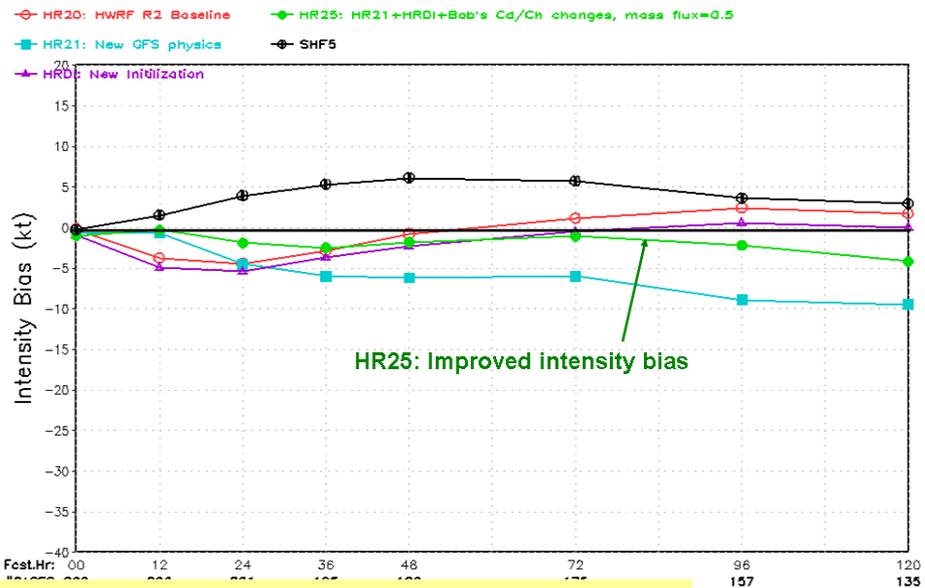
# Average Track Errors (NM)

Statistics Plots – Fay Gustav Hanna Ike Earl Tomas



# Intensity Bias (kt)

Statistics Plots – Fay Gustav Hanna Ike Earl Tomas

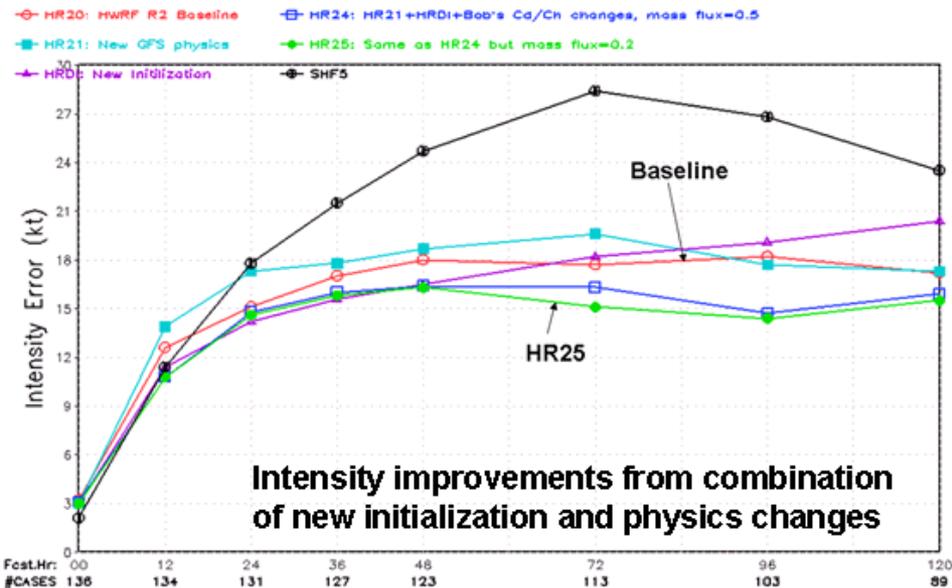


## FY2011 HWRf Pre-Implementation Test Results

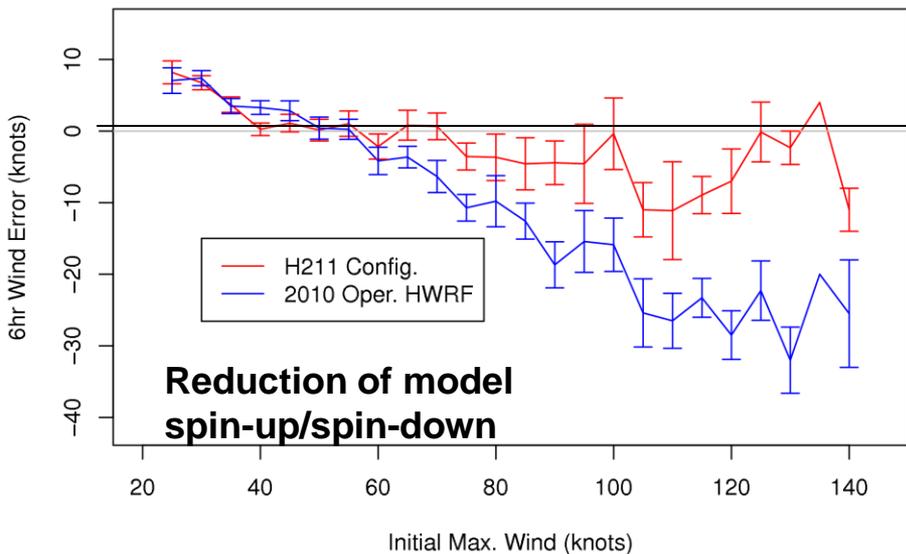
NCEP Hurricane Forecast Project

# Average Intensity Errors (kt)

Statistics Plots – Fay Gustav Hanna Ike Earl Tomas



# 6hr Wind Error (2010 AL & EP): HRD Init vs. 2010 HWRf Init

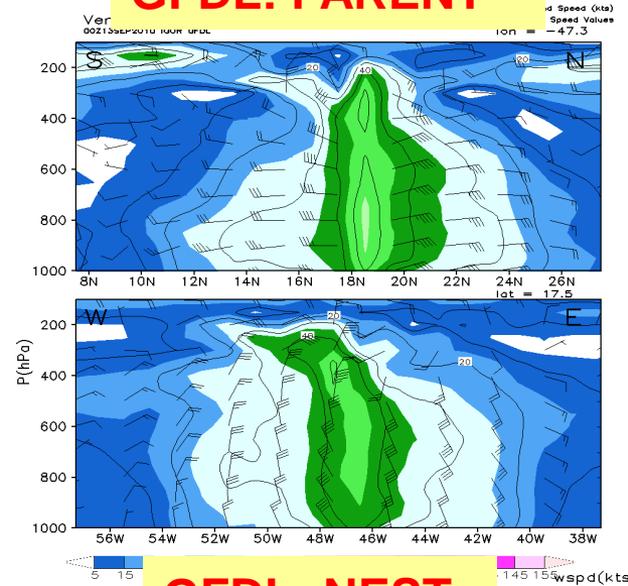
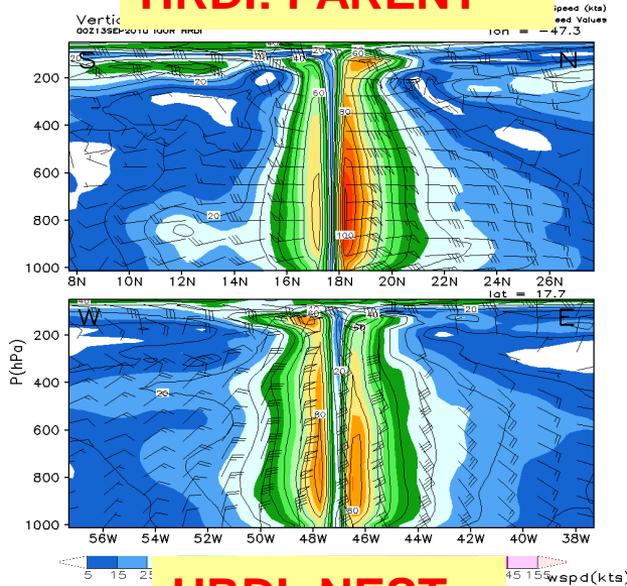
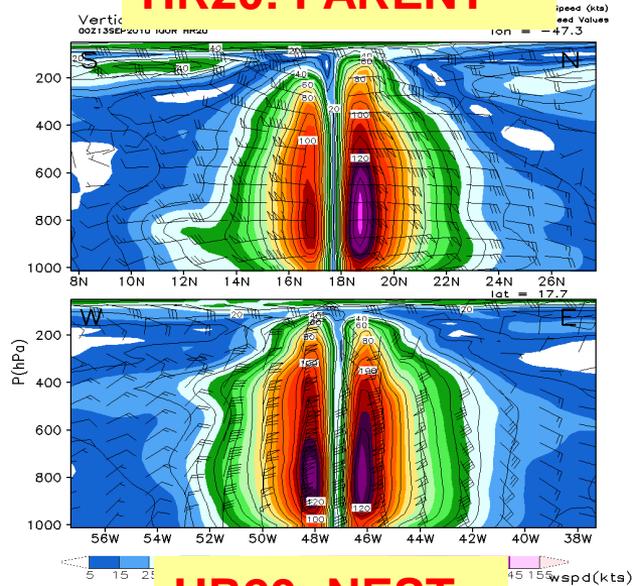


# IGOR 2010091300

## HR20: PARENT

## HRDI: PARENT

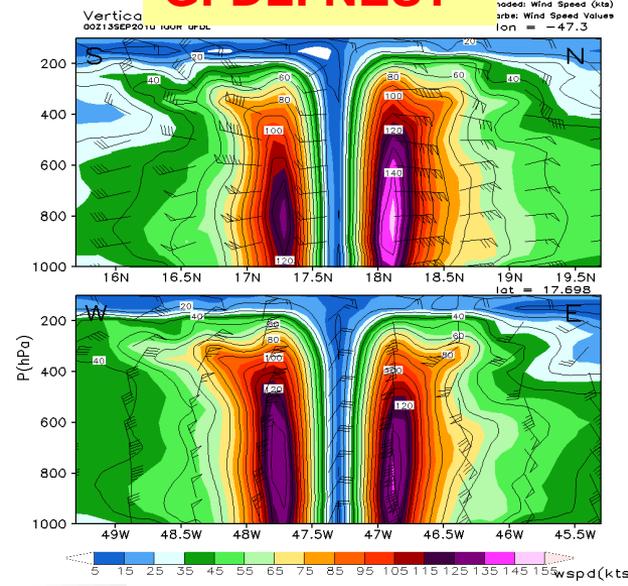
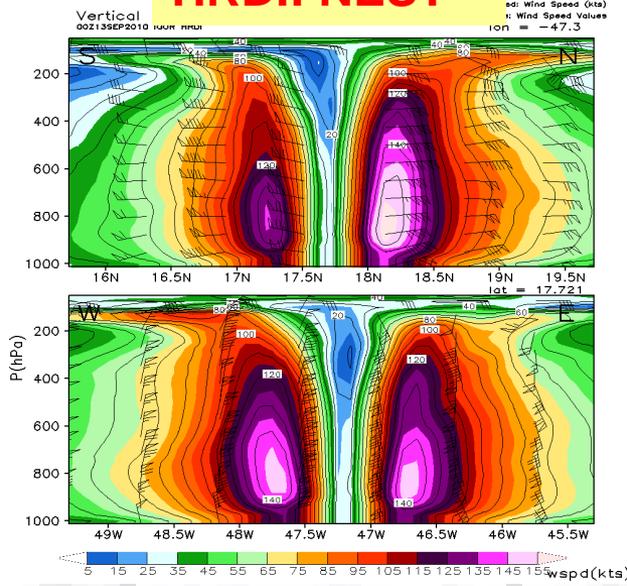
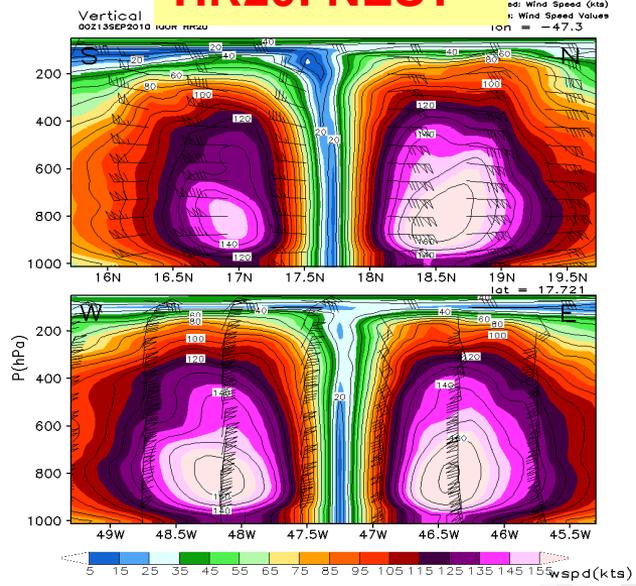
## GFDL: PARENT



## HR20: NEST

## HRDI: NEST

## GFDL: NEST

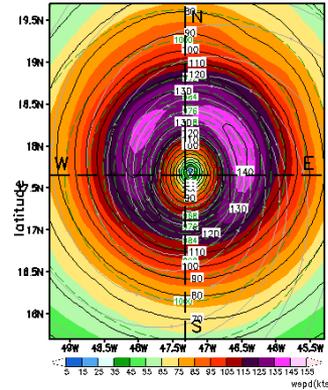


# IGOR 2010091300

## 10m wind speed

Surface Wind Field (Nest)

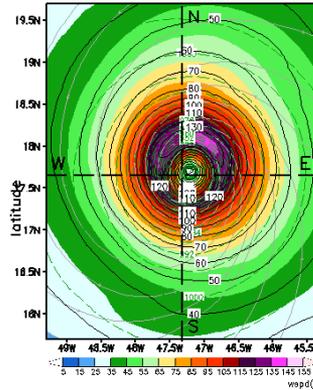
00Z13SEP2010 100R HR20



Shaded: Wind Speed (kts)  
Dashed Green Line: Pressure  
Solid Black Line: Wind Speed

Surface Wind Field (Nest)

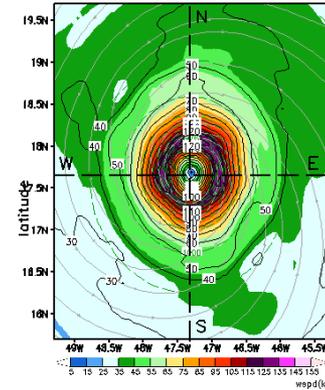
00Z13SEP2010 100R HRDI



Shaded: Wind Speed (kts)  
Dashed Green Line: Pressure  
Solid Black Line: Wind Speed

Surface Wind Field (Nest)

00Z13SEP2010 100R GFDL



Shaded: Wind Speed (kts)  
Dashed Green Line: Pressure  
Solid Black Line: Wind Speed

**HR20: NEST**

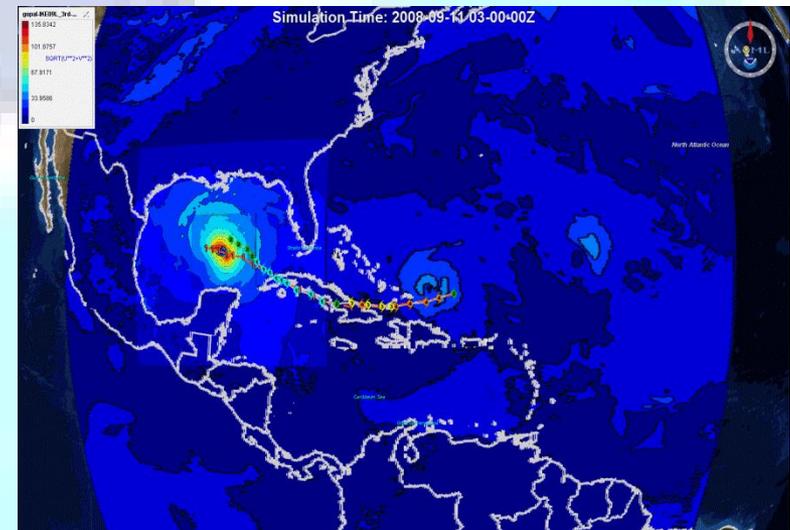
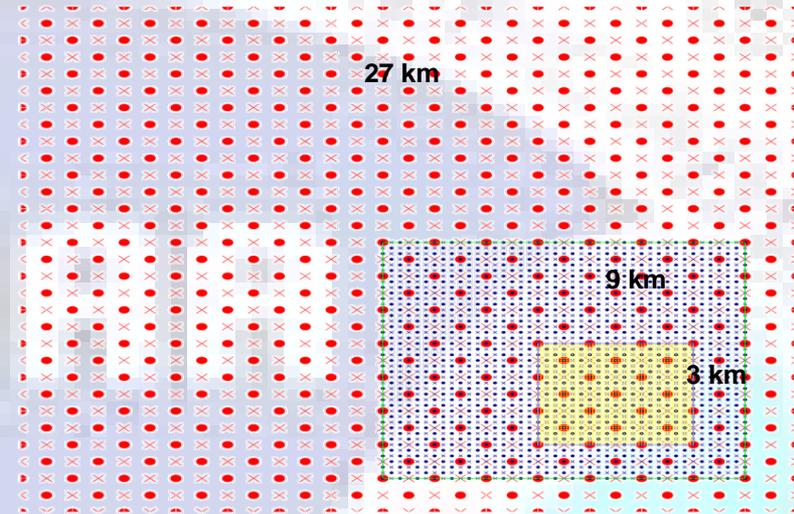
**HRDI: NEST**

**GFDL: NEST**

**Size of the storm is much smaller with modified initialization and comparable to that of GFDL model**

# Ongoing Model development & collaborative efforts (FY2011 and beyond)

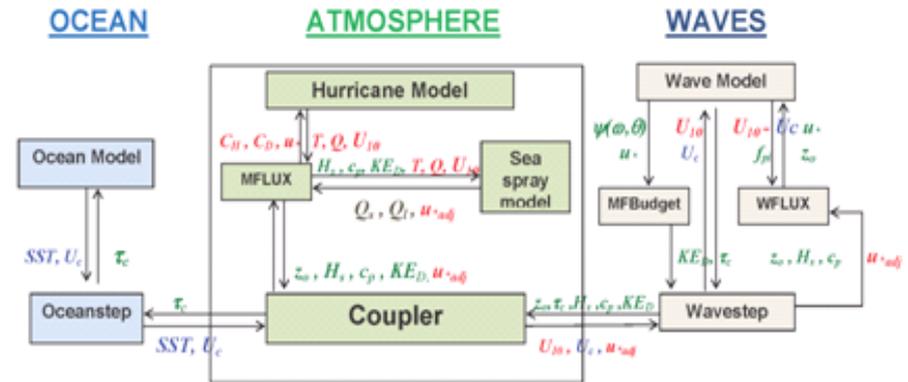
- **Further advancements to the HWRP modeling system (EMC, HRD, URI)**
  - third nest capability, advanced diagnostic capability (diapost), idealized simulations
  - Planned Demo during 2011 hurricane season (HFIP Stream 1.5)
  - Multiple moving nests/ improved model dynamics/ improved physics suitable for high resolution
  - Fully coupled 3-way interactive ocean-wave-atmosphere system
- **Code management and community support (EMC, DTC)**
  - Setup HWRPV3.2+ and provide support to the community through DTC
  - Development of R2O/O2R infrastructure and testing facility at DTC
- **Advanced Data Assimilation (EMC, ESRL, OU & HRD)**
  - Hybrid EnKF/3DVAR DA
  - Assimilation of real-time TDR data
  - Assimilation of advanced satellite datasets



**NOAA Research with goals for transition to operations (27:09:03)**

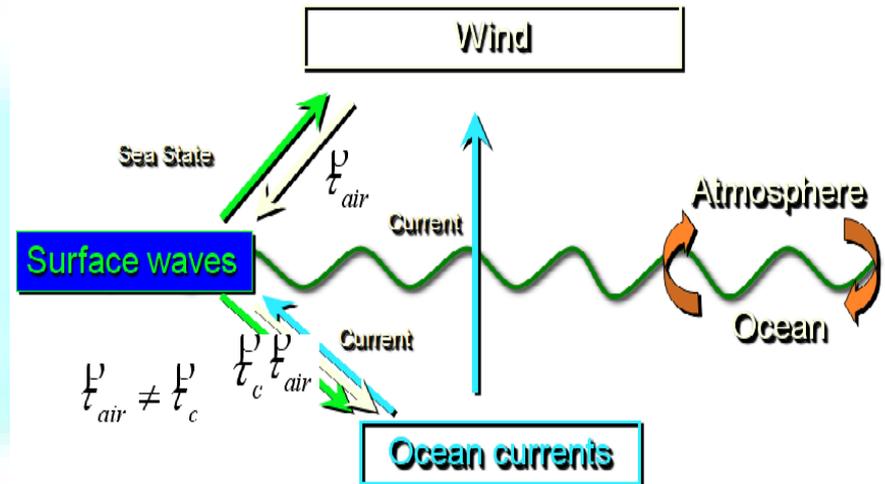
- **HWRF Physics (URI, GFDL, ESRL,HRD)**
  - Surface fluxes, sea spray and wave coupling
  - Physics for high-resolution (convection, micro physics, PBL, LSM )
- **HWRF Diagnostics (HFIP, EMC, NHC, FSU, CIRA, HRD, UMBC/UMD)**
  - Identifying forecast errors from different components of model physics and dynamics
  - Hurricane model diagnostics, evaluation and verification
  - Develop a common and comprehensive diagnostics framework and tools to integrate model output with available observations for verification
  - Enhanced real-time product display and navigation

## Three-way Atmosphere-Ocean-Wave Coupled System

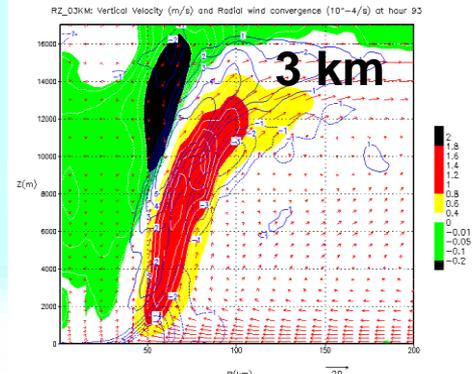
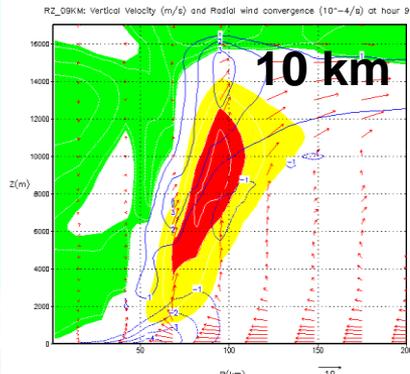
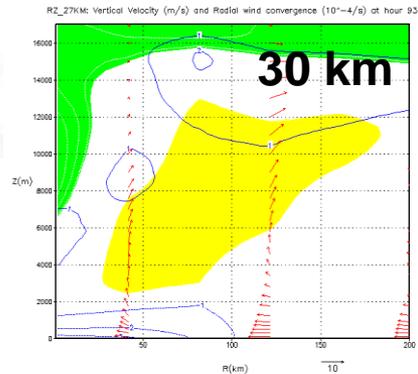
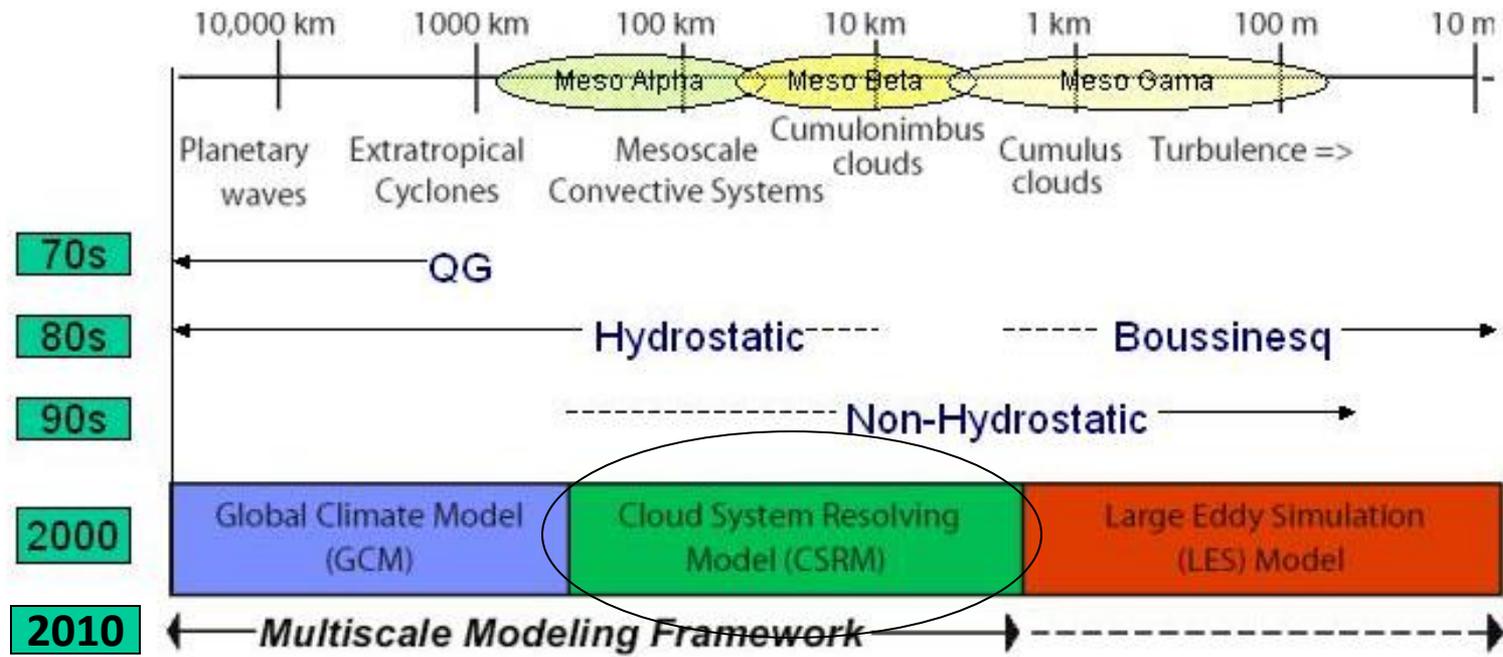


- **HWRF Ensembles**
  - Large Scale Flow Perturbations;
  - Initial Storm Structure Perturbations;
  - Physics-Based Perturbations
- **High-Resolution HWRF and other parallels**
  - Real-time demo of triple nested (27/9/3) HWRF (HFIP Stream 1.5)
  - Real-time demo of high-resolution 9:3 HWRF (HFIP Stream 2)
  - Real-time demo of Doppler Radar DA experiments
  - Real-time demo of NOAA LSM Coupled HWRF

## Wind-Wave-Current Interaction



# Scales of Motion & Multi-Scale Models



# Why do we need higher resolution?

- Current operational resolution of HWRF (9km) cannot resolve critical hurricane features that can impact intensity and rainfall:
  - Mesovortices – ~10-20km wide in radial direction
  - Hot towers – ~5-15km wide in radial direction
  - Inner rainbands – ~10-30km wide
  - Eye, eyewall of small storms etc.
- Recent results from HRD's high-resolution HWRF runs at 9/3 configuration have shown improvements over the operational HWRF runs (despite several differences, including lack of ocean coupling)
- Unified operational/research versions of HWRF modeling system (V3.2) enabled us to examine and evaluate the impacts of higher resolution, and assess the possibilities for transition to operations

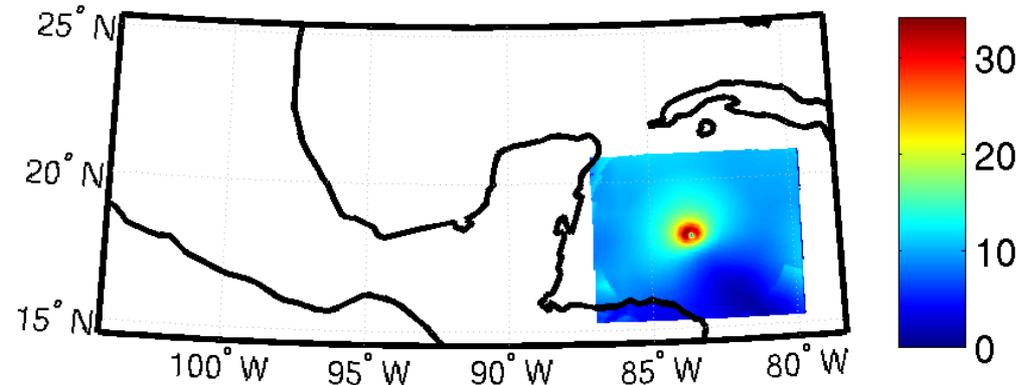
# Results from High-Resolution (9:3) HWRF

- Test operational HWRF with increased horizontal resolution (9km outer domain and 3km inner domain)
- Use operational HWRF physics, vortex initialization, vortex cycling and coupling to POM (no changes to ocean initialization or resolution)
- Run entire 2010 North Atlantic storms (>400 simulations)
- Use these results as a benchmark to test further advancements and to evaluate 27/9/3 configuration for operational purpose

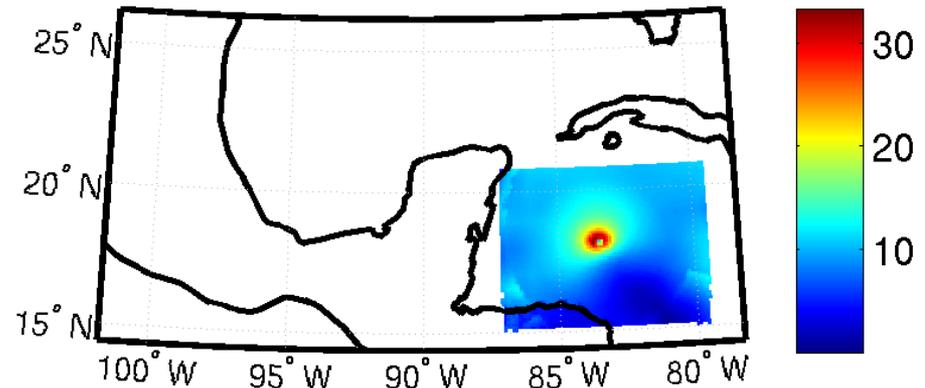
# Example: Karl 13L 2010

- Similar initial vortex.
- After Yucatan, vortex is temporarily destroyed.
- High-res recovers: 30km RMW
- low-res produces 100-200km RMW
- Actual RMW is 9-27km.

9:3 Karl 13L 2010091418 0 hr. Forecast 10m Wind (kt)



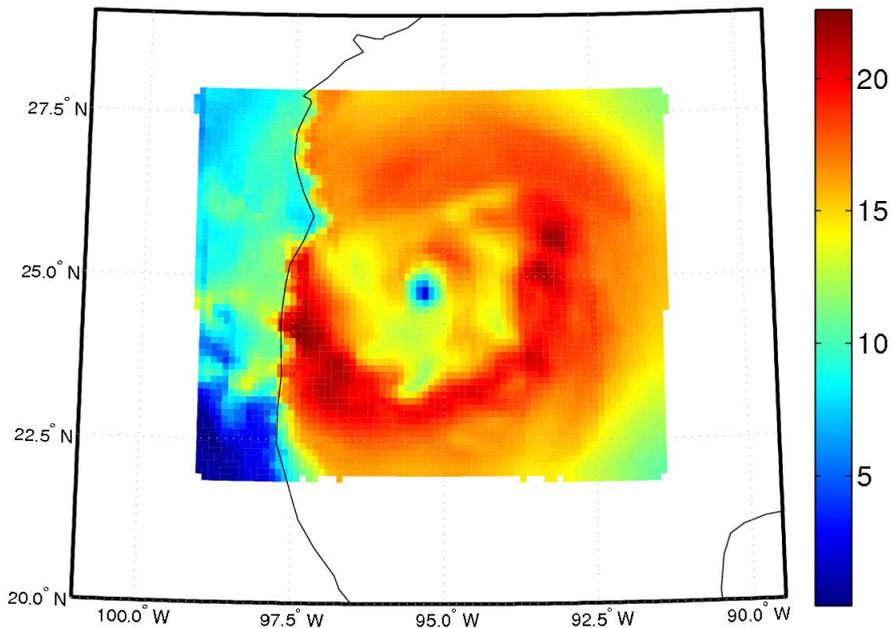
27:9 Karl 13L 2010091418 0 hr. Forecast 10m Wind (kt)



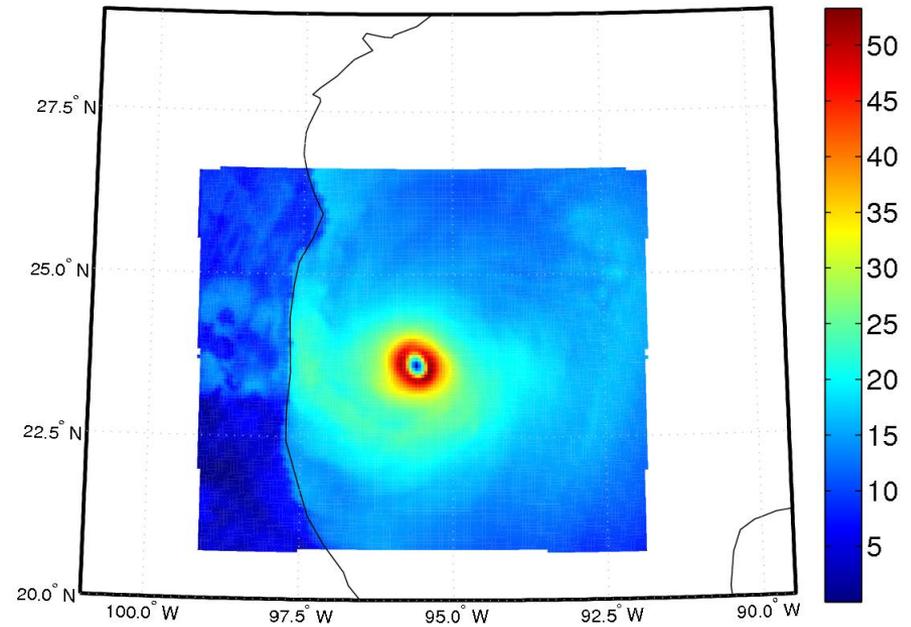
# Example: Alex 01L 2010

- Similar situation as Karl. Correct RMW in 9:3
- Much bigger storm in 27:9

27:9 HWRP 48hr Forecast 10m Winds  
Alex 01L 2010-08-28 18:00



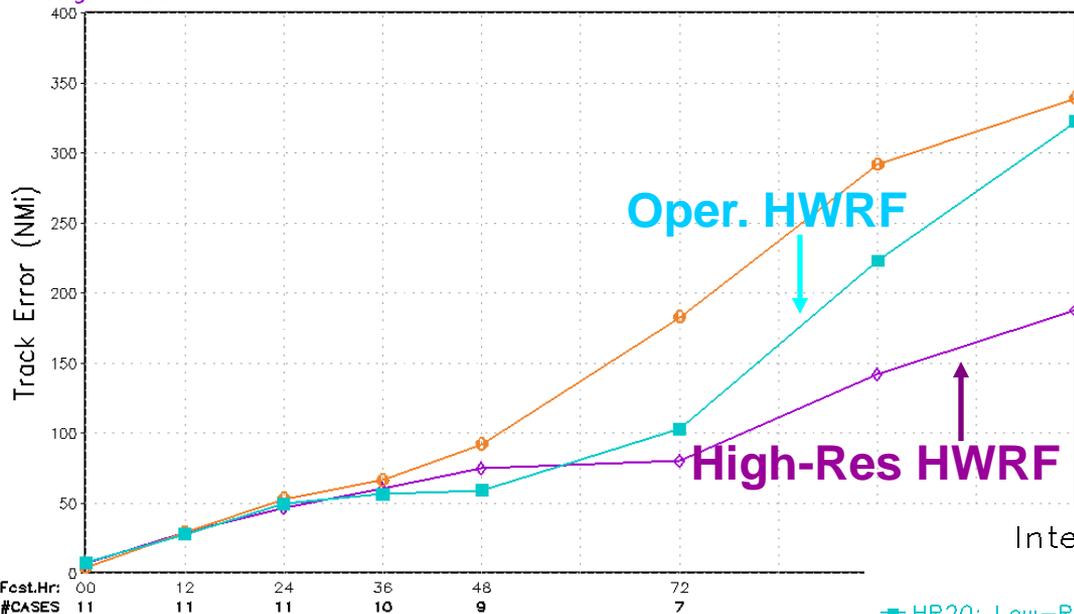
9:3 HWRP 48hr Forecast 10m Winds  
Alex 01L 2010-08-28 18:00



# Track Errors (NMI) For ALEX 01L 2010

Statistics Plots - 9:3 HWRP

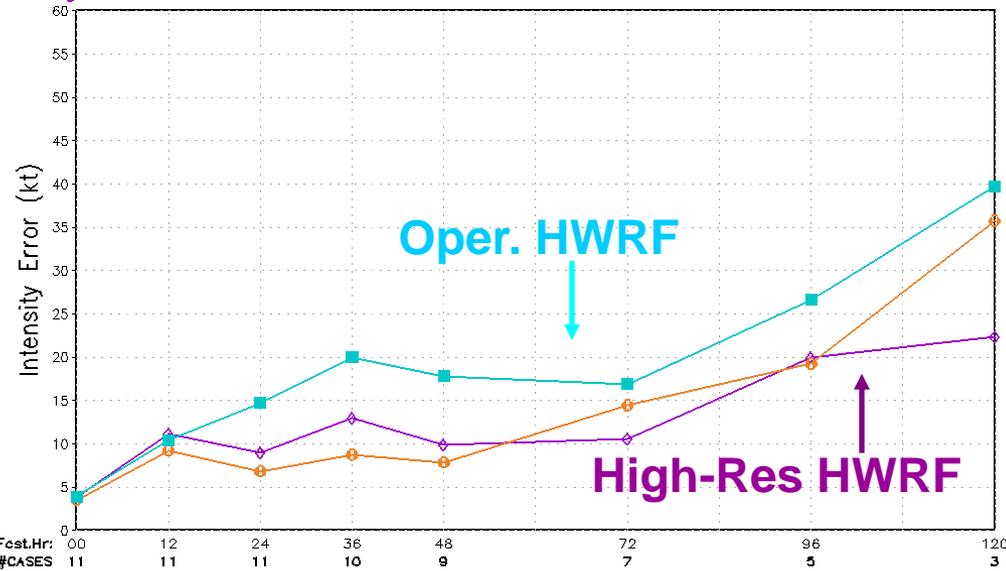
■ HR20: Low-Res HWRP    ● Real-Time HWRP-X  
 ◆ High-Res HWRP



# Intensity Errors (kt) For ALEX 01L 2010

Statistics Plots - 9:3 HWRP

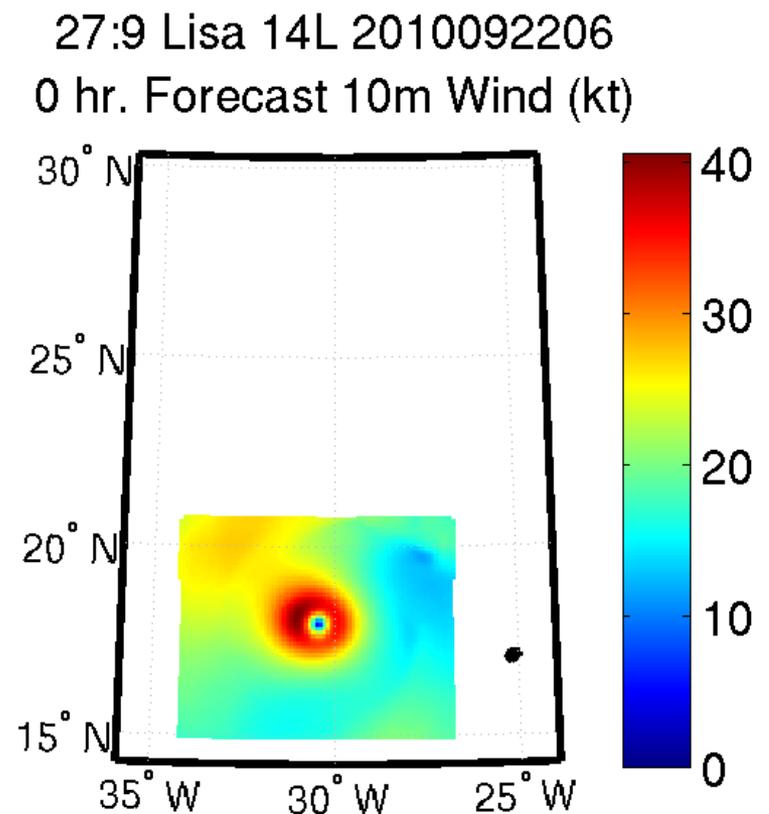
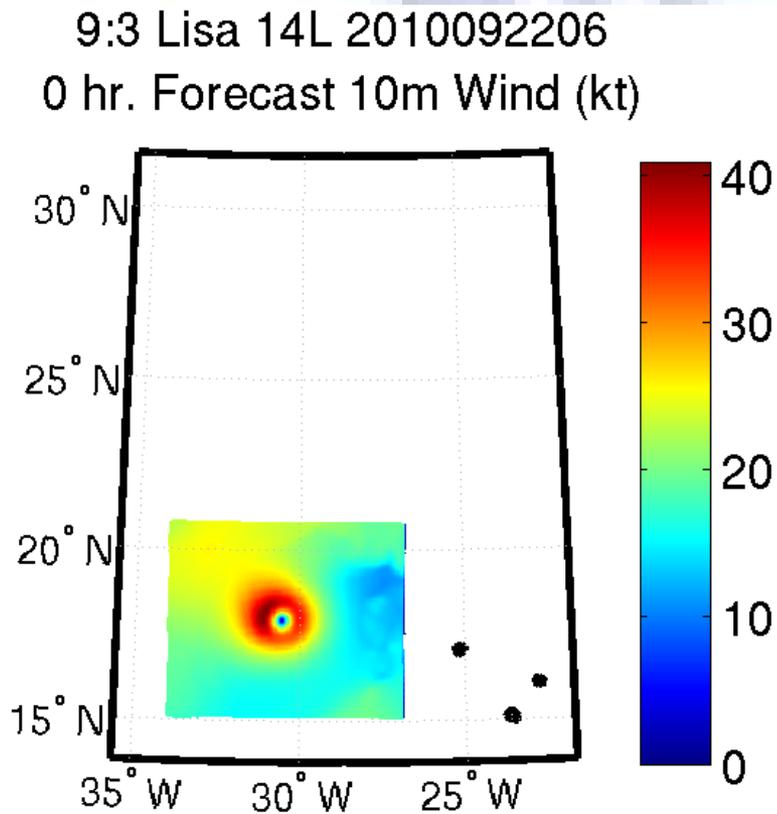
■ HR20: Low-Res HWRP    ● Real-Time HWRP-X  
 ◆ High-Res HWRP



**High Resolution runs greatly improved track and intensity forecasts for Hurricane Alex**

# Example: Lisa 14L 2010

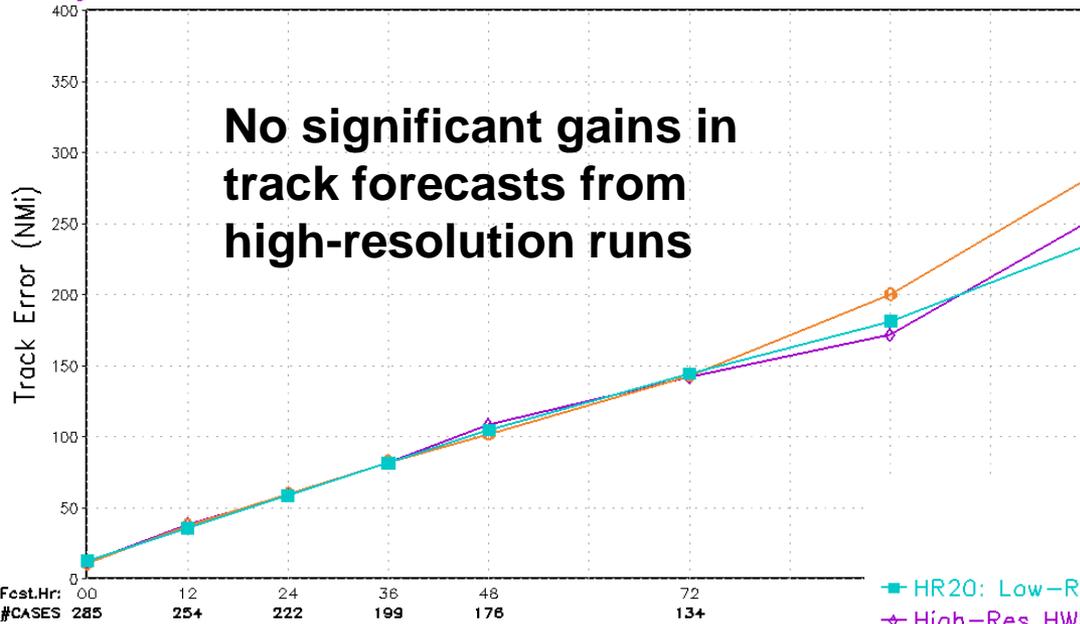
- Low-res vortex too large again and misses real-world eyewall contraction to 18 km at ~48hrs



# Average Track Errors (NMI)

Statistics Plots - 9:3 HWRP

■ HR20: Low-Res HWRP    ◆ Real-Time HWRP-X  
 ◆ High-Res HWRP

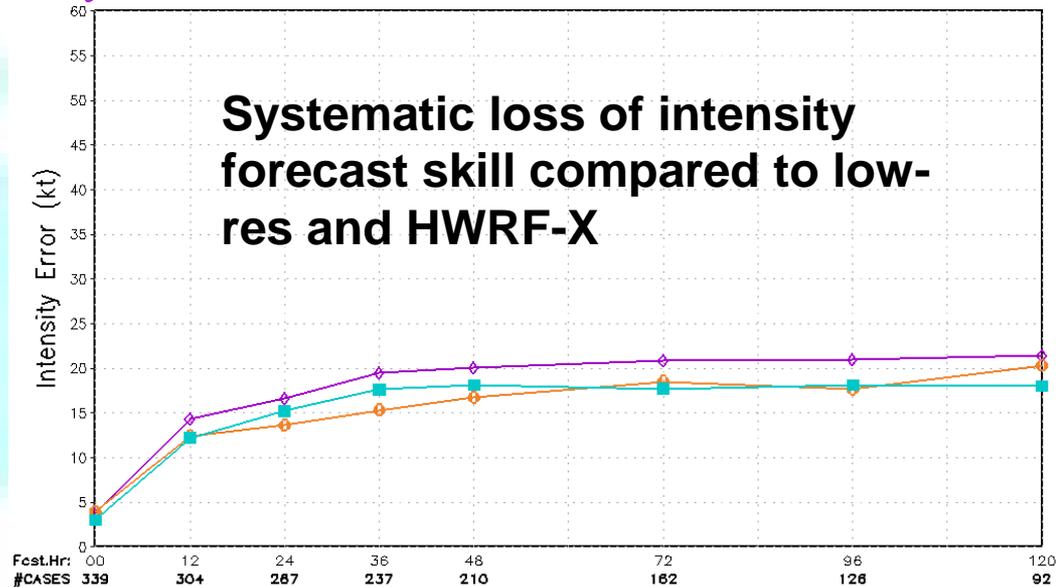


## 2010 Atlantic Seasonal Track and Intensity Statistics

# Average Intensity Errors (kt)

Statistics Plots - 9:3 HWRP

■ HR20: Low-Res HWRP    ◆ Real-Time HWRP-X  
 ◆ High-Res HWRP



# Lessons learned so far.....

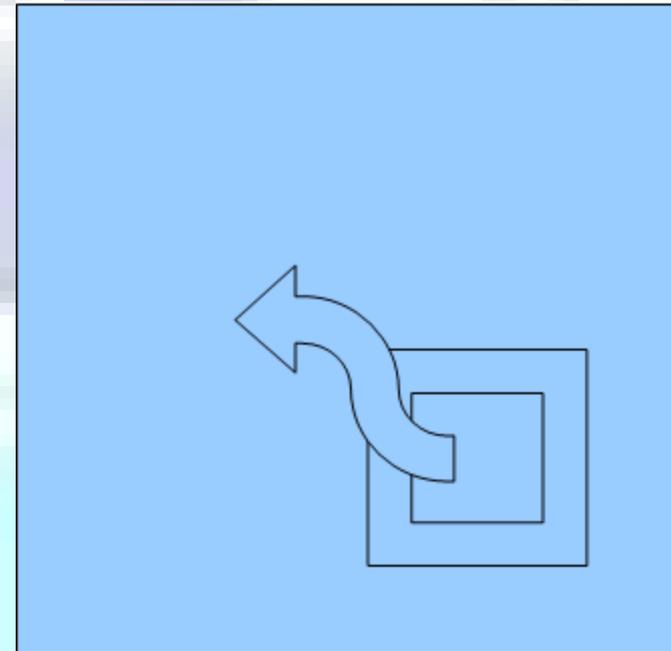
- Higher resolution alone is not enough.
- We need physics appropriate for high res.
- Started seeing better structure from high-res runs
- Vortex initialization requires several changes (we may be able to resolve RMW, eye and eye-wall appropriately). We should explore inner core DA with available obs.
- Operationalization is a big challenge. With optimal configuration, it is possible to fit triple nested domains within existing computational resources (work in progress)
- Providing high-resolution capability within the operational framework allows developers to test new and innovative methods to improve forecast skill.

# Ongoing work.....

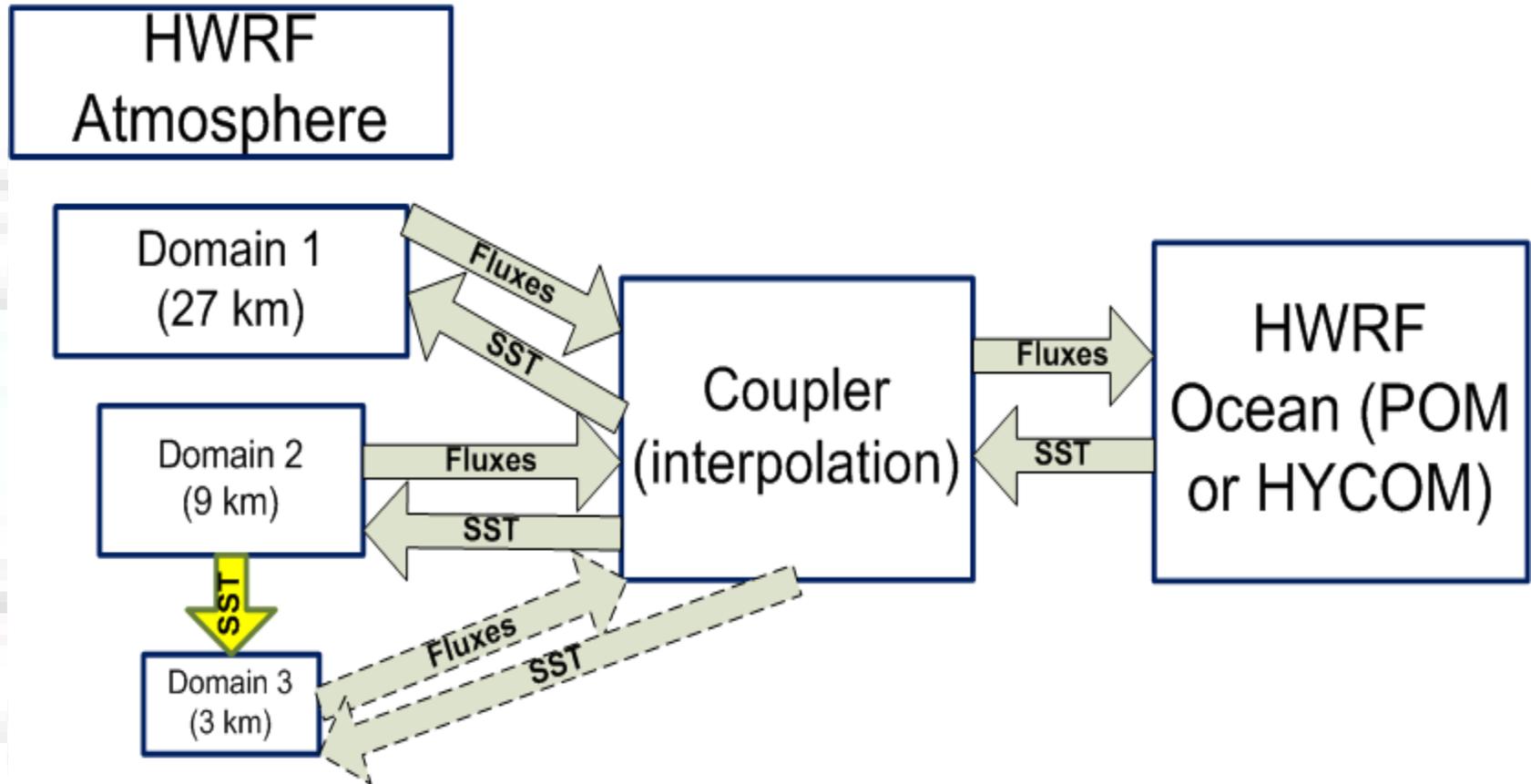
- Porting numerous fixes and upgrades from 2011 HWRF configuration
- Interoperability of several physics packages within WRF framework, idealized tests of NAM & NCAR phys
- WRF-NMM framework issues:
  - NMM core assumes Ferrier scheme, microphysics arrays are zeroed out in many places. Working on fixing this
  - Nest feedback issues, topography and land/sea mask related issues
- 27:9:3 simulation takes about two hours for a 5-day forecast using 128 processors.
- Bottlenecks we can fix:
  - increase domain size to allow more processors
  - base\_state\_parent – wasted calculations in areas where nest is not present ~20% of runtime can be saved
  - 3D boundary arrays – NMM has 12 extra 3D arrays for nest boundary communication, while only 2D and 1D arrays are needed. ~5% of runtime gain removing these arrays.
  - Multiprocessor coupler will allow faster interpolations and reduce overheads.

# Planned 2012 Operational HWRF System

- Three atmospheric telescoping nested domains:
  - 27km resolution 75x75 degree domain
  - 9km resolution ~10x10 degree storm-following
  - 3km resolution ~5x5 degree storm-following
- Include new nest motion algorithm and other dynamics improvements from HRD's developmental version of HWRF
- Coupled with POM/HyCOM ocean model.
- New coupler and modified HWRF vortex initialization for third nest
- Changes to HWRF physics appropriate for 3 km resolution

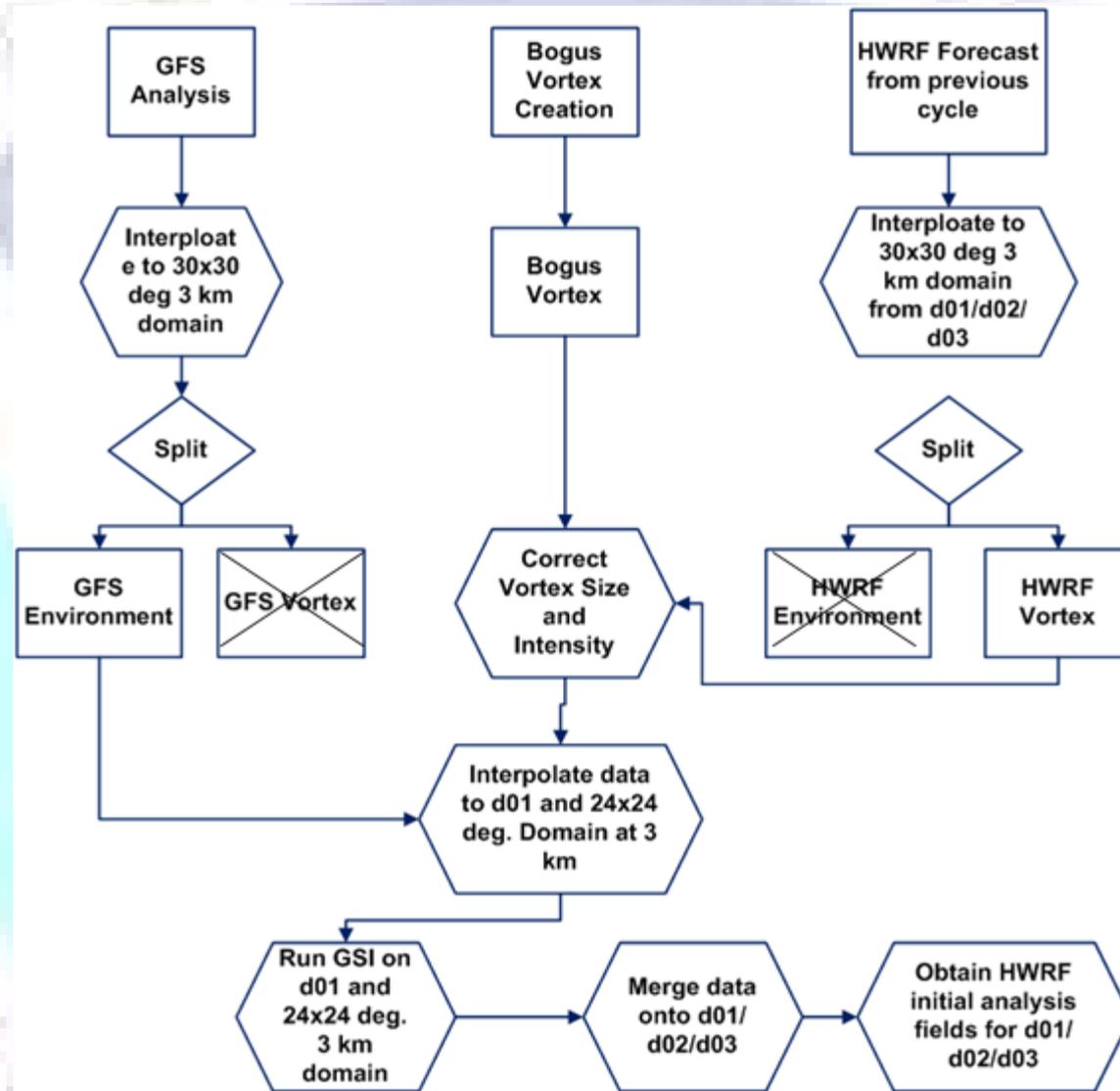


## Coupler for Third Nest



Extension of 2-way interactive NCEP coupler  
(dashed lines represent future development)

## Initialization for Third Nest



# Improved Vortex Initialization and Inner Core Data Assimilation

## Data assimilation and vortex initialization (EMC, ESRL, OU, AOML)

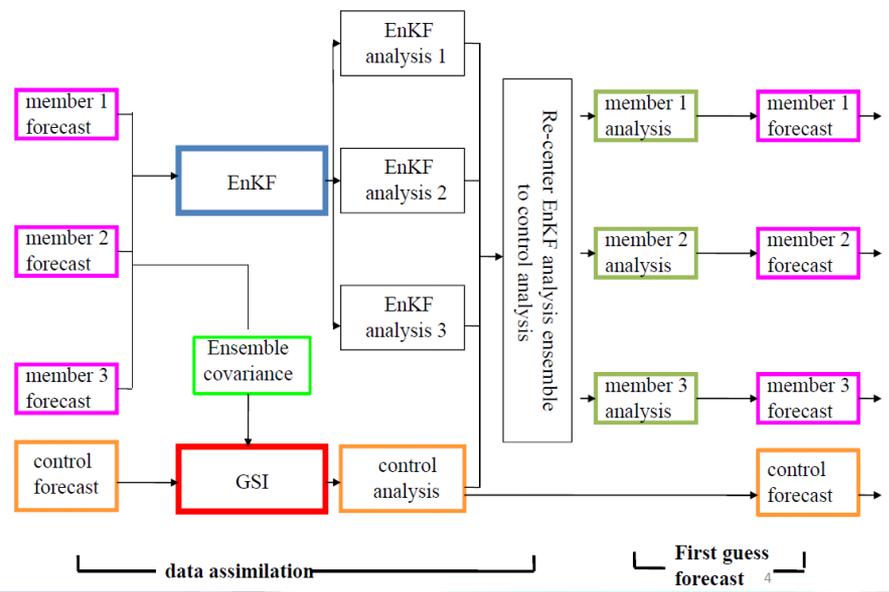
Real-time test of the P3 TDR data flow from aircraft to NCO/TOC/AOC and assimilation using advanced GSI.

Improved vortex initialization (model consistent 3-D balanced vortex)

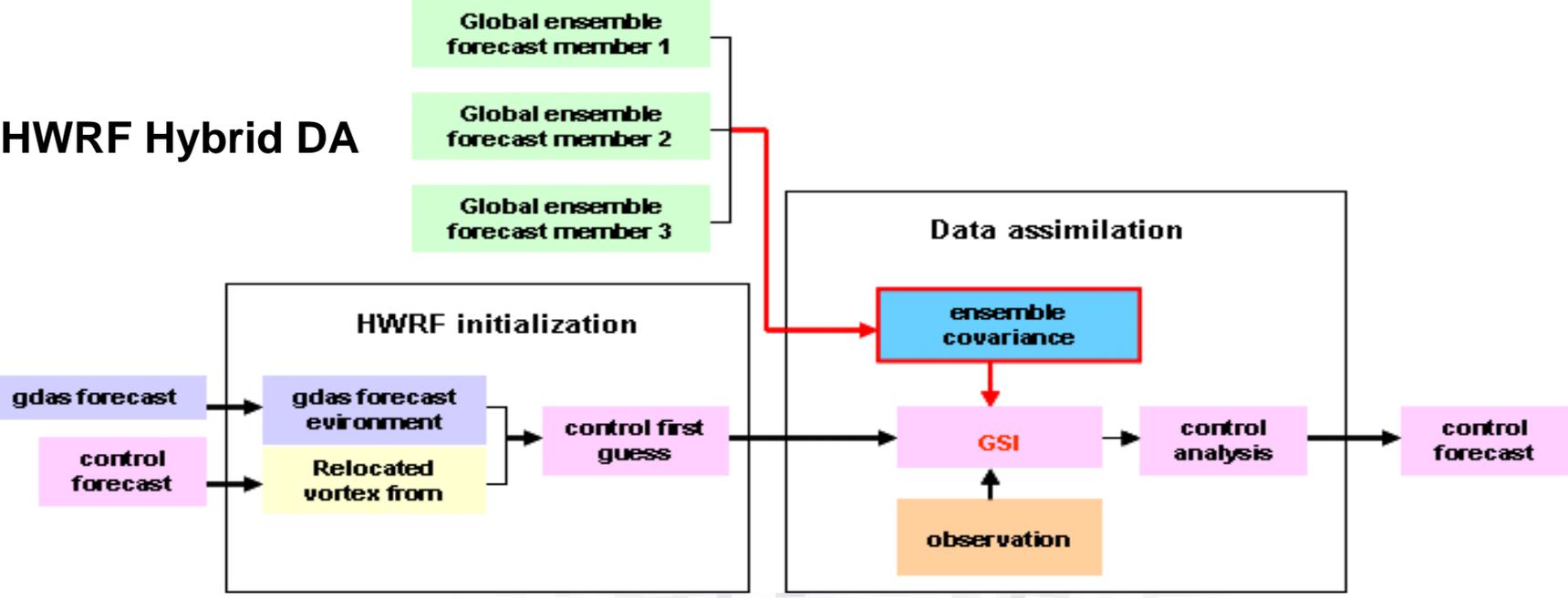
Ensemble data assimilation - hybrid EnKF (ESRL, OU, AOML)

Planned Demo during 2011 hurricane season (HFIP Stream 2)

## Hybrid EnKF-GSI DA system: 2 way coupling



## HWRF Hybrid DA



# Background

## HWRF vortex initialization/relocation

**Warm start:** GFS environment + relocated and modified HWRF 6hr forecast vortex

**cold start:** GFS environment + bogus vortex

$\mathbf{x}$

(multiple time levels of background if FGAT)

...  $\mathbf{x}^{t-1}$ ,  $\mathbf{x}$ ,  $\mathbf{x}^{t+1}$ , ...

## hybrid

short range ensemble  
forecast  $\mathbf{x}_k^{en}$

## GSI (includes Hybrid DA Capability)

Data selection, quality control, data thinning

### Iterative minimization

#### 3DVAR cost function

$$2J(\mathbf{x}) = \mathbf{x}^T \mathbf{B}^{-1} \mathbf{x} + (\mathbf{H}\mathbf{x} - \mathbf{y})^T \mathbf{R}^{-1} (\mathbf{H}\mathbf{x} - \mathbf{y}) + J_c$$

climatological  
isotropic  $\mathbf{B}_c$

flow-dependent  
anisotropic  $\mathbf{B}_a$

hybrid  
 $\mathbf{B} = (\beta_1^{-1} \mathbf{B}_c + \beta_2^{-1} \mathbf{P}^{en} \mathbf{O})$

ensemble covariance  $\mathbf{P}^{en} = \sum \mathbf{x}_k^{en} (\mathbf{x}_k^{en})^T$

Analysis  $\mathbf{x}_a$

Post Balance

126 hours forecast

(3, 6, 9 hr forecast)

## Potential and future obs

NOAA and  
USAF: flight  
level data,  
SFMR data

new dropsonde  
cloud radiance  
data

## EnKF

Update ensemble  
members ( $\mathbf{x}_k^{en}$ )

Ensemble forecast

## Assimilated obs

rawinsonde, pibal,  
class sounding,  
profiler,  
dropsonde,  
AIRCFT, AIRCAR,  
GPSIPW, surface  
marine/land/splas  
h-level/mesonet  
satellite wind

satellite radiance  
data: HIRS,  
AMSU-A, AMSU-  
B/MHS, AIRS,  
GOES sounder  
NOAA P3 TDR  
Pseudo-MSLP

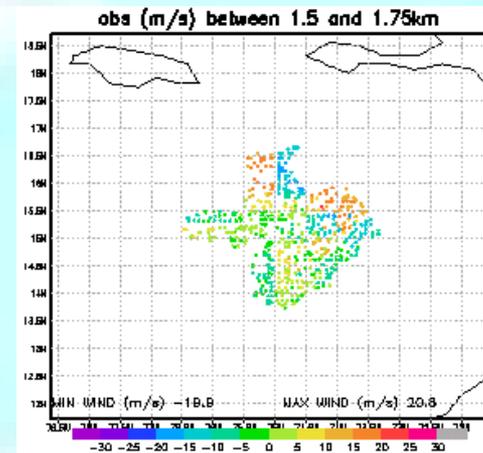
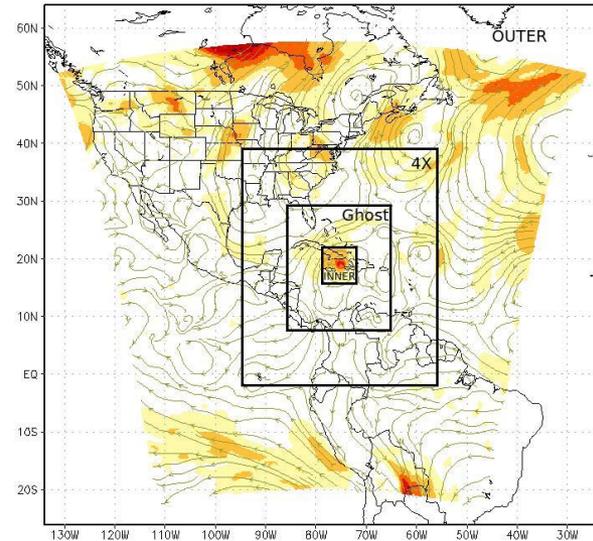
## Planned FY2011 Real-Time Experiments on t-Jet

| Experiment                                   | Physics                               | Coupling      | Init                             | Resources  |
|--|---------------------------------------|---------------|----------------------------------|--|
| Stream 1.5*<br>HWRF 27:9:3                   | Choose from<br>Table 1                | POM           | Chose from<br>Table 1            | <b>172 cores per forecast for 4 hrs</b><br><b>15 GB archive space per forecast</b> |
| Stream 2.0<br>HWRF-NOAH<br>LSM               | NOAH LSM<br>and 2011<br>Oper. Physics | POM           | 2011 Oper.<br>Init w/<br>cycling | <b>To be run on CCS</b>  |
| Stream 2.0<br>HWRF-Hybrid DA <sup>+</sup>    | 2011 Oper.<br>Physics                 | POM           | 2011 Oper.<br>Init w/<br>cycling | <b>172 cores per forecast for 4 hrs</b><br><b>15 GB archive space per forecast</b> |
| Stream 2.0<br>HWRF-HYCOM<br>(Global)         | 2011 Oper.<br>Physics                 | HYCOM         | 2011 Oper.<br>Init w/<br>cycling | <b>232 cores per forecast for 4 hrs</b><br><b>30 GB archive space per forecast</b> |
| Stream 2.0 HWRF<br>27:9:3 HYCOM              | Modified<br>Oper. Phys.               | HYCOM         | 2011 Oper.<br>Init w/<br>cycling | <b>Development in Progress</b><br><b>To be run on CCS or Vapor</b>                 |
| Stream 2.0<br>HWRF 27:9:3 with<br>SC and PBL | GFS Shallow<br>Convection<br>and PBL  | POM/<br>HYCOM | 2011 Oper.<br>Init w/<br>cycling | <b>Development in Progress</b><br><b>To be run on CCS or Vapor</b>                 |
| Stream 2.0<br>HWRF                           | Radiation &<br>Microphysics           | POM/<br>HYCOM | 2011 Oper.<br>Init w/<br>cycling | <b>Development in Progress</b><br><b>To be run on CCS or Vapor</b>                 |

+ Tagged to real-time GFS Hybrid DA Ensemble Runs on CCS or t-Jet

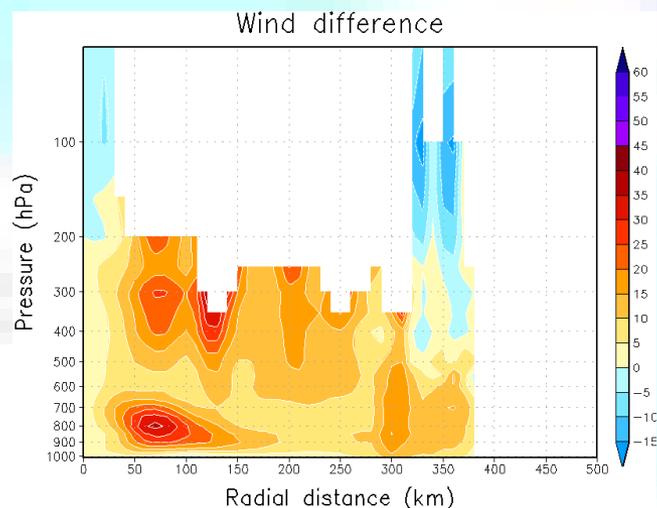
# Assimilation of tail Doppler radar data

- **Analysis domain**
  - Outer domain: 80x80 degree, resolution 27 km
  - Ghost domain: 20x20 degree, resolution 9 km
- **Data assimilated**
  - \* Quality controlled tail Doppler radar radial velocity data within [-3 hr, 3 hr] are assimilated
  - \* rawinsonde, pibal, class sounding, profiler, dropsonde, AIRCFT, AIRCAR, GPSIPW, surface data (marine/land/splash-level/mesonet), satellite wind
  - \* satellite radiance data: AMSU-A, AMSU-B/MHS, HIRS, AIRS, GOES sounder
  - \* Pseudo-MSLP
- **GSI (3DVAR)**
  - \* FGAT is used to represent obs at their appropriate time
  - \* Use flow-dependent anisotropic background error covariance [Riishøjgaard (1998), Purser 2003b, 2005].

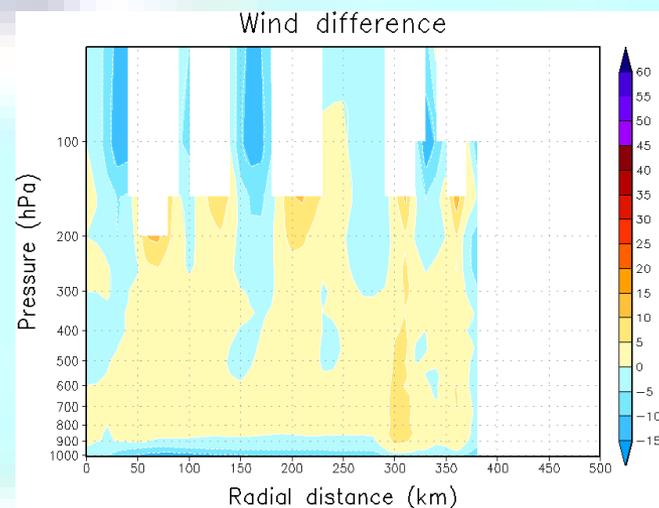


## Post balance

- \* large super gradient wind was found in HWRF's vortex initialization
- \* Tangential wind from TDR data assimilation without additional constraint also shows large departure from gradient wind
- \* Post balance is introduced to improve mass-wind balance for hurricanes
- \* Modify temperature field based on gradient wind balance and hydrostatic balance and adjust surface pressure field corresponding to new temperature field

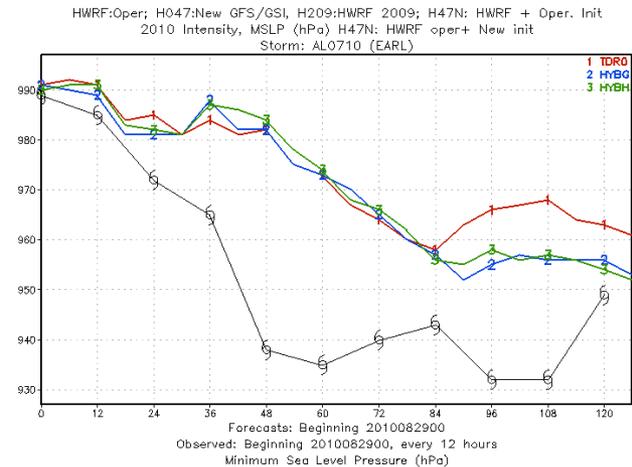
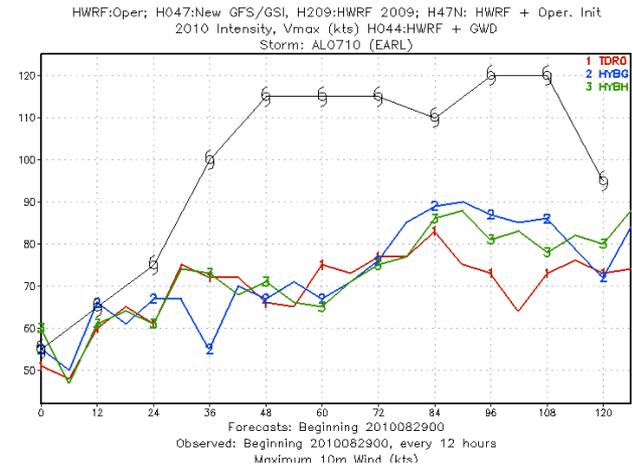
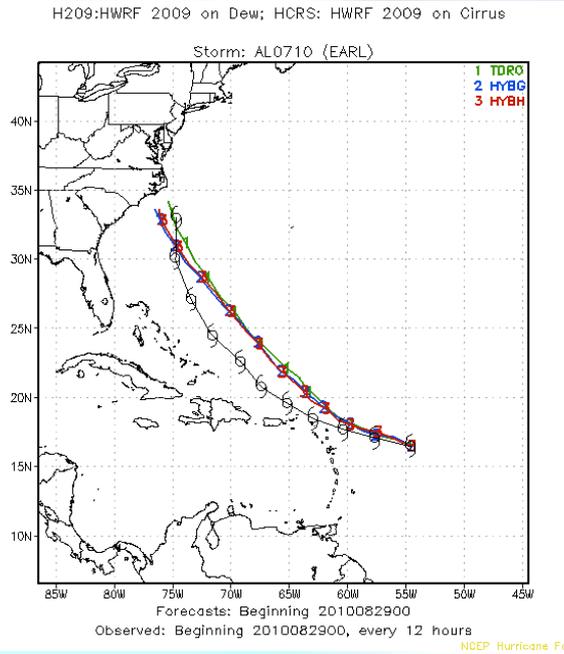


**without post balance**



**with post balance**

# HWRF Hybrid DA with TDR Data



NCEP Hurricane Forecast Project

**TDR0: anisotropic B with post balance**

**HYBG: beta1=0.5, B from global GSI Var/EnKF hybrid ensemble forecast (80 ensemble members), without post balance**

**HYBH: beta1=0.5, B from hwrf ensemble forecast (48 ensemble members), without post balance**

**The storm could not intensify as the analysis storm is quite shallow.**

# Need for a more comprehensive ocean model with DA capability

**GFDL-POM and HWRF-POM are proven systems.**

**Why transition to HYCOM?**

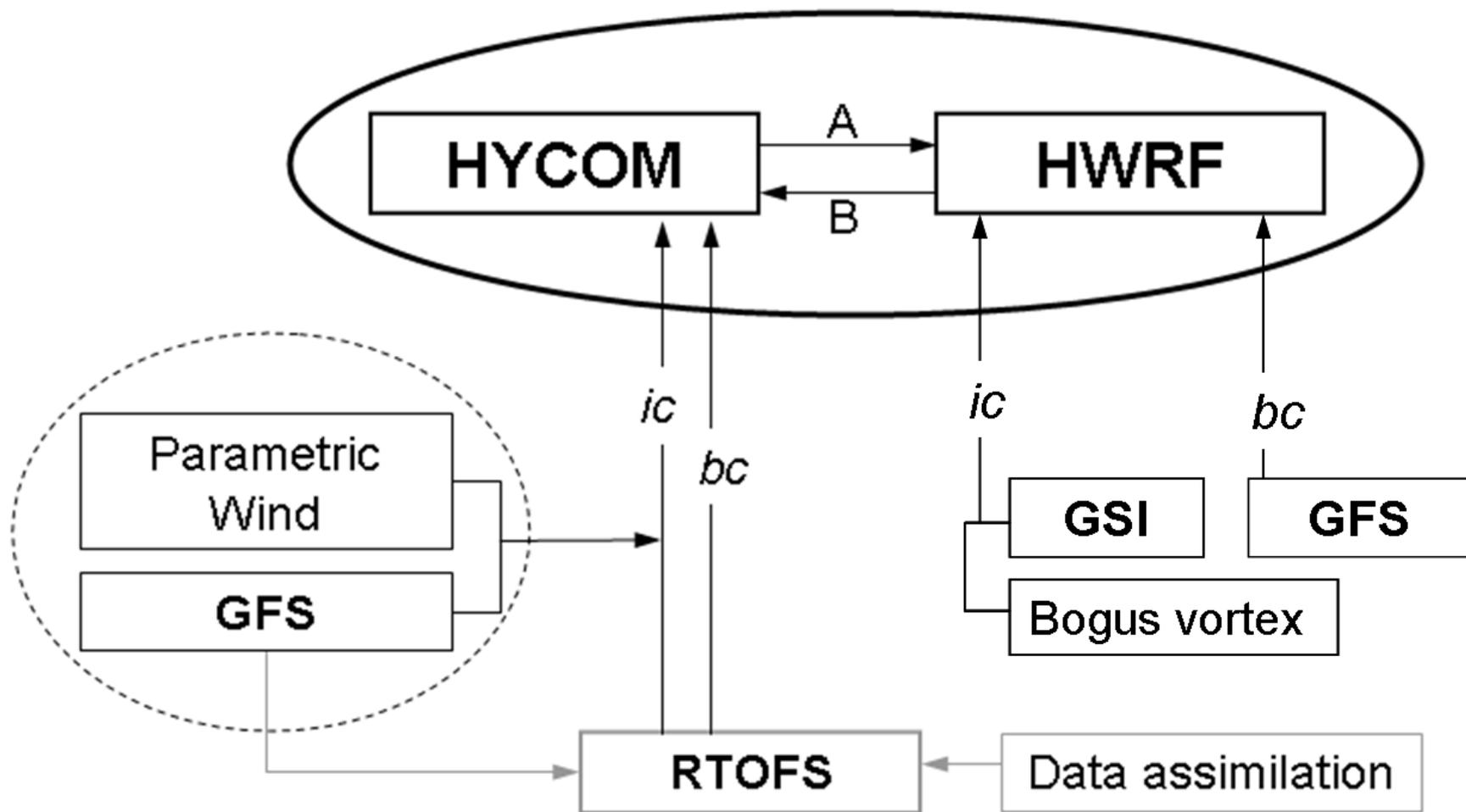
▶ **Scientific / technical issues:**

- Use operational RTOFS-Atlantic model for IC and BC:
  - Realistic real-time ocean
- Full ocean model:
  - Separate support community
  - Solid base for physics based improvement.

▶ **Management of NCEP production suite:**

- No support (at NCEP) for further development of POM based system
- Cannot afford to maintain multiple systems

# The HyWRF Hurricane Prediction System



**GSI: Gridpoint Statistical Interpolation**

# HYCOM:

- one-way nested to RTOFS
- IC: RTOFS using data assimilation
- BC: RTOFS 6-day forecast
- 3-D Primitive governing equations, solved on a curvilinear mesh (8~20 km) and hybrid vertical coordinates (26 layers).
- Staggered Arakawa C-grid
- Numerical Integration: the leap-frog scheme, using 2 split time steps for fast barotropic and slow baroclinic mode.
- Nowcast: one-way Ocean alone 6-hr simulation, forced by GFS melt with parametric winds.

# Model SST – daily average GOES/AVHRR data

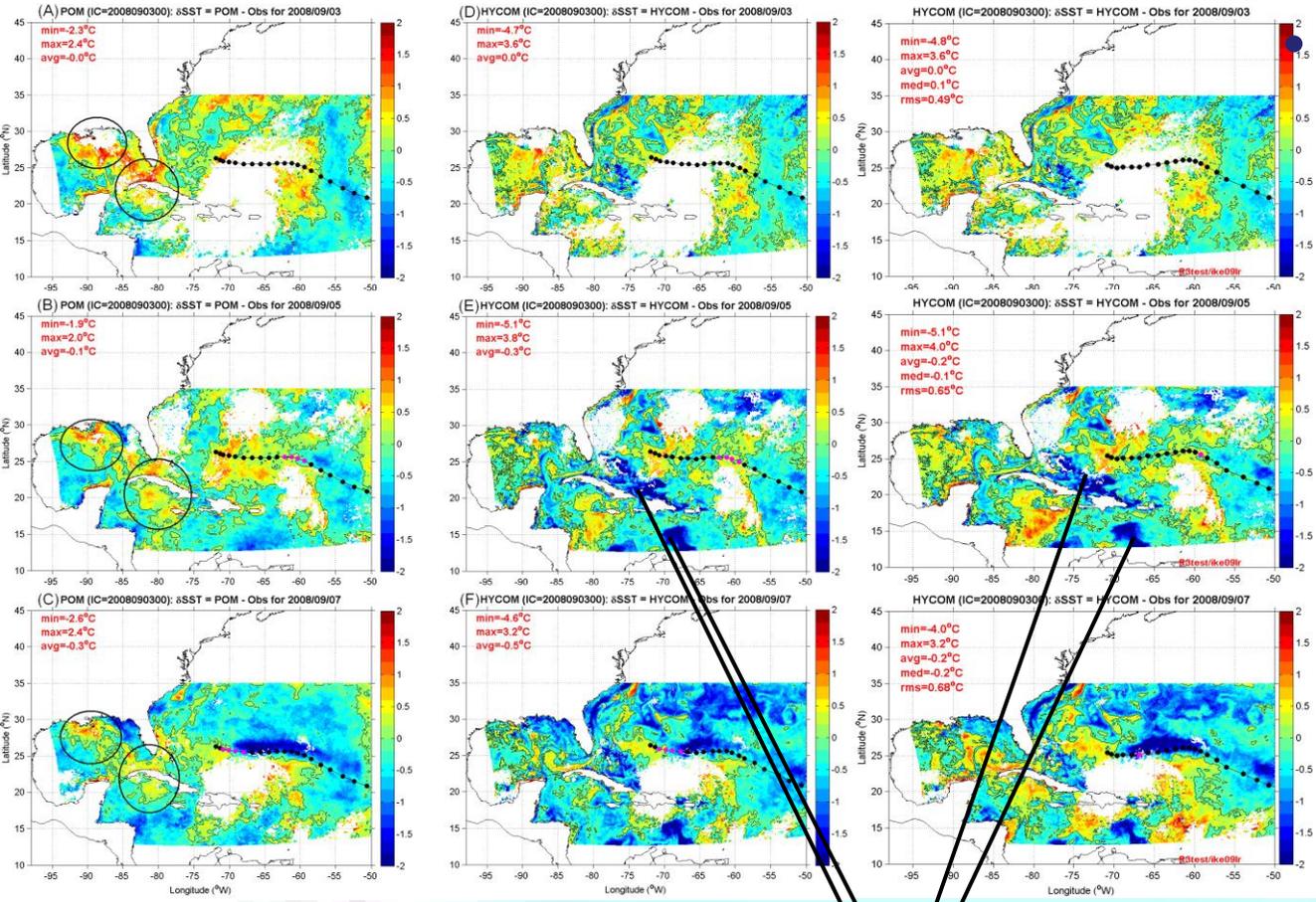
- POM vs HYCOM

## POM-HWRF (R2)

## HYCOM-HWRF (R3)

## HR32

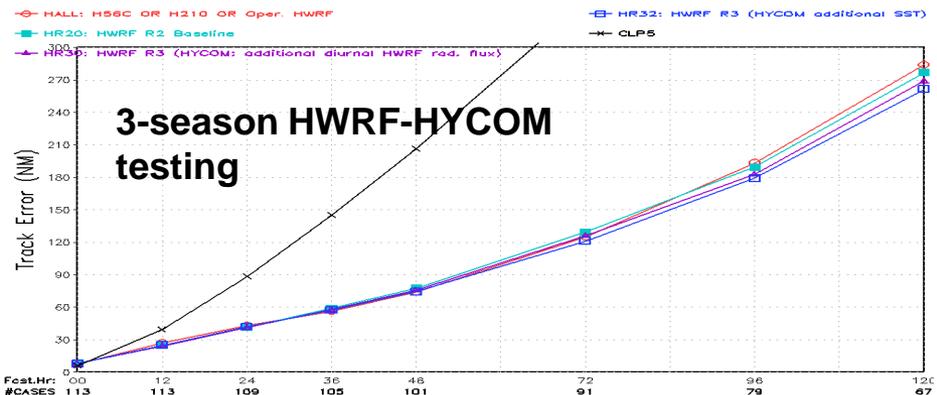
## IKE example



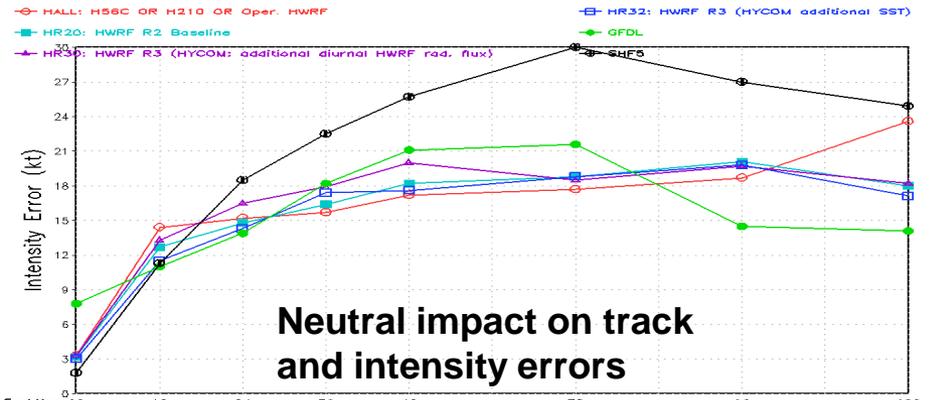
- POM on left, too warm under IKE.
- HYCOM on middle, too cool in general.
- HR32 (right): relatively warmer SST in the tropics, except more colder cold wake.

Known issues in RTOFS, varies in general from season to season.. MMAB is working on addressing these issues

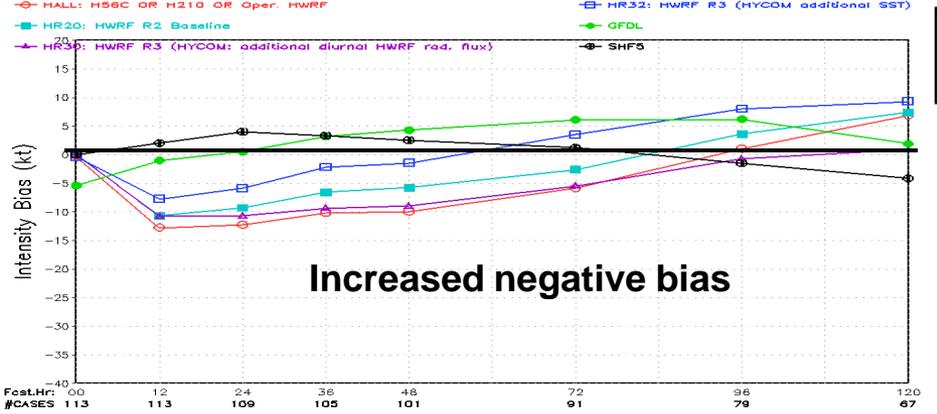
Average Track Errors (NM)  
Statistics Plots - 2008-09 2010 ATL



Average Intensity Errors (kt)  
Statistics Plots - 2008-09 2010 ATL

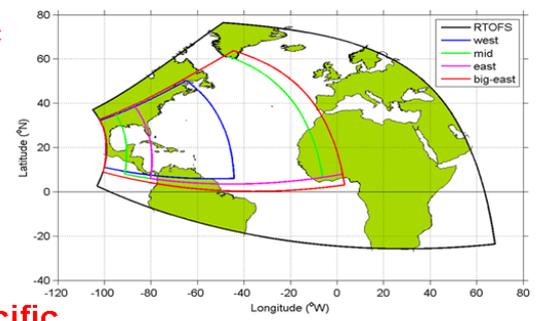


Intensity Bias (kt)  
Statistics Plots - 2008-09 2010 ATL



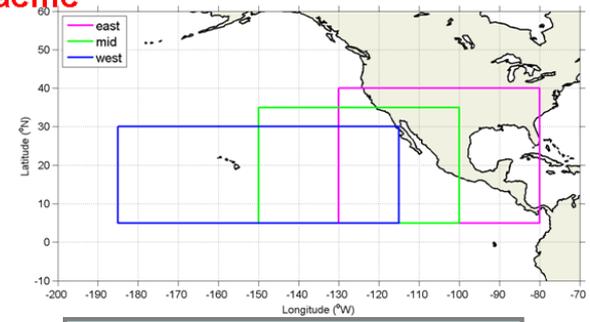
# HYCOM Hurricane Domains

Atlantic

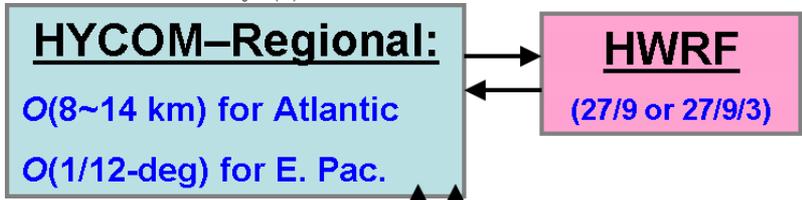


**4 domains**  
resol.: O(8 ~ 14 km)  
& 26 hybrid layers

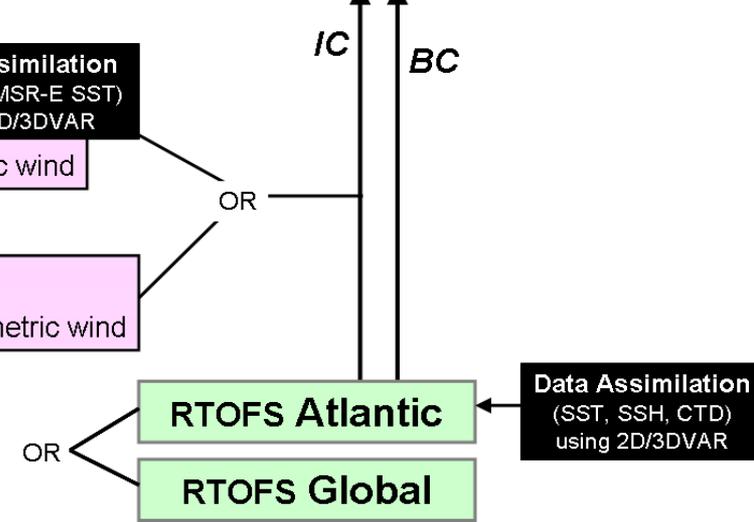
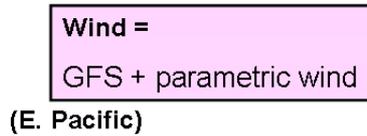
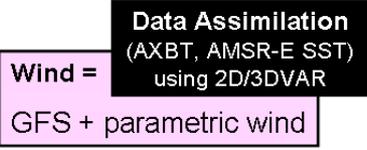
East Pacific



**3 domains**  
resol.: O(1/12 deg)  
& 32 hybrid layers

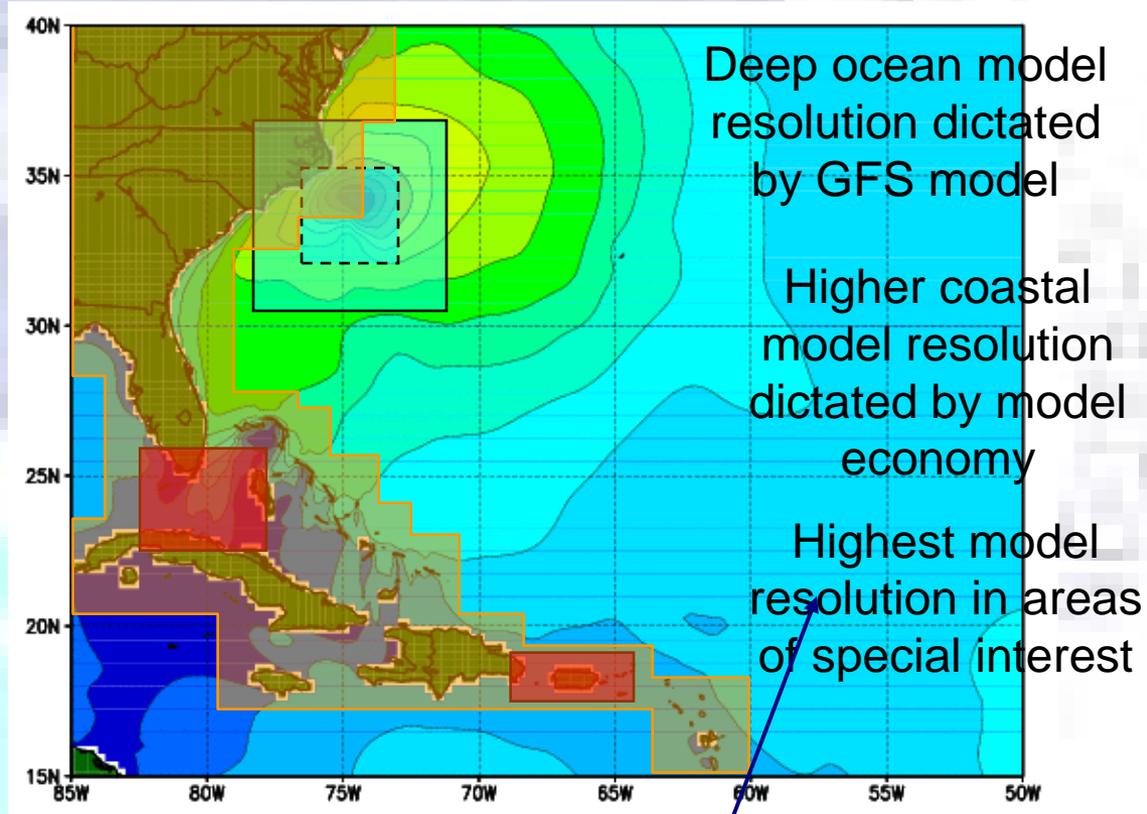


(Atlantic)



# Coupling to Wave-Watch III

- NOAA/NCEP in-house wave model, based on WAM.
- Operational global and (nested) regional model.
- Specialized Atlantic and Pacific hurricane wave models with blended winds from GFS and GFDL model.
- WAVEWATCH III will be coupled to HWRF



Hurricane nests moving with storm(s) like GFDL and HWRF

# Advancing the HWRF System FY2011 & Beyond

|                                     | 2011  | 2012   | 2013   | 2014*   | 2015* |
|-------------------------------------|---|--|--|---|-------|
| Resolution/<br>Infrastructure       | <b>HWRFV3.2+</b><br><b>Triple nested HWRF<br/>(27/9/3 km)</b> |  |  | <b>Increased vertical resolution, higher model top, upgrades to WRF infrastructure, NEMS/ESMF/NMM-B, community R2O efforts (HFIP)</b> |       |
| Physics                             | <b>Deep Convection, Surface Physics</b>                       | <b>Horizontal diffusion, Shallow convection, Microphysics, Radiation, Surface Physics, Coupling to Waves and Land Surface, Physics for high-resolution</b> |  |   |       |
| DA/ Vortex Initialization           | <b>Storm size correction, dynamic mass-wind consistency</b>   | Inner core DA (Doppler Radar, satellite), improved mass-wind balance   | <b>Hybrid-EnKF DA, advanced vortex relocation procedure, improved GSI</b>        |   |       |
| Ocean                               | <b>HYCOM Coupling</b>   | <b>Improved ocean data assimilation, physics and resolution, unified coupled system for ATL &amp; EPAC</b>   |  |   |       |
| Waves                               | <b>One-way Wave Coupling</b>                                  |  | <b>Two-way wave coupling, multi-grid surf zone physics, effects of sea spray</b> |   |       |
| Diagnostics and Product Development |   | <b>HWRF Ensembles, Coupling to Hydrological/ Surge/ Inundation models, diagnostics, product development</b>  |  |   |       |

\*Potential  
Computer upgrade

Ongoing Work

2011 upgrades

Planned developments

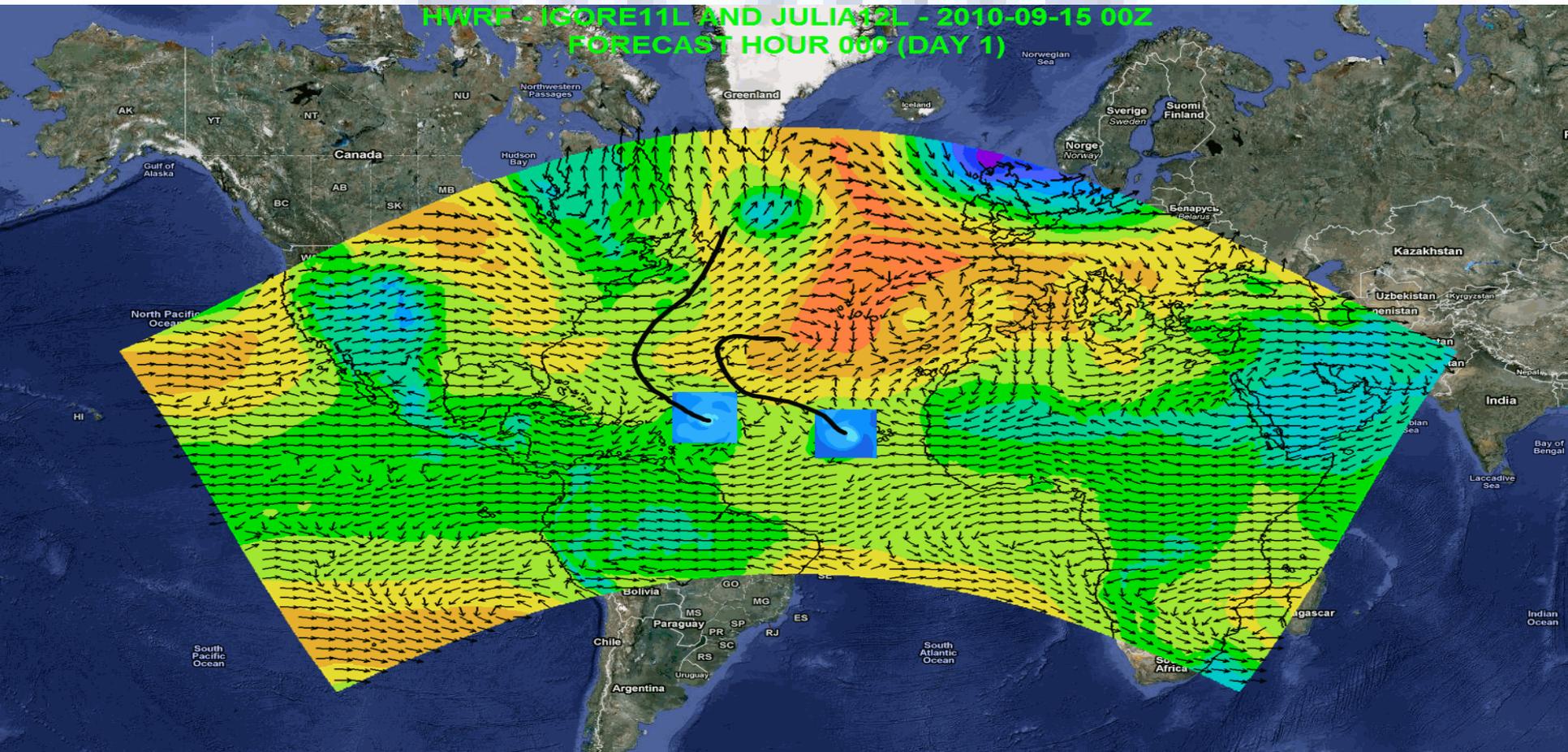


# Next Generation Modeling Efforts with HWRF

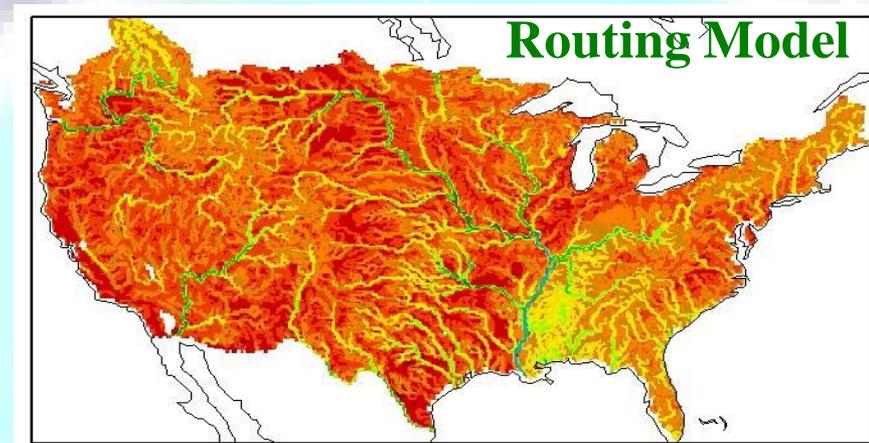
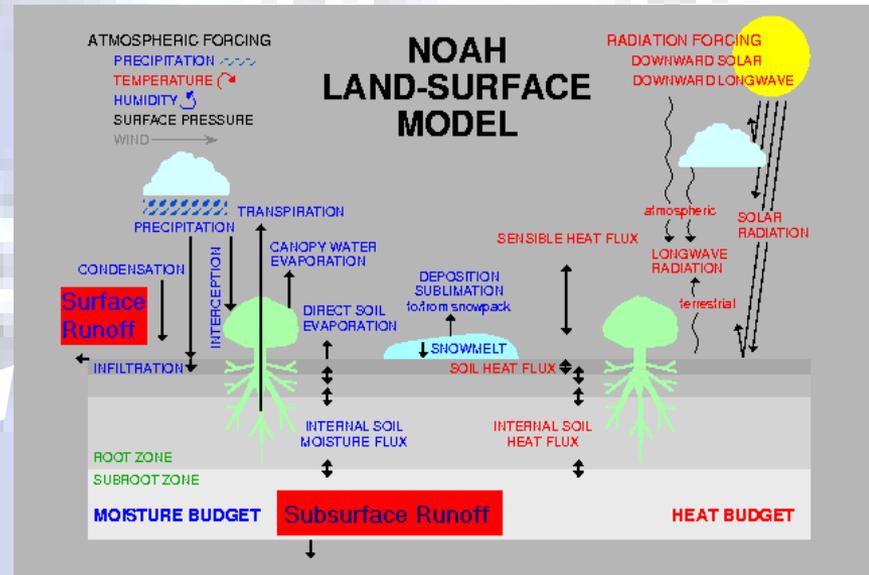
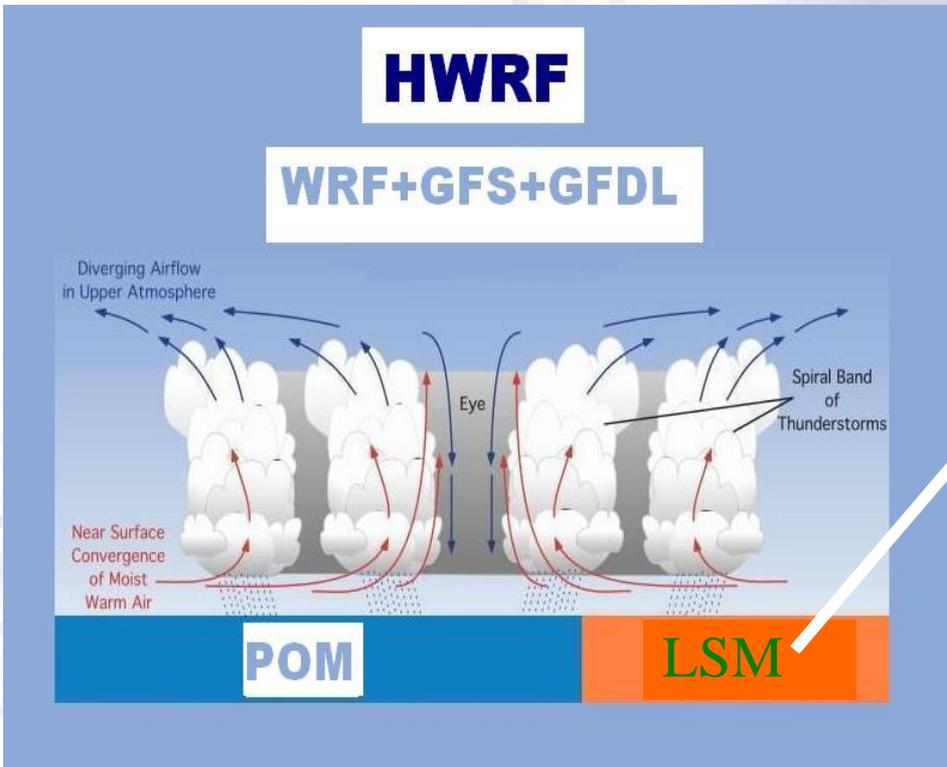
- Next generation modeling efforts include basin scale regional domain with multiple moving nests.
- Downstream applications include serving WFOs for storm surge forecasts, landfall related flooding and inundation forecasts.
- NOAA has signed an MOU with India on application of HWRF modeling system for operational tropical cyclone prediction over Indian Seas (collaboration with AOML, U. Purdue)
- With Global HyCOM becoming operational at NCEP, it is possible to implement coupled HWRF-HYCOM system for all oceanic basins in the world.
- Work is in progress towards flexible vortex initialization procedure (collaboration with DTC).

# HWRF Domain With Multiple Moving Nests

- Basin scale domain
- 7 days forecast
- SDA and cycling
- Regional ensembles/products
- Daily Tropical Outlook/genesis
- Computational Efficiency (27:9; about 2 h; 168 CPUs)



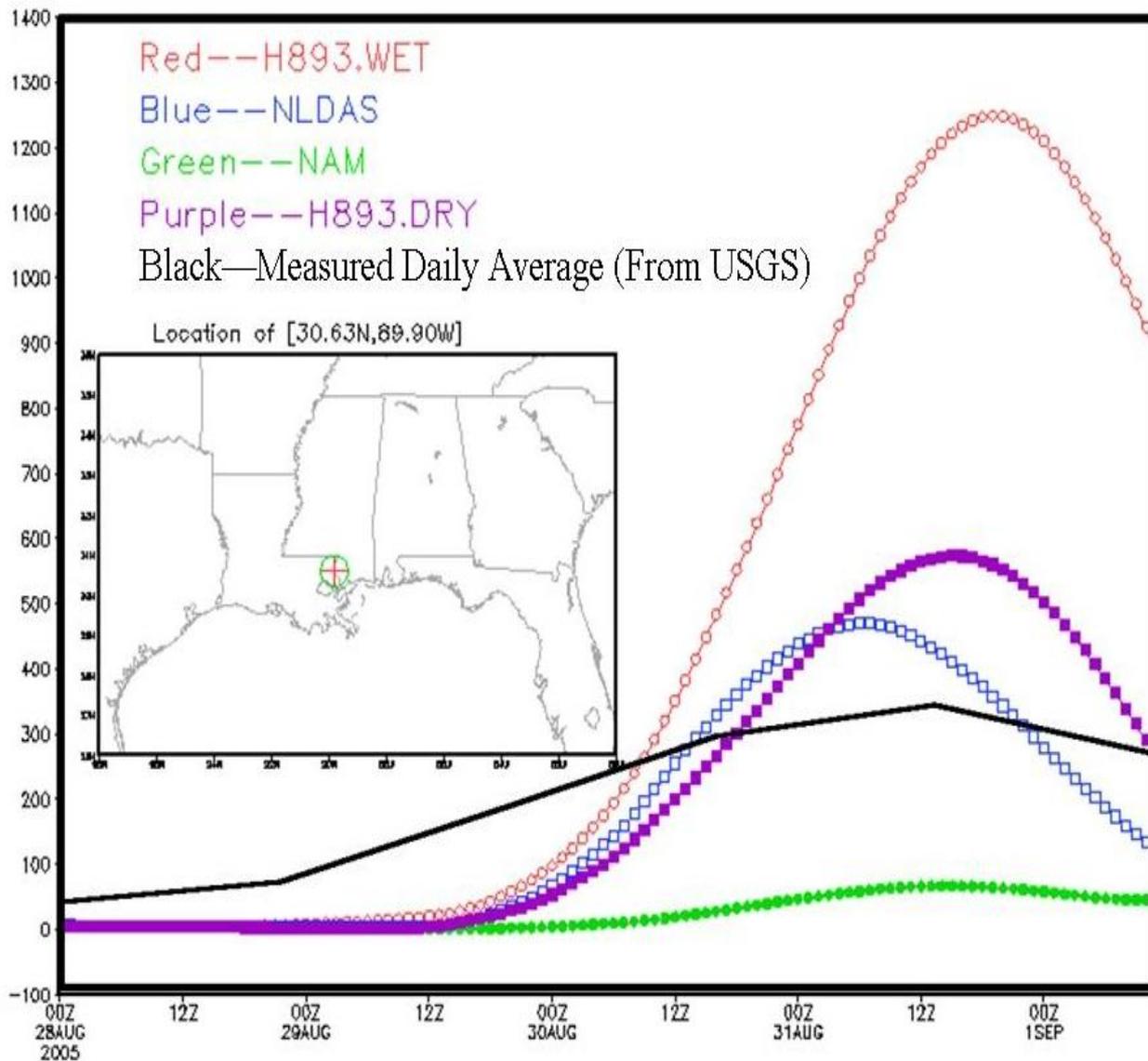
# Coupling to Land Surface Model



Driving Forcing: Surface runoff and baseflow

[www.emc.ncep.noaa.gov/HWRF](http://www.emc.ncep.noaa.gov/HWRF)

# Stream flow At 30.63N and 89.90W

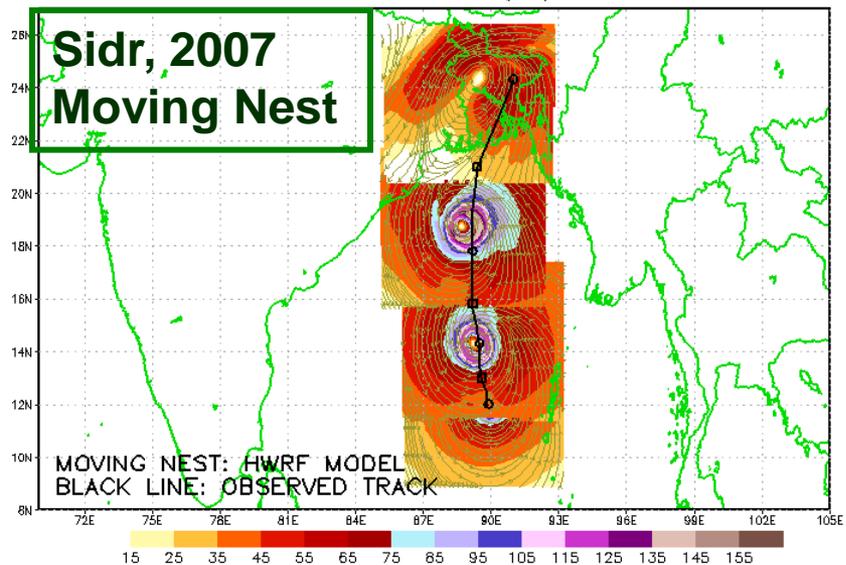


1. The peak in WET run is much higher than in NLDAS, DRY run, NAM and the observed

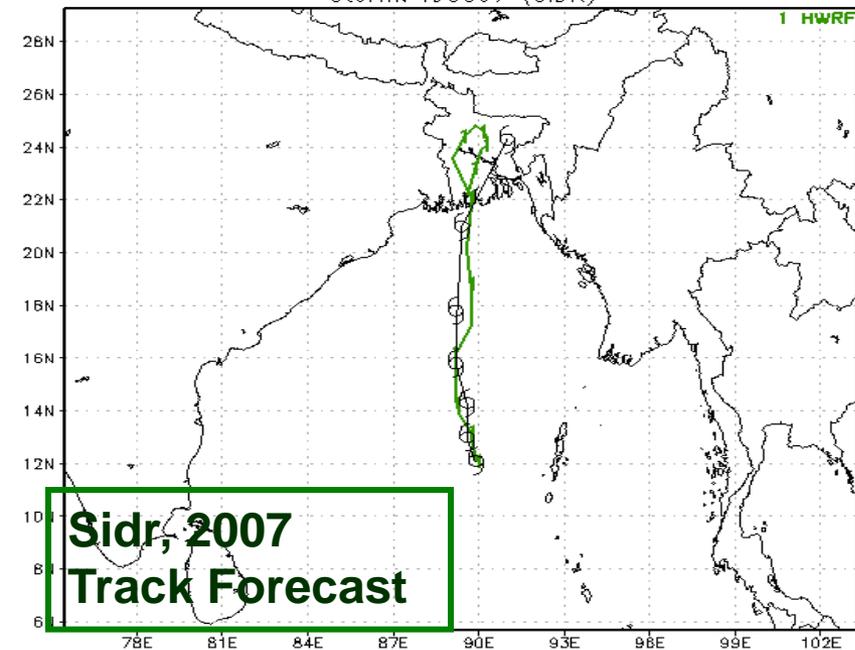
- The peak time in DRY run is more comparable to the observation than in NLDAS.

USGS: <http://waterdata.usgs.gov>

November 13, 2007 00Z: TROPICAL CYCLONE SIDR  
850 hPa WINDS (kts)

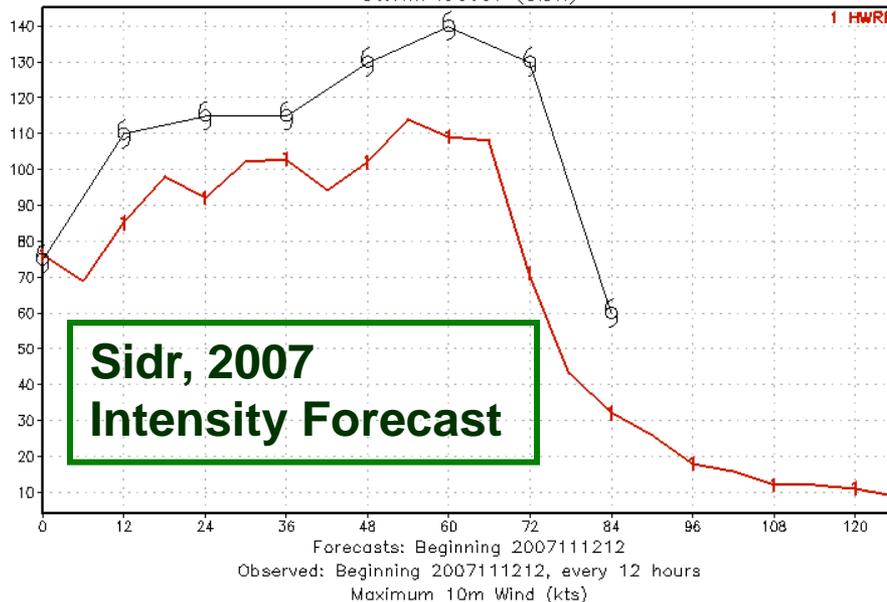


HWRf: Hurricane Weather Research and Forecasting Model  
2007 Tropical Cyclone Tracks  
Storm: IO0607 (SIDR)

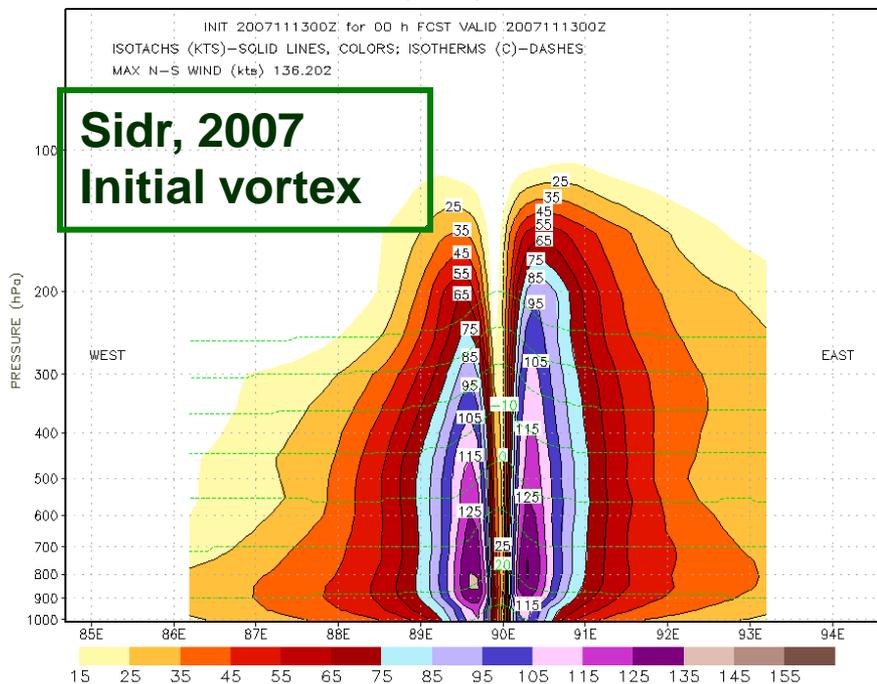


NCEP Hurricane

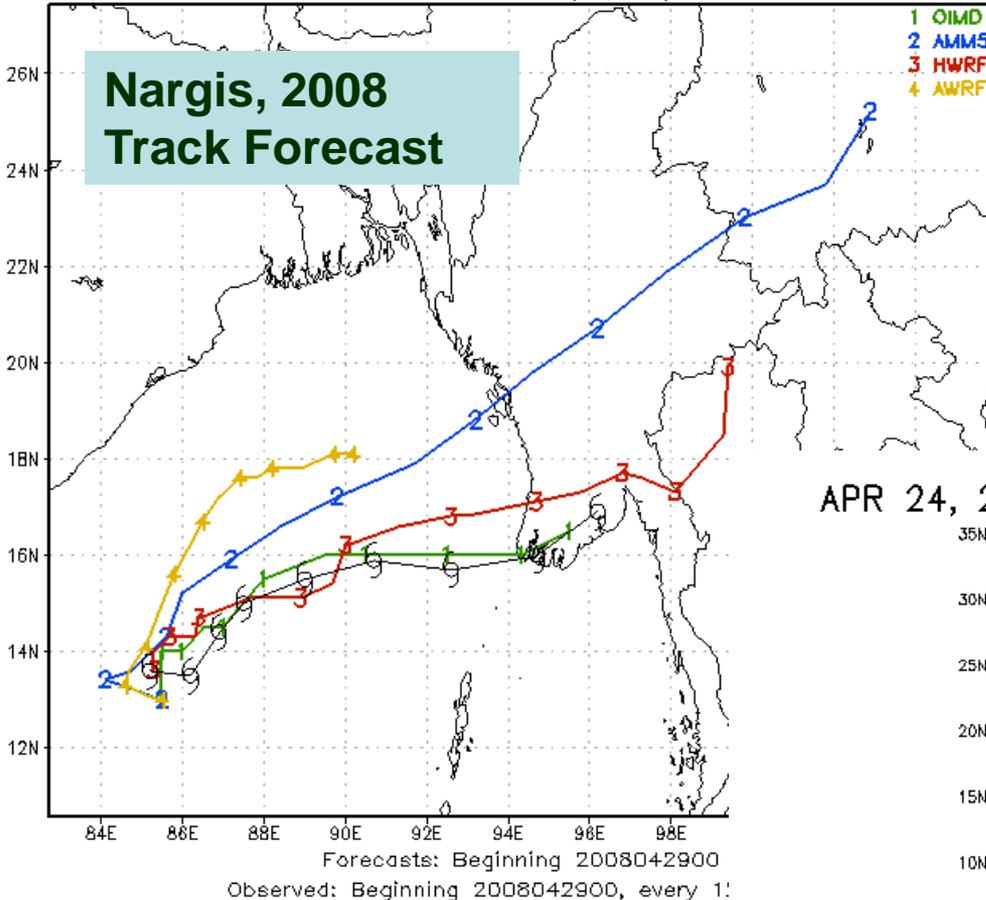
HWRf: Hurricane Weather Research and Forecasting Model  
2007 Tropical Cyclone Intensities, Vmax (kts)  
Storm: IO0607 (SIDR)



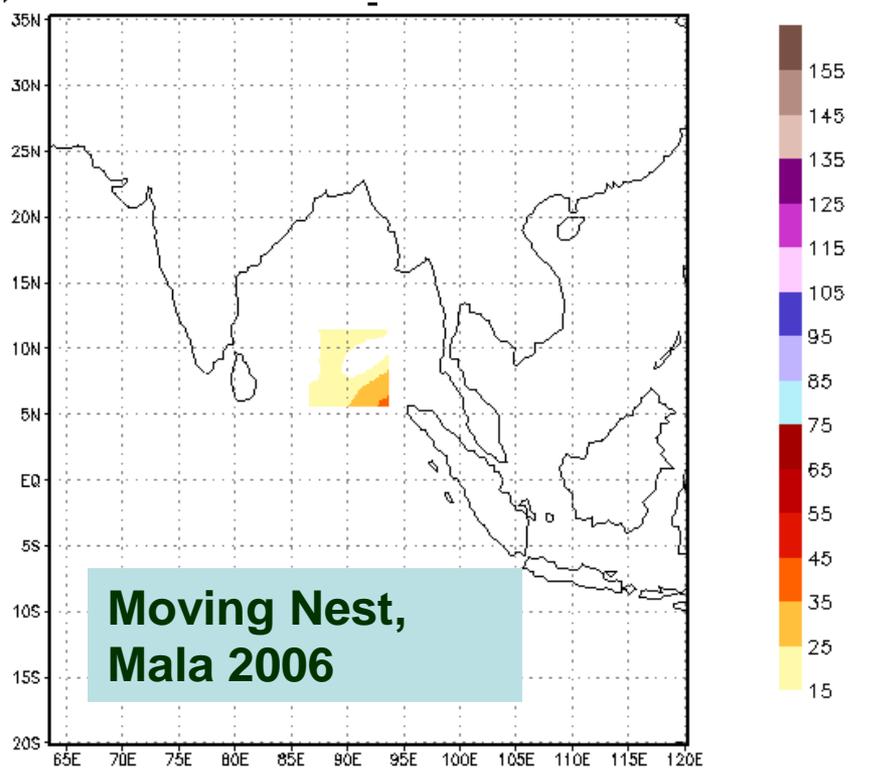
HWRf SIDR 06b VERT (E-W) CROSS SECT LAT = 12.10



NCEP Hurricane Forecast Project



APR 24, 2006 12Z: TS MALA\_ MOVING NEST FCST: 0



## **SUMMARY**

**There has been lot of progress advancing the hurricane modeling capabilities at EMC, thanks to active collaboration between research and operations.**

**Improving intensity/structure forecasts are orders of magnitude more difficult than was track forecasts.**

**Requires substantial effort between research and operational hurricane communities**

**This tutorial is one way to attract young generation to tackle these scientific challenges.**

# Real-time and pre-implementation T&E HWRF products:

[http://www.emc.ncep.noaa.gov/gc\\_wmb/vxt/index.html](http://www.emc.ncep.noaa.gov/gc_wmb/vxt/index.html)

## Thanks for your attention

### Questions?

#### **Acknowledgements:**

*HWRF team at EMC*

*EMC and HFIP Management*

*Collaborations with NHC, DTC, HRD, GFDL,  
URI, CIRA and other HFIP partners*

