Overview of the NCEP Operational HWRF Modeling System

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NOAA HURRICANE FORECAST IMPROVEMENT PROJECT

Outline

- History of Operational HWRF Model Development
- HWRF as a community tropical cyclone modeling system
- Role of academic and research community in HWRF Development Process
- HWRF as a global tropical cyclone modeling system for research and operations
- Performance of the 2013 operational HWRF Model
- Components of the HWRF modeling system
- Ongoing HWRF model developmental efforts for 2014 and beyond

Hurricane WRF (HWRF)

- The Weather Research and Forecast Modeling System for Hurricanes (HWRF) was designed to address the Nation's next generation hurricane forecast problems.
- HWRF was developed at NCEP/EMC utilizing the WRF software infrastructure.
- HWRF became operational in the year 2007 preceded by extensive testing and evaluation for three hurricane seasons (2004-2006), and has been constantly improved to increase the forecast skill for track, intensity and structure of Atlantic and Eastern Pacific hurricanes.
- Starting in 2011, the operational coupled HWRF-POM modeling system became a community tropical cyclone modeling system. The use of same code by research and operations was accomplished through dedicated subversion based code management and community support, facilitating accelerated Operations to Research (O2R) and Research to Operations (R2O).

Evolution of HWRF

- **Initial implementation in 2007 hurricane season**

– **Model design and development of movable nested grid started in 2002 in collaboration with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) scientists and the University of Rhode Island (URI)**

– **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**

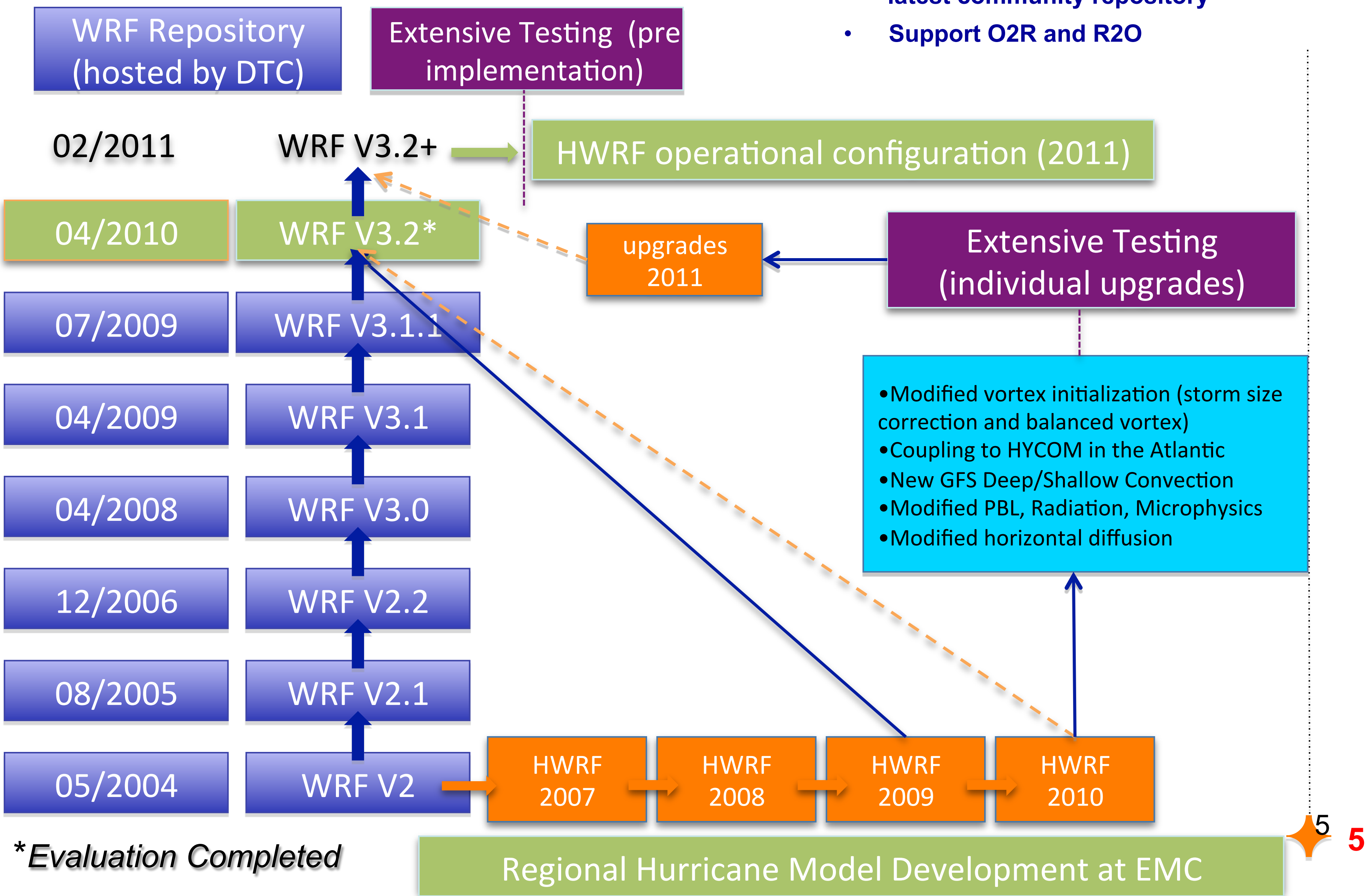
- **Physics and initialization upgrades in 2010 to improve the forecast skill.**

– **Modified surface physics formulation and use of Gravity Wave Drag parameterization**

– **Addition of satellite radiance data assimilation in the hurricane environment**

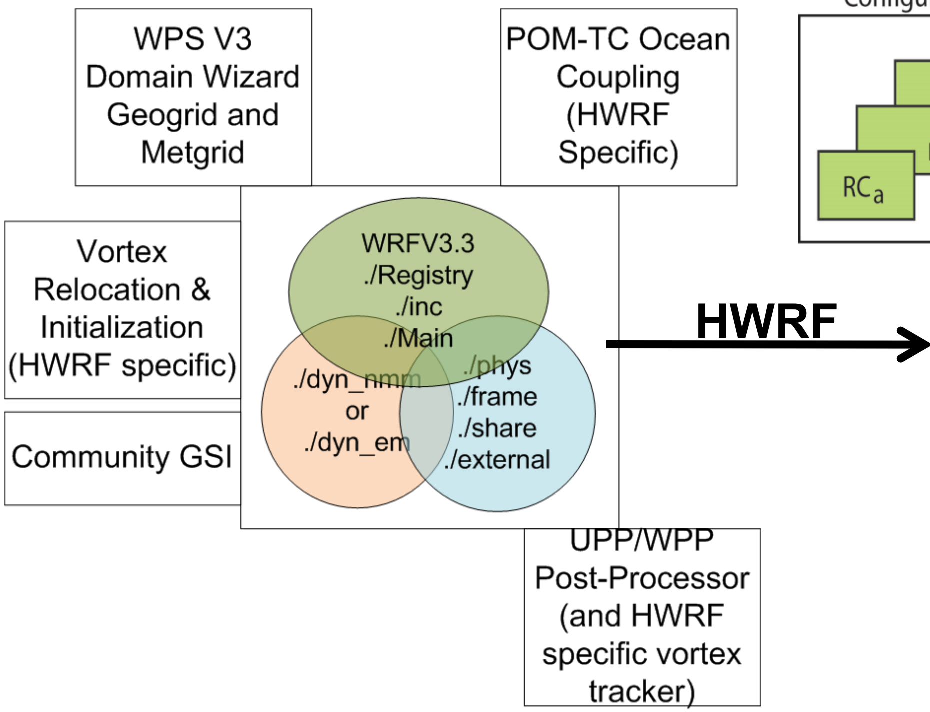
FY2011 Operational HWRF Configuration

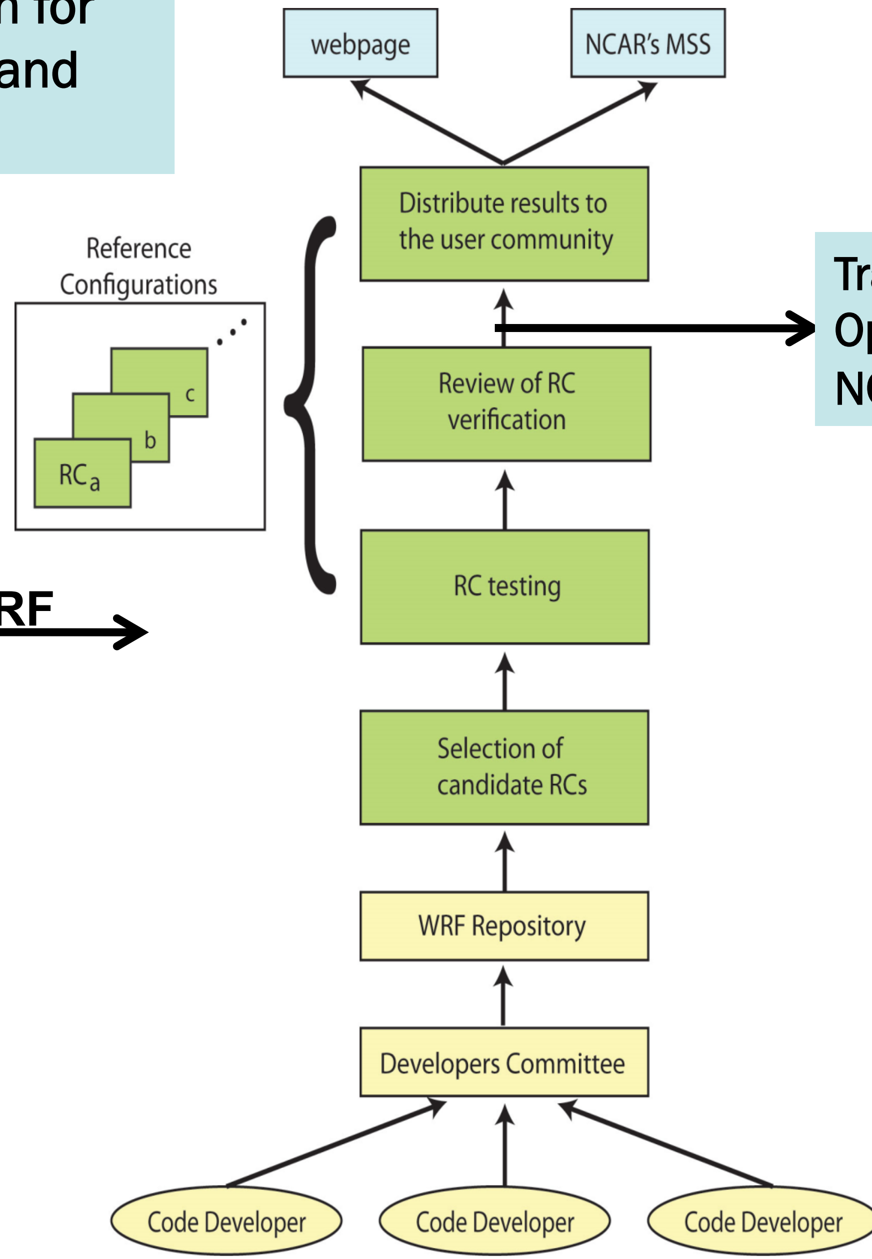
- **2011 HWRF as a community hurricane model supported by DTC**
  - **Upgrade WRF infrastructure to align with latest community repository**
  - **Support O2R and R2O**



*Evaluation Completed

Starting from 2011, NCEP Operational HWRF is a Reference Configuration for WRF (Essential step towards O2R and R2O)

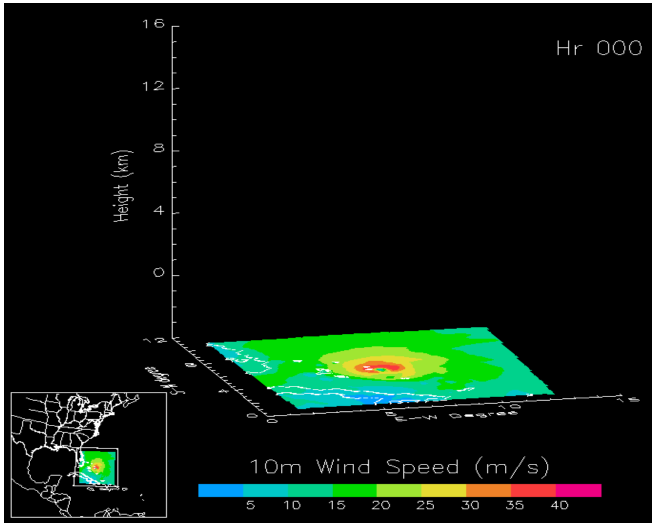




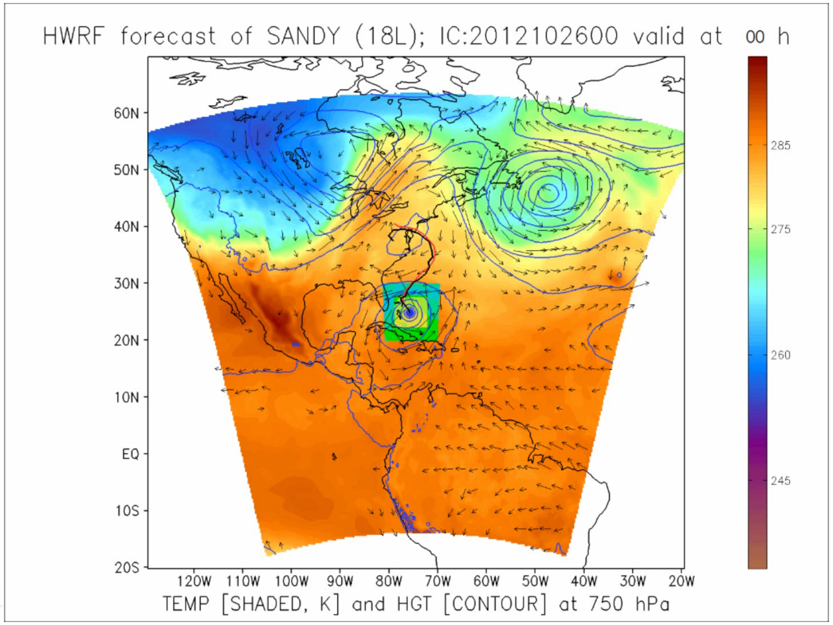
Transition to Operations at NCEP/EMC

FY2012 High-Resolution Triple-Nested HWRF

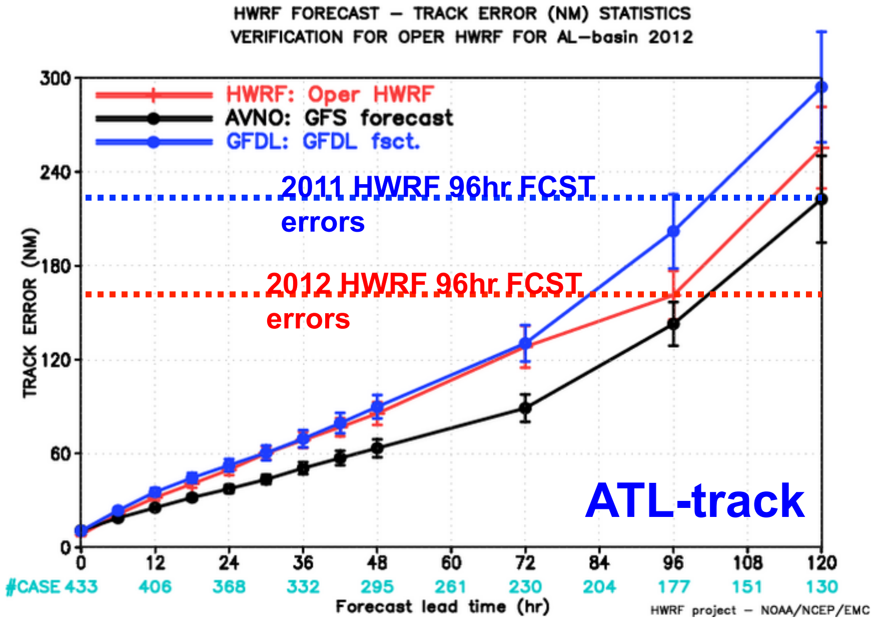
- ***For the first time, a*** ***high-resolution hurricane model operating at cloud-permitting 3km resolution*** ***implemented into NCEP operational system***
- **This upgrade is a result of** **multi-agency efforts supported by HFIP**
  - ***EMC***: *Computational efficiency, nest motion algorithm, physics improvements, 3km initialization and pre-implementation T&E*
  - ***HRD/AOML***: *nest motion algorithm, multiple moving nests, PBL upgrades, interpolation for initialization,*
  - ***DTC/NCAR***: *code management and repository, MPI profiling*
  - ***ESRL***: *Physics sensitivity tests and idealized capability*
  - ***URI***: *1D ocean coupling in East Pac*
  - ***GFDL***: *Knowledge sharing, joint T&E*
  - ***NHC***: *Diagnostics and evaluation of the HWRF pre-implementation tests and real-time guidance*

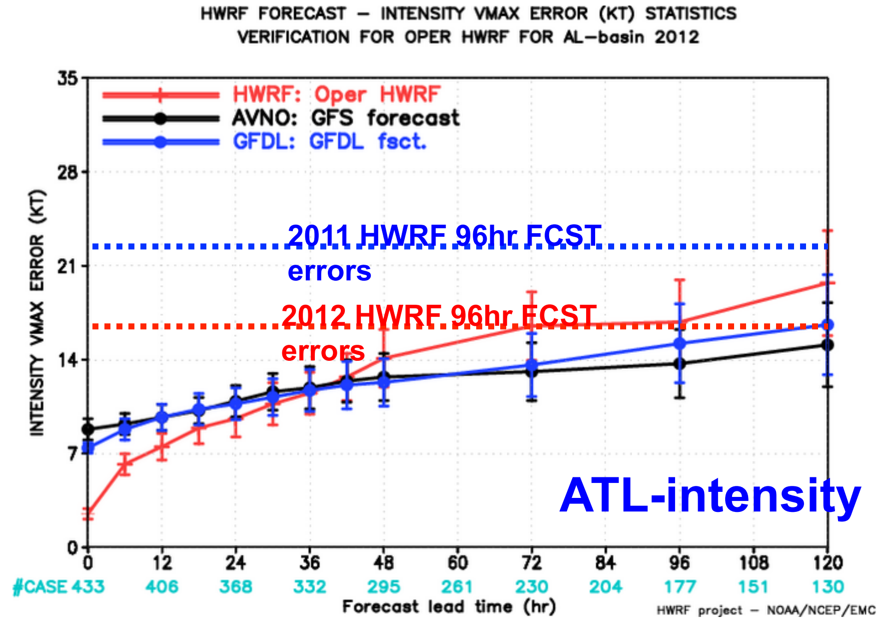


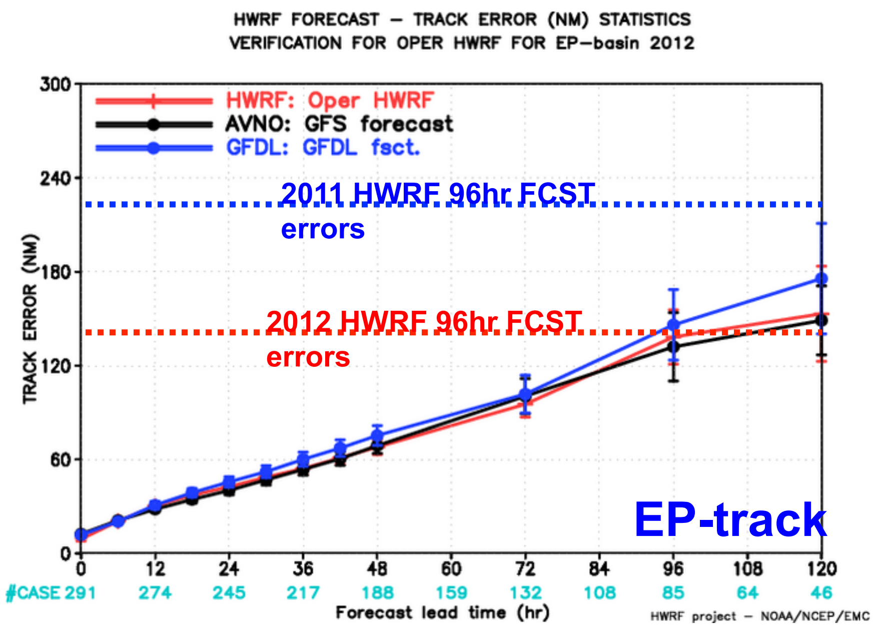
Three telescopic domains: 27km: 75x75°; 9km ~11x10° **3km inner-most nest 6x5.5°**

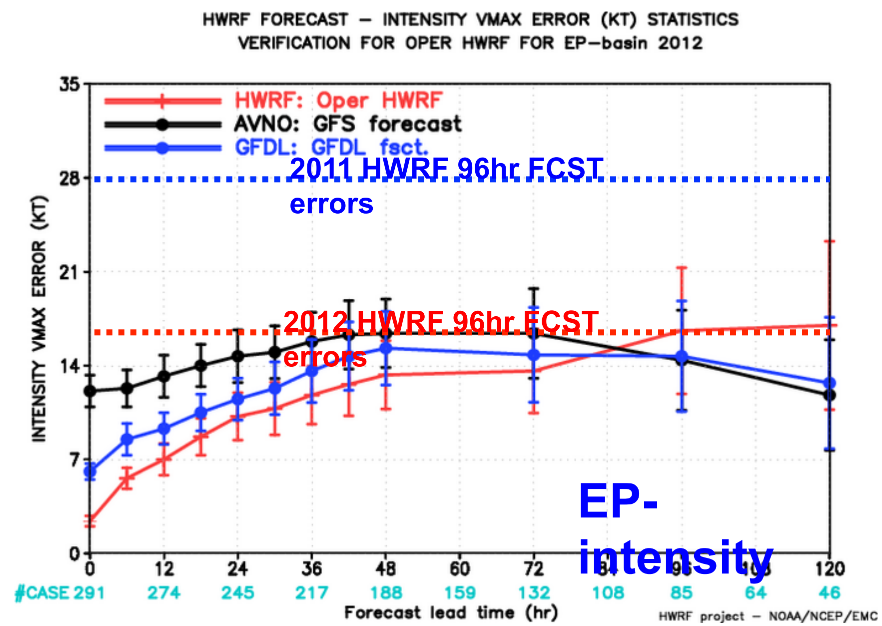


Verification of Operational HWRF for 2012 season

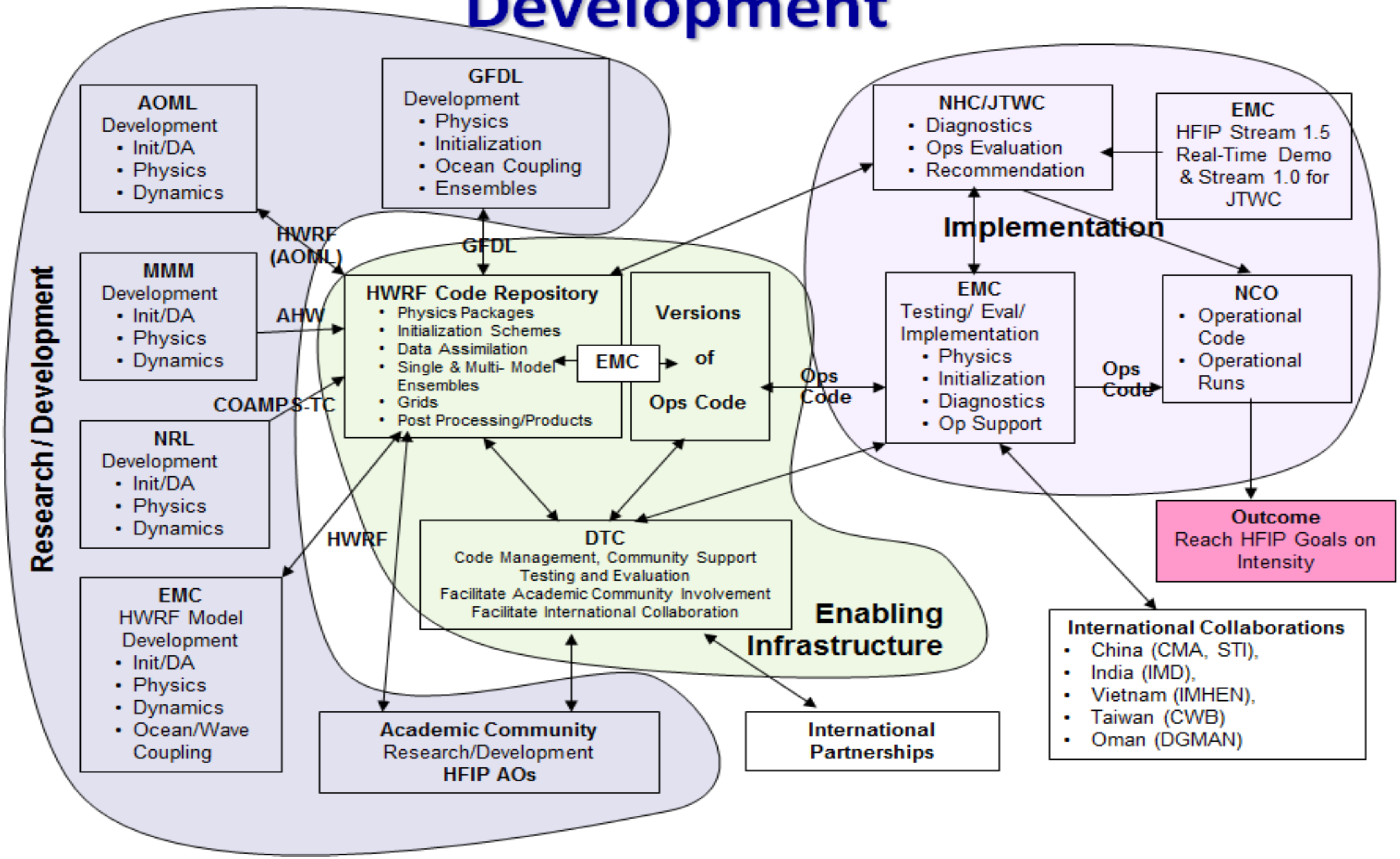








Operational Hurricane Modeling System Development



2013 HWRF pre-implementation Test Plan

EXP	Description	Comments	Platform/# of cases
Pre-Baseline Experiments			
TDRP	FY12 HWRF + One-Way Hybrid GSI	Real-time demo during 2012 season	CCS, All 2012 ATL and EP, 821 cases
HDFL	FY12 HWRF + Flux truncation into POM	DTC's contribution for R2O innovation	Jet, All 2012 ATL and EP, 821 cases
P160	FY12 HWRF + Initialization Changes	Improved size correction, modifications to filter domain and use GFS vortex when initial storm intensity less than 16 m/s	Jet, All 2012 ATL and EP, 821 cases
HNPI	FY12 HWRF + New nest-parent interpolations + New nest movement algorithm	Revised nest-parent interpolations and improved treatment of variables at nest boundaries. Improved nest tracking based on membrane MSLP and Tim's tracker.	Jet, All 2012 ATL and EP and 6 others from 2010-11; 988 cases
HHPC	FY12 HWRF + High Frequency Physics Calls	Increased Physics calling frequency from 180 sec. to 30 sec. Third nest size increased by about 30% from	Jet, A few selected storms from 2012
Baseline Experiment			
H130	All modifications from pre-baseline experiments	2013 HWRF baseline is based on positive outcome from the pre-baseline experiments described above.	Jet/Zeus/WCOSS, All 2010-2011-2012 1870 cases
Physics Upgrades			
H 1 3 1 (Final)	H130 + PBL changes	HWRF PBL to include variable critical Richardson number	Jet, All 2010-12, 1870 cases

Systematic T&E of about 10 different configurations, more than 15000 simulations from 80 storms of 2010, 2011 and 2012 hurricane seasons on CCS/Jet, Zeus and WCOSS, thanks to support from HFIP PO for Jet usage, and from NCO for usage on CCS/WCOSS. Results from these experiments are on HWRF website: http://www.emc.ncep.noaa.gov/gc_wmb/vxt/

Highlights of FY2013 High-Resolution Triple-Nested HWRF V7.0.0

Infrastructure upgrades:

•Upgrade the **nest tracking algorithm**

•Re-design of **nest-parent interpolations**

•**Increased frequency of physics calls** and **increased size of the third domain**

Physics upgrades:

•**Modifications to GFS PBL** and **bug fix for GFDL radiation**

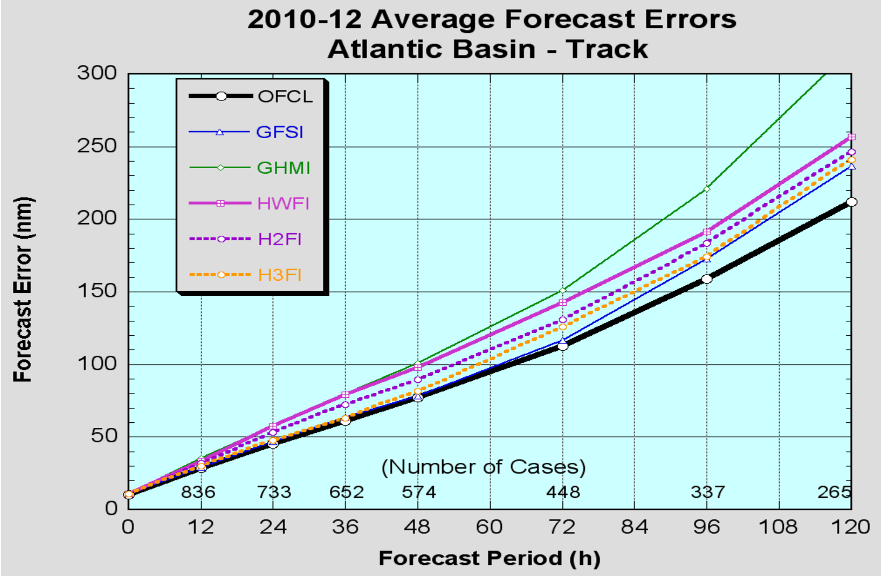
Data Assimilation and Vortex Initialization upgrades:

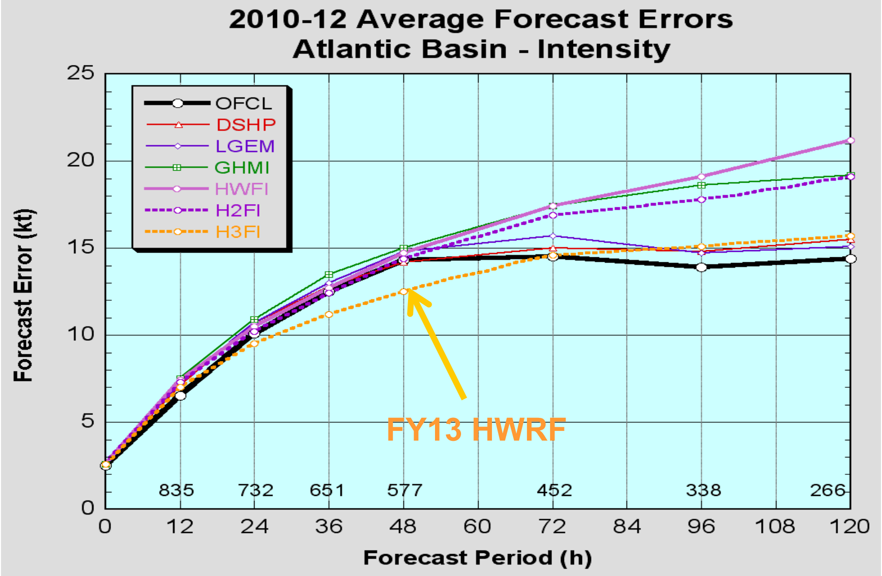
•**One-way hybrid EnKF-3DVAR data assimilation** and **assimilate real-time inner-core TDR datasets**

•**Improved storm size correction, modified filter domain** and **use of GFS vortex** when the storm is weaker than 16 m/s

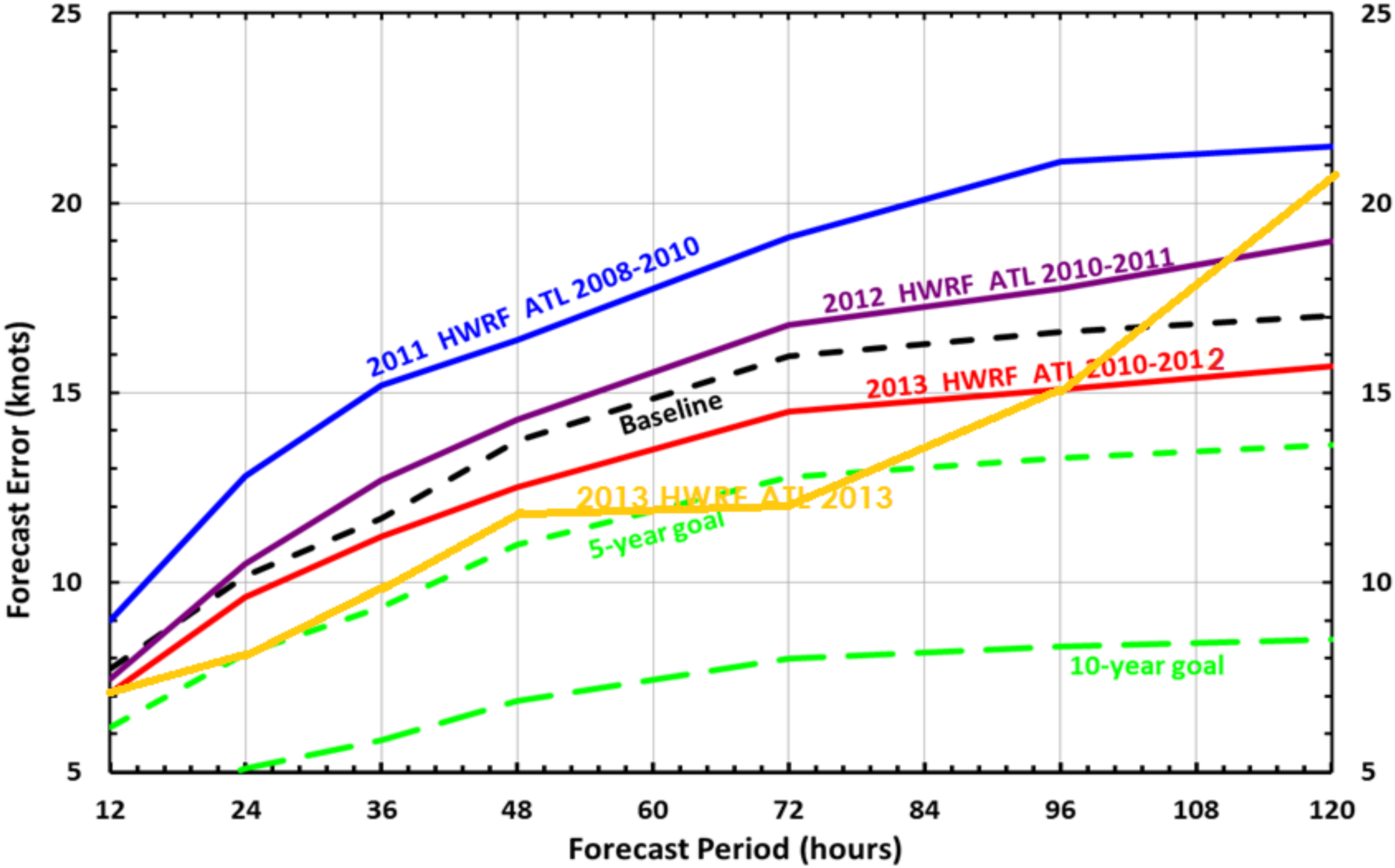
Extensive evaluation:

- **Three-season (2010-12) comprehensive evaluation for NATL/EPAC**
- **2012 typhoon season for WPAC**
- **Implemented on July 2, 2013**



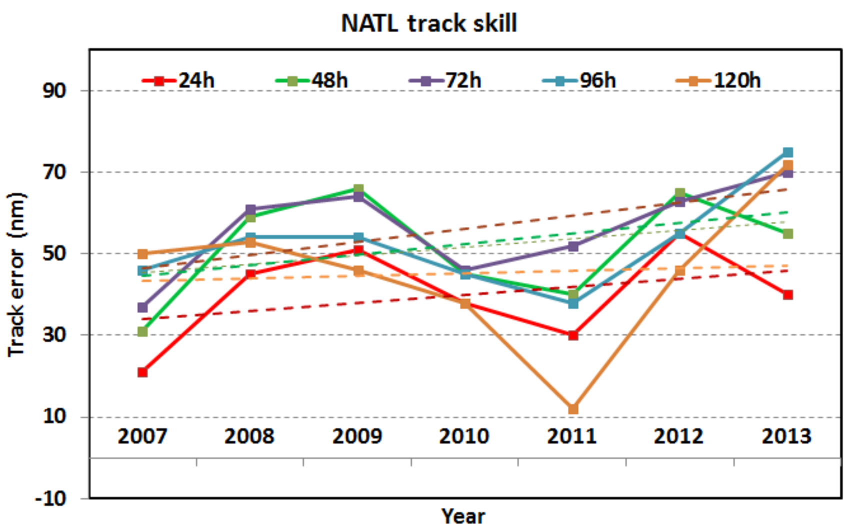


HWRF Intensity ATL Basin: Cumulative Forecast Improvements (Real-Time Performance)

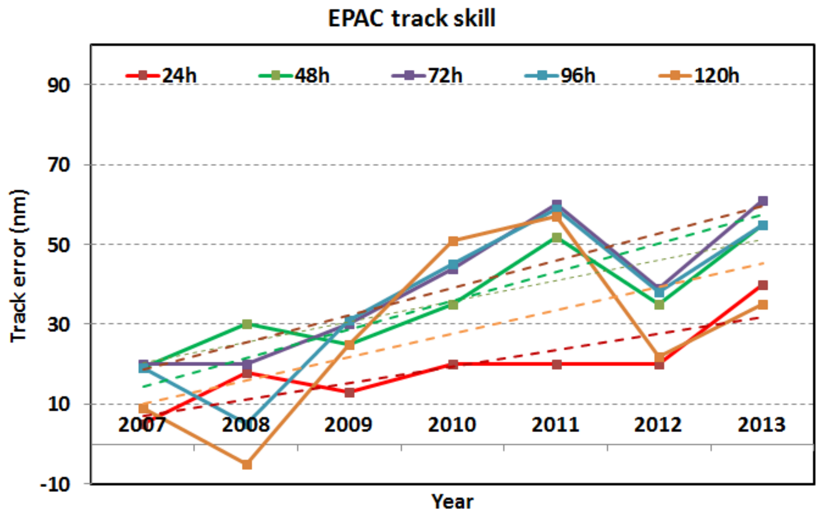


HWRF Forecast Skill Progress & Improvement w.r.t 2012

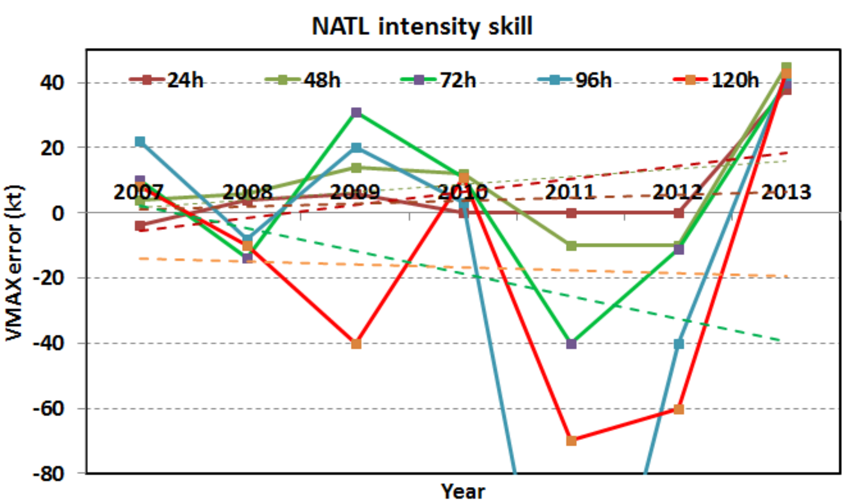
(FY2013 Operational Goals: 10% improvement in track and intensity skill at all times)



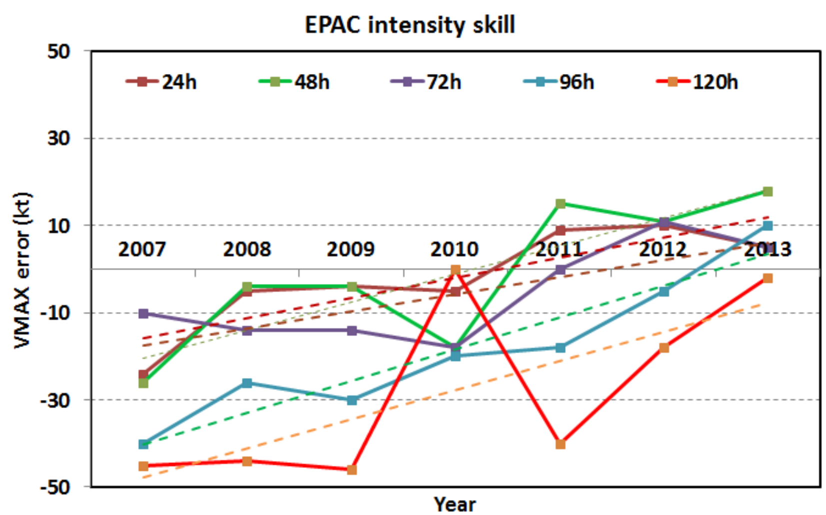
Lead time	24	48	72	96	120
improvement	-15	-10	7	20	26



Lead time	24	48	72	96	120
improvement	20	20	22	17	13



Lead time	24	48	72	96	120
improvement	**33**	**55**	**51**	**82**	**103**



Lead time	24	48	72	96	120
improvement	-5	7	-6	15	16

HWRF as a global tropical cyclone model for operational forecast guidance

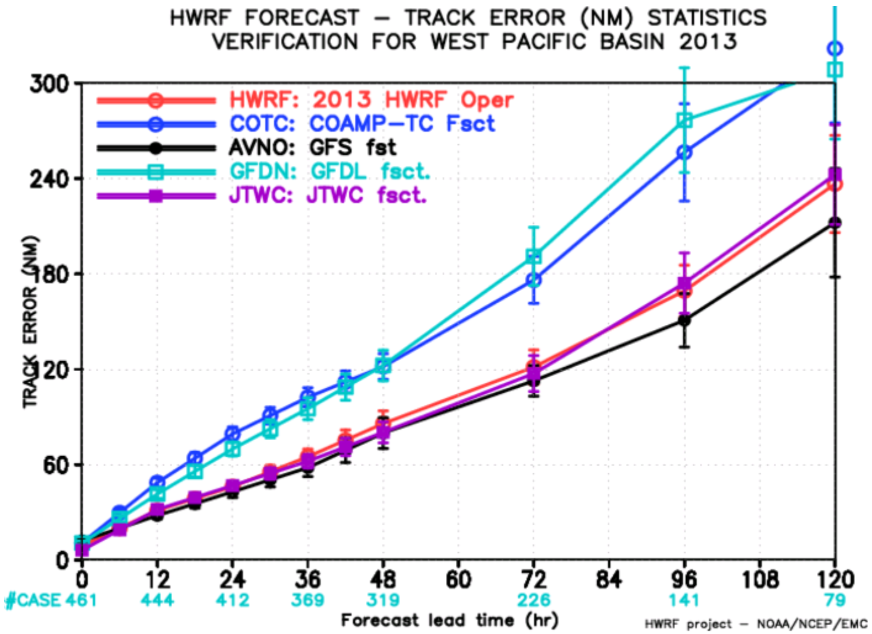
- Starting in 2012, EMC HWRF team has been experimenting real-time forecasts for the WPAC basin, using NCEP Operational HWRF system, thanks to the support from NOAA's Hurricane Forecast Improvement Project (HFIP).
- ~ 85-90% reliability in delivering forecast products to JTWC was accomplished using dedicated resources (three sets of infinite reservations) on HFIP machines in Boulder. **Continued delivering real-time forecast guidance for all tropical systems in the Western Pacific and North Indian Ocean basins in 2013**
- ***"Performance metrics from 2102 confirmed HWRF added value to both track and intensity guidance available to JTWC forecasters, so we implemented its operational use in 2013. The model continues to perform very well, especially for intensity, where it outperformed other mesoscale models out to 72 hrs and was especially useful during the frequent rapid intensification events that occurred in the Western North Pacific this year"***

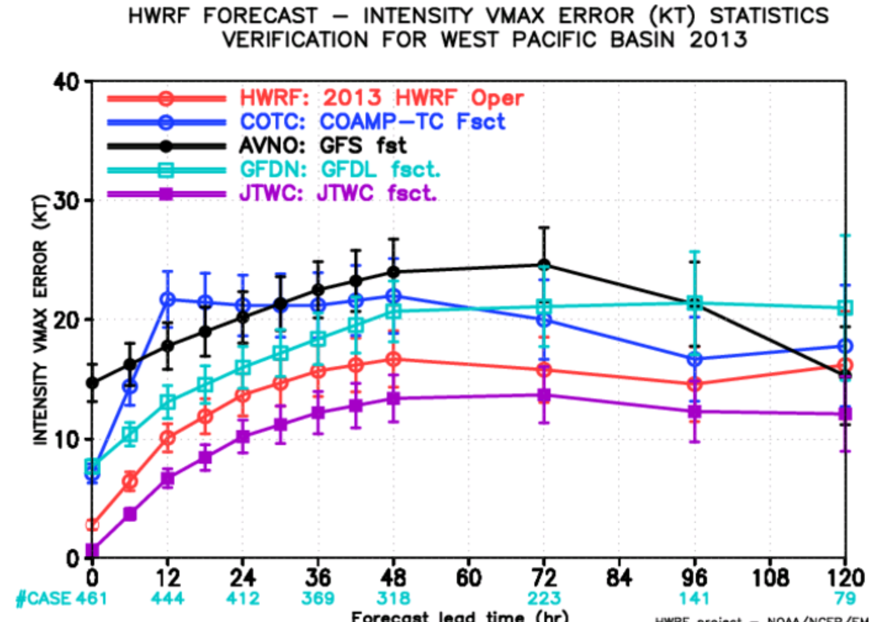
--Bob Falvey, Director, JTWC

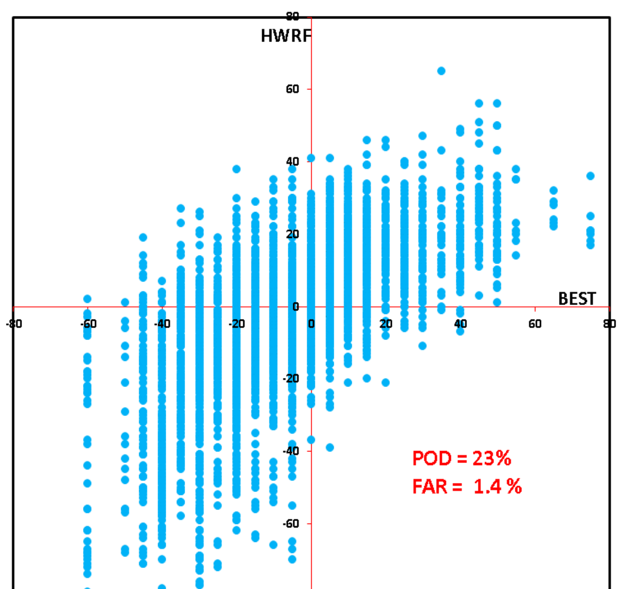
- ***A preliminary analysis of the performance of various models indicate that the performance of NCEP HWRF model was very good. It was a very useful product in terms of track, intensity and landfall forecast guidance as well as rainfall. Its performance was better that that of IMD HWRF.***

-- Dr. Mohapatra, Director, Cyclone Warning Division, IMD, India

Verification of HWRF for 2013 Western Pacific Typhoon Season

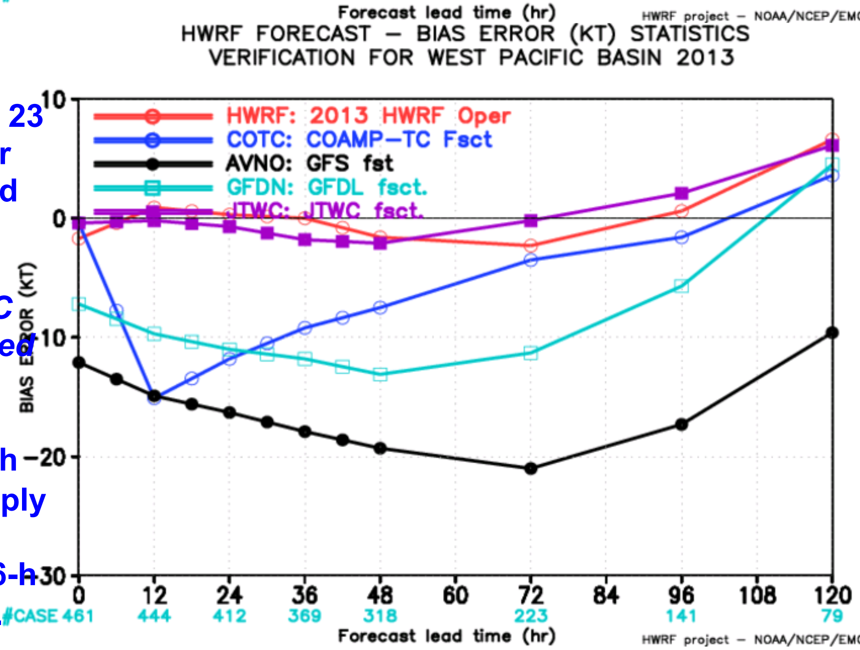




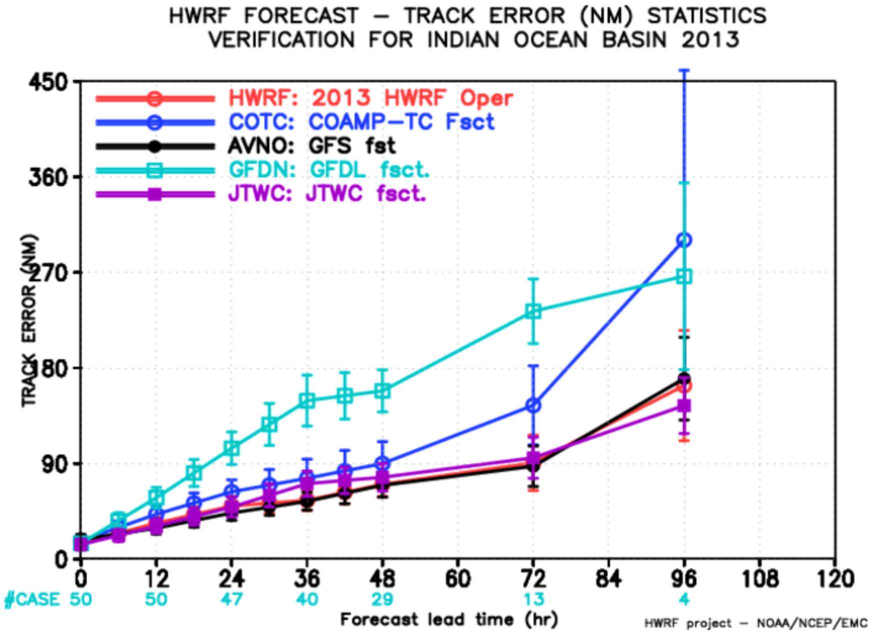


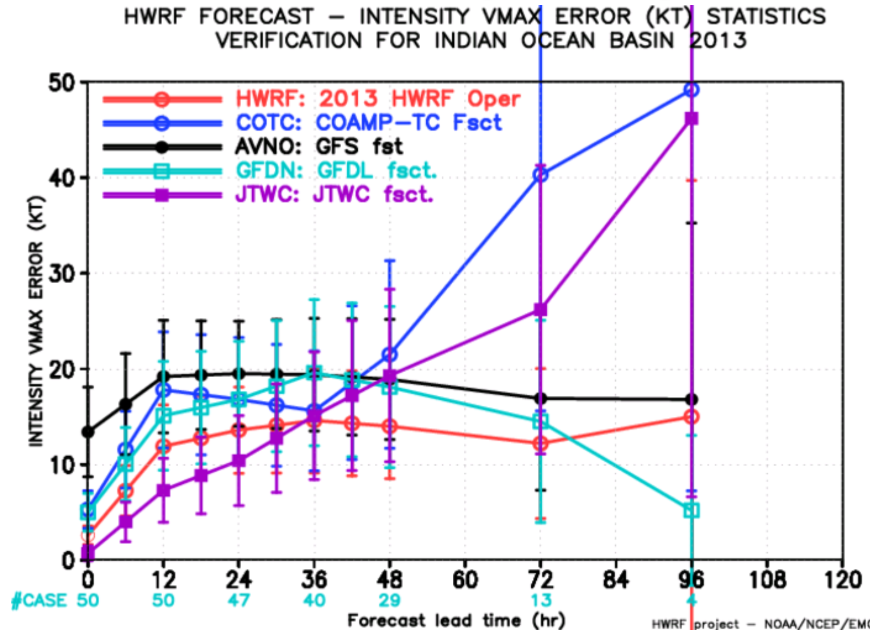
HWRF RI POD skill is ~ 23 % and by far has higher POD index as compared to other models and in other basins *(previous analysis of RI for WPAC from 2012 HWRF showed <10% skill).*

-The POD index is much higher (43%) if one simply considers the intensity change tendency, say 6-h change of VMAX > 5 kt.

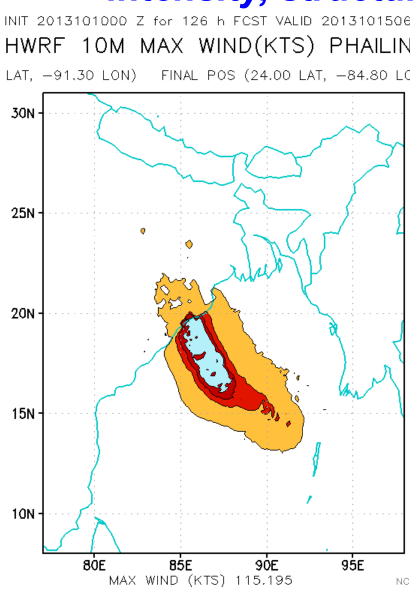


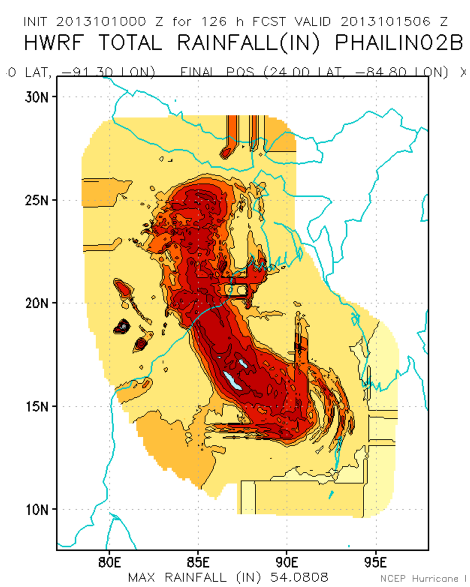
Verification of HWRF for 2013 North Indian Ocean Tropical Cyclones

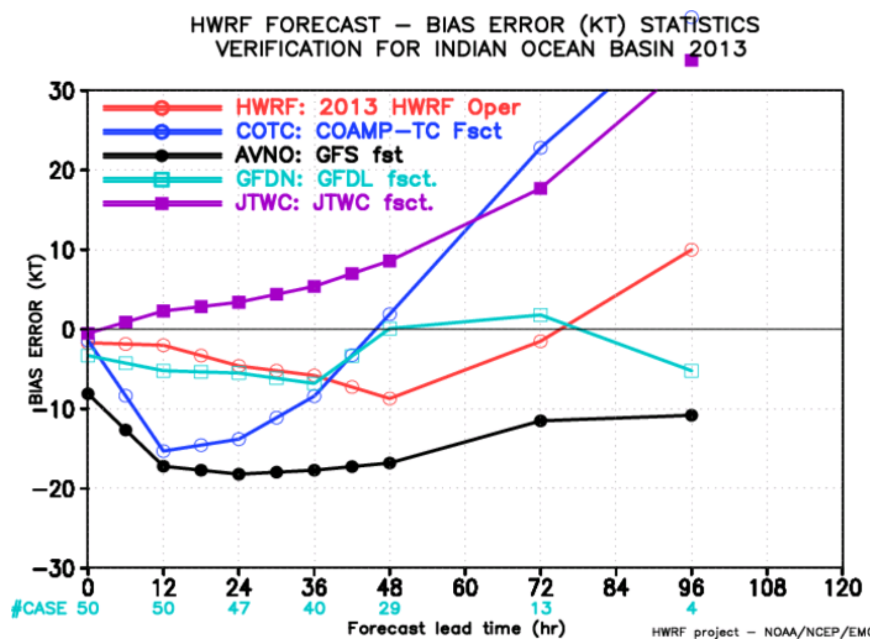




NCEP HWRF forecasts accurately captured the intensity, structure and rainfall of Phailin







Overview of the HWRF Modeling System

- Regional-scale, moving nest, Ocean-Atmosphere coupled modeling system specially designed to advance hurricane forecasts.
- Non-hydrostatic system of equations within the WRF modeling infrastructure and framework
  - rotated latitude-longitude, Arakawa E-grid
  - vertical pressure hybrid (sigma-P) coordinate.
- NMM dynamics modified for inclusion of
  - movable nested grids, coupling to ocean model (POM-TC/HYCOM)
- HWRF vortex initialization includes
  - vortex relocation, correction to winds, MSLP, temperature and moisture in the hurricane region
  - adjustment to actual storm size and intensity
  - assimilation of conventional observations and clear-sky radiance datasets using community GSI (one-way hybrid EnKF-3DVAR data assimilation since 2013)
- Physical parameterization schemes designed and tested for tropical cyclones
- Ocean coupled modeling system using an advanced NCEP coupler.

Components of HWRF Modeling system

- HWRF Pre-processing System (WPS and prep-hybrid)
  - Domain Specification and grid selection
  - Choice of using GFS/GDAS analysis/forecast data in grib format or spectral coefficients (HWRF specific, prep-hybrid utility)
- WRF Model (HWRF dynamical core and HWRF Physics)
  - Initialization programs for real (real.exe – same as NMM dynamical core)
  - Numerical integration program (wrf.exe)
- HWRF Vortex Initialization Software
- One-way hybrid EnKF-3DVAR regional data assimilation system based on community GSI
- Ocean Initialization, Ocean Model (POM-TC) for Atlantic and Eastern Pacific basins
- NCEP Coupler
- Post-Processing Program (UPP)
- GFDL Vortex tracker
- Graphical utilities for both HWRF and POM
- Advanced applications of HWRF modeling system to include:
  - Idealized hurricane simulation capability
  - Advanced physics options
  - Multiple moveable nests (not currently supported)
  - Downstream applications (not currently supported)

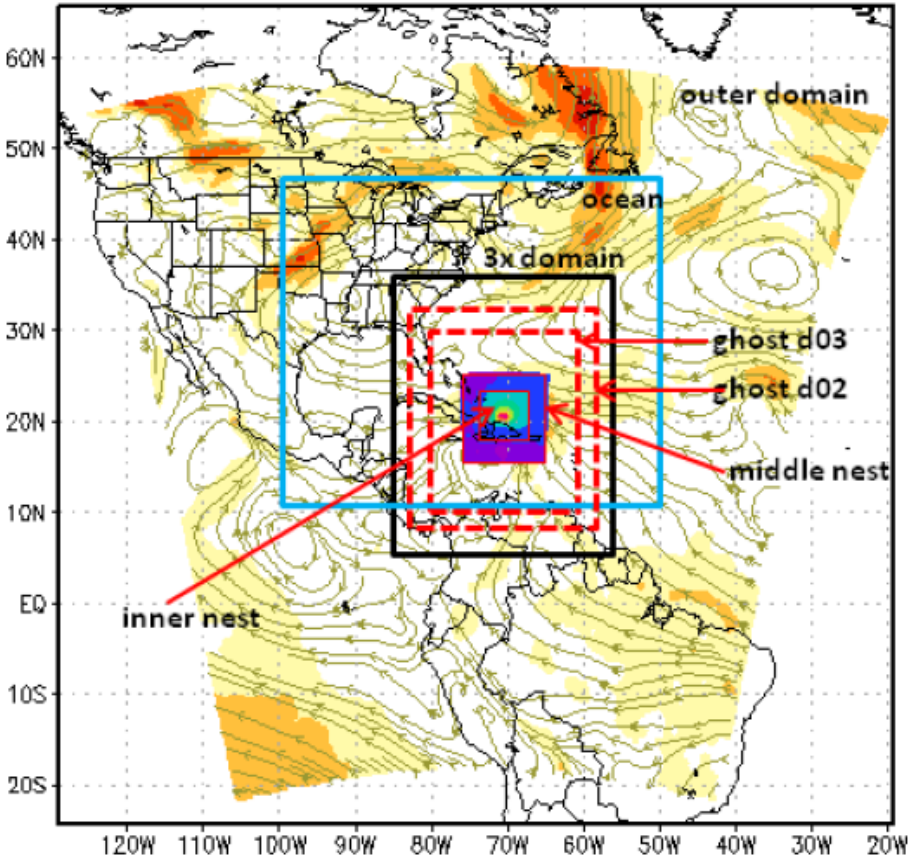
HWRF Pre-Processing System

- WPS
  - Several executable stages with namelist options
    - geogrid.exe (interpolate geostatic data and time-independent fields)
    - ungrib.exe (convert time-dependent Grib-formatted data to simple binary format)
    - metgrid.exe (interpolate time-dependent initial and boundary data)
- Prep_Hybrid
  - A new utility to use native resolution GFS/GDAS analysis/forecast spectral coefficients to generate initial and boundary conditions for HWRF (optional)
- Domain Selection
  - Must chose a pre-determined configuration for both parent and nested domains.
    - Usually determined by specific observed storm center information provided by tcvitals
    - **Three telescopic domains on a rotated lat-lon E- staggered grid projection: Parent, static: 27km: ~80x80°; Movable two-way interactive Intermediate (9km; ~11x10°) and inner-most 3km; ~7.2x6.5° nests**
  - real_nmm.exe sets up 43 vertical sigma-pressure hybrid model levels with model top set at 50 hPa for three-dimensional model input and boundary conditions

Atmospheric model initialization

- Setting up model domains for analysis and vortex initialization:
  - Use previous cycle's 6-hr GDAS forecast data to generate initial conditions for HWRF outer domain and 9-hr GDAS forecast data to obtain 3-hr boundary conditions
  - *Alternately, use current cycle's GFS analysis and 6-hr forecast data to obtain the initial conditions for HWRF outer domain at 27km resolution*.
  - Run atmospheric model to generate "analysis" and "ghost" domains (to generate data for inner nests at 9km and 3km resolution) and a 3X domain at 3km resolution (for the purpose of vortex initialization).
  - Run vortex initialization procedure (contains multiple stages and spans several executables)
  - Run GSI to assimilate observations in the hurricane environment
  - Use current cycle's 126-hr GFS forecast data at 6-hr interval to generate boundary conditions
  - *GDAS/GFS data can be either in Grib format or spectral coefficients*.

More details on HWRF setup by Stark/Biswas



HWRF Model domain configurations

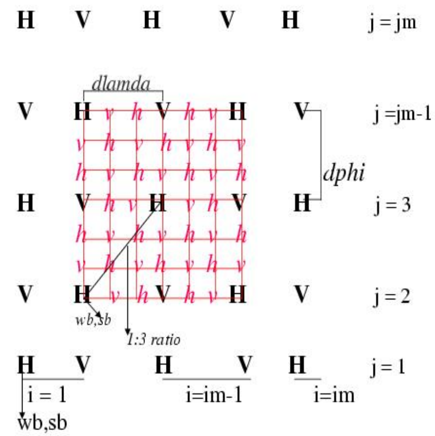
	D01	D02	D03
Grid spacing (deg)	0.18	0.06	0.02
HWRF Forecast	216x432 - 80°x80°	88x170 - 11°x10°	180x324 - 7.2°x6.5°
Analysis run	216x432 - 80°x80°	88x170 - 11°x10°	180x324 - 7.2°x6.5°
Ghost run	216x432 - 80°x80°	211x410 - 24°x24°	529x988 - 20°x20°
3X domain			748x1504 - 30°x30°

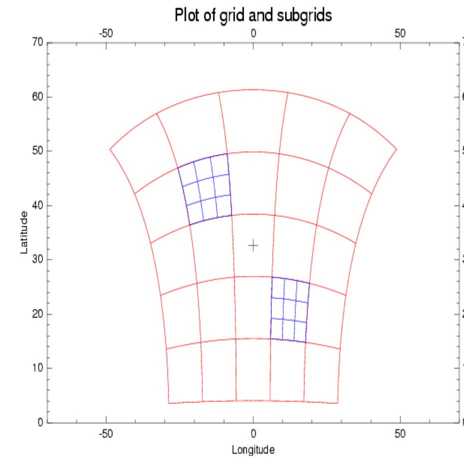
HWRF Dynamics

- Modifications to WRF-NMM dynamic core specific to HWRF configurations include
  - Vortex following two-way interactive movable nests
    - Sophisticated nest movement algorithm based on 9-point tracking
    - Advanced nest-parent interpolations and feedback procedures
  - Horizontal diffusion effect from TKE set to zero
  - Solve_nmm.F modified to include insertions related to Coupler (send fluxes from atmosphere to ocean and pass SSTs from Ocean to atmosphere)

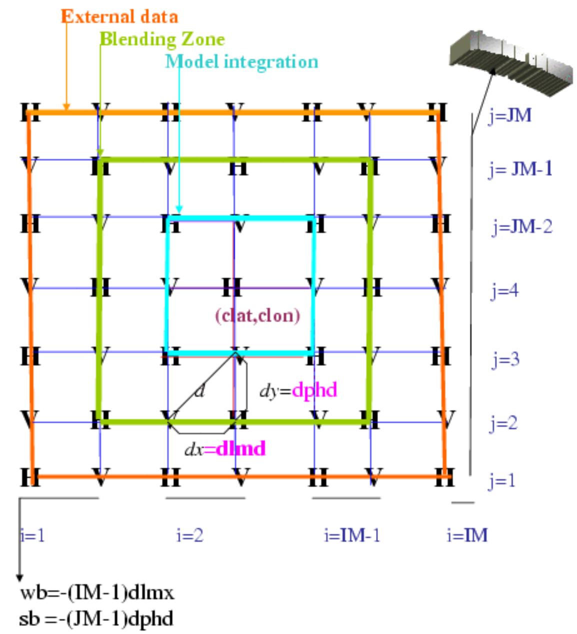
More details on HWRF dynamics by Zavisa Janic

Details specific to nested grid computations





- All interpolations are done on a rotated lat-lon, E-grid with the reference lat-lon located at the centre of the parent domain.
- Consequently the nested domain can be freely moved anywhere within the grid points of the parent domain, yet the nested domain lat-lon lines will coincide with the lat-lon lines of the parent domain at integral parent-to-nest ratio.
- This coincidence of grid points eliminates the need for more complex, generalized remapping calculations in the WRF Framework.
- Because of the E-grid structure and the fact that the input interface is well separated from dynamic interface, boundaries are updated at every time step of parent domain similar to how parent domain is updated at the mass point from the external data source (bc's).



* Given wb,sb, clat and clon, the above rotated lat-lon grid system can be transformed to a lat-lon grid system.

More details on nesting by Xuejin Zhang

Advanced Nest Tracking Algorithm

- Older methods (dynamic pressure, centroid) were found inadequate to accurately track the storm
  - Interactions with other Tropical Cyclones
  - Interactions with Synoptic-Scale Systems
  - MSLP Numerical Difficulties
- New method implemented in 2013 HWRF tracks nine smoothed fields (based on GFDL vortex tracker):
  - Vorticity – 10m, 850 mbar, 700 mbar
  - Wind minimum – 10m, 850 mbar, 700 mbar
  - Height – 850mbar, 700 mbar
  - Membrane MSLP
    - Advanced Mean Sea Level Pressure technique by Hui-Ya Chuang at EMC
- Discard fields that are far from the average
- Final average is new location

More details on nest tracking algorithm by Sam Trahan

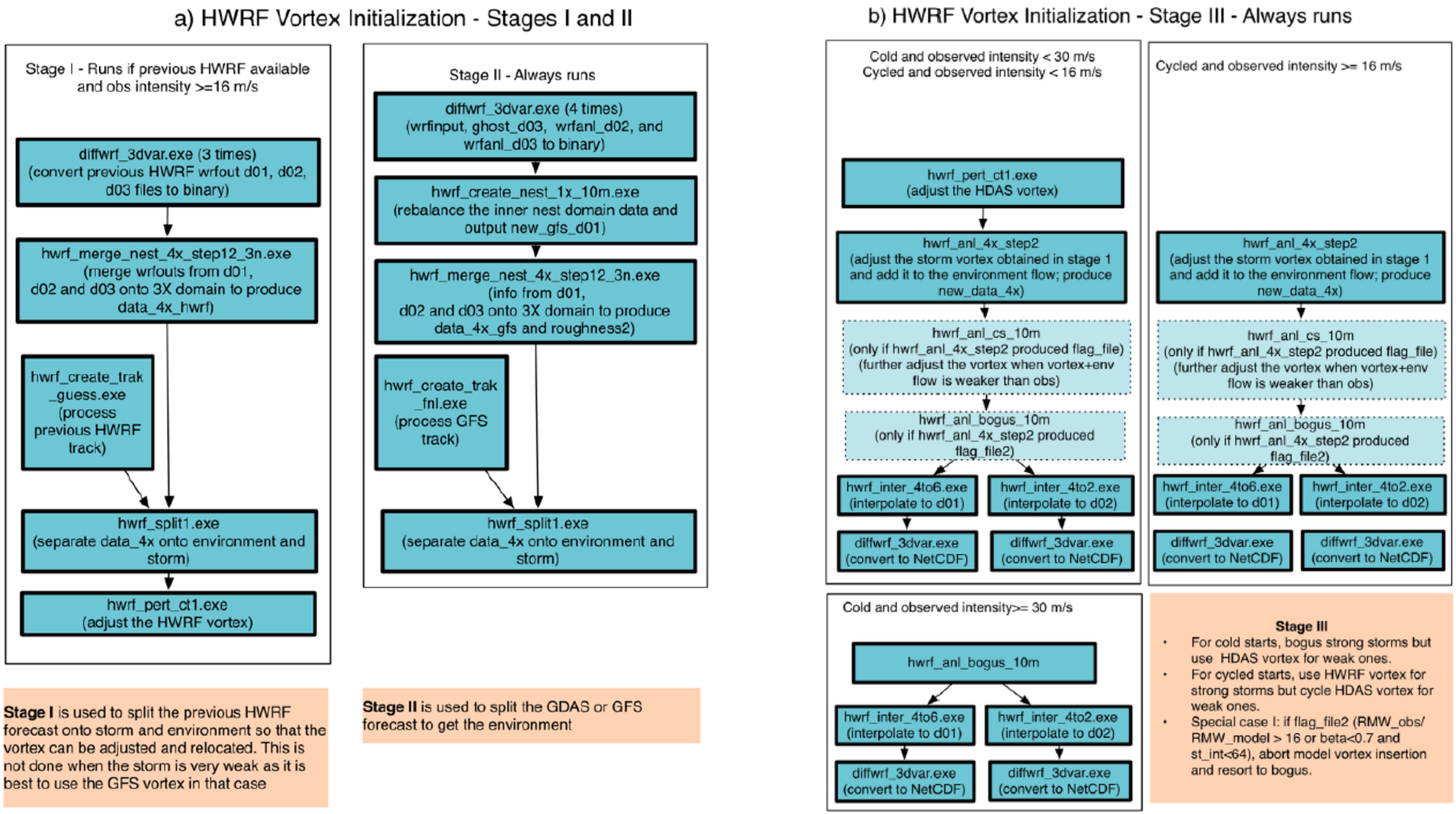
2013 HWRF Model Physics and Dynamics

2013 HWRF system	
Physics schemes	
Microphysics	Modified Ferrier scheme for tropics
Radiation (SW, LW)	GFDL scheme
Surface Scheme	M-O similarity (modified Cd & Ch)
PBL Scheme	GFS non-local mixing scheme
Cumulus Parameterization	Simplified AS (27-9 KM) No convection (3 KM)
Land Surface	GFDL Slab
GWD	Yes(27km); No(9-3km)
Dynamics	
Horizontal Advection	2nd order Adams-Bashforth
Vertical Advection	Crank-Nicolson scheme
Horizontal Grid	Arakawa E-grid (27/9/3km)
Vertical Coordinate	Sigma-P hybrid
Horizontal Diffusion	Second order Smagorinsky type

More details on physics improvements by Young Kwon

HWRF vortex initialization

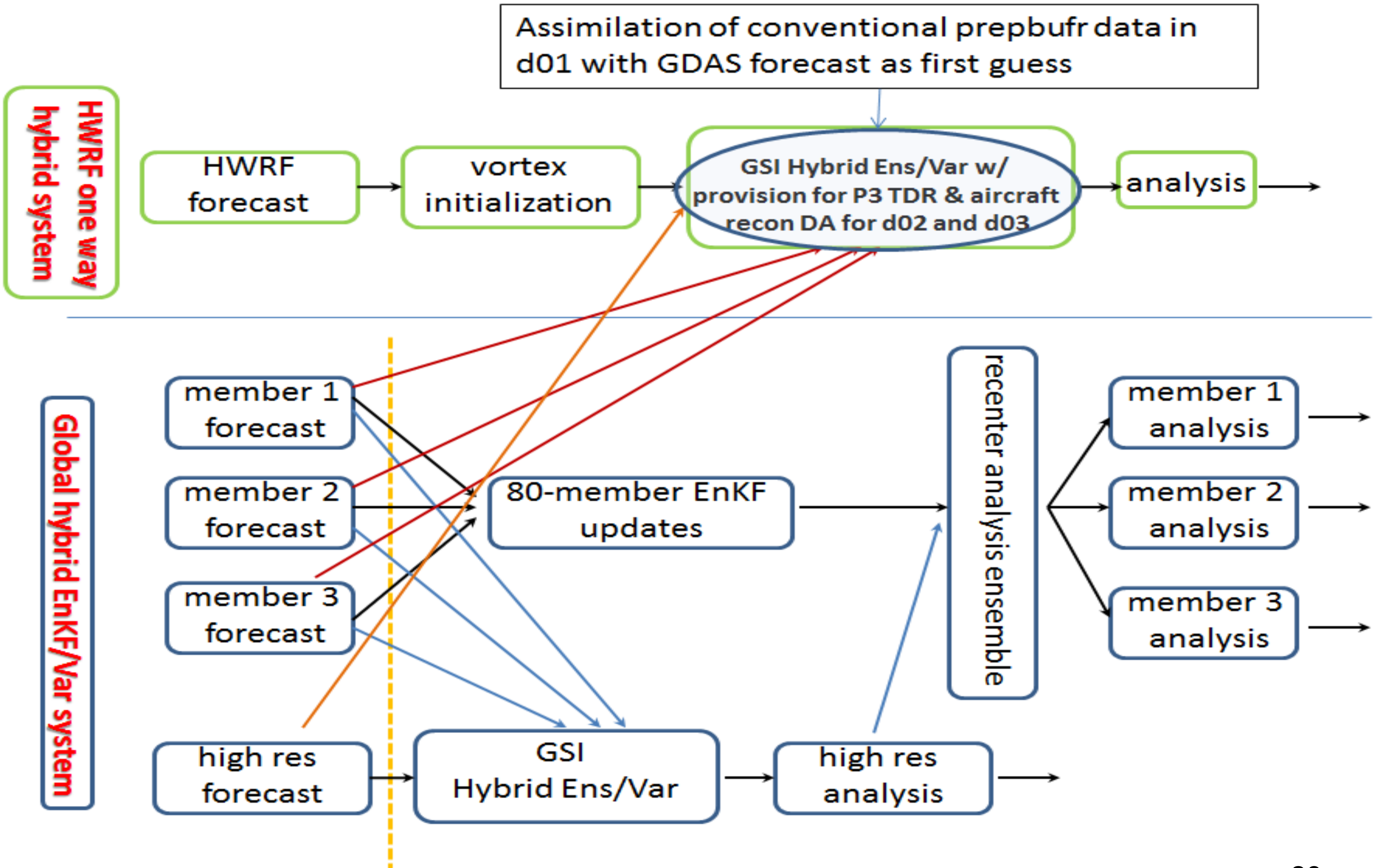
- HWRF model uses an advanced vortex initialization procedure to represent model's initial storm location, intensity and structure based on observed estimates provided by NHC.
- Vortex cycling provides continuity in representing more accurate storm structure with model-developed asymmetries.
- Coordinates of the observed position of the storm are used to relocate (correct) the storm's initial location.
- A blend of synthetic vortex and storm perturbation from previous cycle's 6-hr forecast (if available) are used to adjust (correct) storm's initial, intensity and size to match the observed estimates.
- Done in three stages, based on initial storm intensity and availability of previous cycle's 6-hr forecast



HWRF Vortex initialization is the most complex part of the modeling system, designed to handle various storm conditions (weak, strong, sheared, developing, decaying ….) and has lot of safeguards to prevent corrupting the model initial state.

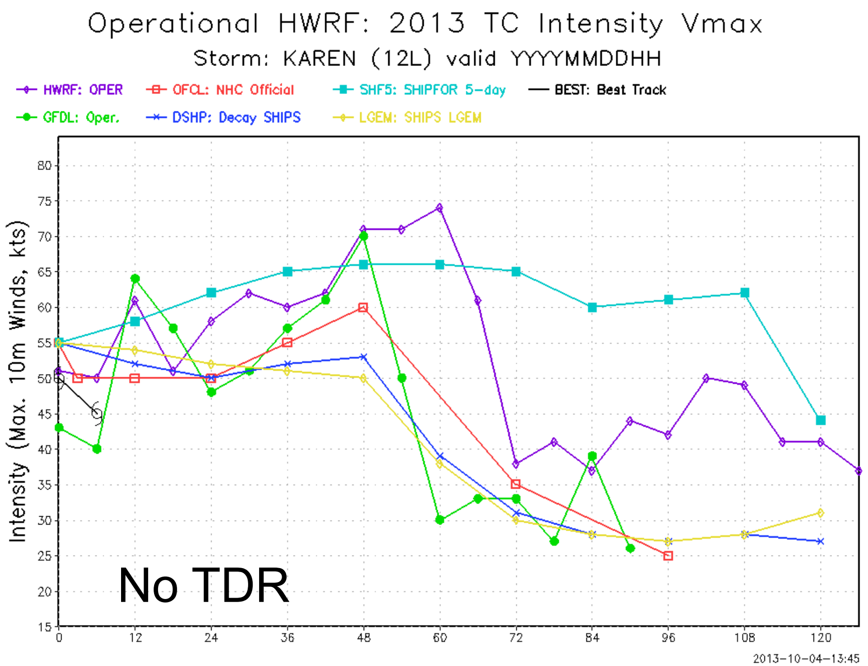
More details on vortex initialization by Qingfu Liu

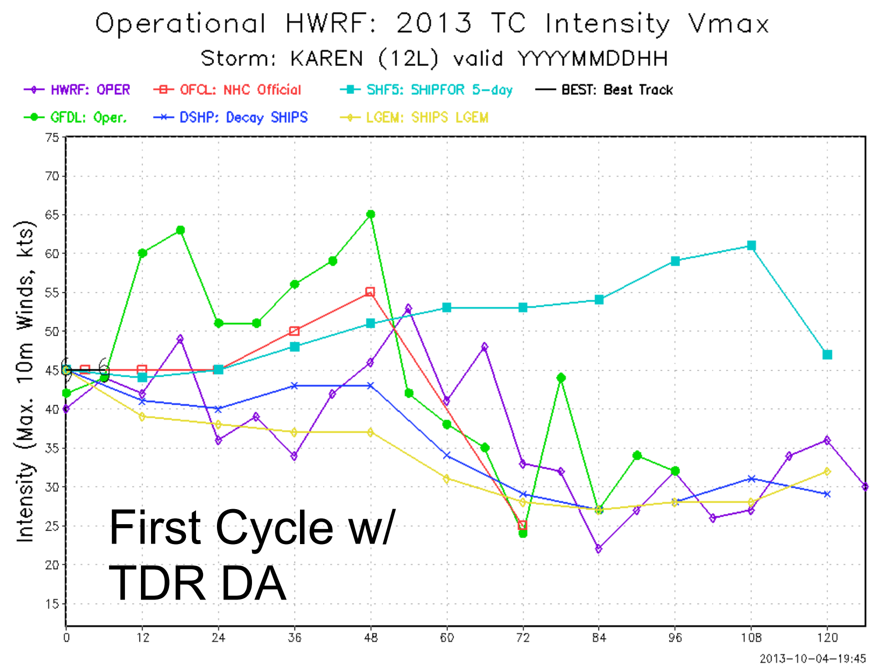
HWRF Data Assimilation System



More details on HDAS by Mingjing Tong

Impact of TDR DA on operational HWRF for TS Karen:





Impact of HWRF forecasts with TDR DA on NHC Operational Forecasts

NHC Forecast Discussion on October 4, 5 PM:

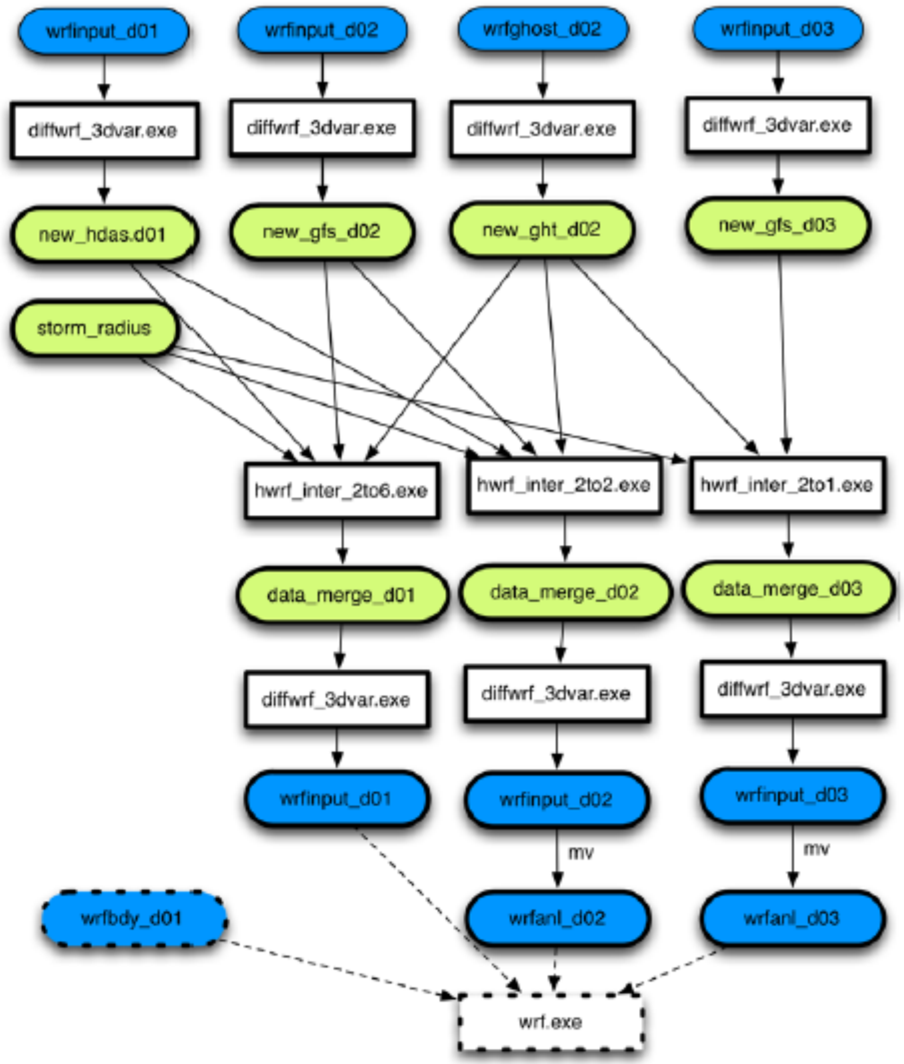
- **THE 12Z HWRF RUN SHOWED CONSIDERABLY LESS INTENSIFICATION WITH KAREN COMPARED TO PREVIOUS RUNS AFTER ASSIMILATING DATA FROM THE FROM THE NOAA P-3 TAIL DOPPLER RADAR. THIS MARKS THE FIRST TIME DOPPLER RADAR DATA HAVE BEEN ASSIMILATIED INTO AN OPERATIONAL HURRICANE MODEL IN REAL TIME.**

-- Forecaster Brennan

Real-time assimilation of NOAA P3 TDR DA for operational HWRF – A First in many years of flying.

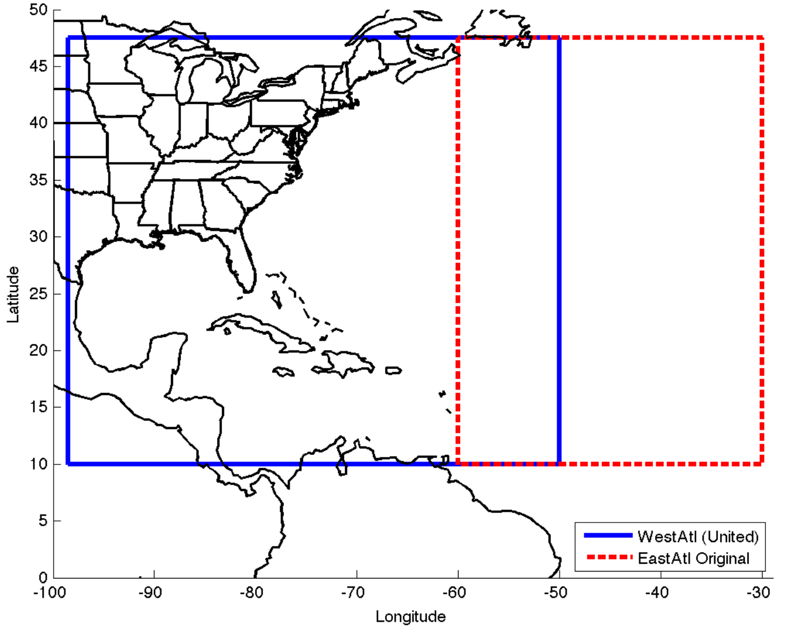
- Fix issues related to transmission of TDR data to NCO (storm id mismatch etc.)
- Conduct experiments to maximize the effective utilization of inner core data

Merge



The final step in HWRF Pre-Processing is to merge (project) the information from various vortex initialization and HDAS procedures on to the parent and nested grids for forecast integration.

Princeton Ocean Model for Tropical Cyclones (POM-TC) & NCEP Coupler



- HWRF model is coupled to Princeton Ocean Model (POM) in the Atlantic (3D) and Eastern Pacific (1D) basins to provide accurate SST fields as input to HWRF.
- POM-TC model is driven by heat, radiative and momentum fluxes passed from HWRF and the SST response from POM is transferred back to HWRF.

- POM-TC is initialized with a realistic, three-dimensional temperature and salinity field to generate realistic ocean currents and to incorporate the preexisting hurricane-generated cold wake.
- Ocean initialization employs a feature-based procedure that incorporates historical and near-real time observations of the ocean to accurately represent the spatial structure and location of oceanic fronts including gulf stream, loop current, warm and cold core eddies.
- A sophisticated "Coupler" was designed and developed at NCEP to enable exchange of information between the atmosphere and ocean during the model integration.

More details on POM-TC by Rich Yablonsky, Coupler by Dmitry Sheinin

HWRF coupled model Integration

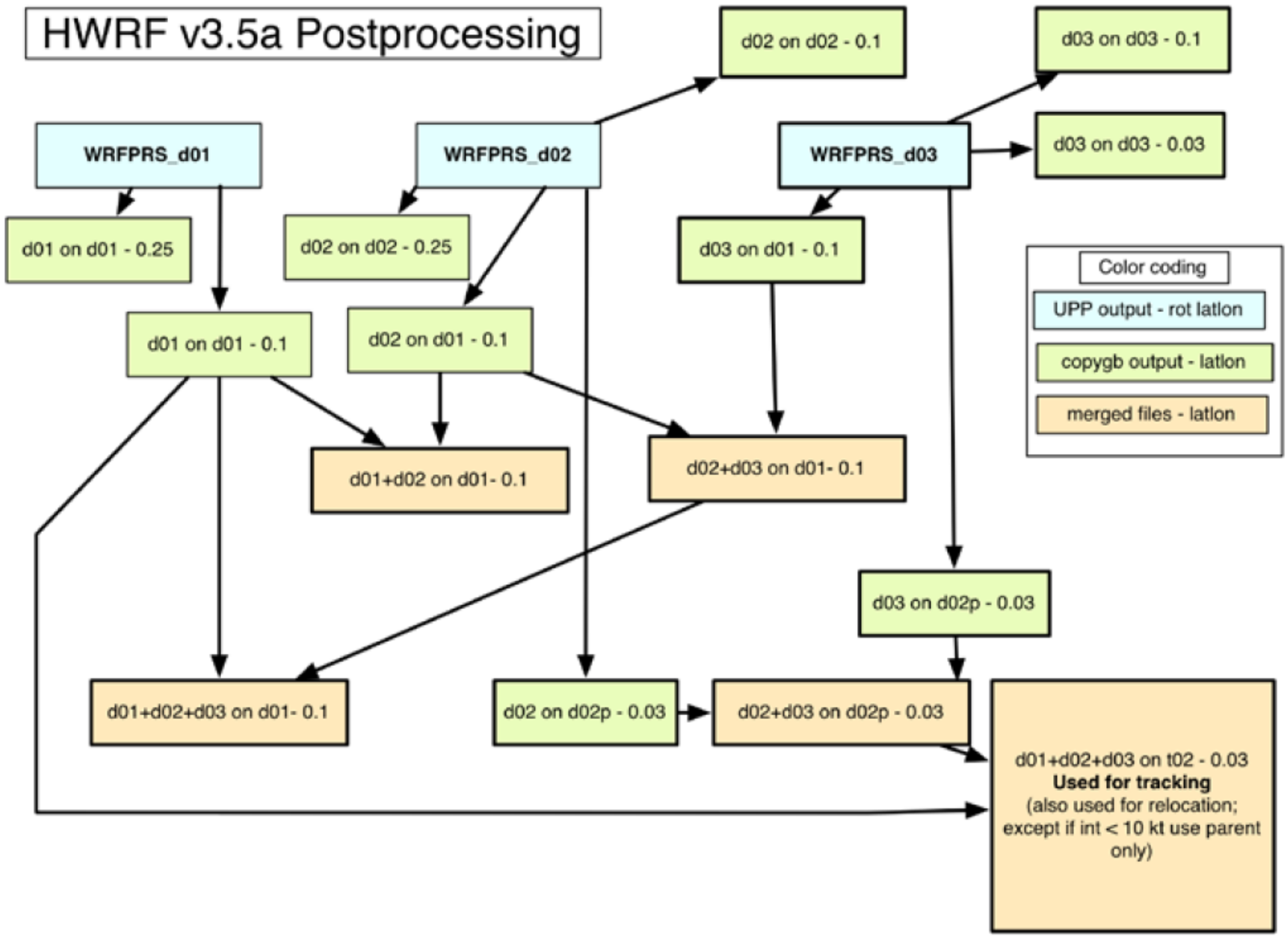
- Time integration of HWRF coupled model is done using three executables working in MPMD mode (multiple program multiple data).
- Coupler serves as a hub for MPI communications between HWRF and POM and performs the interpolation of the surface fluxes from the fixed and moving HWRF grids to the POM grid and of the SST from the POM grid to the two HWRF grids.
- HWRF specific namelist file contains description of grid dimensions, time steps, options for HWRF physics and controls for history interval and auxiliary output
- HWRF supports binary and NetCDF io formats. NetCDF is the default option. Separate designated IO servers can handle writing various output fields.
- Resource requirements and MPI/memory configurations depend on the platform on which the model is run.
- Typical resource requirements for operational HWRF model on NCEP supercomputing (WCOSS) are 152 processors (144 processors for atmospheric model, 1 for POM-TC, 1 for coupler and 6 IO servers) with 300 GB memory. It takes about 74 minutes to produce 126-hr forecast.
- Cut-off time for HWRF model forecast delivery is t+5.45 for each cycle for as many as 5 storms. End-to-end model run time is about 2.30 hrs.

More details on HWRF coupled model integration by Stark and Biswas

WRF POST-processing and product generation

- Post-processing of HWRF output (wrfout_d01,wrfout_d02 and wrfout_d03 files) is done using a Post-Processor developed at NCEP (UPP).
- UPP generates output in standard grib format. Output from parent domain is post-processed to a uniform grid resolution of 0.25 deg. lat/lon and the output from nested grids are post-processed to 0.1 deg. and 0.02 lat/lon resolution.
- A selected set of variables (required for vortex tracker) are collected from both parent and nest grib files and combined to generate 0.1 deg. resolution output on a 20x20 degree domain. These include u, v components of wind at 10m, 850, 700 and 500 hPa; absolute vorticity and geopotential height at 850 and 700 hPa and mean sea-level pressure.
- A separate post-processor job is run to generate synthetic satellite imagery from various geostationary and polar-orbiting satellite channels.
- Auxiliary output includes hourly 2-D fields for 10-m wind and rainfall to generate wind and rain swaths.
- A very high frequency (every model time step) output for storm center location, max. winds, MSLP and location of max winds and MSLP are also output in a text format.

More details on HWRF post-processing by Hua-Chuang



Various parts of HWRF Post-Processing and Product Generation

GFDL/NCEP Vortex tracker

- A unified vortex tracking algorithm was developed at GFDL and is used at NCEP to track the storm movement and intensity in the model output.
- The grib files on “combined” 20x20 degree domain are provided as input to the vortex tracker, which generates storm track forecast files in ATCF format.

More details on Vortex Tracker by Tim Marchok

Graphical utilities

- HWRF model output on native grid is in rotated lat/lon (E-grid), and cannot be viewed using several standard visualization tools including NCL, MATLAB, IDL as they cannot ingest the staggered E-grid format. However, there are many tools including “RIP” that can facilitate projecting the output into graphical form.
- HWRF model output in GRiB format can be viewed using several software including GrADS, GEMPACK etc. A set of sample GrADS and GEMPACK scripts are provided with the distributed software.
- POM model output is in standard FORTRAN binary format, and a set of sample GrADS scripts are provided to visualize ocean model output.

More details in HWRF practical sessions

Expanded capabilities for operational HWRF

- Starting with 2013 HWRF release, idealized hurricane simulation capability is included in the distributed code.
- A great research tool for testing the sensitivity of model forecasts to various forcings in an idealized framework.
- HWRF now can be run in any Northern Hemispheric oceanic basin (uncoupled in basins other than Atlantic and Eastern Pacific basins). Southern Hemispheric capability will be included in 2014 release version.
- Design and development of Ocean coupling capability for all basins is currently in progress.
- HWRF can also be designed with a three-way ocean-wave-atmosphere coupled system (not currently supported)
- Basin-scale HWRF with multiple moveable nests is currently being integrated into the HWRF community modeling system, and will be included in 2014 release version (not currently supported).
- Limited support for many of the developmental branches managed at DTC may be available for interested researchers.

Limitations of DTC supported HWRF model

- **HWRF V3.5a configuration, although much more flexible compared to it's previous releases, defaults to match the operational HWRF configuration run at NCEP. Limitations include:**
  - Limited flexibility in specifying the dimensions of either parent or nest domains (due to vortex initialization and coupling requirements)
  - Limited options for available physics (not all combinations are tested). Non-Ferrier Microphysics support is included in the HWRF V3.5.
  - Currently, coupling is supported only for the Atlantic and Eastern Pacific basins.
  - Restart capability exists, but not tested extensively.
  - Static domains are possible, with options to turn off the feedback (not tested or supported).

Applications of HWRF model

- **Apart from canned cases for tutorial purpose, atmospheric HWRF (stand-alone) can be run for any storm in all Northern Hemispheric basins provided GFS initial and boundary conditions are obtained. Coupled model can be run for any storm in the North Atlantic (united or eastern Atlantic domain) or the North Eastern Pacific basin. If data for loop current and/or warm/cold core eddies are not present, POM-TC initialization uses climatology.**
- **Idealized HWRF can be set to run using standard sounding for tropical cyclones.**
- **There are unlimited applications that can be designed for HWRF model. NOAA HFIP, DTC, NCEP, NESDIS, AOML, ESRL and various other agencies provide opportunities to work on HWRF model for further improvements to the operational modeling system.**
- **Various international operational and research centers have adopted HWRF for tropical cyclone forecast applications, opening new opportunities for expanding the outreach and utility of HWRF model.**

What to expect from practical hands-on sessions

- Students will learn
  - How to obtain and compile the HWRF software
  - How to initialize HWRF model, WPS and vortex initialization
  - How to initialize POM
  - How to configure and run HWRF coupled modeling system (cold start as well as cycling)
  - How to post-process HWRF and POM model output
  - How to generate track forecast files

More details on practical sessions by Biswas and Stark

User support

- If you have any questions regarding HWRF, please write to wrfhelp@ucar.edu
- Extended support available from HWRF developers at NCEP, DTC, AOML and ESRL for users with specific projects. Contact Ligia.Bernardet@noaa.gov or Vijay.Tallapragada@noaa.gov
- Online tutorial, HWRF documentation and latest release notes is available from DTC http://www.dtcenter.org/HurrWRF/users/index.php
- Operational model implementation details are available from EMC HWRF Website: http://www.emc.ncep.noaa.gov/index.php?branch=HWRF

Advancing the HWRF System FY2014 & Beyond

	2014*	2015*	2016*	2017*
Resolution/ Infrastructure	Increased vertical resolution with higher model top	community R2O efforts (HFIP), Multiple moving domains	Upgrades to infrastructure - NEMS/ESMF/NMM-B, Other oceanic basins, HWRF Ensembles, Global to local scale modeling for hurricanes	
Physics	Microphysics, Radiation, Land Surface	TKE based PBL, Advanced microphysics including impacts of dust and aerosols, Coupling to Waves and Sea Spray, Physics for high-resolution		
DA/ Vortex Initialization	Inner core DA (TDR, dropsonde, aircraft recon, clear sky satellite radiances), invest cycling	Hybrid-EnKF DA, advanced vortex relocation procedure, improved GSI/Hybrid techniques, DA for moving nests, HWRF Ensembles in DA, cloudy radiance assimilation Two-Way regional Hybrid DA		
Ocean	High-resolution (1/12) POM with unified Atlantic basins, 3D ocean for East Pacific	Improved ocean data assimilation, physics and resolution, unified coupled system for ATL & EPAC		
	HWRF-HYCOM for all oceanic basins (driven by Global RTOFS)			
Waves	Atmosphere-Ocean-Wave Coupling	Multi-grid surf zone physics, effects of sea spray		
Diagnostics and Product Development	HWRF Ensemble based products, Coupling to Hydrological/ Surge/ Inundation models, advanced model diagnostics based on observations, improved product development			

2014 upgrades

Planned/ongoing developments

*Resource permitting

Future Outlook 5 to 25 years??????

	5-10 years	2020+
Resolution/ Infrastructure	Basin-Scale HWRF with multiple moveable nests (at cloud resolving resolutions) and high-resolution HWRF ensembles Downstream applications (including landfall related storm surge, waves, flooding and inundation)	Global to Local Scale Modeling to capture multi-scale interactions High-Resolution Ensembles for events of interest
Physics	Observations based physics Incorporate effects of sea-spray, aerosols, waves, boundary layer rolls – explicit representation of inner core processes	Ensemble based physics approach
DA/ Vortex Initialization	Hybrid/EnKF with 4-D VAR Vortex initialization within the DA, focus on assimilation of all-weather radiances and aircraft data	Part of the data assimilation for global system
Ocean/Wave/ Land	Fully coupled ocean-wave-land-atmosphere system	
Products & Downstream applications	Meeting the next-generation needs of Hurricane Specialists at NHC and JTWC	