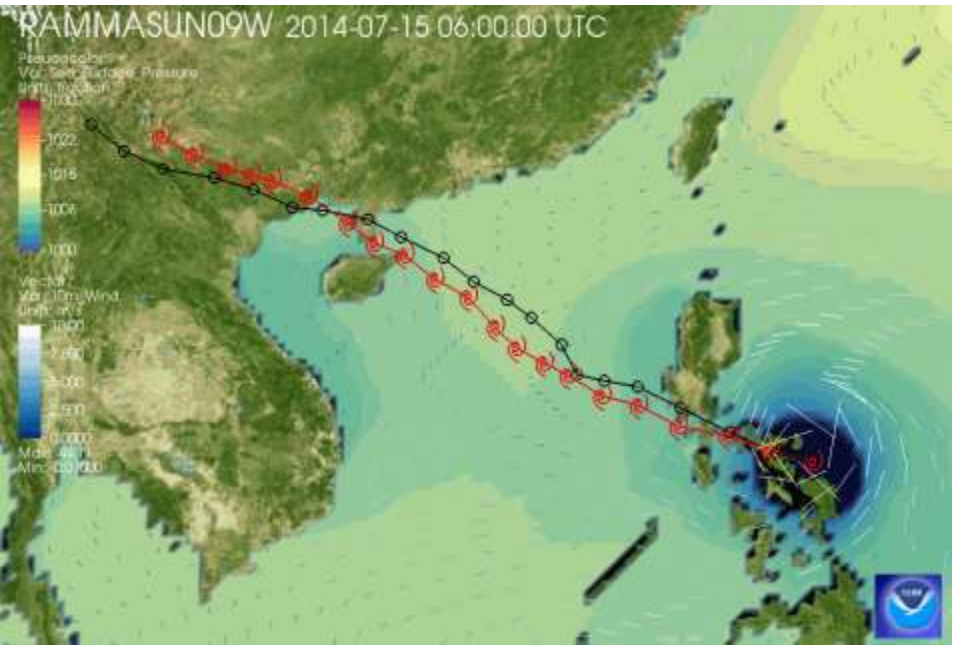
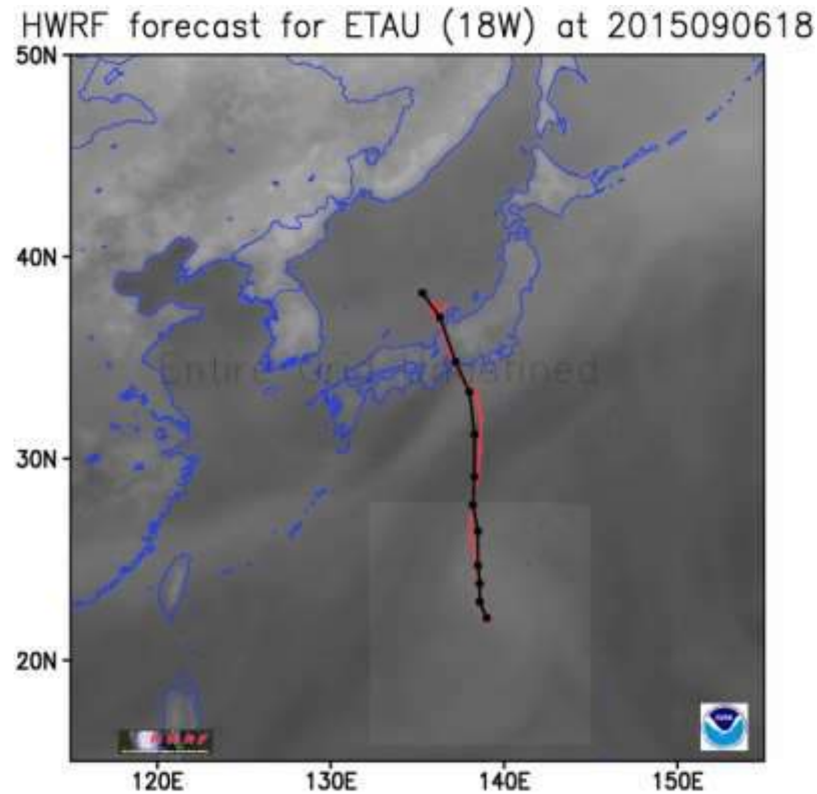
Improved global tropical cyclone forecasts from NOAA: Lessons learned and path forward

NOAA HURRICANE FORECAST IMPROVEMENT PROJECT





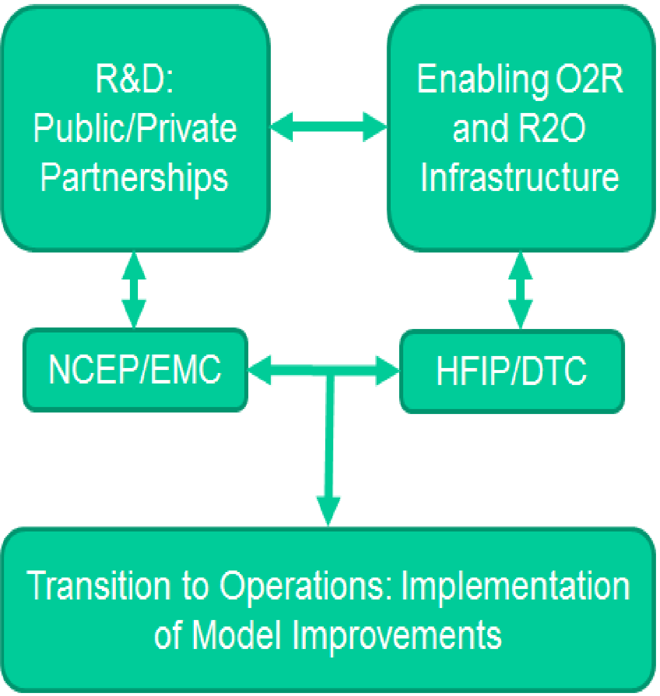
Dr. Vijay Tallapragada
Chief, Global Climate and Weather Modeling Branch
& HFIP Development Manager
NOAA National Weather Service/NCEP/EMC, USA

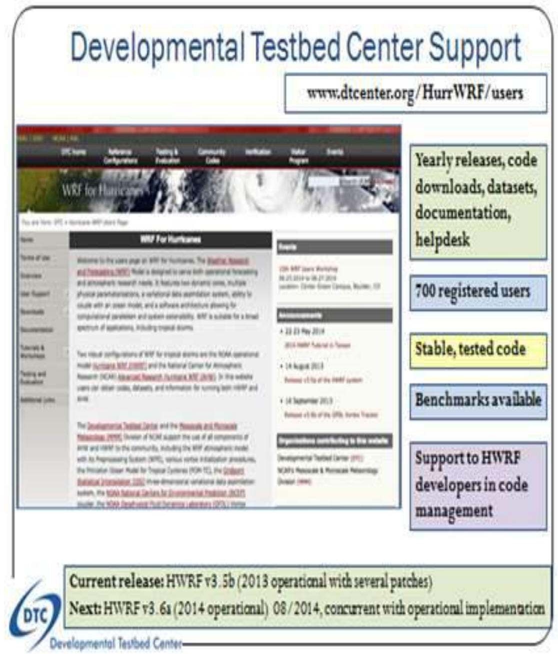
Typhoon Seminar, JMA, Tokyo, Japan.
January 6, 2016

Rapid Progress in Hurricane Forecast Improvements

Key to Success: Community Engagement & Accelerated Research to Operations

Operational Hurricane Modeling System Development



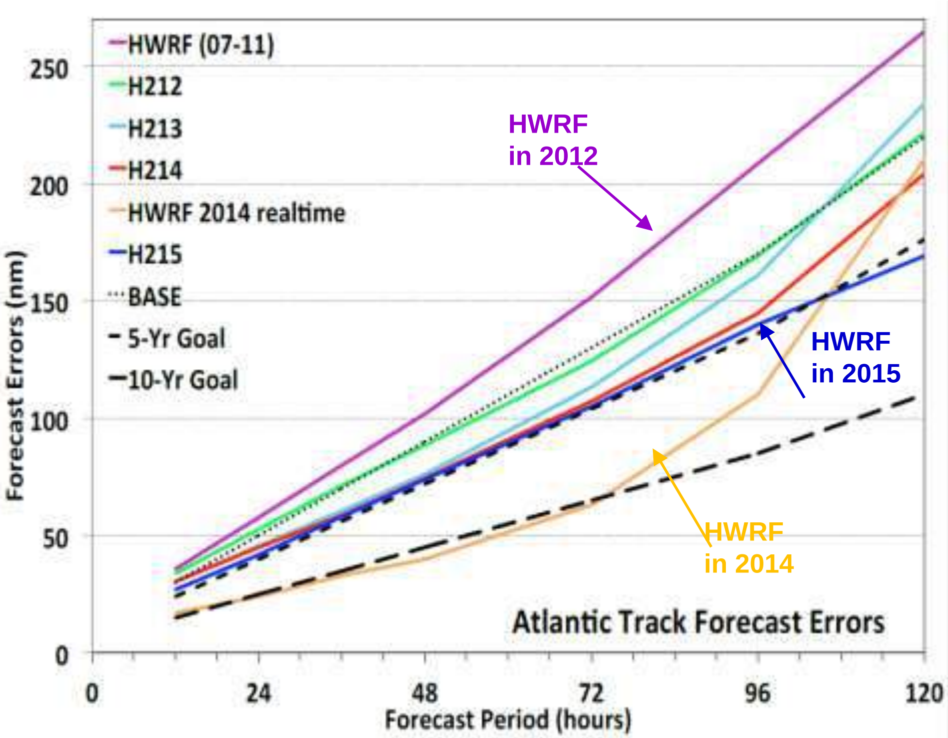


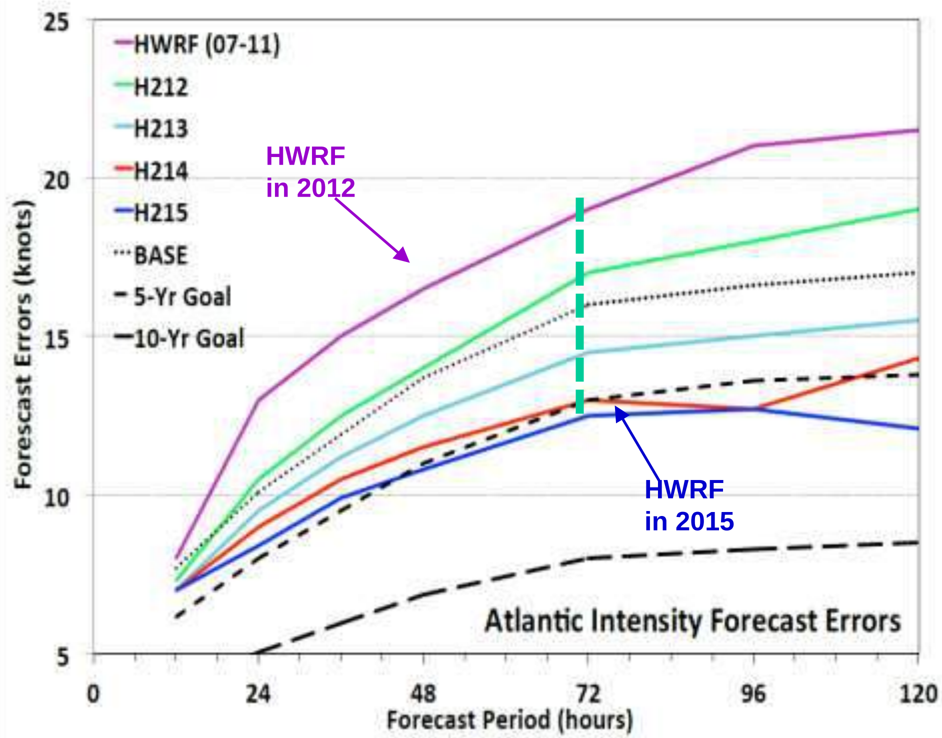
Continue the community modeling approach for accelerated transition of research to operations

International partnerships for accelerated model development & research

Effective and accelerated path for transitioning advanced research into operations

Significant improvements in Atlantic Track & Intensity Forecasts





Improvements of the order of 10-15% each year since 2012

What it takes to improve the models and reduce forecast errors???

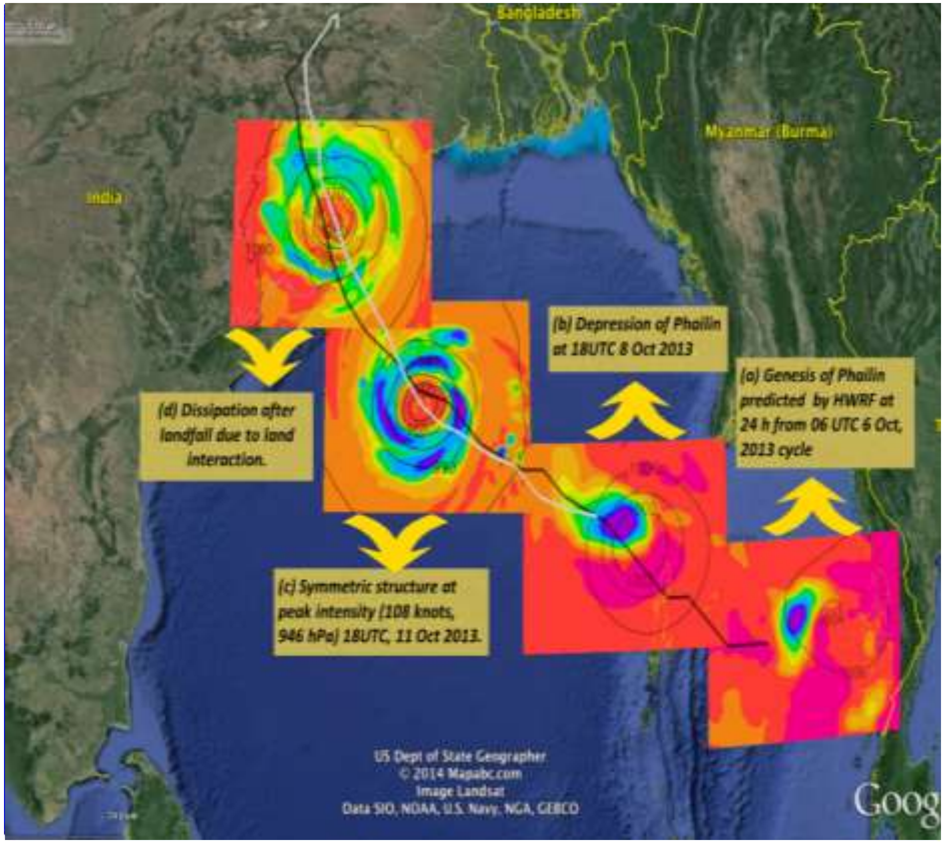
- **Resolution**
- **Physics**
- **Data Assimilation**

Targeted research and development in all areas of hurricane modeling

Lives Saved

Only 36 casualties compared to >10000 deaths due to a similar storm in 1999

- **1999 Orissa Cyclone**
  - Deadliest storm since 1971
  - 155 mph winds and 8m (26 ft) storm surge at landfall
  - <u>*10000 causalities, damages ~5 Billion USD*</u>
  - Operational NWP at IMD based on 24-hr forecasts from NCEP QLM
  - Accurate 48-hr forecast lead time for tracks, no skill for intensity forecasts
  - Inadequate guidance on storm surge, rain & flood



Advanced modelling and forecast products given to India Meteorological Department in real-time through the life of Tropical Cyclone Phailin

2014 DOC Gold Medal - HWRF Team

A reflection on Collaborative Efforts between NWS and OAR and international collaborations for accomplishing rapid advancements in hurricane forecast improvements

NWS: Vijay Tallapragada; Qingfu Liu; William Lapenta; Richard Pasch; James Franklin; Simon Tao-Long Hsiao; Frederick Toepfer

OAR: Sundararaman Gopalakrishnan; Thiago Quirino & Frank Marks, Jr.

HWRF™ The Hurricane Weather Research And Forecast System

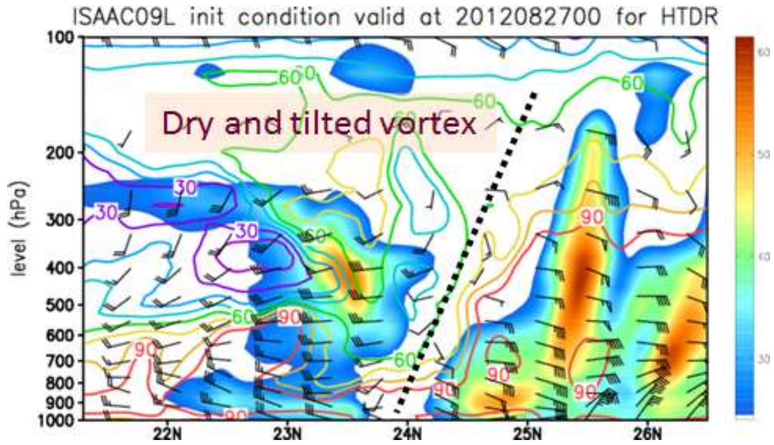
NOAA HURRICANE FORECAST IMPROVEMENT PROJECT

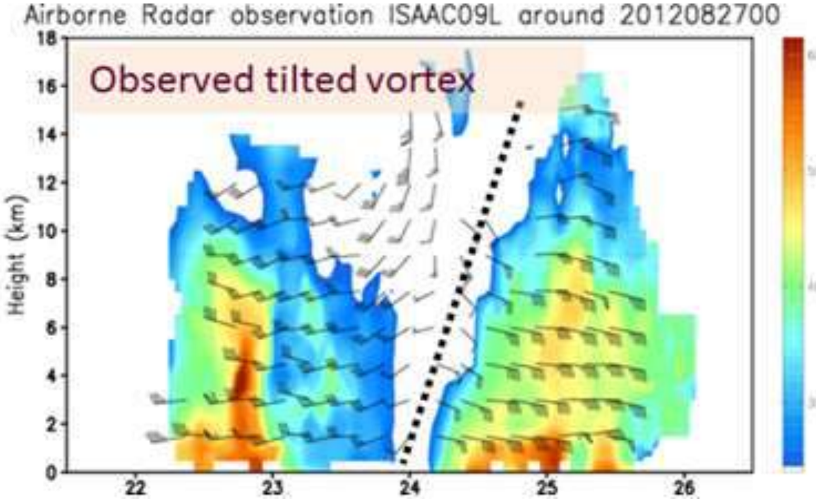
Advanced Research to Operations Transitions

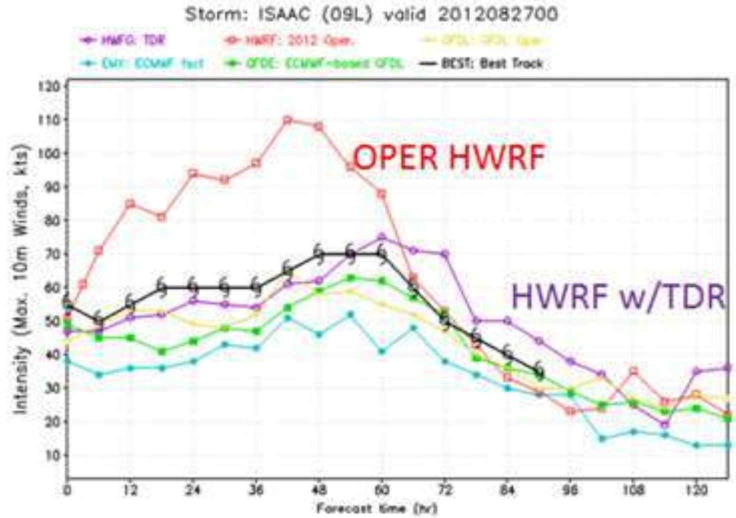
Accurate representation of storm structure using advanced DA methods

Collection, transmission and assimilation of inner core hurricane observations using Tail Doppler Radar directly from NOAA's P3 aircraft

Significant impact of TDR Data Assimilation on Initial Vortex Structure







<u>HWRF is the only model in the world assimilating real-time hurricane inner core Tail Doppler Radar (TDR) data from NOAA's P3 aircraft</u>

New in 2015 for HWRF in Operations

➢ System & Resolution Enhancements

- Replace current partial HWRF python based scripts with complete Python based scripts for a unified system
- *Increase the horizontal resolution of atmospheric model for all domains from 27/9/3 to 18/6/2 km.*

➢ Initialization/Data Assimilation Improvements

- Upgrade and improve HWRF vortex initialization scheme in response to both GFS and HWRF resolution increases
- Upgrade Data Assimilation System with hybrid 40-member HWRF-based high-resolution ensembles and GSI system.

➢ Physics Advancements

- Upgrade Micro-physics process (Ferrier-Aligo); replace GFDL radiation with RRTMG scheme including sub-grid scale partial cloudiness; Upgrade surface physics and PBL, replace current GFDL slab model to more advanced NOAH LSM.

➢ First time in 2015….

- ➢ *Self cycled HWRF ensembles based warm start for TDR DA*
- ➢ *Expand HWRF capabilities to all global (including WP/SH/IO) basins through 7-storm capability in operations to run year long*

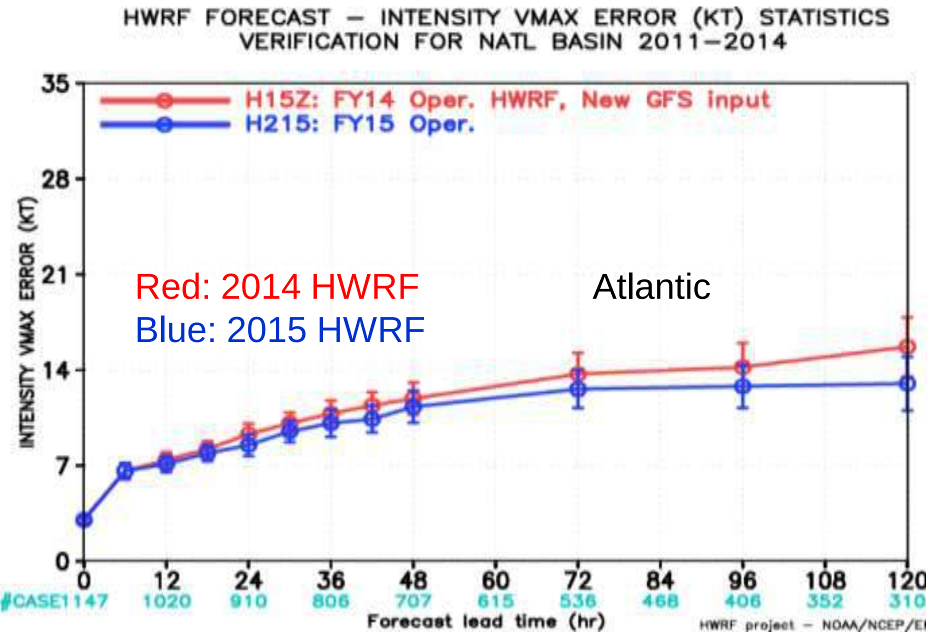
HWRF Upgrade Plan for 2015 Implementation

Multi-season Pre-Implementation T&E

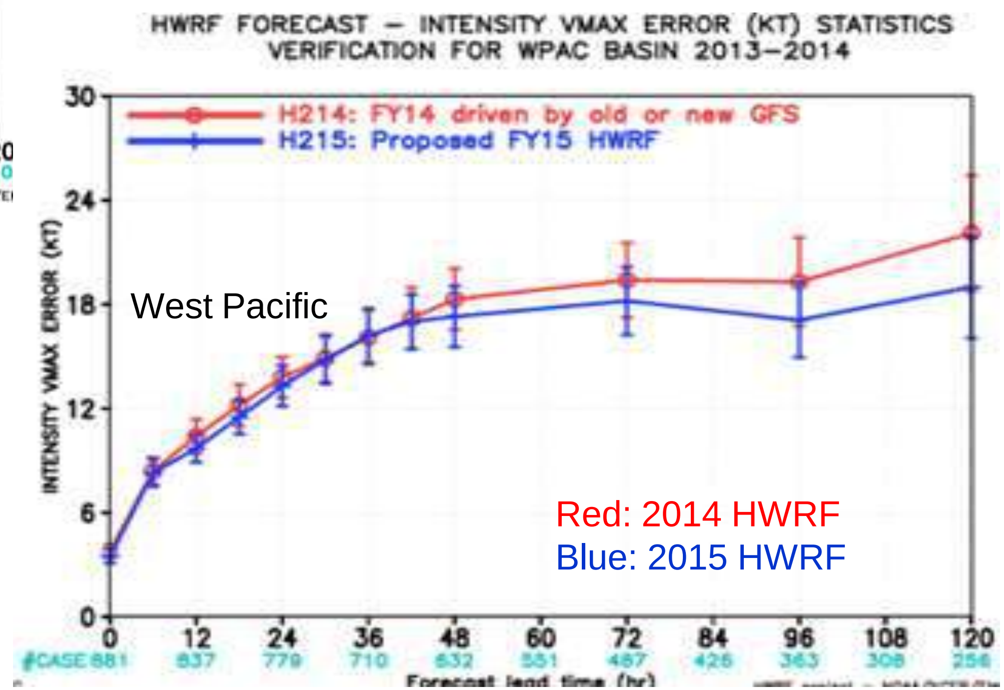
	GFS Upgrades	Model upgrades	Physics and DA upgrades				Combined
	Control (H15Z)	**Baseline (H15B)**	**NOAH LSM (H15W)**	**Upgraded Ferrier (H15W)**	**RRTMG/ PBL/ Surface Physics (H15W)**	**DA* (H15T)**	**H215**
Description	Create a new control configuration of 2014 Operational HWRF run with newly upgraded GFS T1534 IC/BC	1.Resolution increase: 18/6/2km w/ same domain size; 2. Python scripts 3. New GFS T1534 4. Init improvement, GFS vortex filter	NOAH LSM (w/ Ch cap over land)	Separate species, w/o advection	1.Radiation 2.Variable α 3.Scale-aware partial cloudiness scheme	Hybrid GSI/ HWRF-EPS based DA	Baseline + NOAH/LSM +newMP+RRTMG+ Surface Physics + PBL + DA changes
Cases	Four-season 2011-2014 simulations in ATL/EPAC, cases (~2300)	Four-season 2011-2014 simulations in ATL/EPAC, cases (~2300)	Priority cases	Priority cases	Priority cases	Only TDR cases for 2011-2014	Four-season 2011-2014 simulations in ATL/EPAC, cases (~2300) WP/SH/IO 2013-2014 (~1200 cases)
Platforms	Jet/WCOSS	Jet	WCOSS	Jet	Jet/Zeus	Jet	Jet/WCOSS/Zeus

3x computer resources within the HWRF operational time window.

2015 HWRF: Further improvements in the Hurricane Intensity Forecasts in All Basins

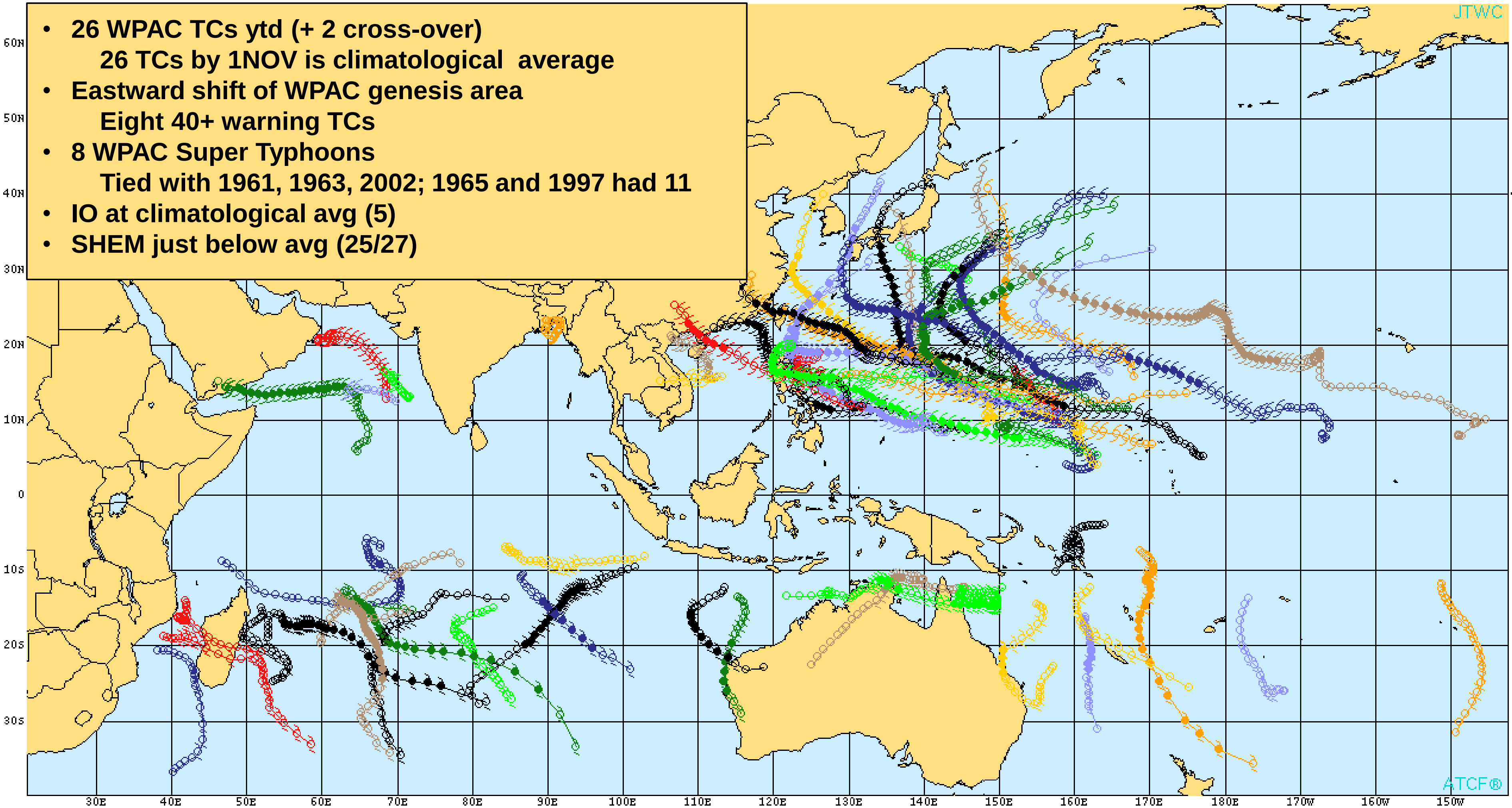


Retrospective forecasts for
1147 cases in the North Atlantic
881 cases in the Western North Pacific

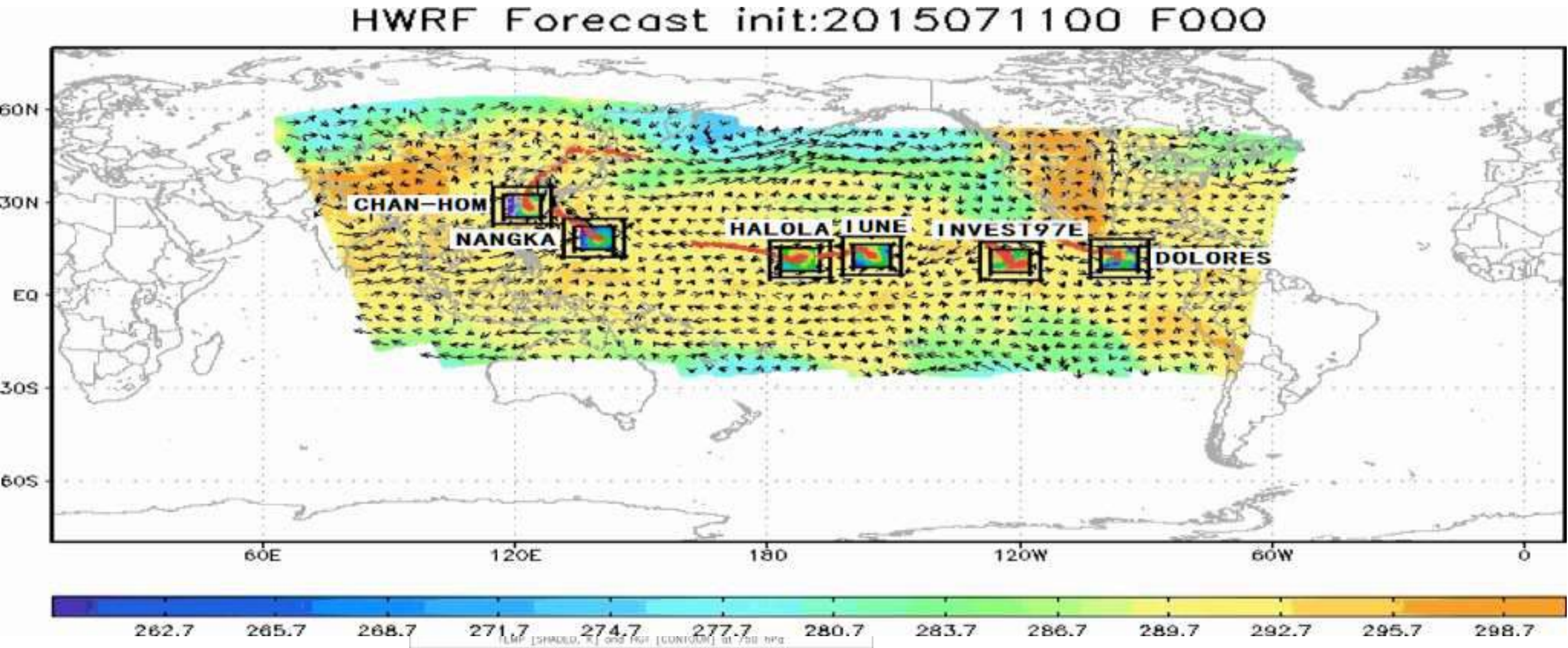


The Threat

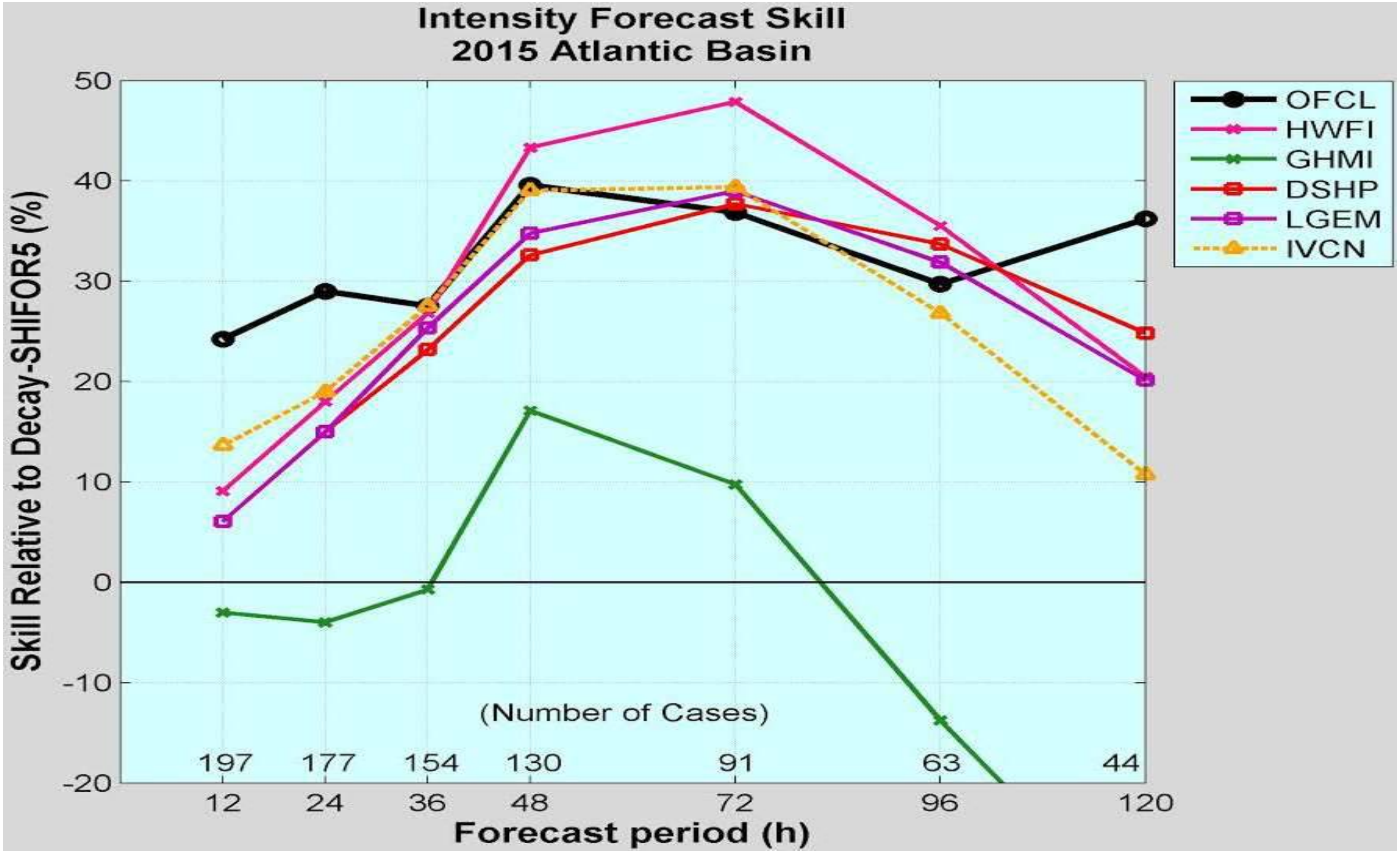
- **26 WPAC TCs ytd (+ 2 cross-over)**
  26 TCs by 1NOV is climatological average
- **Eastward shift of WPAC genesis area**
  Eight 40+ warning TCs
- **8 WPAC Super Typhoons**
  Tied with 1961, 1963, 2002; 1965 and 1997 had 11
- **IO at climatological avg (5)**
- **SHEM just below avg (25/27)**



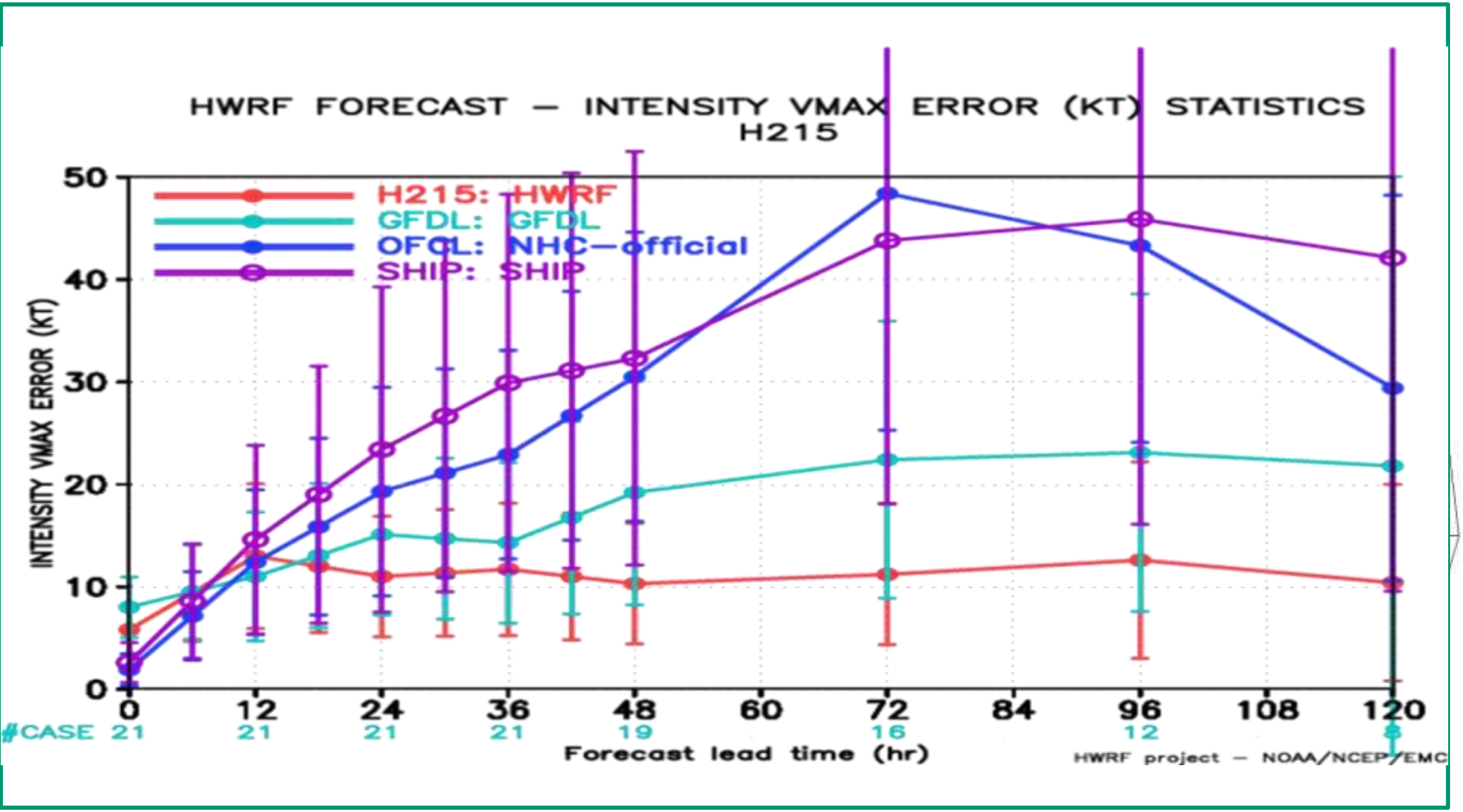
Real-time Operational Configuration for 2015 HWRF



Highlights of 2015 HWRF

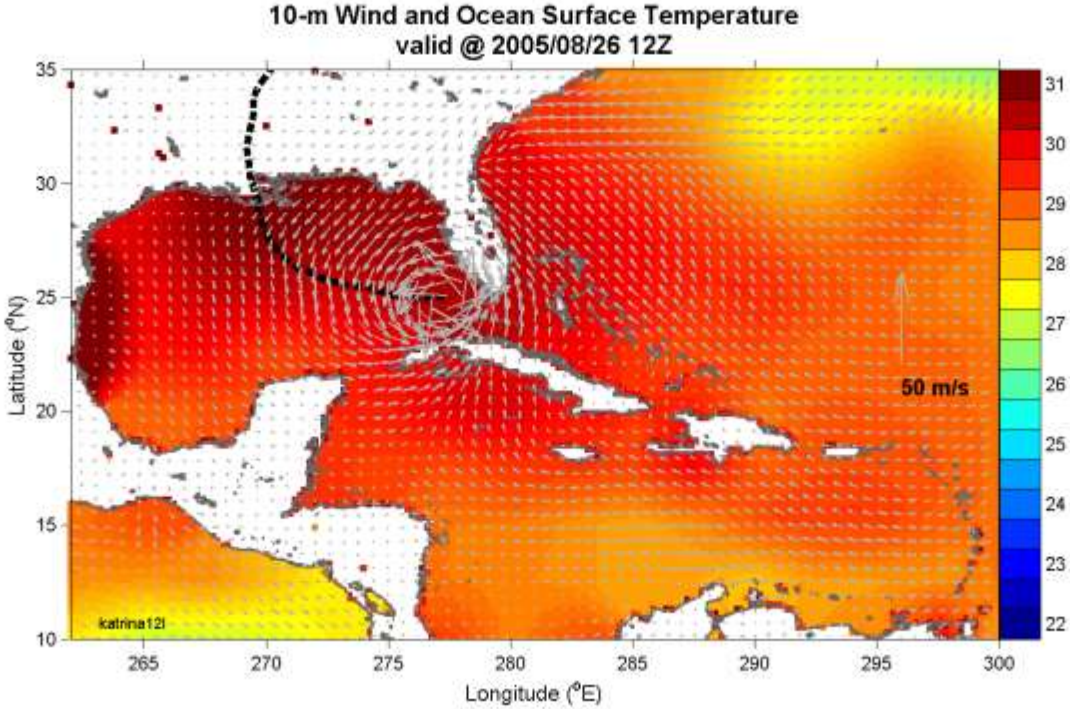


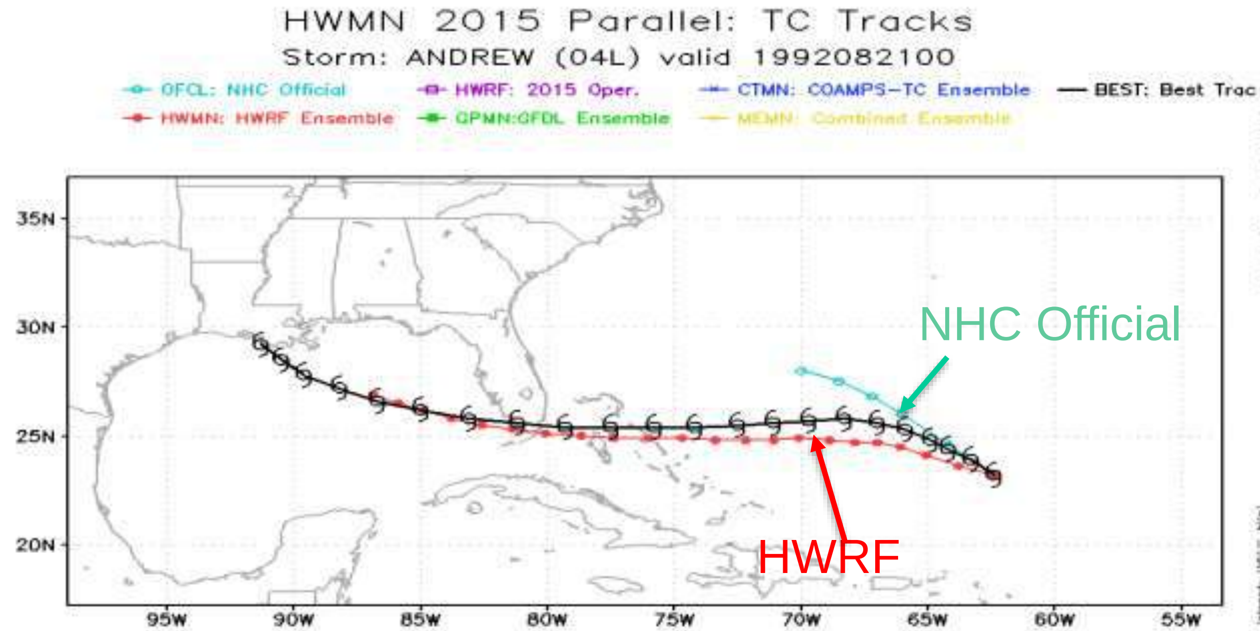
Have the models improved in the past decade?

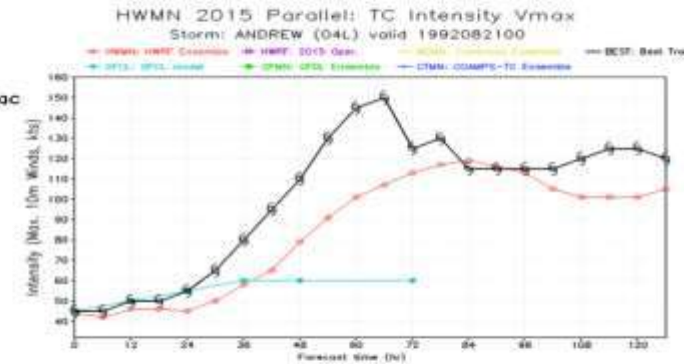


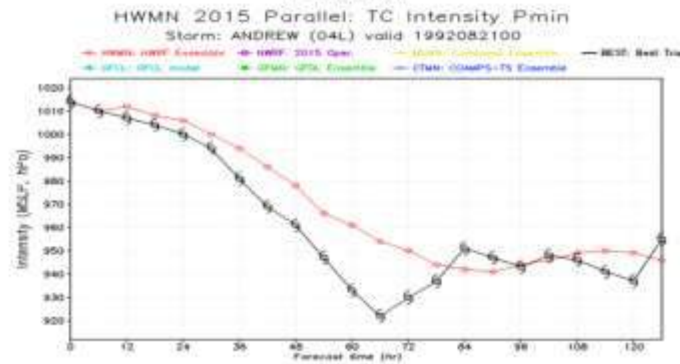
Improved Modeling of Hurricane Dynamics, Physics, and Air-Sea-Wave-Land Interactions

- **Hurricane Katrina reminds us of critical and complex interactions between atmosphere, ocean, waves and land – all need to be accurately represented in numerical models for improving the forecast guidance**
- **NCEP Operational HWRF has demonstrated significant progress in improving the forecasts for high-impact events like Katrina**
- **Future efforts will continue with emphasis on high-resolution solutions for further improvements in hurricane intensity forecasts**

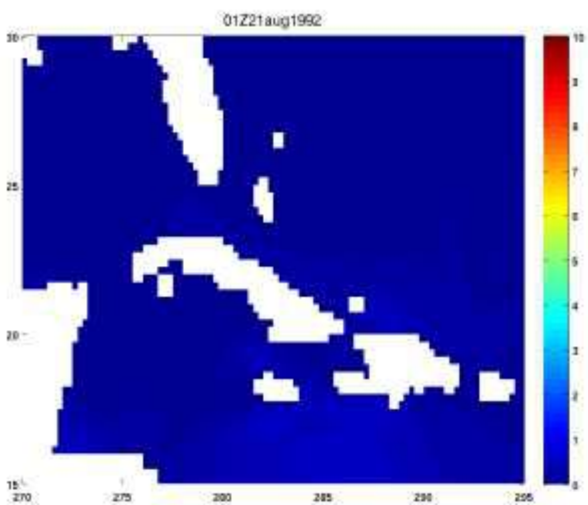


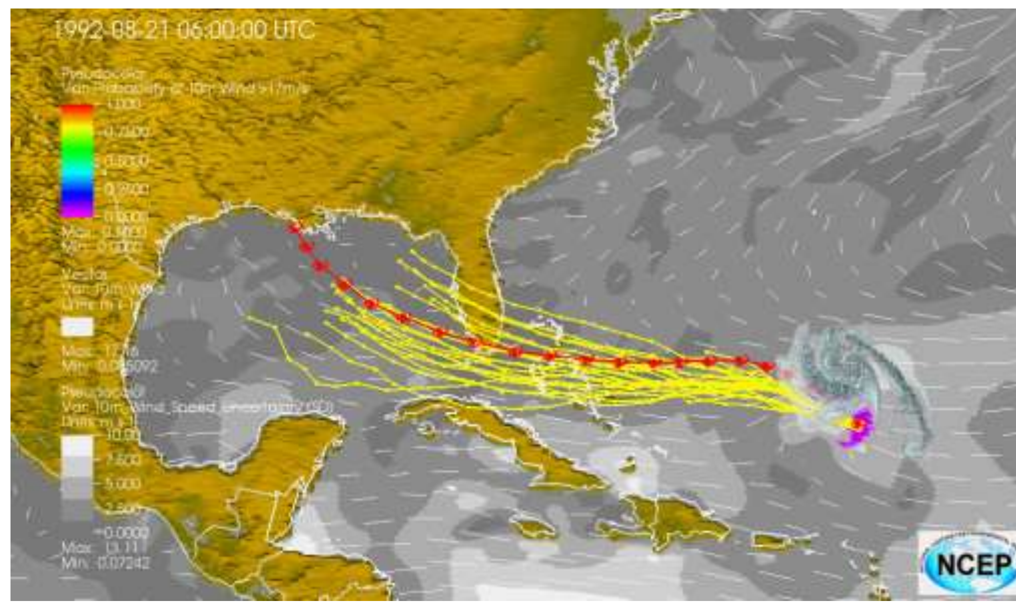




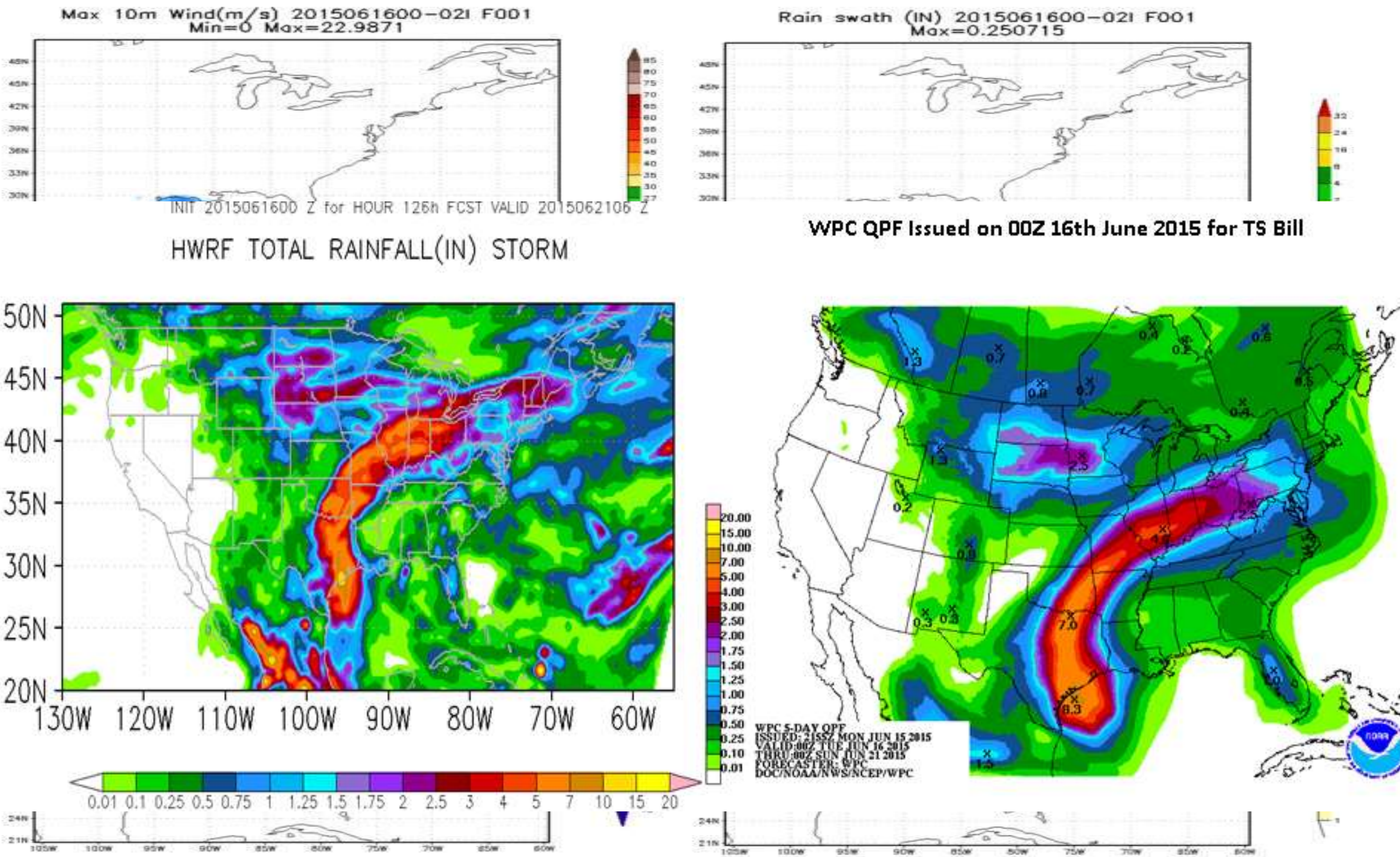


High-Resolution HWRF Forecasts for Hurricane Andrew

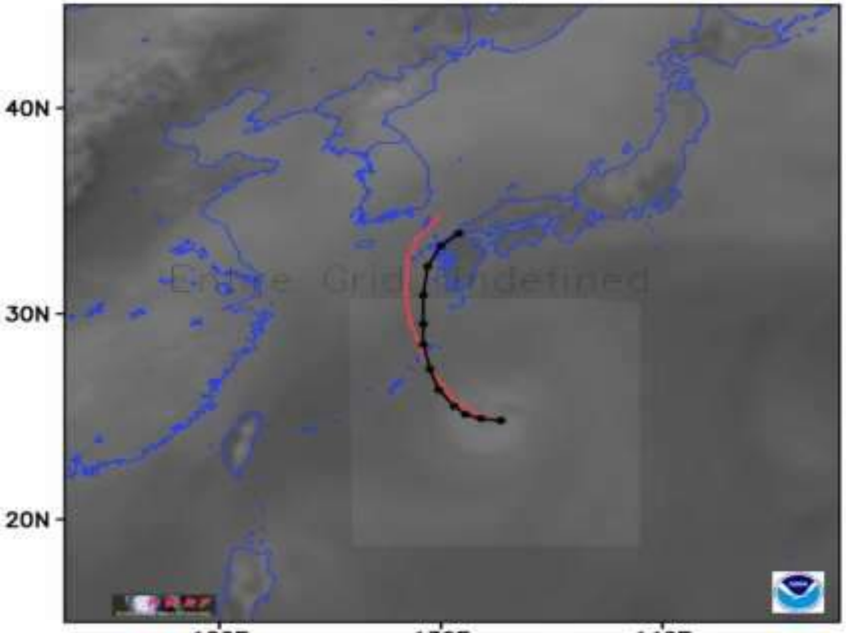




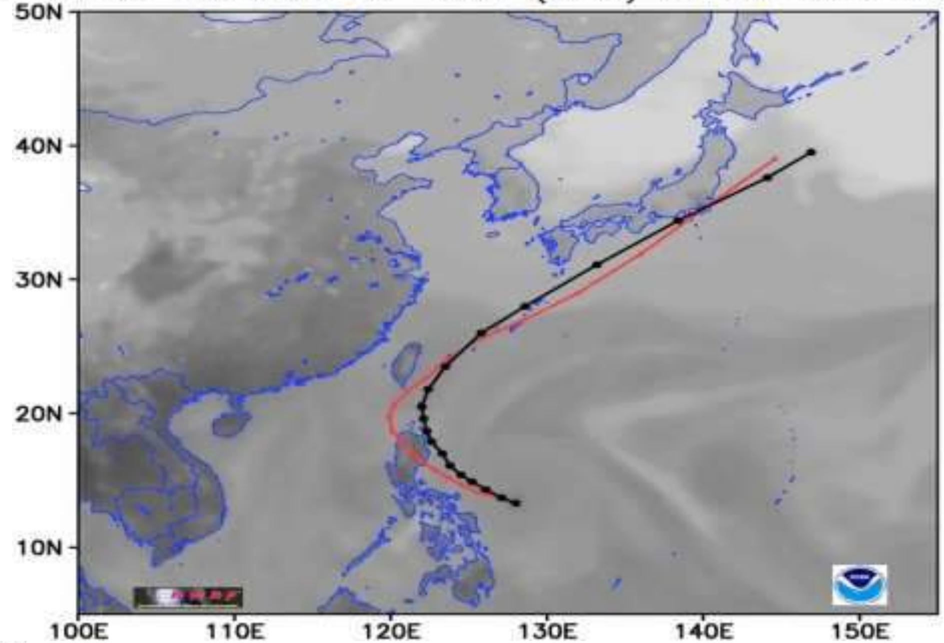
New Products from 2015 HWRF



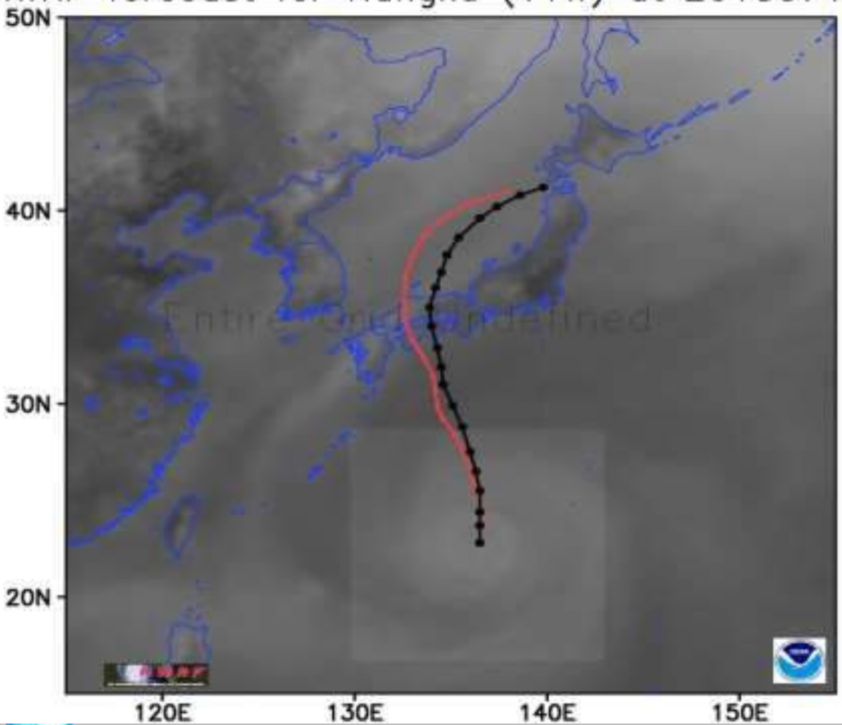
HWRF forecast for HALOLA (01C) at 2015072400



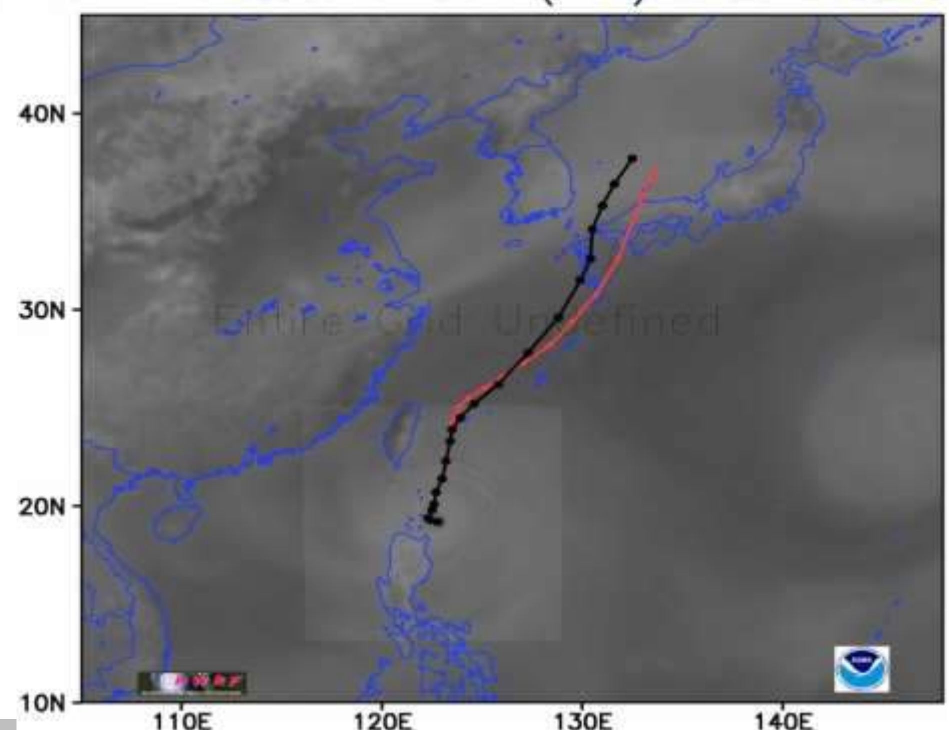
HWRF forecast for Noul (06W) at 2015050812

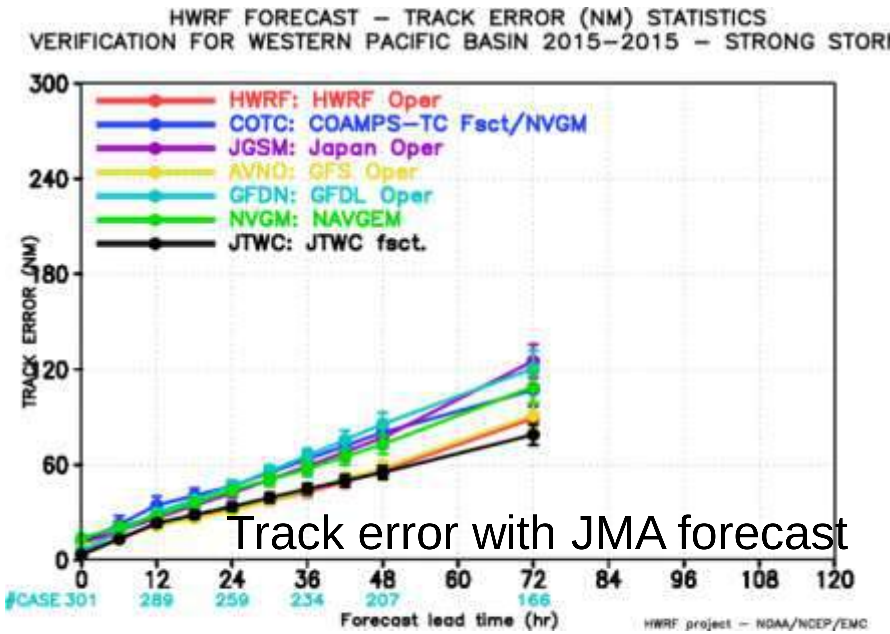


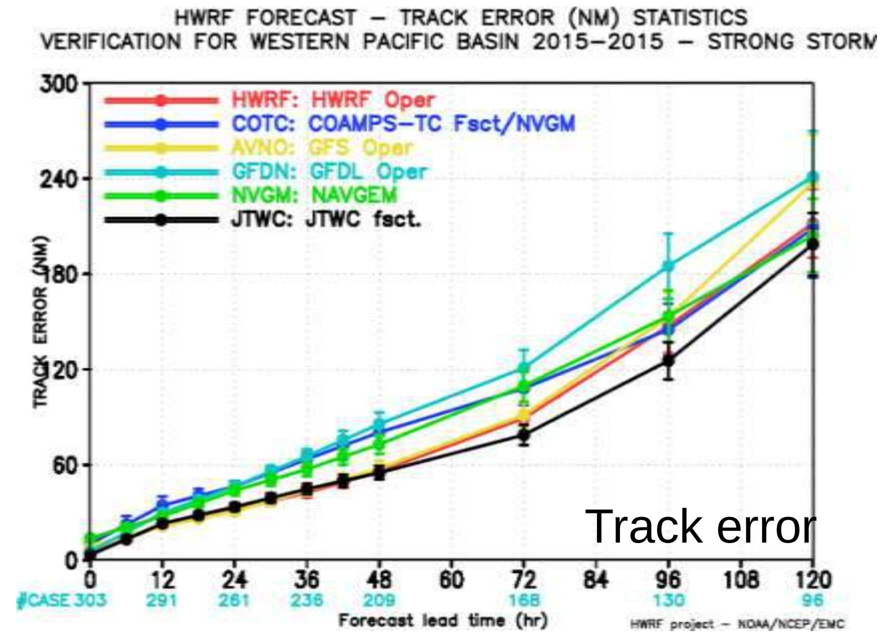
HWRF forecast for Nangka (11W) at 201507140

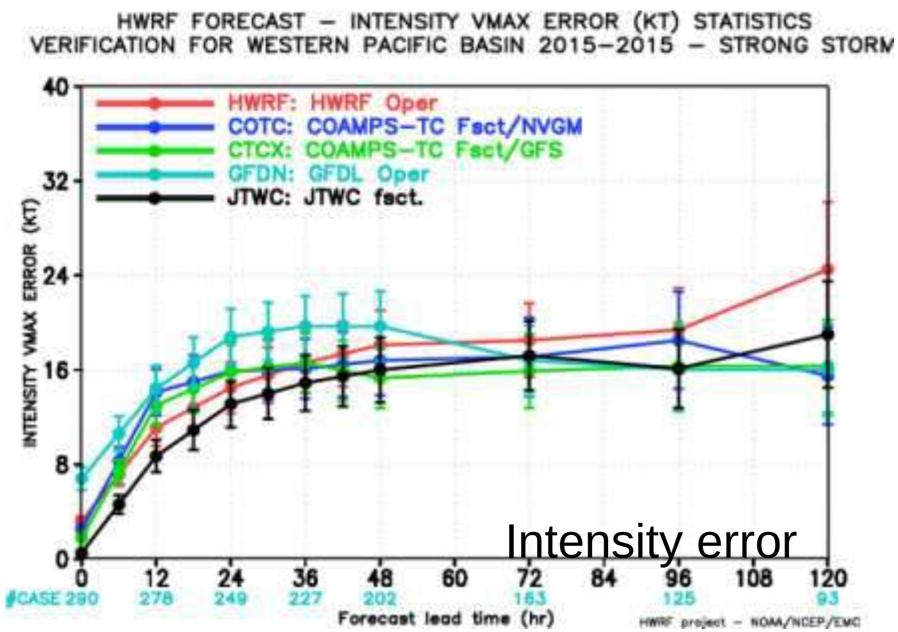


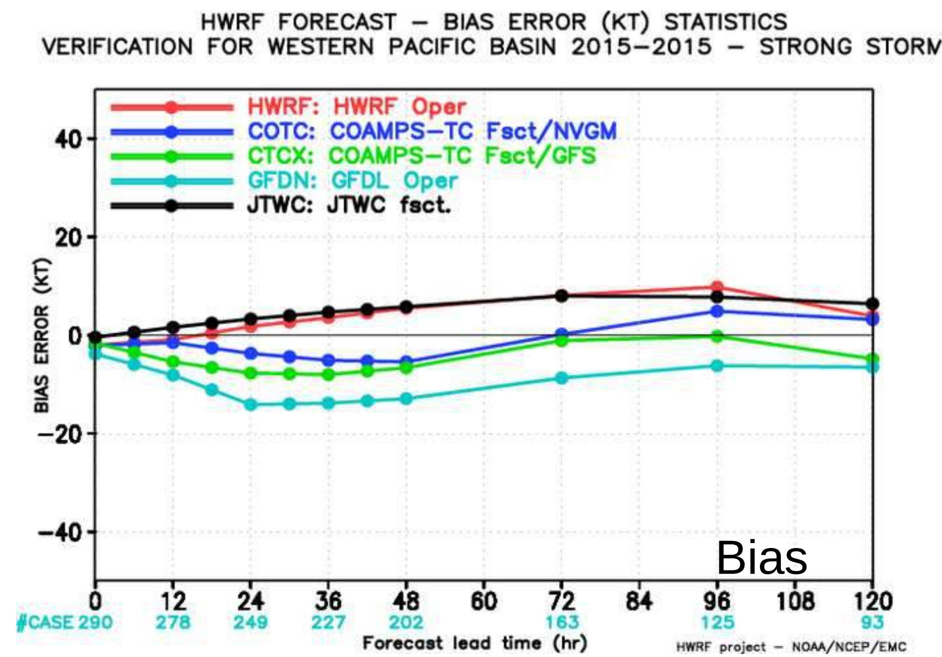
HWRF forecast for GONI (16W) at 2015082100




HWRF FORECAST – TRACK ERROR (NM) STATISTICS
VERIFICATION FOR WESTERN PACIFIC BASIN 2015–2015 – STRONG STORM
HWRF: HWRF Oper
COTC: COAMPS–TC Fsct/NVGM
JGSM: Japan Oper
AVNO: GFS Oper
GFDN: GFDL Oper
NVGM: NAVGEM
JTWC: JTWC fsct.
TRACK ERROR (NM)
Track error with JMA forecast
#CASE 301 289 259 234 207 166
Forecast lead time (hr)
HWRF project – NOAA/NCEP/EMC


HWRF FORECAST – TRACK ERROR (NM) STATISTICS
VERIFICATION FOR WESTERN PACIFIC BASIN 2015–2015 – STRONG STORM
HWRF: HWRF Oper
COTC: COAMPS–TC Fsct/NVGM
AVNO: GFS Oper
GFDN: GFDL Oper
NVGM: NAVGEM
JTWC: JTWC fsct.
TRACK ERROR (NM)
Track error
#CASE 303 291 261 236 209 168 130 96
Forecast lead time (hr)
HWRF project – NOAA/NCEP/EMC


HWRF FORECAST – INTENSITY VMAX ERROR (KT) STATISTICS
VERIFICATION FOR WESTERN PACIFIC BASIN 2015–2015 – STRONG STORM
HWRF: HWRF Oper
COTC: COAMPS–TC Fsct/NVGM
CTCX: COAMPS–TC Fsct/GFS
GFDN: GFDL Oper
JTWC: JTWC fsct.
INTENSITY VMAX ERROR (KT)
Intensity error
#CASE 290 278 249 227 202 163 125 93
Forecast lead time (hr)
HWRF project – NOAA/NCEP/EMC


HWRF FORECAST – BIAS ERROR (KT) STATISTICS
VERIFICATION FOR WESTERN PACIFIC BASIN 2015–2015 – STRONG STORM
HWRF: HWRF Oper
COTC: COAMPS–TC Fsct/NVGM
CTCX: COAMPS–TC Fsct/GFS
GFDN: GFDL Oper
JTWC: JTWC fsct.
BIAS ERROR (KT)
Bias
#CASE 290 278 249 227 202 163 125 93
Forecast lead time (hr)
HWRF project – NOAA/NCEP/EMC

Forecasting Rapid Intensification: A scientific challenge

Verification of Rapid Intensification Forecasts from NCEP Operational HWRF

- *Significant RI predictability skill first demonstrated in the Western North Pacific basin*
- *RI Skills are much lower in the Atlantic and Eastern Pacific basins*

Conditions for triggering Rapid Intensification in HWRF Model

- *Phase-Lock Mechanism for RI Onset*
- *High POD and Low FAR compared to other models*

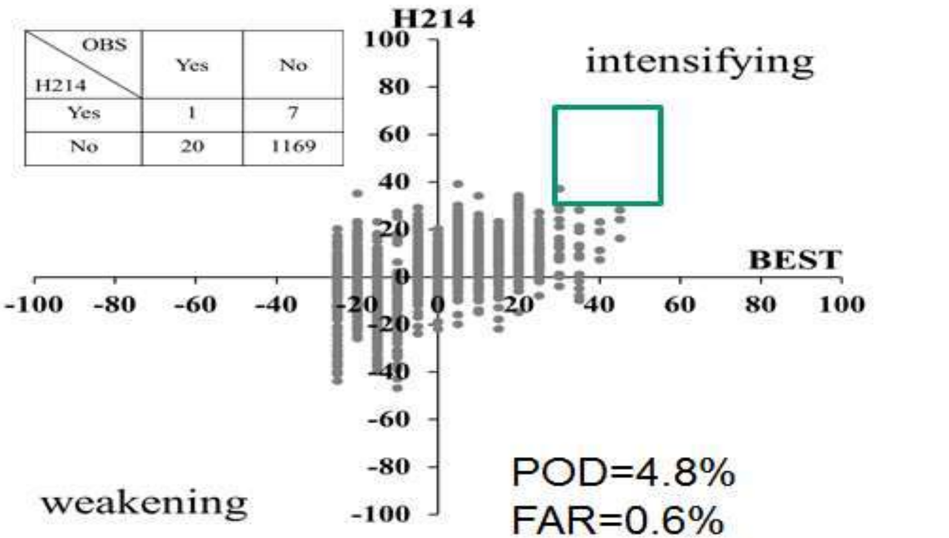
Structure of HWRF Model Storms at Extremely Strong Intensity Stage

- *Development of Double Warm Core Structure for intense TCs*
- *Possible connections with warmer stratospheric air*

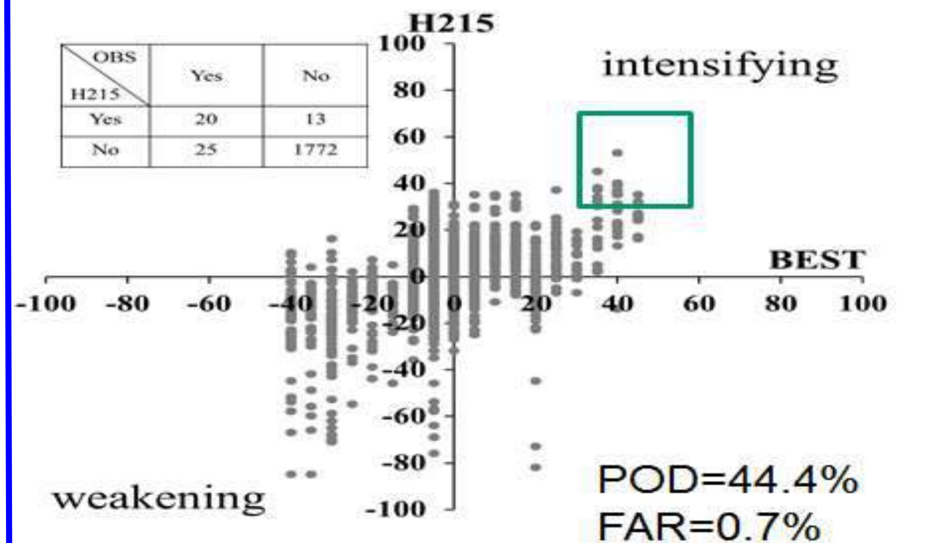
Scientific Challenges for improved tropical cyclone RI forecasts

- *HWRF is good at developing SEFs but not ERCs*
- *Role of advanced scale-aware physics for more accurate representation of physical processes for RI events*

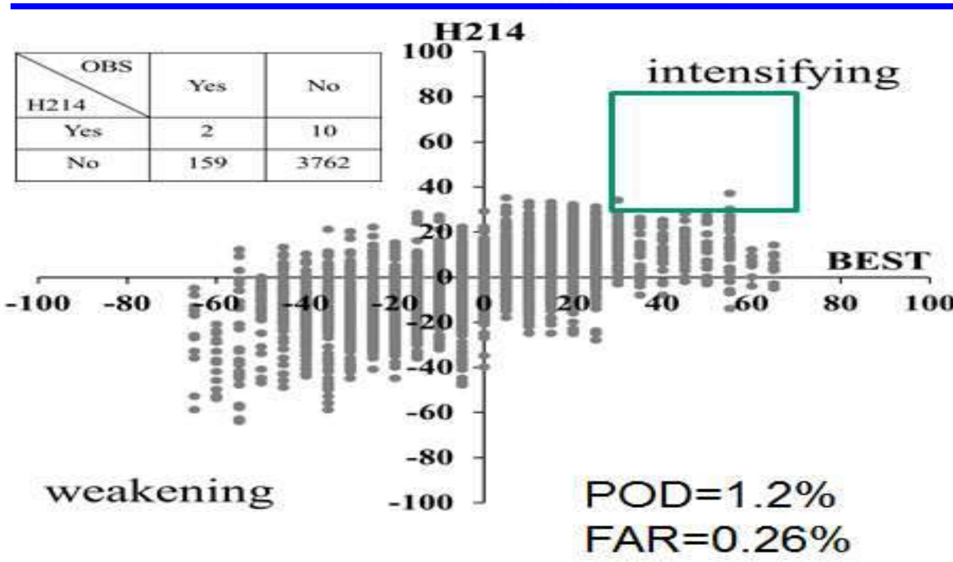
Improvement in RI Forecasts: North Atlantic and Eastern Pacific Basins



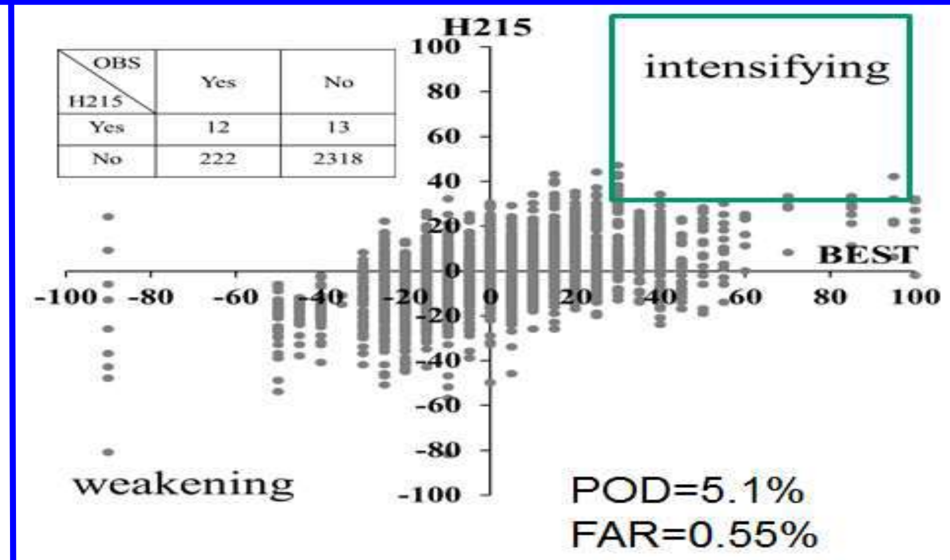
H214 \ OBS	Yes	No
Yes	1	7
No	20	1169



H215 \ OBS	Yes	No
Yes	20	13
No	25	1772

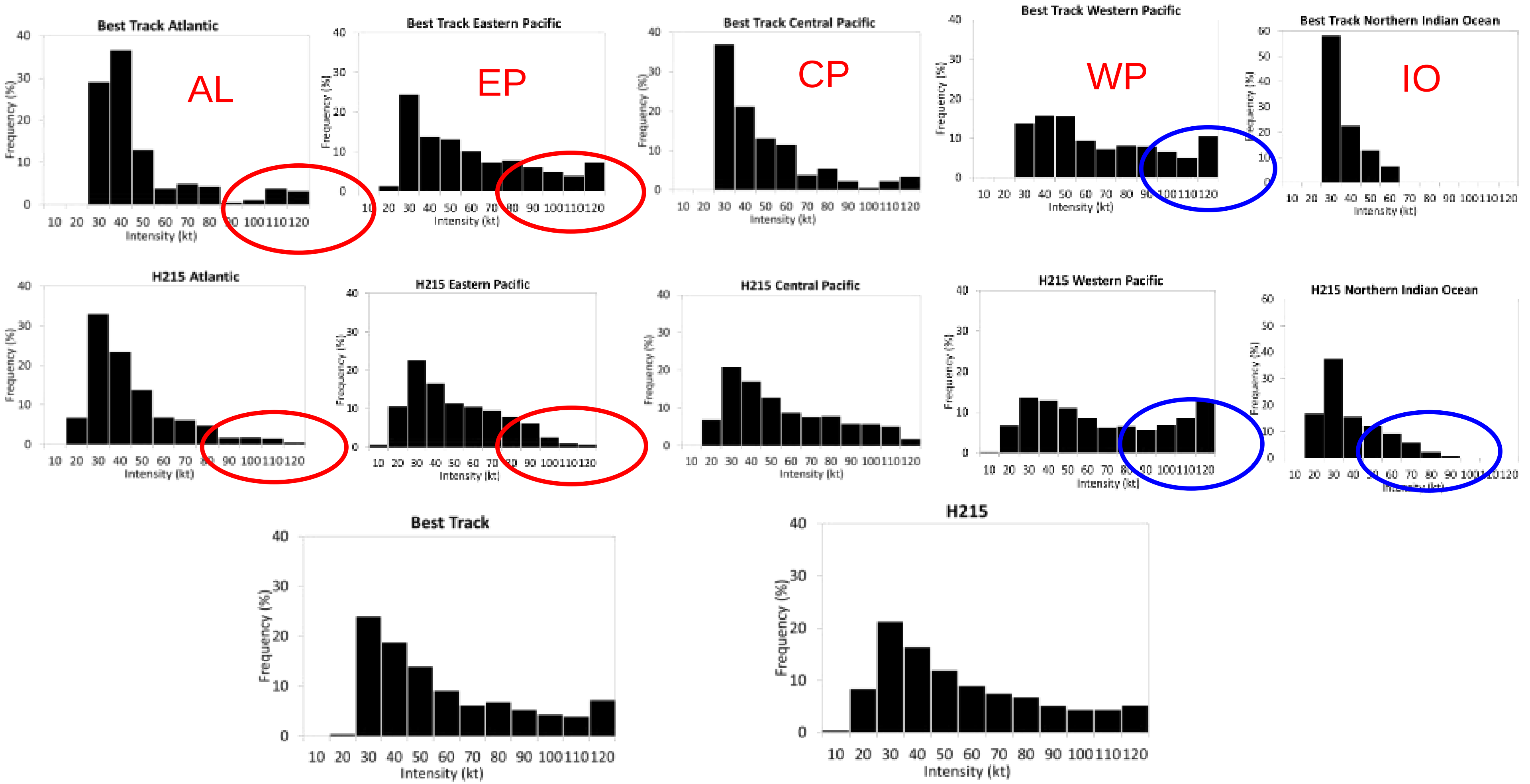


H214 \ OBS	Yes	No
Yes	2	10
No	159	3762

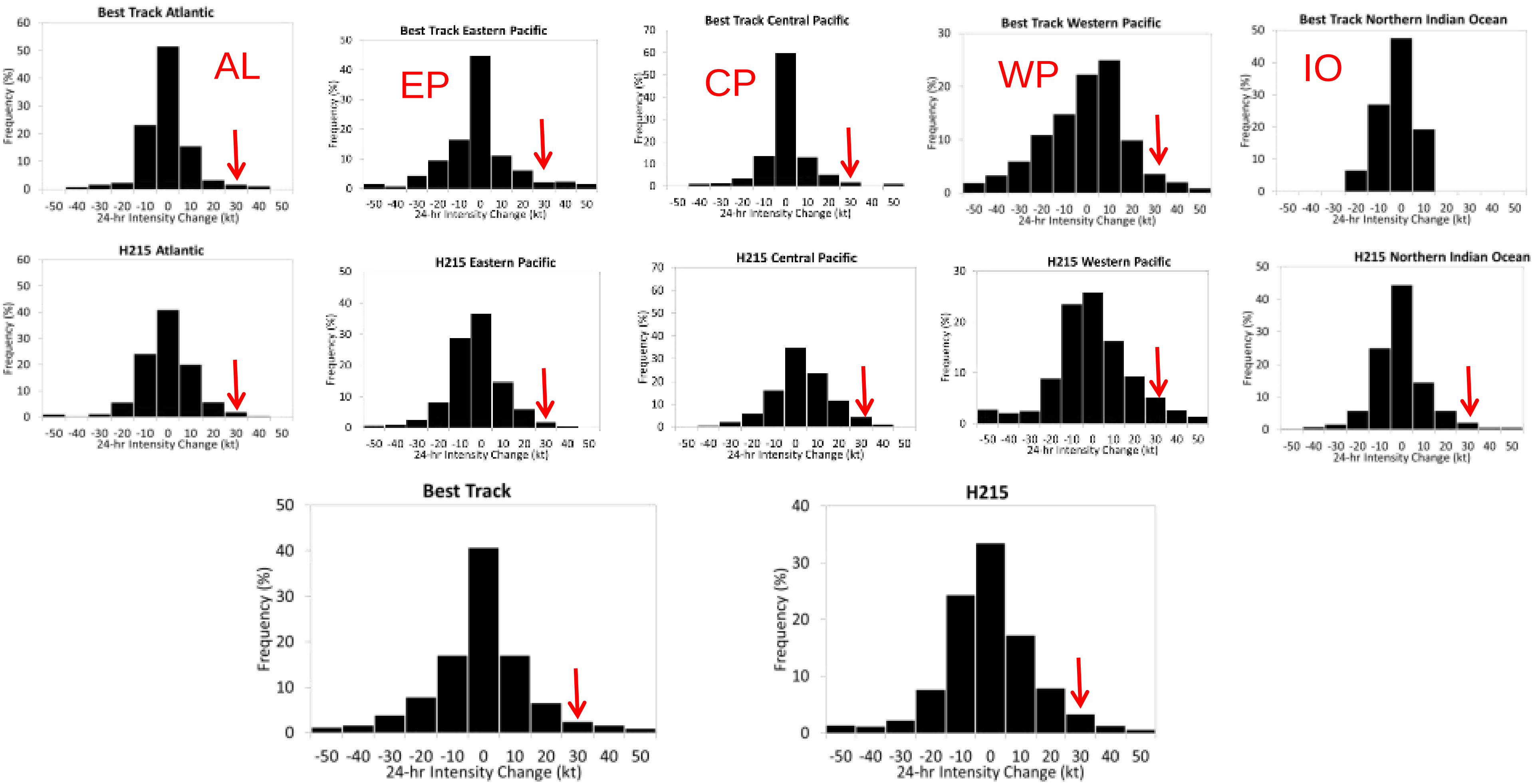


H215 \ OBS	Yes	No
Yes	12	13
No	222	2318

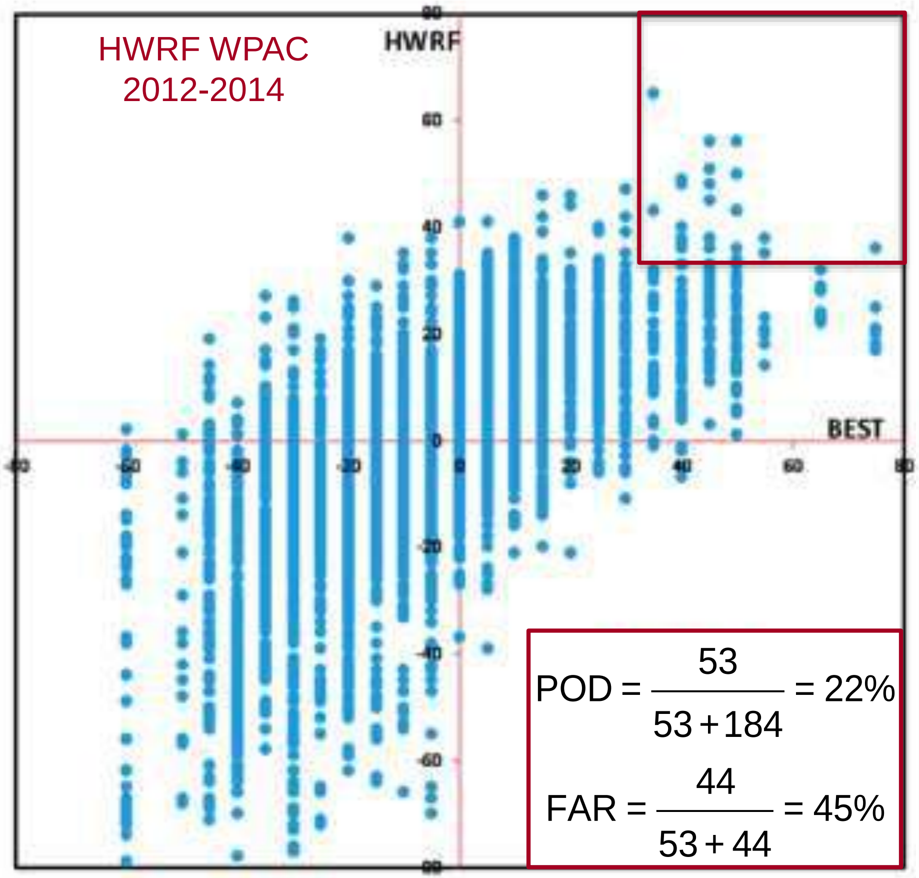
PDF Comparison of HWRF Predicted Intensity and Observed Intensity



PDF Comparison of HWRF Predicted 24h Intensity Changes and Observed 24h Intensity

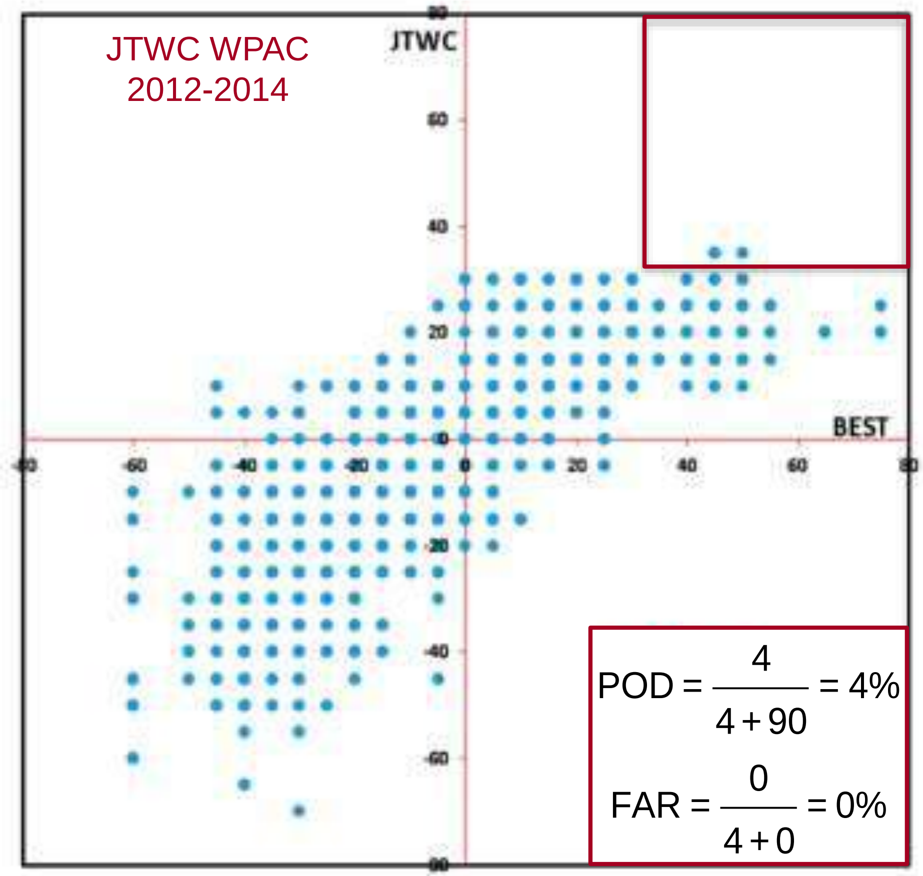


Verification of RI in the HWRF model
Western North Pacific basins



$$POD = \frac{53}{53+184} = 22\%$$

$$FAR = \frac{44}{53+44} = 45\%$$

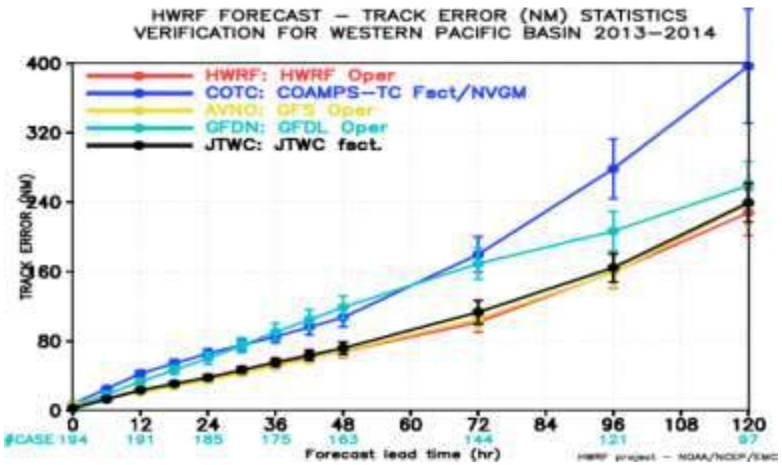


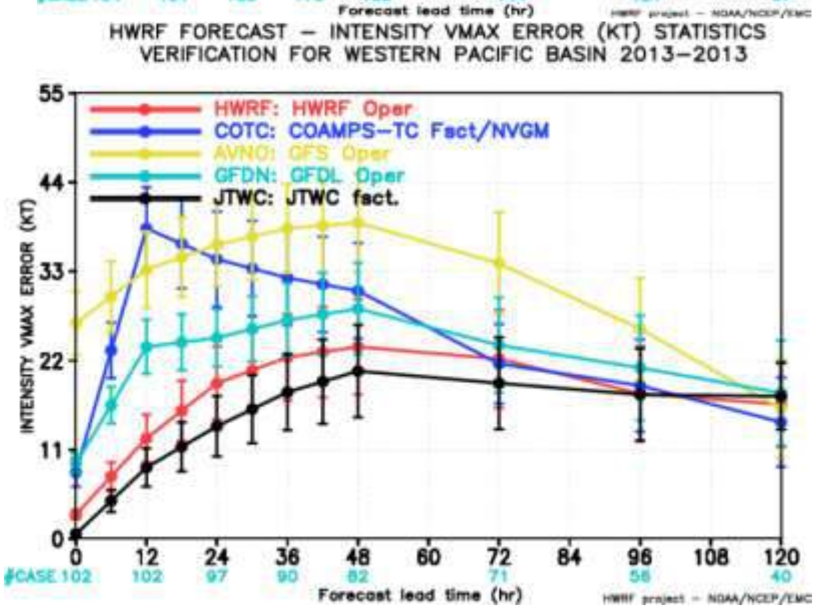
$$POD = \frac{4}{4+90} = 4\%$$

$$FAR = \frac{0}{4+0} = 0\%$$

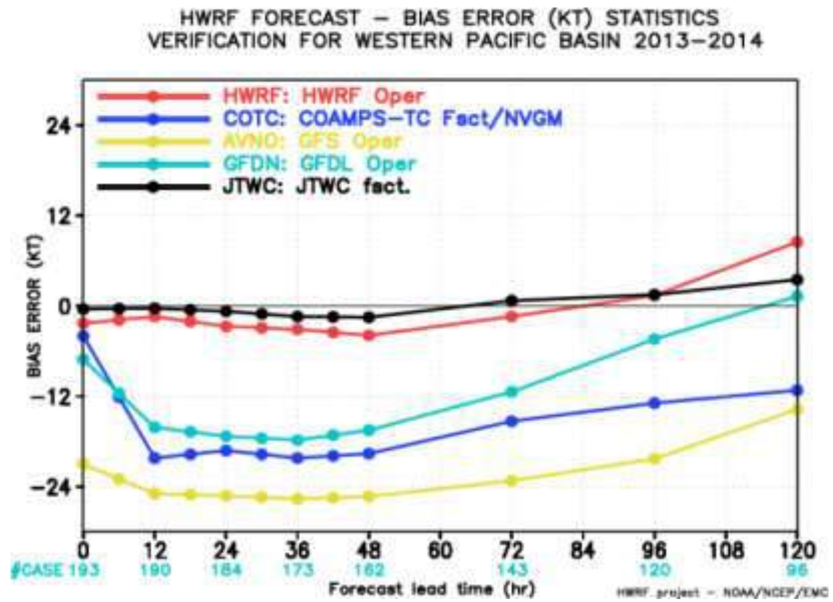
POD increased to 36% with 2km 2015 HWRF

HWRF Forecasts for 2013-2014 Western Pacific STYs



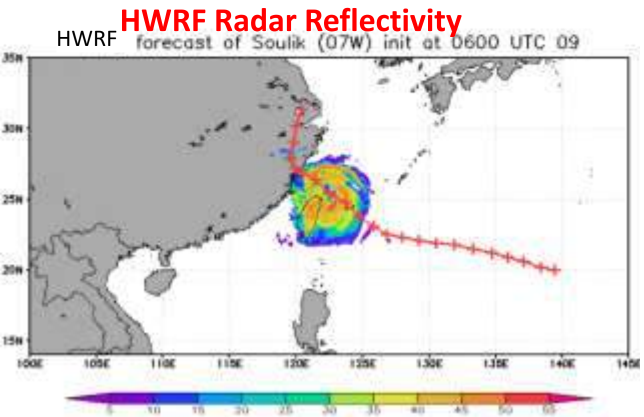


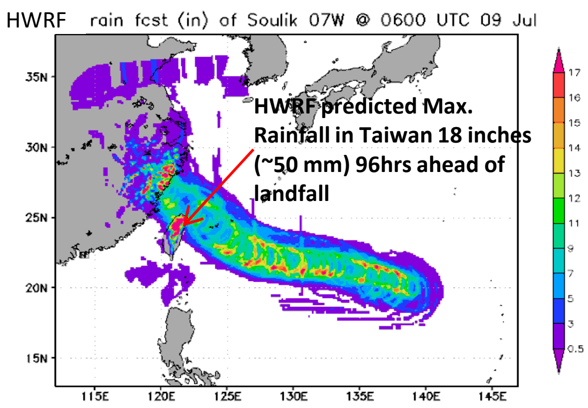
For the six Super Typhoons (STYs) in 2013-2014 (17W USAGI, 26W FRANCISCO, 28W LEKIMA, 31W HAIYAN, 11W HALONG and 19W VONGFONG), HWRF track and intensity forecasts are the best, with close to zero intensity bias and significantly lower intensity errors.



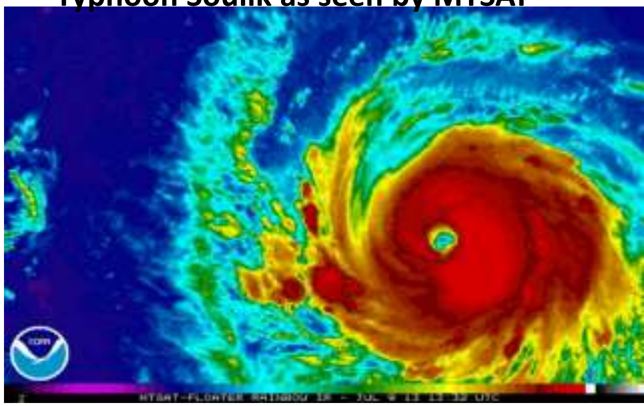
HWRF in 2013 West Pac: Typhoon Soulik

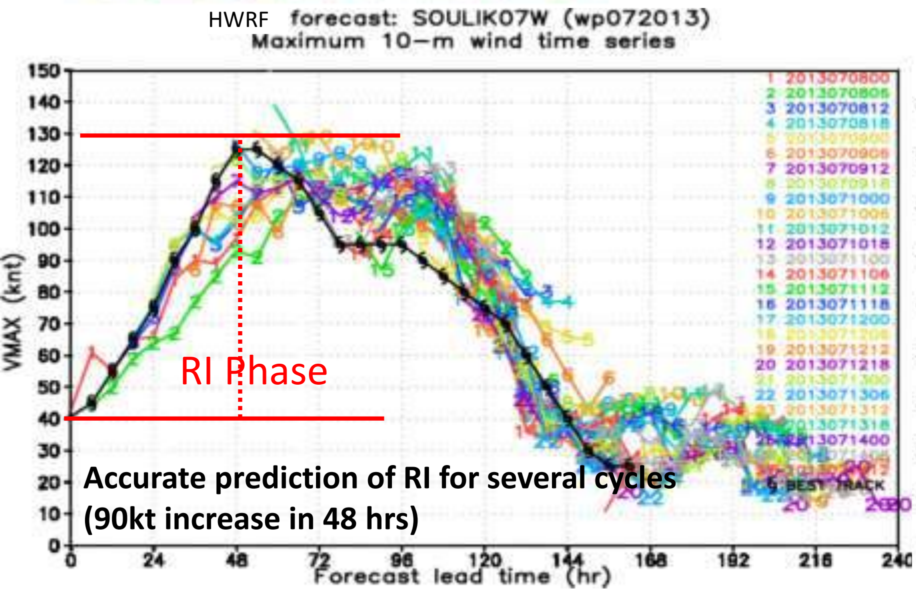
Performance of Operational HWRF for Typhoon Soulik with accurate track, intensity, structure, rainfall and RI forecasts

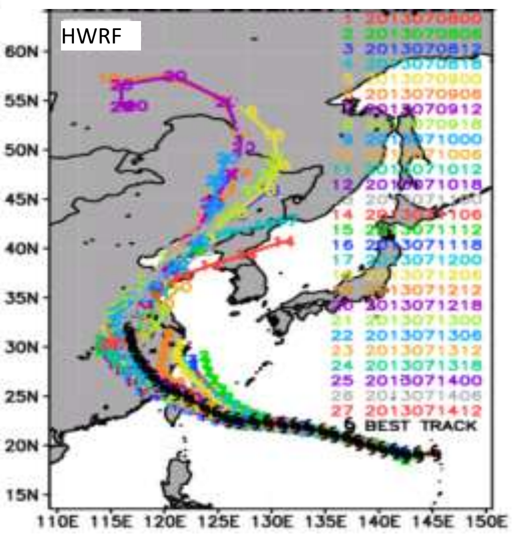




Typhoon Soulik as seen by MTSAT





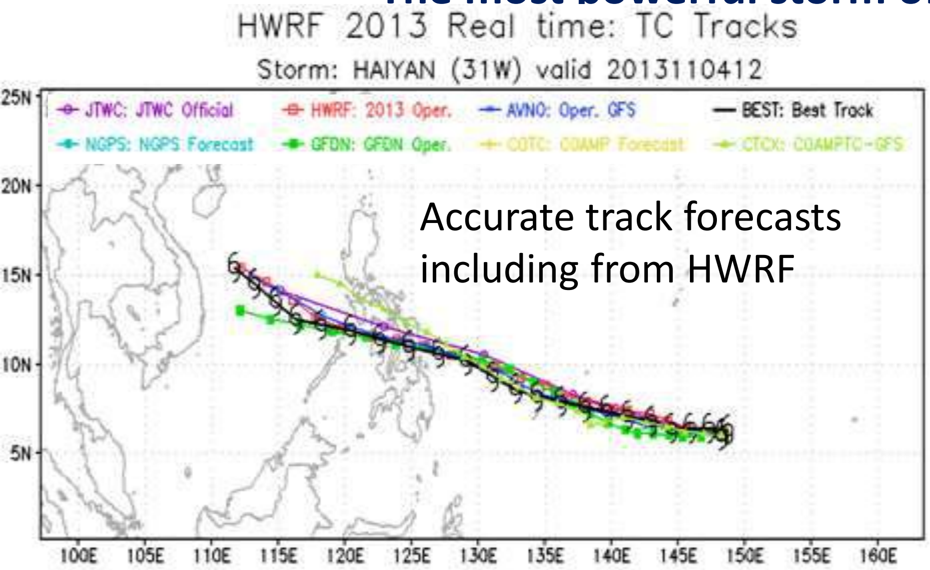


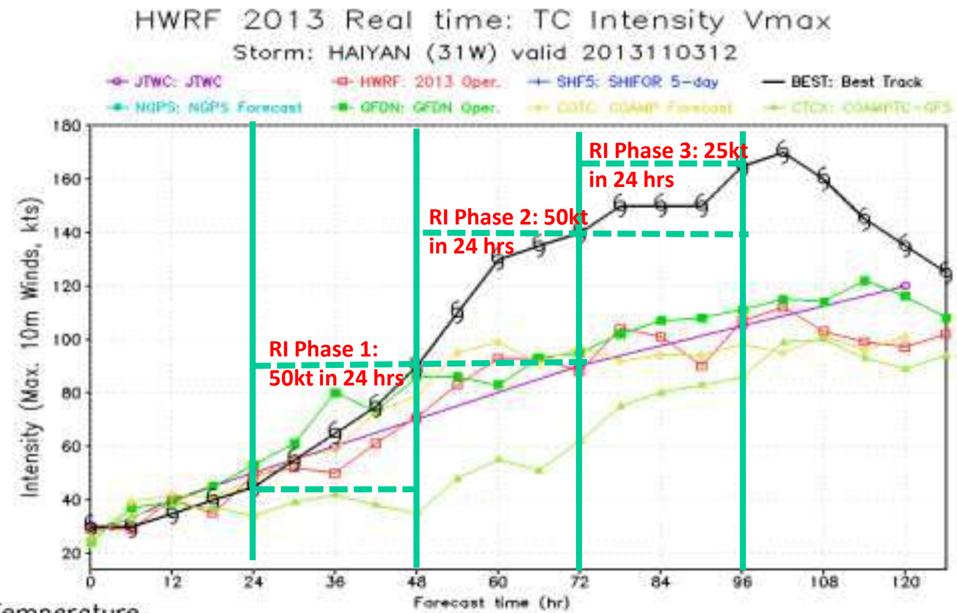
Formed; July 7, 2013
Dissipated: July 15, 2013
Highest winds 10-minute sustained: 185 km/h (115 mph), Lowest pressure: 925 mb
Fatalities: 11 total
Damage: USD $557 million
Areas affected Ishigaki Island,Batanes, Taiwan, Fujian, Zhejiang, Jiangxi,Guangdong

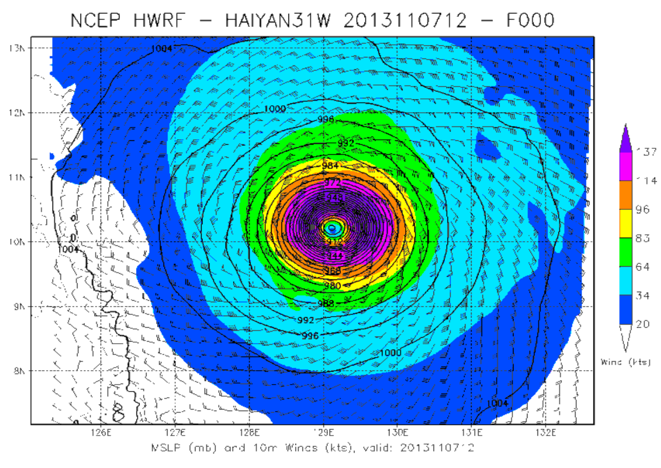
Source: Wikipedia

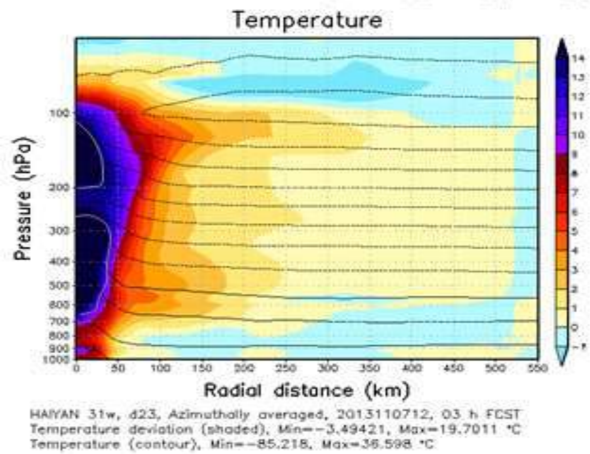
HWRF in 2013 West Pac: Typhoon Haiyan

The most powerful storm of 2013: Super Typhoon Haiyan





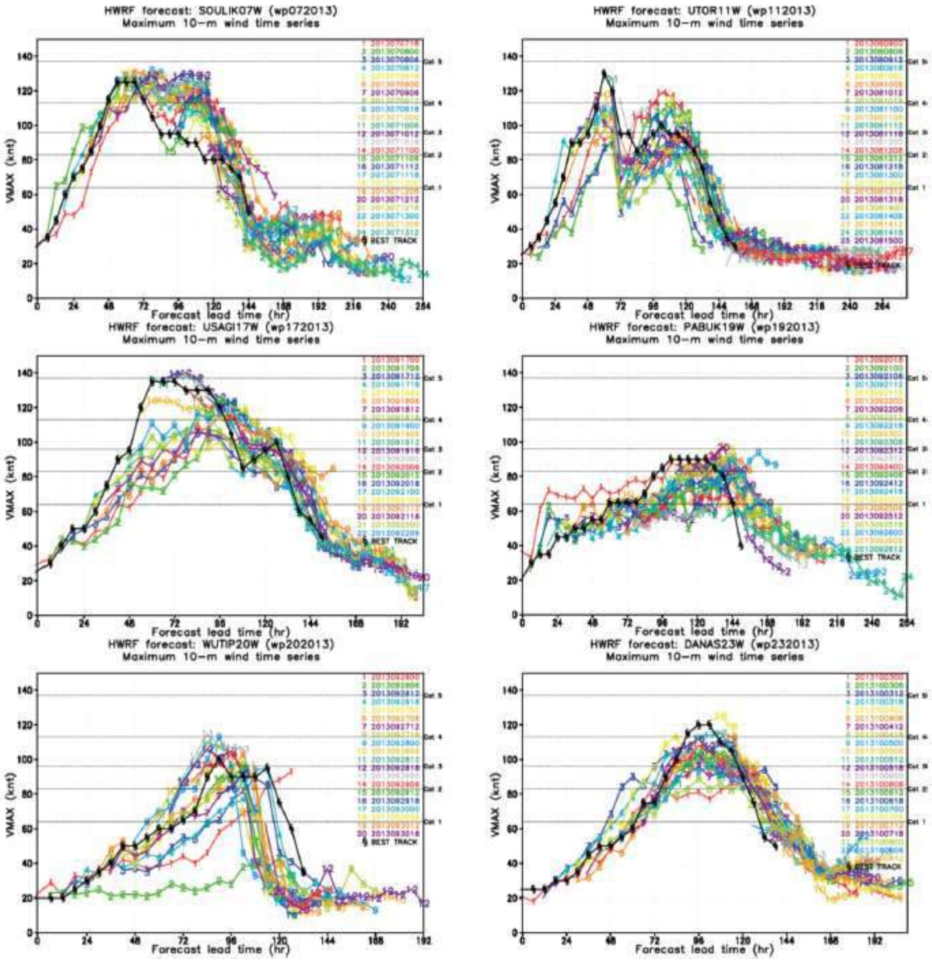


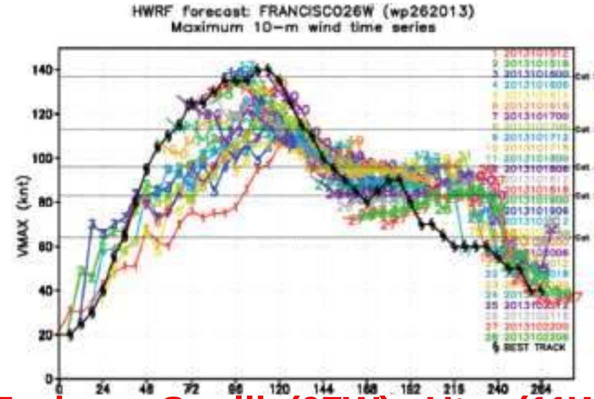


Models showed intensification trend, but failed to match the RI magnitude despite impressive structure predictions from HWRF including distinct double warm core at peak intensity

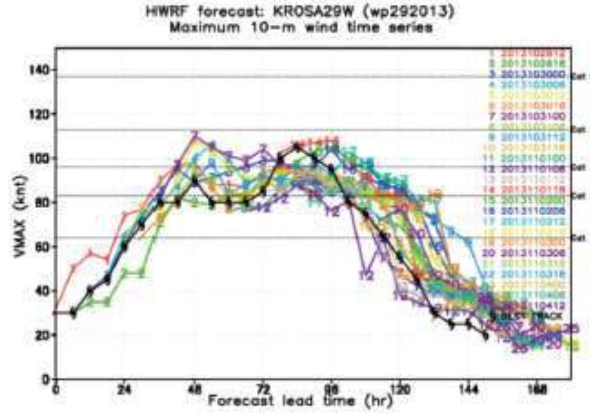
RI Forecasts for all storms in the WPAC Basin in 2013

HWRF captured RI for all 10 Super Typhoons of 2013

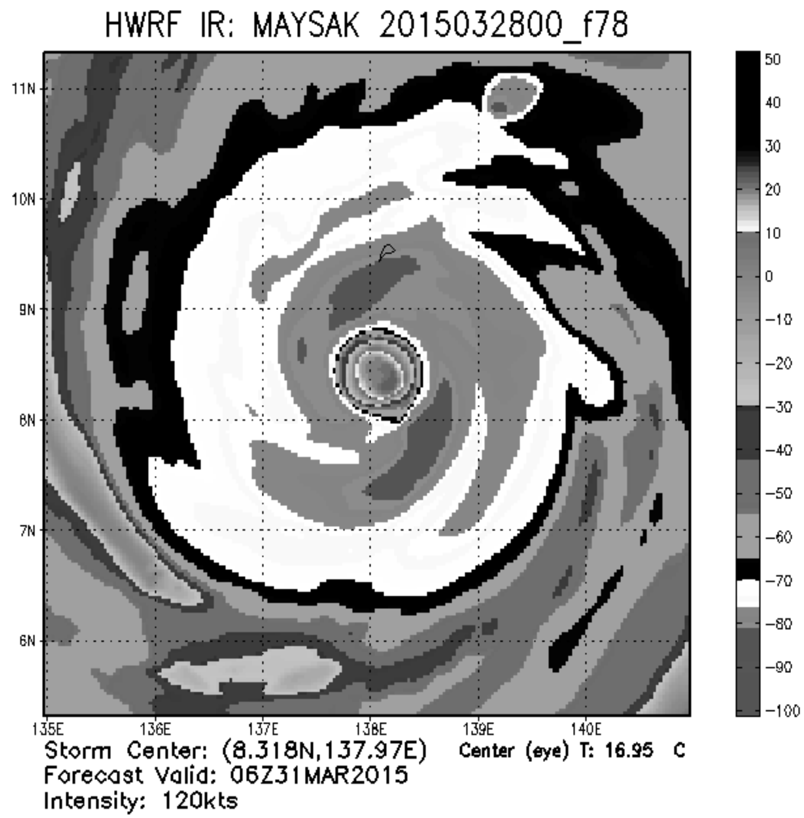




Typhoon Soulik (07W) , Utor (11W), Usagi (17W), Pabuk (19W), Wutip (20W), Danas (23W), Nari (24W), Francisco (26W), Lekima (28W), Krosa (29W), and Haiyan (31W).

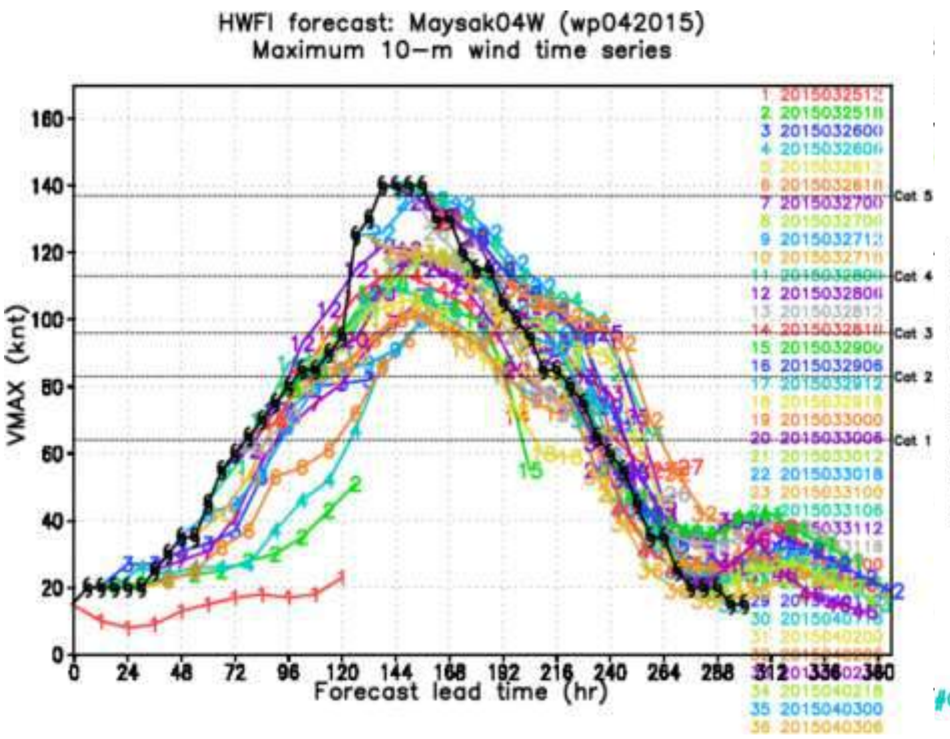


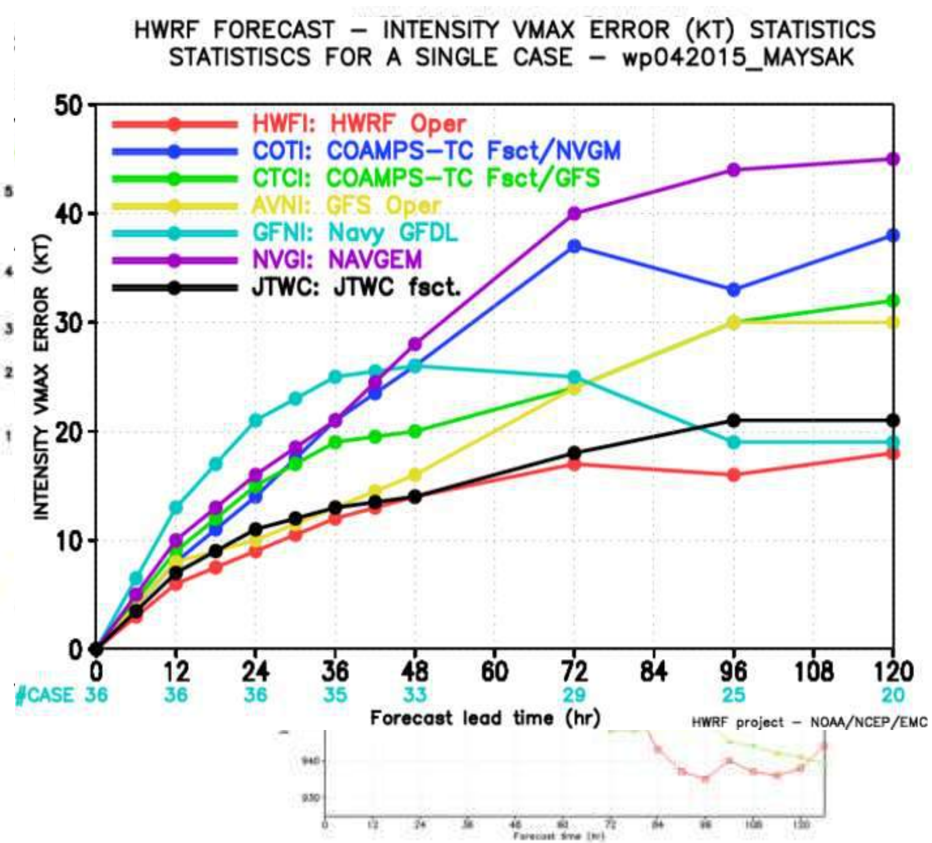
78-hr HWRF Forecast location and intensity valid at 00Z 28 March 2015 for Typhoon Maysak



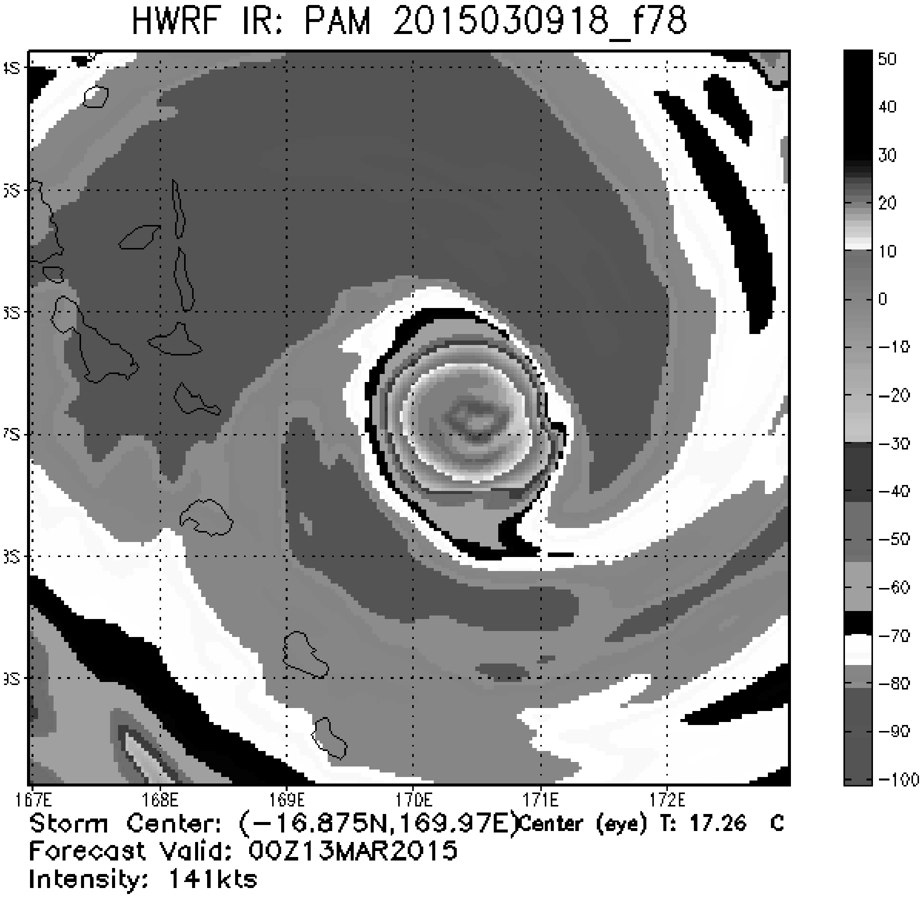
Observed intensity: 140 kts
78-hr Predicted intensity: 120 kts

Real-time Forecasts from HWRF: 60hrs before pass over Chuuk State and 84hrs before reaching Category 5



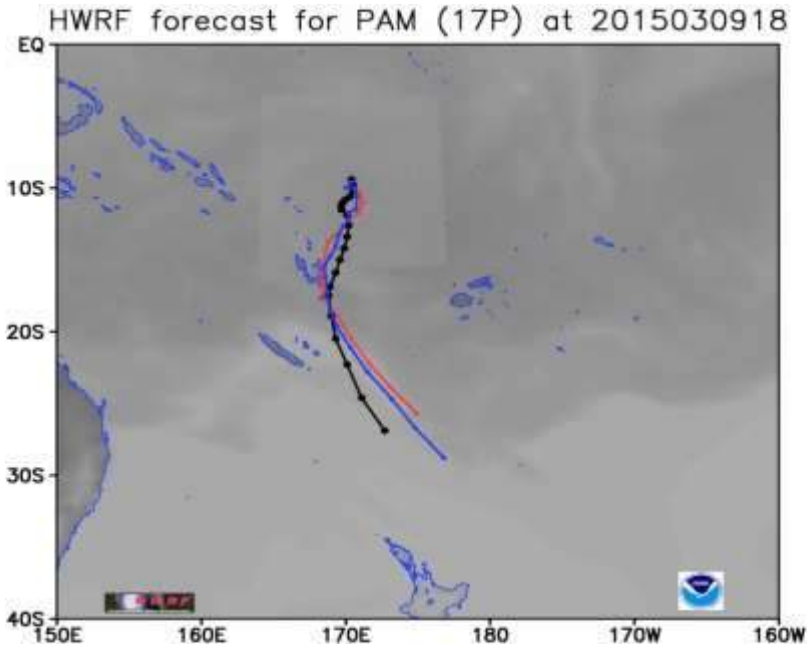


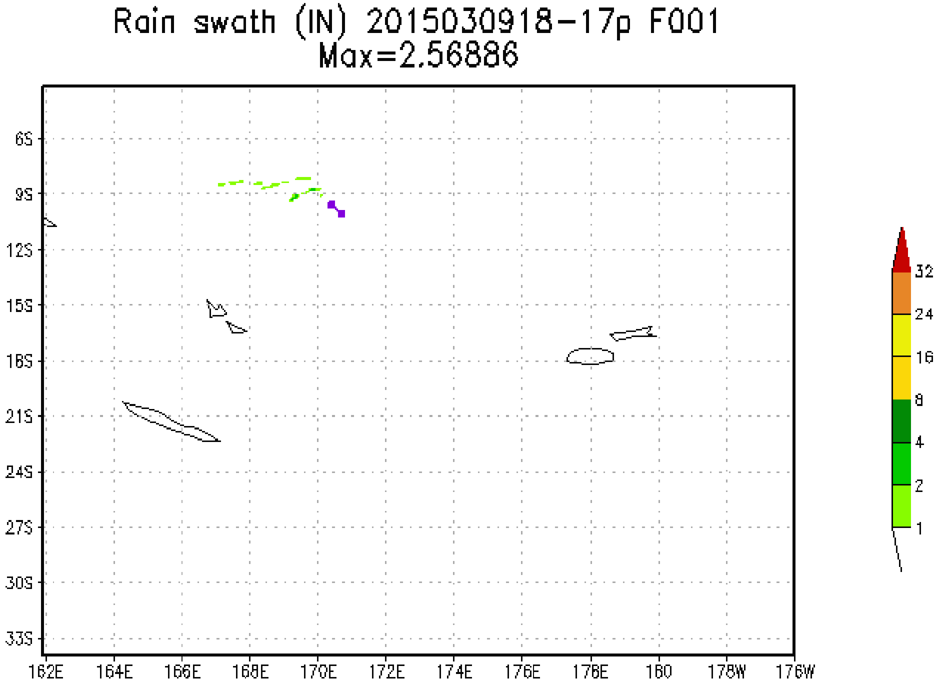
78-hr HWRF Forecast location and intensity valid at 00Z 13 March 2015 for TC Pam



Observed intensity: 140 kts
72-hr Predicted intensity: 141 kts

High-Resolution Animations of Simulated Radar Reflectivity, IR Imagery and accumulated rain swath for Tropical Cyclone PAM





60-hrs before reaching category 5 of Tropical Cyclone PAM:
HWRF (red), GFS (blue) and **Best Track (Black)**

Tropical Cyclone PAM captured by the HWRF outer domain

Phase-lock between warm core, storm strength and mid-level moisture at RI Onset

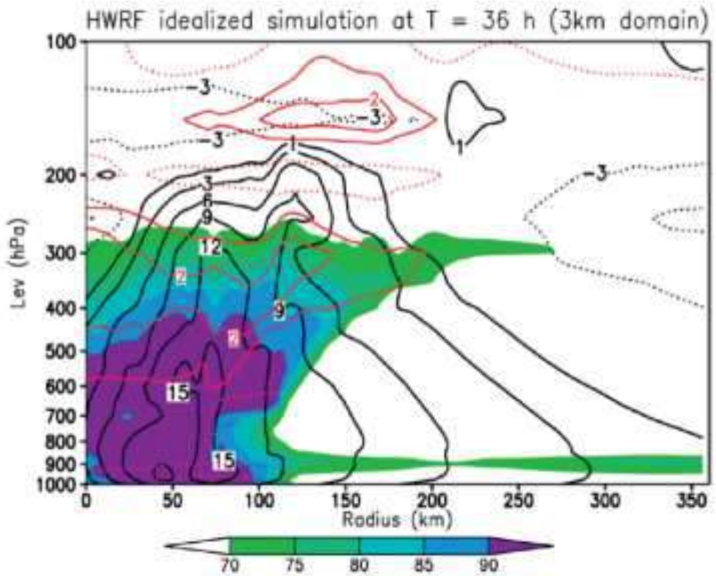
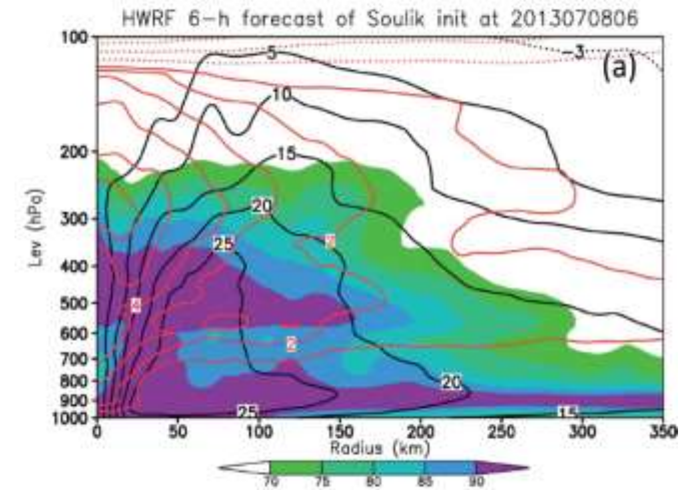


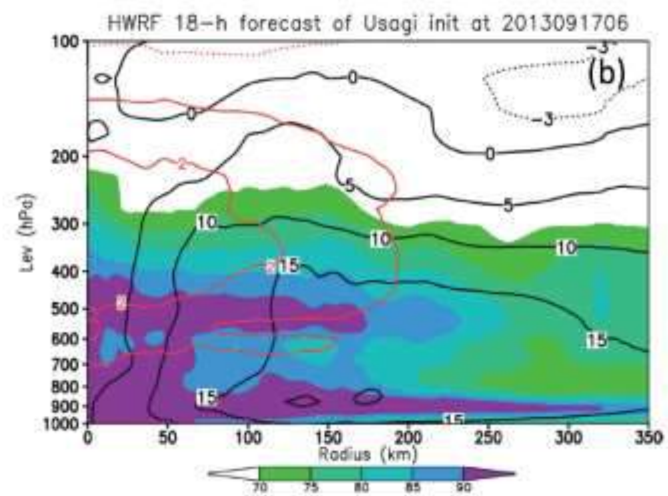
FIG. 1. Radius-height cross section of the relative humidity (shaded, unit %), the tangential wind (black contours at intervals of 3 ms^{-1}), and potential temperature anomalies with respect to the far-field environment (red contours at interval of 1^{o}K, solid/dotted contours for positive/negative values) in an idealized experiment with the HWRF model (Kieu *et al.* 2014).

All idealized exps show a consistent structure at the onset of RI including a warm core at 500-300 hPa, a saturated core from surface to ~ 500 hPa, and sufficient tangential wind (> 18 ms^{-1})

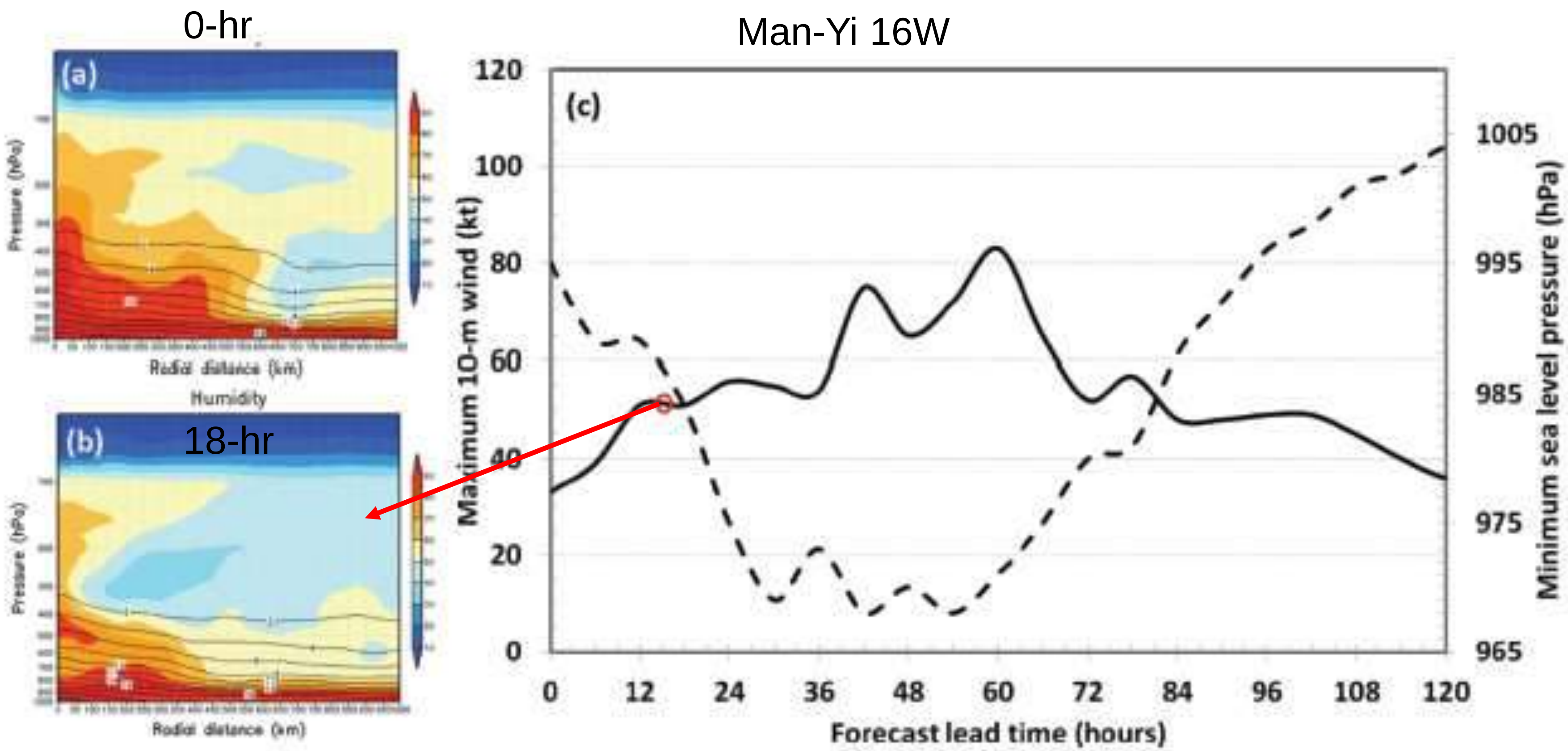
Of all ~100 real-time RI cases in the WPAC from HWRF we analyzed, the phase-lock mechanism is observed in all of them at the time of RI onset.

Phase-lock conditions are necessary but not sufficient for triggering the RI. Interactions with dry air, topography etc. could prevent the model to experience RI even after possessing the phase-lock conditions



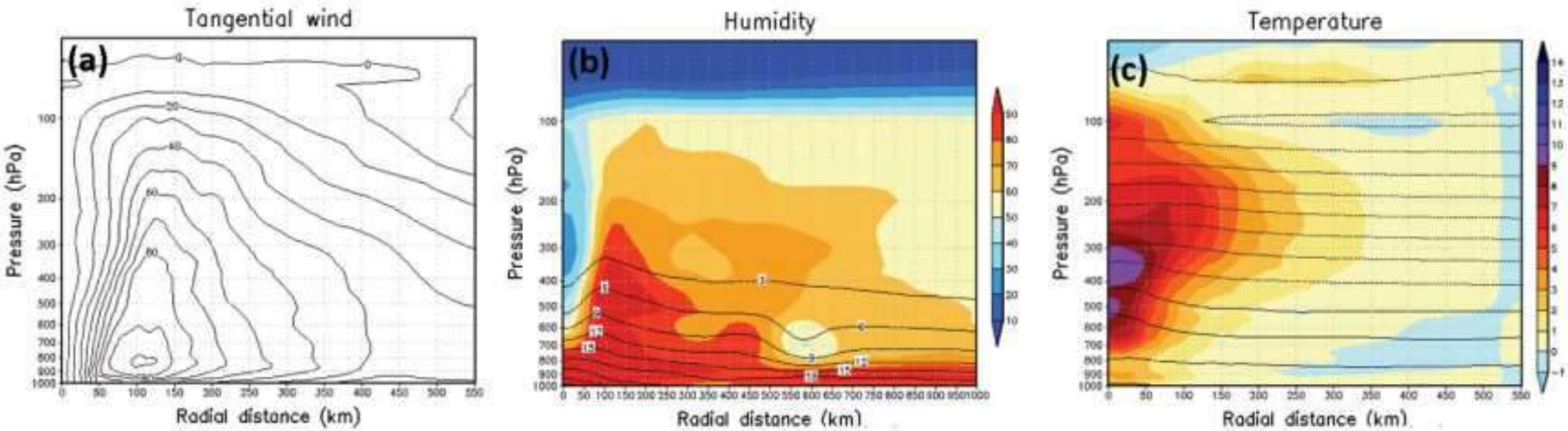


Phase-Lock not sufficient for RI: Influence of external factors: Land interaction



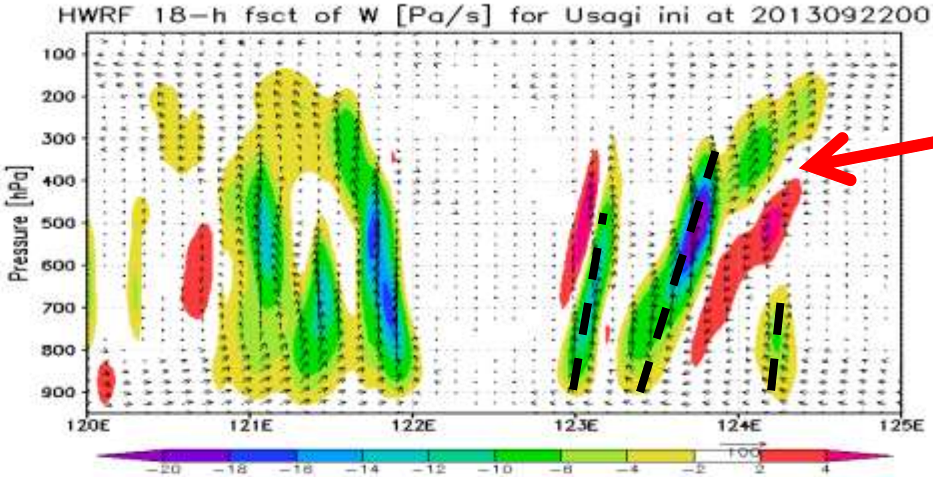
Phase-lock mechanism seen in non RI events as well – however, RI was not imminent for several cases due to "external" factors (here, it is land interaction for Typhoon Man-Yi 16W, 12Z Sept. 13, 2013

HWRF fails to predict RI when the initial storm is >hurricane strength

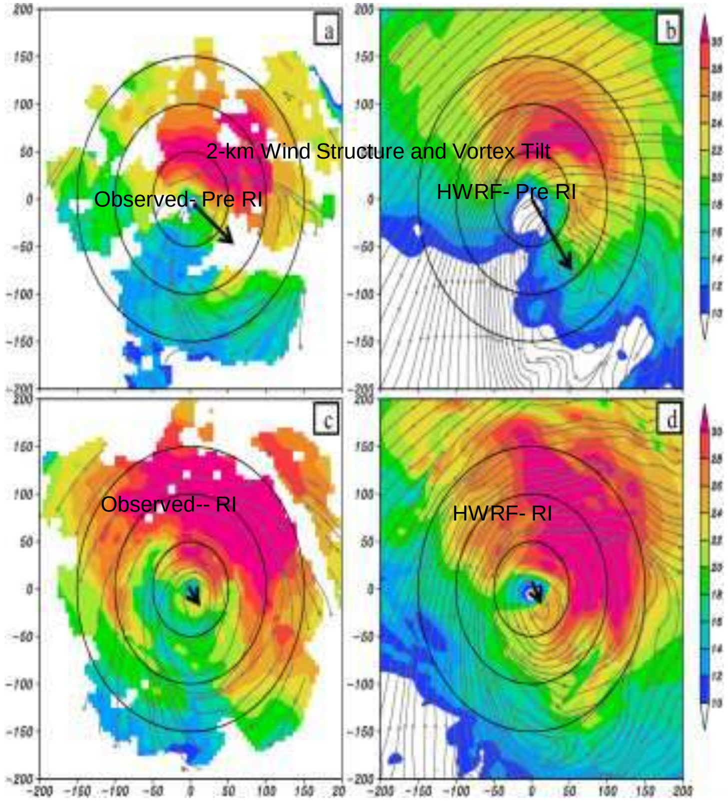


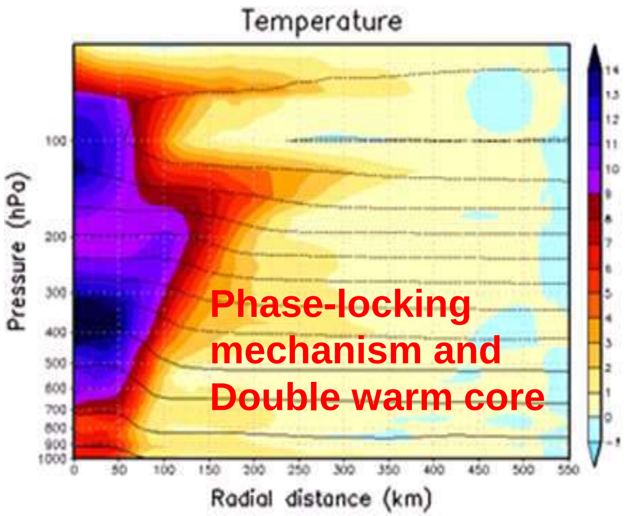
Vertical cross-sections of (a) tangential wind (ms^{-1}); (b) relative humidity (shaded %) and specific humidity (contours, g/kg) and (c) temperature anomaly (shaded, K) and absolute temperature (contours, K) for the mature state of Super Typhoon Usagi (17W) after 48-h into integration, initialized at 0000 UTC 19 September 2013.

Additional findings from HWRF on Rapid intensification



Triple eye-wall formation and subsequent eye-wall replacement for Typhoon Usagi (insufficient temporal frequency of output)

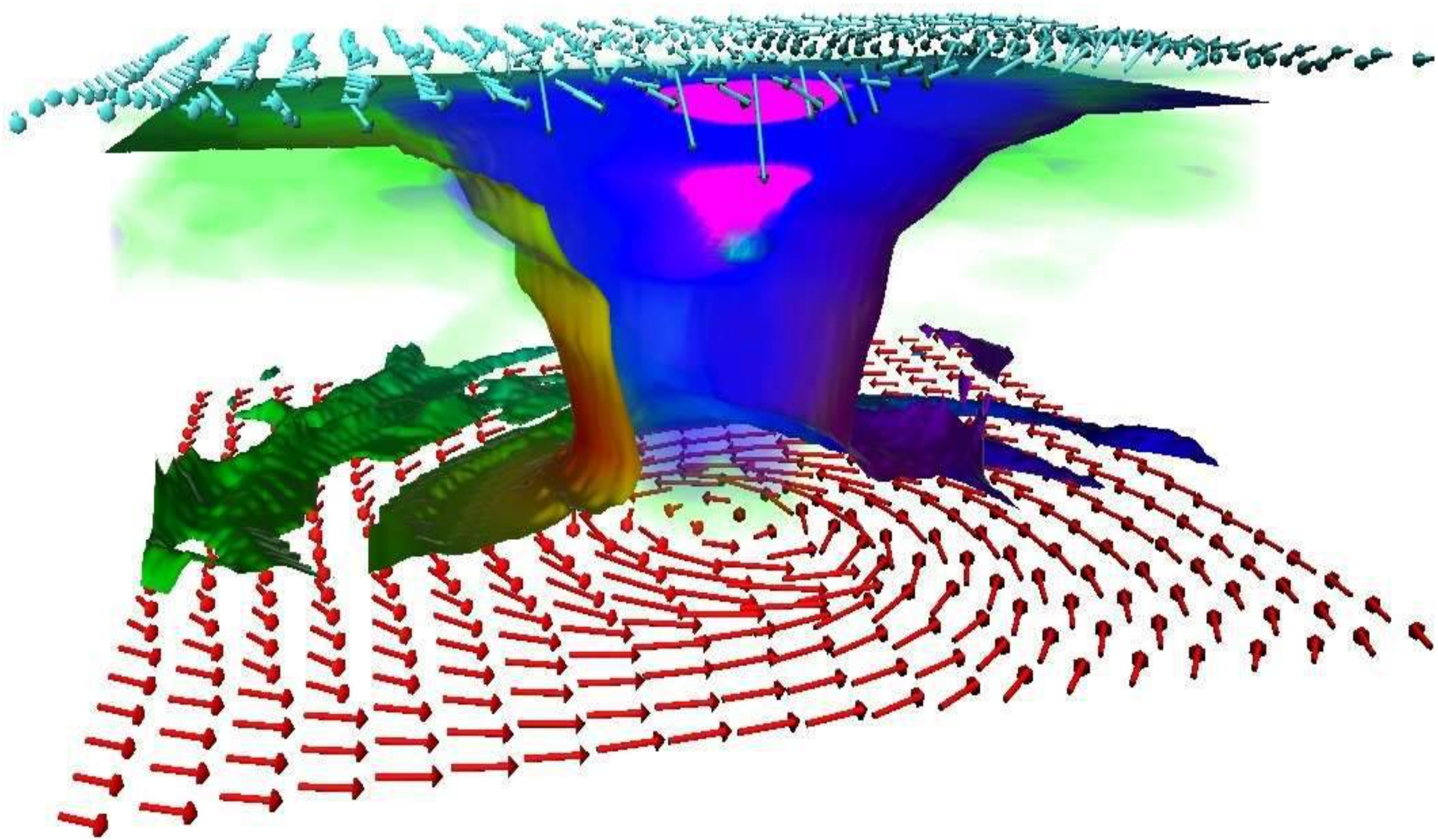




Phase-locking mechanism and Double warm core

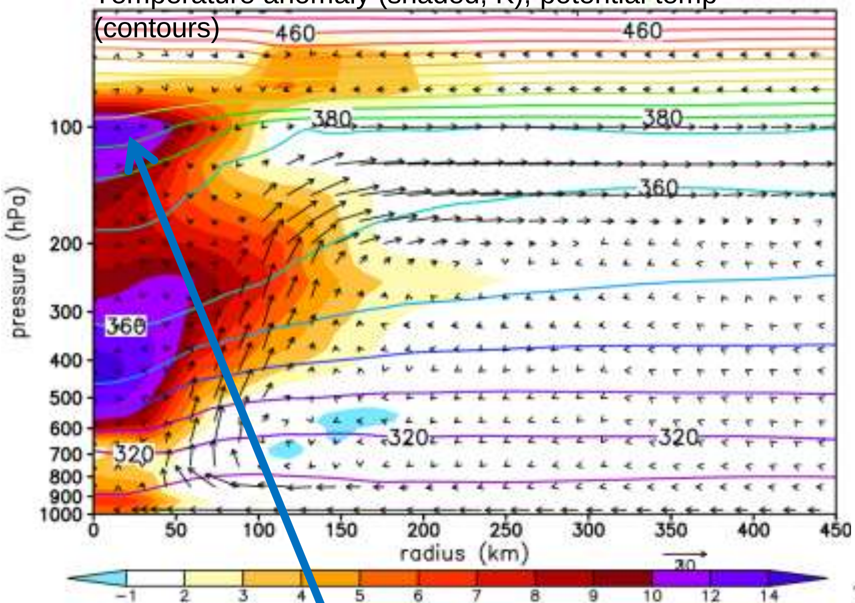
Asymmetric RI for H. Earl matching observed findings from NOAA P3 TDR

Question: Is DWC a realistic phenomena?



HWRF double-warm core structure

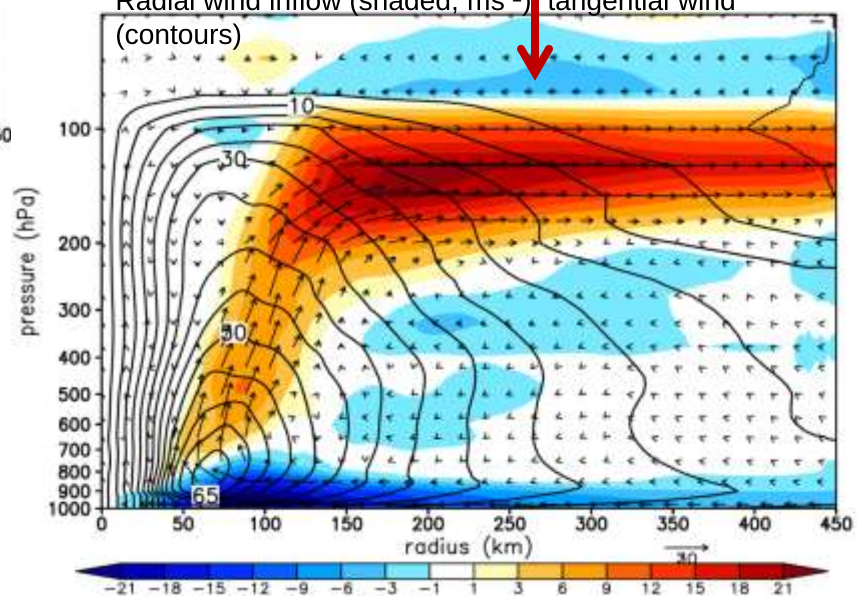
Temperature anomaly (shaded, K), potential temp (contours)



Persistent double warm core structure for all STY cases during 2012-2015 seasons

Strong upper-level inflow above the typical outflow layer

Radial wind inflow (shaded, ms^{-1}), tangential wind (contours)



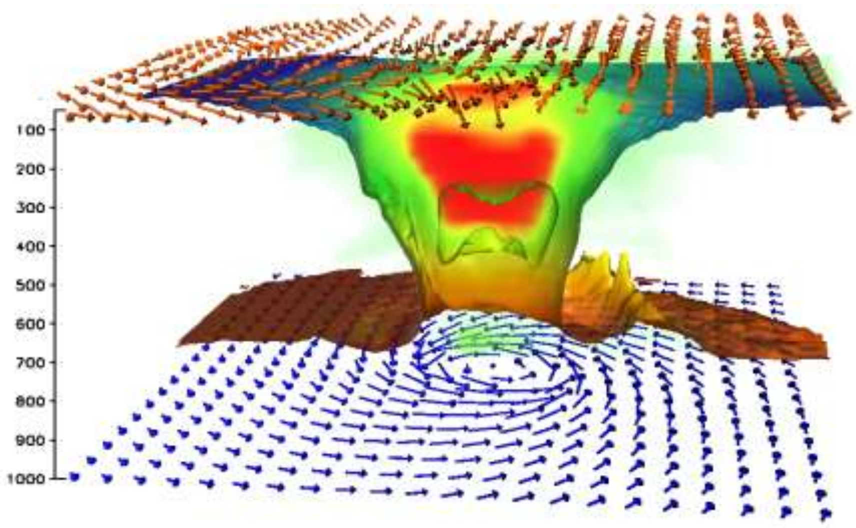
Hypotheses

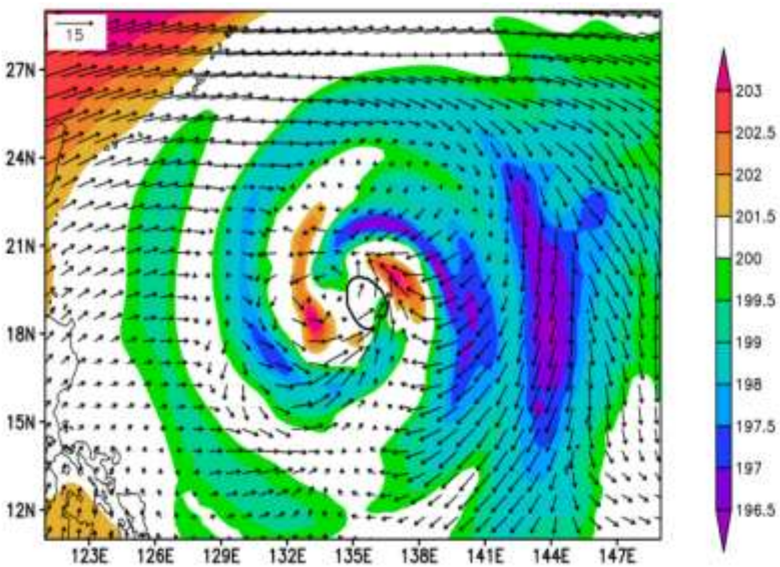
- Hypothesis 1: At high intensity (Vmax > 65 ms^{-1}), the lower stratosphere can interact with TCs and produce a DWC structure, allowing TCs to further strengthen and maintain their high intensity.

- Hypothesis 2: The lower stratosphere can moderate the distribution of intense TCs and thus play a significant role in the TC-climate relationship.

Case study: DWC structure

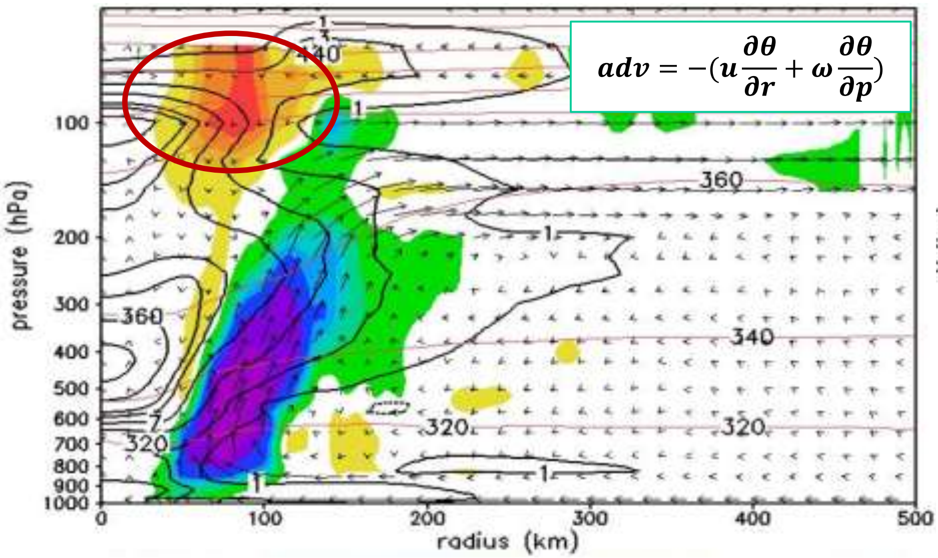
3D cross section at 72-h of Francisco initialized at 1200 UTC 17 July 2013,



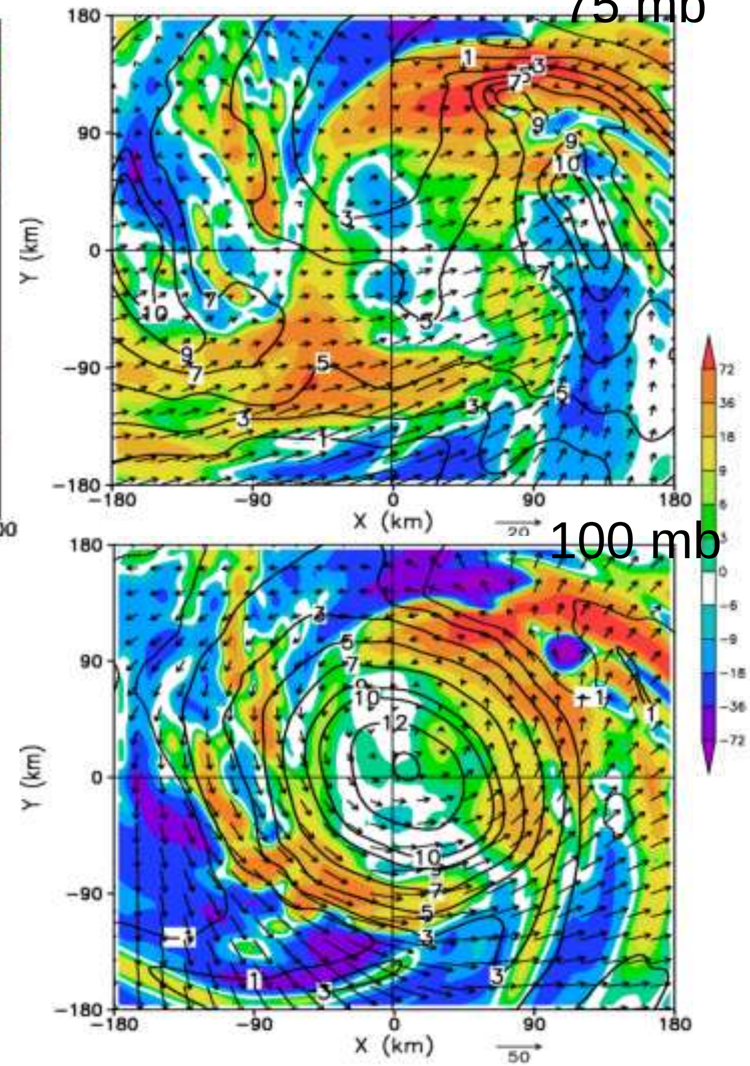


Upper level inflow (UIL) is wide spread and is above the outflow (at 75hPa)

Case study: UIL-induced warming tendency



$$adv = -\left(u\frac{\partial\theta}{\partial r} + \omega\frac{\partial\theta}{\partial p}\right)$$

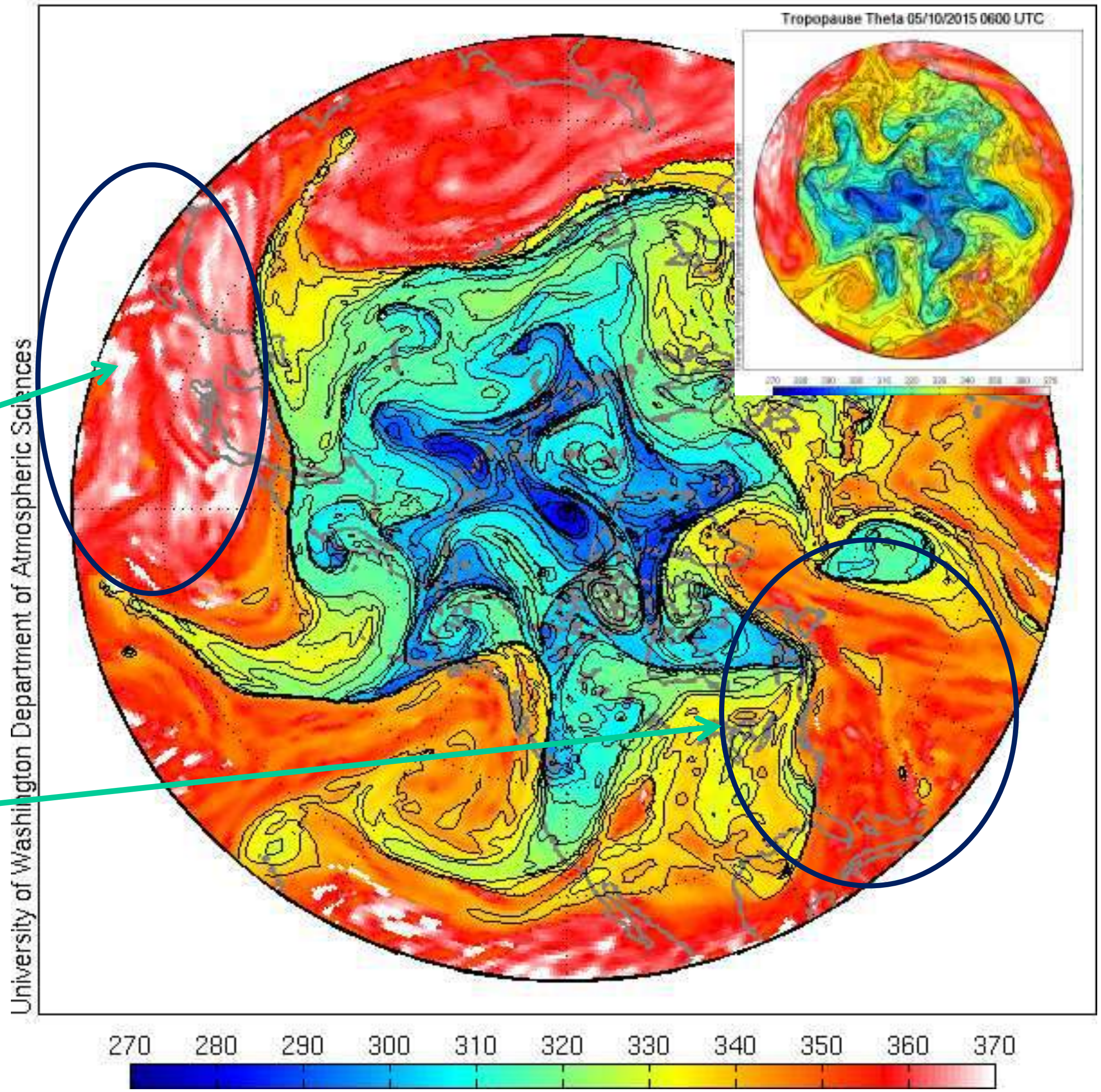


UIL could induce a substantial amount of warm advection from the lower stratosphere toward storm center;

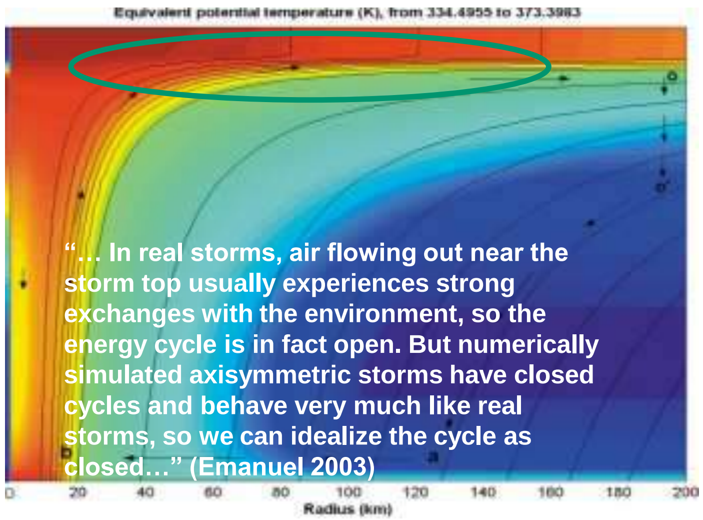
Low stratosphere: NATL/WPAC 2013

WPAC: more TCs with double warm core??? How about the higher MPI with colder outflow temperature?

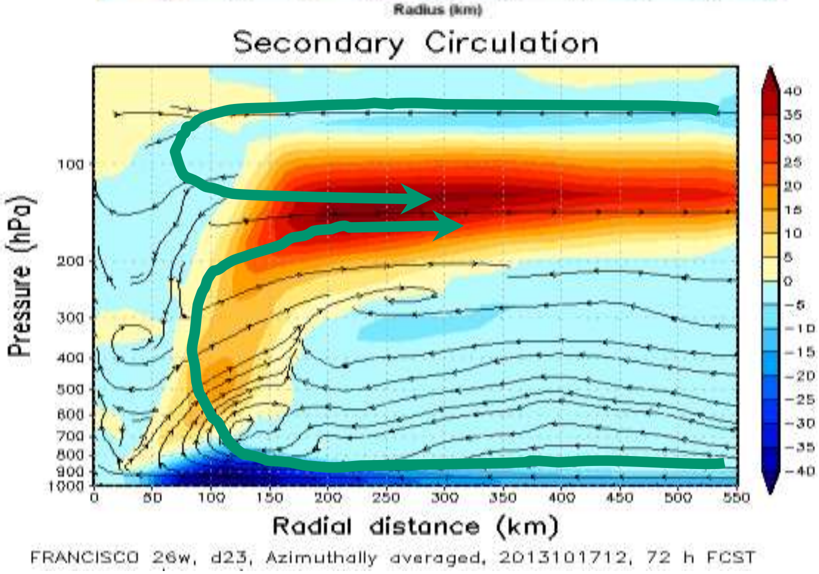
NATL: less TCs with no double warm core



Implications

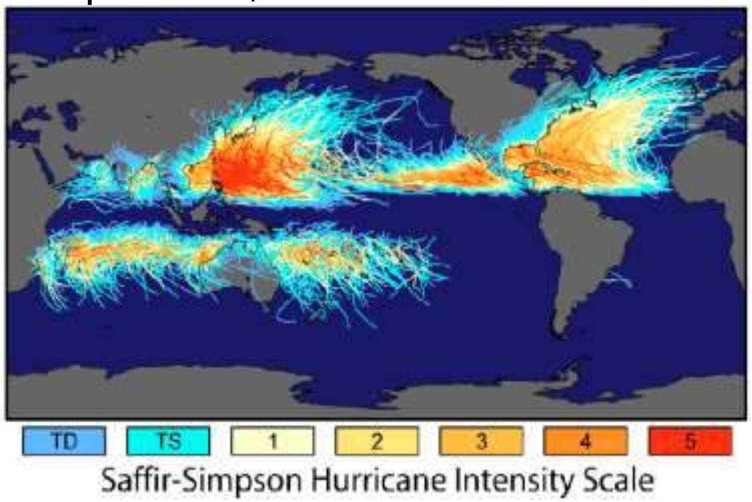


"… In real storms, air flowing out near the storm top usually experiences strong exchanges with the environment, so the energy cycle is in fact open. But numerically simulated axisymmetric storms have closed cycles and behave very much like real storms, so we can idealize the cycle as closed…" (Emanuel 2003)

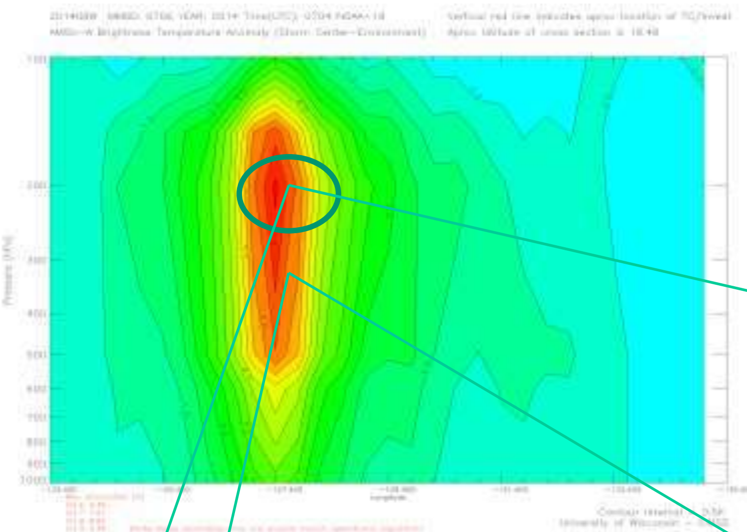


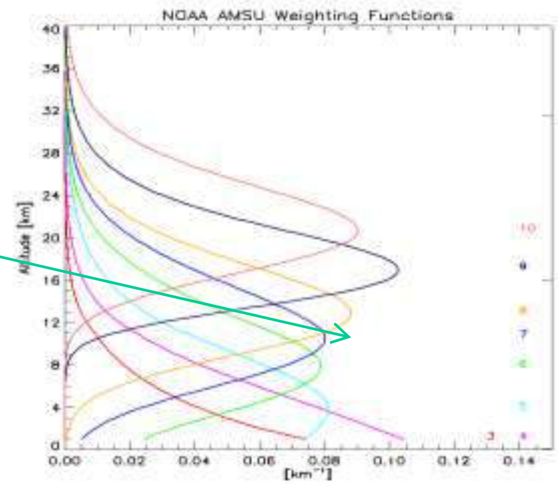
The DWC structure may go outside the traditional framework of a TC with a single warm core.

Distribution of intense TCs should take into account the lower stratosphere beyond the outflow temperature;

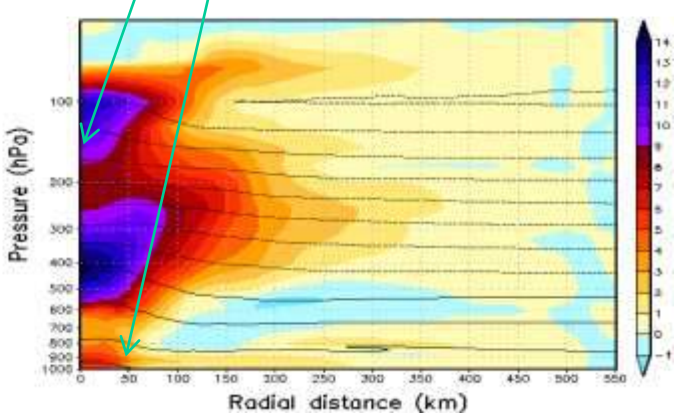


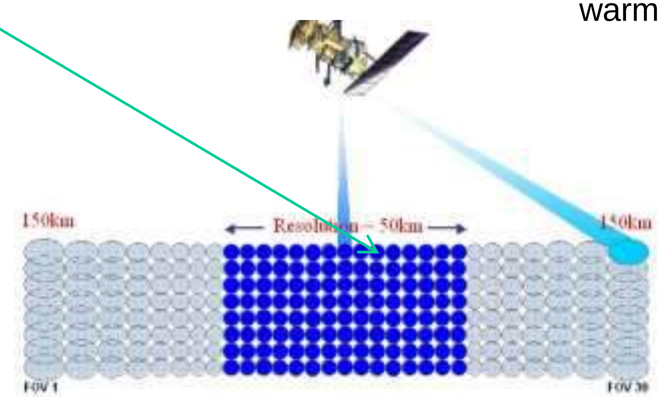
Can we see DWC from AMSU data?





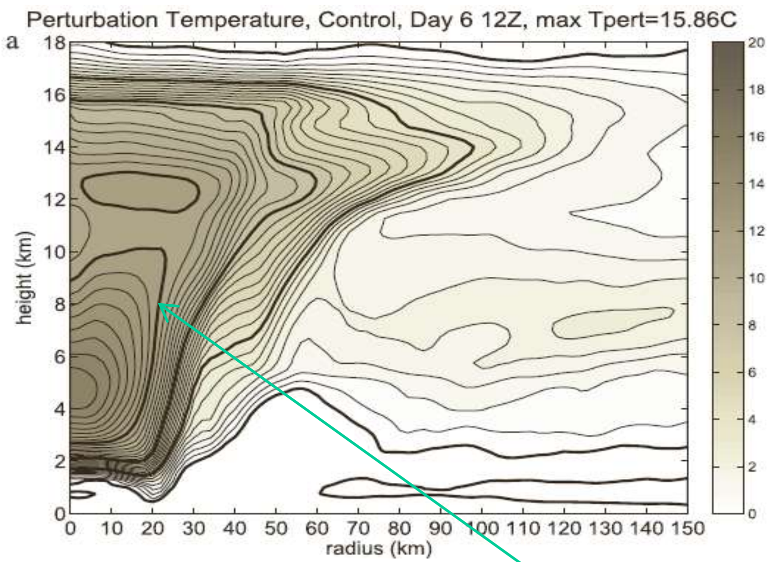
- 50 –km resolution from ATMS AMSU data is too coarse to resolve the DWC;
- AMSU channels 5, 6,7,8 appear to be insufficient to resolve the gap between 2 warm cores;

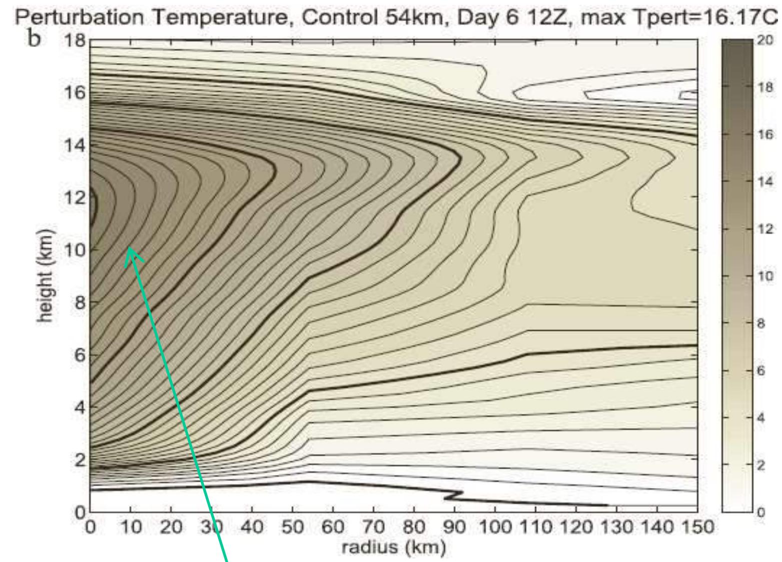


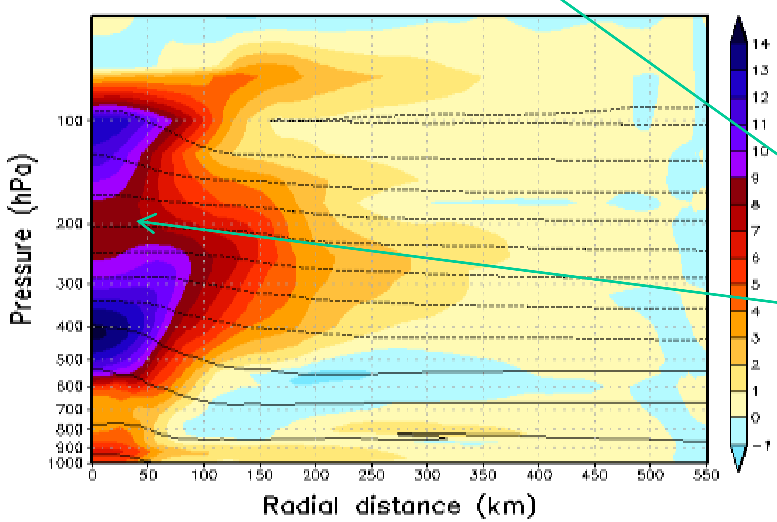


AMSU Scanning Geometry and Resolution

Can we see DWC from AMSU data?







The same DWC structure vanishes, using the thinning method for 50-km resolution (Stern and Nolan 2012)

DWC visible in high resolution idealized and real-time simulations

Secondary Eyewalls and Eyewall Replacement Cycles: New research frontiers for TC intensity

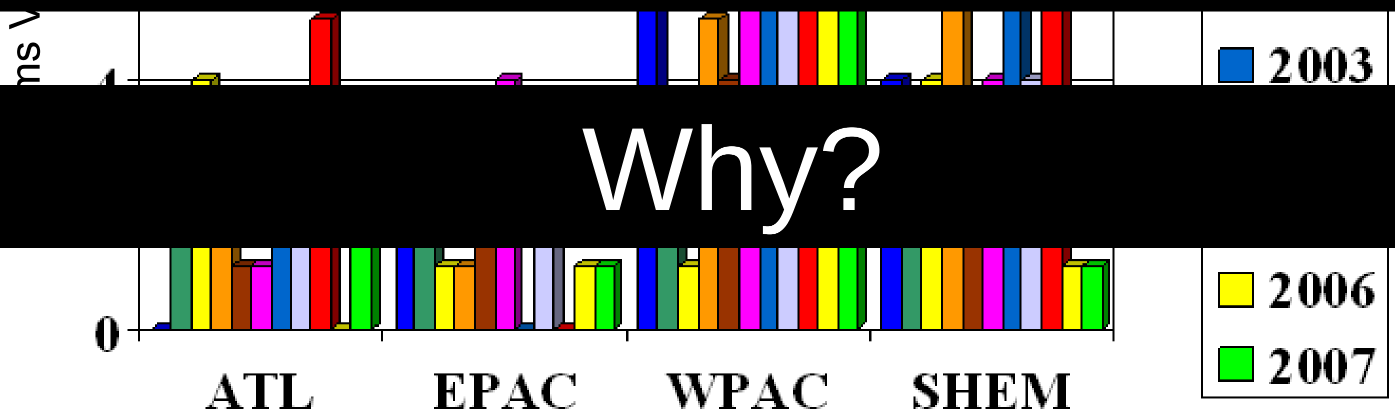
SEs are a common feature of intense storms

Not in mesoscale simulations!

~6% in AHW

~30% in HWRF

Why?



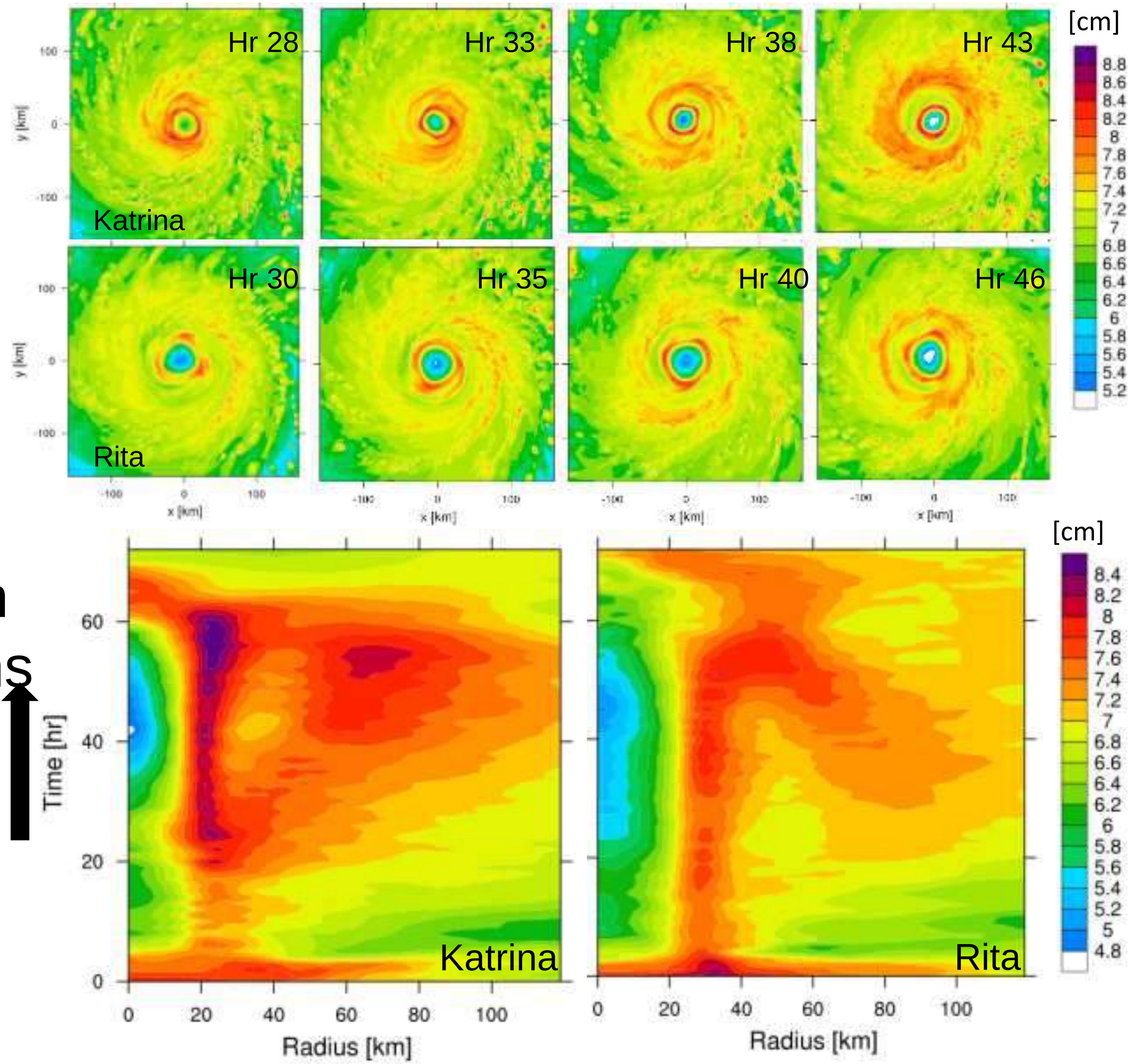
77% 56% 81% 50%

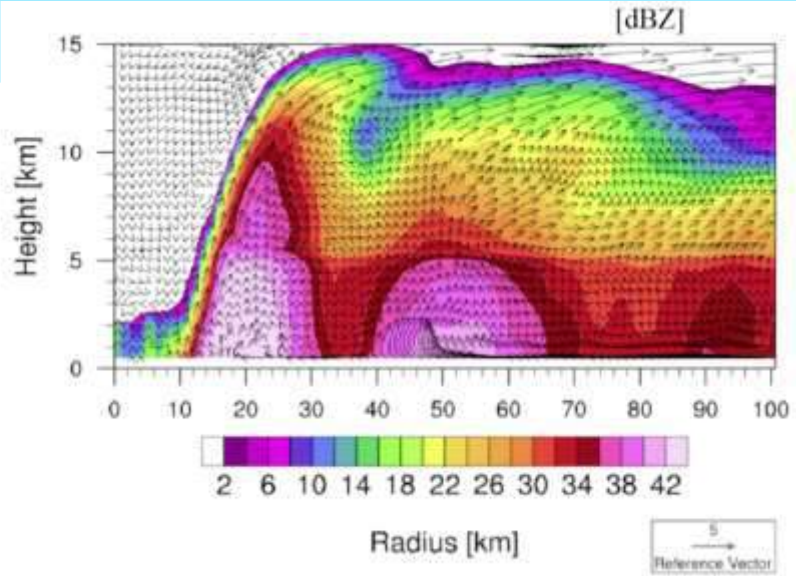
% with Concentric Eyewalls

Hawkins and Helveston (2008)

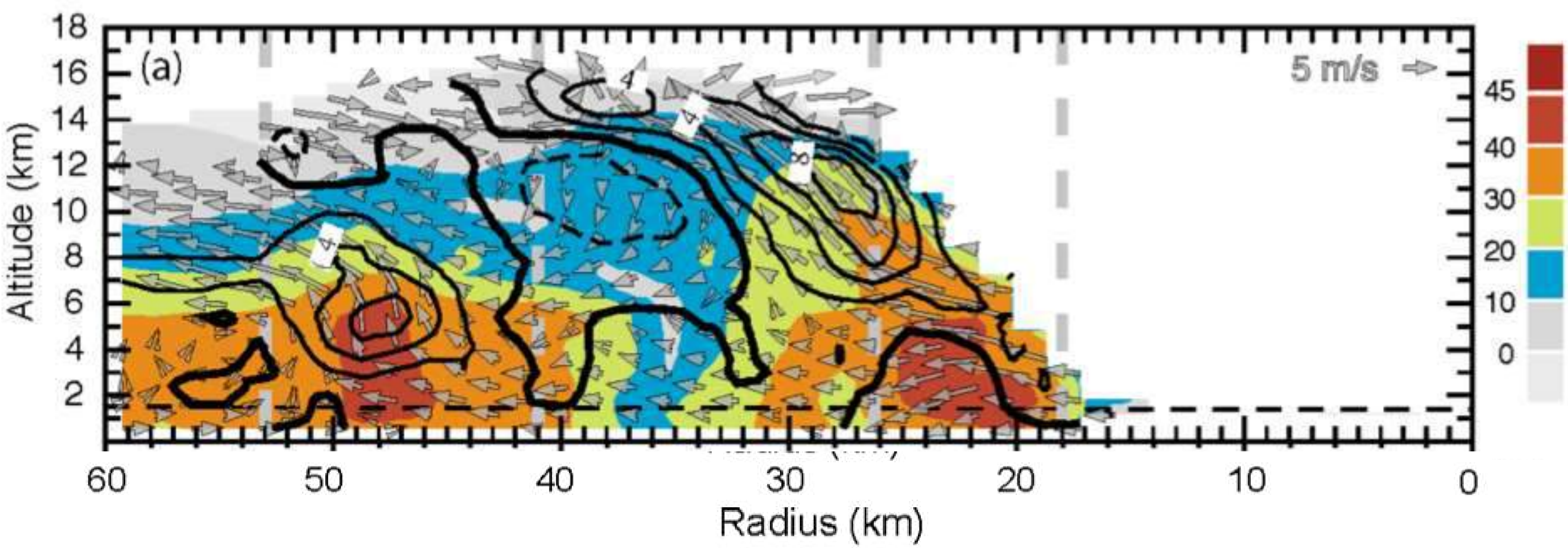
Precipitable Water (PW)

Secondary eyewall Formation in the simulations



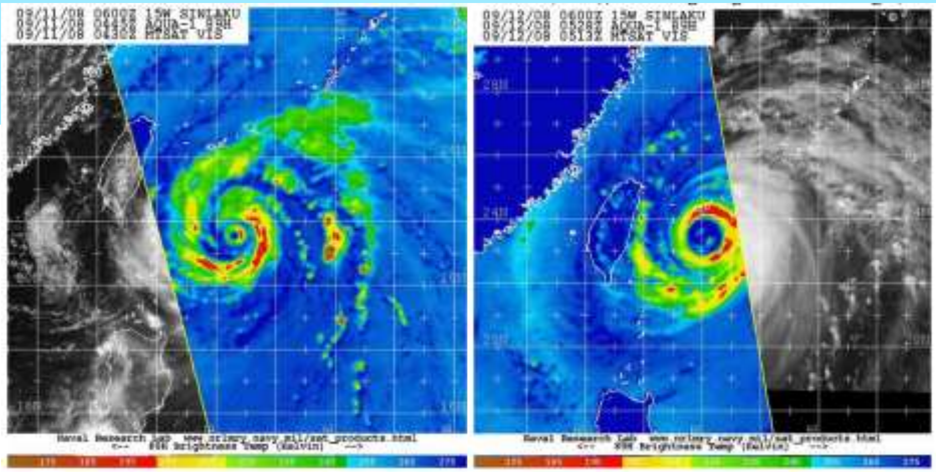


Abarca and Corbosiero (2015)



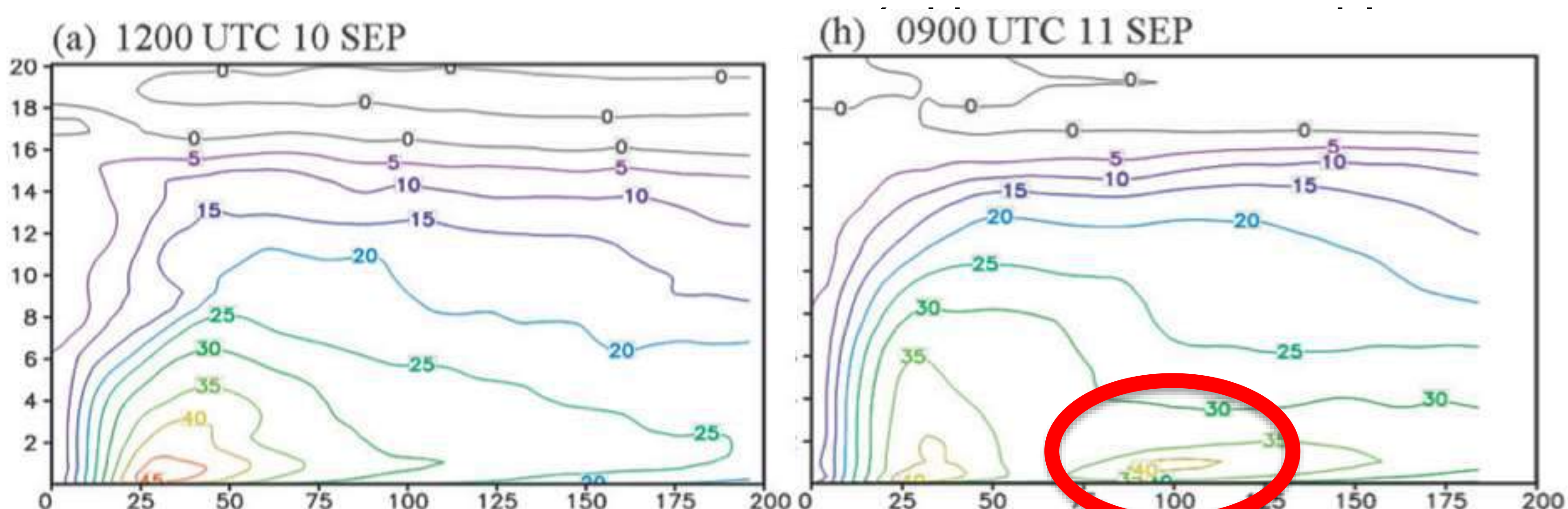
Observations

- Description of structures
- Evaluation of numerical simulations



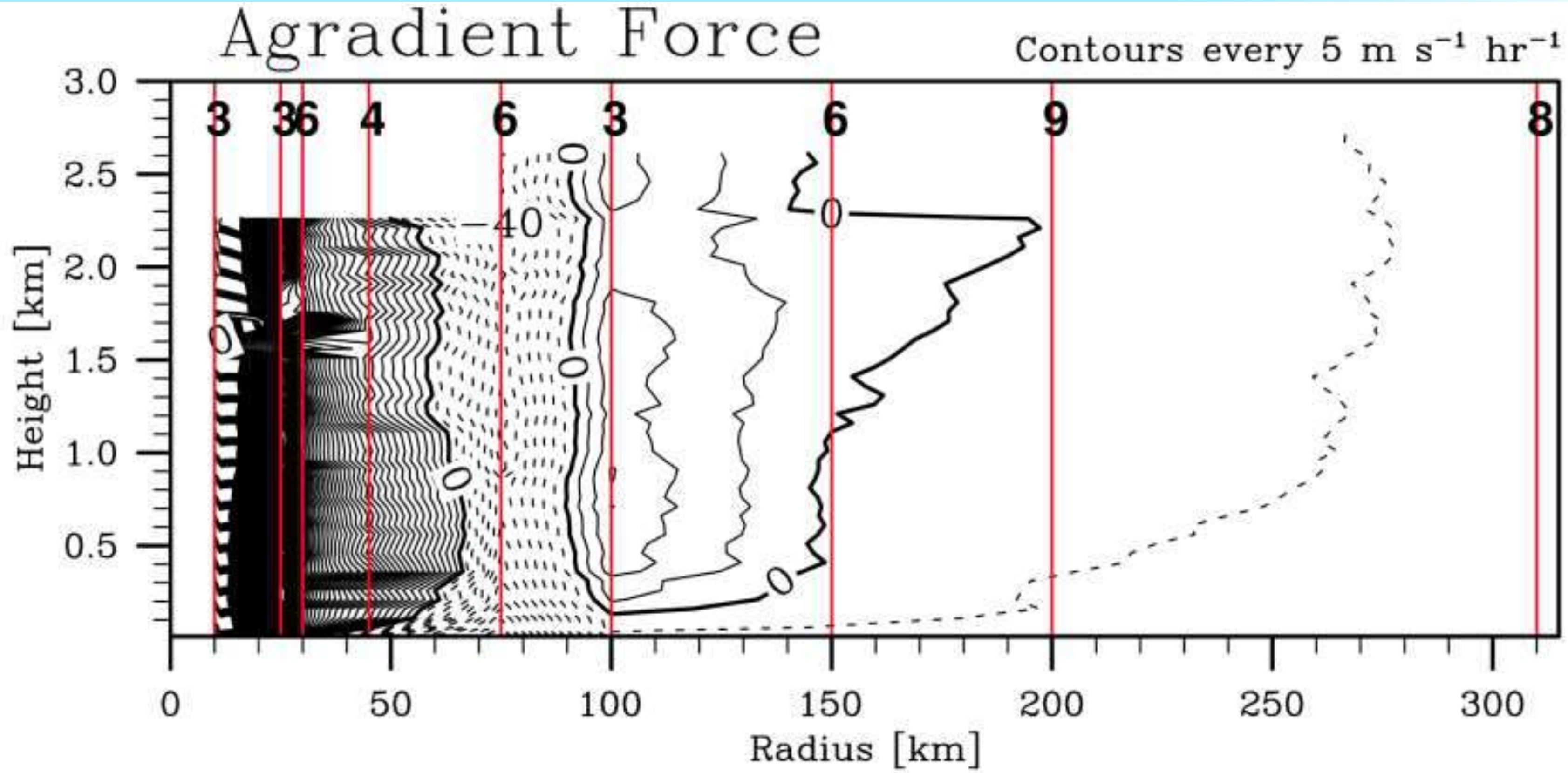
Typhoon Sinlaku (2008)

WRF



model/observation- consistent dataset

Wu et al. (2012)

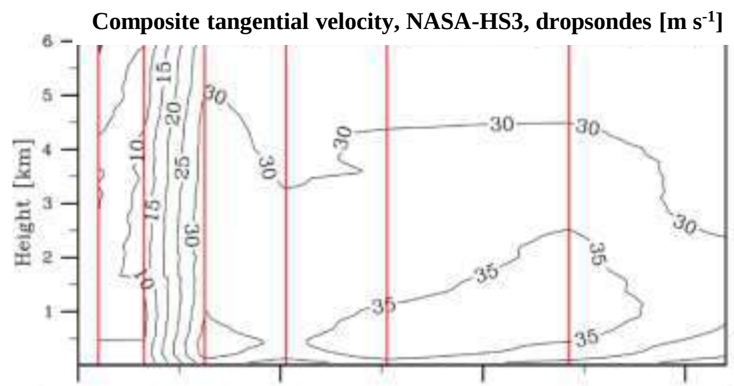


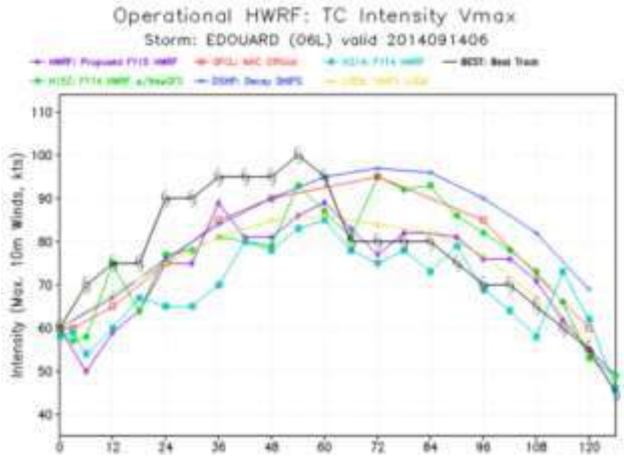
$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial r} - w\frac{\partial u}{\partial z} - \overline{u'\frac{\partial u'}{\partial r}} - \overline{w'\frac{\partial u'}{\partial z}} + \boxed{\frac{v^2}{r} + fv - \frac{1}{\rho}\frac{\partial p}{\partial r}} + F_u$$

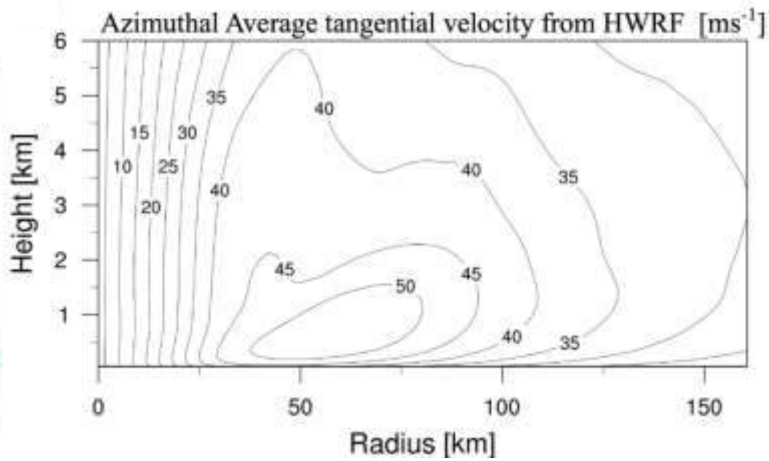
Supergradient flow during SEF

Edouard (2014)

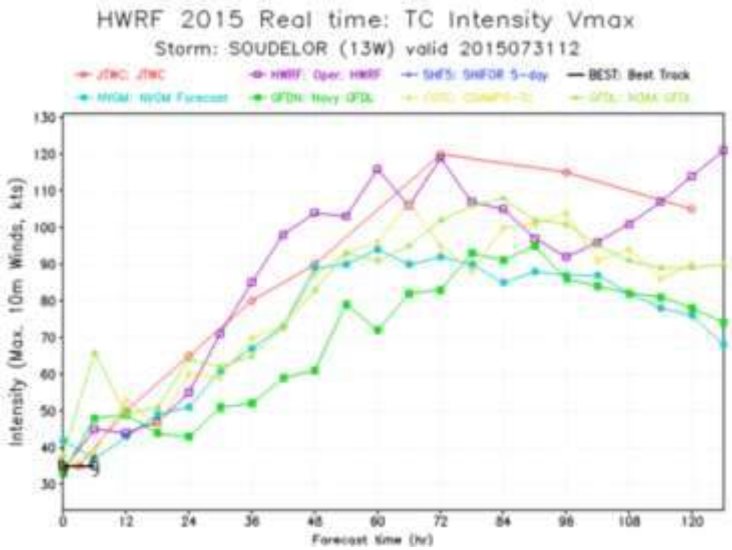
Secondary eyewall observed in
- ✓ **Nature**
- ✓ **HWRF 2015**

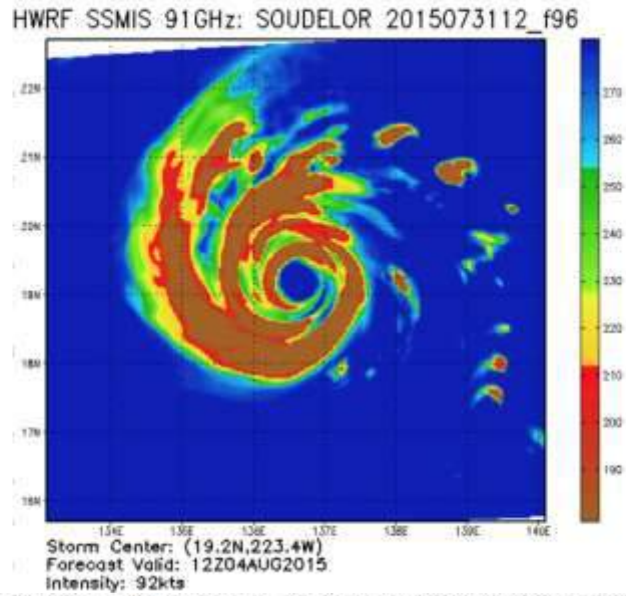


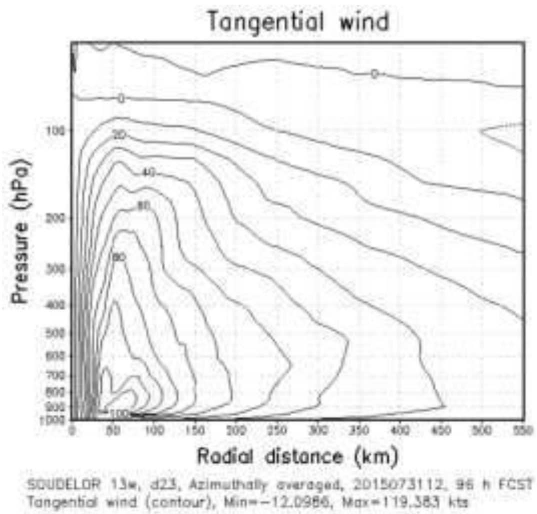




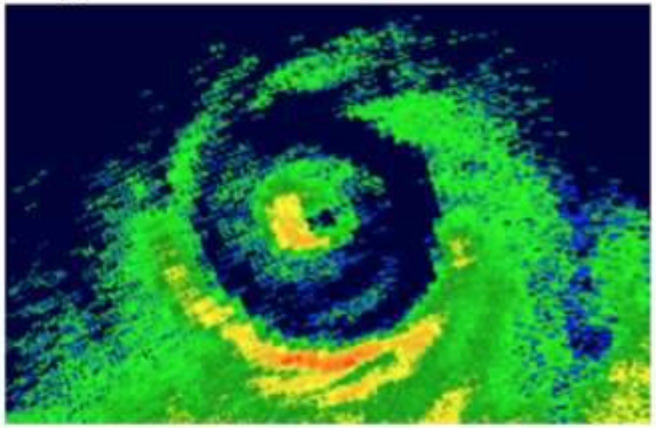
Operational HWRF generates secondary eyewalls
but they are rare, as in other mesoscale models (ARW or RAMs)





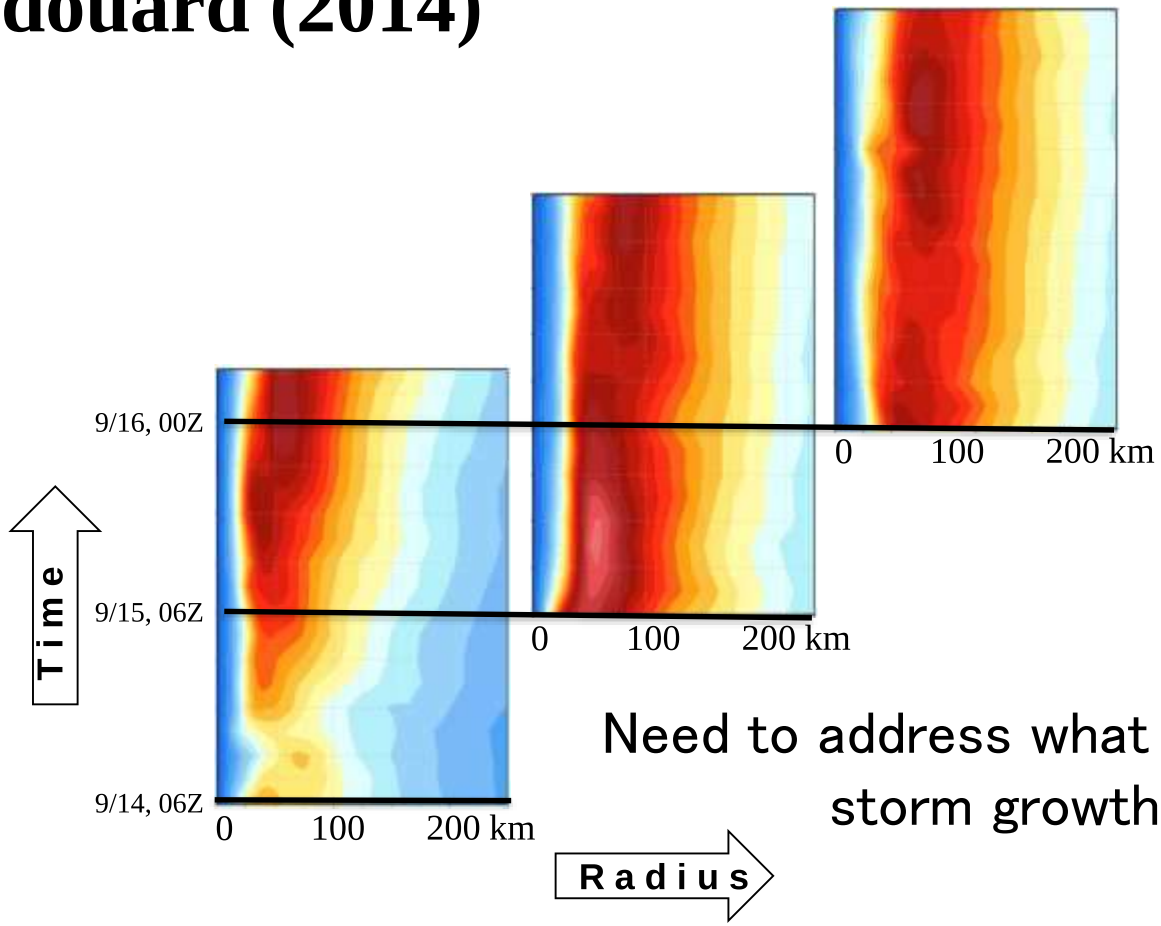


Reflectivity from the Guam radar on 8/03 0000 UTC



HWRF 2015
Edouard (2014)

<V>, [m s^{-1}]
900 hPa



Need to address what controls storm growth

Secondary eyewalls

It is now established that HWRF is capable of generating secondary eyewalls

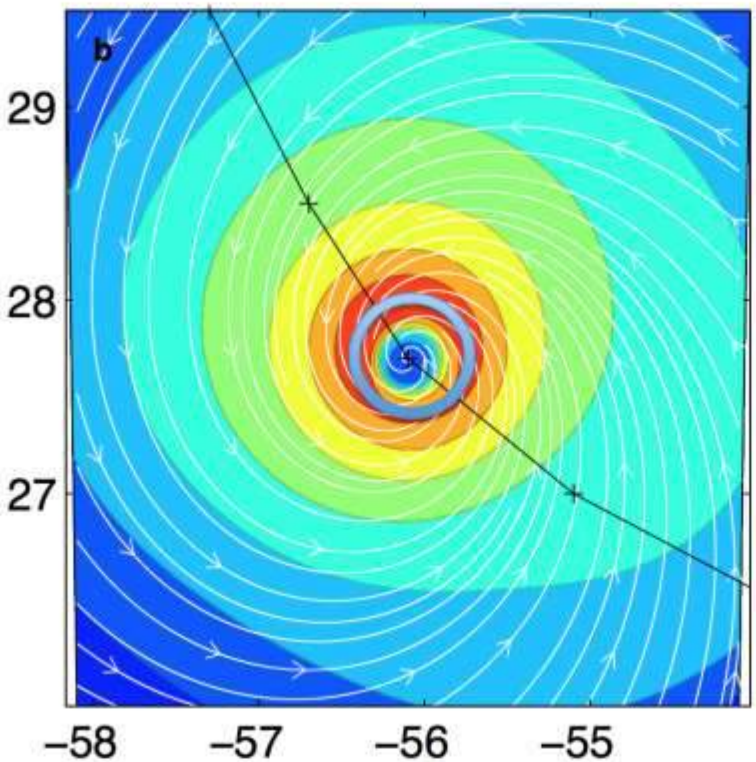
Now assessing:

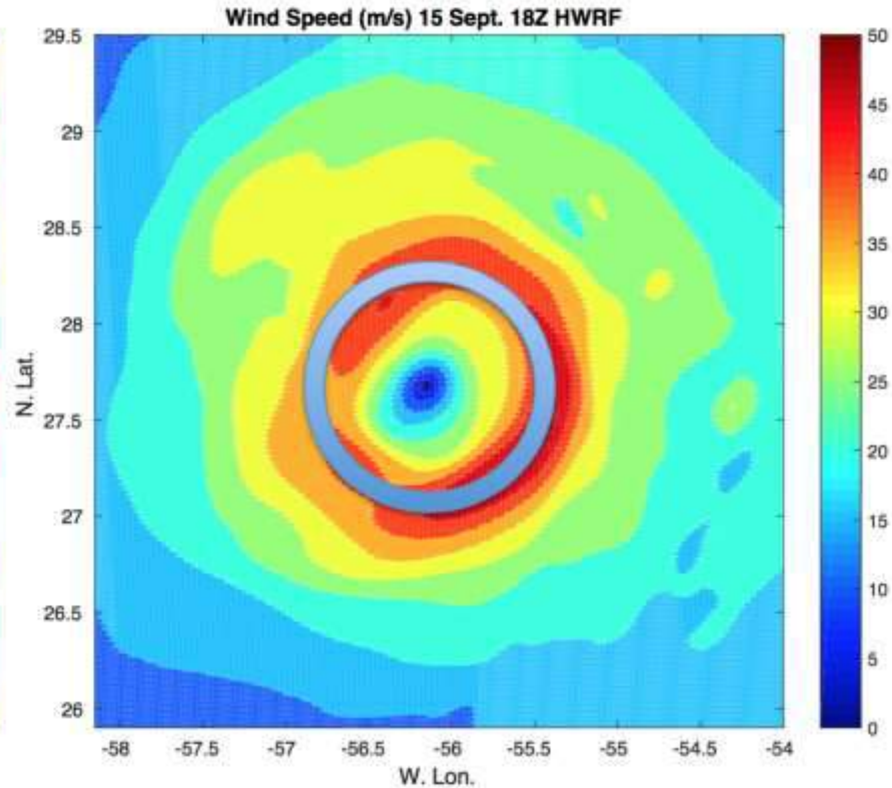
- **How well HWRF captures secondary eyewall characteristics**
  - **Duration**
  - **Radial position**
  - **Azimuthal average kinematic structure of the storm**

Hurricane Edouard: 10m Wind Speed (ms^{-1})

RMW~2x!!

Valid: September 15th 18Z



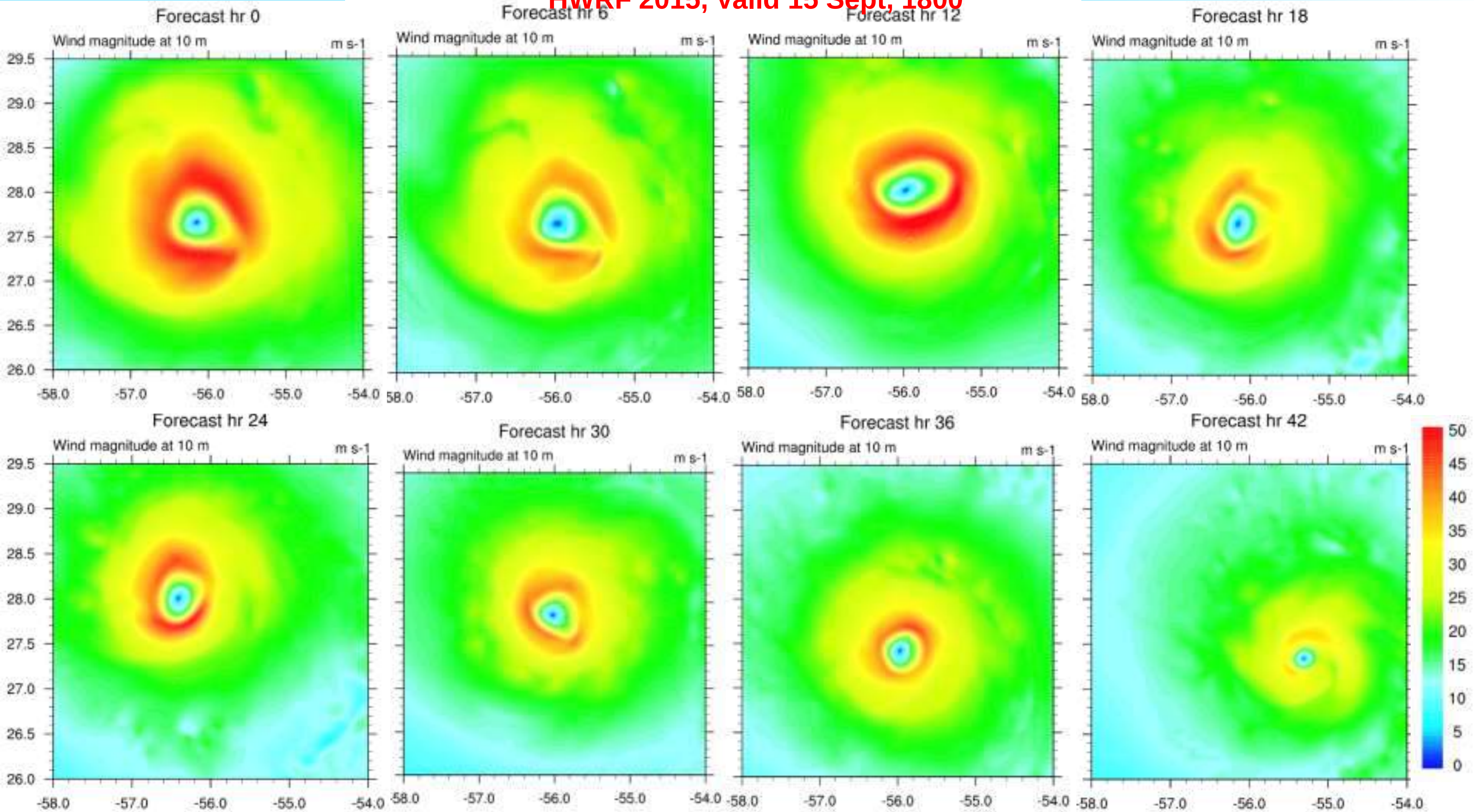


OBSERVATIONS

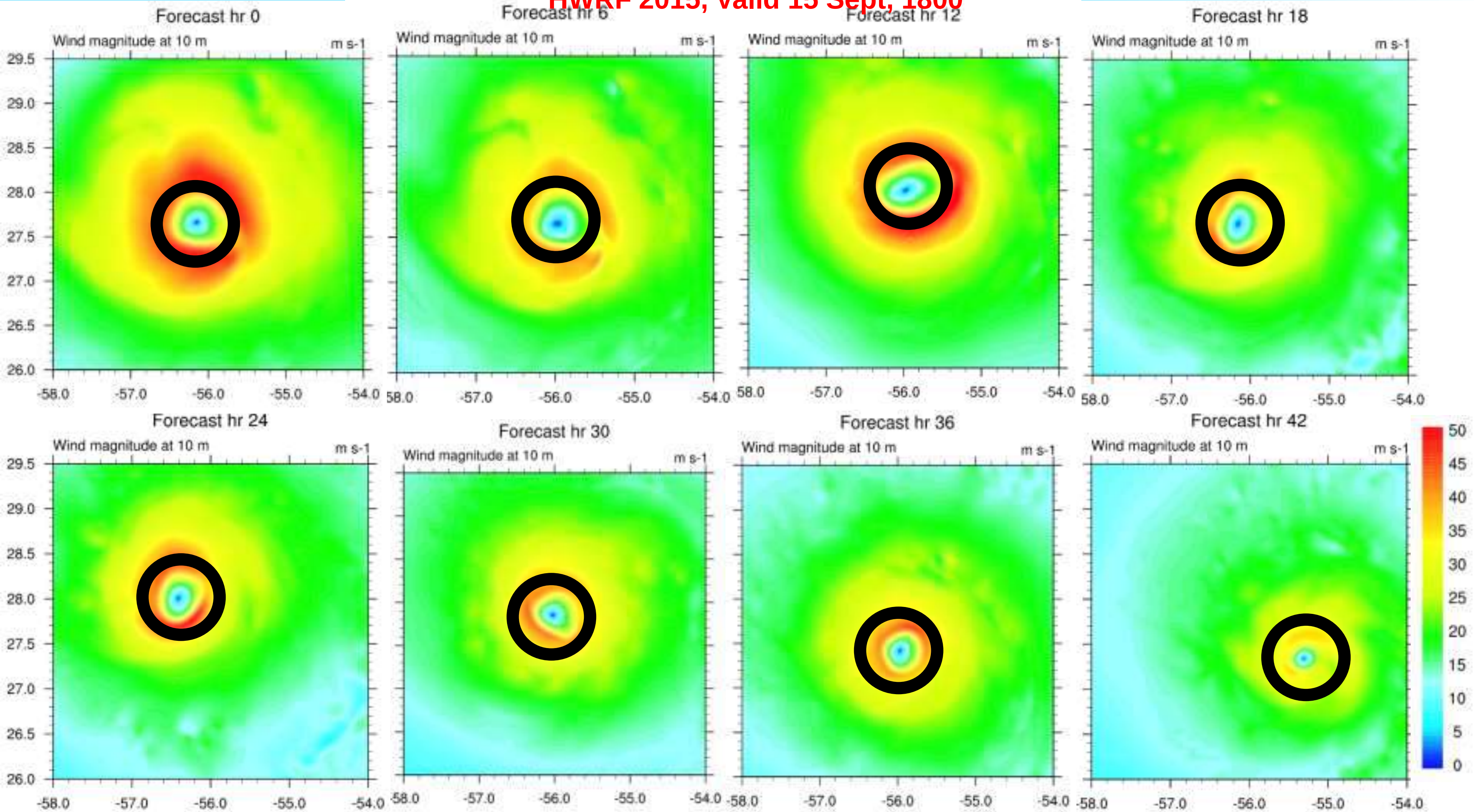
HWRF (t=0)

Does initial size matter?

HWRF 2015, Valid 15 Sept, 1800

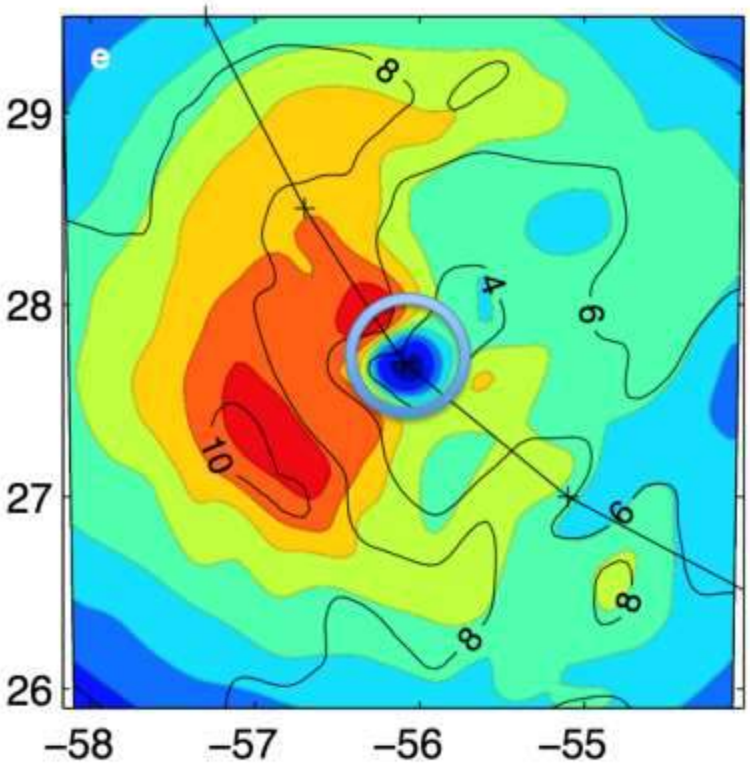


HWRF 2015, Valid 15 Sept, 1800

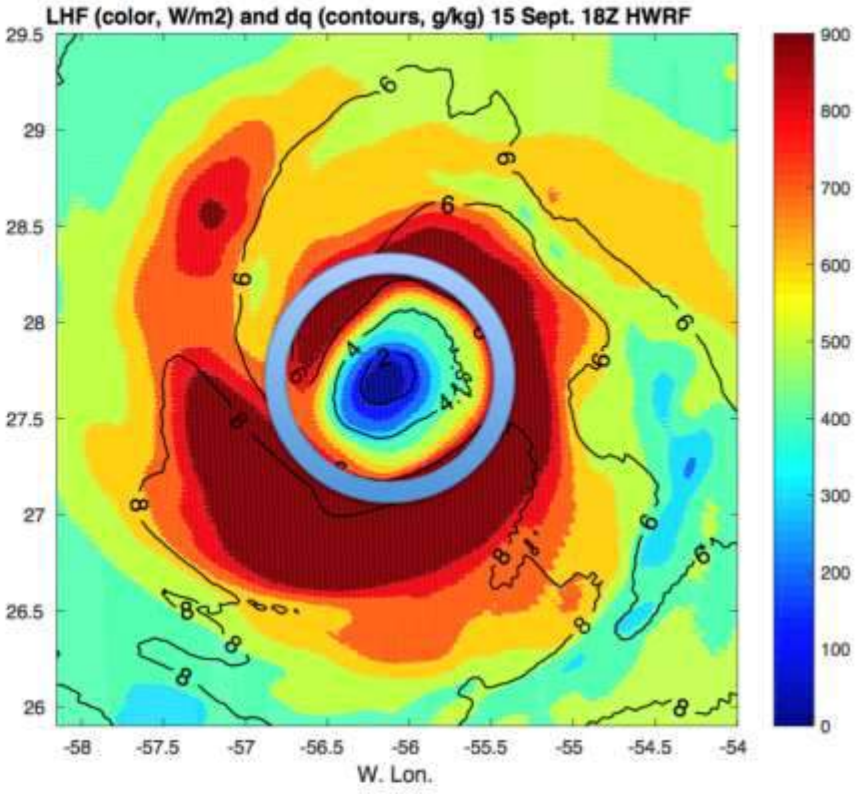


Hurricane Edouard: Surface Latent Heat Flux (Wm^{-2})

Valid: September 15th 18Z

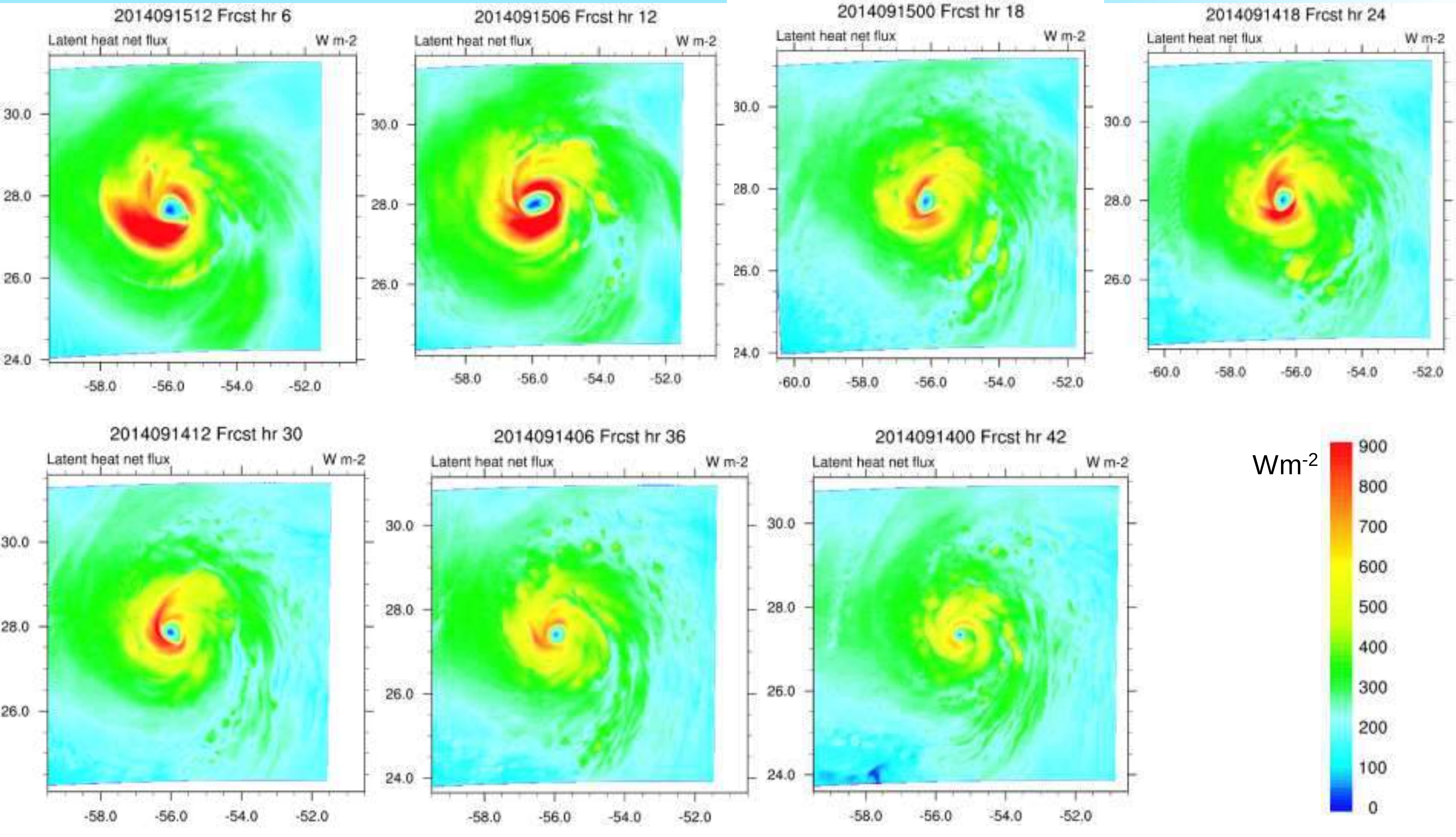


OBSERVATIONS

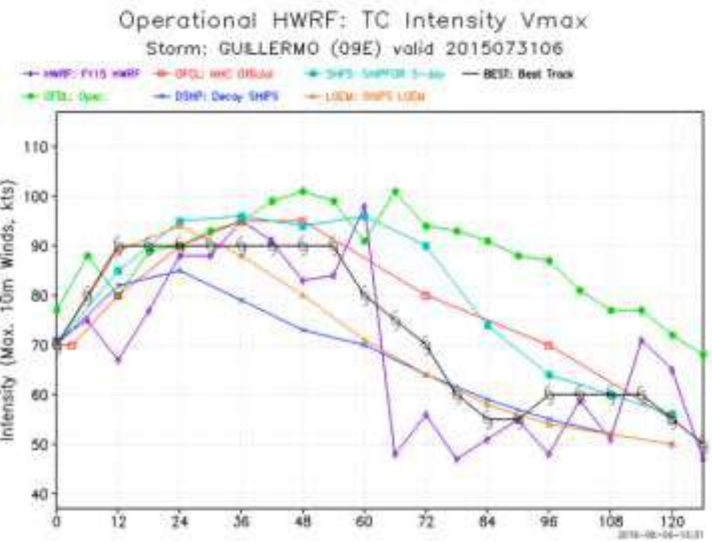


HWRF (t=0)

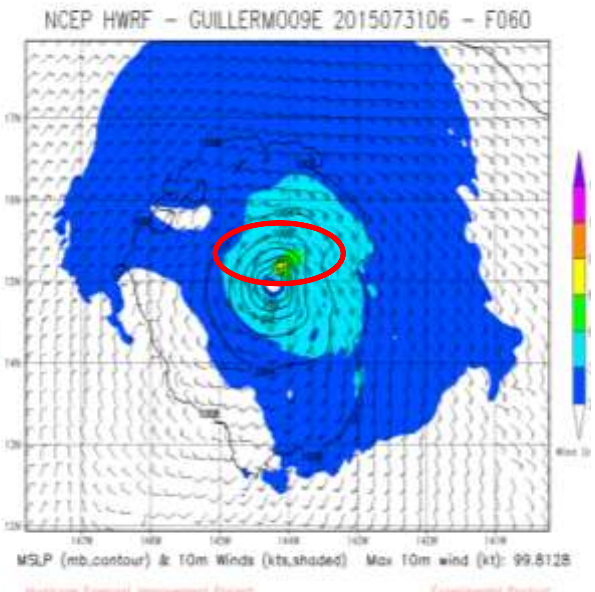
Preferential treatment of heat fluxes



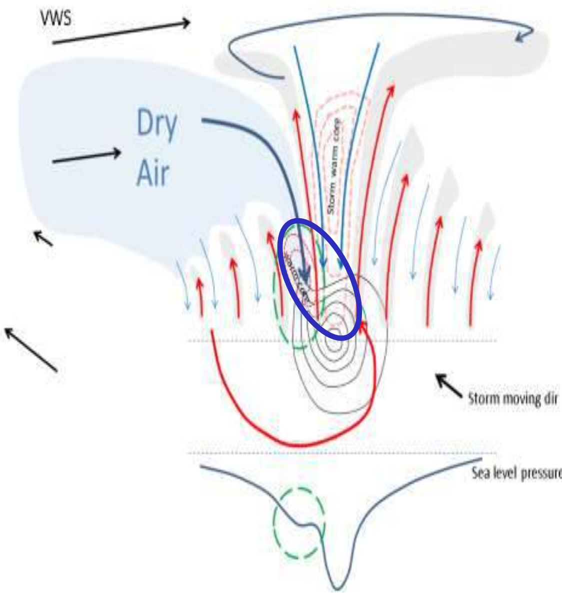
Advanced Research Findings from HWRF Model



Sudden weakening of Hurricane Guillermo (2015)



Indication of local wind maximum with "hook" type MSLP structure



Interaction of dry air, vertical wind shear, and creation of local lower level warm cores

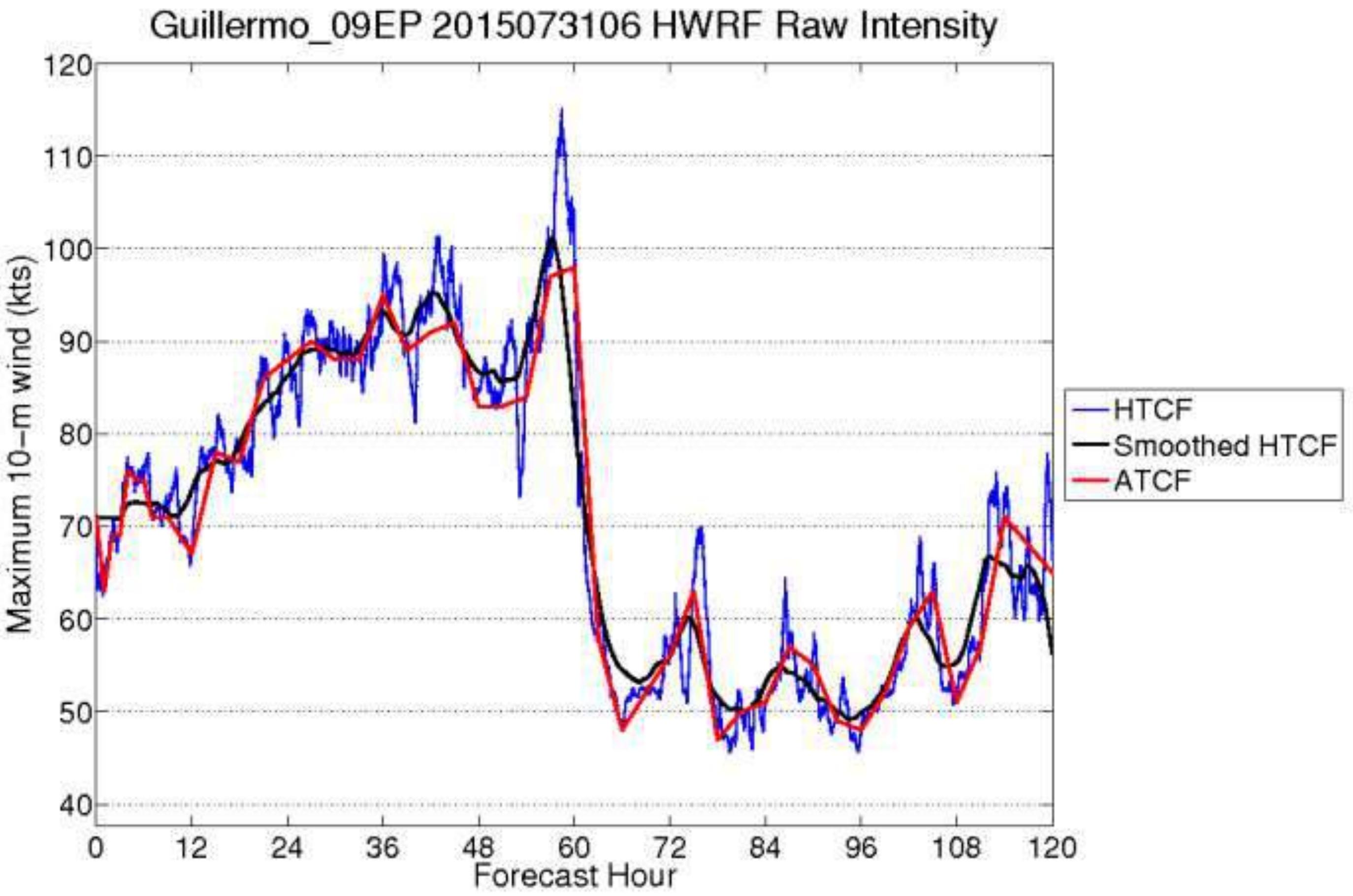
Rapid weakening and a new "hook" Feature triggering sudden demise

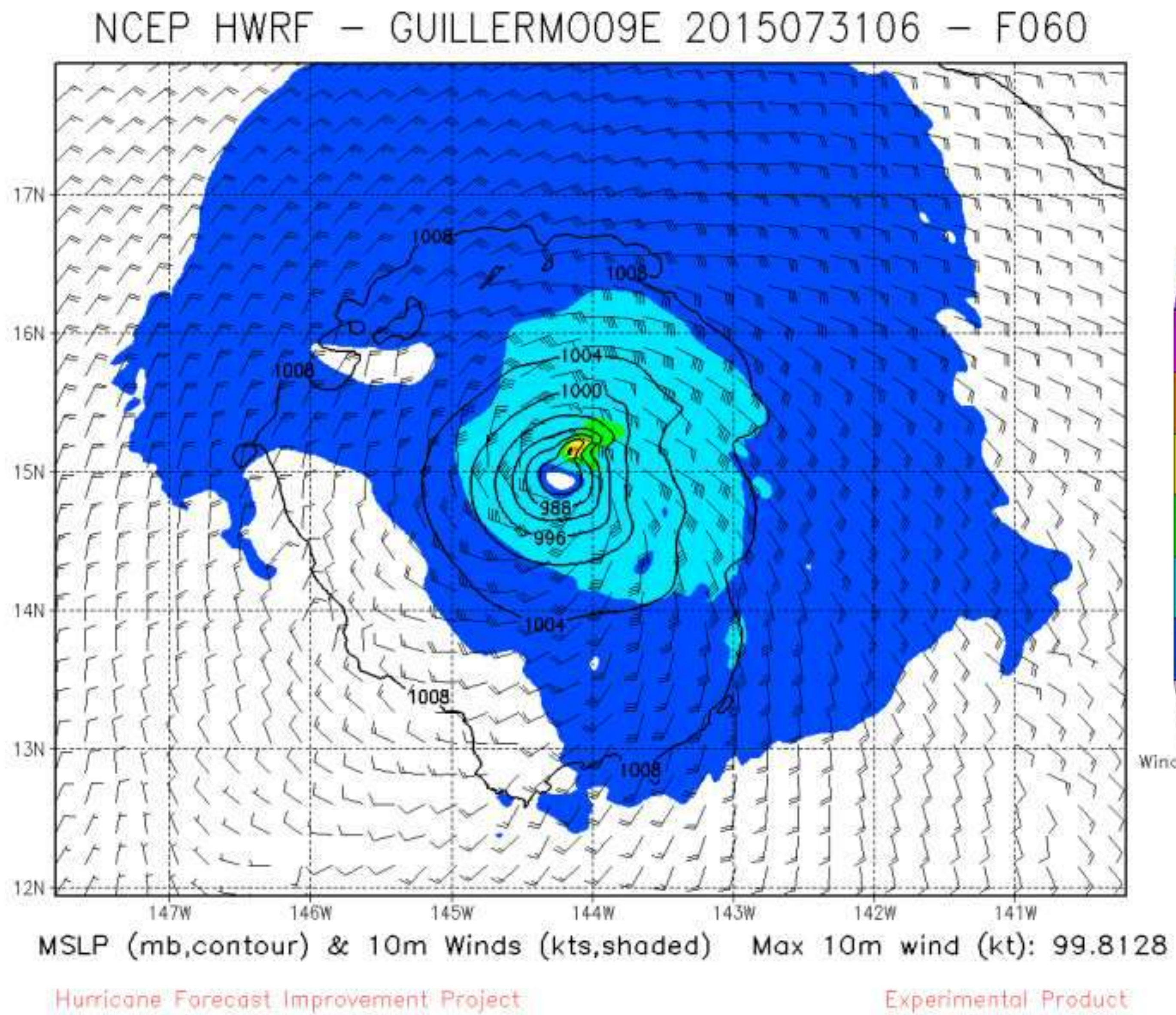
Vertical wind shear (VWS) and dry air intrusion weaken the storm by tilting the warm core

Downdrafts associated with dry intrusion generate a local warm core leading to formation of MSLP hook pattern

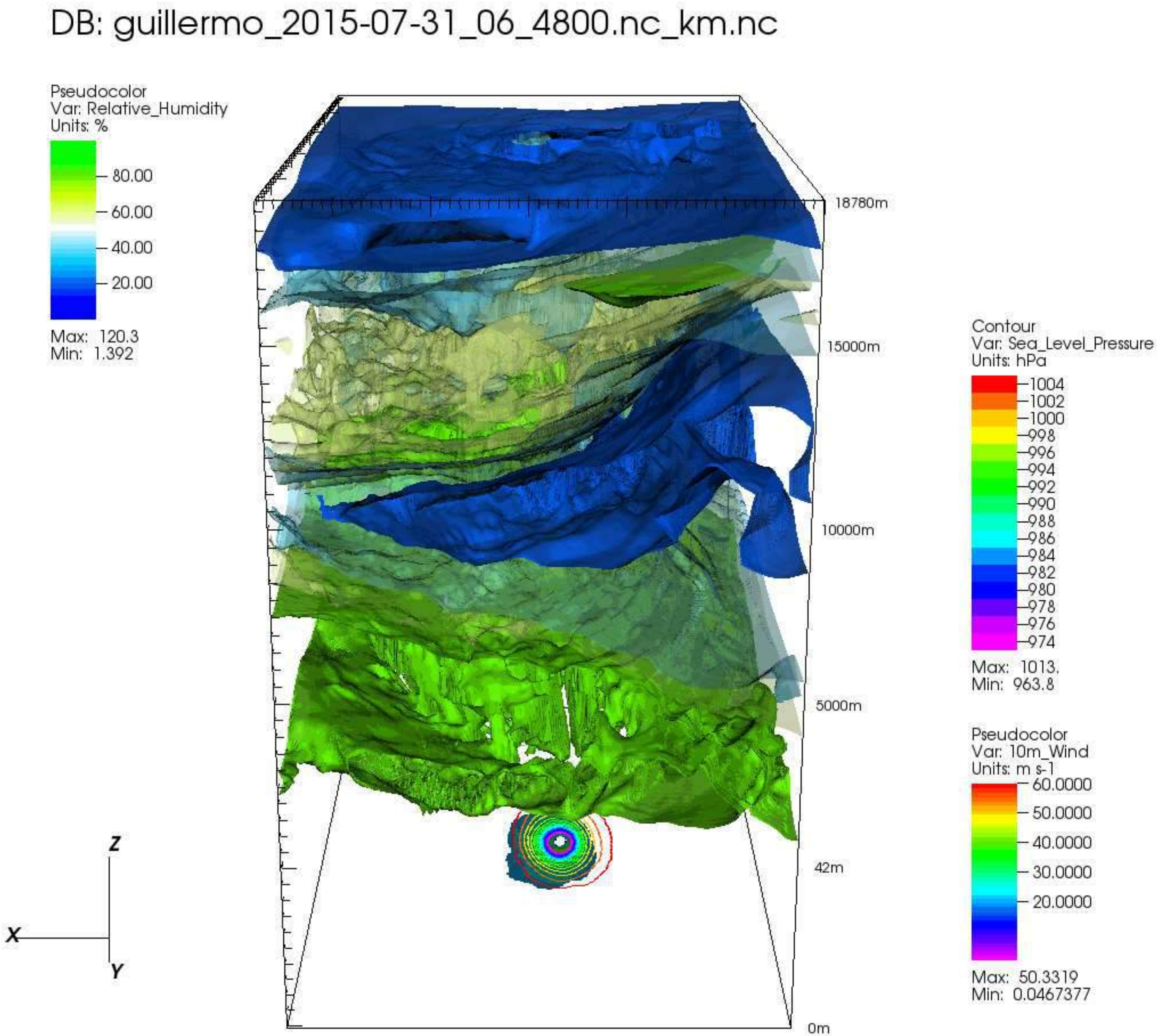
HWRF model is providing new opportunities to explore tropical cyclone dynamics and intensification

Rapid Weakening: New findings





Narrow wavenumber 1 asymmetry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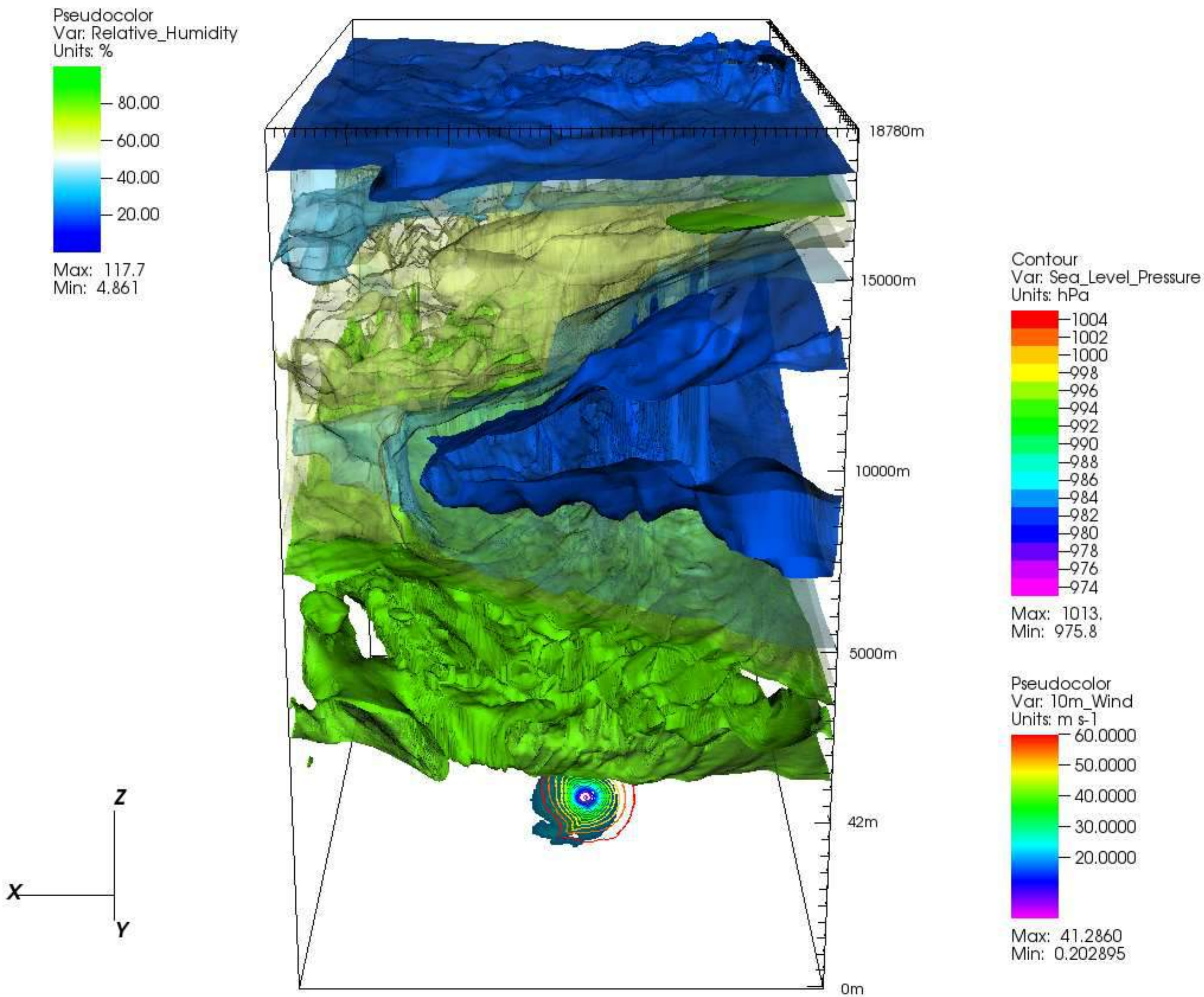
Pseudocolor
Var: Relative_Humidity
Units: %
80.00
60.00
40.00
20.00
Max: 120.3
Min: 1.392
18780m
15000m
10000m
5000m
42m
0m
Contour
Var: Sea_Level_Pressure
Units: hPa
1004
1002
1000
998
996
994
992
990
988
986
984
982
980
978
976
974
Max: 1013.
Min: 963.8
Pseudocolor
Var: 10m_Wind
Units: m s-1
60.0000
50.0000
40.0000
30.0000
20.0000
Max: 50.3319
Min: 0.0467377
Z
X
Y

DB: guillermo_2015-07-31_06_6000.nc_km.nc

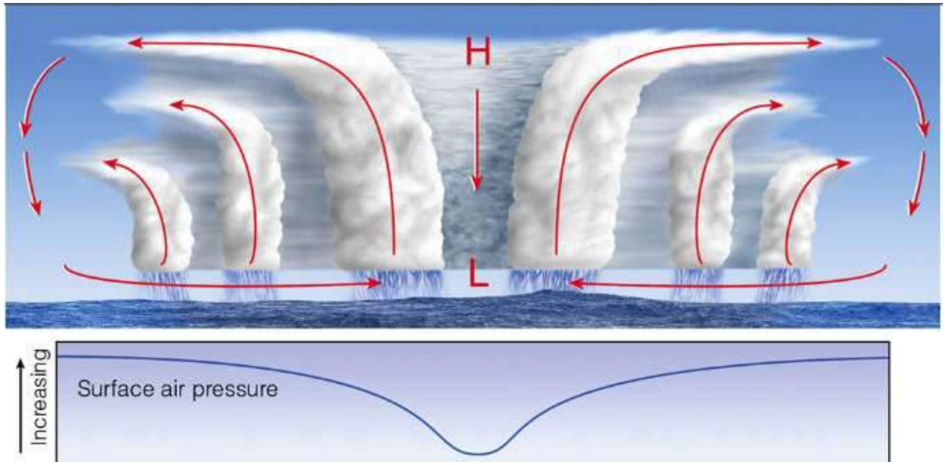


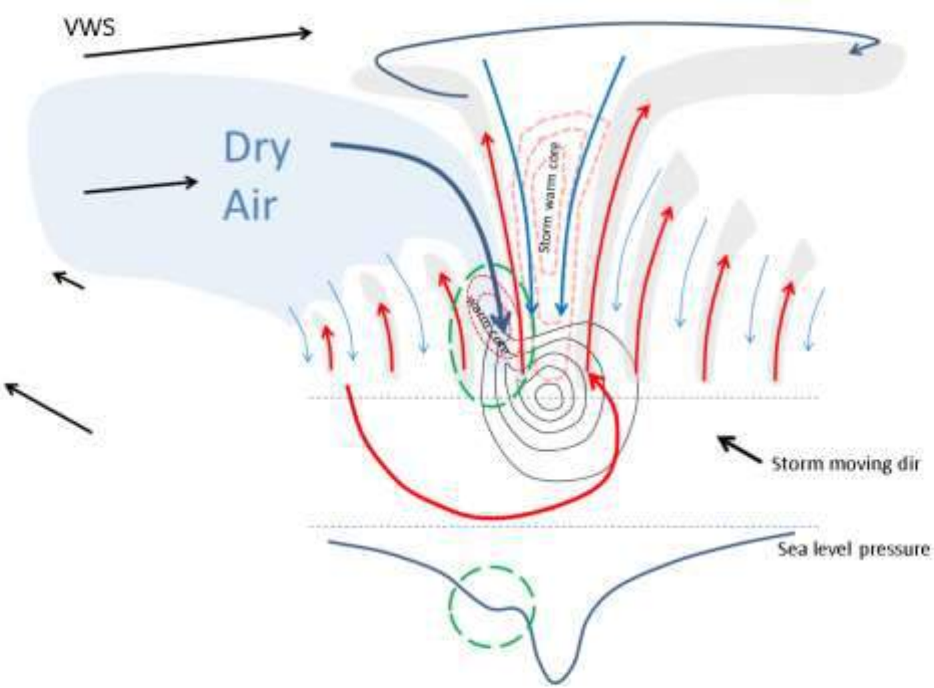
Presence of hook feature in several storms……

VERY MUCH SO SOMEWHAT

- Guillermo (2015 09E) – most cycles after 2015073000
- Maysak (2015 04W) - 2015041112
- Higos (2015 02W) - basically every cycle
- Amanda (2014 01E) - any cycle after 2014052312
- Vance (2014 21E) - there are hints of it in many cycles, but it gets worse after 2014110306
- Eduoard (2014 06L) - maybe, not a priority case, could be ET as well
- Fay (2014 07L) - cycles beginning with 2014101106, could be ET later
- Bertha (2014 03L) - 2014080400-2014080412 and maybe a few around those
- Hagupit (2014 22W) - 2014120306-2014120406 (after this forecasts took it over land)
- Tapah (2014 06W) - 2014042718-2014042900
- Faxai (2014 03W) - looks like a few cycles starting with 2014022218, but not as clear
- Ana (2014 02C) - 2014101700-2014101900 (before this land interaction with Hawaii)
- Francisco (2013 26W) - 2013102200-2013102418
- Lorenzo (2013 13L) – 2013102118-2013102218
- Jerry (2013 11L) – 2013092900-2013092906
- Gabrielle (2013 07L) – 2013091112

RW and SLP hooks by VWS and Dry Intrusion





- VWS and dry intrusion weaken the storm
- Downdrafts generate a local warm core => slp/hgt hooks
  - Dry intrusion related downdraft
  - Environmental VWS related downdraft
  - Compensational downdraft associated with strong convections in eyewall and rain bands
- VWS can also tilt storm warm core, resulting in slp/hgt contour hooks/curves

Physics Strategy: Parameterization development general direction

To improve HWRF performance, with regard to:

- **Track and intensity guidance**
- **Physically based criteria**
  - » **Rapid intensification**
  - » **Secondary eyewalls**
    - **Formation, evolution and kinematic characteristics**
  - » **Any other identified model bias**

- Scale aware
  - **To allow unified physics across model scales and applications**

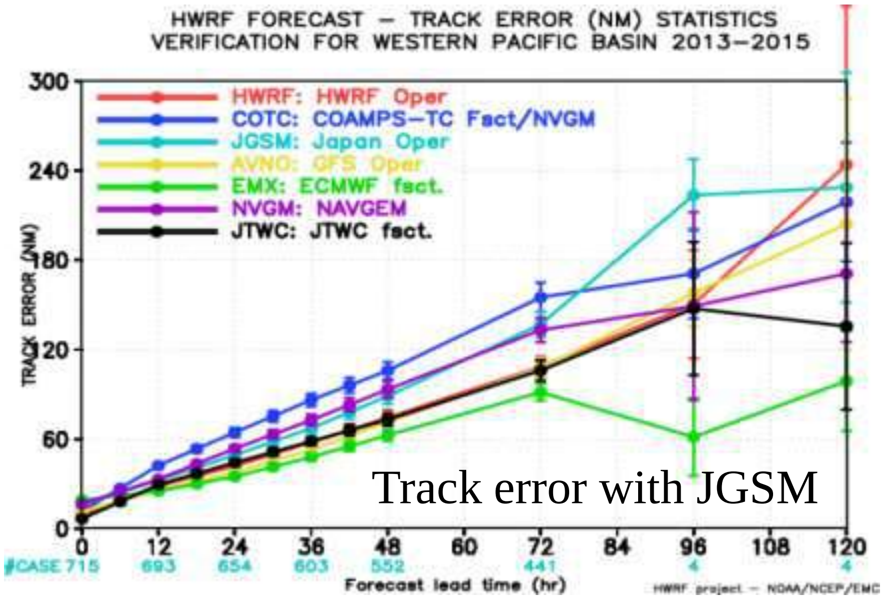
- Stochastic physics
  - **To account for uncertainty, and variability in nature**

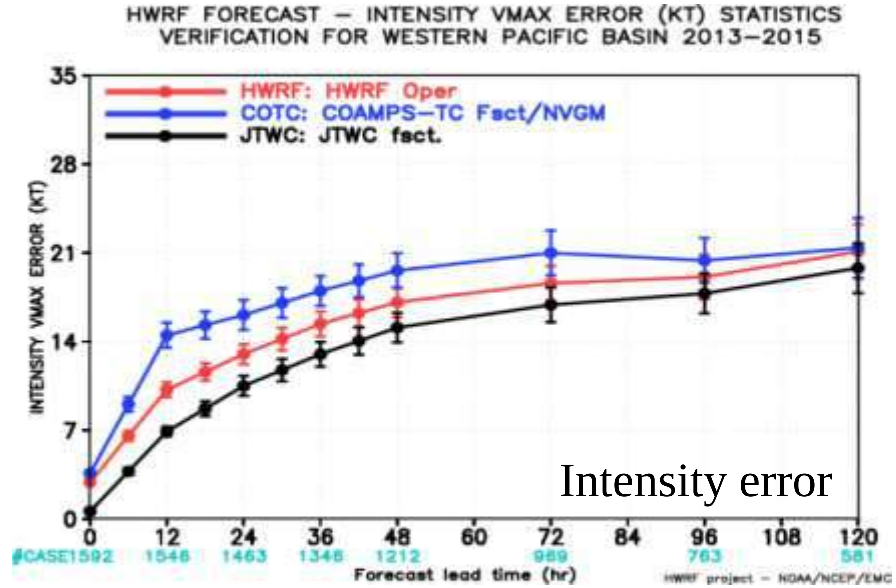
Verification Issues

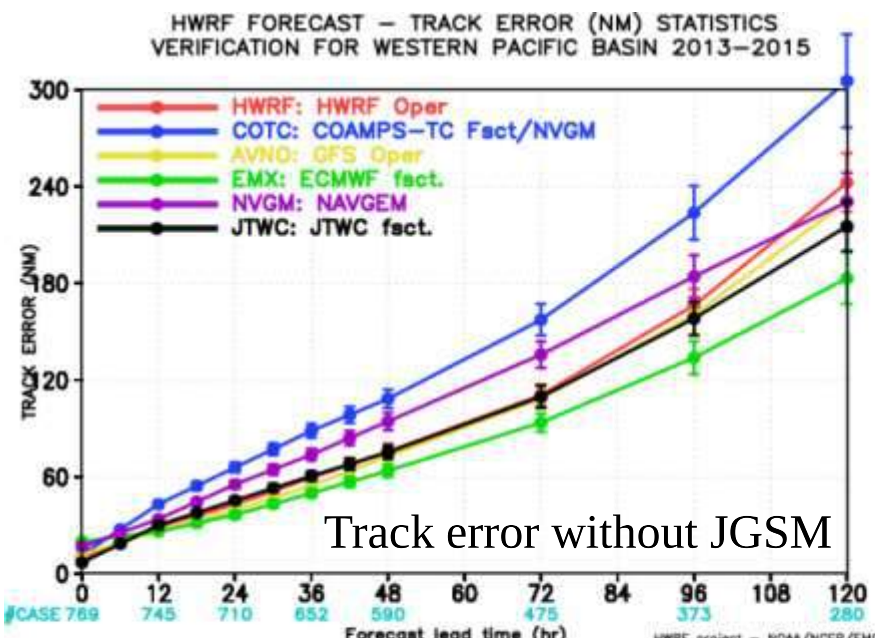
Model development strategies critically depend on verification results

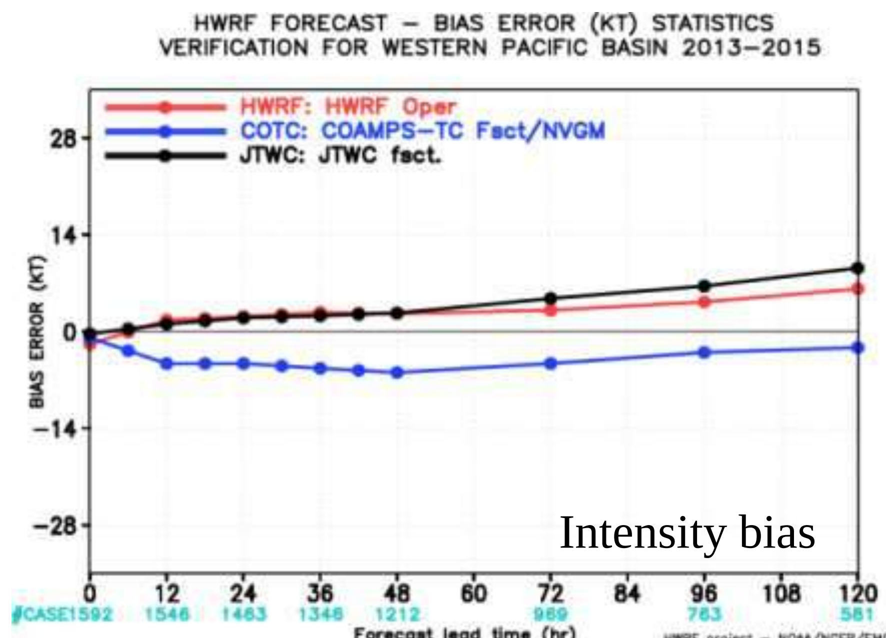
Observational uncertainty can be dealt with, but differences in various best track data can hurt evaluation procedures (and future model developments).

JTWC's best track

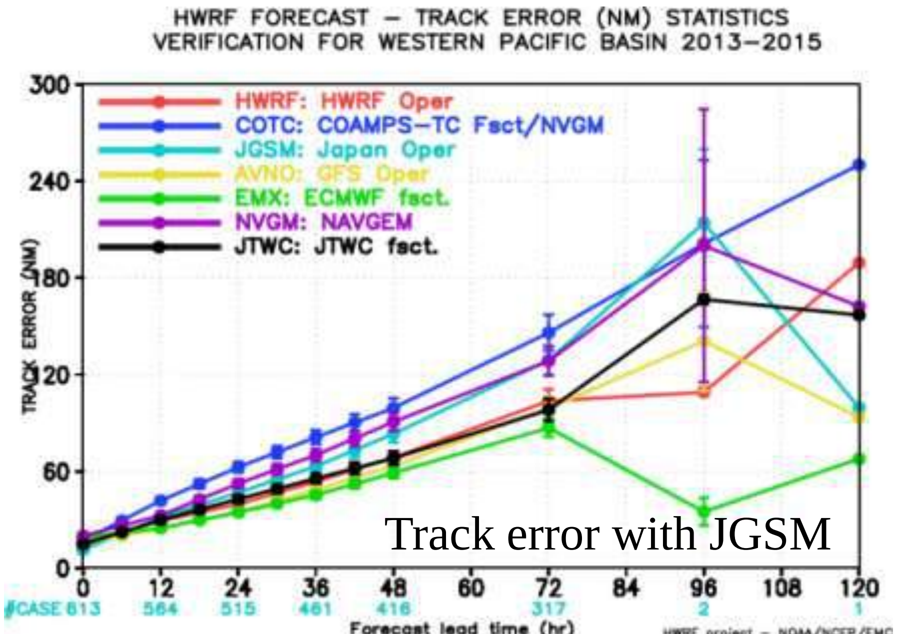


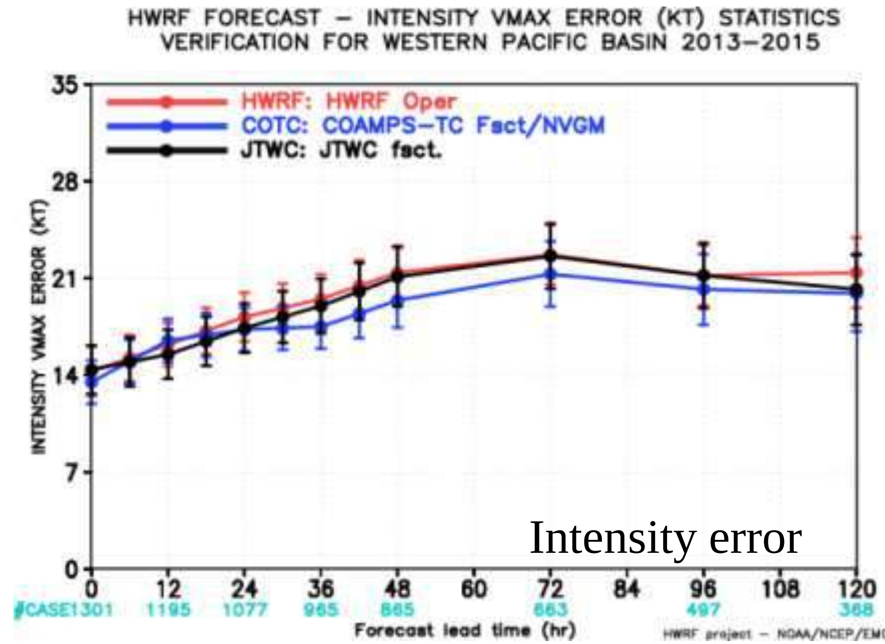


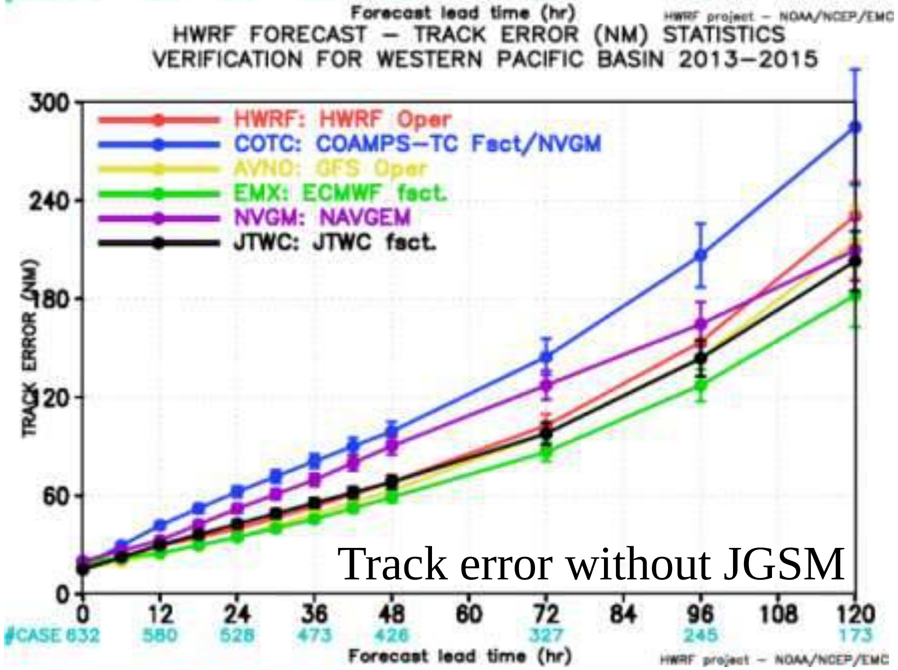


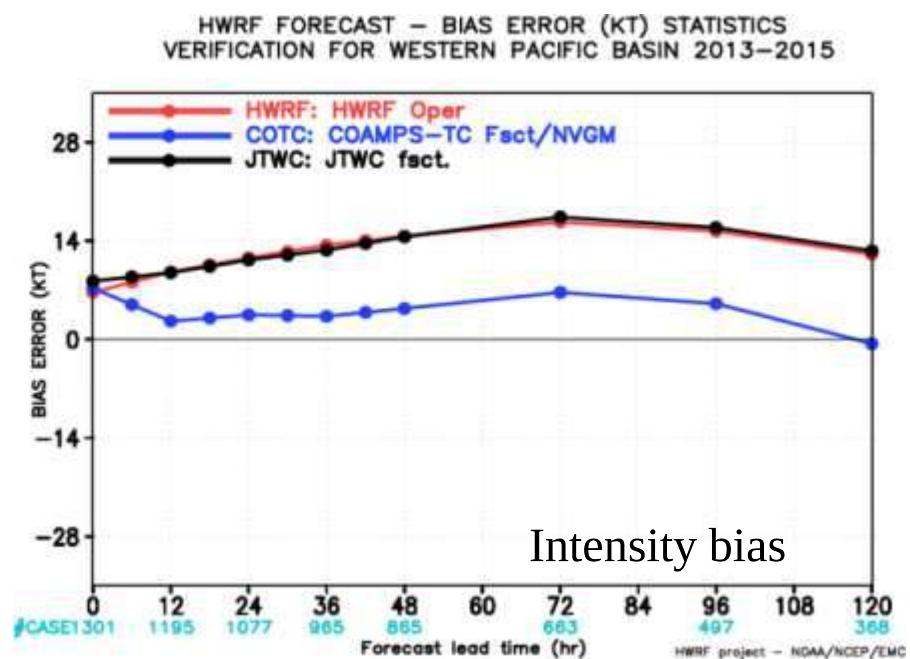


JMA's best track

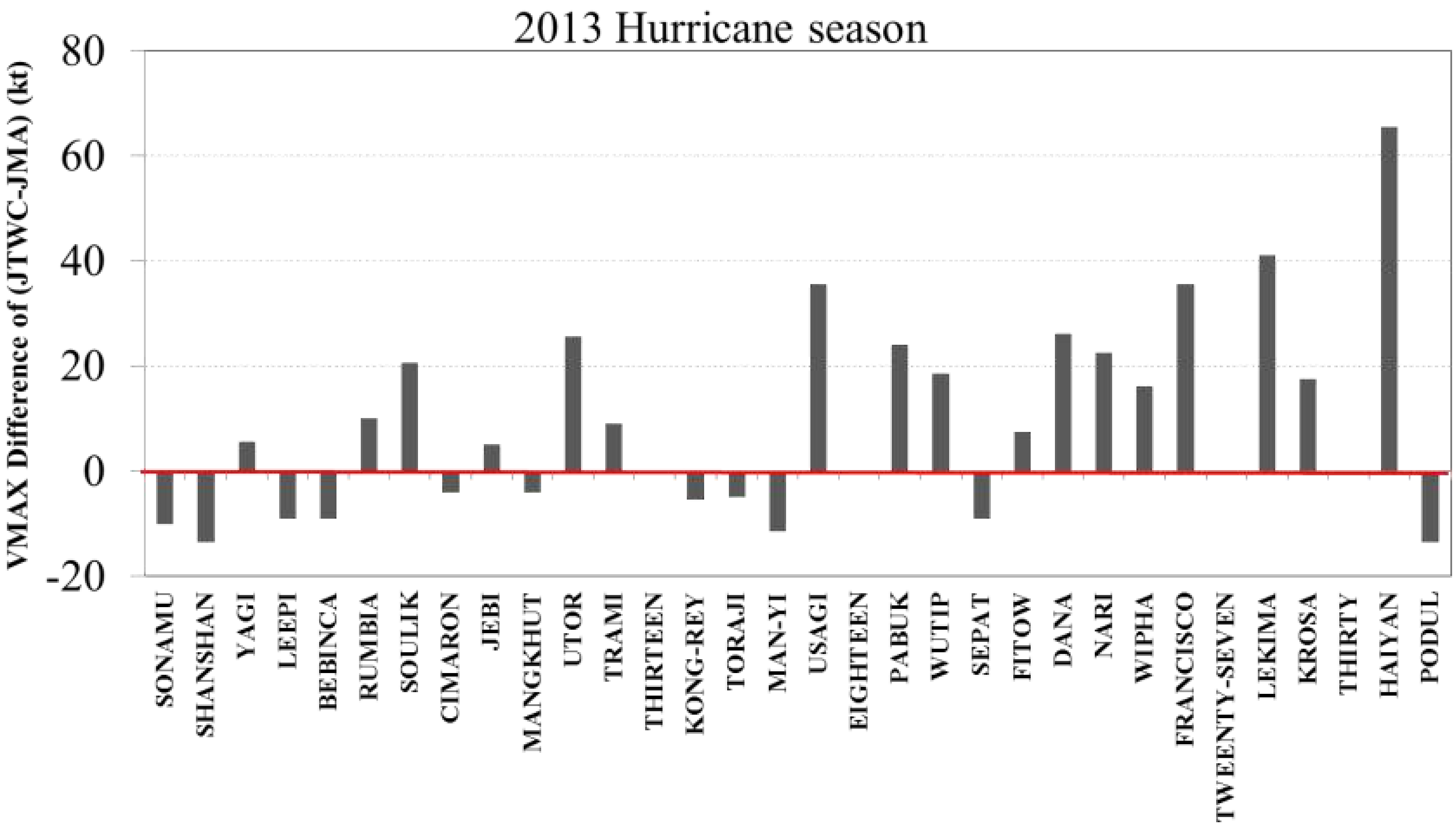




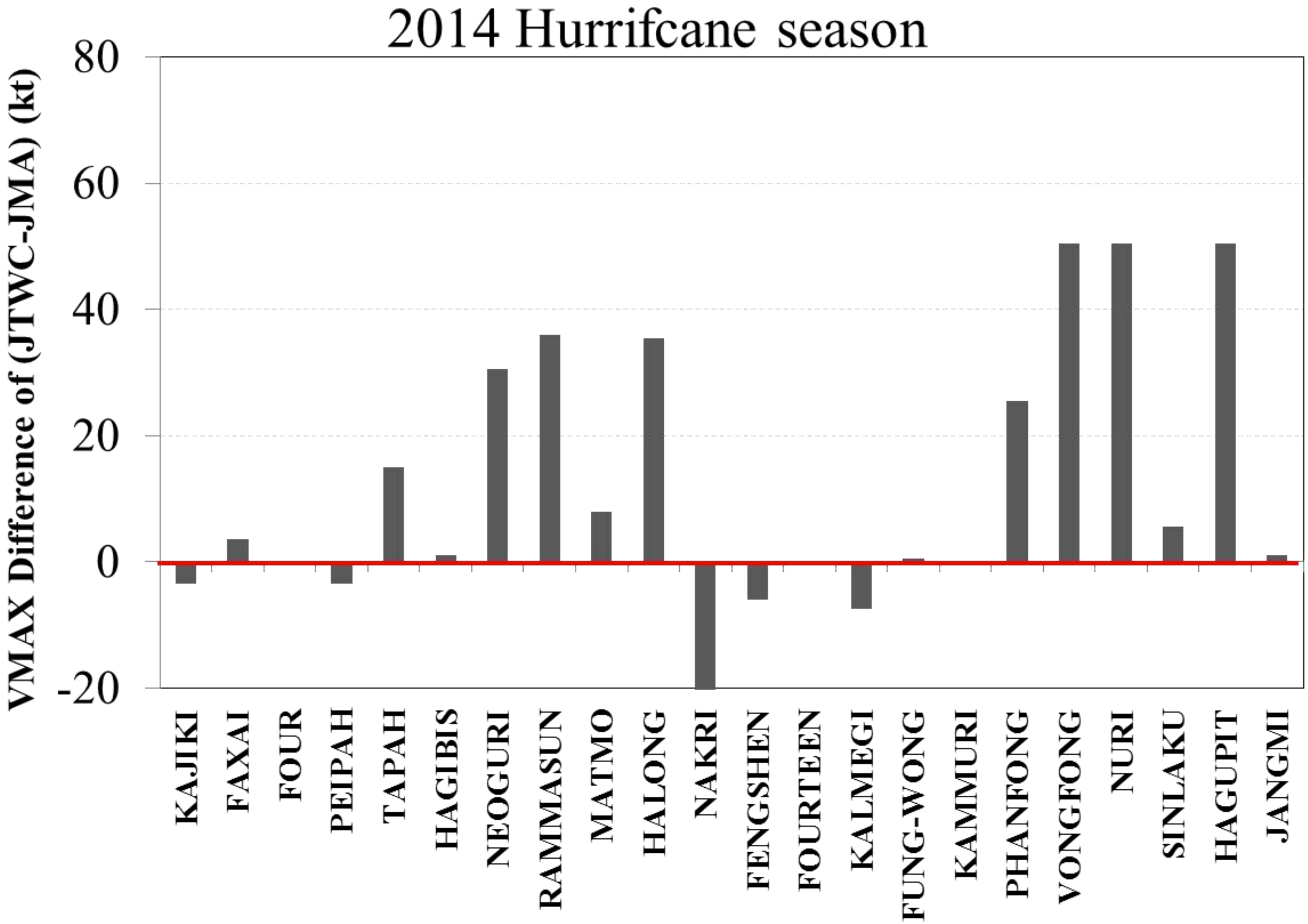




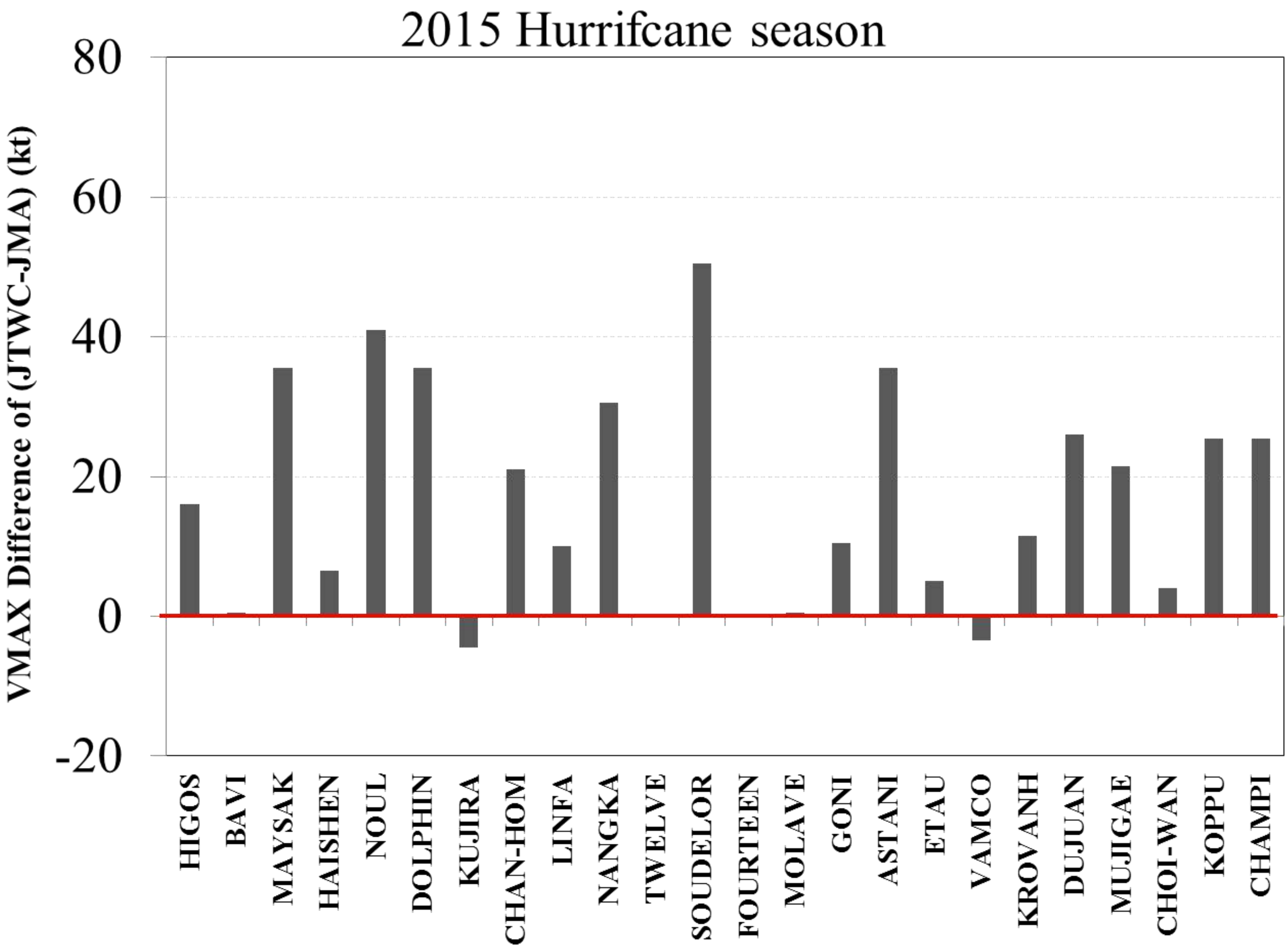
JTWC Vs JMA peak intensity difference



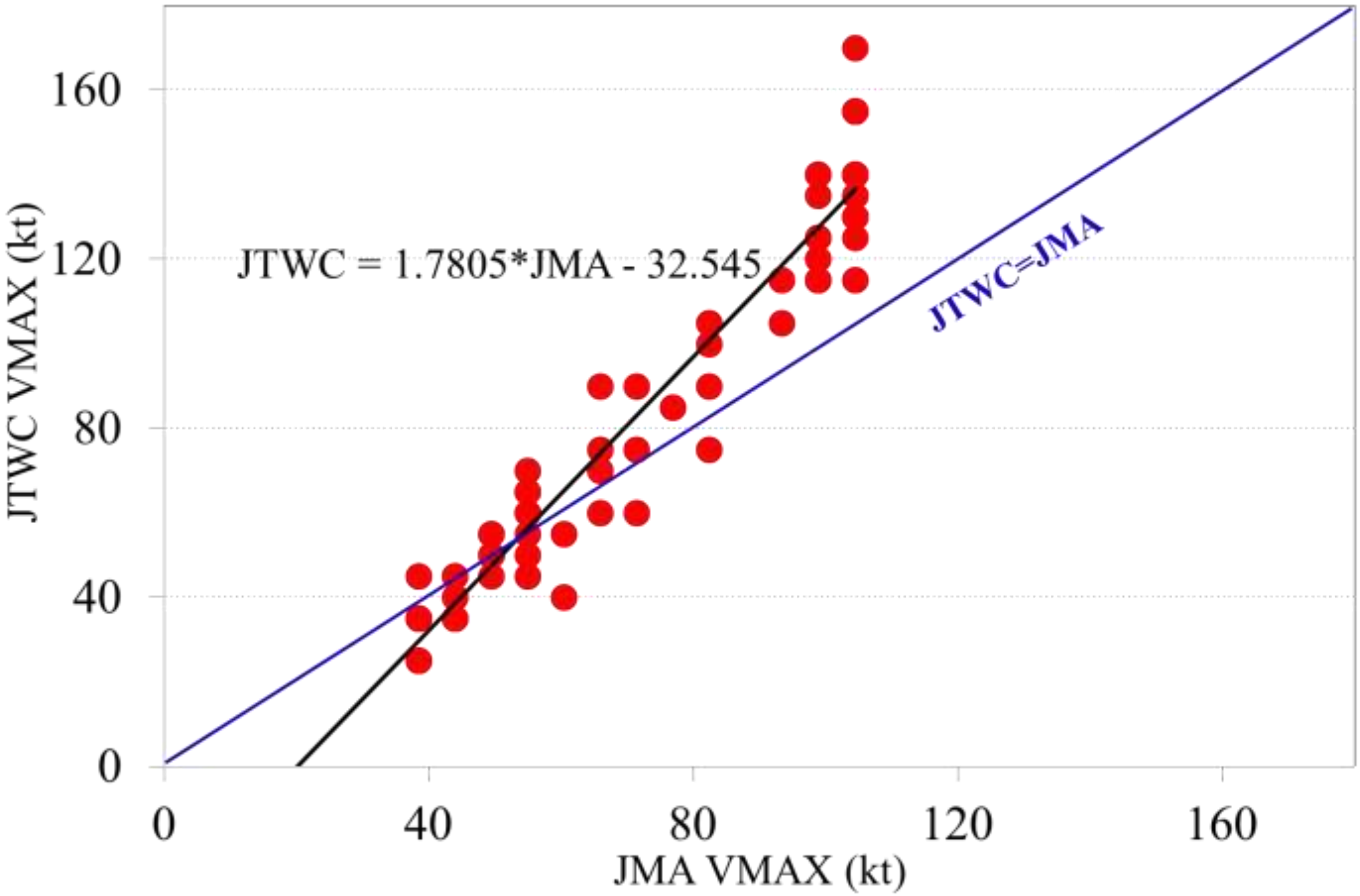
JTWC Vs JMA peak intensity difference



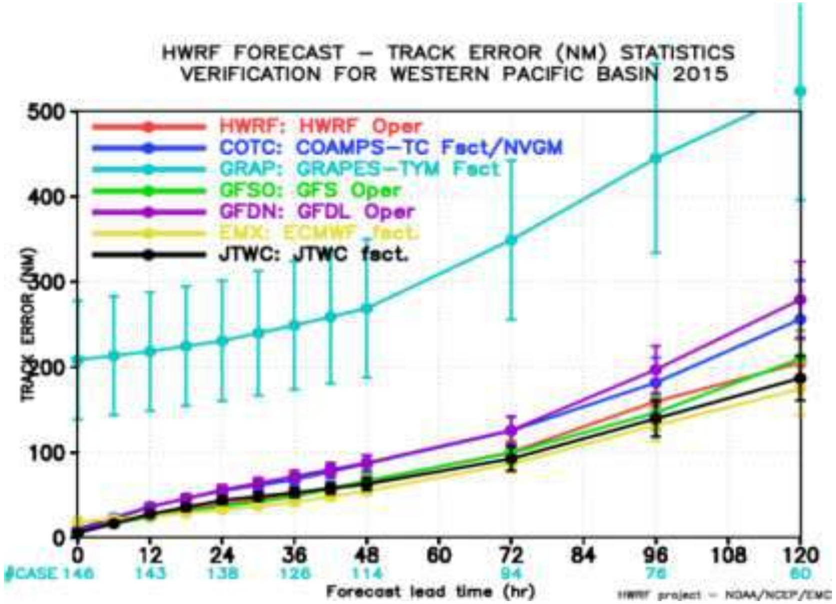
JTWC Vs JMA peak intensity difference

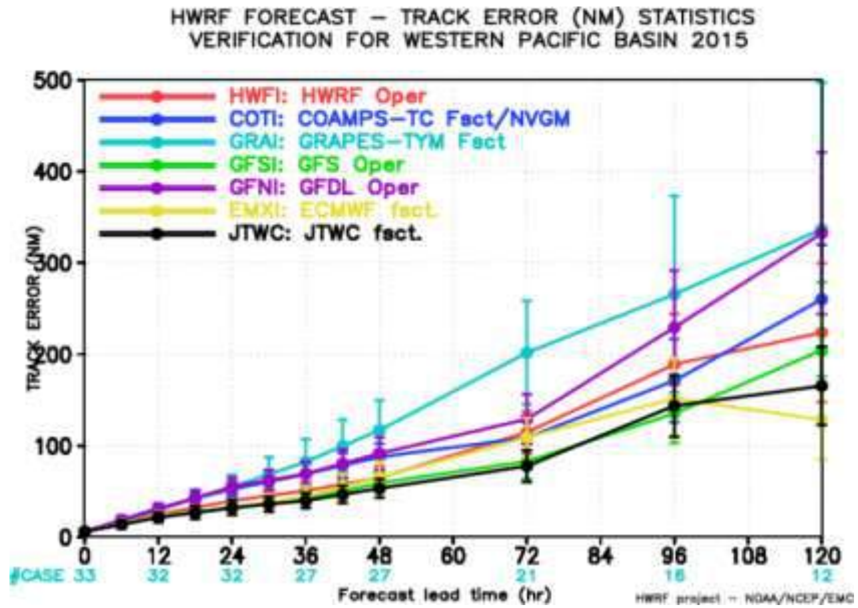


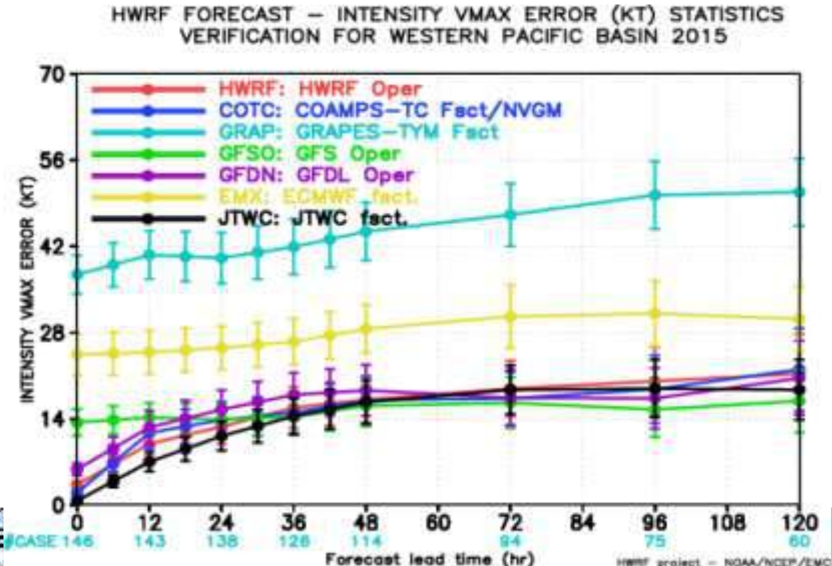
JTWC Vs JMA peak intensity comparison during 2013-2015

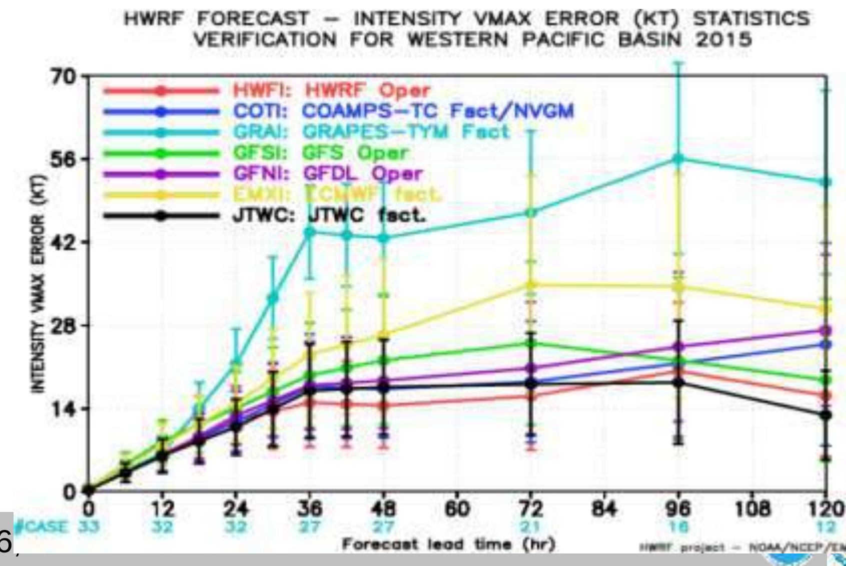


Track and intensity statistic plots of Western Pacific Basin (with GRAPEs) compared with JTWC best track data

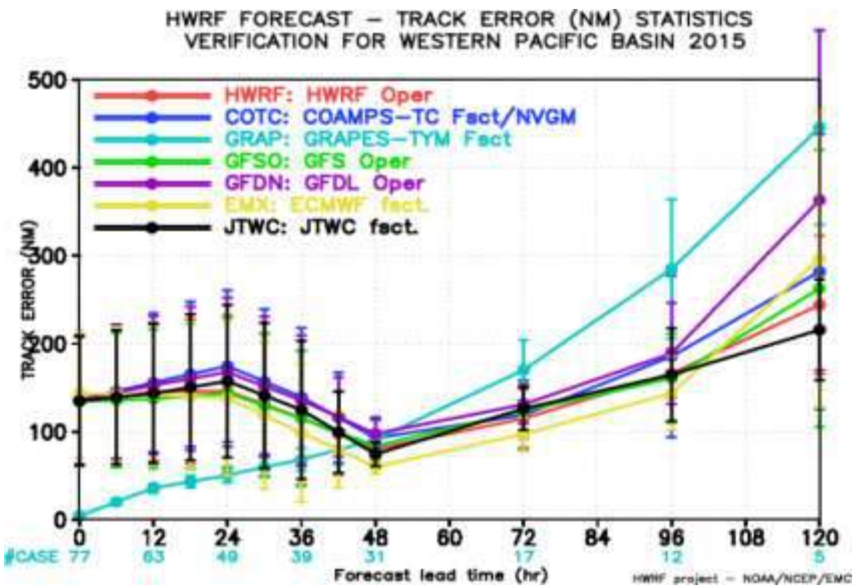


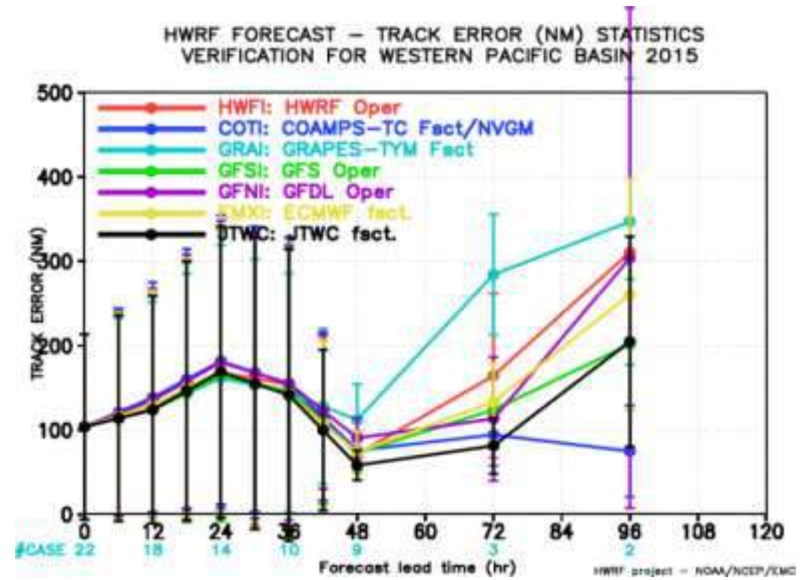


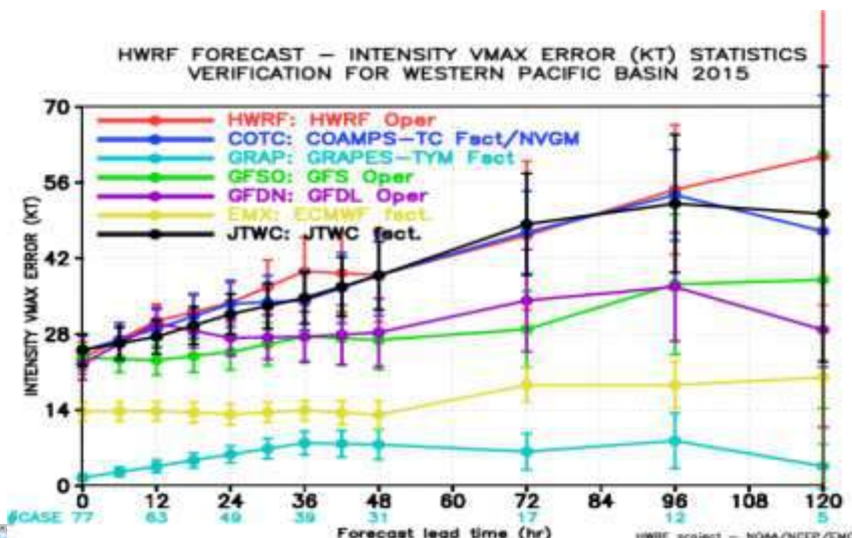


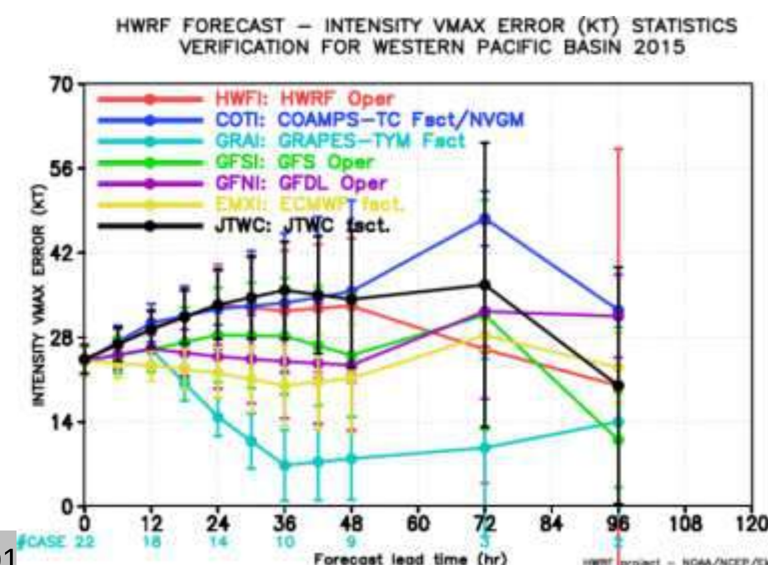


Track and intensity statistic plots of Western Pacific Basin (with GRAPEs) compared with CMA's best track data



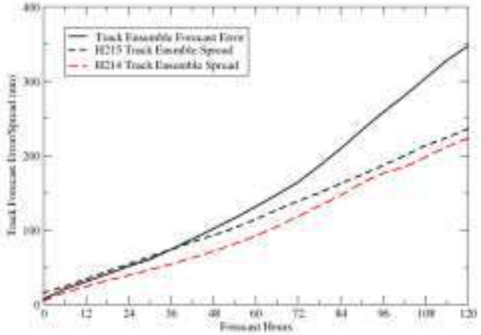


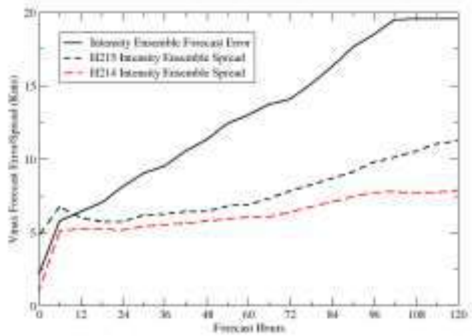


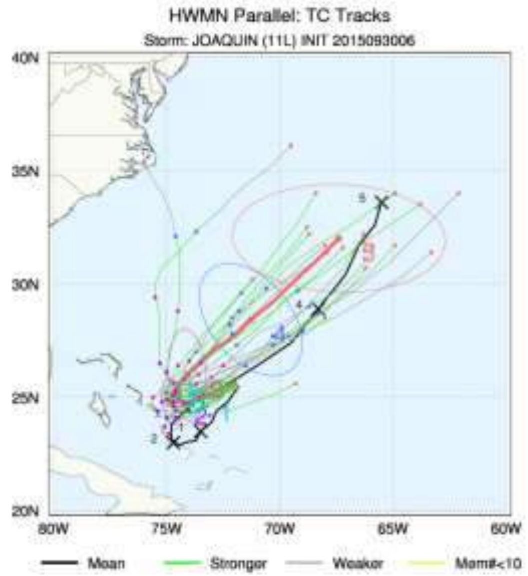


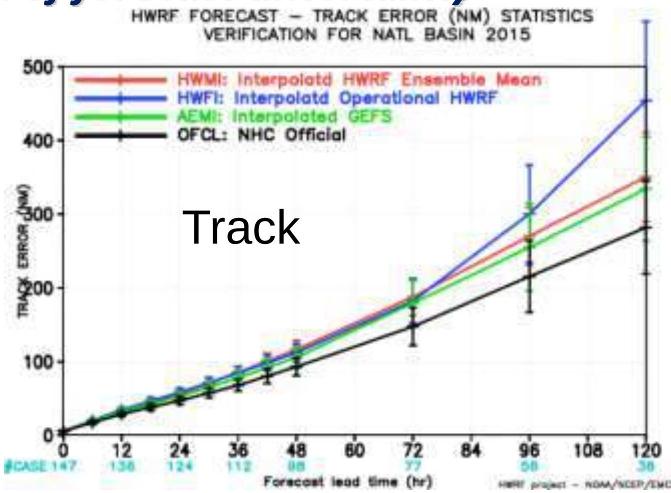
HFIP Experimental Regional Ensemble Prediction System in 2015

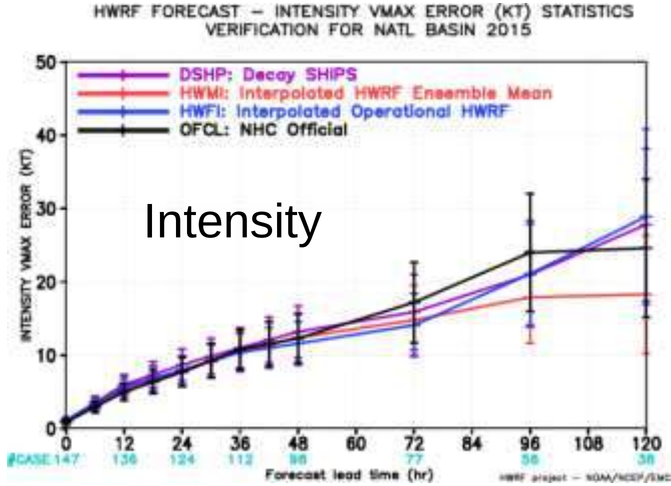
High-Resolution HWRF based Ensembles for Hurricane Forecasts at NATL
Advanced probabilistic guidance with representation of forecast uncertainty









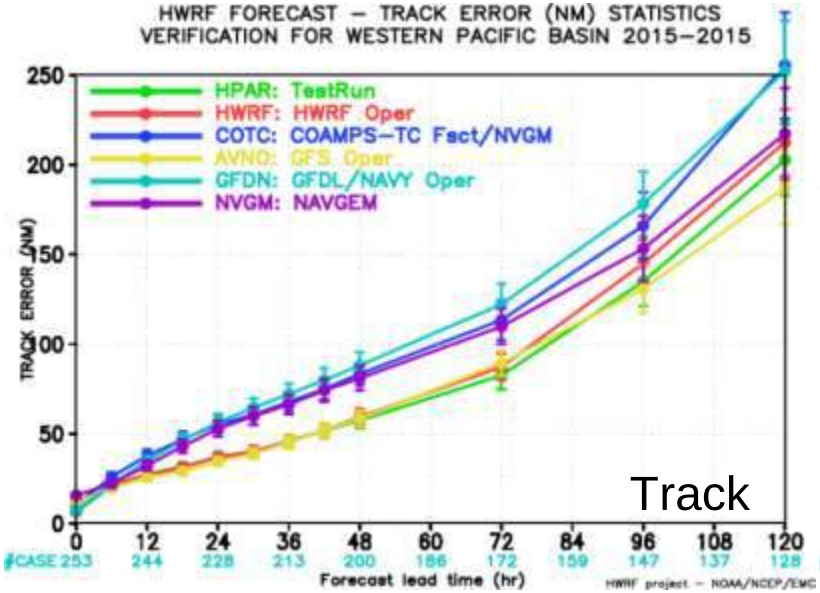


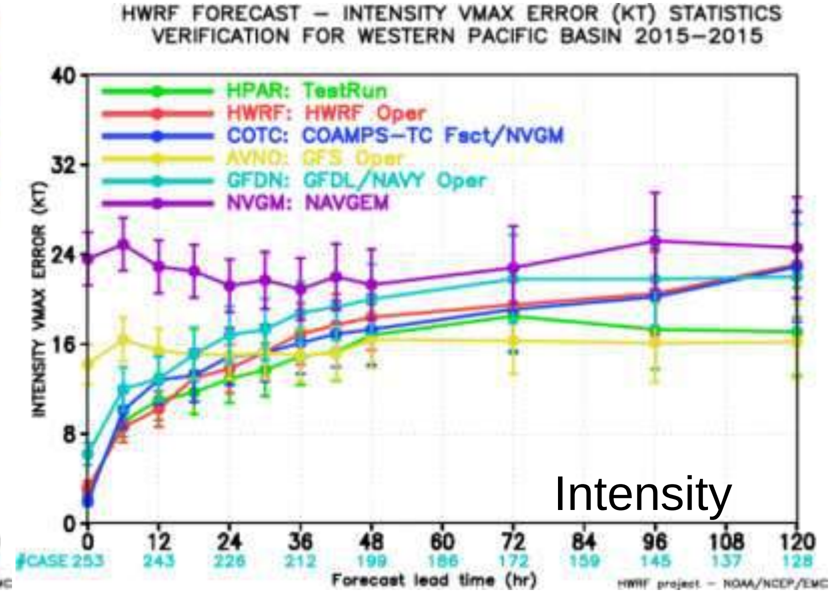
- ***20-member 3km HWRF ensembles driven by GEFS for IC/BC and stochastic convective and PBL perturbations***
- ***High-resolution probabilistic products provide forecast uncertainty in track, intensity, structure (size) and rainfall, along with ensemble mean products***

Planned HWRF Model improvements for 2016 hurricane season

- **Dynamic and Baseline Upgrades**
  - 2016 GFS upgrade for boundary and lateral boundary conditions
  - WRF-NMM dynamic core upgrade: V3.7.1a; Retaining non-hydrostatic state when nests move
  - Integration time step increase, 38+4/7s to 30s;
  - Support up to eight storms in operations
- **Physics upgrades**
  - PBL upgrades, align with latest GFS EDMF PBL scheme,;
  - Microphysics upgrades, Advected Ferrier-Aligo or Thompson scheme;
  - Scale-aware convection scheme: Grell-Freitas scheme or GFS SAS;
- **Ocean/Wave Coupling**
  - ATMOS/Ocean/WAVE three-way coupling Intended to improve air-sea exchange coefficients and mixing in the oceanic upper layer
  - **Ocean model upgrades: MPIPOM or HYCOM for all ocean basins including WPAC**
- **Data Assimilation**
  - HWRF ensemble based background covariance for all basins for observations
  - Increment Adjustment Upgrade (IAU) to avoid initial spin up/down
- **Additional Products**
  - New grid for MAG and AWIPS;
  - Sustained wind swath

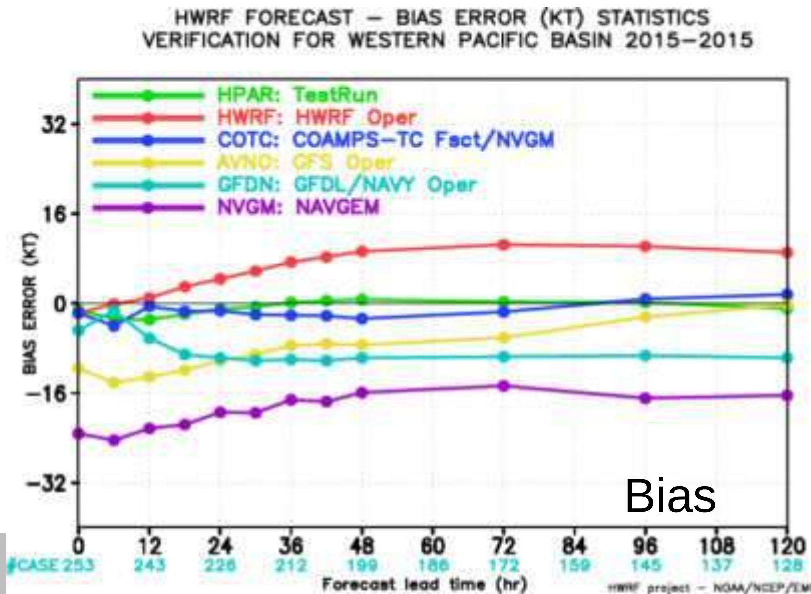
Forecast verification for WPAC with ocean coupling





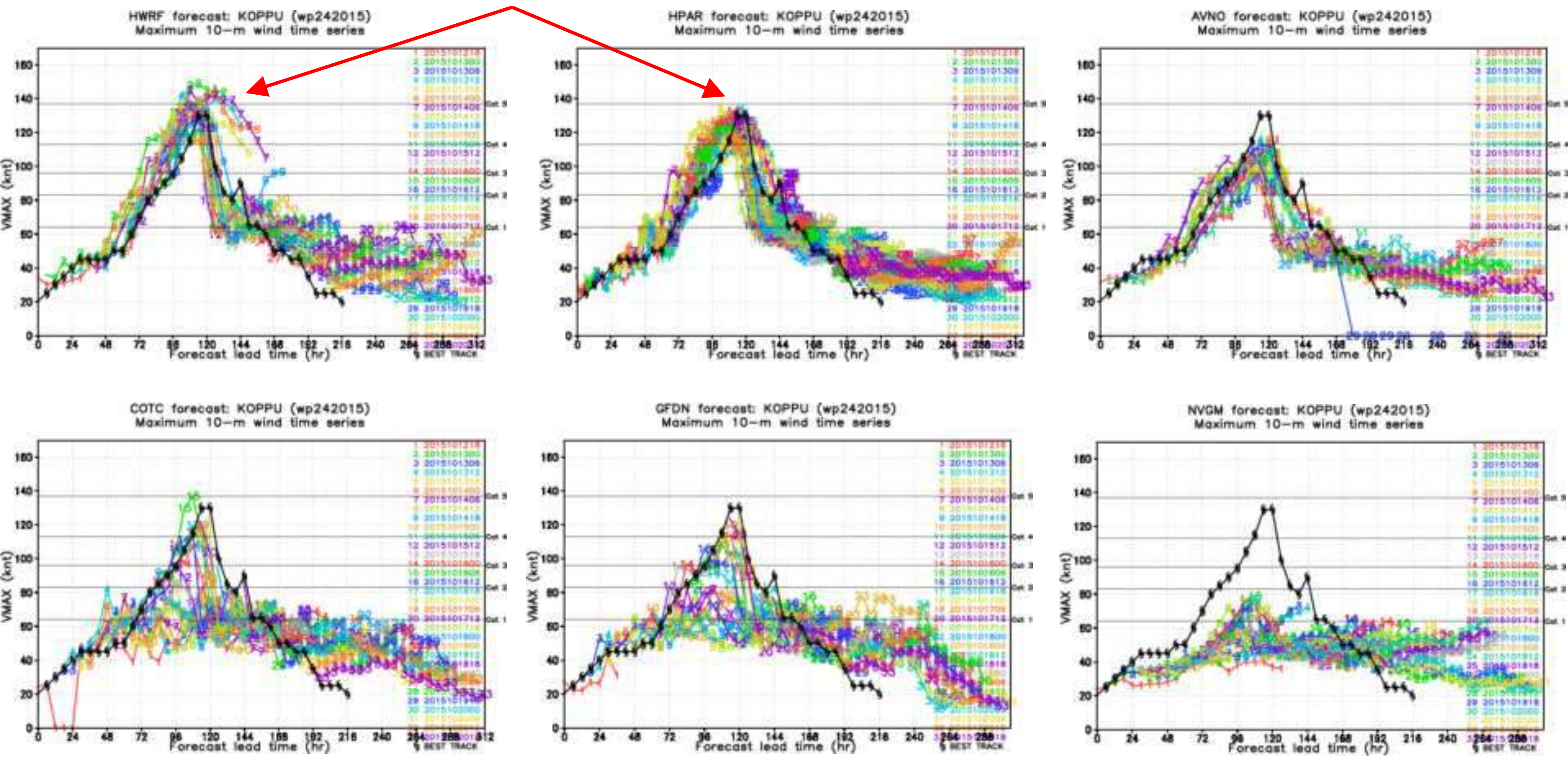
HWRF: Operational HWRF for WPAC without ocean coupling

HPAR: HWRF for WPAC with ocean coupling

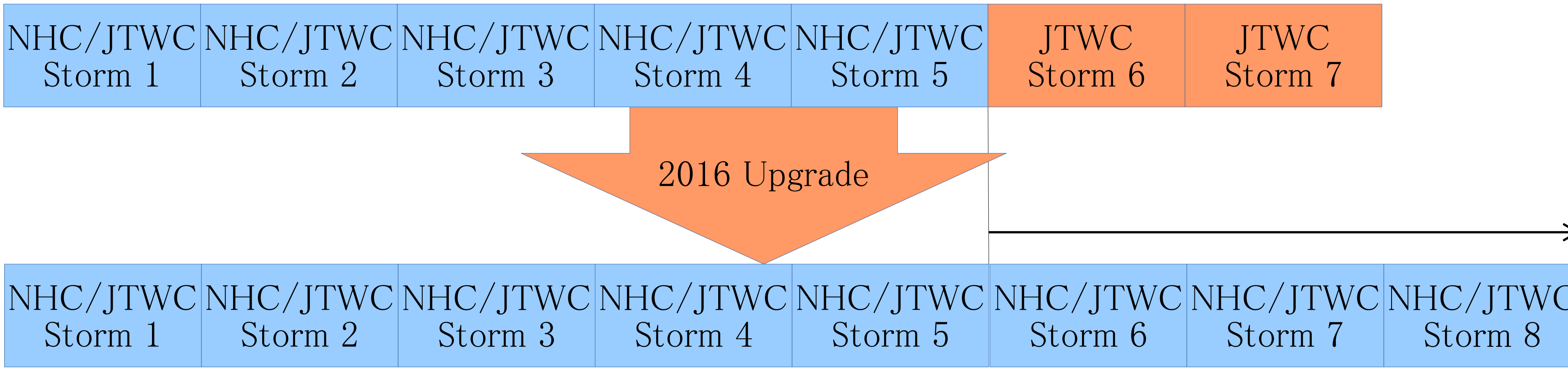


Chan-Hom 09W
Nangka 11W
Soudelor 13W
Goni 16W
Etau 18W
Dujuan 21W
Mujigae 22W
Koppu 24W

Intensity Composite for Koppu 24W



New in 2016: Eight Storms Support Requested by NHC



NHC/CPHC storms have higher priority.

- 2016 upgrade: NHC/CPHC can use all eight slots,
- **Storm Choices require a human (forecaster) decision if nstorms > 8.**

Test Plan and Upgrade Schedule: 2016 HWRF

	Sensitivity Tests	GFS Upgrade 2015 HWRF	Infrastructure Upgrades (Baseline)	Physics Test	Wave Model Test	Final 2016 HWRF Test	EMC/NCO Transition
	Multiple	H16Z	H16B	H16P	H16W	H216 (EMC)	HWRF (NCO)
Detail	Old GFS Various HWRF sensitivity tests	New GFS Old HWRF with minimal bug fixes	New GFS HWRF with infrastructure upgrades. Some physics and dynamics upgrades.	All physics upgrades	Wave coupling included	Final HWRF config	NCO runs parallel of fake storms to test dataflow. Customers verify. Repeat until approval.
Cases	Limited Storms 2011-2015	2013-2015 All AL CP EP	2013-2015 Mostly AL CP EP	2013-2015 Mostly AL CP EP	2013-2015 Storms of wave interest	2013-2015 All Bains	Fake Storms
Platform	WCOSS Jet/Theia	TO4 & Jet	TO4 & Jet	TO4 & Jet	TO4 & Jet	TO4 & Jet	TO4 (NCO)
Dates	2015 June-Jan	2016 Jan-June	2016 Jan-Feb	2016 Jan-Feb	2016 Jan-Feb	2016 Mar-June	2016 May

Long-Term Plans for Hurricane Modeling at NCEP

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

Development, T&E and Implementation Plans for HNMMB (supported by HFIP and HIWPP)

2016 June-Nov: uncoupled real-time demo
2016 Nov: single-storm, coupled, no-DA ready
2016 Nov-Dec: skill proven better than GFDL & comparable to HWRF
2017 Jan-May: HNMMB pre-implementation test
2017 Jun: HNMMB replaces GFDL operationally

HWRF-HYCOM-WAVEWATCHIII in 2016/2017

Three-way coupled system development is in mature stage

HYCOM for all global tropical storms:

- Climatology based MPIPOM has exposed the limitations in Eastern Pacific basin in 2015 with strong El-Nino conditions
- HYCOM with RTOFS initialization has been in the development
- OMITT helped improve the initialization and physics of HYCOM
- 2016 HWRF upgrades will include testing of HWRF-HYCOM (or HWRF-MPIPOM with RTOFS initial conditions)

One-way or two-way coupling with WaveWatchIII Hurricane Wave Model (multi2)

- Possible unification of hurricane wave model with HWRF for all tropical cyclones (UMAC recommendations)
- Two-way coupled system expected to enhance the representation of wave impacts on surface layer physics
- 2016 HWRF upgrades will include either of these options, with fully coupled system planned for 2017

High-Resolution HWRF Ensembles in 2018

2016	2017	2018	2019	2020
GFDL ——— HNMMB		**10-member HWRF/ HNMMB Ensembles**		NEMS Global Nests (NGGPS)

HWRF Ensembles have been showing value during the past three years (HFIP Demo).

Surge in computing at NCEP operations allows us to plan for implementing high-resolution HWRF ensembles

Take advantage of ensemble DA, perturbations in physics and IC/BCs

Develop products that directly benefit NHC operations to improve deterministic forecasts

2016/2017: Continue HWRF ensemble HFIP Demo (multi-model regional ensembles); add HNMMB members to the mix

2016/2017: Develop advanced products for providing guidance on guidance and probabilistic forecasts

2018: 10-member HWRF/HNMMB ensemble implementation

Basin-Scale Multi-Storm HWRF/HNMMB in 2018

2016	2017	2018	2019	2020

Basin-Scale HWRF/NMMB———Tropical NMMB Domain

Large basin-scale domains that forecast multiple storms at the same time.

Need to show the value (cost vs. benefit)

Primary focus is for NATL/EPAC basins

Seven day forecasts including genesis.

Such large domains are needed for good wave forecasts

HNMMB could do a "tropical domain": -60 to +60 latitude, cyclic in longitude; Covers all storms.

2016: HWRF/HNMMB basin-scale parallel

2017: HWRF/HNMMB basin-scale operational (???)

2018:

- **HNMMB basin-scale operational**
- **HNMMB tropical domain parallel**

2019: HNMMB tropical domain operational

2020 onward: develop global nests to replace HNMMB tropical domain with the new non-hydrostatic dycore (NGGPS)

Tropical Domain HNMMB in 2019

2016	2017	2018	2019	2020

Basin-Scale HWRF/NMMB———**Tropical NMMB Domain**

2017 Nov: Full DA, basin-scale, system ready.

2018 Jun: HNMMB with DA operational

- Basin-scale, just like HWRF.
- Upgrade at same time as HWRF.

2018 Nov: “Tropical” domain ready

2019 Jun: “Tropical” HNMMB model operational

2019 onward:

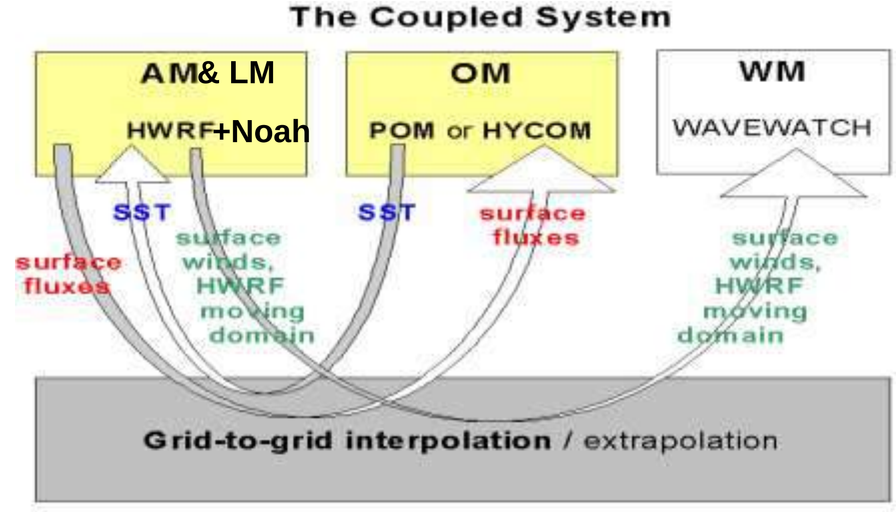
- **Development switches to global nesting implementation.**
- **Three-way global coupling (wave/ocean/atmos)**
- **Target 2021 for parallel.**
- **Target 2022 for implementation.**
- **Follows the path of NGGPS for hurricanes.**
- **Assists in developing advanced modeling techniques for NGGPS hurricane components**

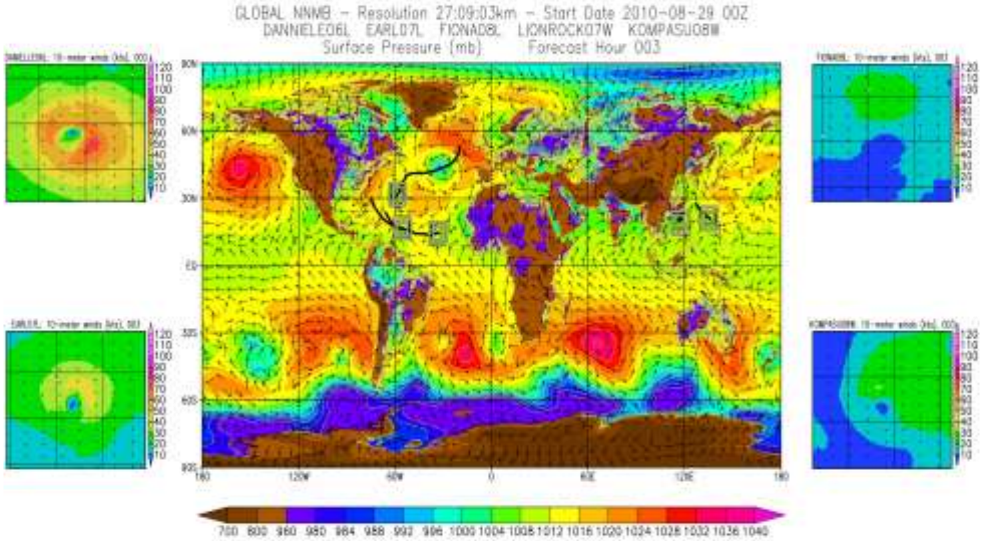
Future Plans: Hurricane Physics

Align with HFIP and NGGPS Physics Strategy

Focus on improved air-sea interactions and inner core processes

Advanced scale-aware and stochastic physics with focus on multi-scale interactions

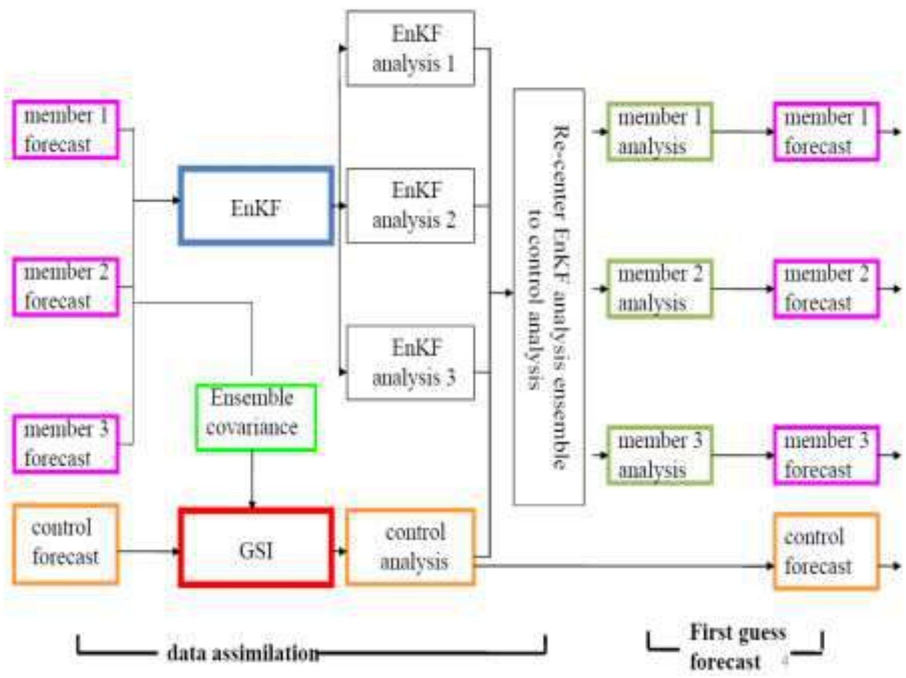




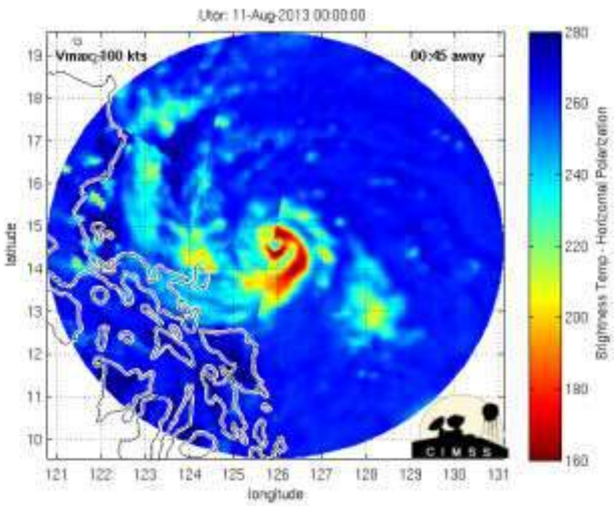
Future Plans: Hurricane Data Assimilation

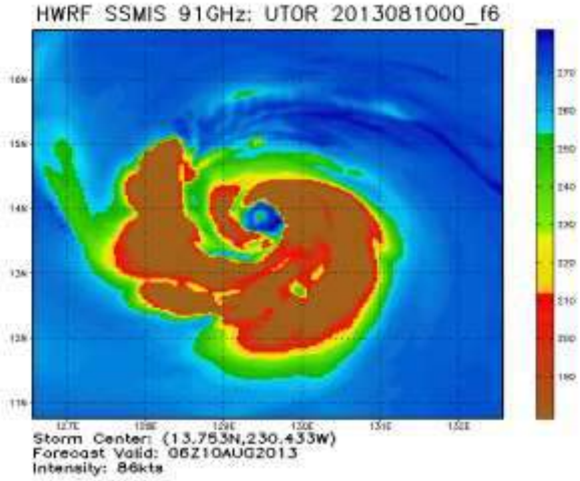
- Align with HFIP DA Strategy
- Focus on inner core aircraft and all-sky radiance data assimilation
- Advanced self-cycled HWRF EnKF-GSI Hybrid Data Assimilation System (HDAS)
- Vortex relocation and initialization become part of Data Assimilation

Hybrid EnKF-GSI DA system: 2 way coupling



Challenges Ahead to Address the Next-Generation Forecast Needs





Is HWRF capable of representing/predicting SEF/ERC?

Goals: Increase forecast accuracy at all lead times, especially during periods of rapid intensity changes; raise confidence levels for all forecast periods.

Tallapragada and Kieu, 2014: Real-Time Forecasts of Typhoon Rapid Intensification in the North Western Pacific Basin with the NCEP Operational HWRF model. TCRR, 2014, 3(2): 63-77.
Kieu, Tallapragada and Hoggsett, 2014: Vertical structure of tropical cyclones at onset of the rapid intensification in the HWRF model Geophysical Research Letters; Volume 41, Issue 9, 16 May 2014, Pages: 3298–3306
Kieu, Tallapragada and Zhang, 2015: On the development of Double Warm Cores in intense Tropical Cyclones. J. Atmos. Sci. (submitted)

Rosado: Ph.D. Dissertation on relationship of lightning and RI in HWRF model
Carter: MS Thesis on downstream impacts of RI for landfalling storms

Summary/Concluding Remarks

- HWRF has dismal RI predictability skills in the NATL and EPAC basins, getting better with time…
- HWRF has shown somewhat higher RI predictability in the WPAC basin
- A phase-lock mechanism is identified as a necessary condition for RI but not sufficient. Many external factors could inhibit model RI
- HWRF has better RI predictability when the initial storm intensity is weak. For storms with intensity > hurricane strength, HWRF fails to predict the RI
- HWRF captured very persistently DWC during the peak intensity for intense TCs (> 120 kt for longer than 12 h);
- HWRF real-time simulations show specific conditions for the DWC to take place;
- More observations/higher model resolution at upper level should be conducted to capture the existence of high level returning inflow.
- Possible solutions for improved RI: (a) increased resolution; (b) improved physics including scale aware features; (c) better initialization and DA and (d) high-resolution ensembles

Real-time and pre-implementation T&E HWRF products:
http://www.emc.ncep.noaa.gov/HWRF