Future of Operational Hurricane Modeling at EMC

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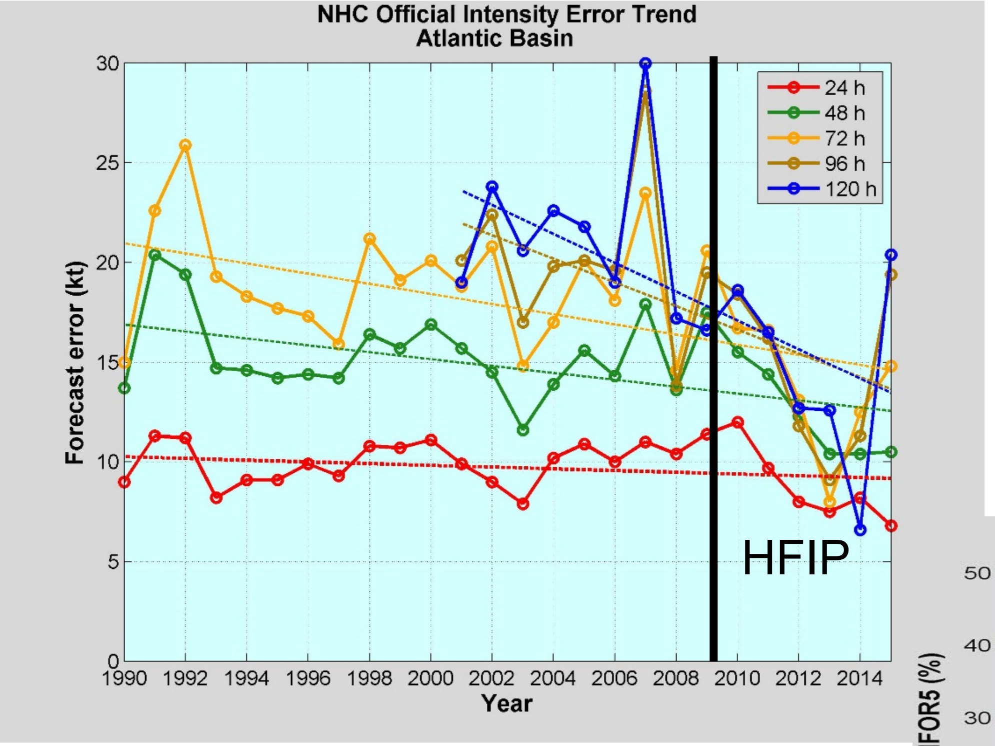
- HWRF in 2015
- Operational hurricane modeling plans for the future:
  - **Three-way coupled HWRF-HYCOM-WaveWatchIII System**
  - **Transition of HWRF into HNMMB (Replacement for GFDL)**
  - **Hurricane Ensemble Modeling Plans**
  - **Basin-Scale and Tropical Hurricane Modeling Plans**
  - **Global-to-local Scale Hurricane Modeling Plans (NGGPS)**
- Accelerated transition of HFIP/HIWPP/NGGPS supported research to operations; continue community modeling approach.
- Unified regional and global modeling concepts adopted by NCEP (recommended by UMAC).
- Strategies for serving the next-generation needs of operational hurricane forecasters

Forecasting Rapid Intensification: A scientific challenge

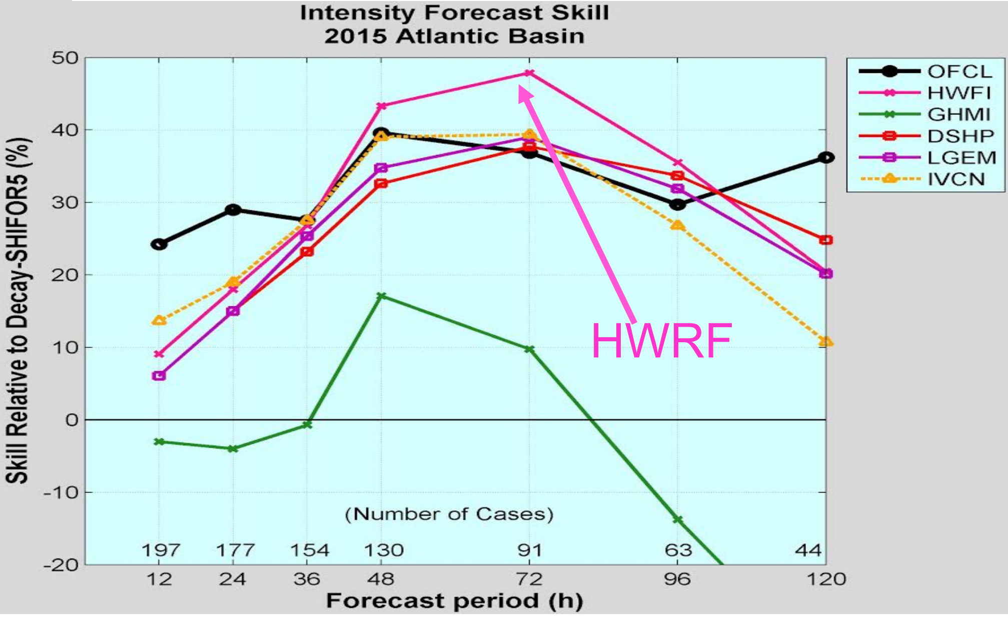
- **Verification of Rapid Intensification Forecasts from NCEP Operational HWRF**
  - *Significant RI predictability skill first demonstrated in the Western North Pacific basin*
  - *RI Skills are much lower in the Atlantic and Eastern Pacific basins*
- **Conditions for triggering Rapid Intensification 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*

Intensity forecast improvements from operational HWRF



Long term trends show slow improvement in intensity forecasts.

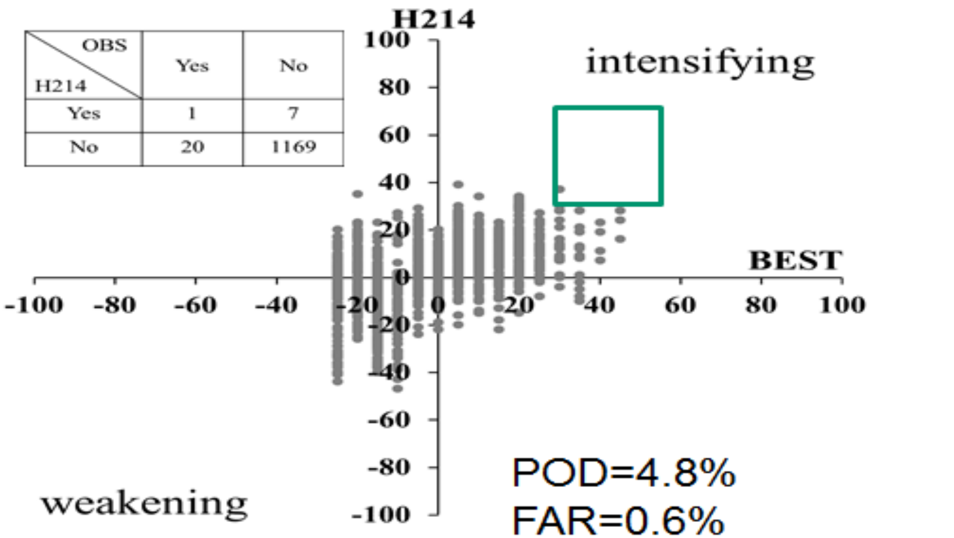
HWRF intensity forecast skill highest among other model guidance for 2015



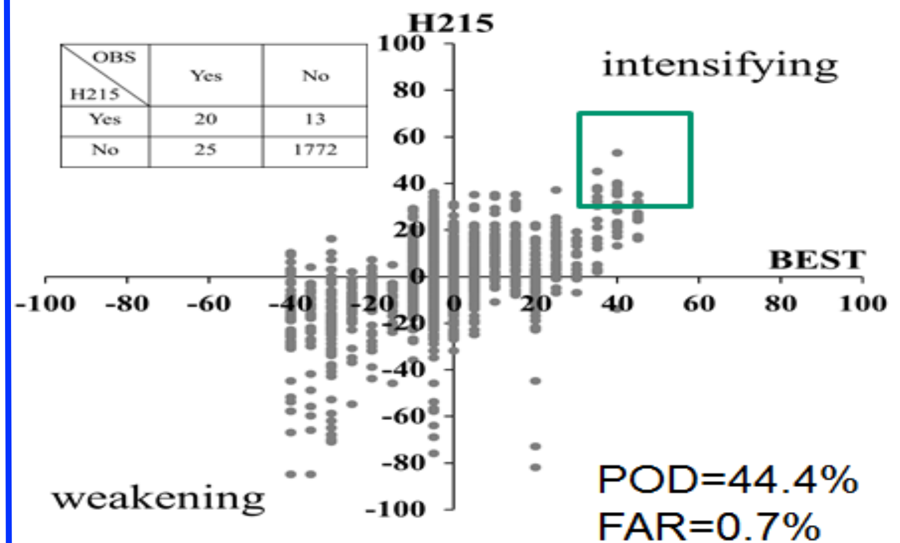
Courtesy: James Franklin & Eric Blake, NHC

Improvement in RI Forecasts: North Atlantic and Eastern Pacific Basins

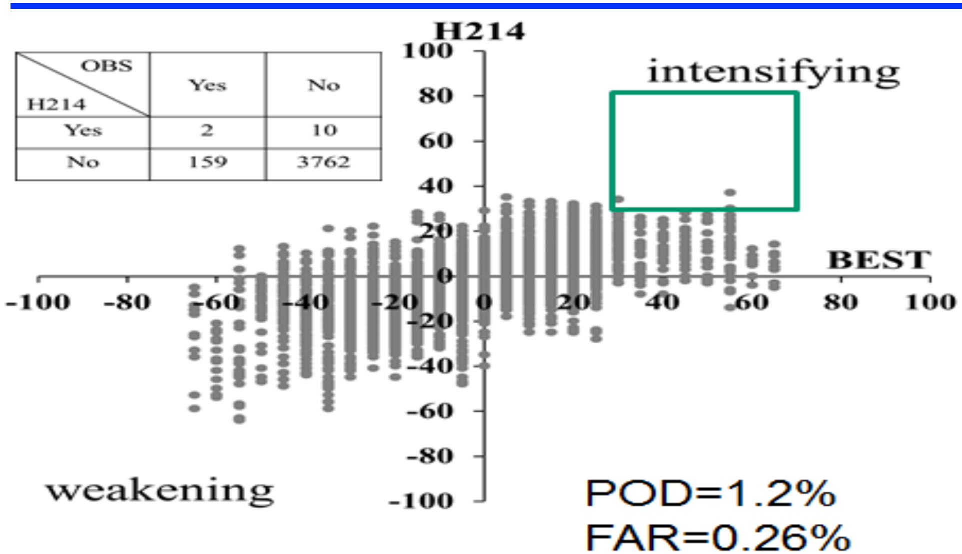
OBS / H214	Yes	No
Yes	1	7
No	20	1169



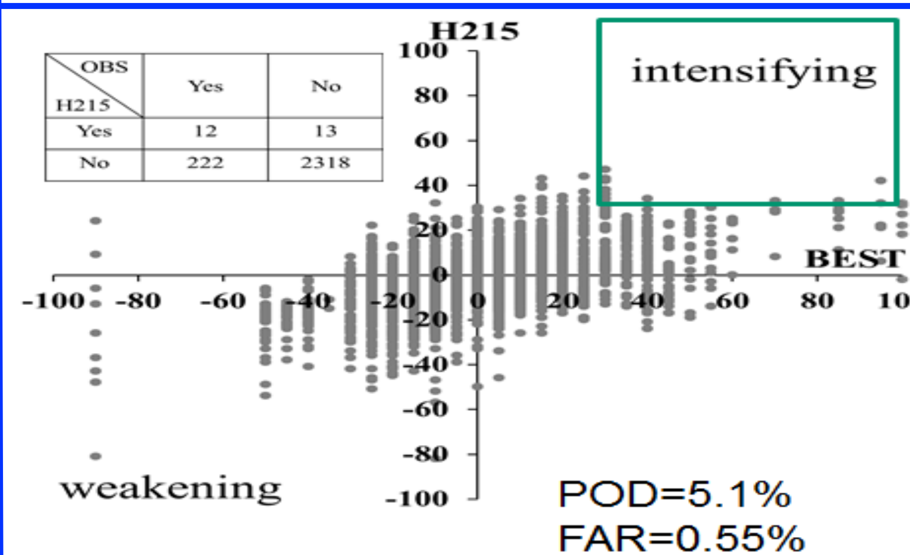
OBS / H215	Yes	No
Yes	20	13
No	25	1772



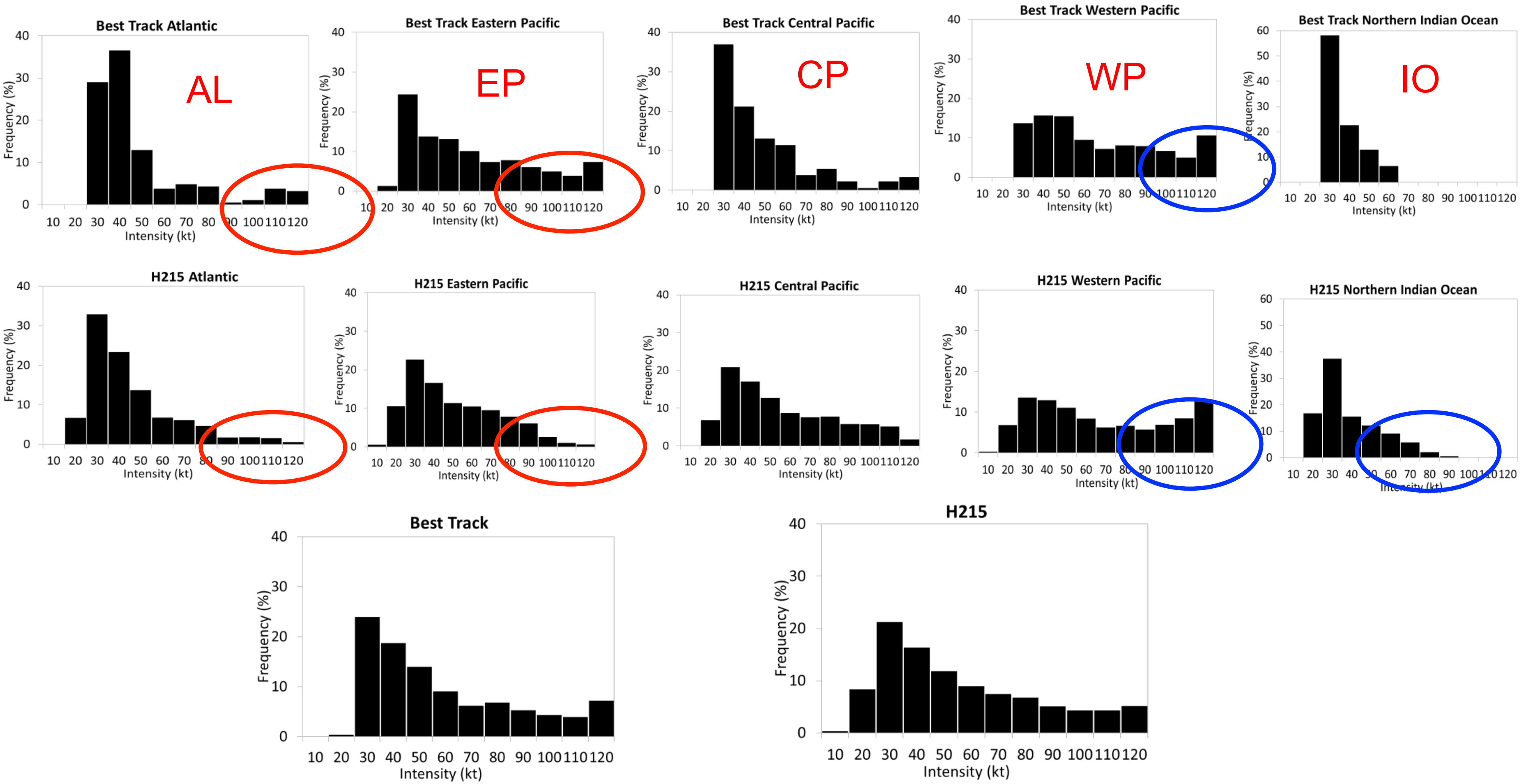
OBS / H214	Yes	No
Yes	2	10
No	159	3762



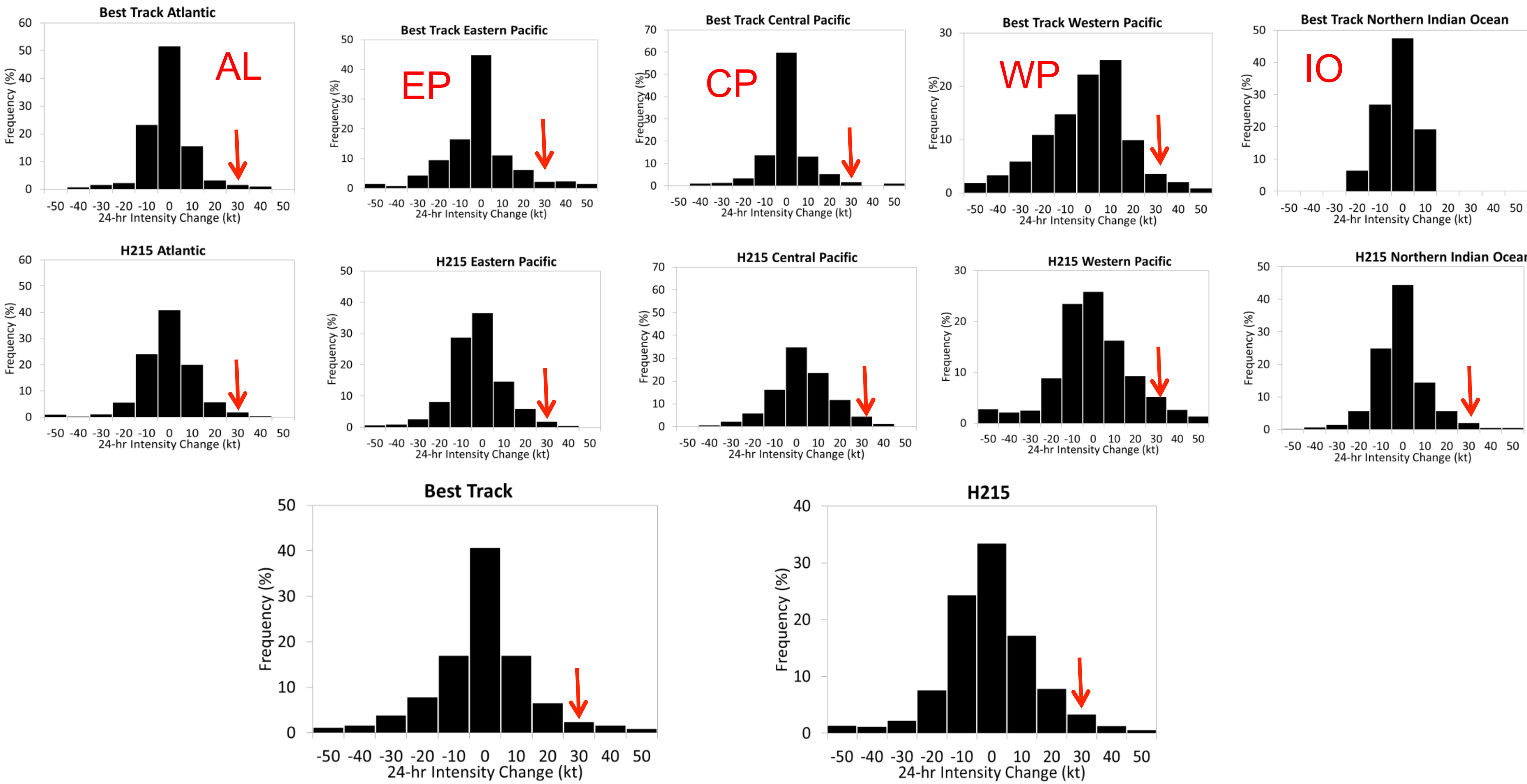
OBS / H215	Yes	No
Yes	12	13
No	222	2318



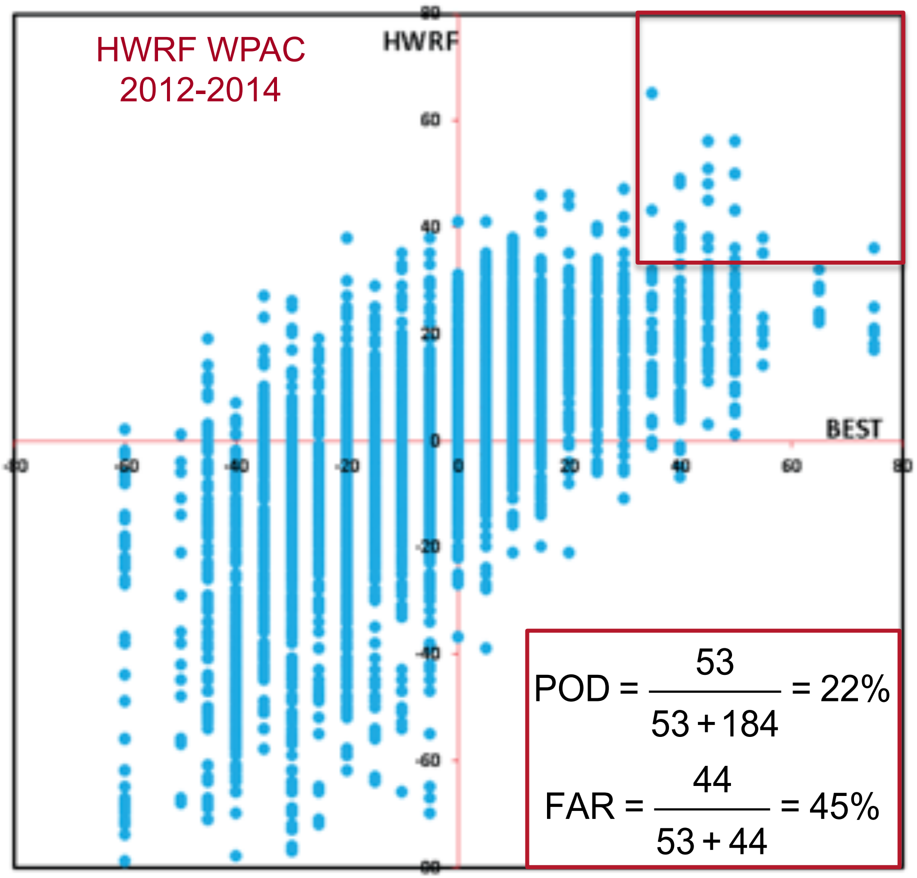
PDF Comparison of HWRF Predicted Intensity and Observed Intensity

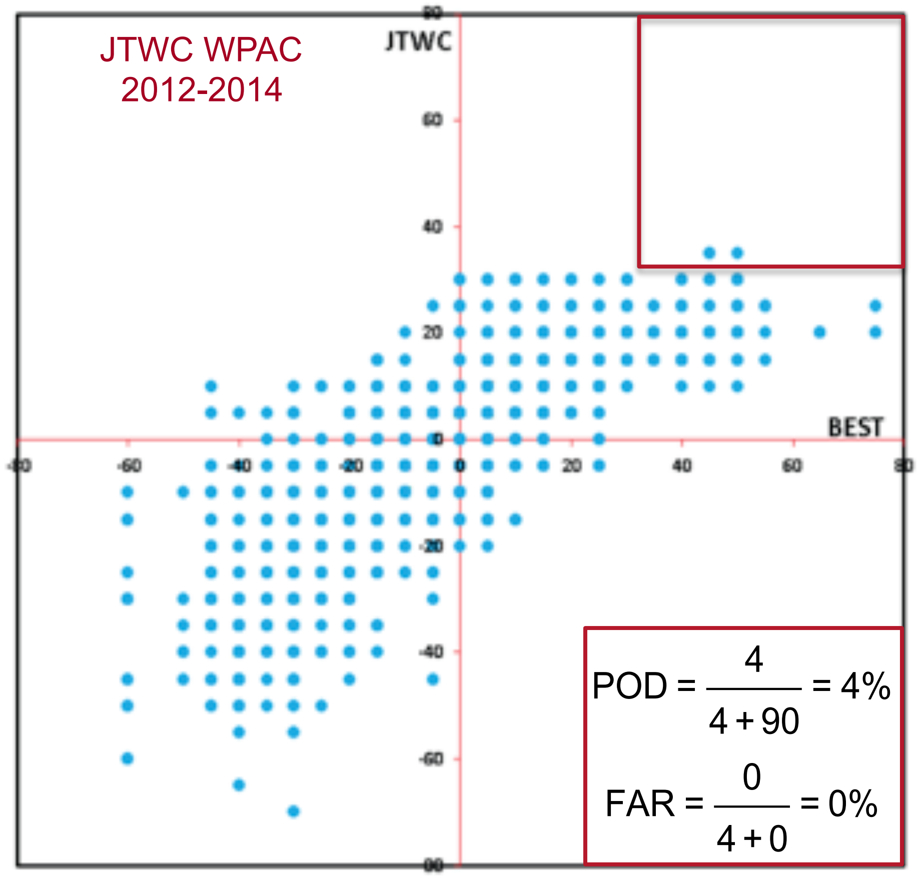


PDF Comparison of HWRF Predicted 24h Intensity Changes and Observed 24h Intensity



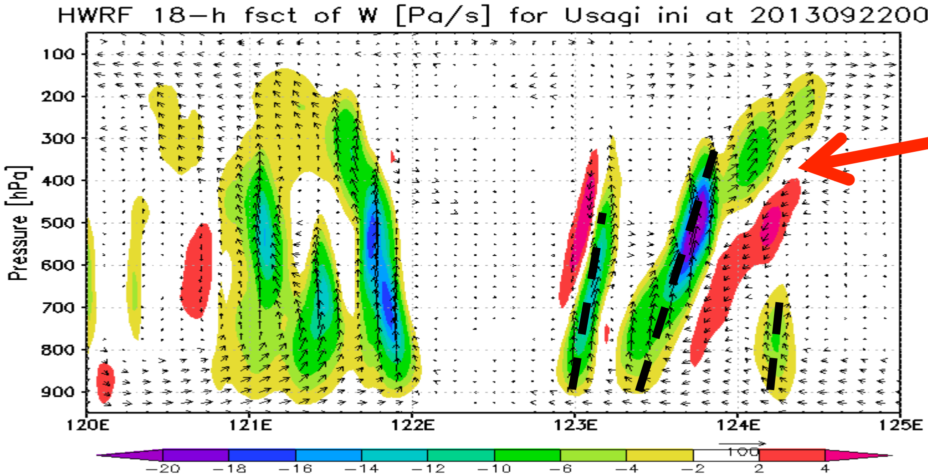
Verification of RI in the HWRF model
Western North Pacific basins



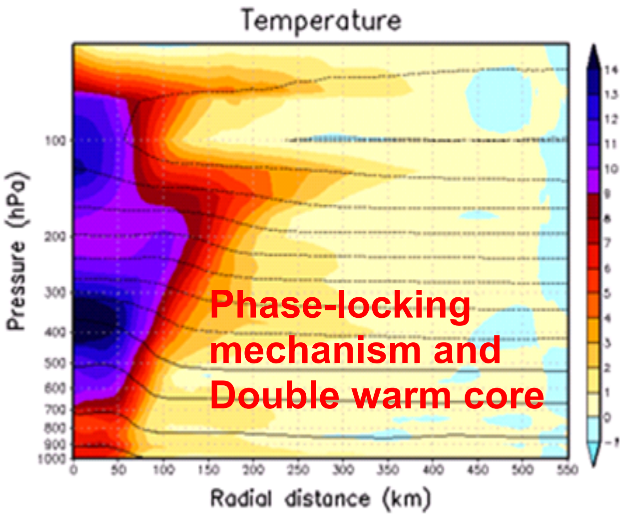


POD increased to 36% with 2km 2015 HWRF

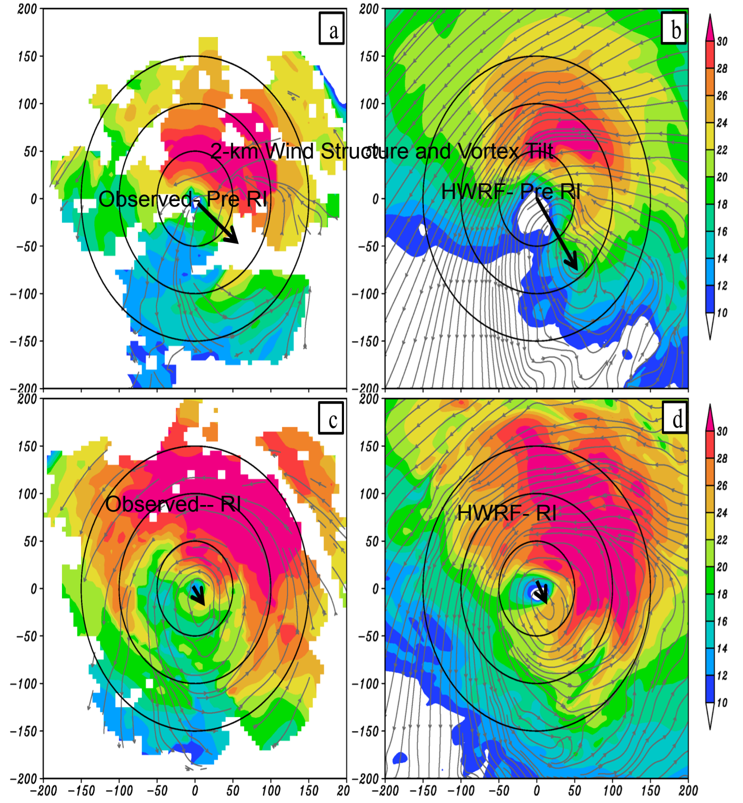
Findings from HWRF on Rapid intensification



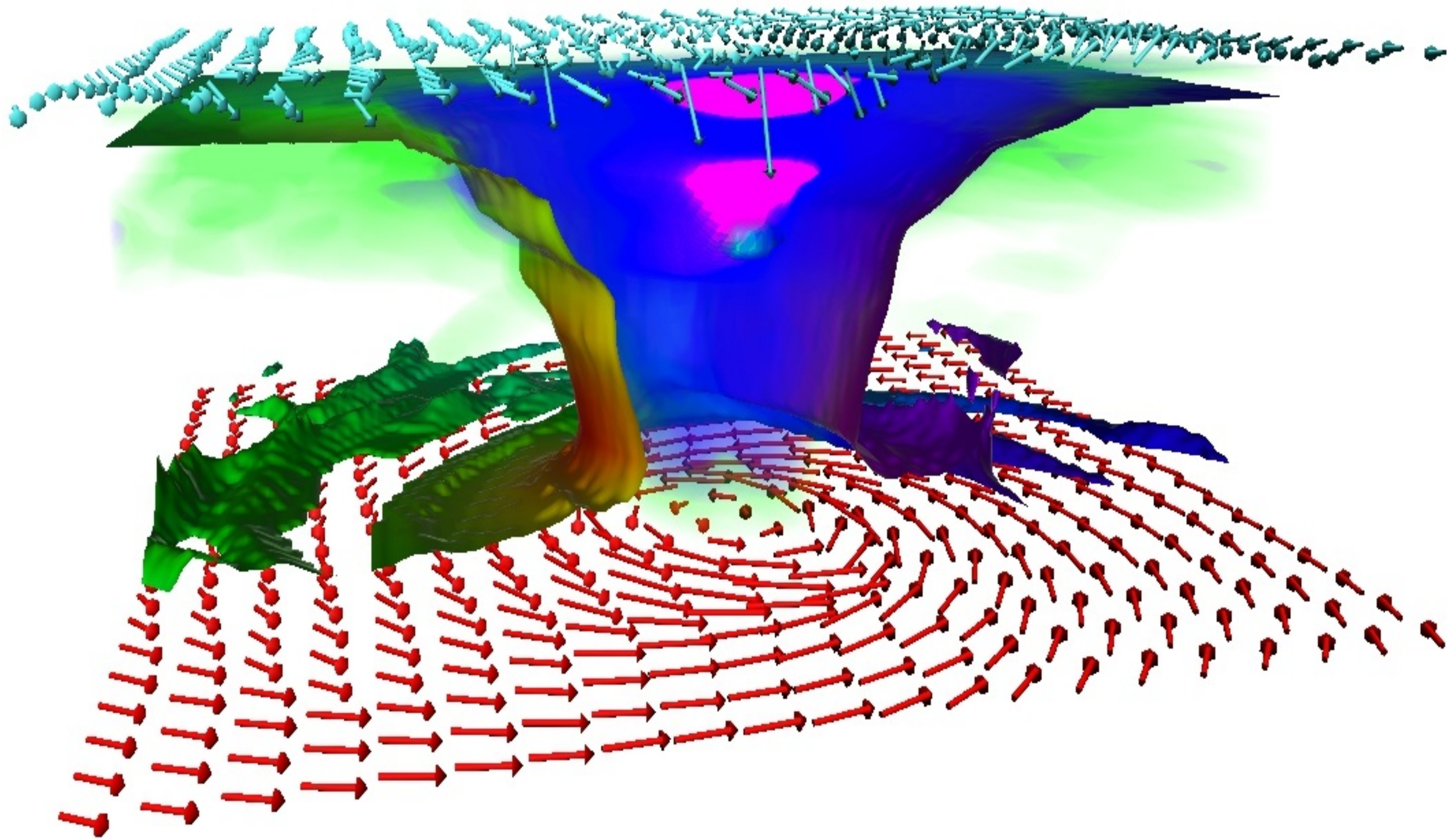
Triple eye-wall formation and subsequent eye-wall replacement for Typhoon Usagi (insufficient temporal frequency of output)



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

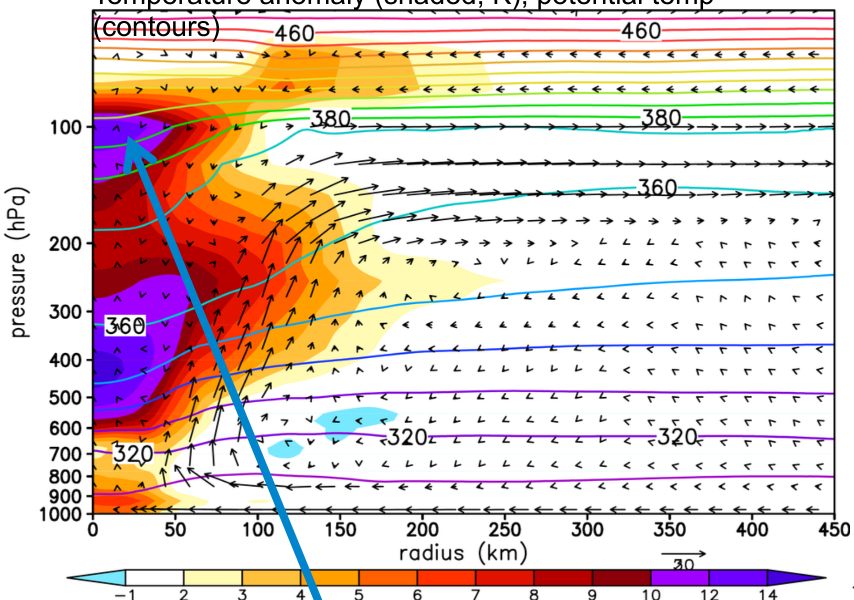


Question: Is DWC a realistic phenomena?



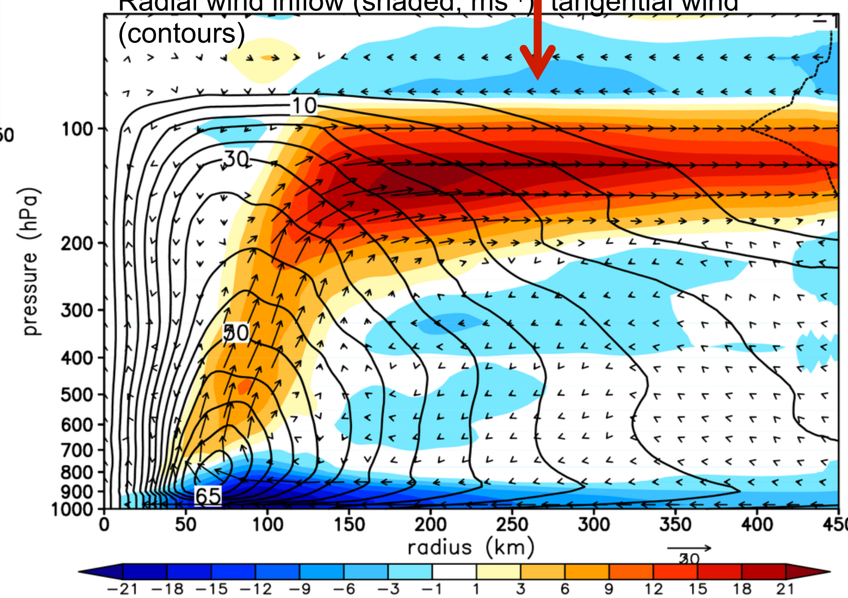
HWRF double-warm core structure

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



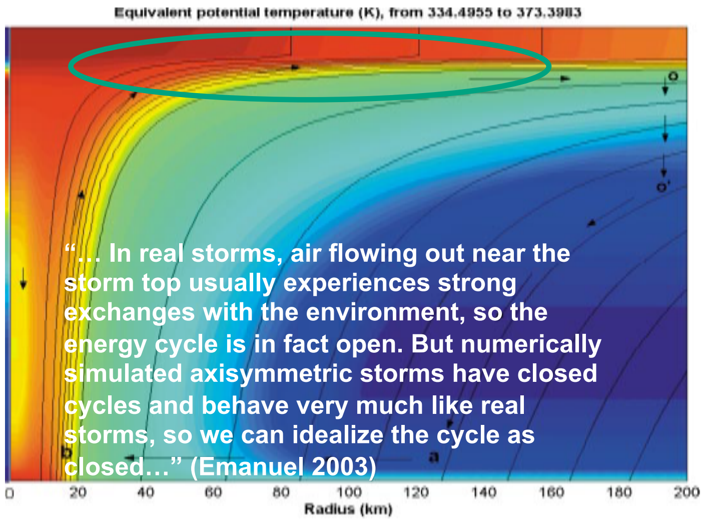
Strong upper-level inflow above the typical outflow layer

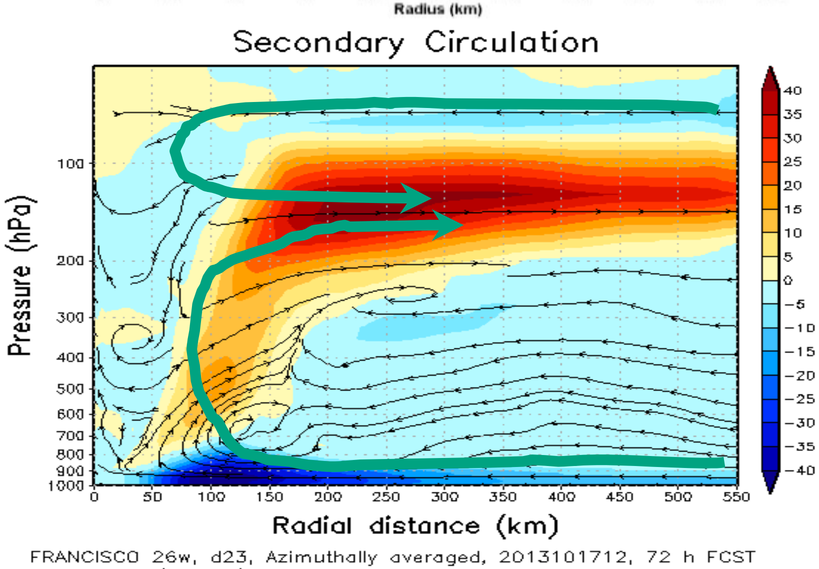
Radial wind inflow (shaded, ms-1), tangential wind (contours)



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

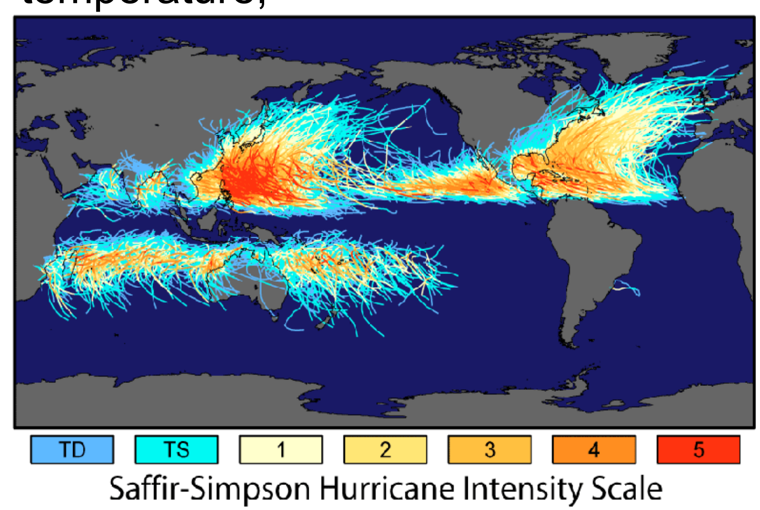
Implications





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;



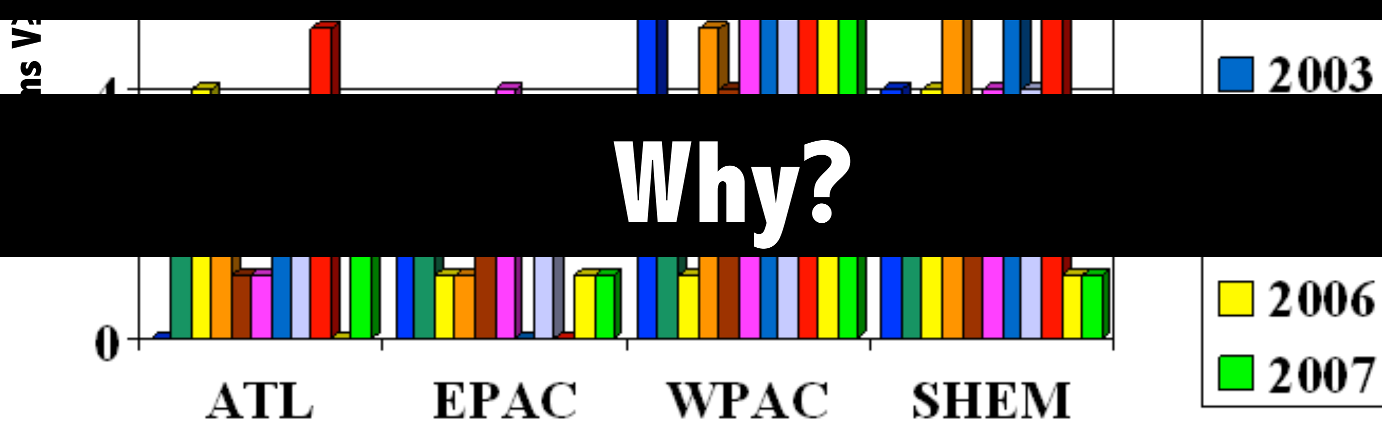
Secondary Eyewalls and Eyewall Replacement Cycles: New research frontiers for TC intensity

SEs are a common feature of intense storms

Not in mesoscale simulations!

~6% in AHW

~30% in HWRF



Why?

ATL	EPAC	WPAC	SHEM
77%	56%	81%	50%

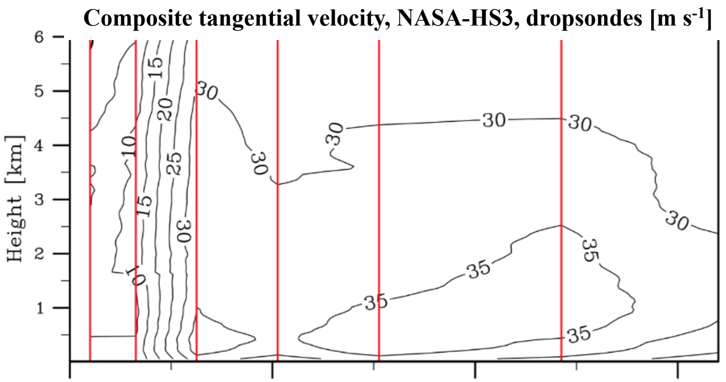
% with Concentric Eyewalls

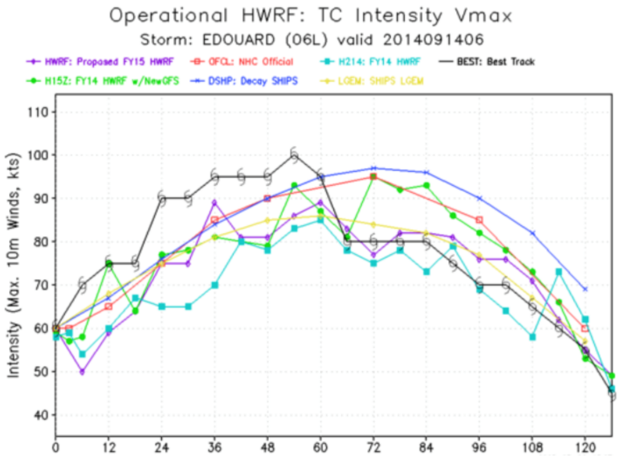
Hawkins and Helveston (2008)

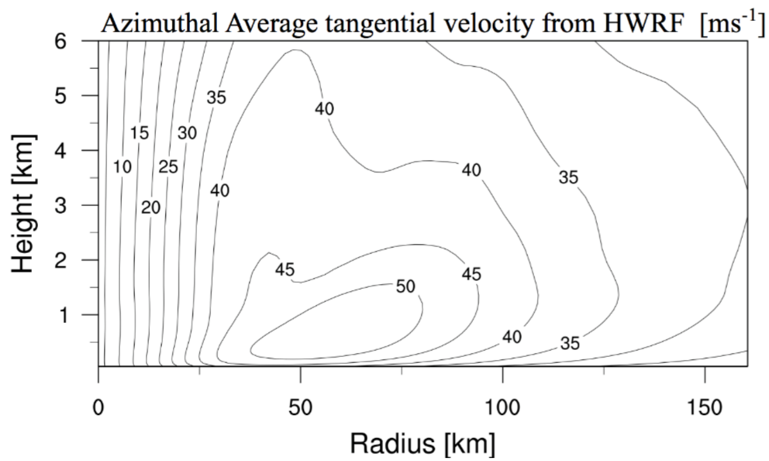
Hurricane Edouard (2014)

Secondary eyewall observed in

- ✓ **Nature**
- ✓ **HWRF 2015**

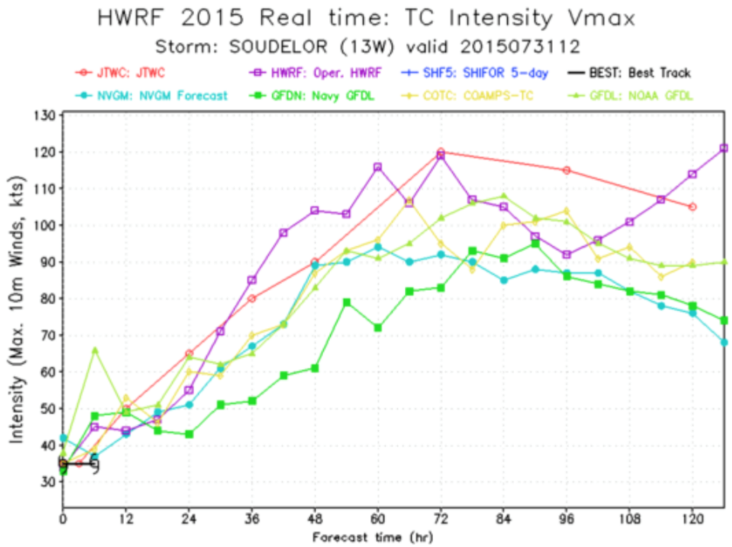


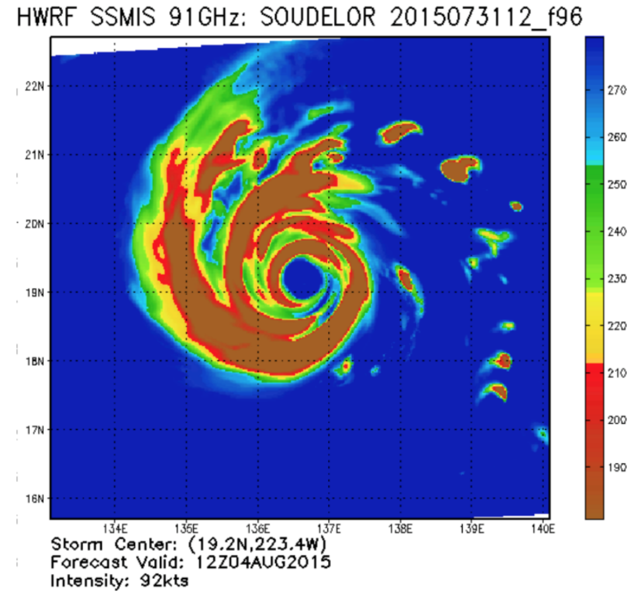


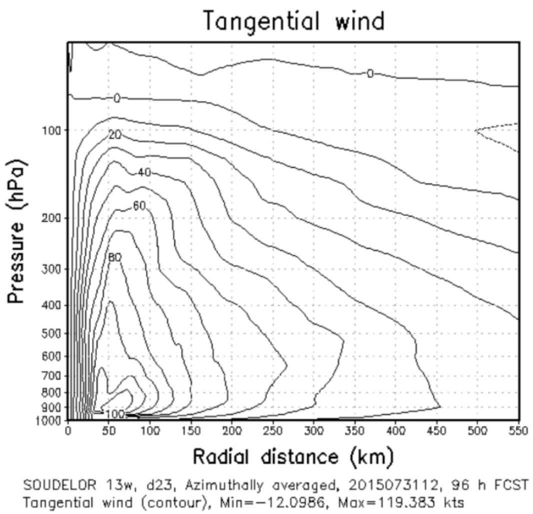


Operational HWRF generates secondary eyewalls
but they are rare, as in other mesoscale models (ARW or RAMs)

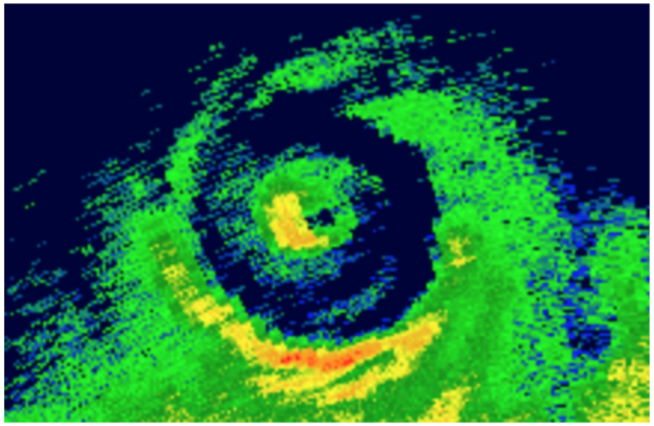
HWRF generates SEF for several strong storms







Reflectivity from the Guam radar on 8/03 0000 UTC



Physics Strategy: Parameterization development general direction

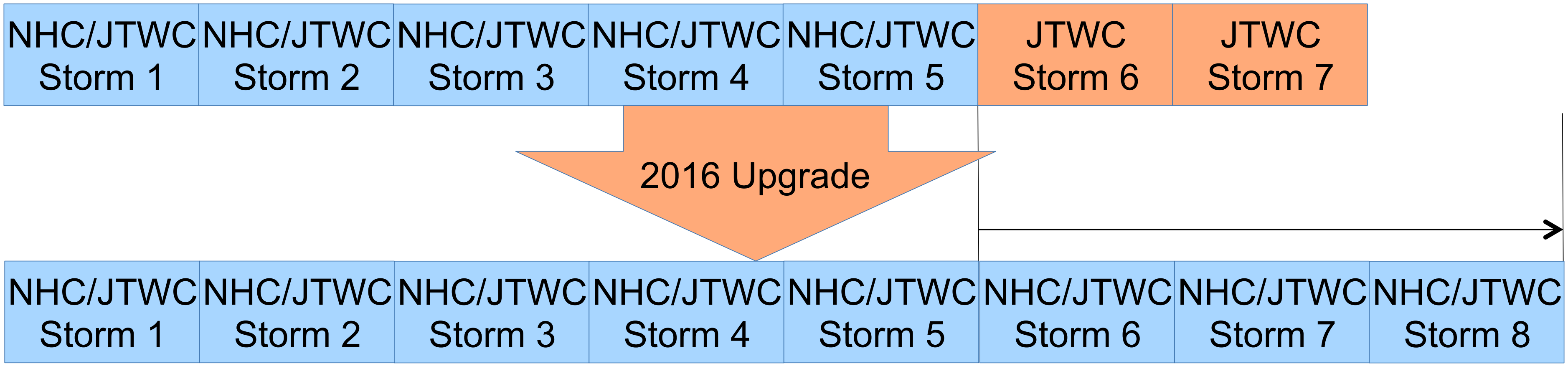
To improve HWRF performance, with regard to:

- 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

HWRF Future Plans: 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

Unification of Hurricane and Hurricane Wave Models; NMMB for hurricanes to replace GFDL

- Hurricane Wave Model is a separate model in operations driven by hourly forcing from operational HWRF. Combining HWRF and Hurricane Waves through implementation of three-way coupled system will help simplify the production suite (UMAC recommendations)

- **Hurricane Wave Model will be absorbed by the HWRF Model by 2017.**

- Having two independent NCEP atmospheric hurricane model forecasts has provided a critical increase in overall NCEP hurricane forecast skill. GFDL hurricane model is nearing it's lifetime and there is a need for replacing GFDL with high-resolution non-hydrostatic hurricane model

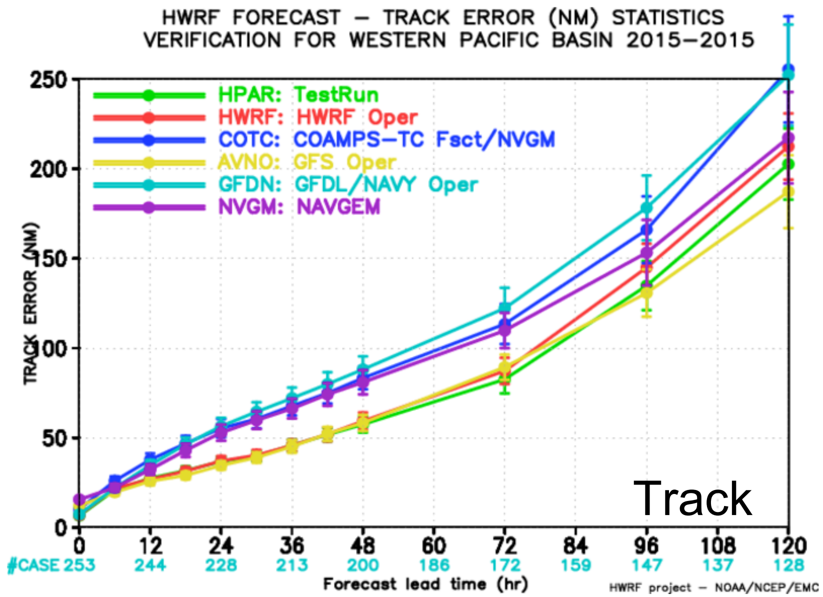
- **GFDL Model will continue in operations for 2016 hurricane season with several major bug fixes in the SAS Convection Scheme. Significant improvements expected.**

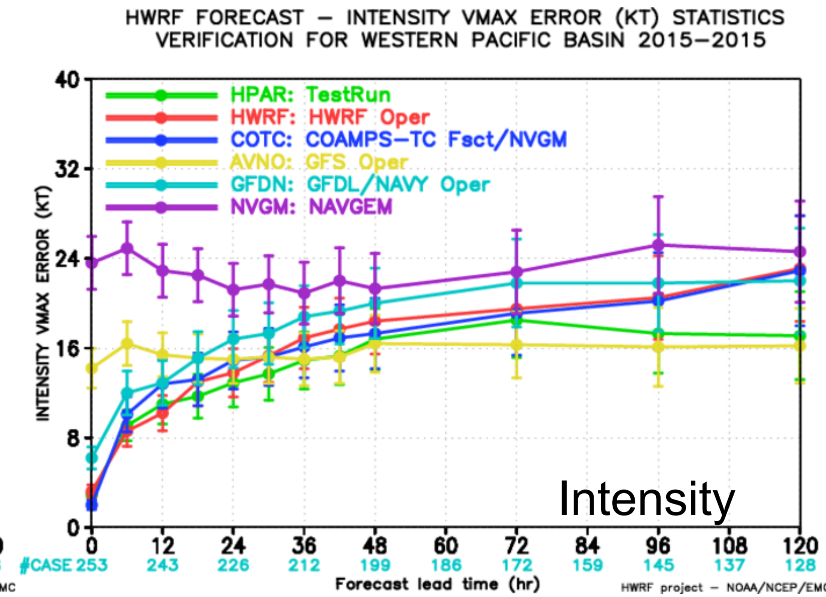
- **NEMS based NMMB for hurricanes will replace the GFDL Hurricane Model by 2017 while HWRF continues in operations.**

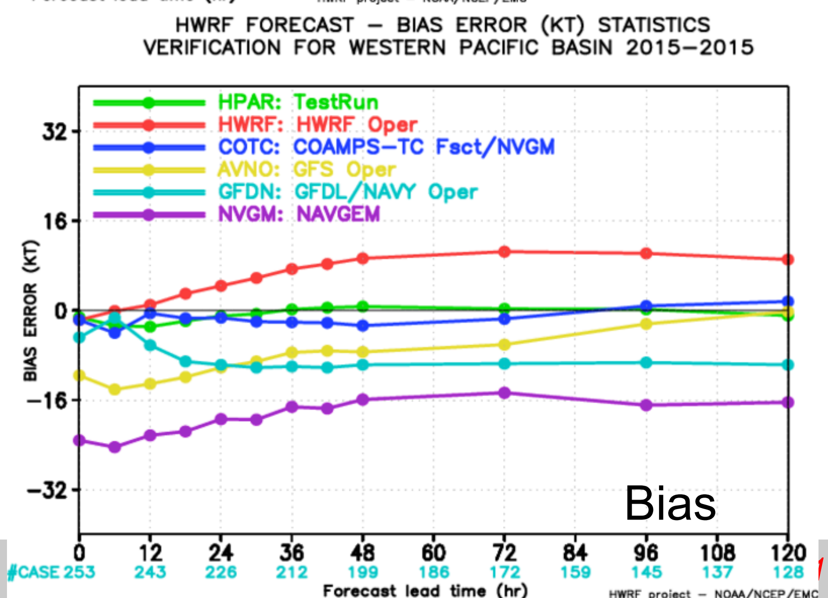
HWRF-HYCOM-WAVEWATCHIII in 2016/2017

- 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

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

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

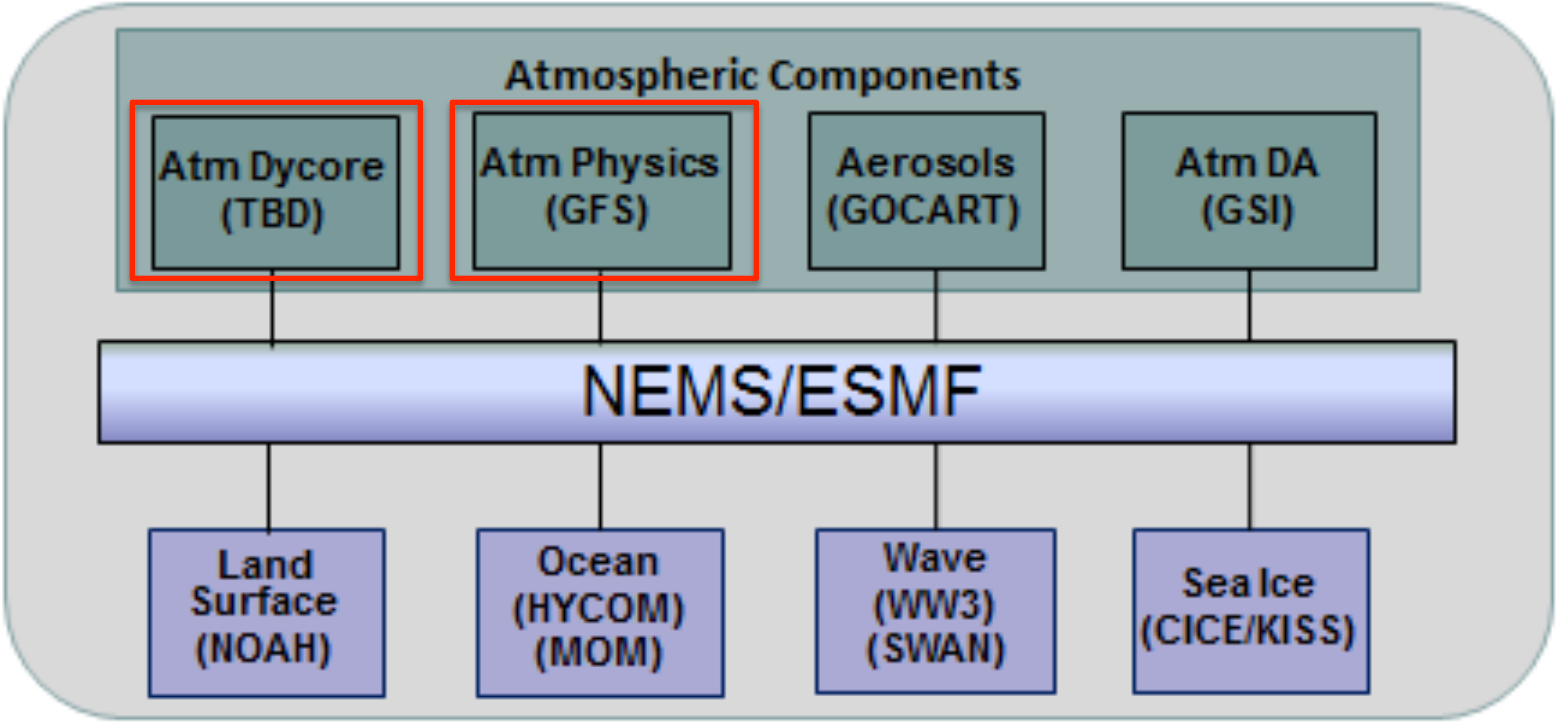
2019 onward:

- **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 of Global Modeling at EMC

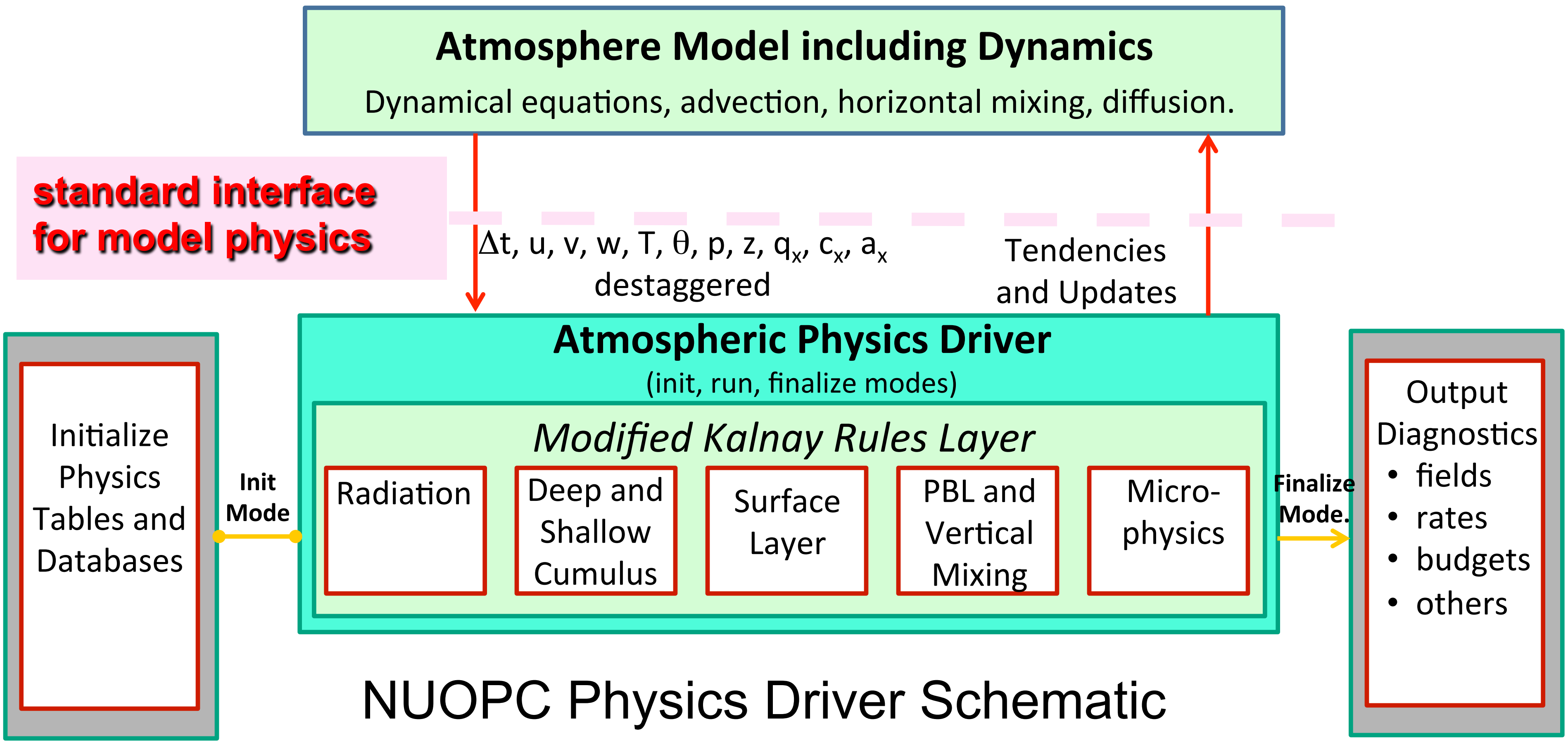
- NWS Initiative on developing Next Generation Global Prediction System
- **GOAL: Global Weather Prediction: Becoming Second to None**
- There are multiple ongoing efforts in developing non-hydrostatic dynamic cores for NCEP operations, both inside and outside the EMC global group.
- If we identify one that can meet our basic requirements, we will adopt it and evolve it to meet our full needs.
- A significant O2R2O process must then be implemented in order to make this effort an ultimate success.
- Two Phases of Testing for selection of new dycore for NGGPS

NGGPS and NEMS / ESMF



Modular modeling, using ESMF to modularize elements
in fully coupled unified global model
(+ *ionosphere* , *ecosystems* , ……)

NGGPS physics



Version 1.0 delivered June 2015

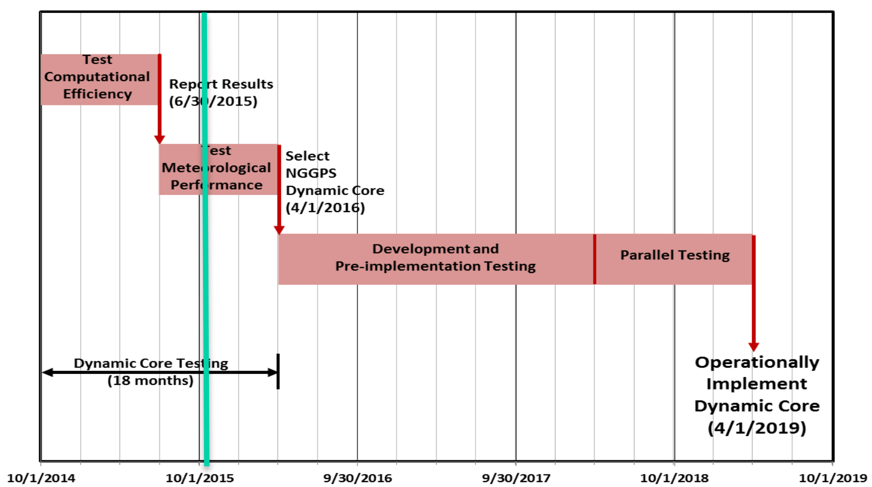
NGGPS Phase 1 Dycore Test Candidate Model Dynamic Cores

- FV3 (GFDL): Cubed-sphere finite-volume with flexible Lagrangian vertical coordinate (z or p base) with nesting or stretched grid capability
- MPAS (NCAR): Finite-volume C-grid staggering, icosahedral (z coordinate) with unstructured mesh refinement capability.
- NIM (ESRL): Icosahedral unstaggered A-grid mesh, finite-volume (z coordinate)
- NMM-UJ (EMC): Finite-difference, cubed-sphere version of Non-hydrostatic Mesoscale Model (p coordinate); Uniform Jacobian cubed sphere grid replaced lat/lon grid version with staggered B-grid (NMMB)
- NEPTUNE (Navy): Spectral-element (horizontal and vertical) cubed-sphere grid (z coordinate) with adaptive mesh refinement

Global Spectral Model not included – Non-hydrostatic version not available

NGGPS dycore

- Selecting a new dynamic core for global model to serve the NWS for the coming decades.
  - Architecture suitable for future compute environments.
  - Non-hydrostatic to allow for future convection-resolving global models.
- 18 month process to down-select candidate cores.
- 5 year plan to replace operations.
- Core → NEMS → applications.
  - ~~GSM-NH (EMC)~~
  - MPAS (NCAR)
  - FV3 (GFDL)
  - ~~NIM (ESRL)~~
  - ~~NEPTUNE (NRL)~~
  - ~~NMMB-UJ (EMC)~~



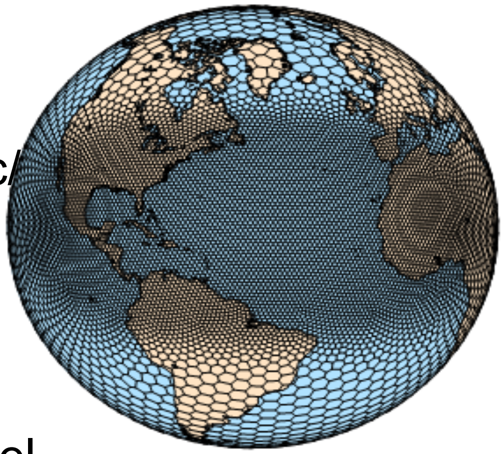
Hurricane prediction

- NEMS hurricane nests dycore requirements
  - Two-way feedback (upscale feedback captures effect of hurricane on environment)
  - Storm-following nests
- NEMS hurricane nests other requirements
  - Scalable physics
  - Multi-grid combined GRIB products directly from model (plus custom hurricane products)
  - Coupled atmos-wave-ocean

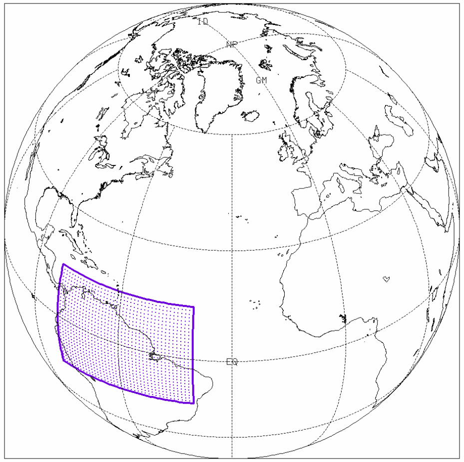
NGGPS Plans for Hurricanes (Nesting & Convective Systems)

- Static/Moving
- 1-way/2-way interactive (nests)
- Multiple nests run simultaneously
- Bit reproducible and restartable (static/ moving/ 1-way/2-way)
- ***Very fast and efficient!***
- Dynamics, physics and initialization appropriate and applicable for high-resolution nests within the global model

MPAS



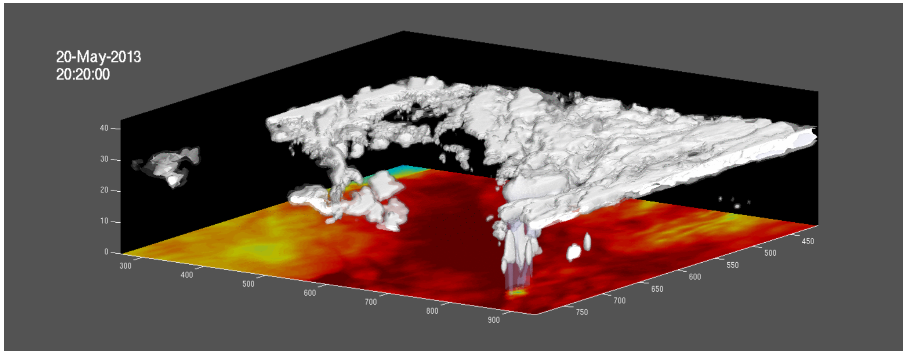
NMMB



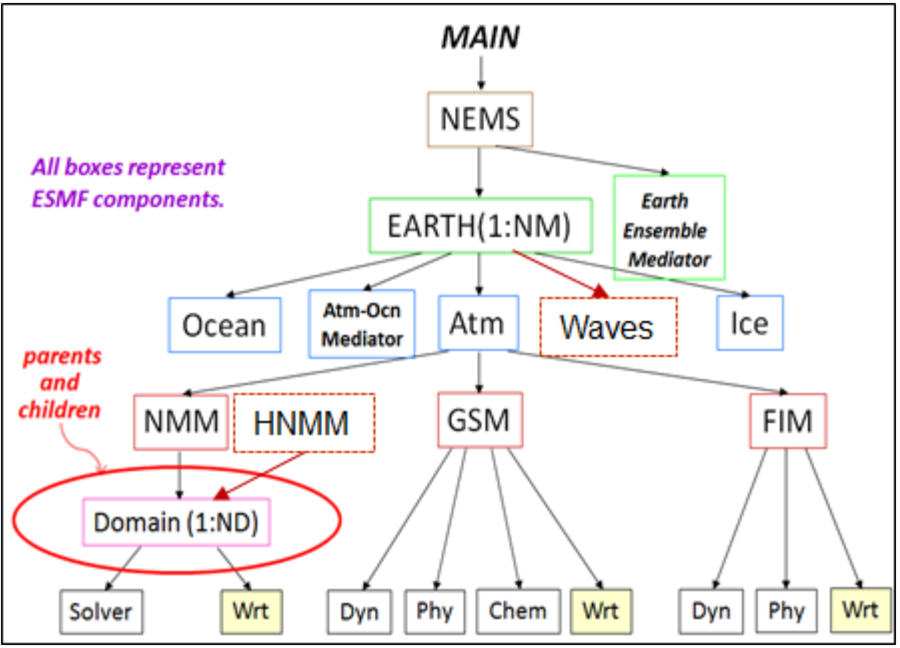
MPAS: Mesh Generation: Lloyd's Method *(iterative, using a user supplied density function)*

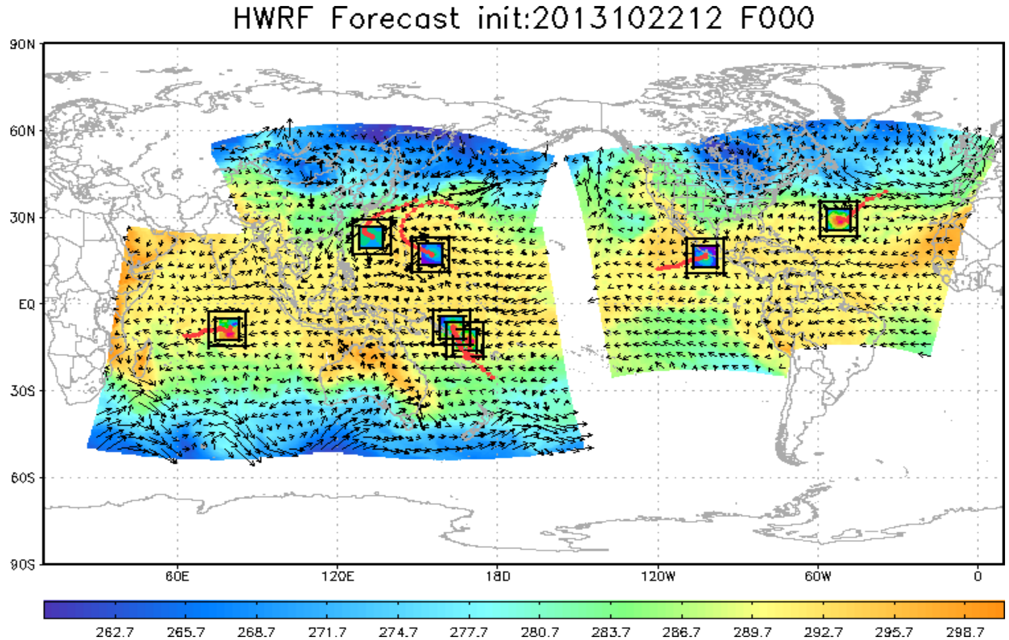
Two-way nests in FV3 designed for simultaneous, consistent, coupled regional and global solutions

GFDL FV3

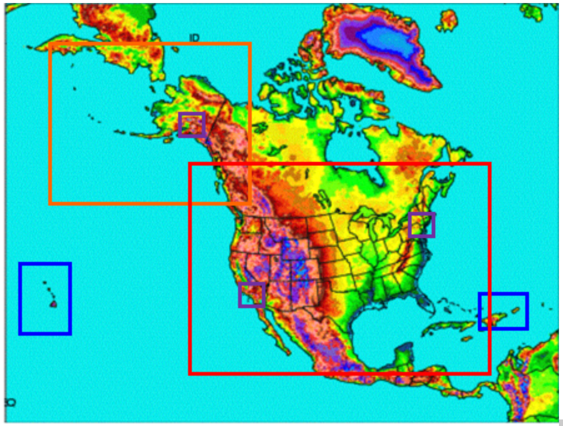


Current Operational Nests for Regional Models: NAM and HWRF





2015 HWRF Global Tropical Cyclone Forecasts: 7-storm capability



NAM: Parent runs at 12 km to 84 hr
Four static nests run to 60 hr

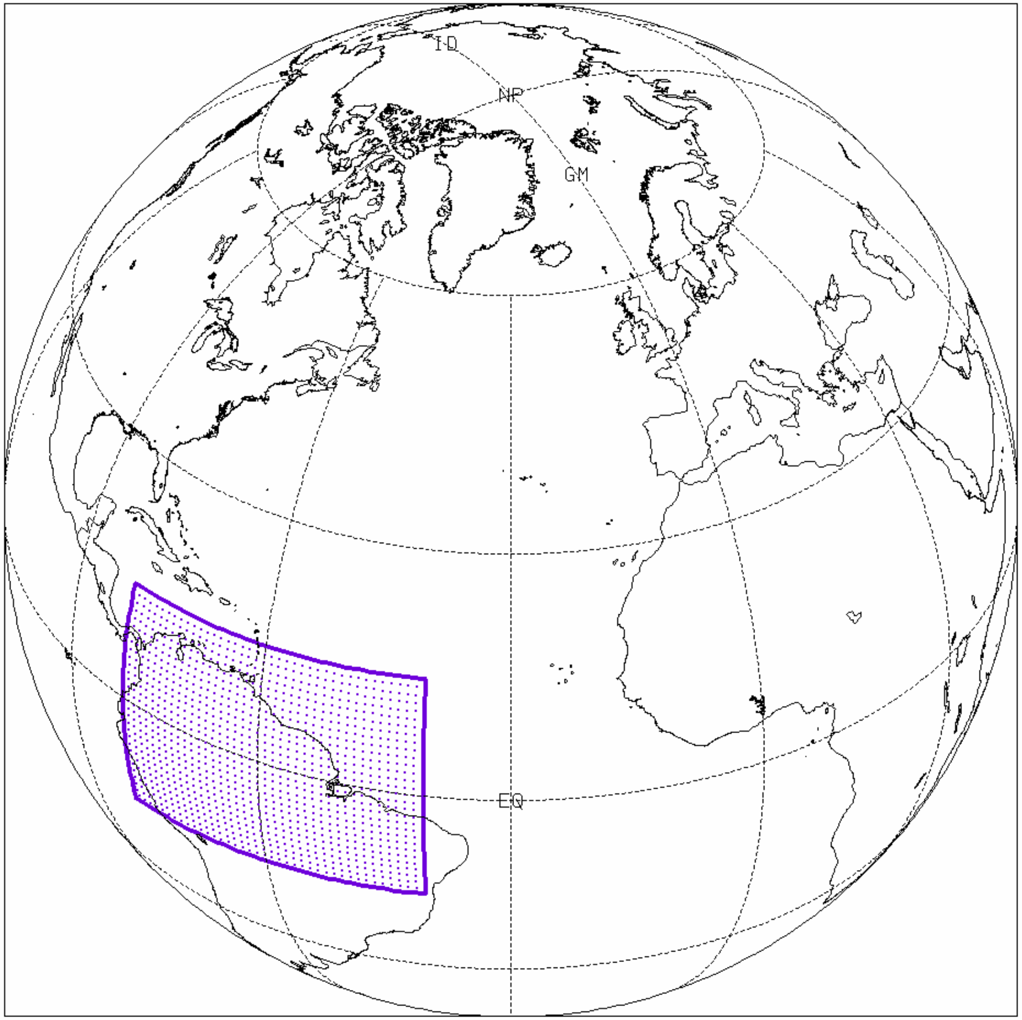
- **4 km CONUS nest (3-to-1)**
- **6 km Alaska nest (2-to-1)**
- **3 km HI & PR nests (4-to-1)**

Single relocatable 1.33km or 1.5km FireWeather grandchild run to 36hr (3-to-1 or 4-to-1)

HWRF: Parent runs at 18 km with storm following 2-way interactive nests at 6 km and 2 km resolution out to 126 hr

- **Coupled to Ocean (and Waves)**
- **ENSVAR inner core aircraft DA**
- **Seven storms all over the world**
- **Transition to NMMB/NEMS in progress**

Parent-associated nest vs. freestanding nest on a global lat/lon

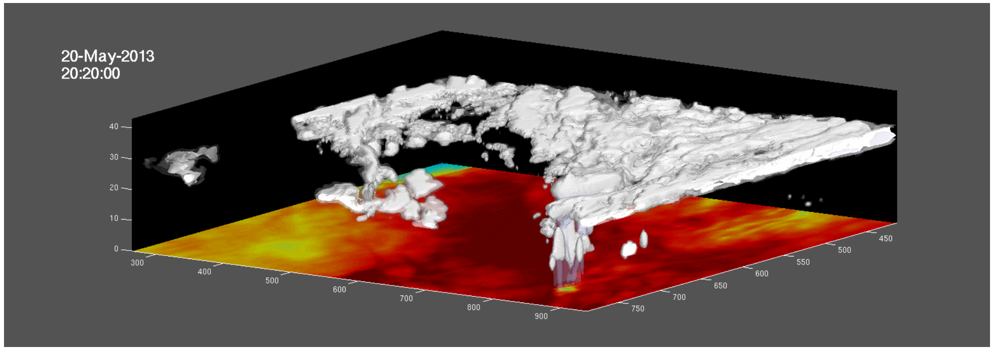


Freestanding => on a projection different from the parent's

Actively being developed for NMM in NEMS framework. Courtesy: Tom Black

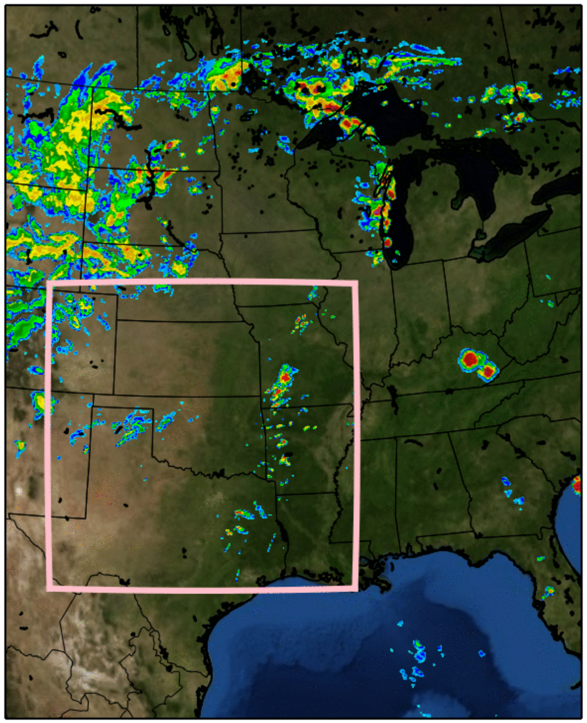
Two-Way Nesting Capabilities in GFDL FV3

(Recent developments using HiRAM and FV3)



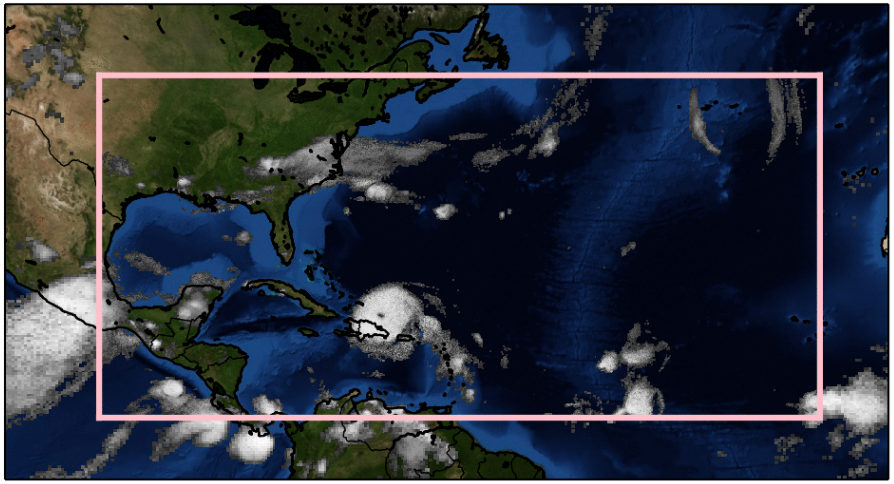
Examples of high-resolution nested grid simulations using HiRAM and FV3

2013-05-20 12:30:00



three-day HiRAM forecasts of severe convection during the Moore, OK tornado outbreak of May 2013, in a simulation nesting down to 1.3 km over the southern plains (using HIWPP 3km global runs)

2005-09-01 01:30:00



Year-long nonhydrostatic HiRAM simulation using 2005 SSTs, using an 8-km nest over the tropical Atlantic

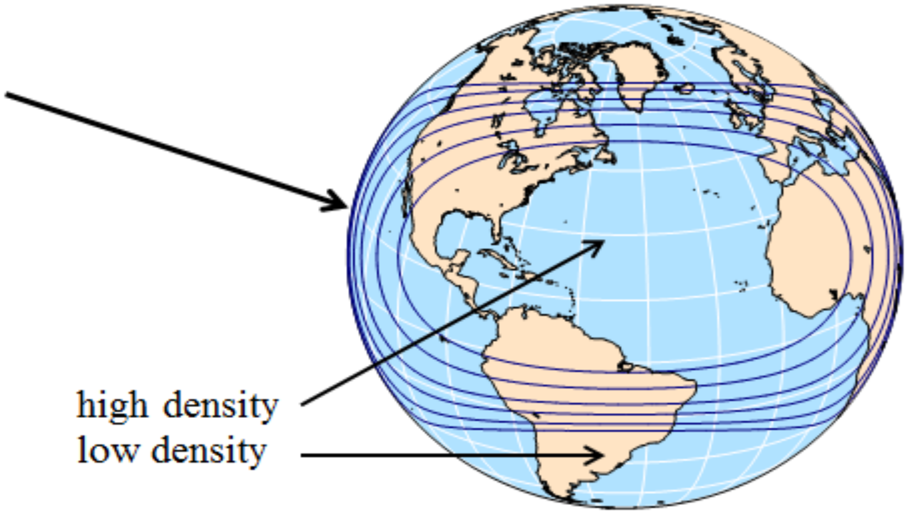
Slide courtesy: Lucas Harris, GFDL

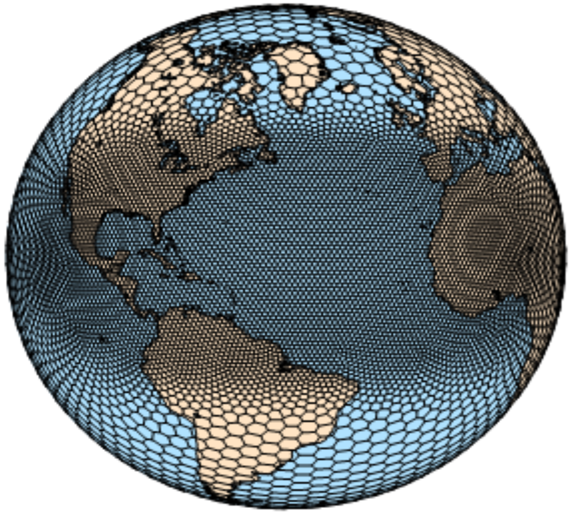
Mesh Refinement Capabilities in NCAR MPAS: Mesh Generation

(1) User-specified density function

(2) Lloyd's method

1. Begin with any set of initial points (the generating point set)
2. Construct a Voronoi diagram for the set
3. Locate the mass centroid of each Voronoi cell
4. Move each generating point to the mass centroid of its Voronoi cell
5. Repeat 2-4 to convergence

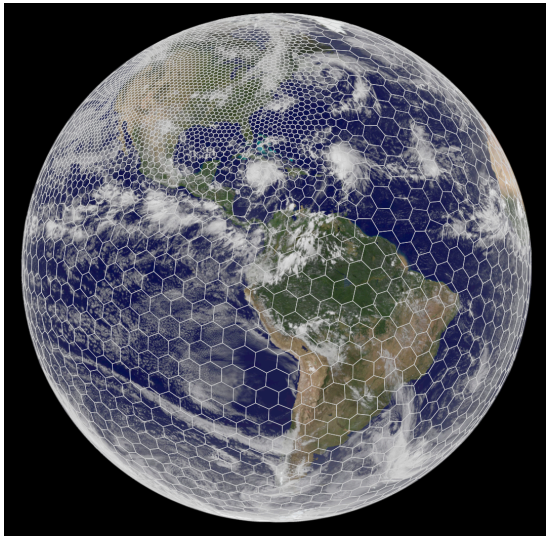




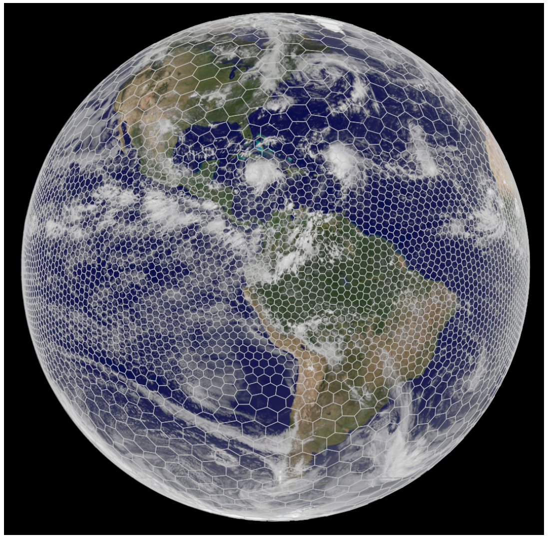
MPAS
Model for Prediction Across Scales

MPAS: Mesh Generation: Lloyd's Method

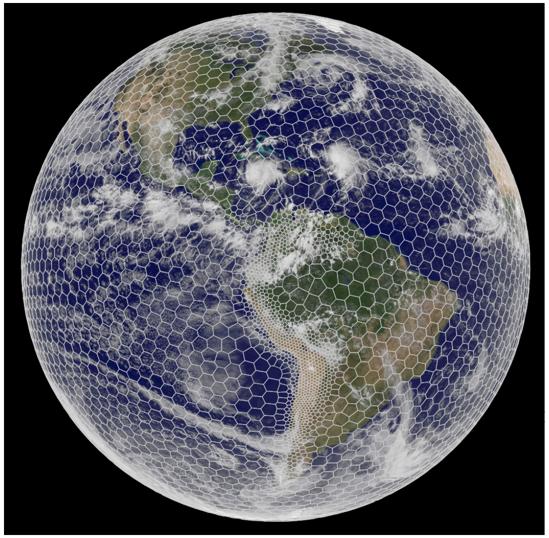
(iterative, using a user supplied density function)



North American refinement



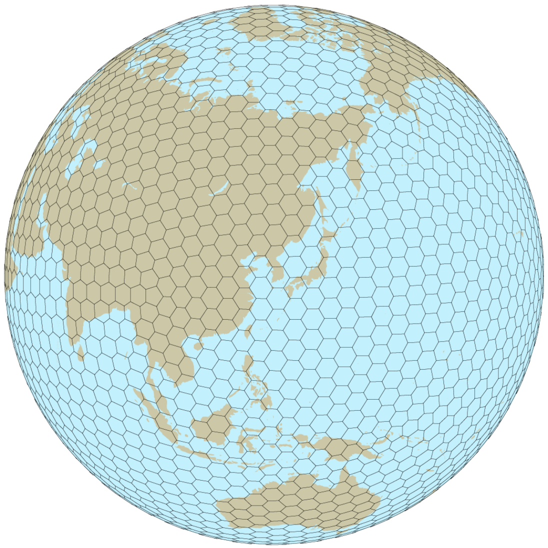
Equatorial refinement



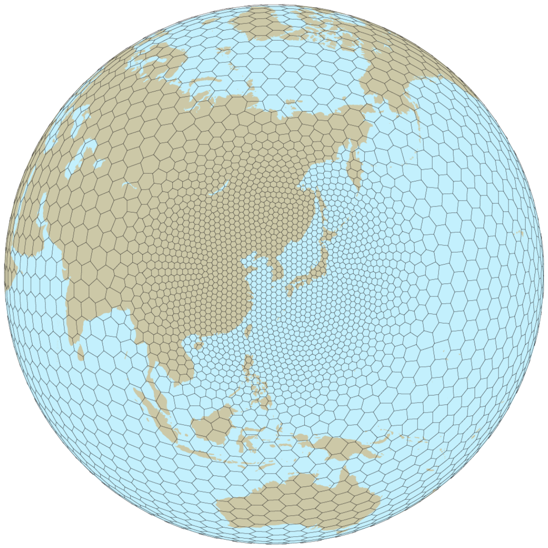
Andes refinement

MPAS
Model for Prediction Across Scales

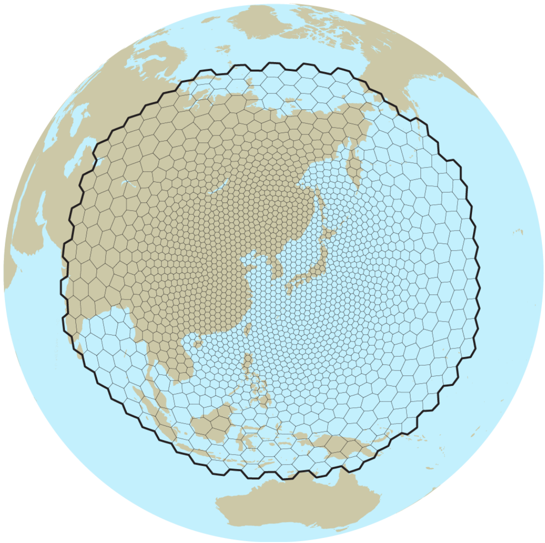
MPAS: Global Mesh and Integration Options



Global Uniform Mesh



Global Variable Resolution Mesh



Regional Mesh - driven by
(1) previous global MPAS run
(no spatial interpolation needed!)
(2) other global model run
(3) analyses

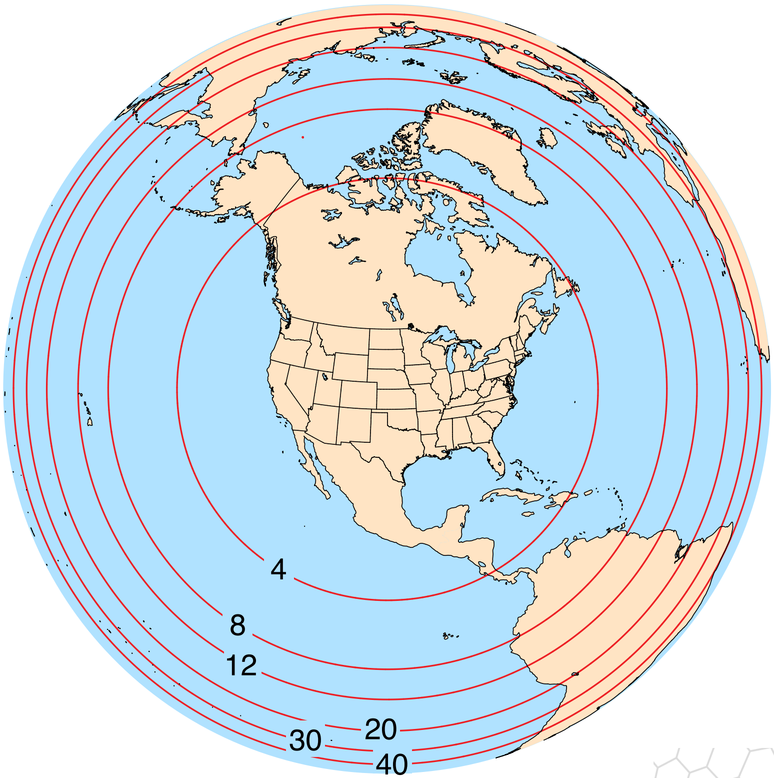
Voronoi meshes allows us to cleanly incorporate both downscaling and upscaling effects (avoiding the problems in traditional grid nesting) & to assess the accuracy of the traditional downscaling approaches used in regional climate and NWP applications.

MPAS
Model for Prediction Across Scales

Slide courtesy: Bill Skamarock, NCAR

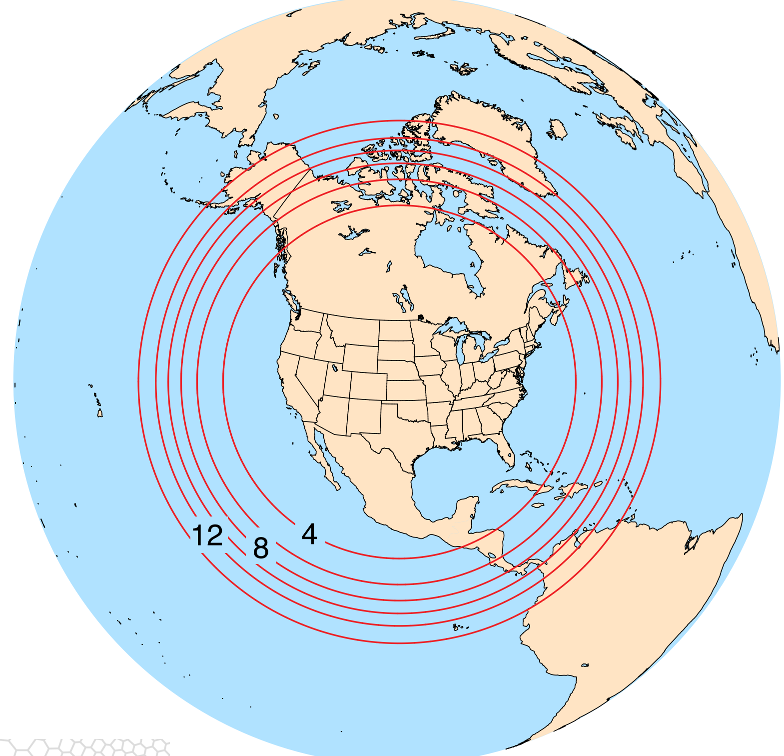
MPAS Forecast Experiments with Variable-Resolution Meshes

HWT Spring Experiment
5-day forecasts, 50 – 3 km mesh
1-31 May 2015



3-50 km mesh, Δx contours 4, 8, 12, 20, 30, 40
approximately 6.85 million cells
68% have < 4 km spacing

PECAN field campaign
3-day forecasts, 15 – 3 km mesh
7 June – 15 July 2015



3-15 km mesh, Δx contours
approximately 6.5 million cells
50% have < 4 km spacing

MPAS
Model for Prediction Across Scales

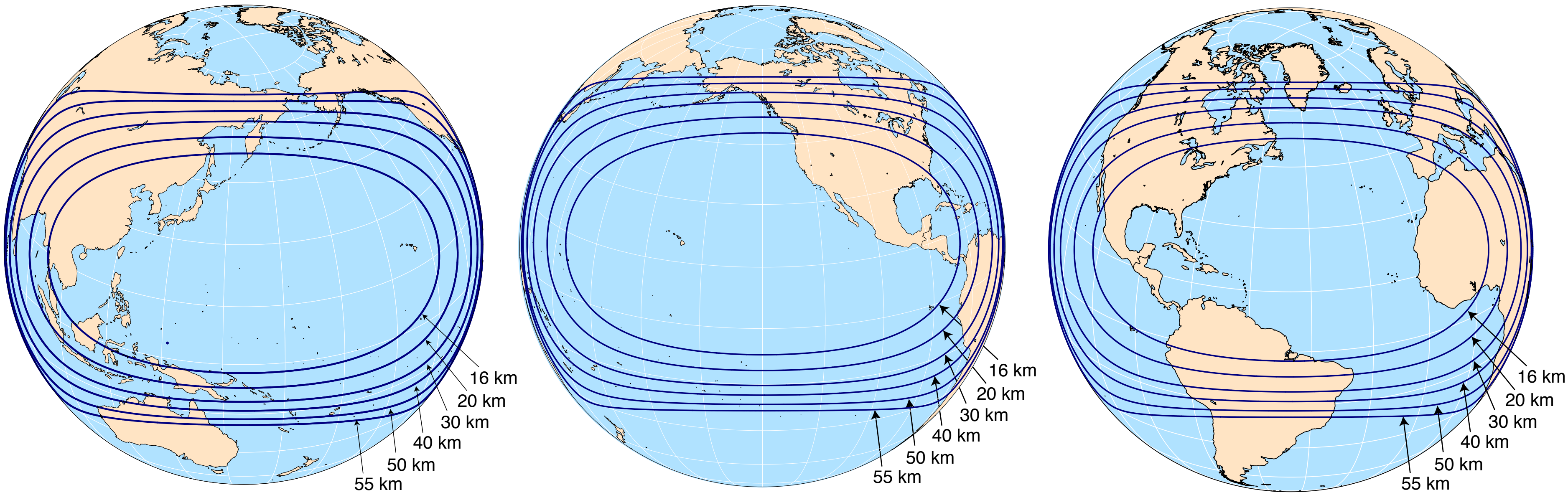
Forecast Experiments with Variable-Resolution Meshes

MPAS-Atmosphere 2013-2014-2015

Tropical Cyclone Forecast Experiments

daily 10-day forecasts during the NH tropical cyclone season

Western Pacific basin mesh | Eastern Pacific basin mesh | Atlantic basin mesh

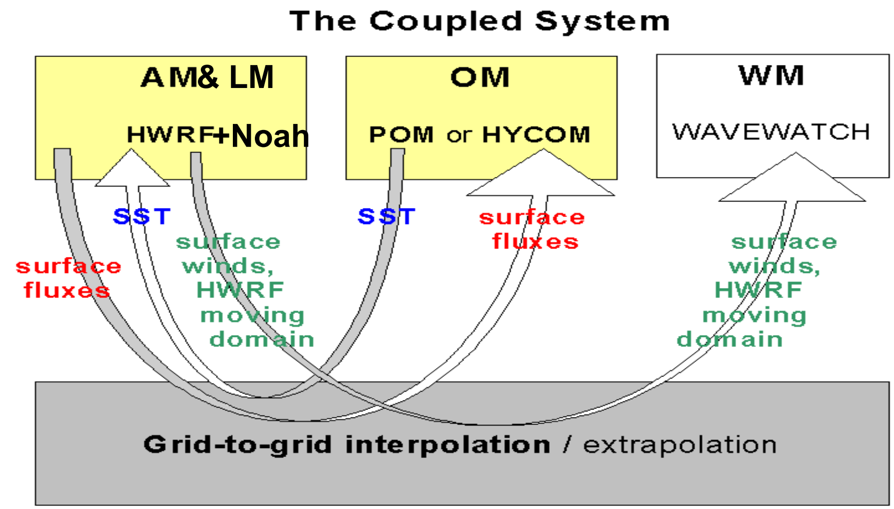


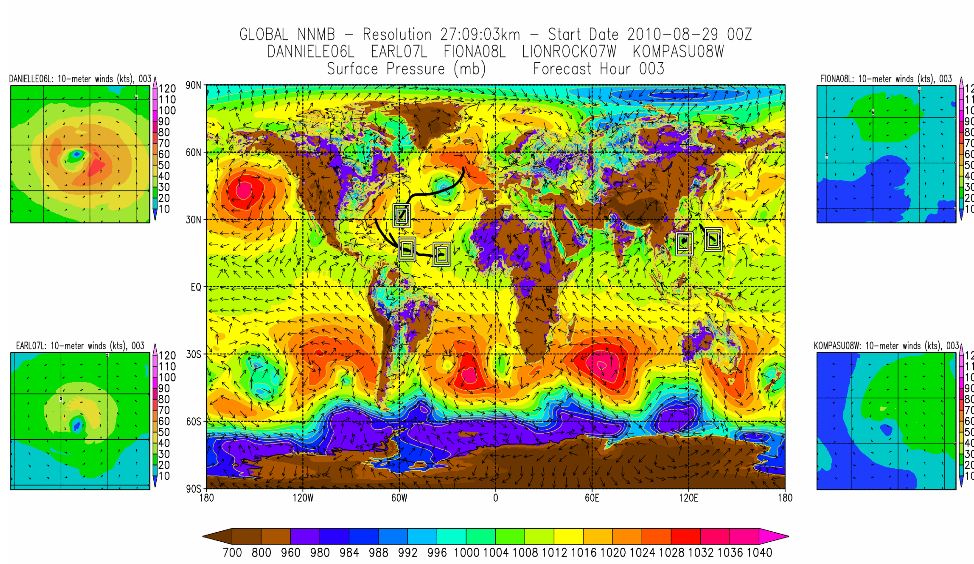
MPAS
Model for Prediction Across Scales

Slide courtesy: Bill Skamarock, NCAR

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

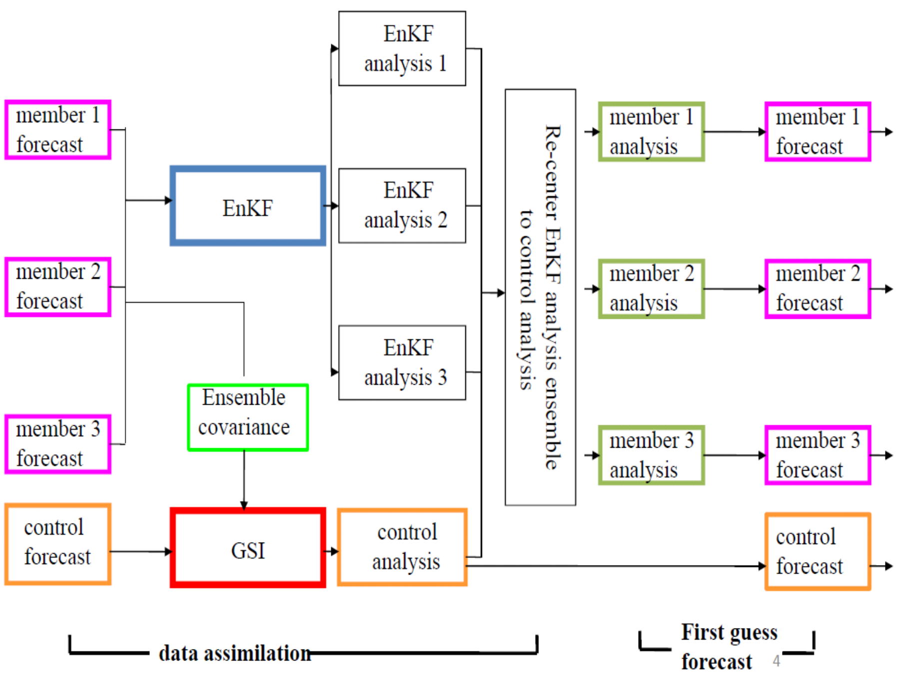




Future Plans: Hurricane Data Assimilation

- 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



Summary

Good prospects for 2016 HWRF Upgrade

2017 targets:

- HWRF basin-scale with ENKF, new PBL and surface layer
- HNMMB with no DA replaces GFDL
- HWRF produces all standalone hurricane wave outputs
- Standalone hurricane wave model is retired.

2018:

- HNMMB basin-scale with wave forecasts and DA
- HWRF wave forecasts as good as standalone
- 10-member HWRF/HNMMB Ensembles

2019:

- HNMMB single tropical outer domain for all storms

2020 onward: development switches to global nests.

Opportunities are available to engage in advanced research transition to operations. Contact DTC or EMC or HFIP for details.

QUESTIONS?