Advances and Challenges in the Operational Hurricane Modeling Systems at NCEP/EMC

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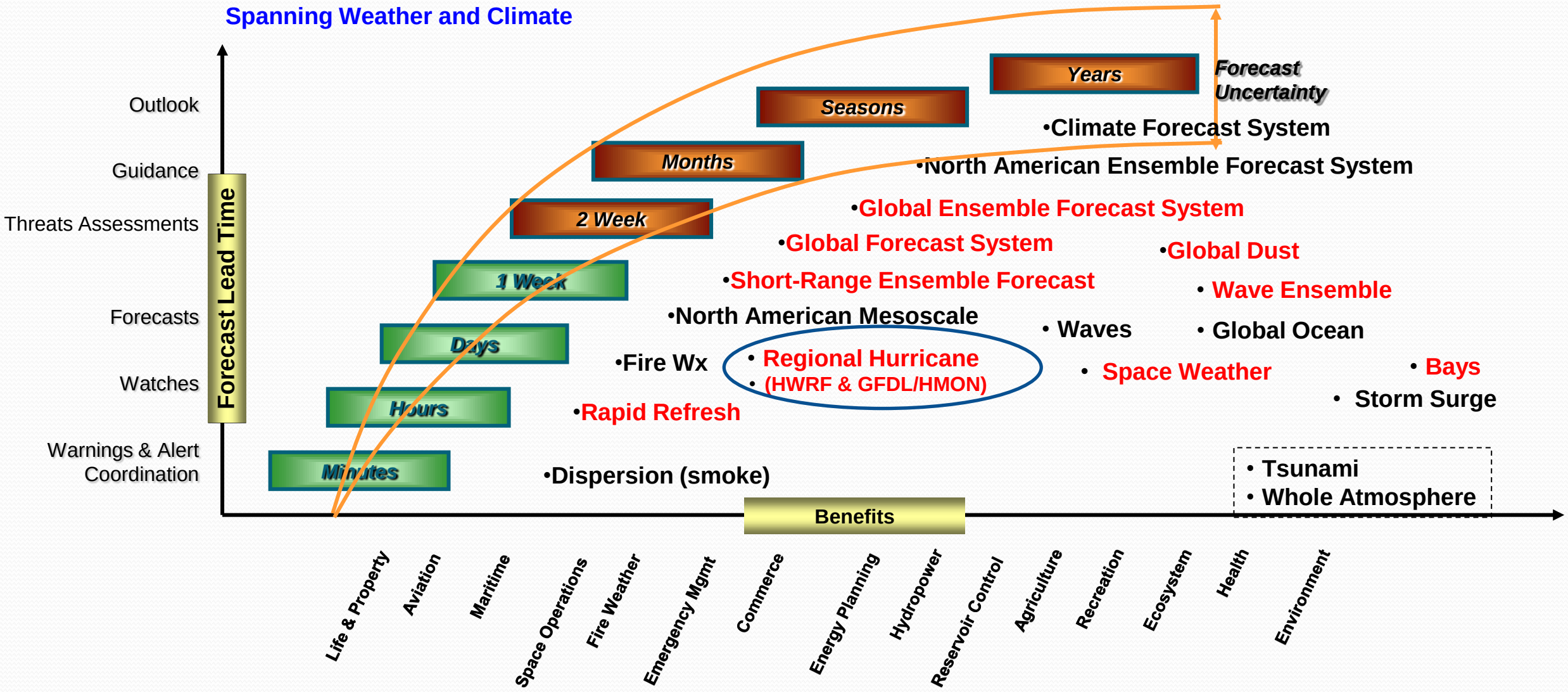
Outlines

- Operational hurricane model development at NCEP/EMC
- FY2018 HWRF/HMON model upgrades
- Challenges to next generation of hurricane model system
  - Hurricane inner-core data assimilation
  - Scale-aware model physics
  - Hurricane ensemble prediction system
- Future plans

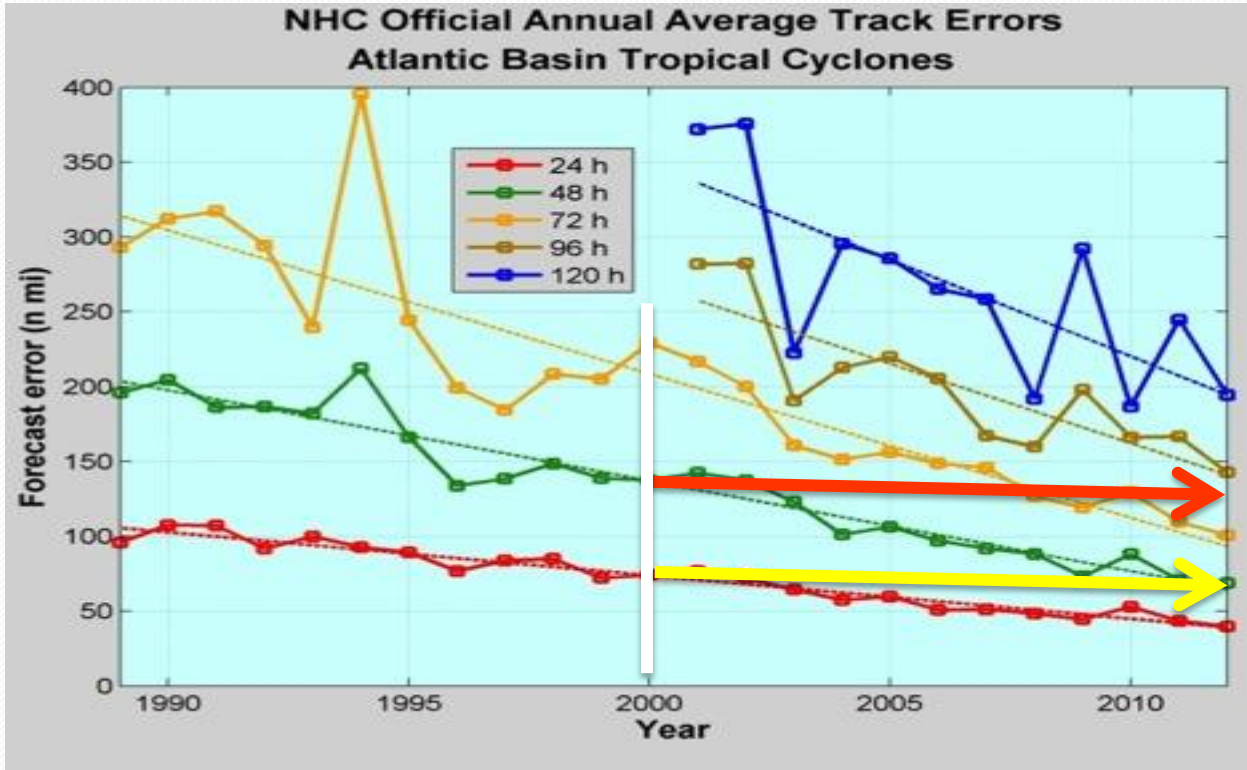
Seamless Suite of NOAA Operational Numerical Guidance Systems

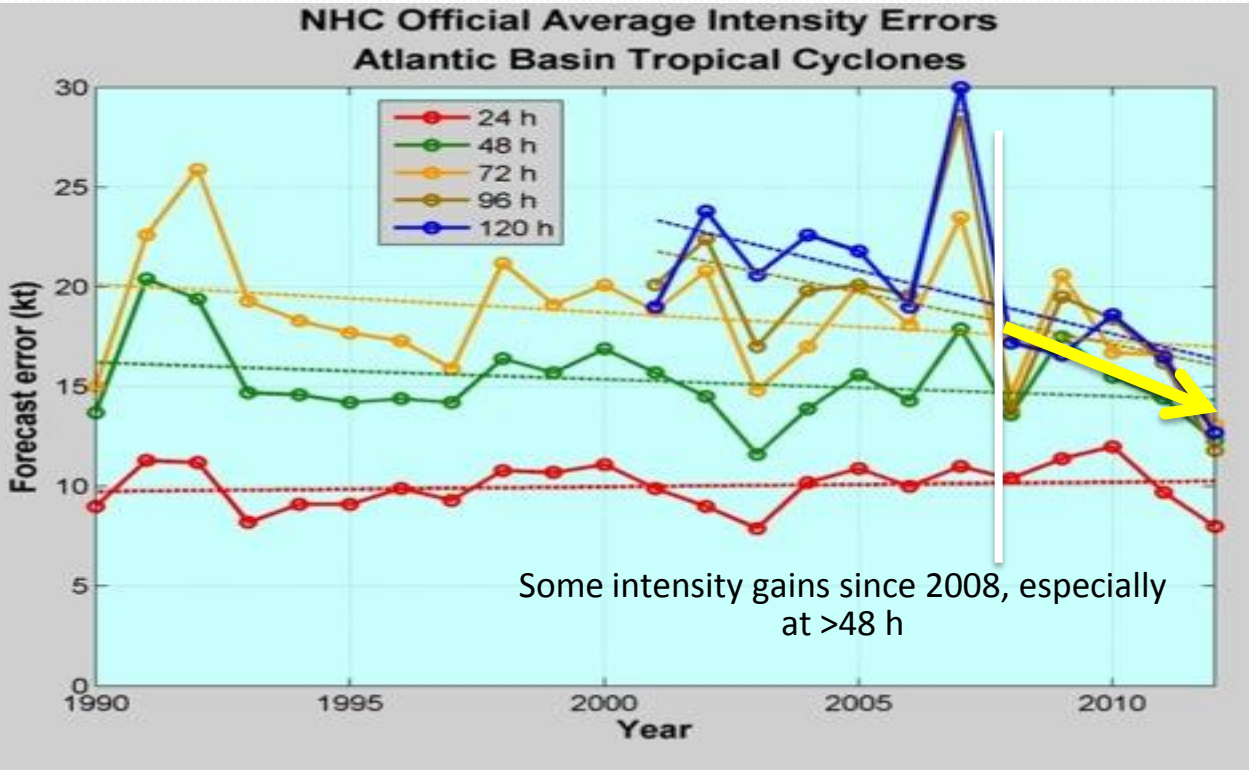


Current Capabilities

Good – track forecast improvements

Not so Good – Modest intensity gains





- Errors cut in half over past 15
- 10-year improvement - As accurate at 48 h as we were at 24 h in 2000

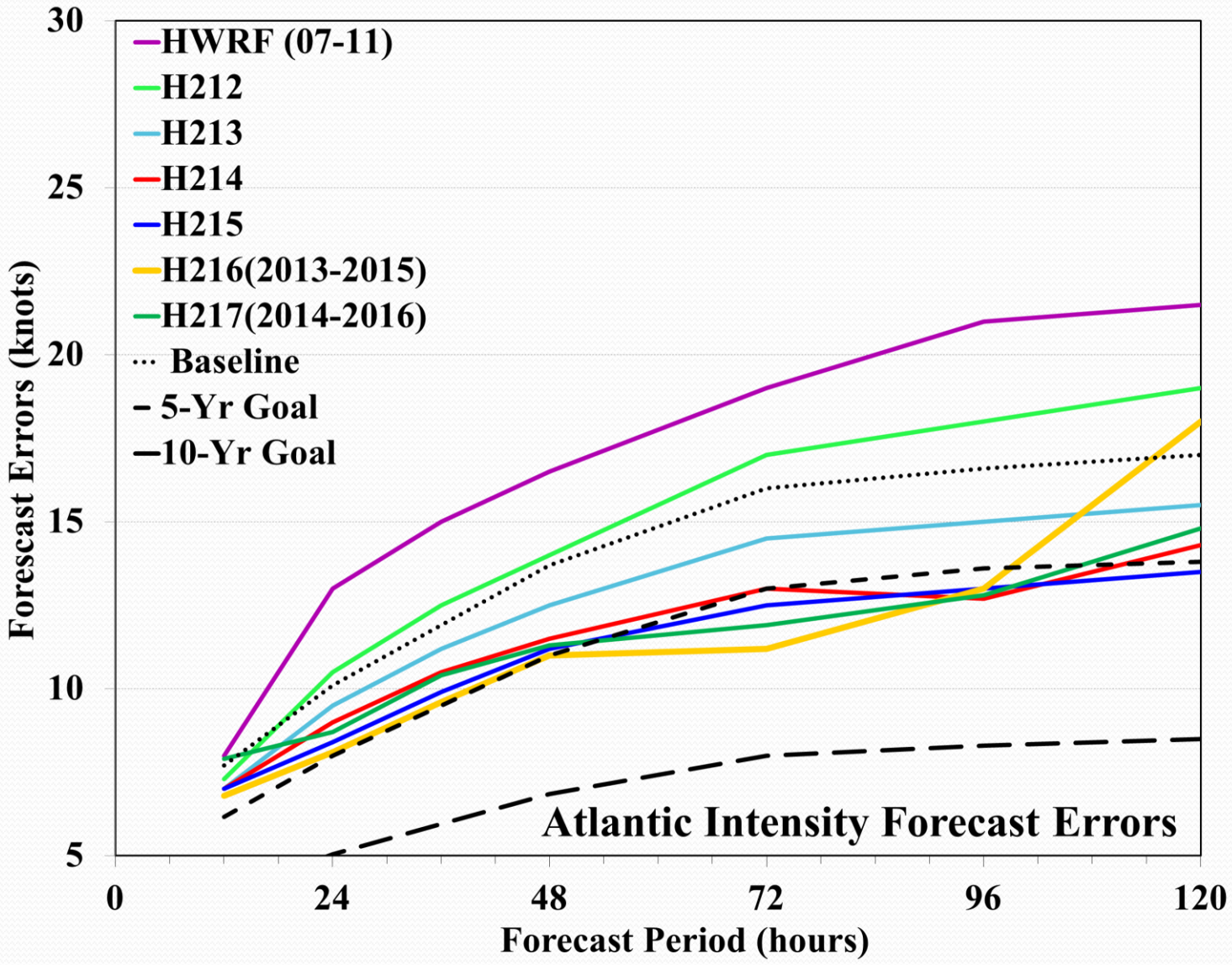
- 24-48 h intensity forecast off by **1** category
- Off by **2** categories perhaps 5-10% of time

The HFIP Project – Vision/Goals

started 2009 plan for 10 years

- Vision
  - Organize the hurricane community to dramatically improve numerical forecast guidance to NHC in 5-10 years
- Goals
  - Reduce numerical forecast errors in track and intensity by 20% in 5 years, 50% in 10 years
  - Extend forecasts to 7 days
  - Increase probability of detecting rapid intensification at day 1 to 90% and 60% at day 5

HWRF Intensity Forecast Improvements



Milestones Operational Hurricane Models Development

- HWRF was initially implemented in 2007 (27/9km, L43)
- First time cloud-permitting high resolution triple nest (27/9/3 km, L43) operational model system implemented in 2012 for HWRF
- One-way hybrid EnkF-3DVAR DA and assimilating real-time inner-core TDR dataset in 2013 in HWRF
- HWRF increased vertical resolution from L43 to L61 and coupled MPIPOM with 3D ocean for EPAC in 2014
- HWRF increased horizontal resolution from 27/9/3 to 18/6/2 km in 2015

Milestones Operational Hurricane Models Development

- HWRF DA upgraded with hybrid 40-member HWRF-based high-resolution ensemble in 2015
- Expand HWRF capabilities to all global basins in 2015
- HWRF added ocean coupling for CPAC, WPAC and NIO and one-way coupling to hurricane wave model in 2016
- HWRF increased vertical level from L61 to L75 with 10 hPa model top
- used fully self-cycled HWRF ensemble hybrid DA for TDR and priority storms
- HMON was implemented in 2017 with uncoupled in NATL and coupled in EPAC (replacing legacy GFDL hurricane model)

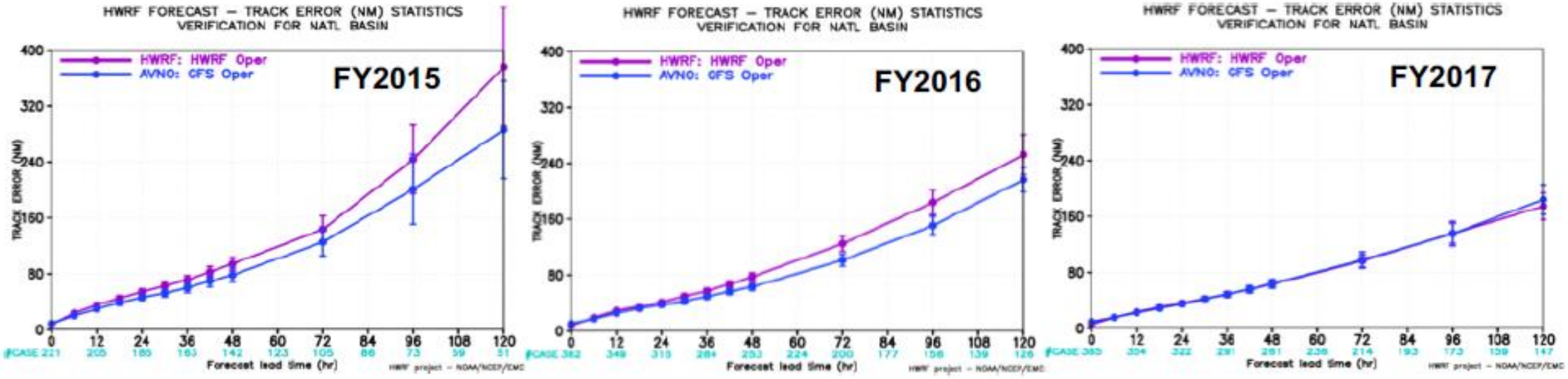
Physics in 2018 Operational HWRF

Scheme	Description	Origin
Land Surface	Noah (LSM)	WRF community
Surface layer	Monin-Obukhov similarity, with closer match of C_d, C_h with obs	GFDL model
PBL	Eddy-diffusivity and mass flux (EDMF)	GFS model
Convection	Scale-aware Simplified Arakawa-Schubert (SAS)	GFS model
Microphysics	Ferrier-Aligo	Regional ETA/NMMB models
Radiation	RRTMG	GFS model
Partial cloudiness		WRF community

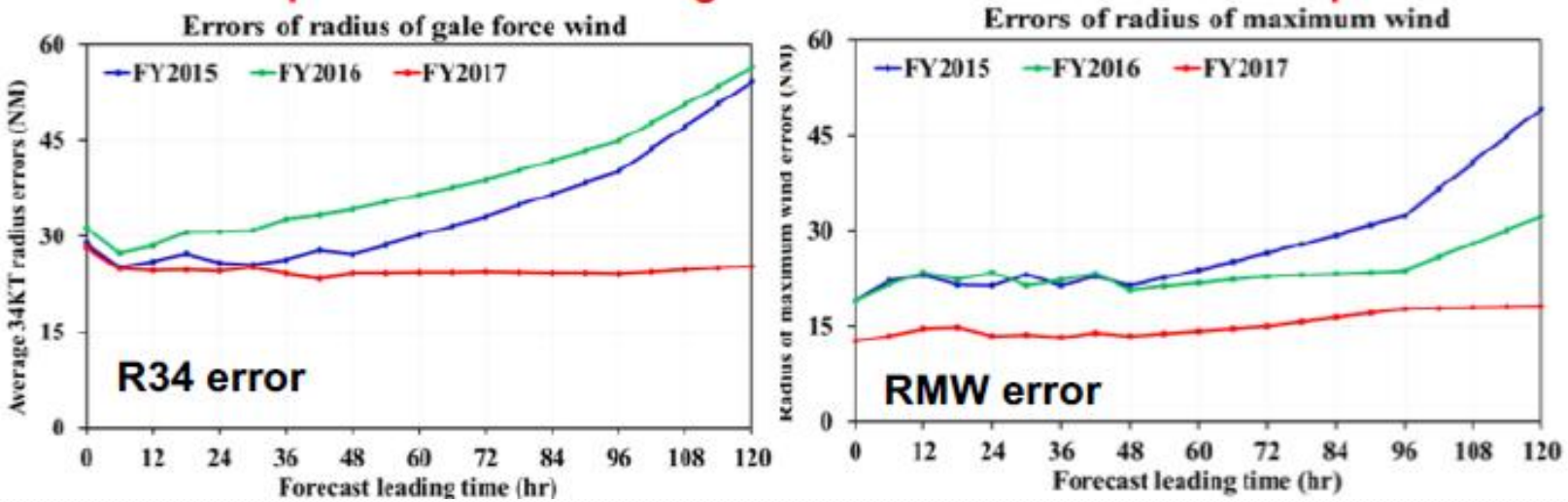
HWRF Physics schemes started from GFDL hurricane model and evolved in time

HWRF track and size forecasts in NATL

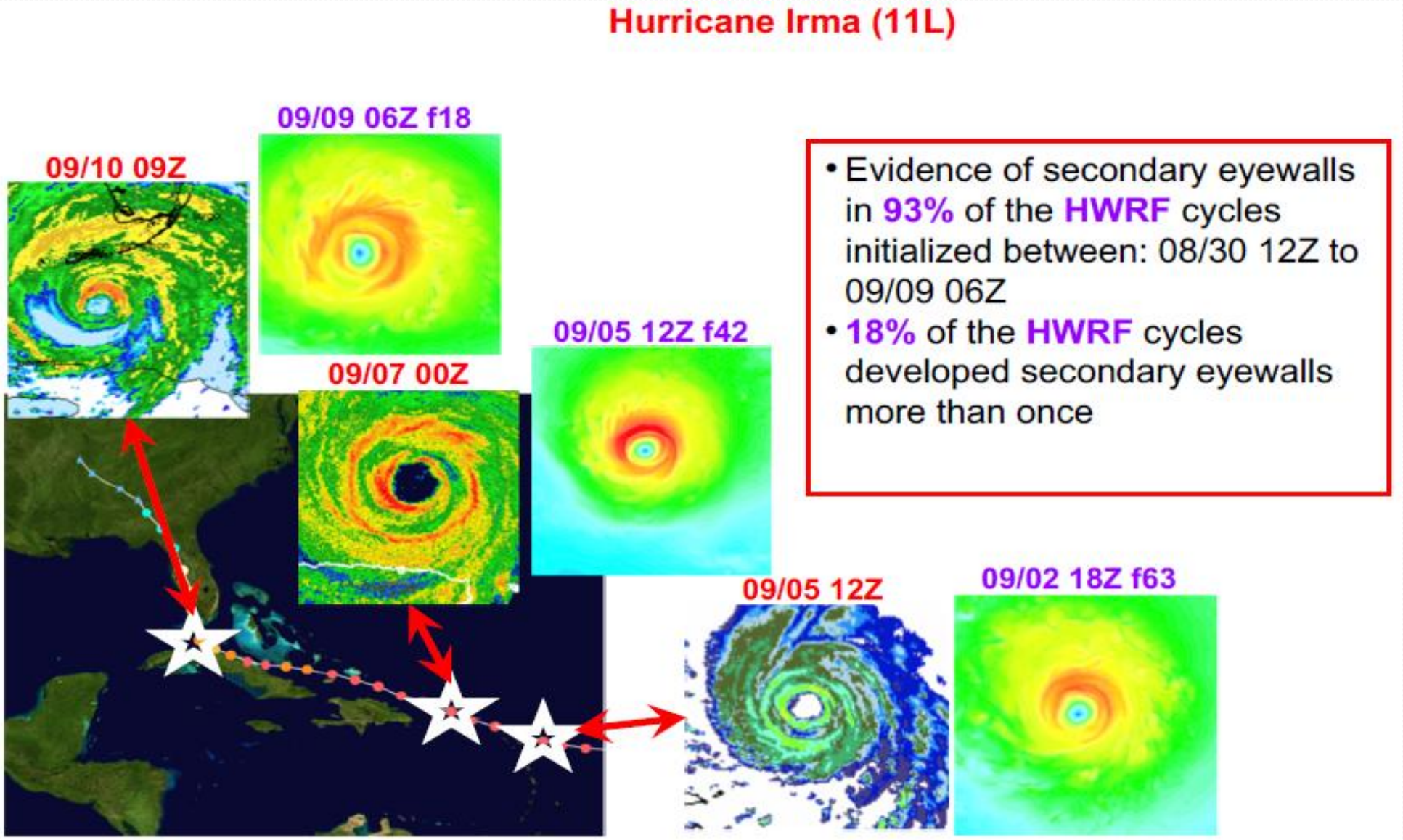
Real-Time Performance for FY2015-2017



Impressive catch-up in track forecasting and substantial storm size improvement

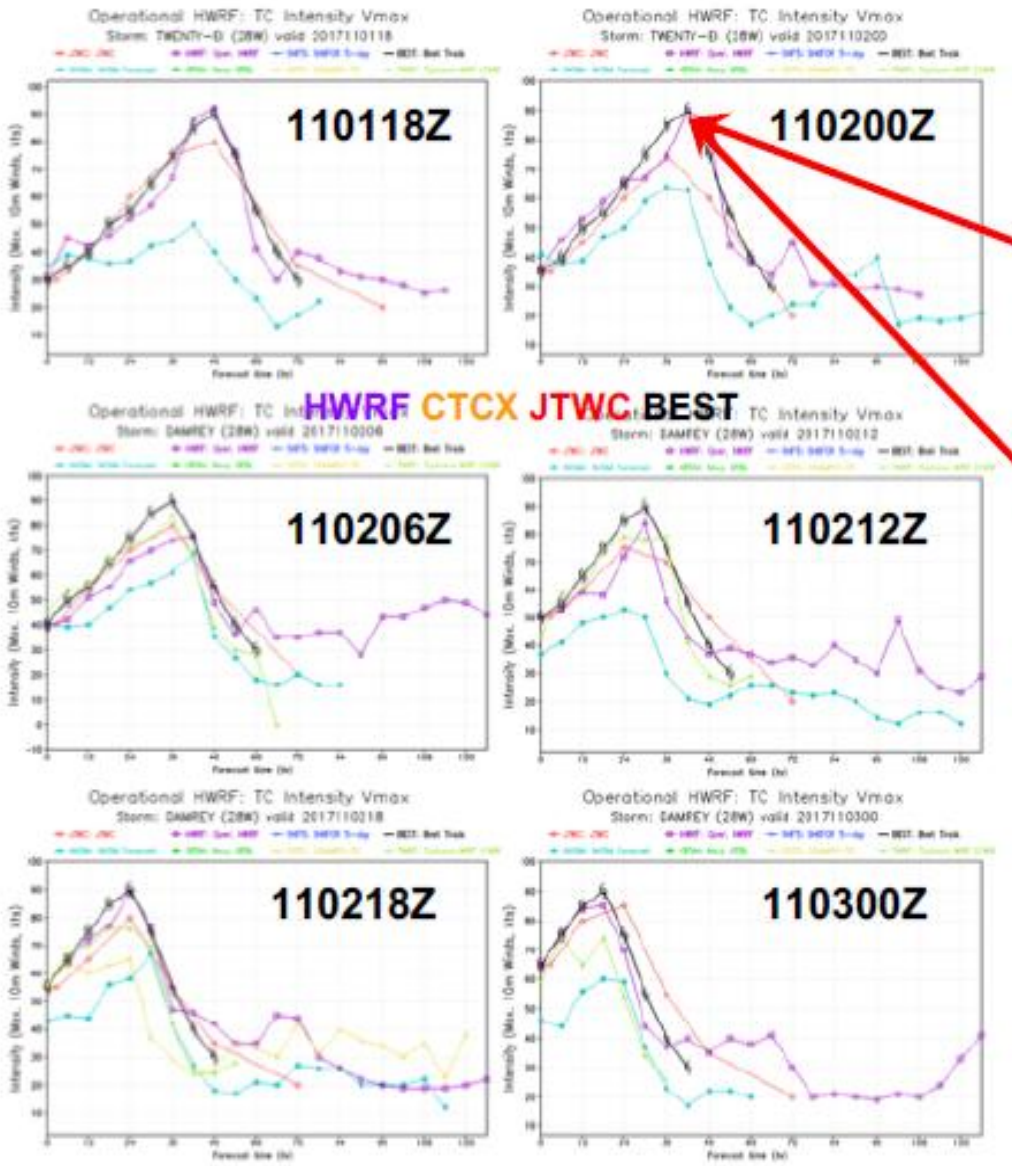


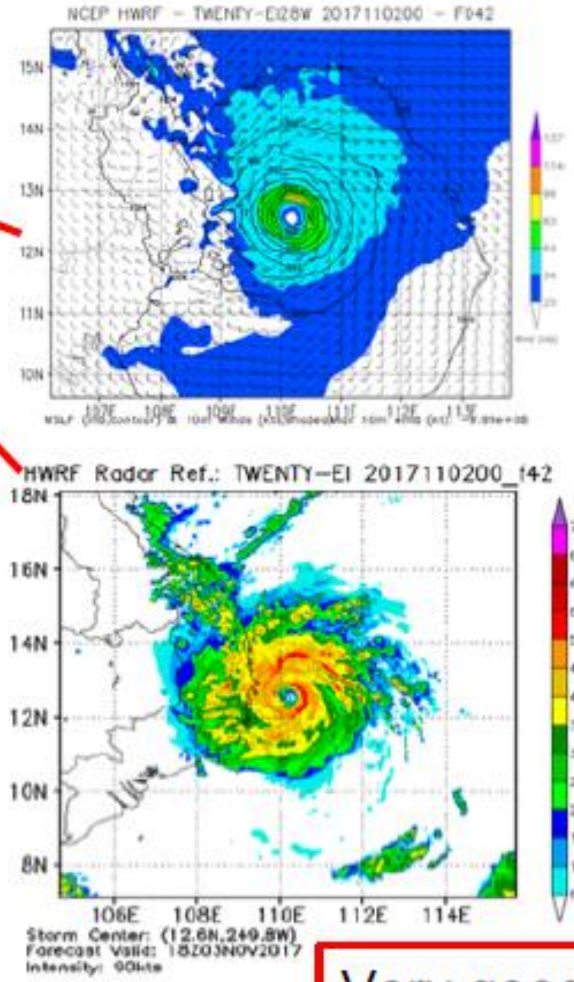
2017 HWRF forecast for concentric eyewalls

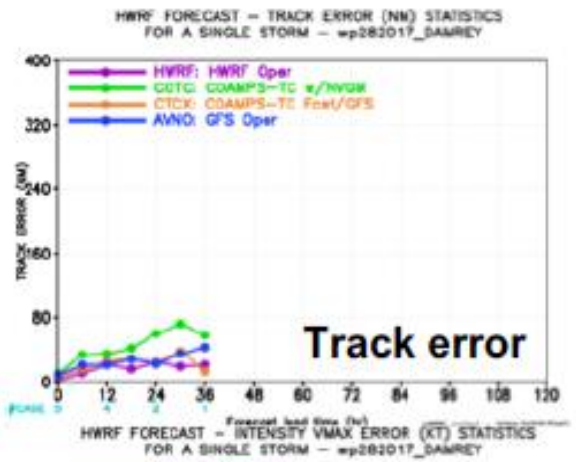


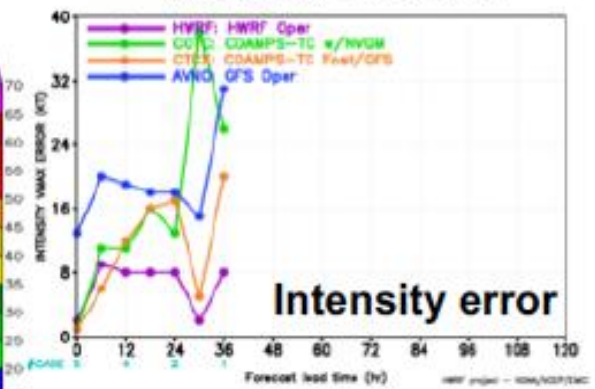
- Evidence of secondary eyewalls in 93% of the HWRF cycles initialized between: 08/30 12Z to 09/09 06Z
- 18% of the HWRF cycles developed secondary eyewalls more than once

HWRF Forecast for Typhoon Damrey (28W)





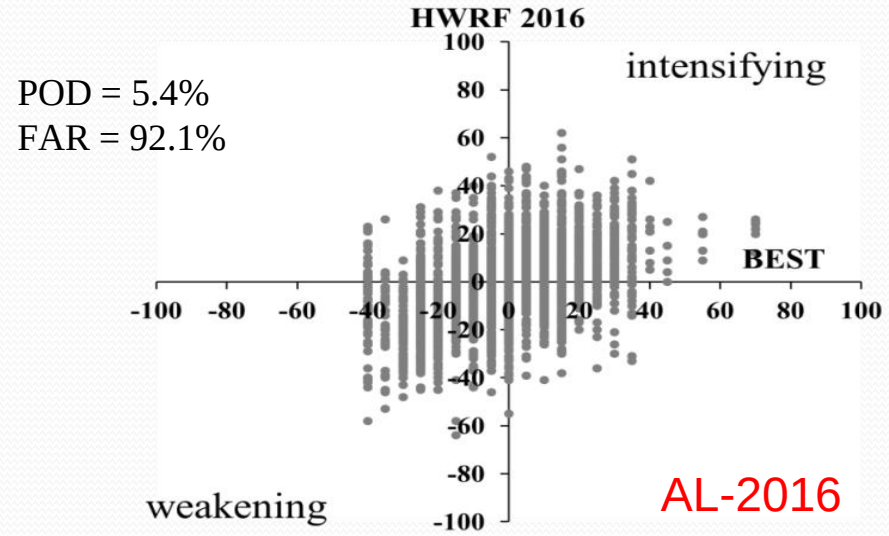


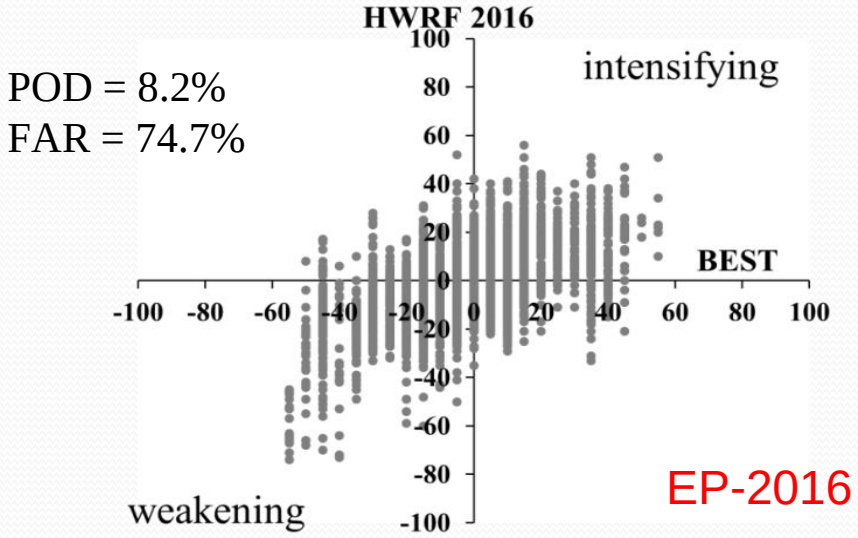


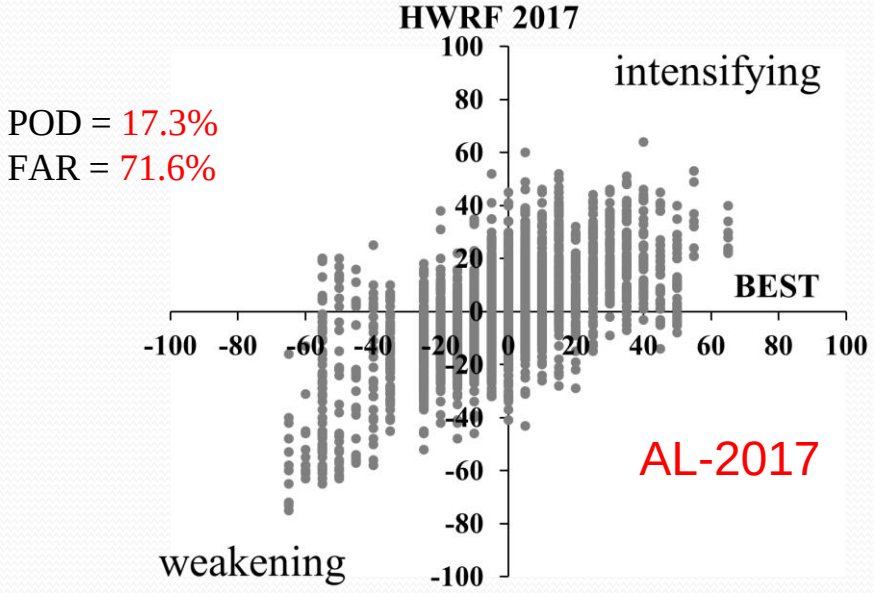
Very good track forecast

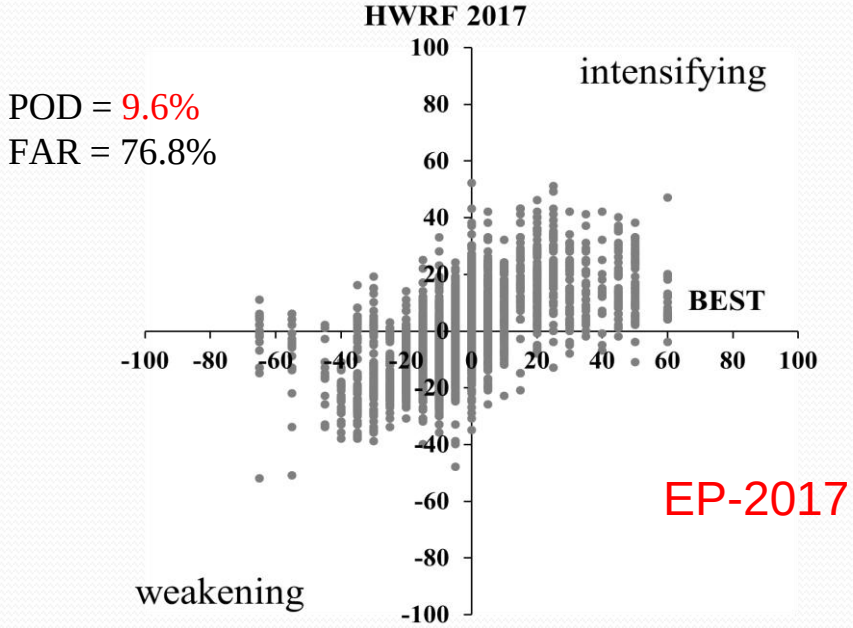
Phenomenal intensity forecast

POD Verification in AL and EP Basins
Rapid Intensity Forecast

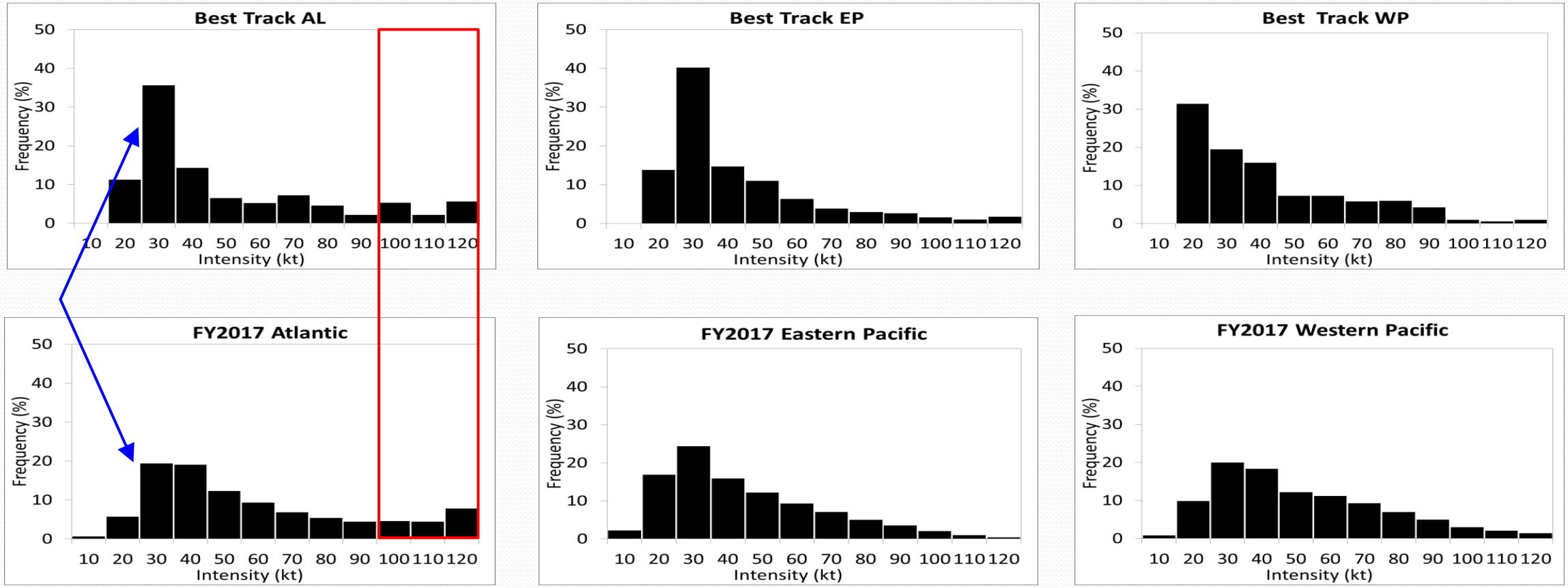








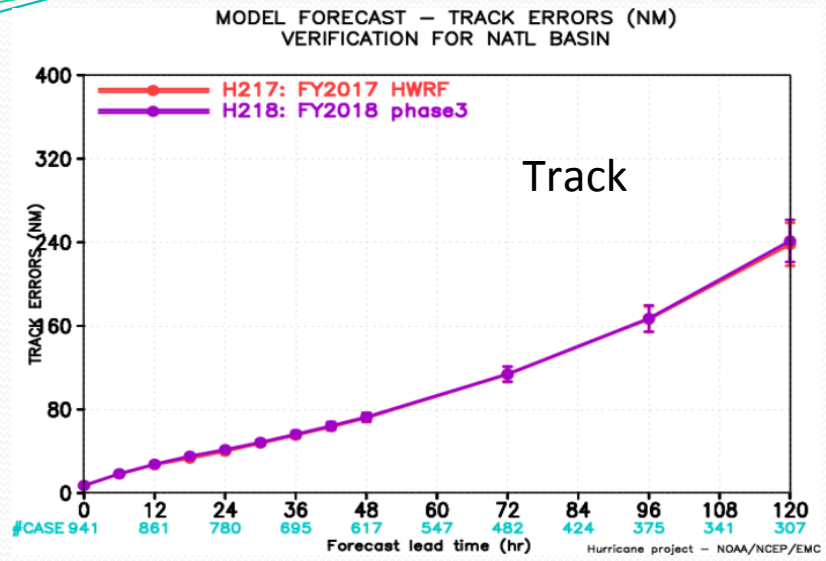
Intensity Distribution, 2017 HWRF Real-Time Performance

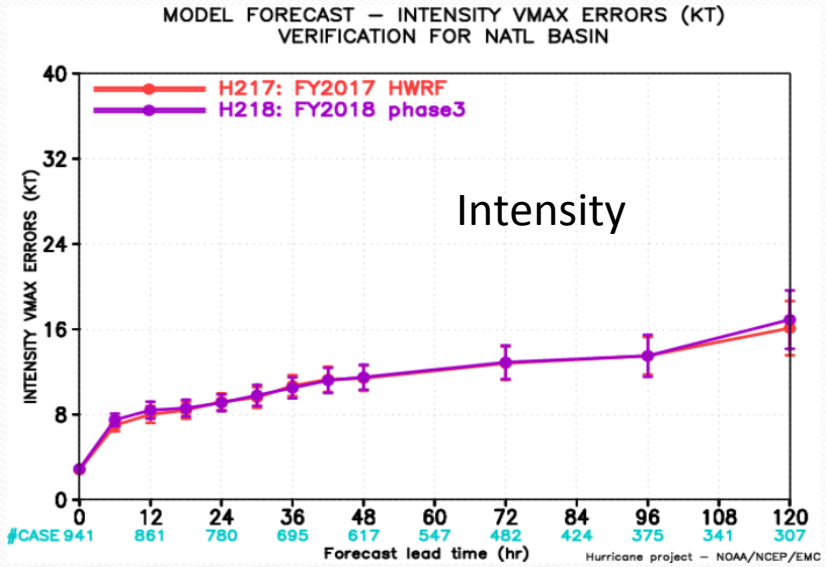


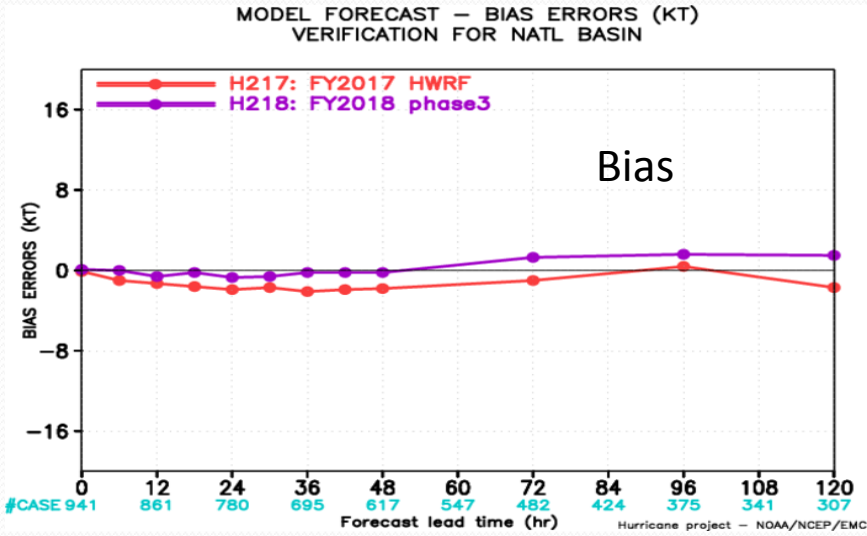
Scope of FY2018 HWRF Upgrades

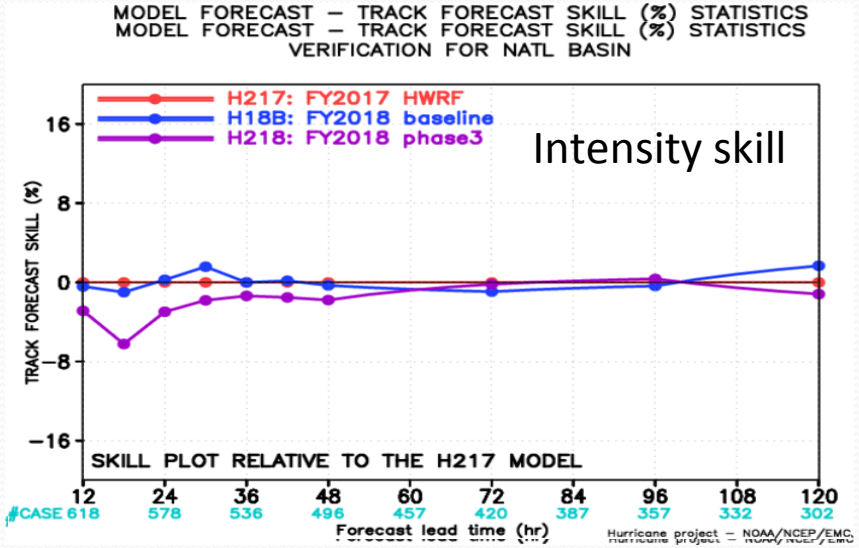
- **System & Resolution Enhancements**
  - Framework upgrade to WRFV3.9.1 with bug fixes
  - T&E with 2017 GFS IC/BC
  - Increase horizontal resolution to 13.5/4/5/1.5 km, with adjusted domain sizes for d02 and d03
  - Increase vertical resolution for non-NHC basins from L61 to 75 levels
- **Physics Advancements**
  - Radiation, RRTMG- cloud overlap
  - Adjust surface flux exchange coefficients
- **Initialization/DA Improvements**
  - Stochastic physics for DA ensembles
  - GSI upgrades, changes (disable SSMI Channel 2)
  - Admit new data sets (GOES-16 AMV's, NOAA-20, SFMR, Dropsonde drifts, TDR from G-IV)
- **Coupling and other upgrades**
  - Add ocean coupling (HYCOM) for Southern Hemisphere basins
  - Wave initial conditions from global wave model

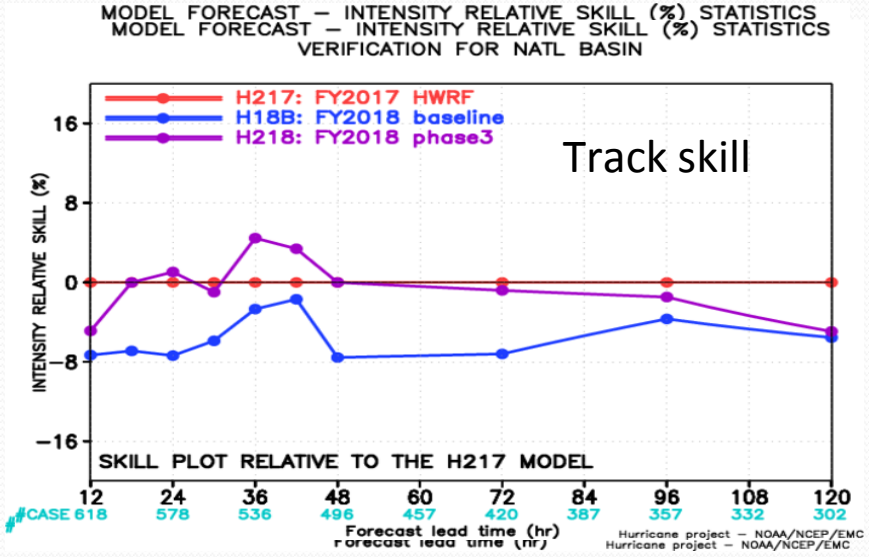
Evaluation of 2018 HWRF for NATL (2015-2017 storms)



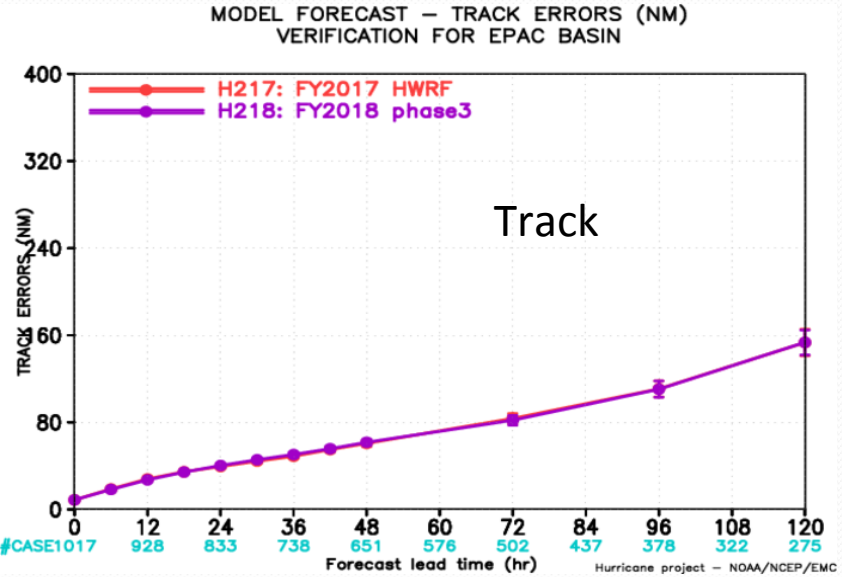


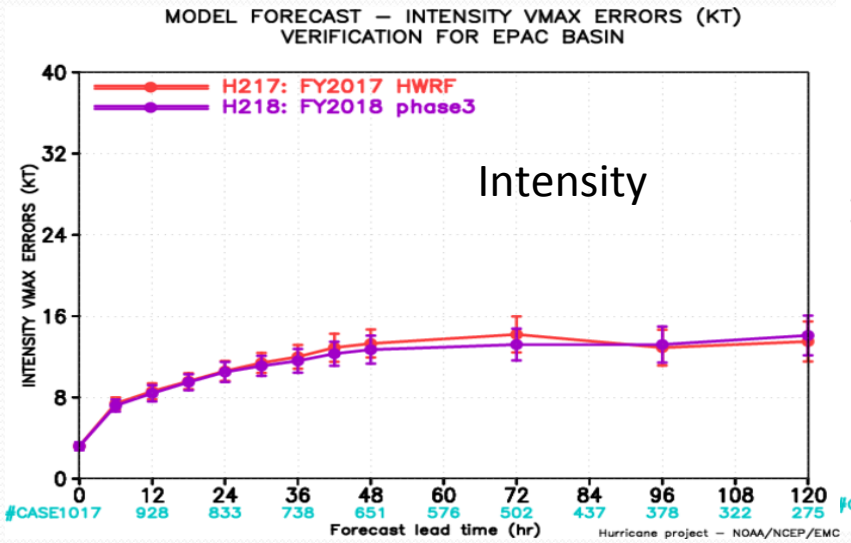


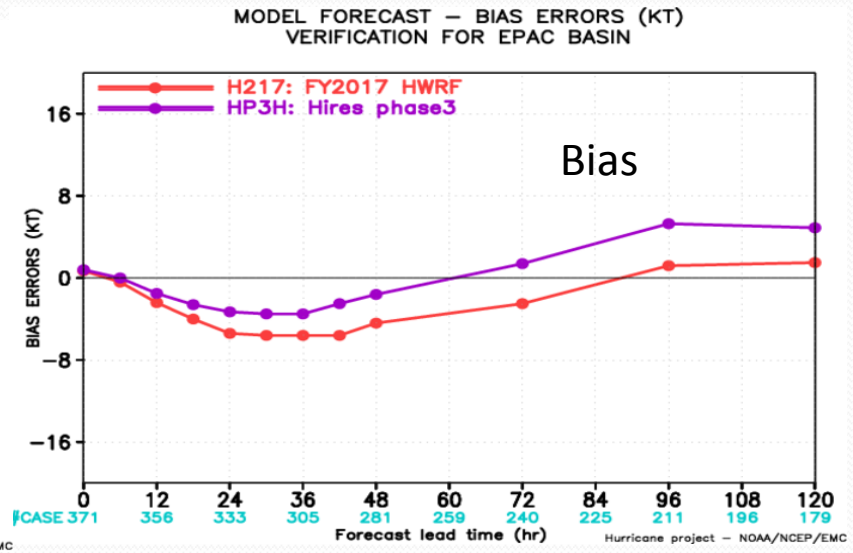


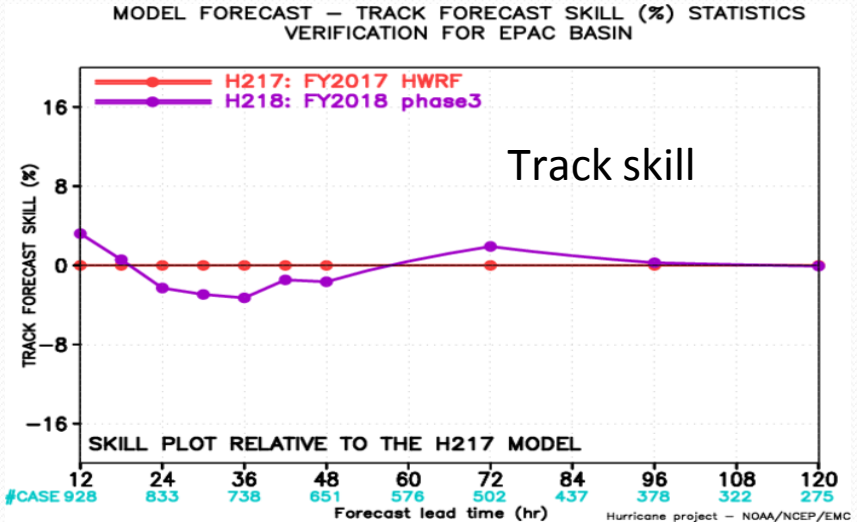


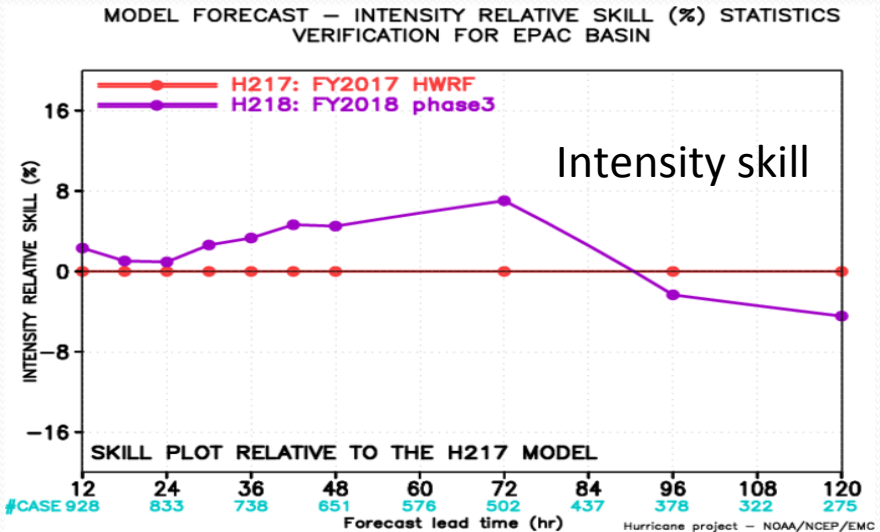
Evaluation of 2018 HWRF for EPAC
(2015-2017 storms)



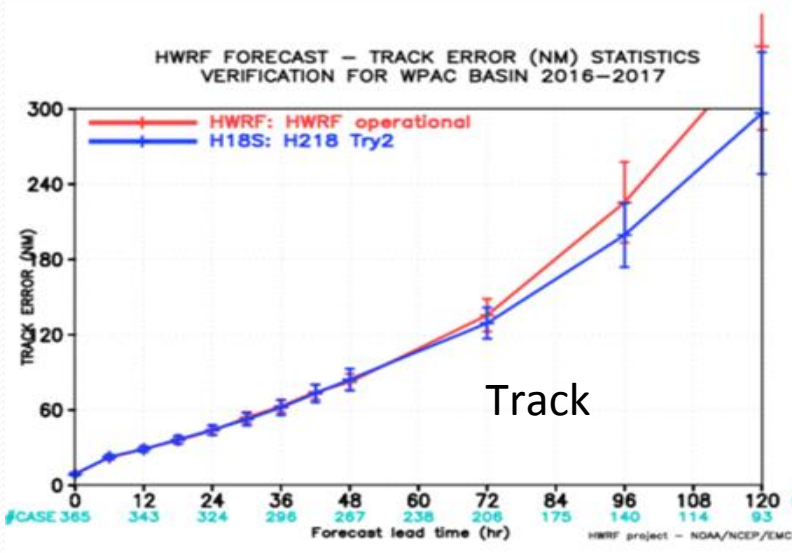


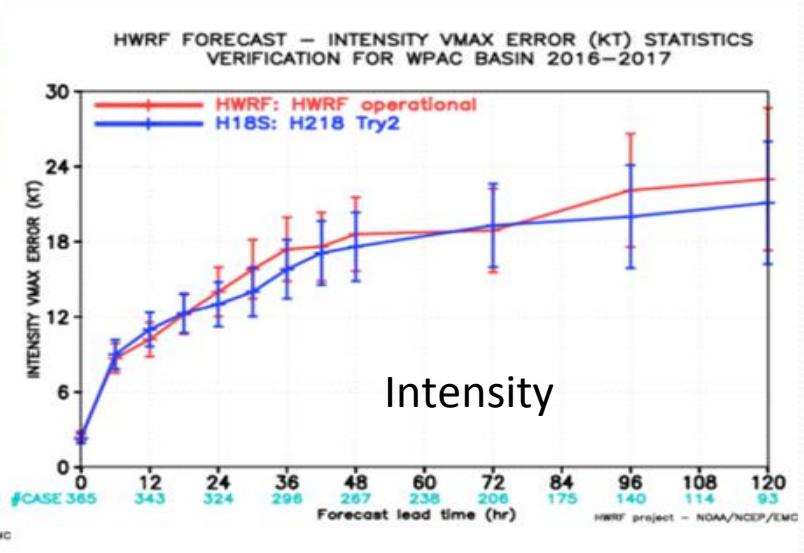


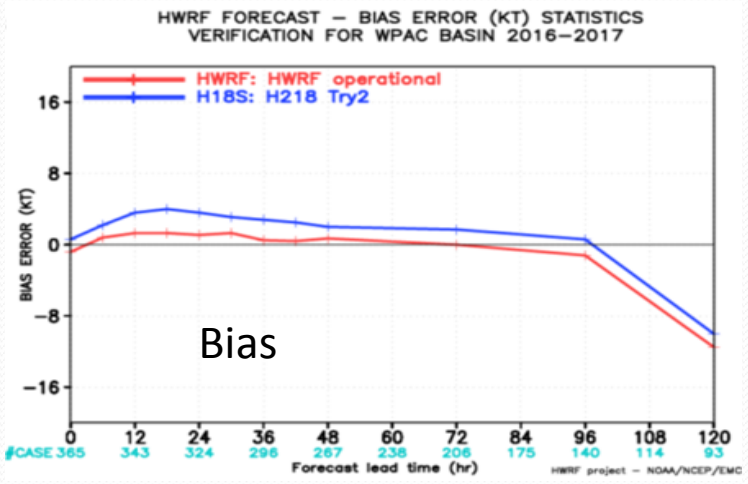




Evaluation of 2018 HWRF for WPAC
(2016-2017 priority storms)

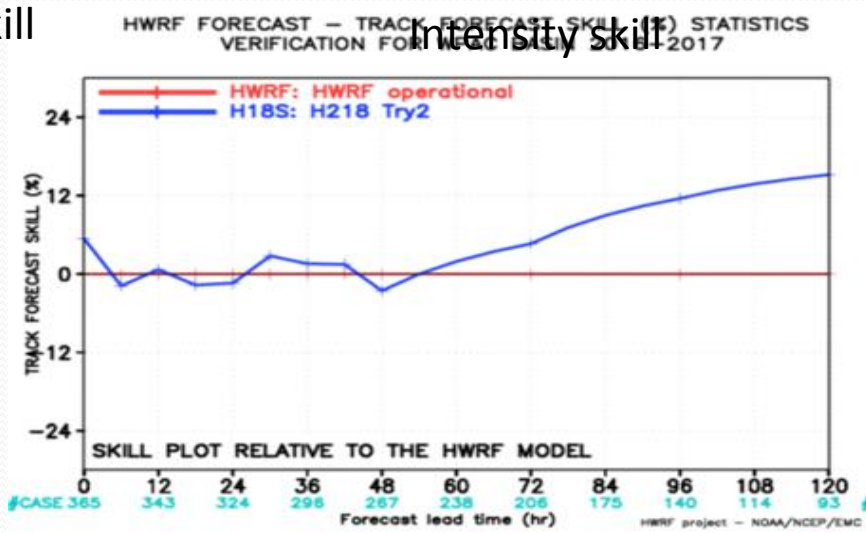


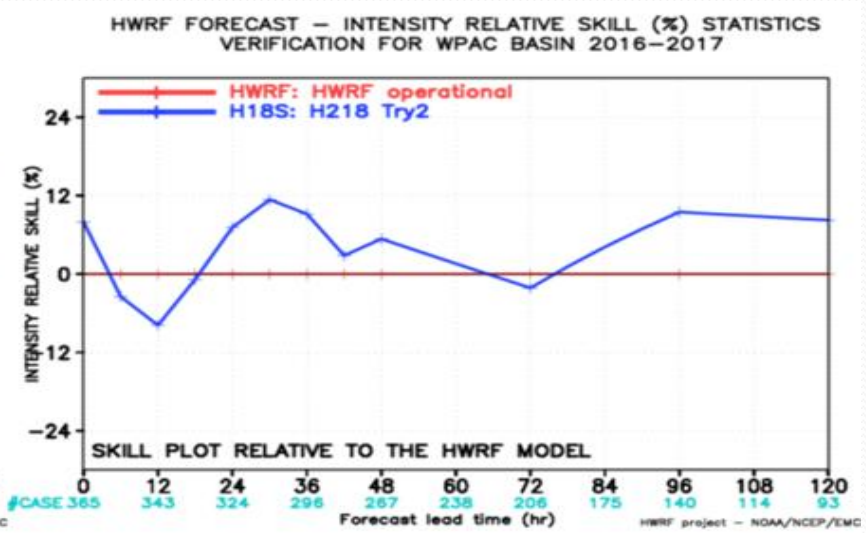




Track skill

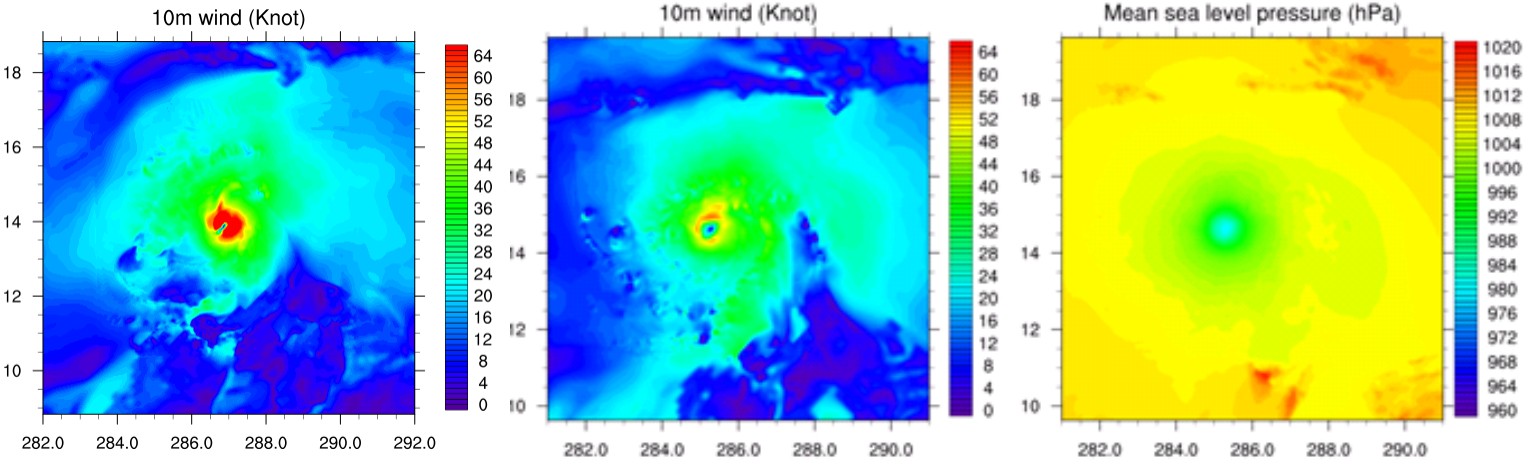
Intensity skill

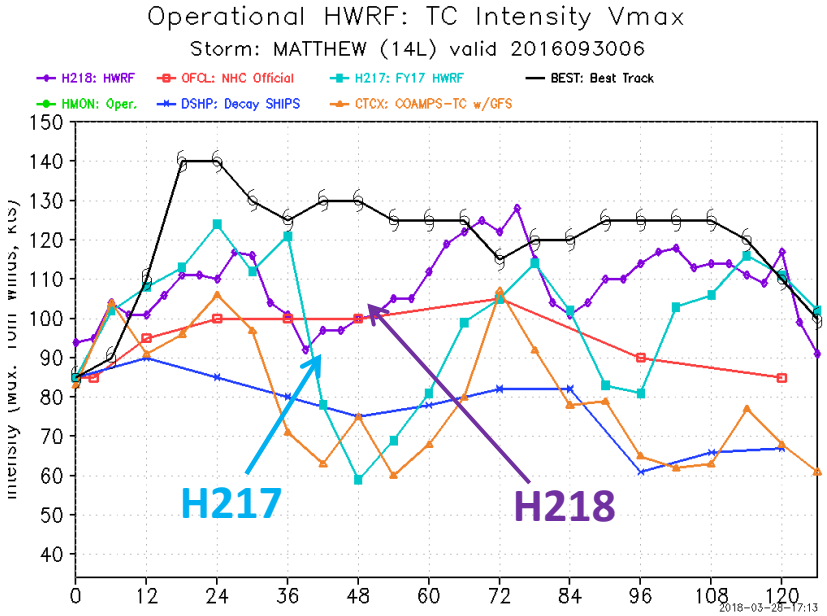




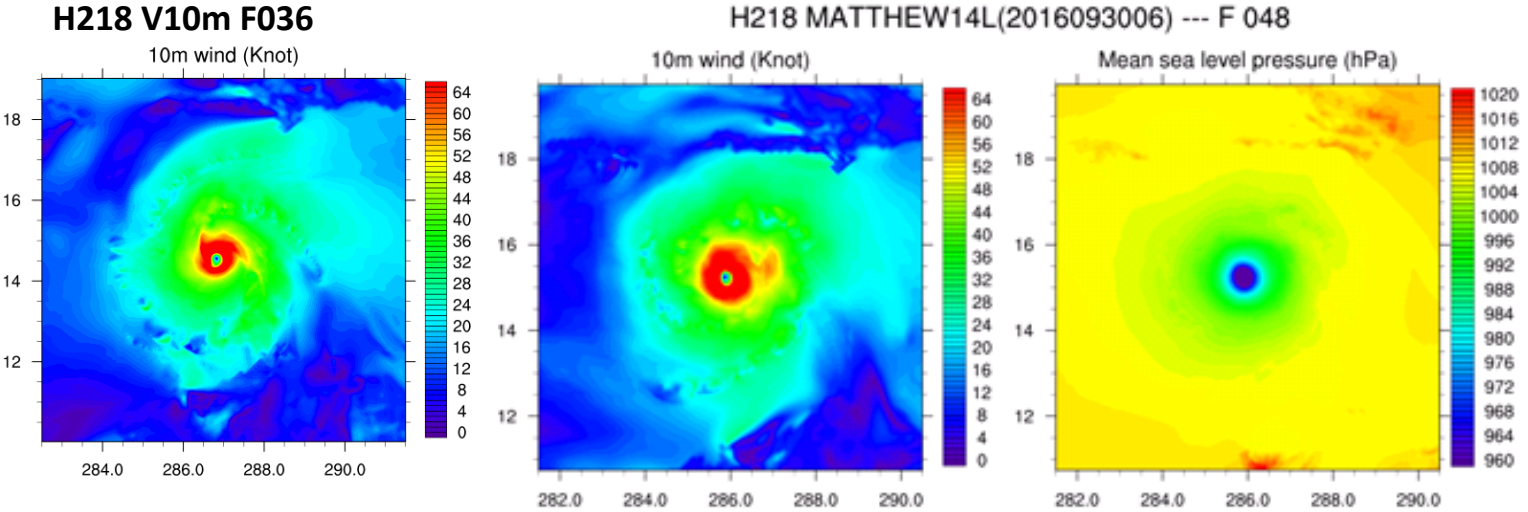
Intensity Oscillations Improved in H218

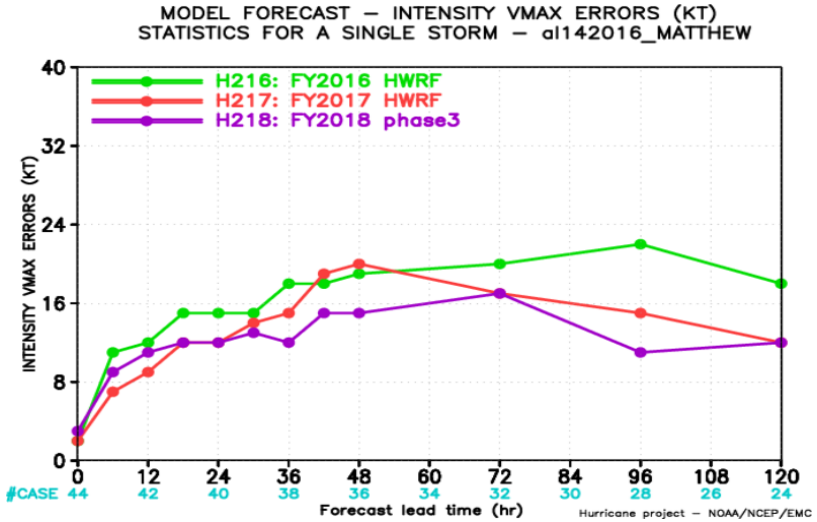
H217 V10m F036



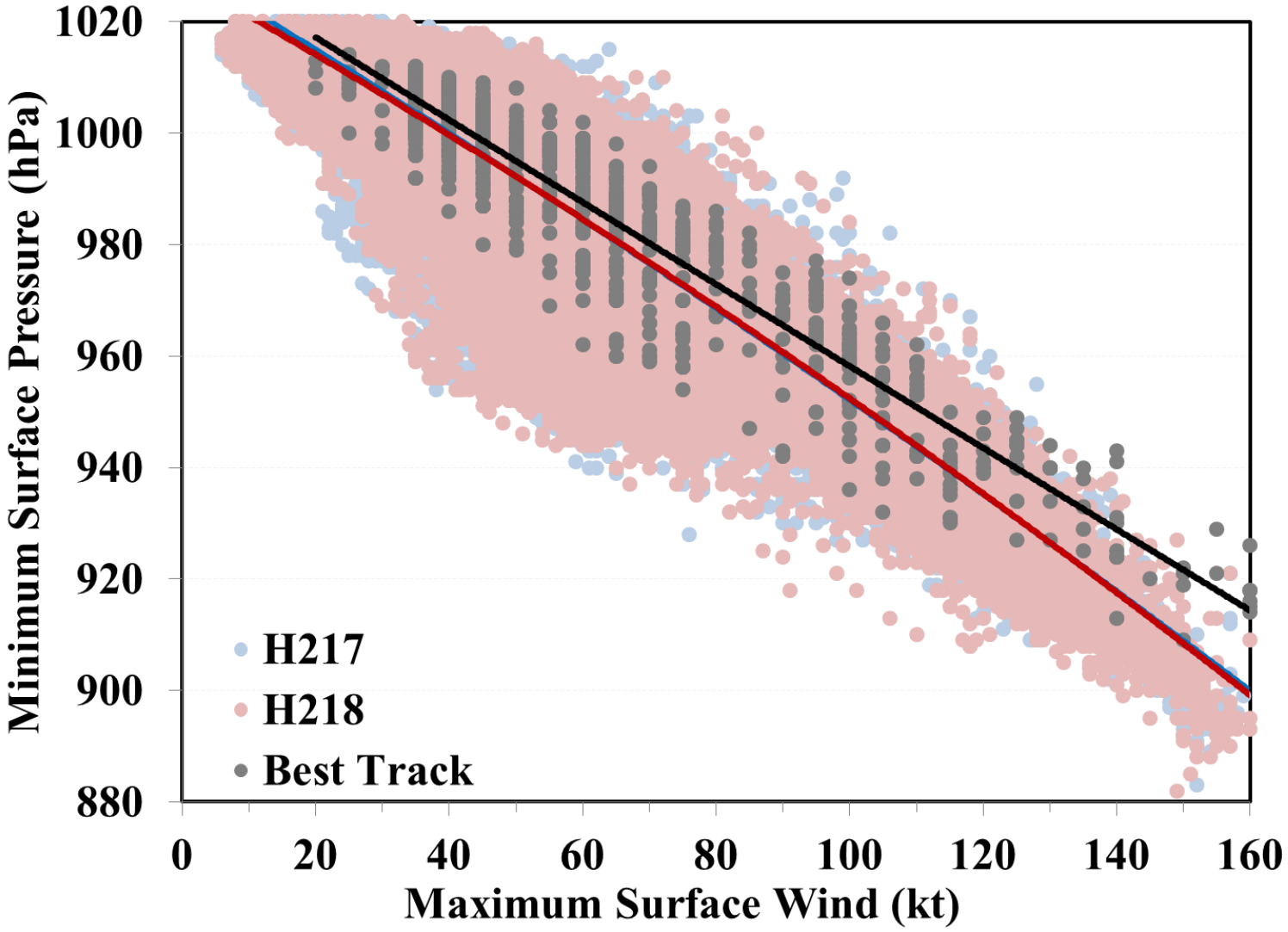


H218 V10m F036





HWRF Wind-Pressure Relationship



FY2018 HWRF Modeling System Configurations

Note: Items in Red are upgraded.

Basin	Ocean	Wave Coupling	Data Assimilation	Ensemble	Vertical	Model Top	Horizontal resolution
NATL	3D POM GDEM	WW3-1way	Always	TDR self-cycled	75 level	10 hPa	**13.5/4.5/1.5 km**
EPAC	3D POM RTOFS	WW3-1way	Always	TDR self-cycled	75 level	10 hPa	**13.5/4.5/1.5 km**
CPAC	3D POM RTOFS	WW3-1way	None	None	75 level	10 hPa	**13.5/4.5/1.5 km**
WPAC	HYCOM	None	None	None	**75** level	10 hPa	**13.5/4.5/1.5 km**
NIO	HYCOM	None	None	None	**75** level	10 hPa	**13.5/4.5/1.5 km**
SIO	**HYCOM**	None	None	None	**75** level	**10** hPa	**13.5/4.5/1.5 km**
SPAC	**HYCOM**	None	None	None	**75** level	**10** hPa	**13.5/4.5/1.5 km**

HMON

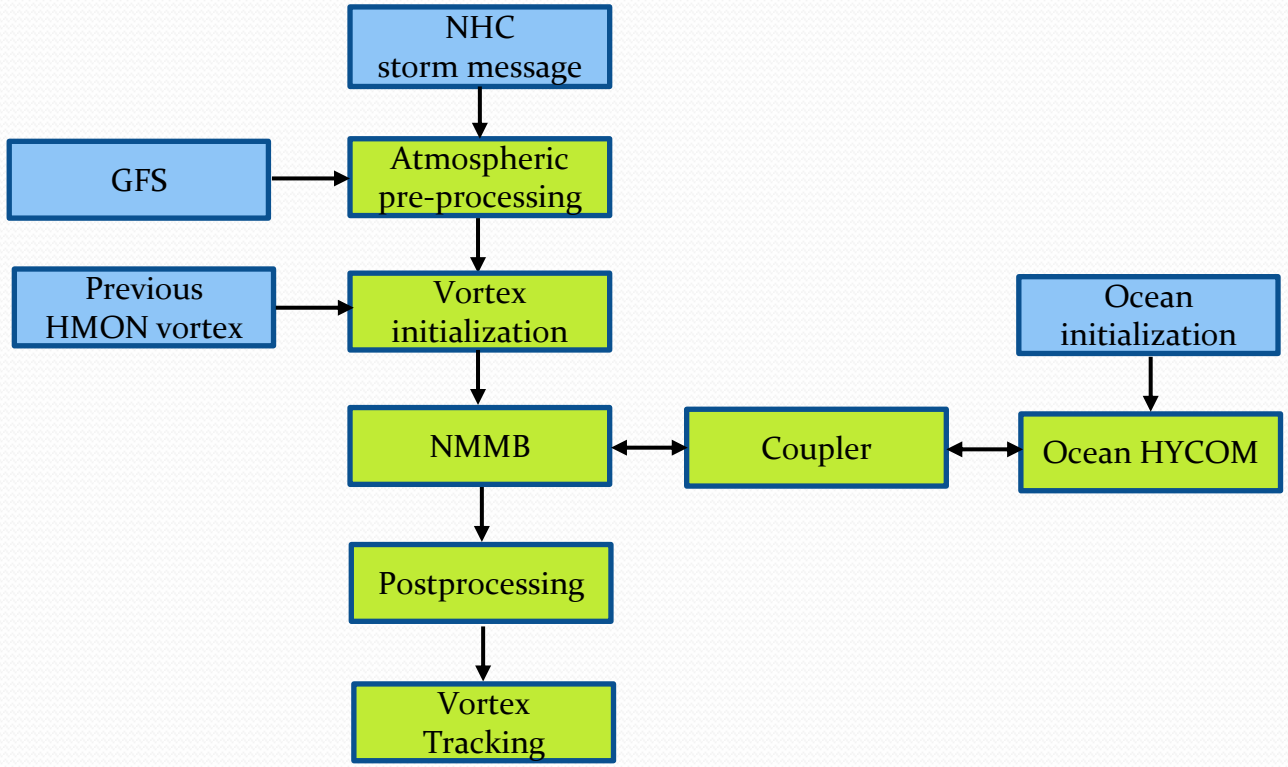
Hurricanes in a Multi-scale Ocean coupled Non-hydrostatic model

One of the operational hurricane forecast systems at NCEP

- Dynamic core: NMM-B (18/6/2km, L42)
- Vortex initialization
- Triple nested with two moving nests
- Well-tuned Physics package
- Coupled to Ocean models (HYCOM)

Note: No data assimilation yet.

NATL/EPAC/CPAC



Scope of FY2018 HMON Upgrades

- **System & Resolution Enhancements**
  - Upgrade NMMB source code with bug fix
  - Increase vertical levels from L42 to L51
  - Change diffusion parameterization
- **Physics Advancements**
  - Use scale-aware SAS scheme
  - Update momentum and enthalpy exchange coefficients (Cd/Ch)
  - Use GFS-EDMF PBL scheme
- **Initialization**
  - Update vortex initialization
- **Coupling and other upgrades**
  - Add ocean coupling (HYCOM) for North Atlantic basin

FY2018 HWRF/HMON configurations diversity

Note: Items in Red are different

	HWRF	HMON
Dynamic core	Non-hydrostatic, NMM-E	Non-hydrostatic, NMM-B
Nesting	13.5/4.5/1.5 km; 77°/18°/6°; 75 vertical levels; Full two-way moving	18/6/2 km; 75°/12°/8°; 51 vertical levels; Full two-way moving
Data Assimilation and Initialization	Vortex relocation & adjustment Self-cycled hybrid EnKF-GSI with inner core DA (TDR)	Modified vortex relocation & adjustment, no DA
Physics	Updated surface (GFDL), GFS-EDMF PBL, Updated Scale-aware SAS, NOAH LSM, Modified RRTM, Ferrier	Surface (GFDL), GFS-EDMF PBL, Scale-aware SAS, NOAH LSM, RRTM, Ferrier
Coupling	MPIPOM/HYCOM, RTOFS/GDEM, WaveWatch-III	HYCOM, RTOFS/NCODA, No waves
Post-processing	NHC interpolation method, Updated GFDL tracker	NHC interpolation method, GFDL tracker
NEMS/NUOPC	No	Yes with moving nests

HWRF as a Unique Global Tropical Cyclone Model

Developmental Testbed Center Support

www.dtcenter.org/HurrWRF/users

- Yearly releases, code downloads, datasets, documentation, helpdesk
- 700 registered users
- Stable, tested code
- Benchmarks available
- Support to HWRF developers in code management

Current release: HWRF v3.5b (2013 operational with several patches)
Next: HWRF v3.6a (2014 operational) 08/2014, concurrent with operational implementation

Developmental Testbed Center

Continue the community modeling approach for accelerated transition of research to operations

NOAA HURRICANE FORECAST IMPROVEMENT PROJECT

NATIONAL HURRICANE CENTER

Japan Meteorological Agency

International partnerships for accelerated model development & research

Operational Real-time forecast guidance for all global tropical cyclones in support of NHC, JTWC and other US interests across the Asia Pacific, North Indian Ocean and Southern Hemisphere ocean basins

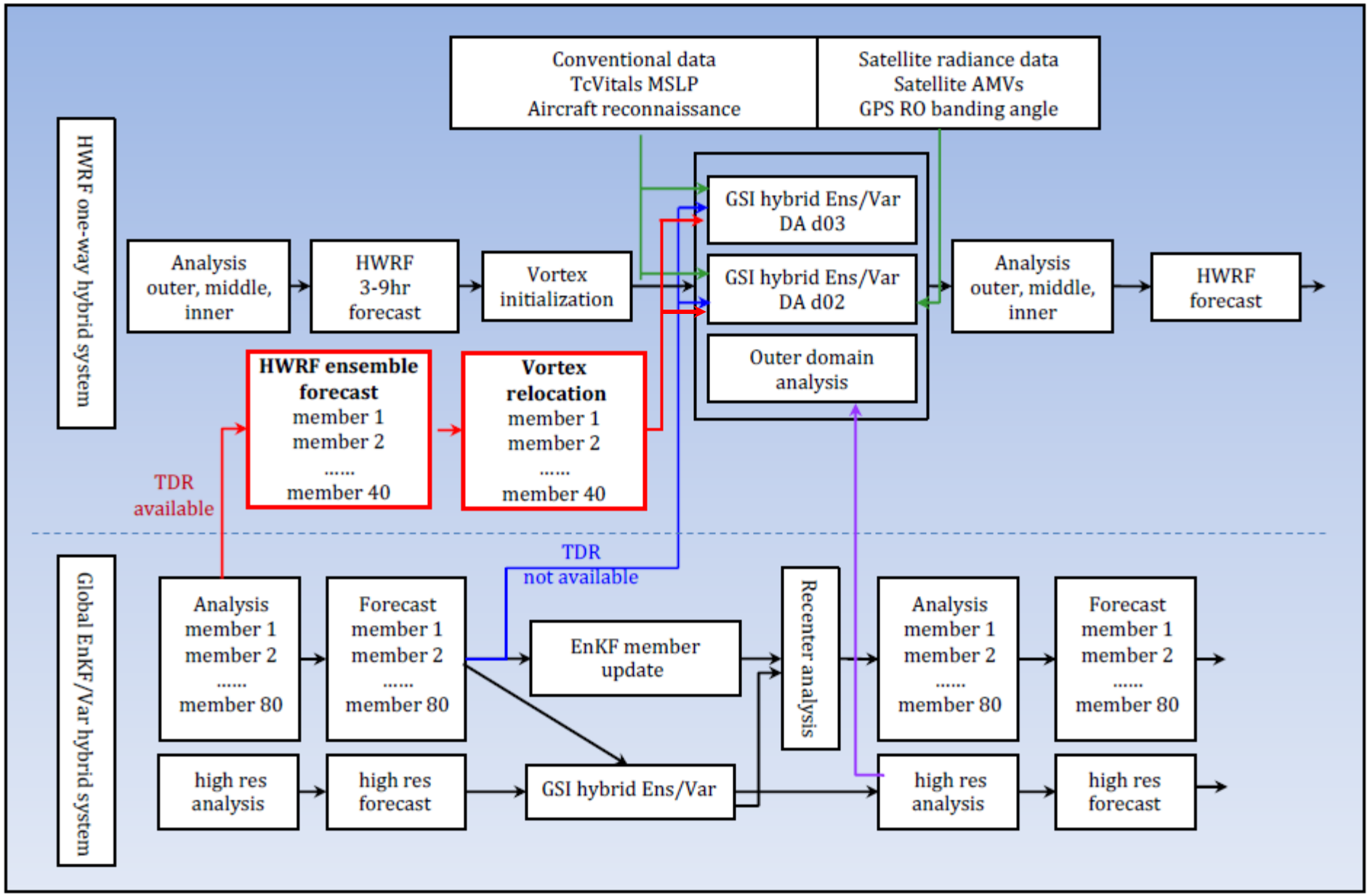
Challenges in Hurricane Modeling

Inner-core data assimilation

- Initial spin down/up issues due to inconsistence between initialization process and data assimilation
- Representation of flow-dependent error background covariance
- Under-disperse of ensemble forecast fields
- All-sky data assimilation

HWRF hybrid data assimilation system

Use the same HWRF deterministic model, model physics un-certainties are not included in 2017 version of HWRF



FY2018 HWRF ensemble configuration used in DA

- **Use operational deterministic HWRF model**
- **IC/BC perturbations (large scale): 6h forecast from 40 members of GDAS analysis**
- **Dual-resolution Hybrid Data Assimilation**
- **Model physics perturbation (vortex scale):**
  - Stochastic convective trigger perturbations in SAS: -50 hPa to + 50 hPa white noise;
  - Stochastic boundary layer height perturbations in PBL scheme, -20% to +20%;
  - Stochastic surface drag coefficient Cd perturbations.

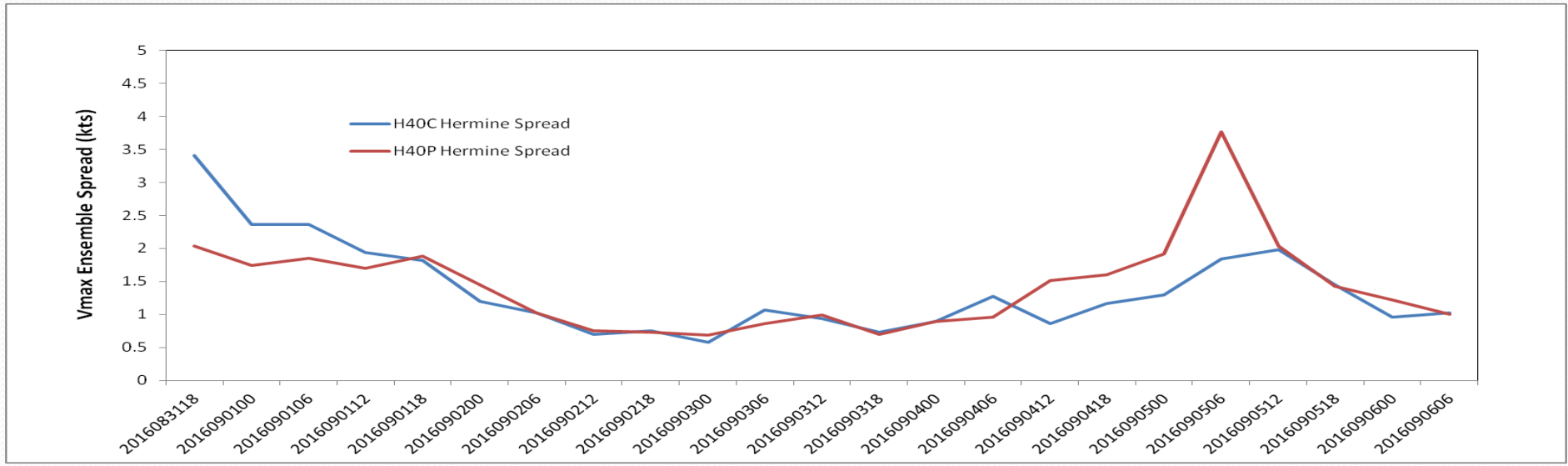
Vmax Ensemble Spread
(Top: Hermine, 09L top, Bottom: Matthew 14L)

Mean Vmax 6h ensemble spread over 265 cycles:

H40C: 3.27 kts
H40P: 3.28 kts

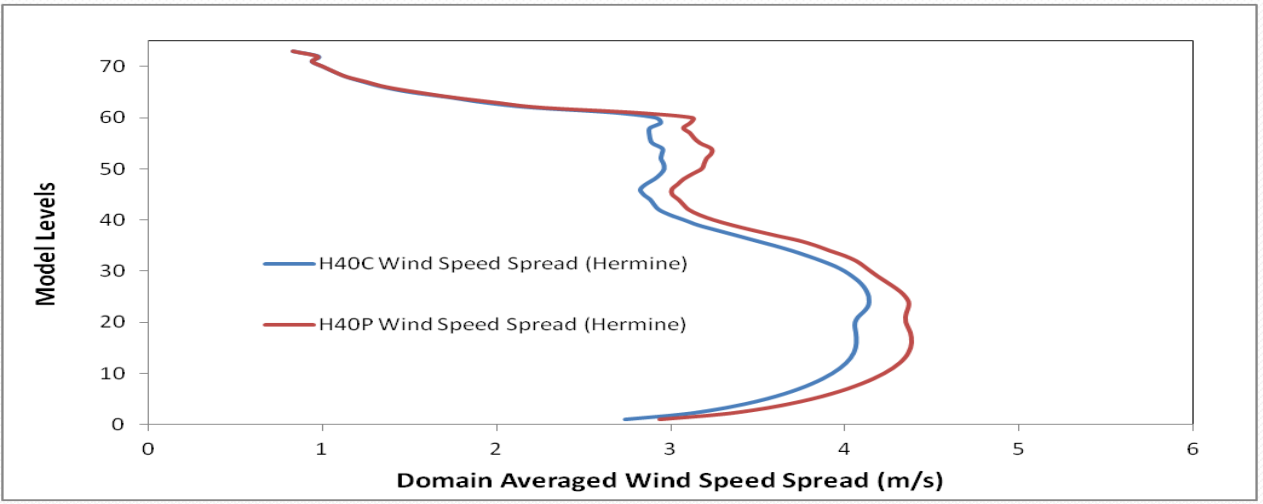
Mean Vmax 6h forecast error over 265 cycles:

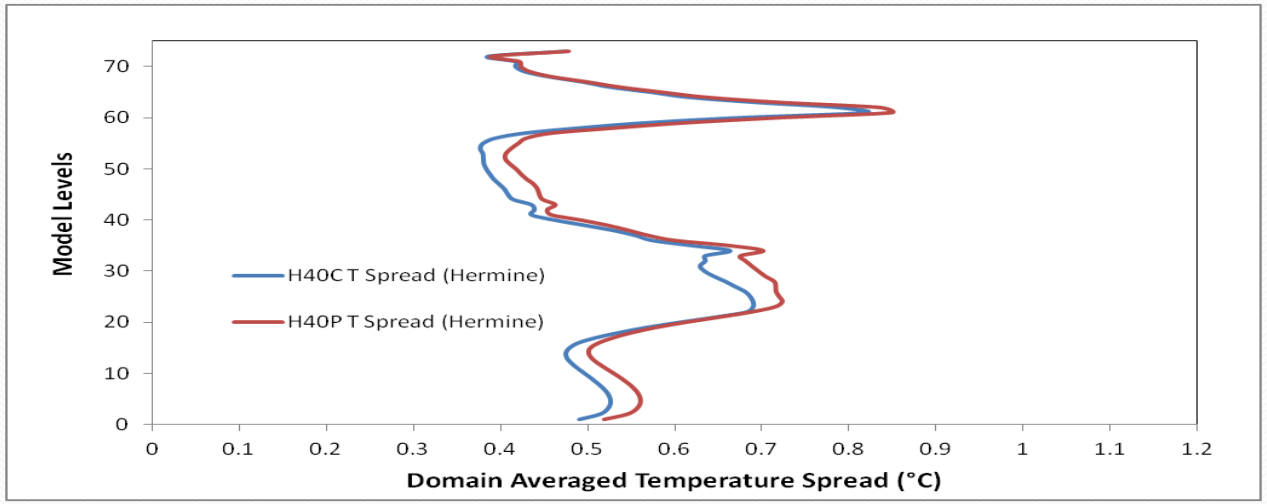
H40C: 6.99 kts
H40P: 6.60 kts

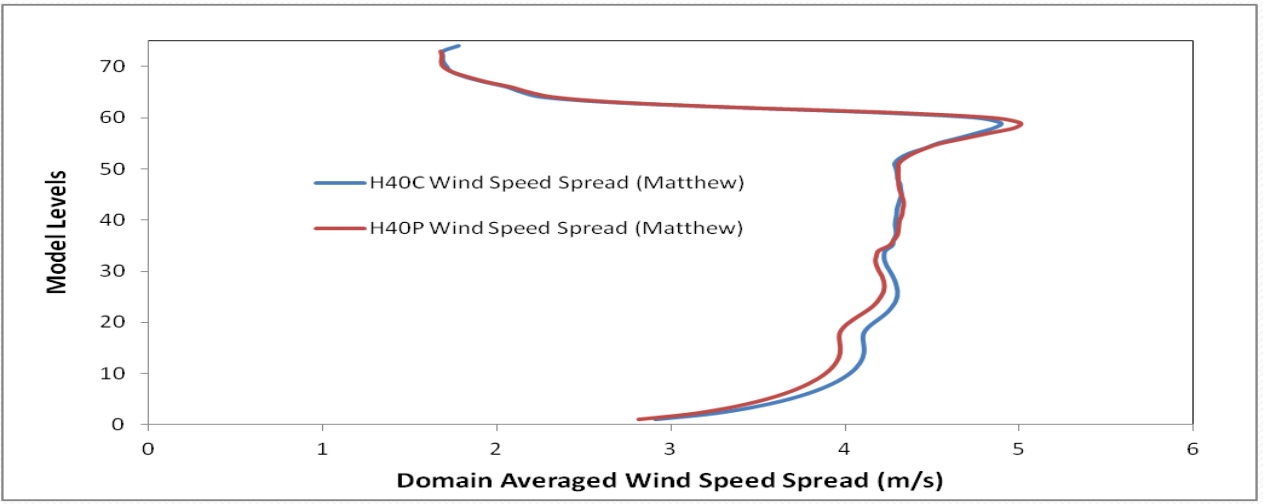


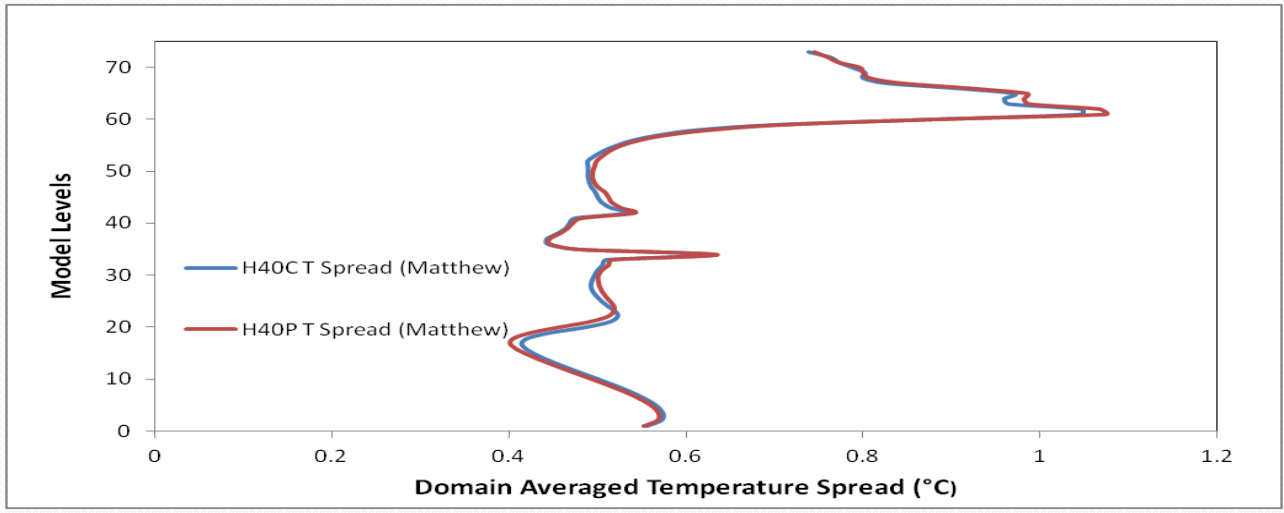
Vertical Profiles of Wind Speed and Temperature Ensemble Spread

(Top: Hermine, 09L top, Bottom: Matthew 14L)







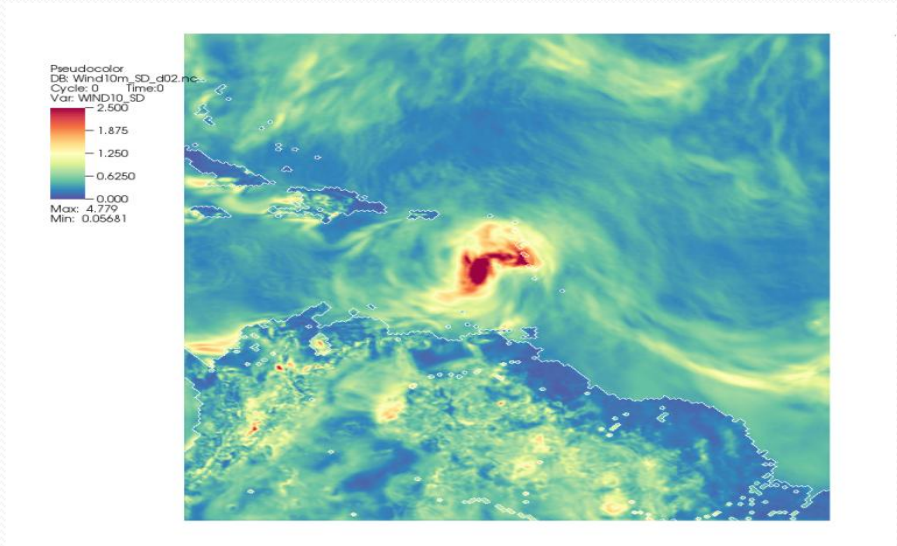


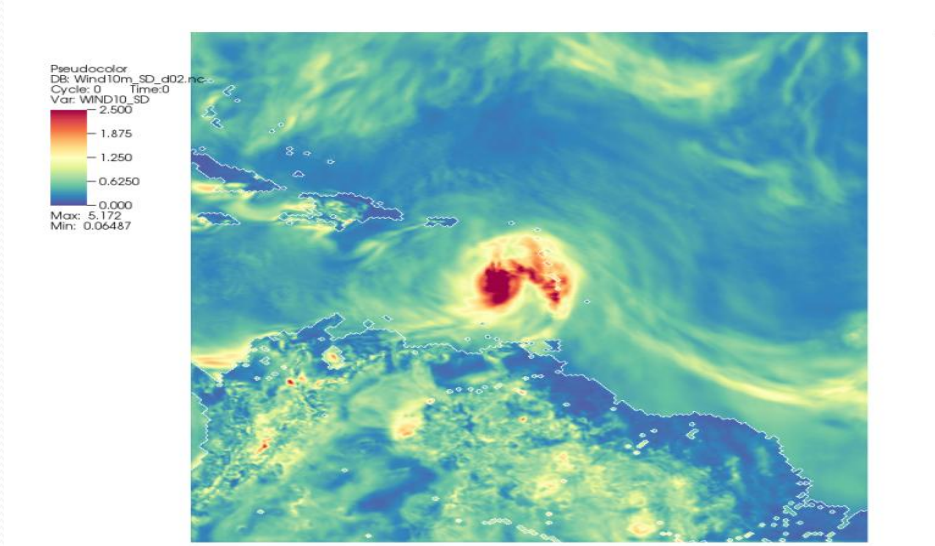
Ensemble Spread of T at 2m and Wind Speed at 10m

H40C

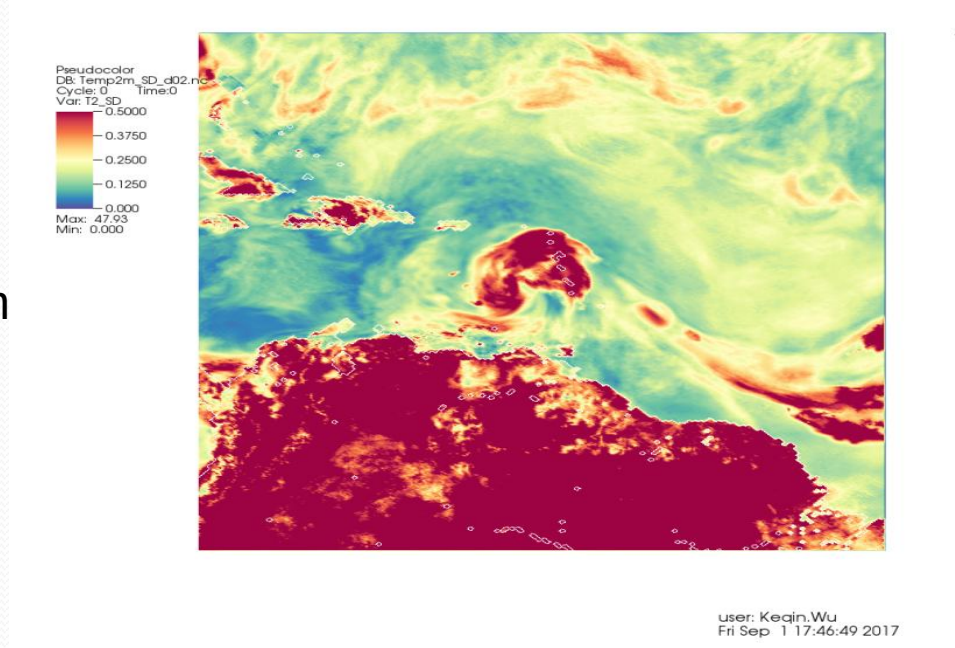
H40P

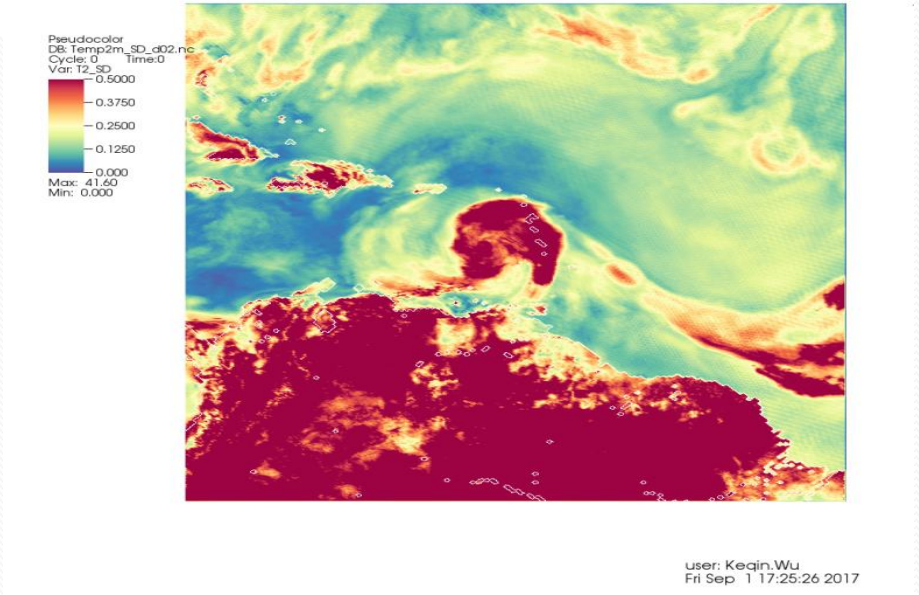
V10m





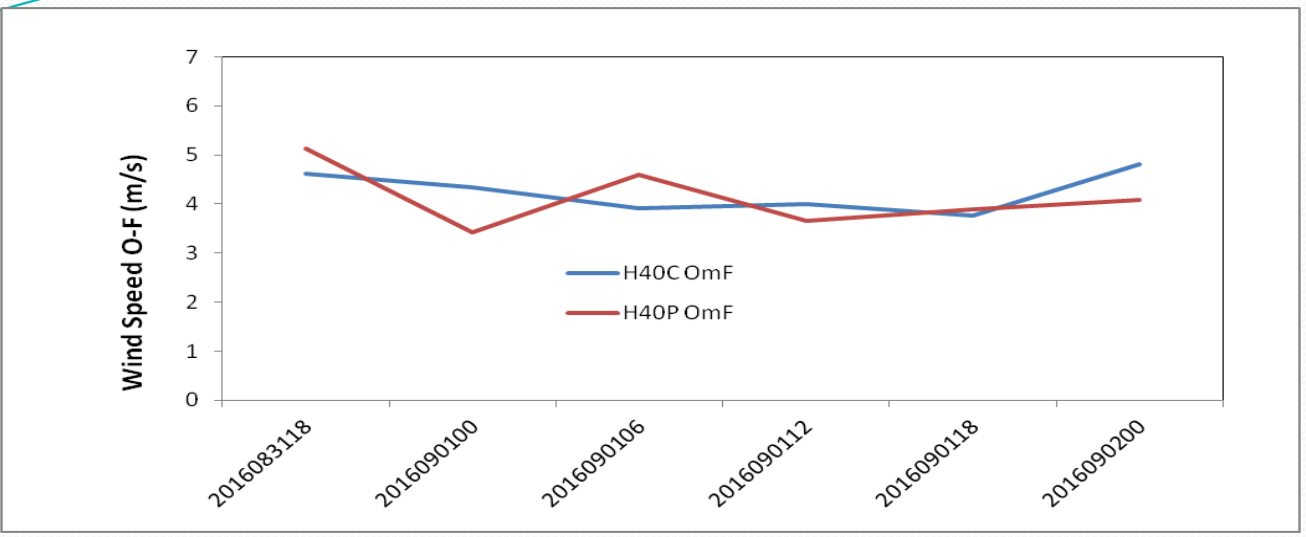
T2m

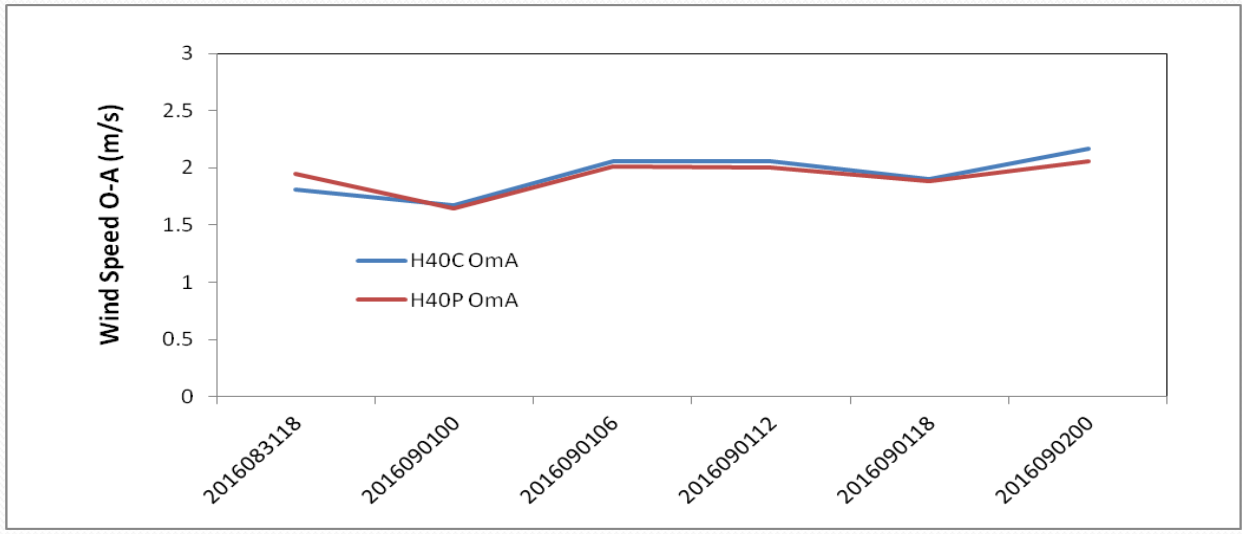


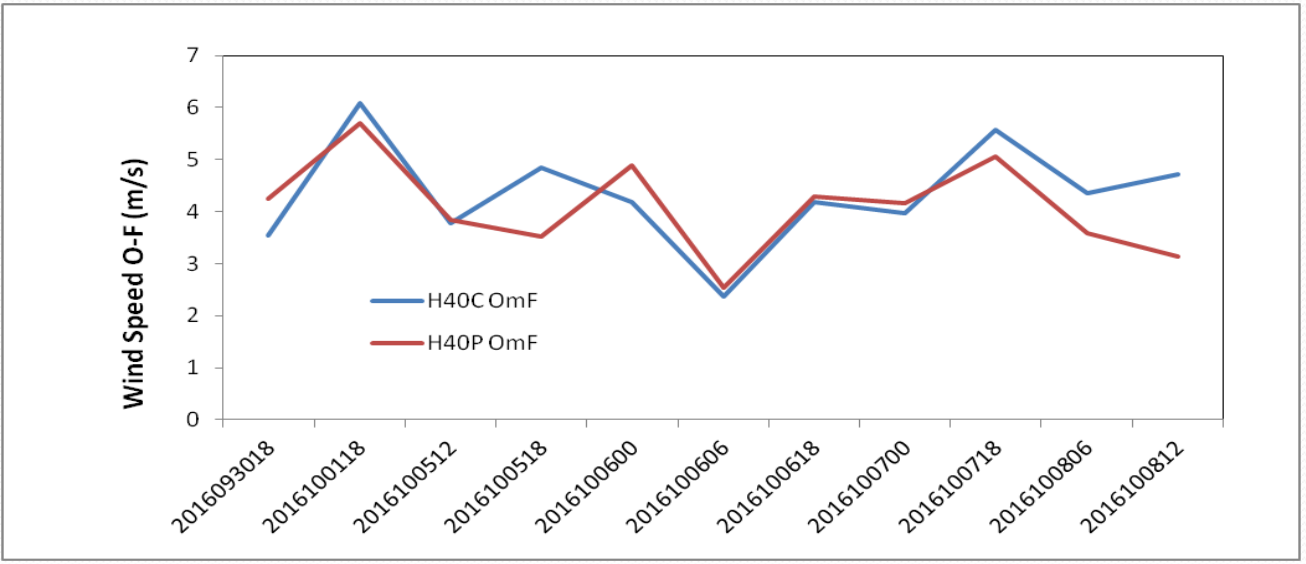


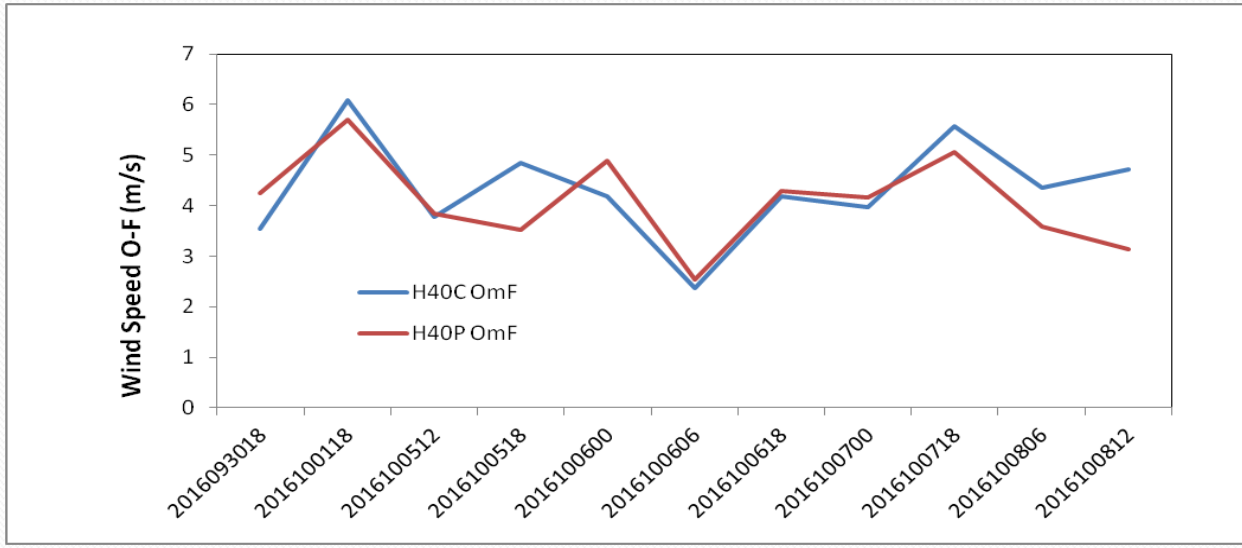
RMS of OmF and OmA (Obs: TDR Radial Wind)

(Top: Hermine, 09L top, Bottom: Matthew 14L)

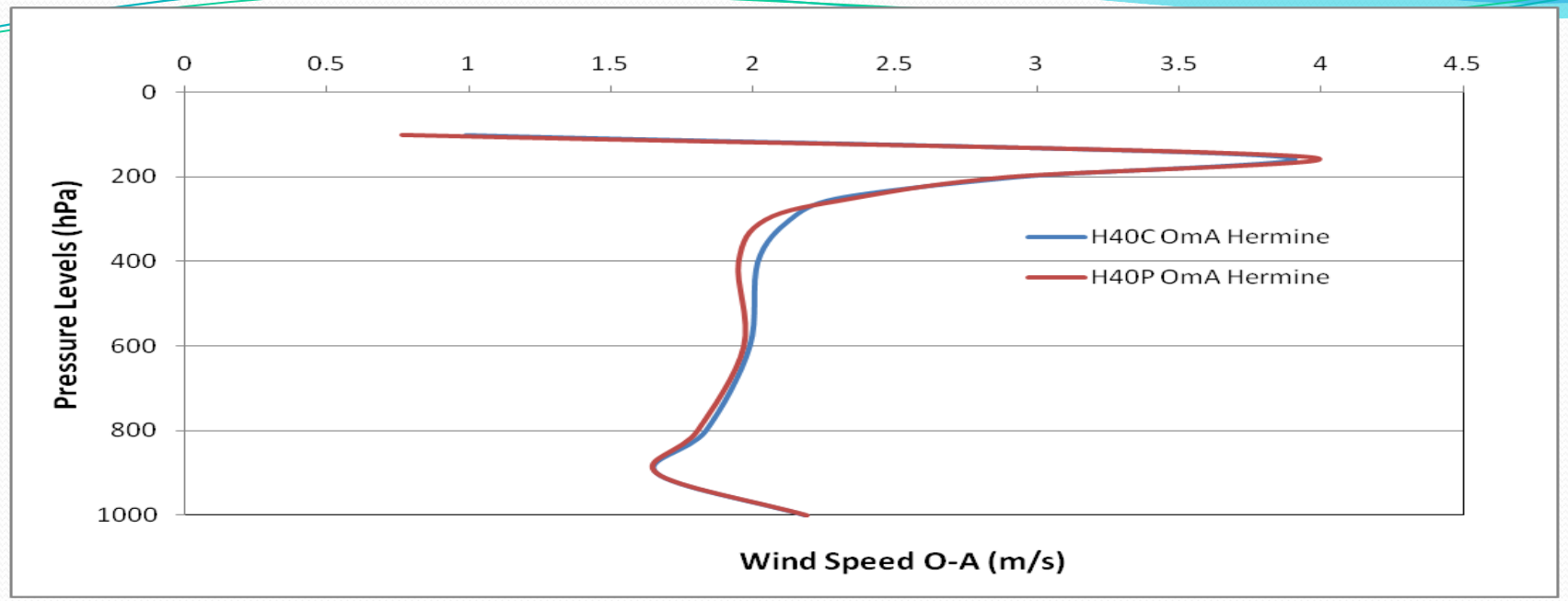


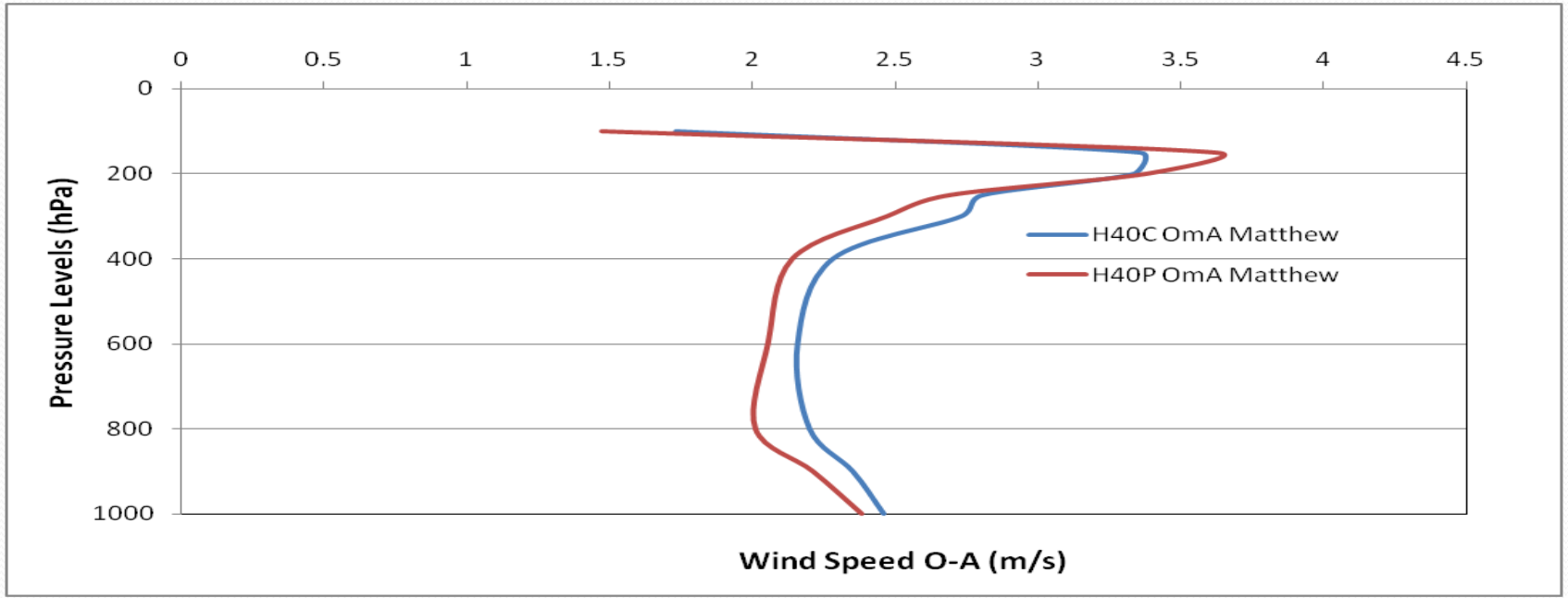




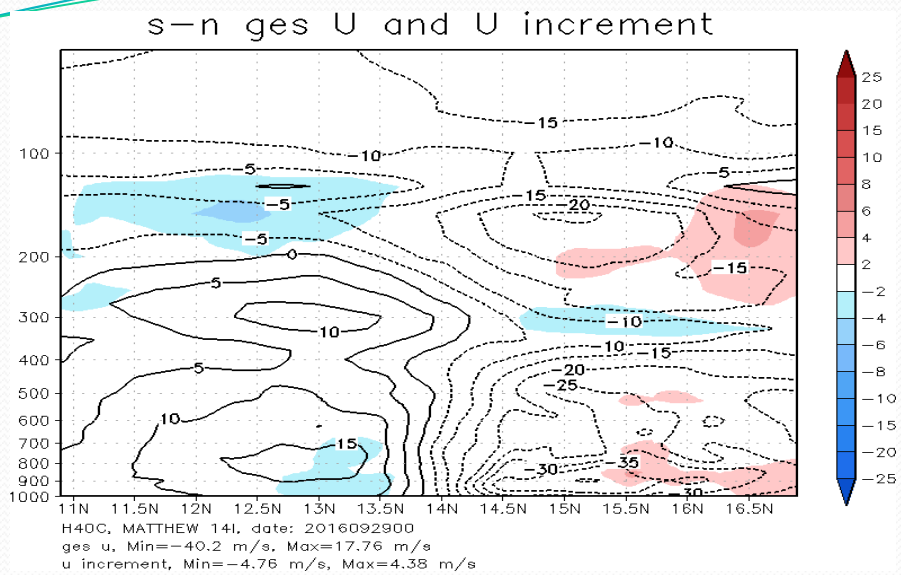


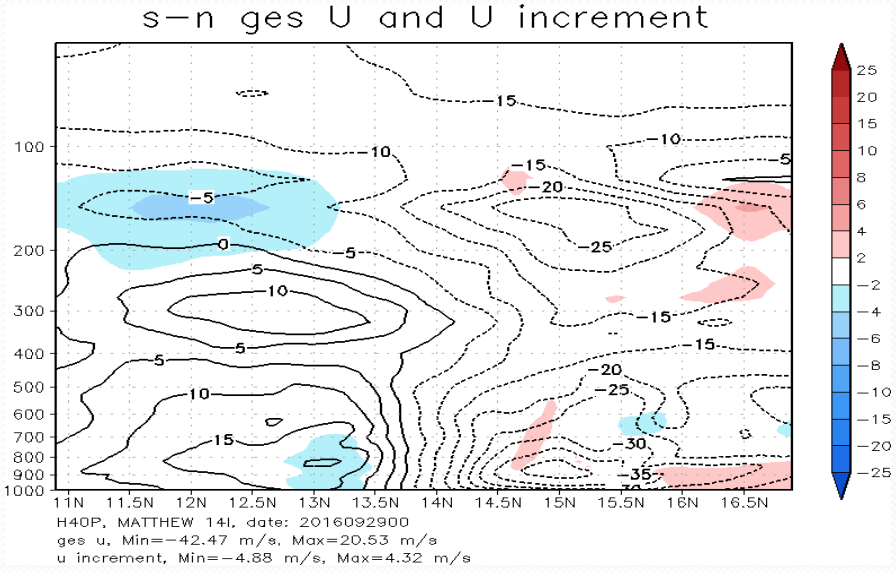
Vertical Profiles of RMS (TDR radial wind Observation-Analysis)



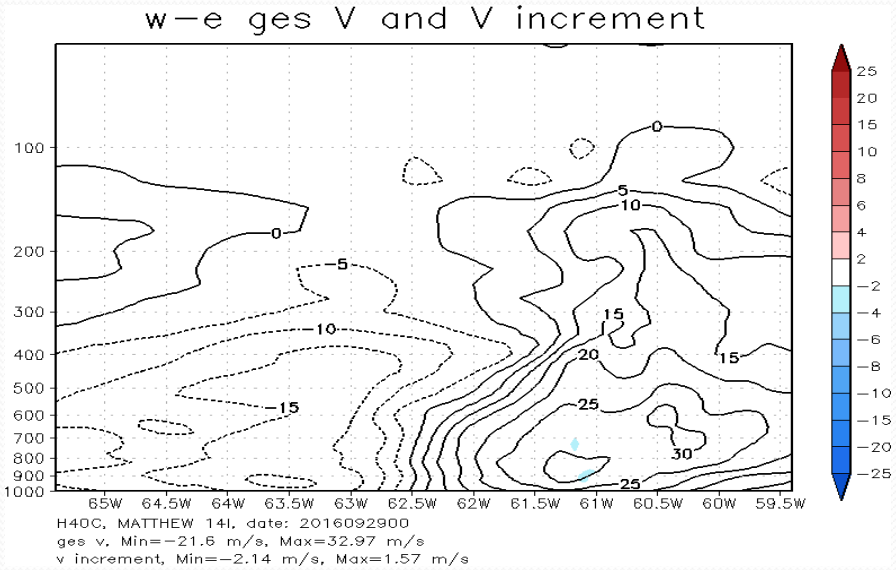


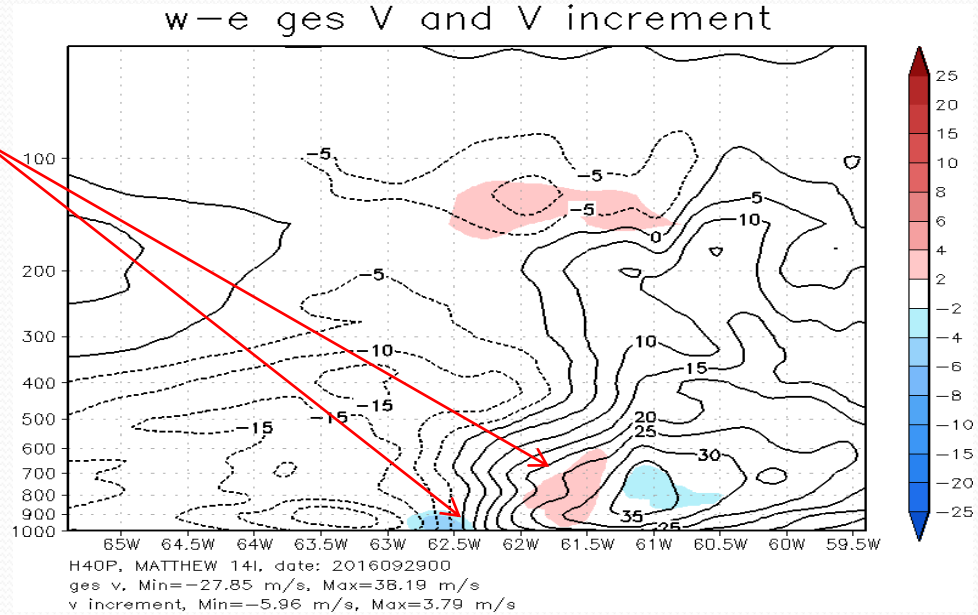
Comparison of DA Increment, H40C vs H40P



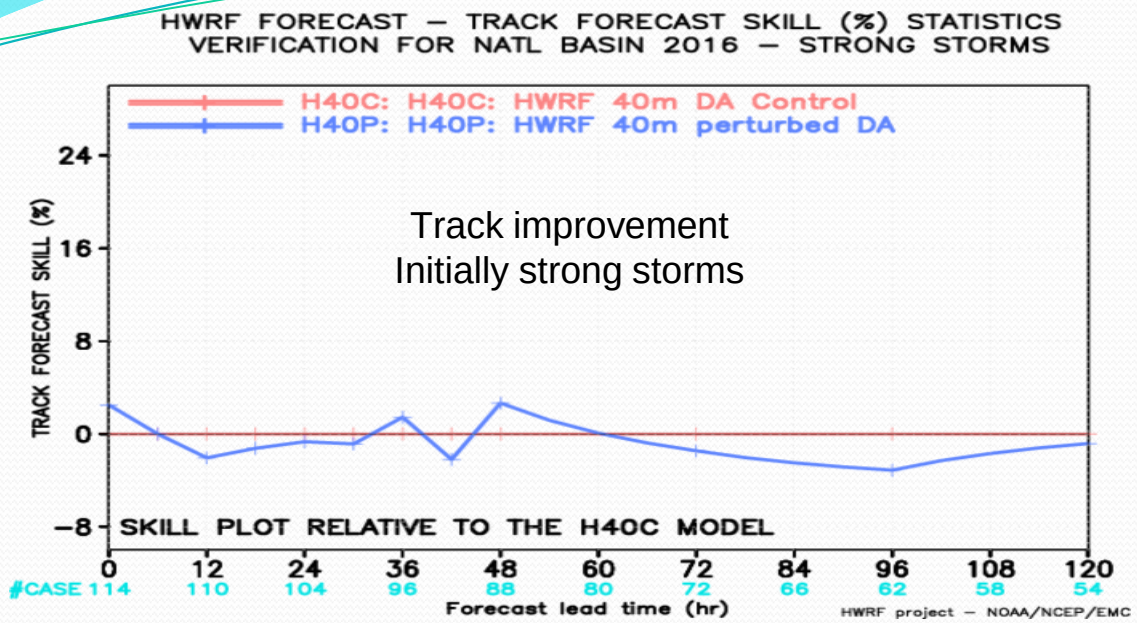


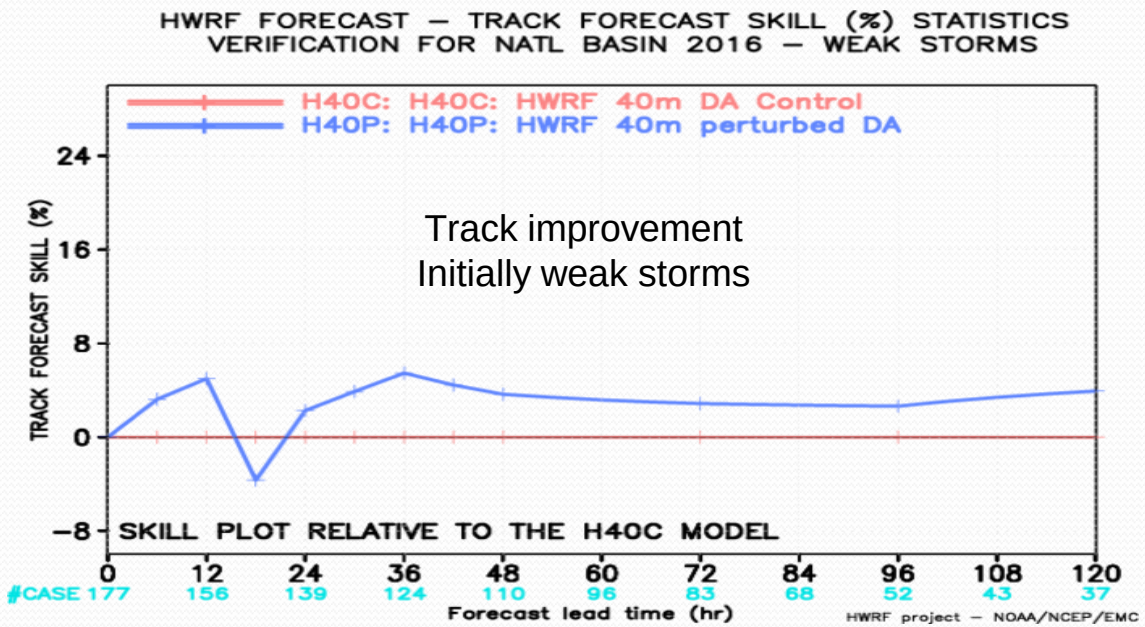
More DA increments stochastic experiment

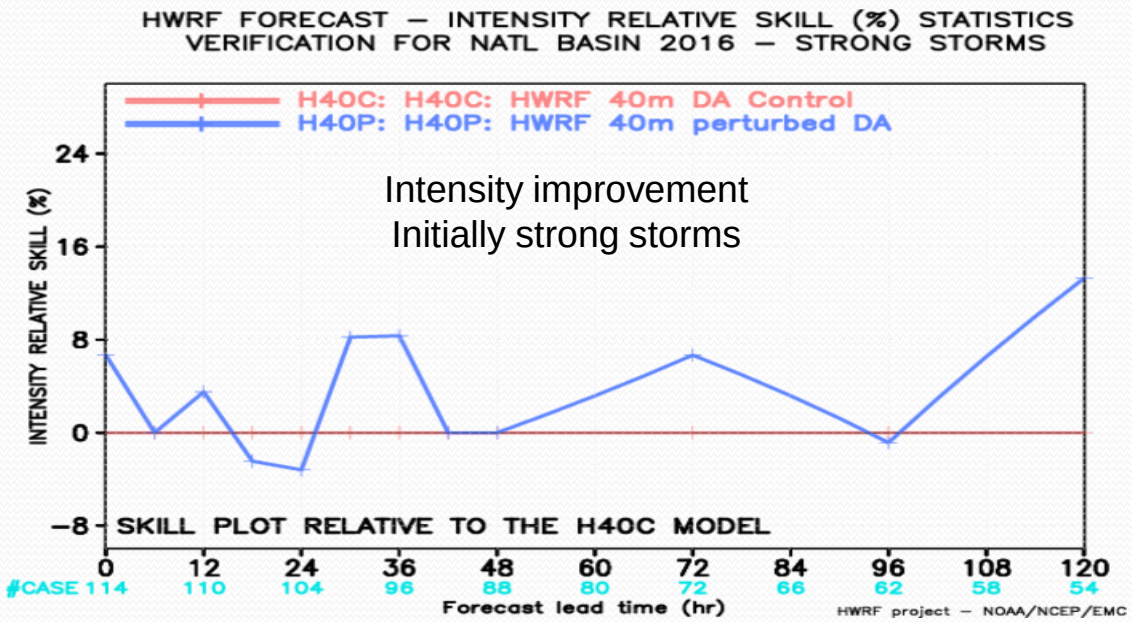


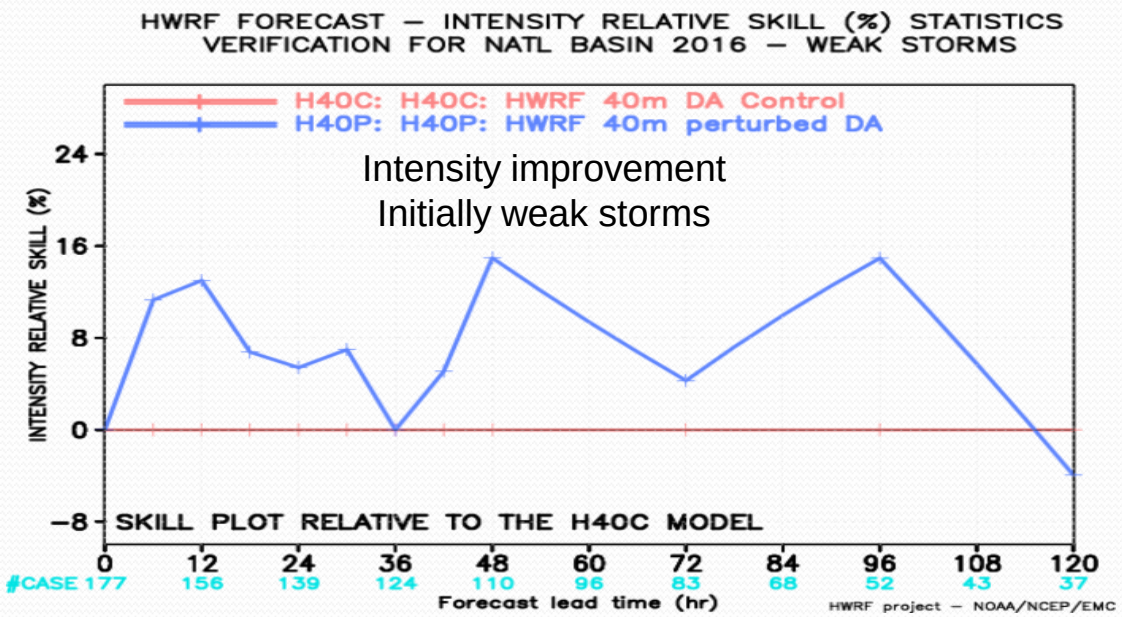


Track/Intensity Verification Comparison (H40C vs H40P)

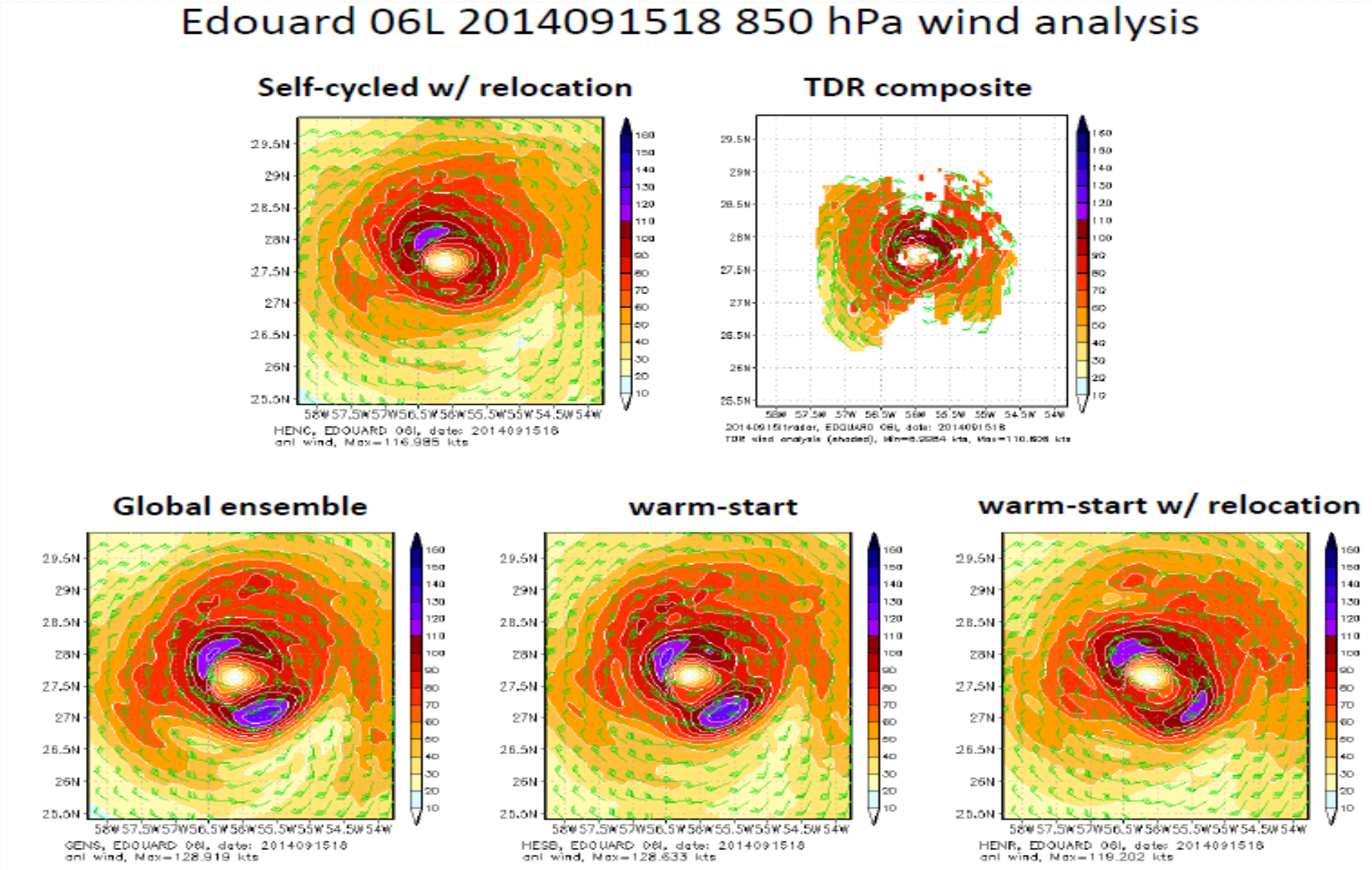








Impact of different hybrid methods



Use of observations

	Conventional data	Satellite data	Aircraft Reconnaissance observations
Current	radiosondes; aircraft reports (AIREP/PIREP, RECCO , MDCRS-ACARS, TAMDAR, AMDAR); surface ship and buoy observations; surface observations over land; pibal winds; wind profilers; radar-derived Velocity Azimuth Display (VAD) wind; WindSat scatterometer winds; and integrated precipitable water derived from the Global Positioning System.	•Radiances from IR instruments: HIRS,AIRS, IASI, GOES Sounders •Radiances from MW instruments: AMSU-A, MHS, ATMS •Satellite derived wind: IR/VIS cloud drift winds, water vapor winds •GPS RO bending angle	Dropwindsondes TDR Flight-level
Future	ground-based radar data	New instruments (GOES-16, JPSS .....) Cloudy radiance	SFMR, G-IV radar, G-V radar, UAS

Challenges in Hurricane Modeling

Scale-Aware model physics

Model physics depends on sub-grid processes, as hurricane model resolution increases, scale awareness of convective and boundary layer parameterizations become extremely important to address grey zone issues (grid point vs. sub-grid point processes,) with convection and boundary layer clouds and shallow convection

Scale-aware SAS

- Old scheme usually assumes updraft area << grid size.
- For the grid sizes of 500m ~ 10 km, in which strong updrafts are partially resolved, a scale-aware parameterization is necessary so that SAS effect is reduced when condensation processes can be partially resolved by dynamics and microphysics scheme

$$m_b' = \underbrace{(1-\sigma_u)^2}_{\text{Scale factor}} m_b \qquad \sigma_u = \frac{\pi R_{conv}^2}{A_{grid}}$$

σ_u: updraft area fraction (0~1.0)

m_b : original cloud base mass flux from AS quasi-equilibrium closure

m_b' : updated cloud base mass flux with a finite σ_u

A_{grid} : grid cell area

$\boldsymbol{R}_{conv}$: updraft radius, 0.2/$\boldsymbol{\varepsilon}$. ε : the updraft entrainment rate.

Modified parameterization of updraft fraction (σ_u) for scale-aware SAS

1) Arakawa & Wu, 2013:

$$\lambda(1-\sigma_u)^3 - \sigma_u = 0 \qquad \lambda = \frac{(\overline{w'h'})_E}{\delta w \delta h}$$

Use of vertical velocities at the cloud base

$$\delta w = w_u - \overline{w}, \quad \delta h = h_u - \overline{h}$$

$$\rho w_u = a_1 M_b \qquad a_1 = 0.1$$

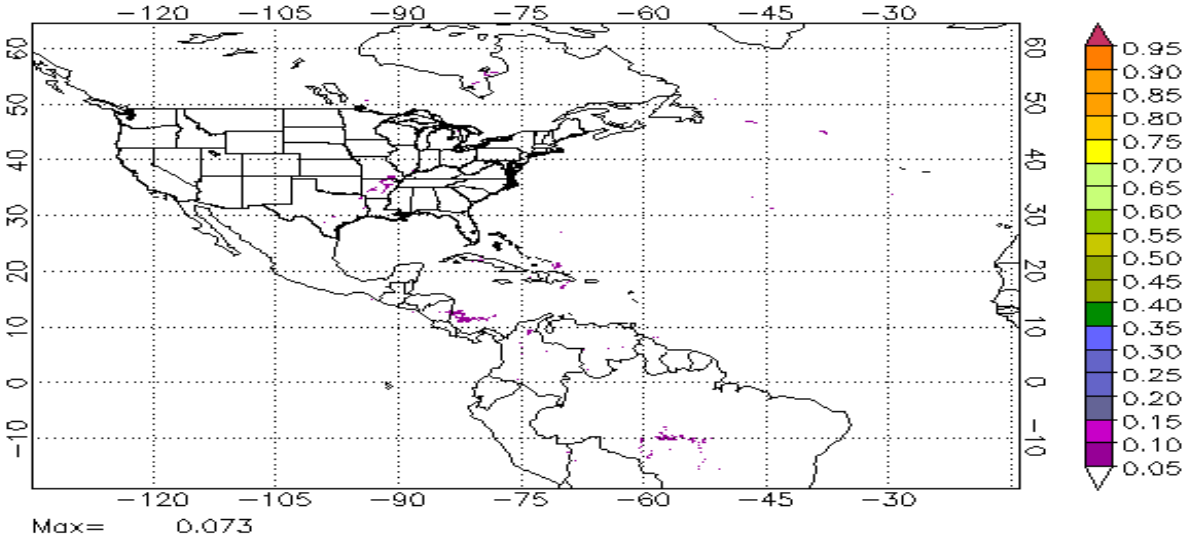
2) Grell & Freitas (2014):

$$\sigma = \frac{\pi R^2}{A_{grid\ cell}}, \; R_{conv} = \frac{0.2}{\varepsilon}, \; \varepsilon = 7 \times 10^{-5}$$

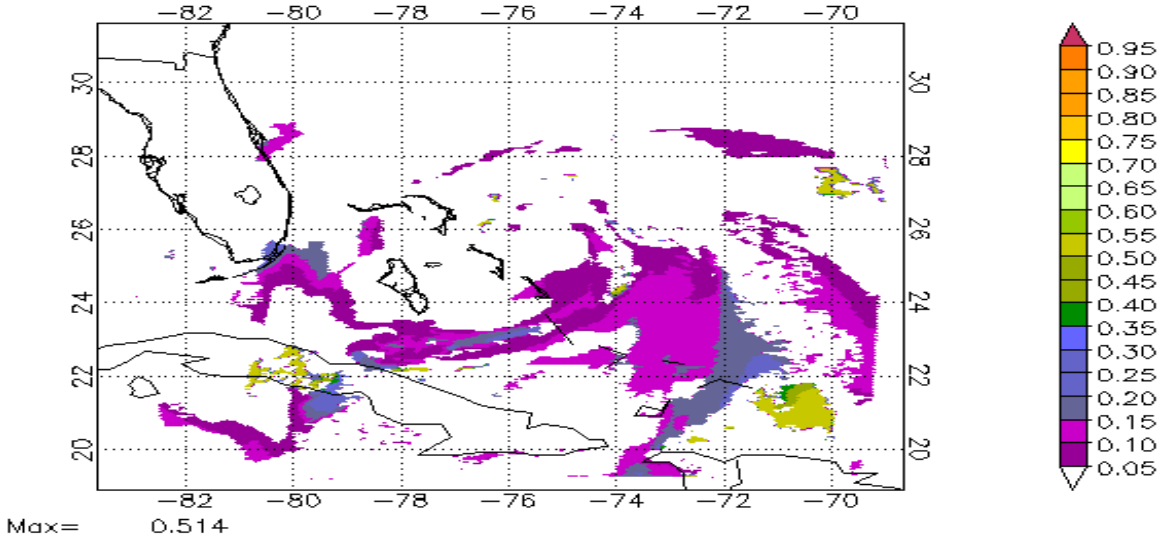
3) Modified Grell & Freitas:

Actual entrainment rate at the cloud base is used to compute the cumulus radius rather than the constant value

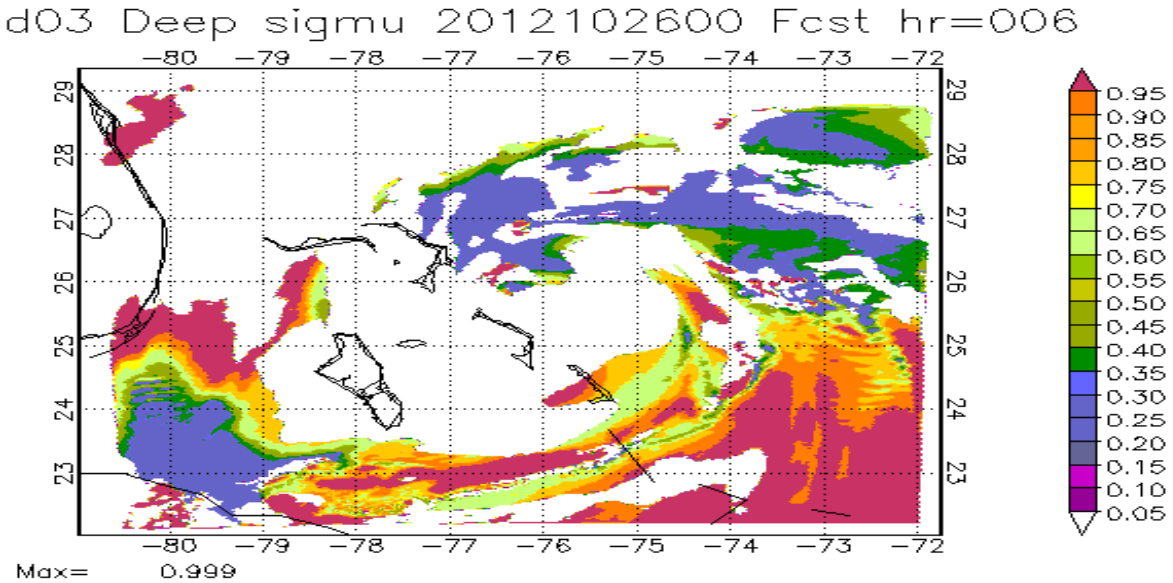
18-km domain



6-km domain



2-km domain



Example of Updraft Fractional Area

- fractional area is larger for smaller grid spacing

Challenges in Hurricane Modeling

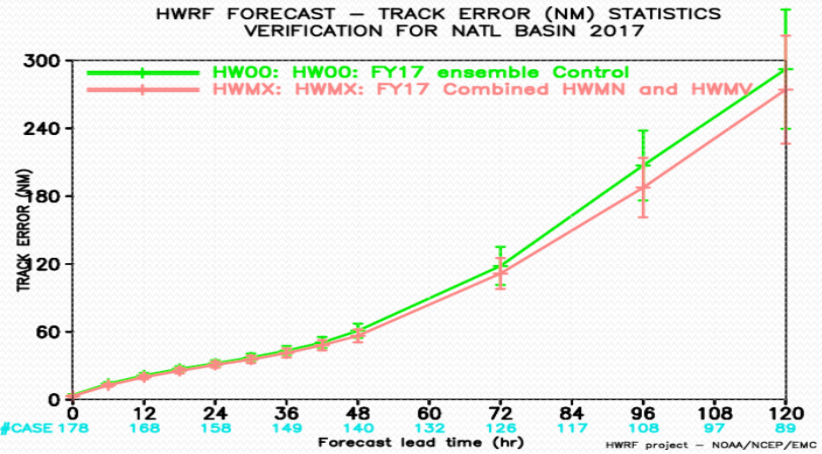
Hurricane ensemble prediction system

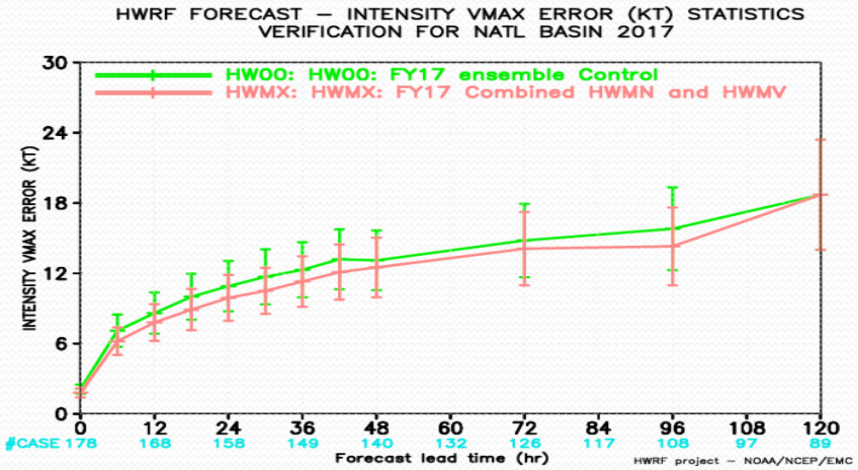
- Better sampling model uncertainty
  - Initial uncertainty vs. model physics uncertainty
  - Single model vs. multi-model ensemble
- Better representing ensemble forecasts
  - Averaged ensemble mean vs. weighted ensemble mean
  - Probabilistic ensemble forecasts

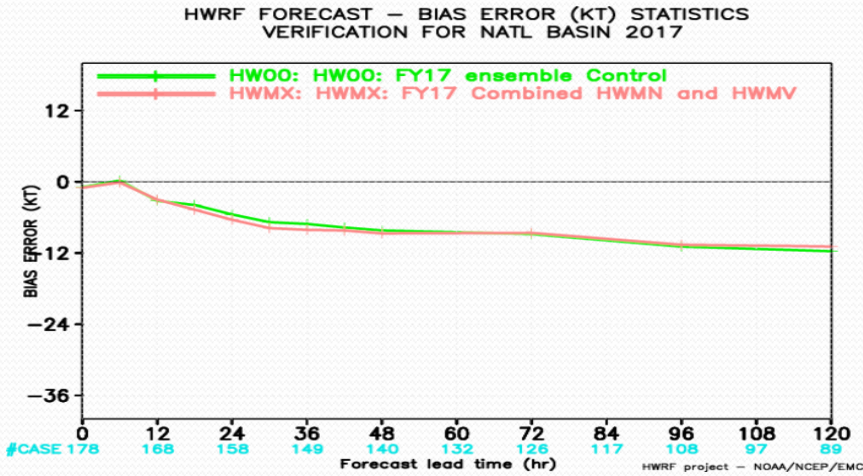
FY2018 HWRF ensemble configuration used in DA

- **Use operational deterministic HWRF model**
- **IC/BC perturbations (large scale): 6h forecast from 40 members of GDAS analysis**
- **Dual-resolution Hybrid Data Assimilation**
- **Model physics perturbation (vortex scale):**
  - Stochastic convective trigger perturbations in SAS: -50 hPa to + 50 hPa white noise;
  - Stochastic boundary layer height perturbations in PBL scheme, -20% to +20%;
  - Stochastic surface drag coefficient Cd perturbations.

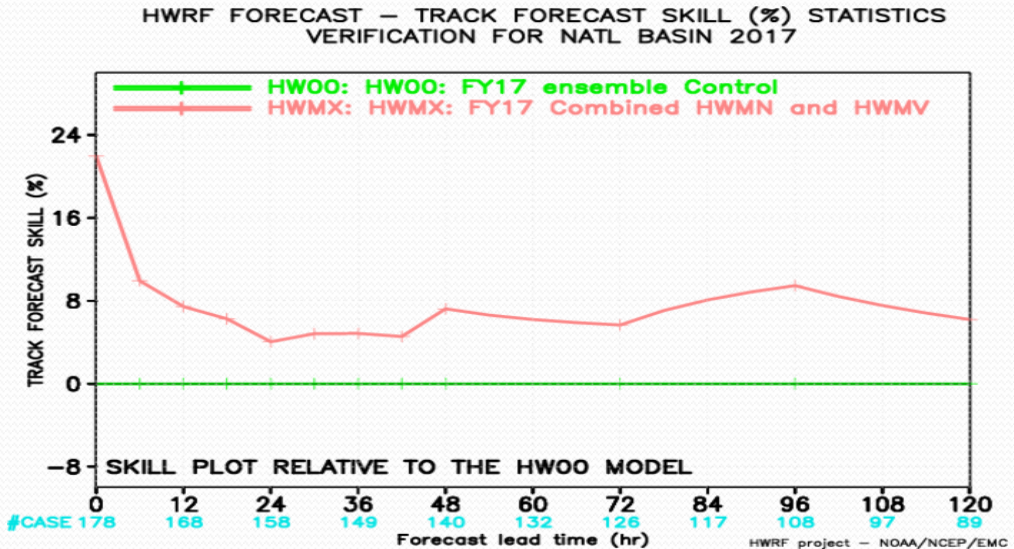
Verification: HWRF-EPS vs Deterministic HWRF
2017 Atlantic Storms

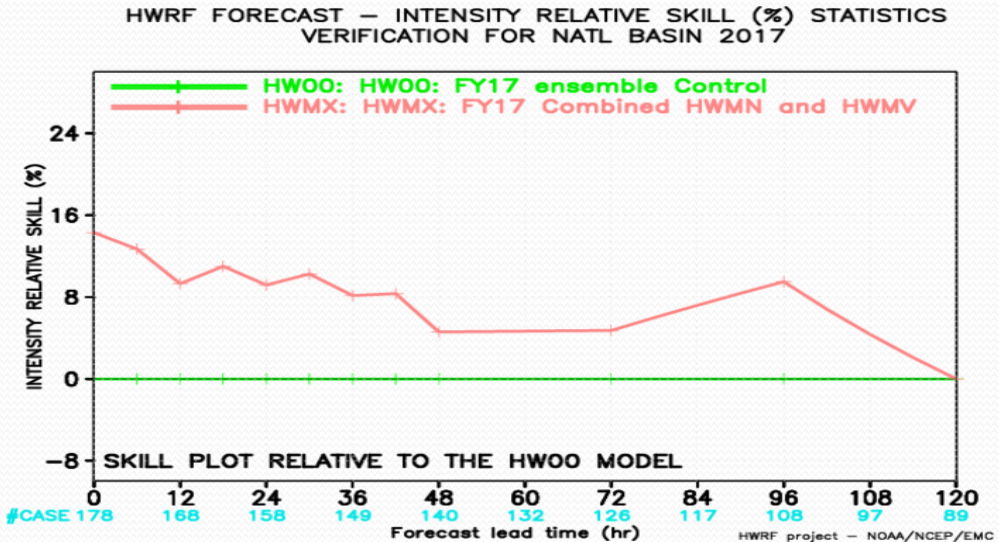






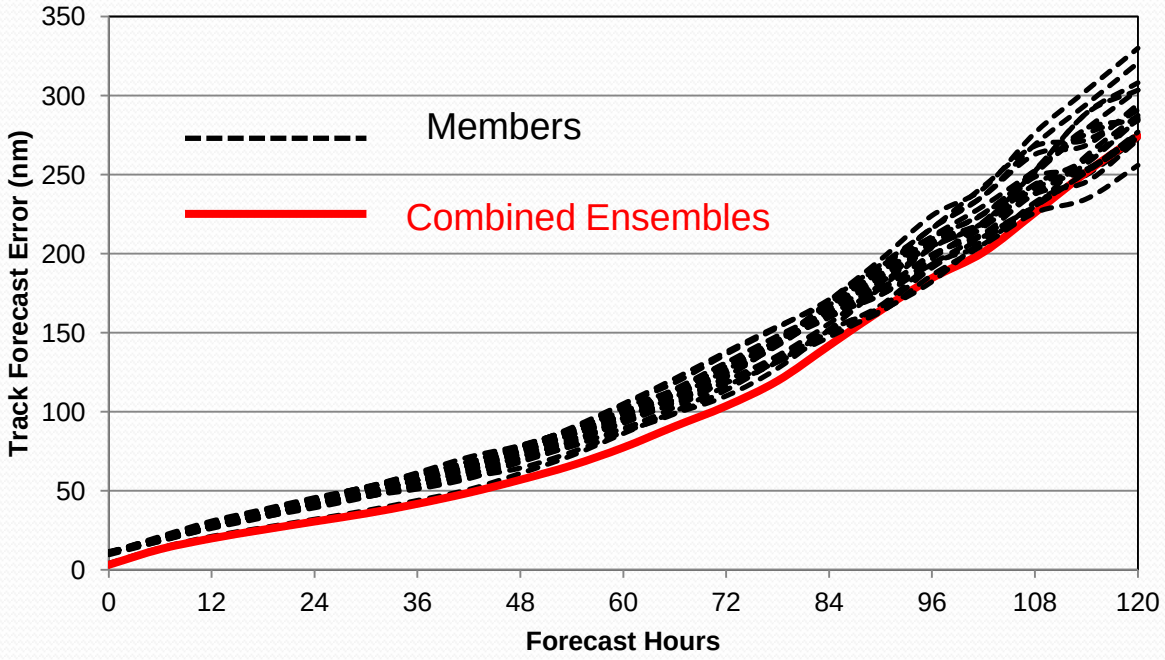
HWRF-EPS provides about 8% track and intensity forecast skill improvements in average over its deterministic system (HW00)



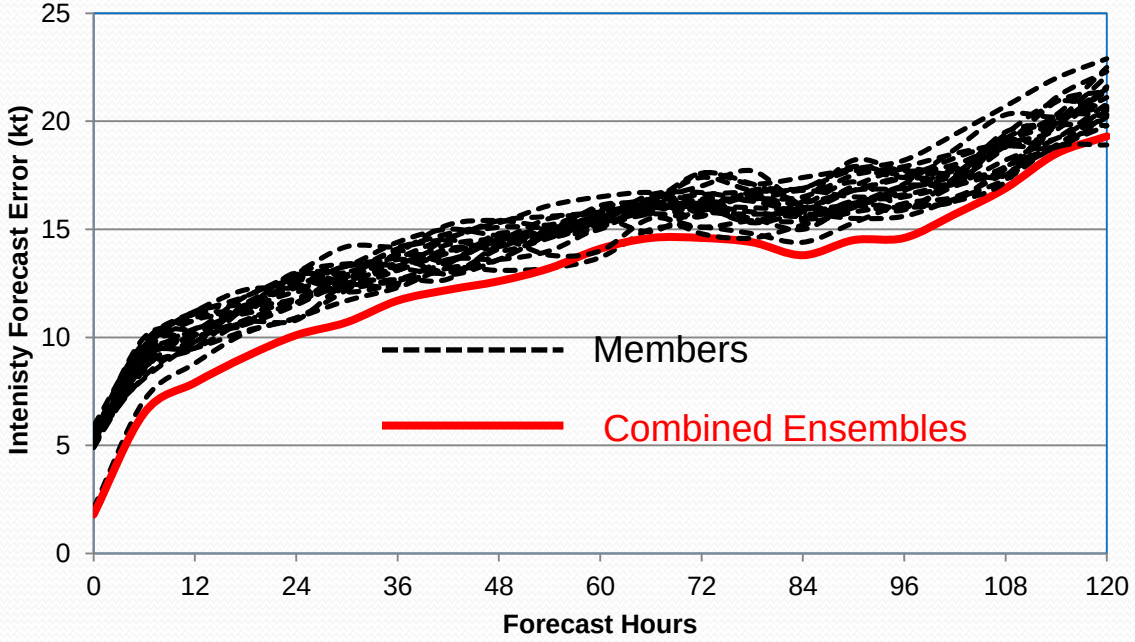


Verification Comparison
Individual ensemble members vs. Combined Ensembles

Track



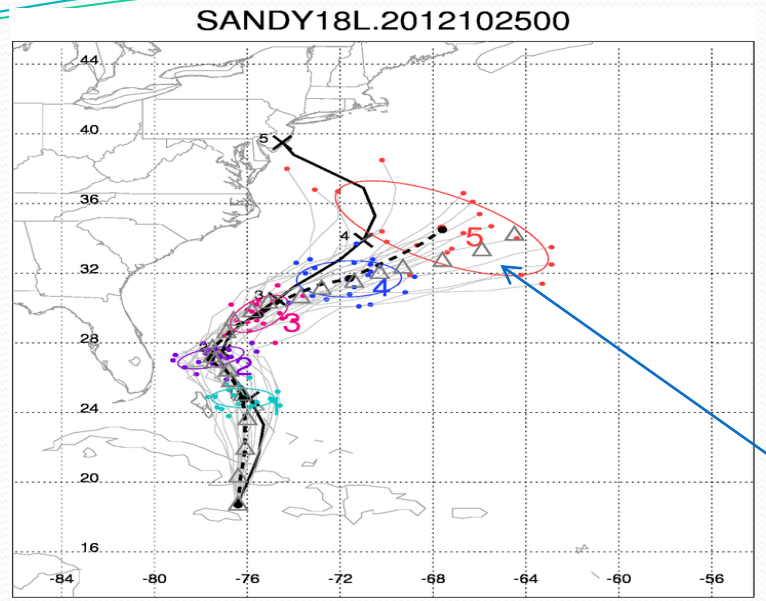
Intensity



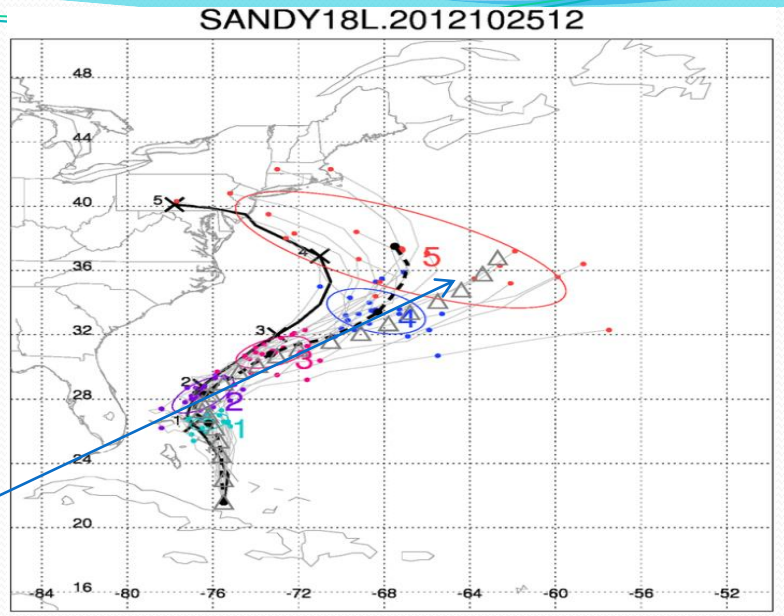
All 2017 Atlantic Storms

Track Probability Forecasts for Hurricane Sandy

Few members turned west

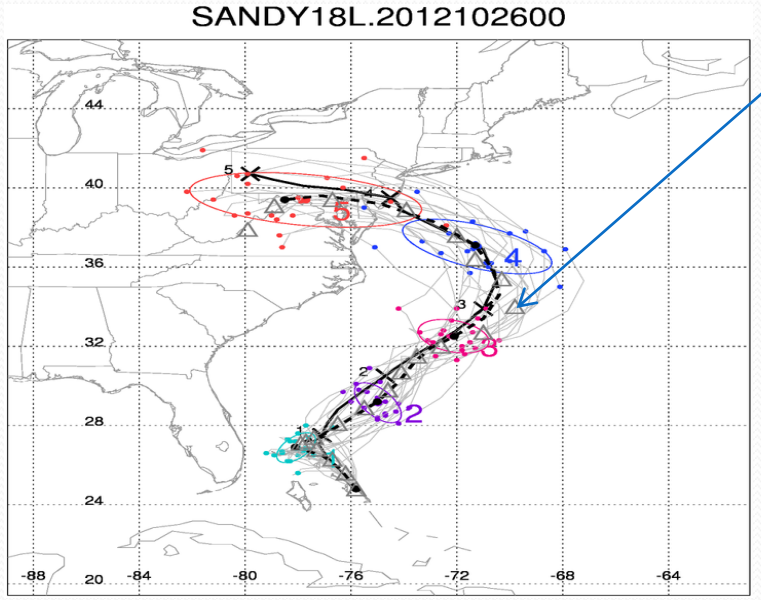


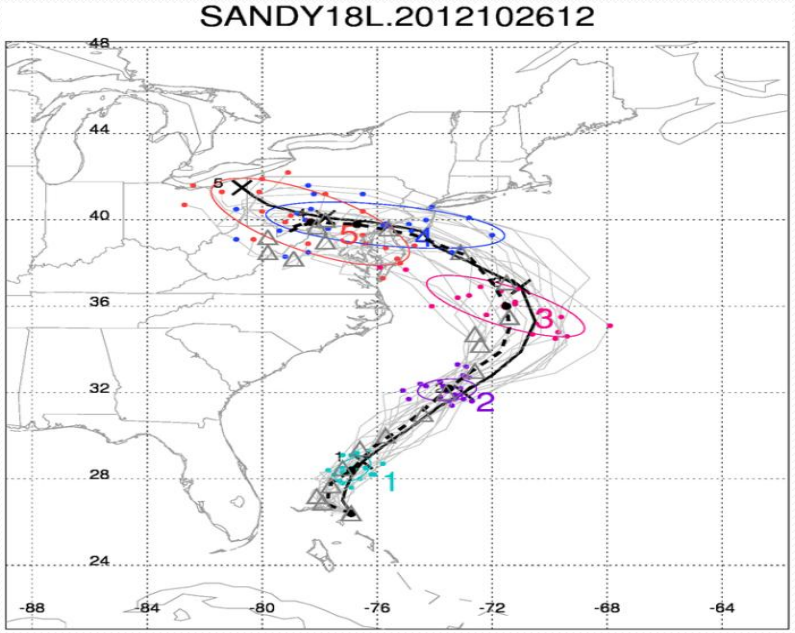
More members turned west



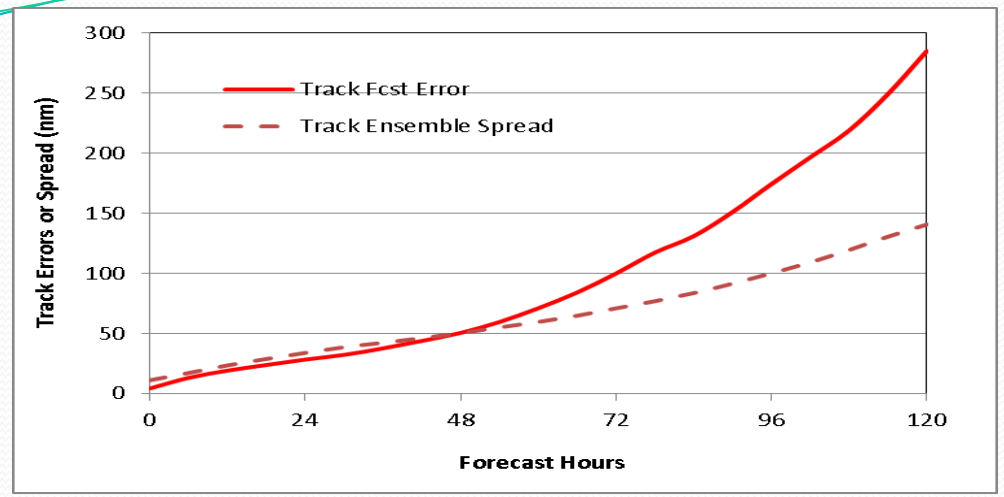
FY13

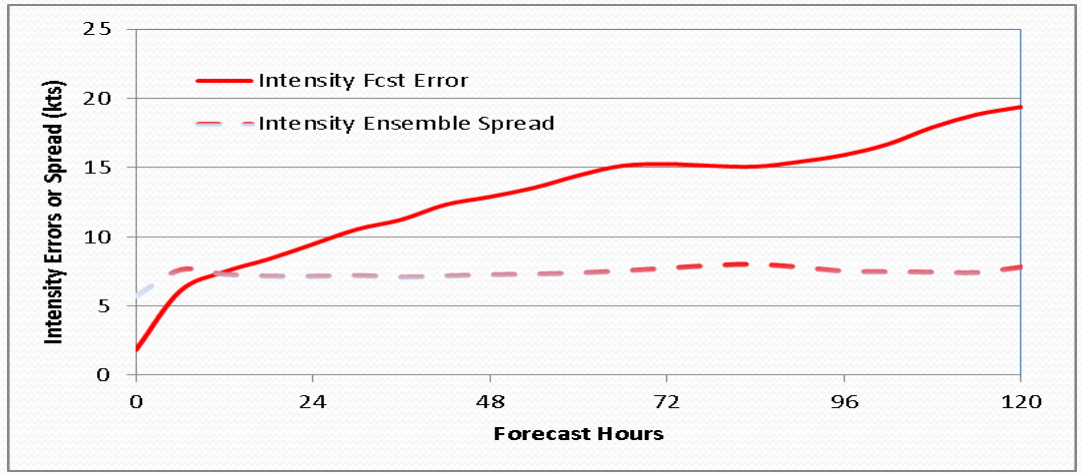
All members turned west



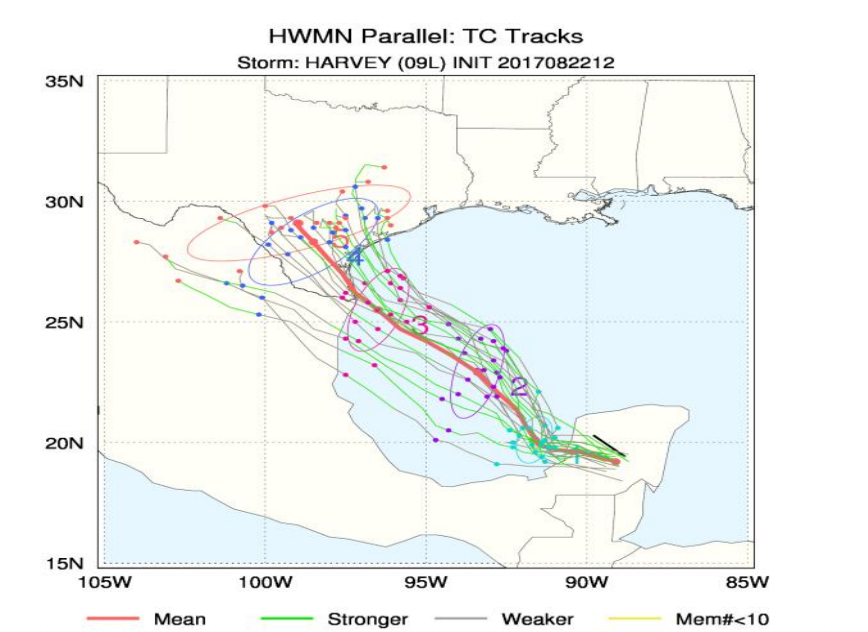


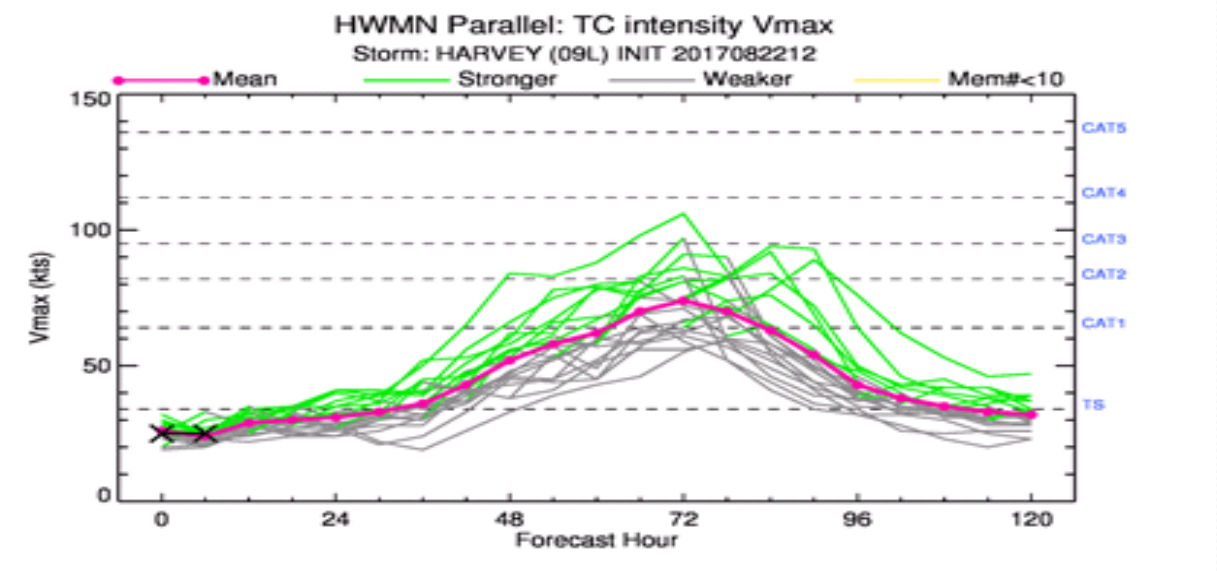
HWRF-EPS Ensemble Spread





HWRF-EPS is under-dispersed in average.



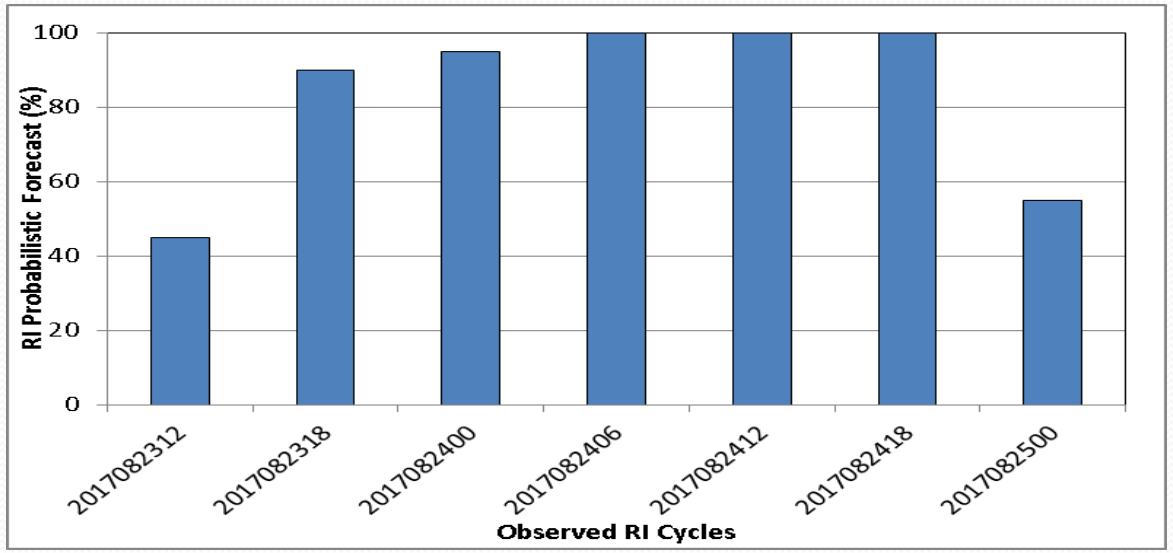


HWRF-EPS Rapid-Intensification Prediction

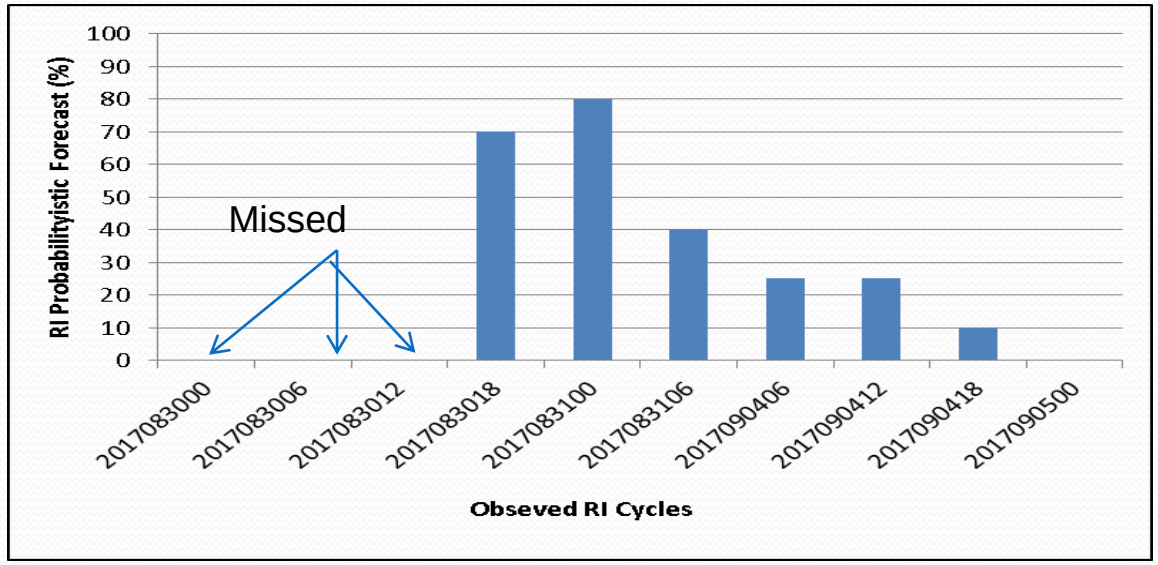
P=RI/ALL

RI: number of ensemble members that predicted storm Rapid Intensification;
All: Total number of ensemble members

Harvey 09L

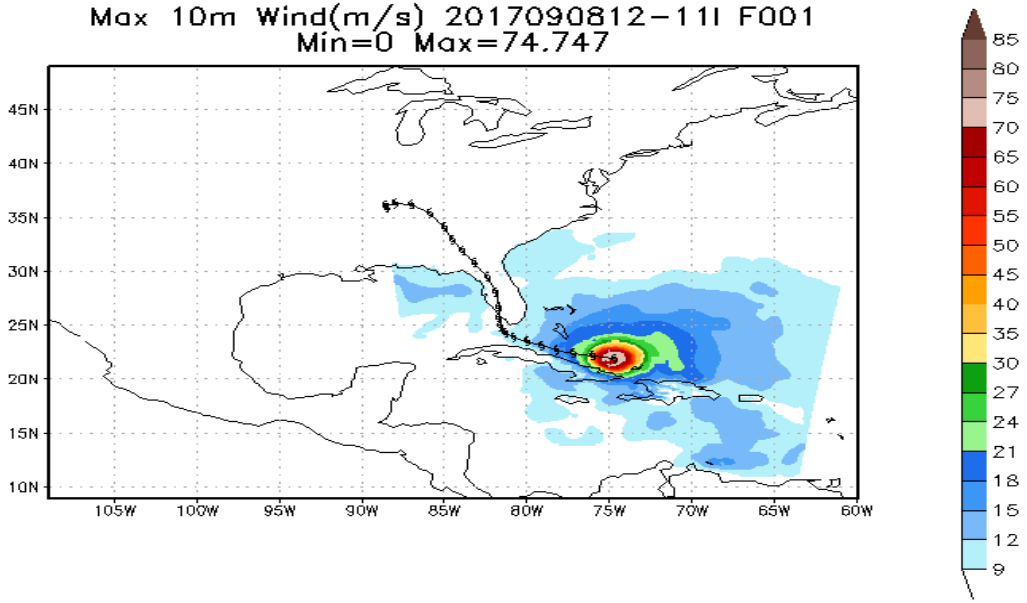


Irma 11L

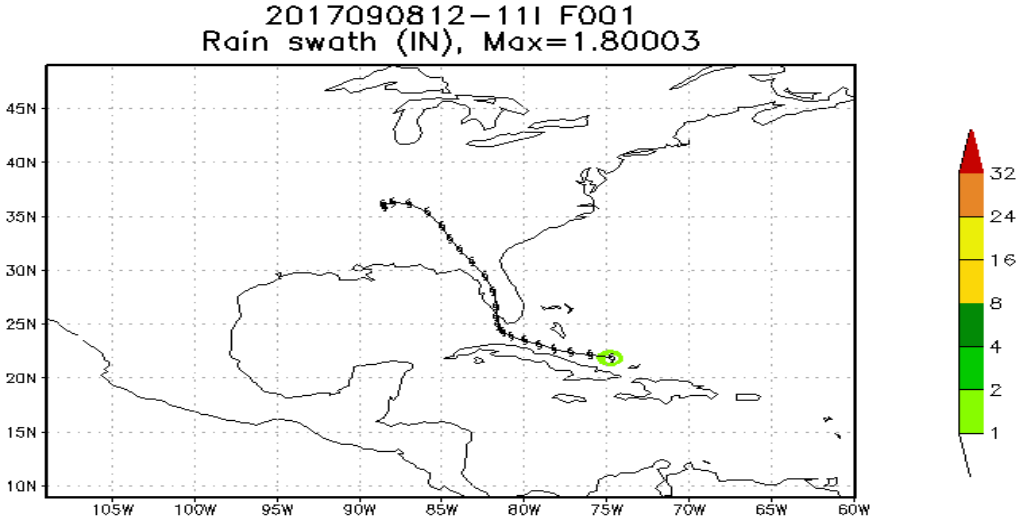


HWRF-EPS Probabilistic Prediction

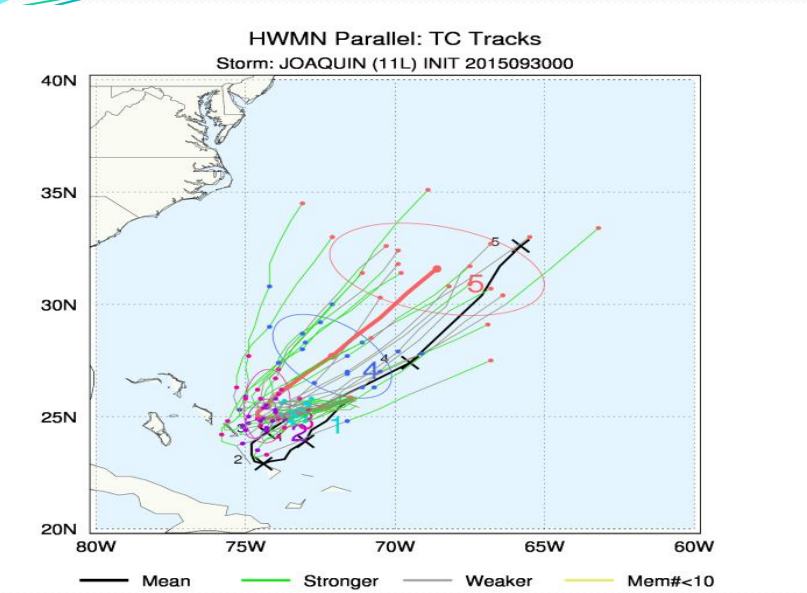
Wind Speed at 10m

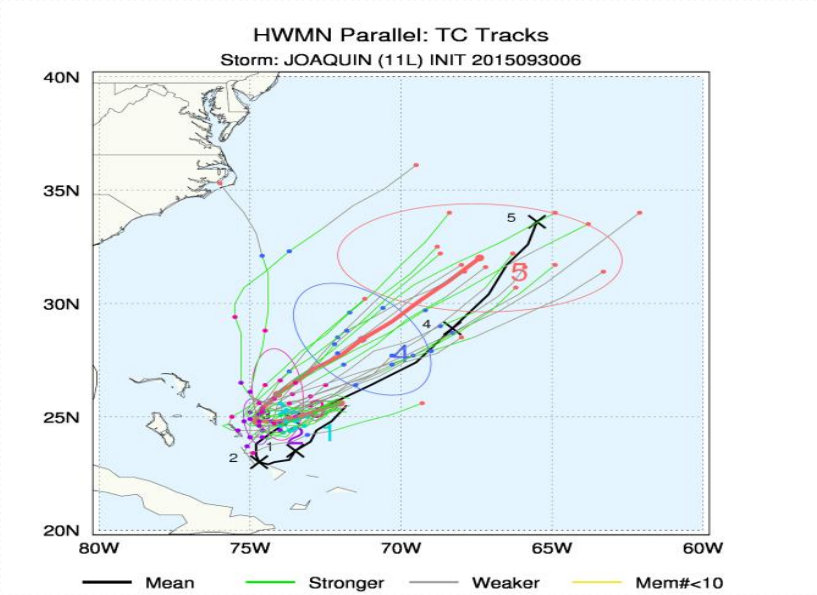


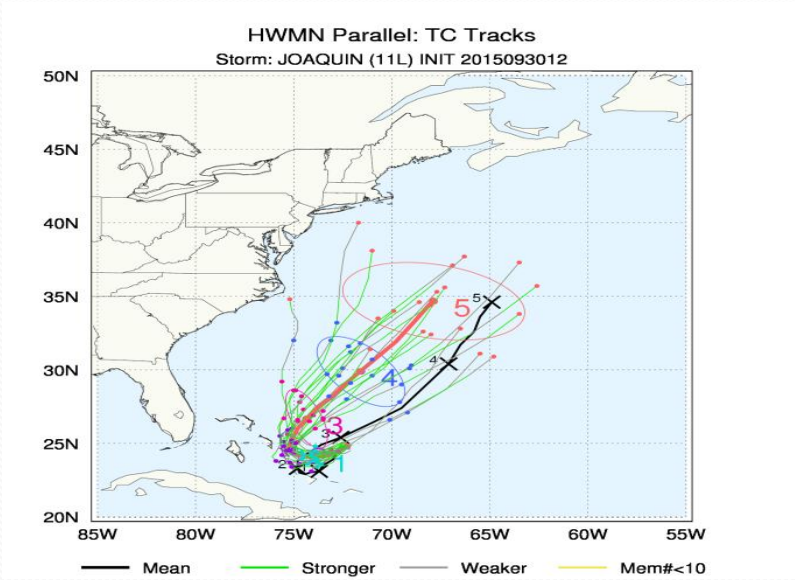
Rainfall Swath

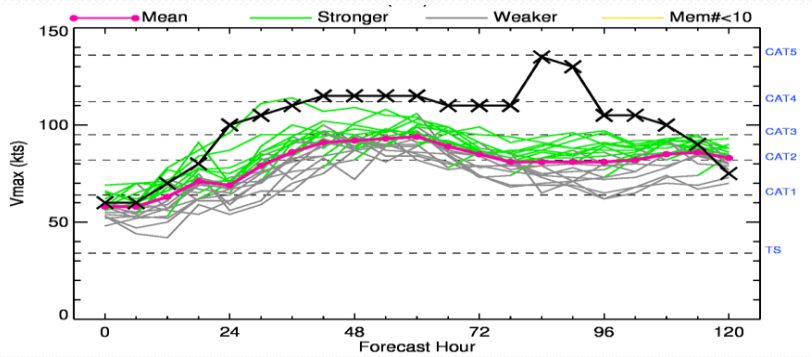


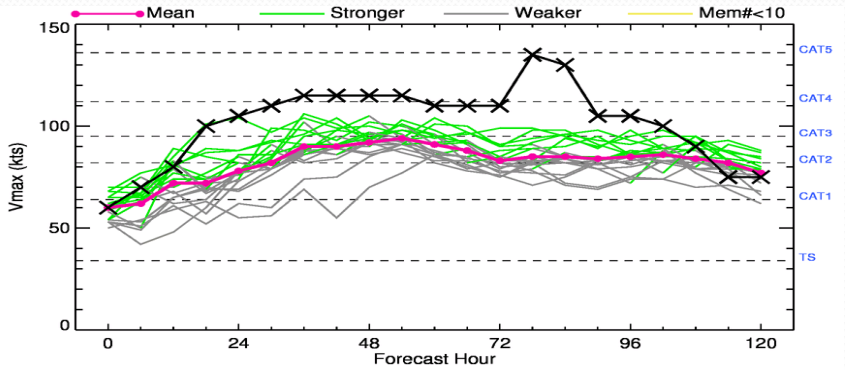
Sample HWRF-EPS Forecast
Joaquin 11L, 20150930

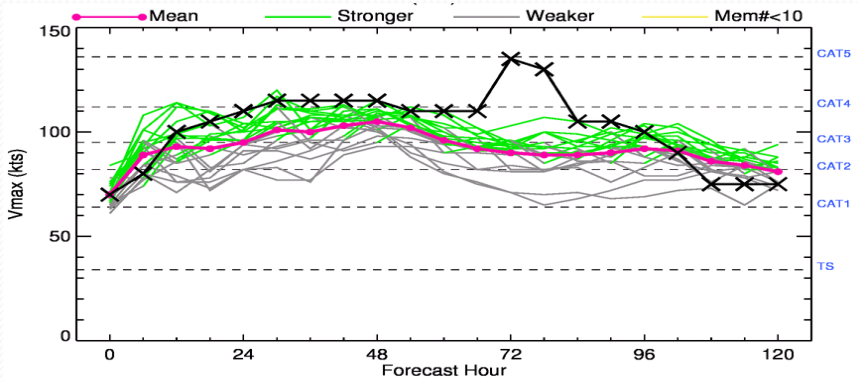






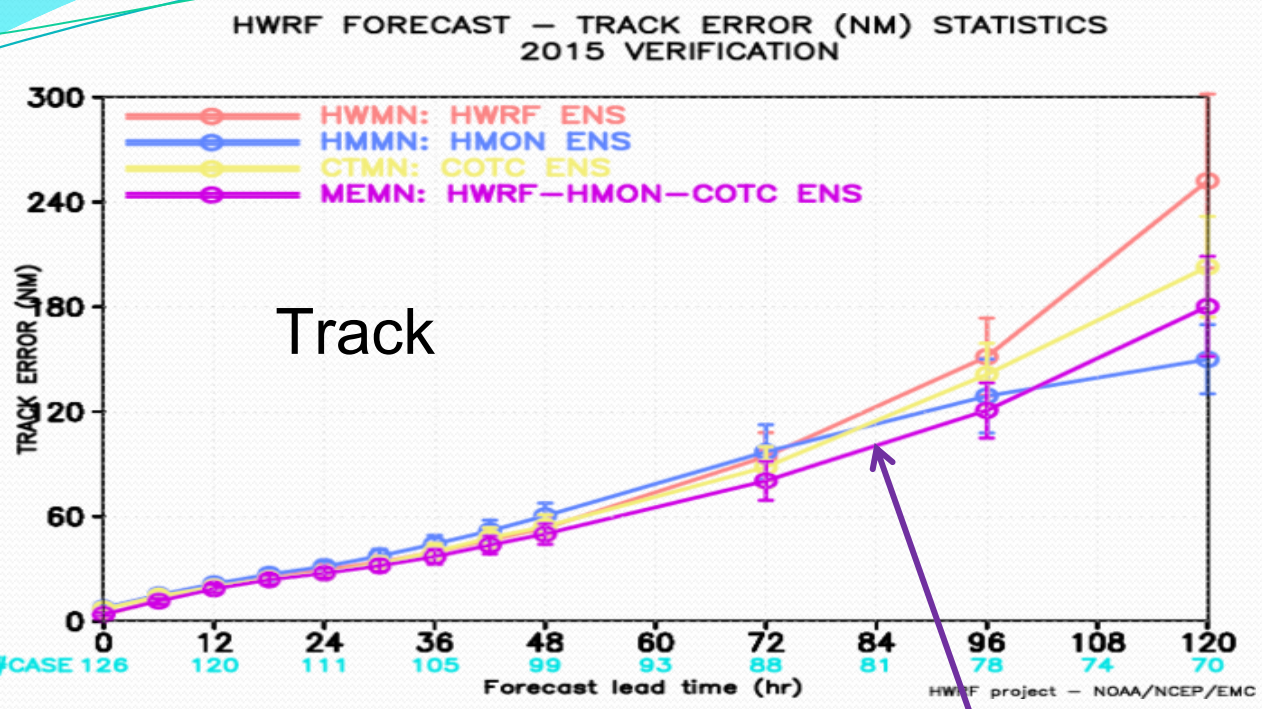


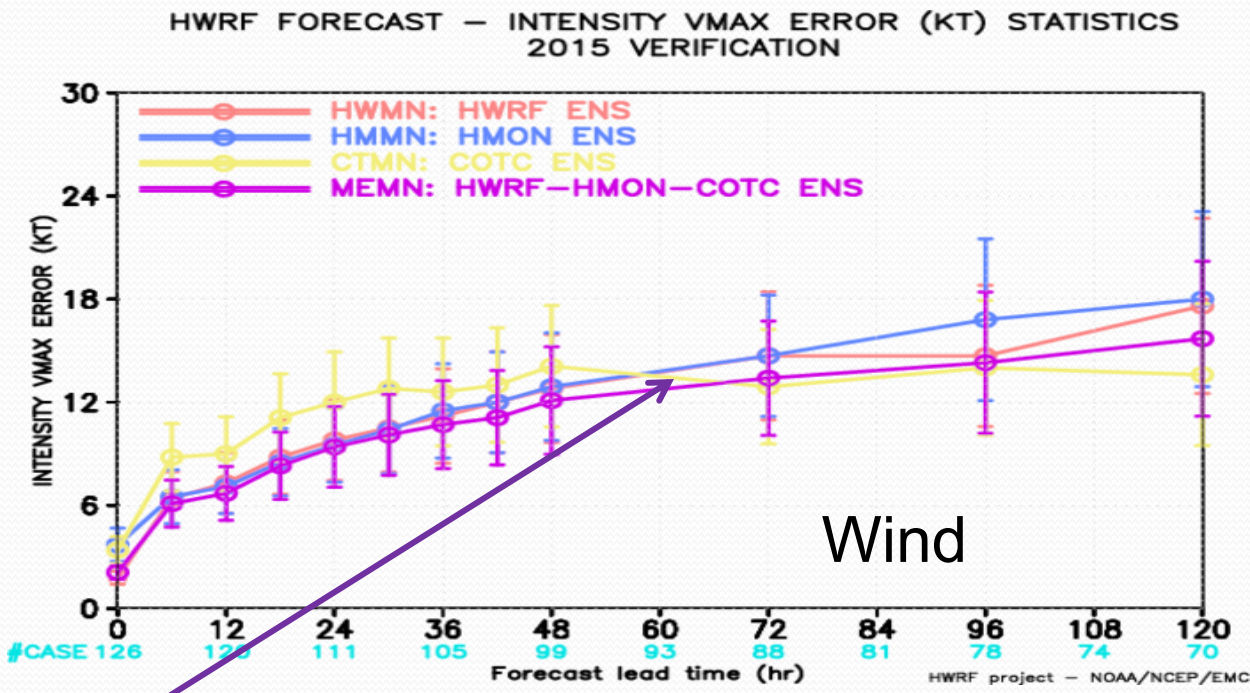




00Z **06Z** **12Z**

Multi-Model EPS (HWMN+HMON+CTMN)





Combined Multi-Model Ensemble

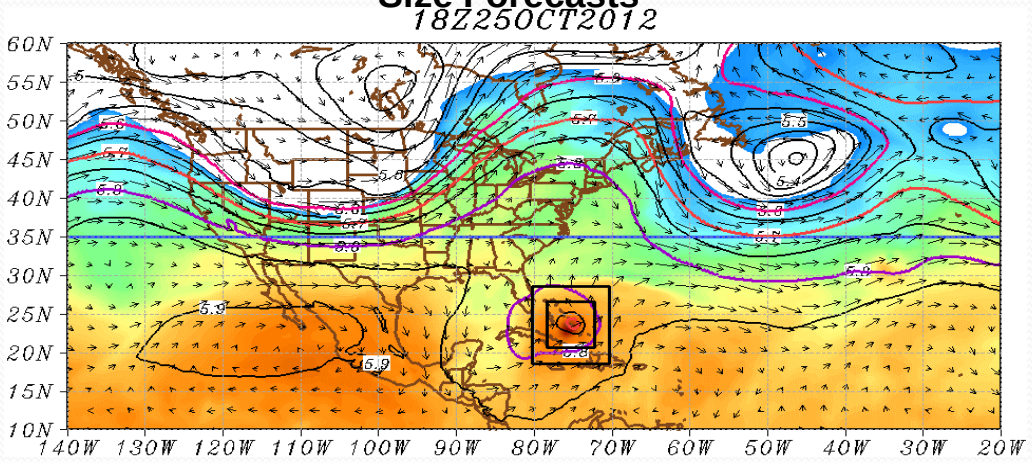
Near-term plans at NCEP/EMC*

- 2019-:
  - Annual upgrades for HWRF/HMON
  - Potential fully cycled DA for HWRF
  - Three-way coupling (Atmos/Ocean/Wave) for HWRF
  - Further improve scale-aware physics
  - Explore higher resolution for both HWRF/HMON
  - Possible operational HWRF ensemble
- 2020-beyond:
  - Integrating HWRF & HMON into FV3GFS,
  - Explore multi-storm capability
  - High resolution nests into global system with moving nests strategy.
  - Advanced unified physics and data assimilation with developments of UFS
  - Potential fully cycled DA for storm inner-core

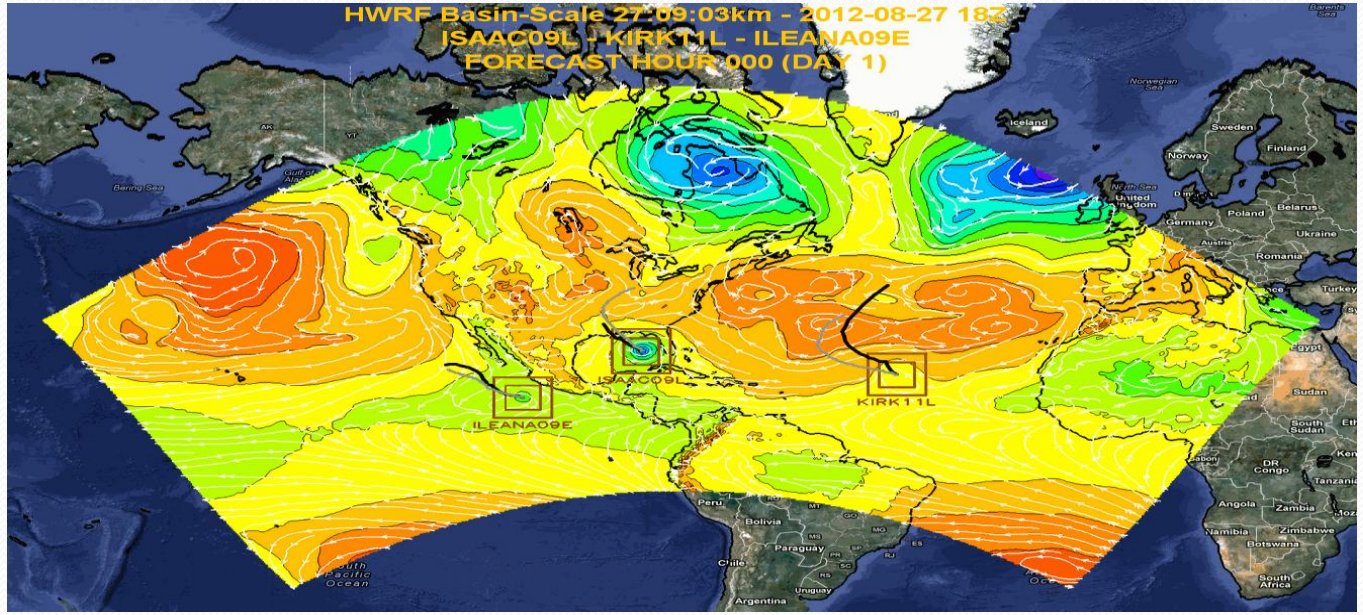
* All upgrades depend upon availability of computing resources at NCEP.

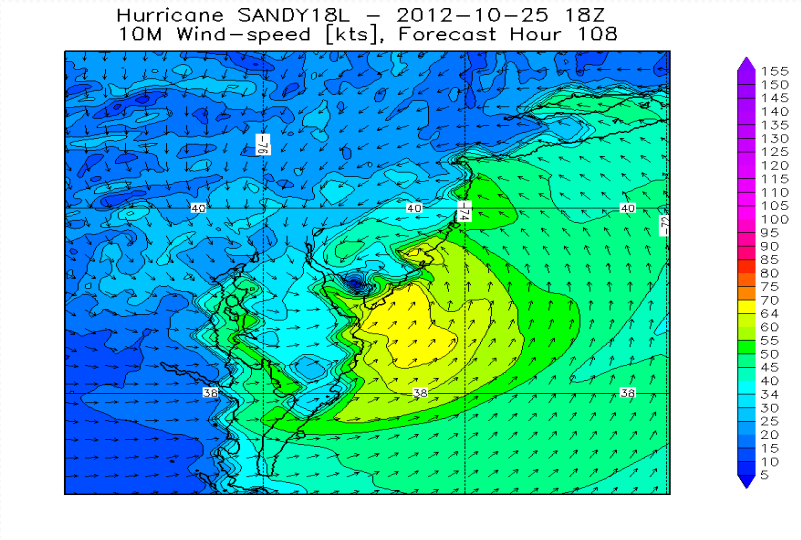
Future advancements for Operational HWRF

Improved Scale Interactions and Improved Track and Size Forecasts

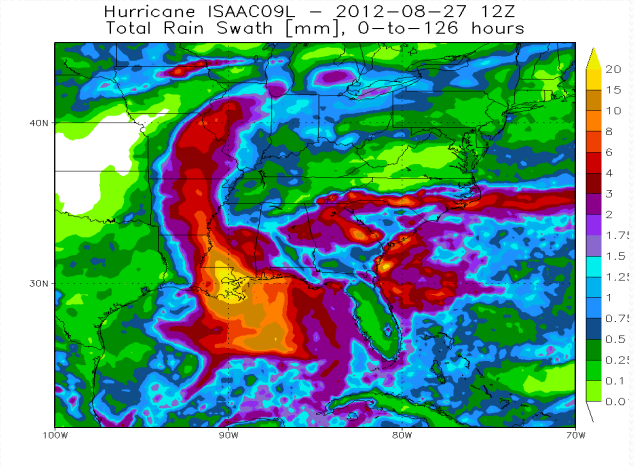


Basin-Scale HWRF: Real-time Multi-nested 3km predictions





Comprehensive large-scale/vortex-scale interactions in a unified framework, with high-resolution hurricane forecast guidance



HWRF/HMON Future Plans

2016	2017	2018	2019	2020
HWRF Operational Model Continues Followed by Ensembles				
GFDL ——— HMON		**10-member HWRF/ HMON Ensembles**	NEMS Global Nests (NGGPS)	
Basin-Scale HWRF/HMON/FV3——— Global/Tropical Domains				
Hurricane Models take over Hurricane Wave Forecasts				

Thank You !

Real-time NCEP operational model guidance for all global TCs

HWRF: http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF

HMON: http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HMON

On May 22nd, 2018, HWRF web page reached 1 million page views from 178 Countries and Territories since May 2015