Tropical Cyclone Modeling
From HWRF to HAFS & Beyond!

Ghassan J. Alaka, Jr.
w/ contributions from EMC, OSTI, and the HRD Modeling Team

NHC-WMO RA-IV Workshop
April 8, 2024

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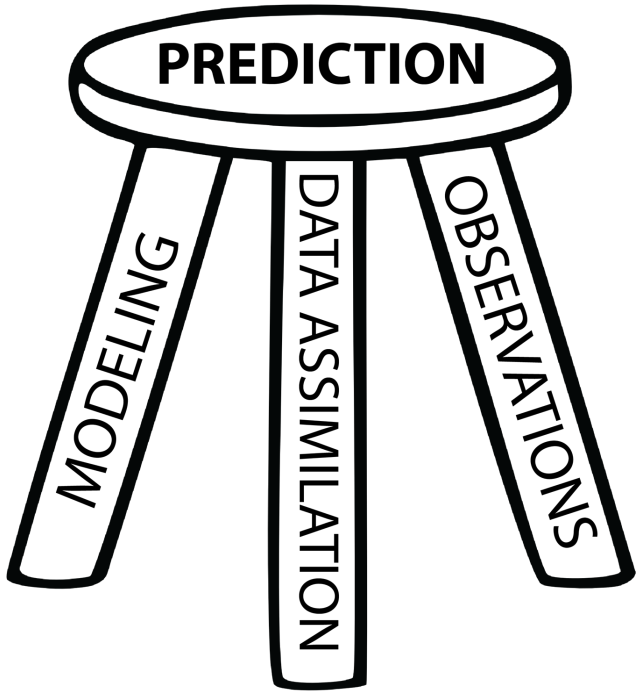
OAR

Outline

- Background: Improving hurricane predictions & HFIP
- A Short History of HWRF, the old guard of hurricane modeling
- HAFS: NOAA's flagship hurricane prediction model
- HAFS Research and Potential Transitions

Background: Improving Forecasts



- Good forecasts require good modeling, data assimilation, and observations
- All of this requires substantial investment – no free lunch!

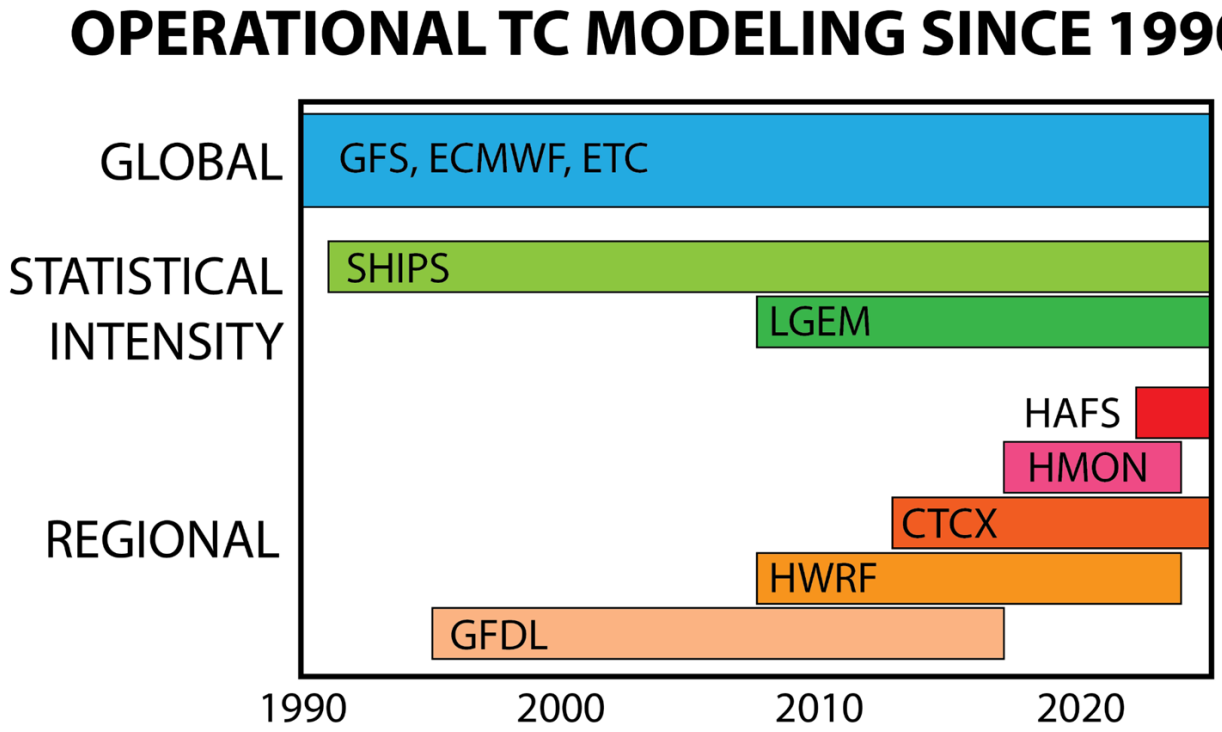
Background: Needed Investments

MODELING
- Computing
- Research
- People

OBSERVATIONS
- Instruments & platforms
- Research
- People

DATA ASSIMILATION (DA)
- Computing
- Research
- People

Background: Modeling



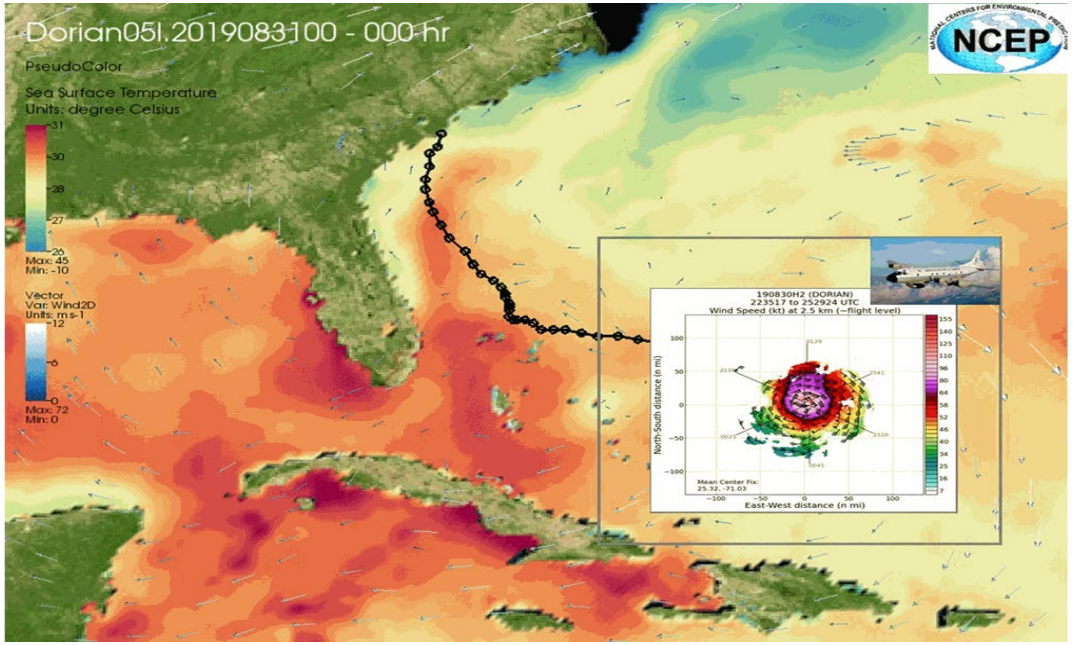
Models used by NHC since 1990

HFIP | HURRICANE FORECAST IMPROVEMENT PROGRAM

ABOUT PRODUCTS DOCUMENTS HAFS EVENTS RELATED LINKS

Advancing Hurricane Forecasting

Hurricane Weather Research and Forecasting (HWRF) Model: Gold standard for intensity predictions!



NOAA's flagship model for TC intensity prediction (2007-2022)

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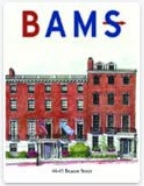
New BAMS Paper on HWRF's Performance



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Lifetime Performance of the Operational Hurricane Weather Research and Forecasting (HWRF) Model for North Atlantic Tropical Cyclones

Ghassan J. Alaka Jr., Jason A. Sippel, Zhan Zhang, Hyun-Sook Kim, Frank D. Marks, Vijay Tallapragada, Avichal Mehra, Xuejin Zhang, Aaron Poyer, and Sundararaman G. Gopalakrishnan

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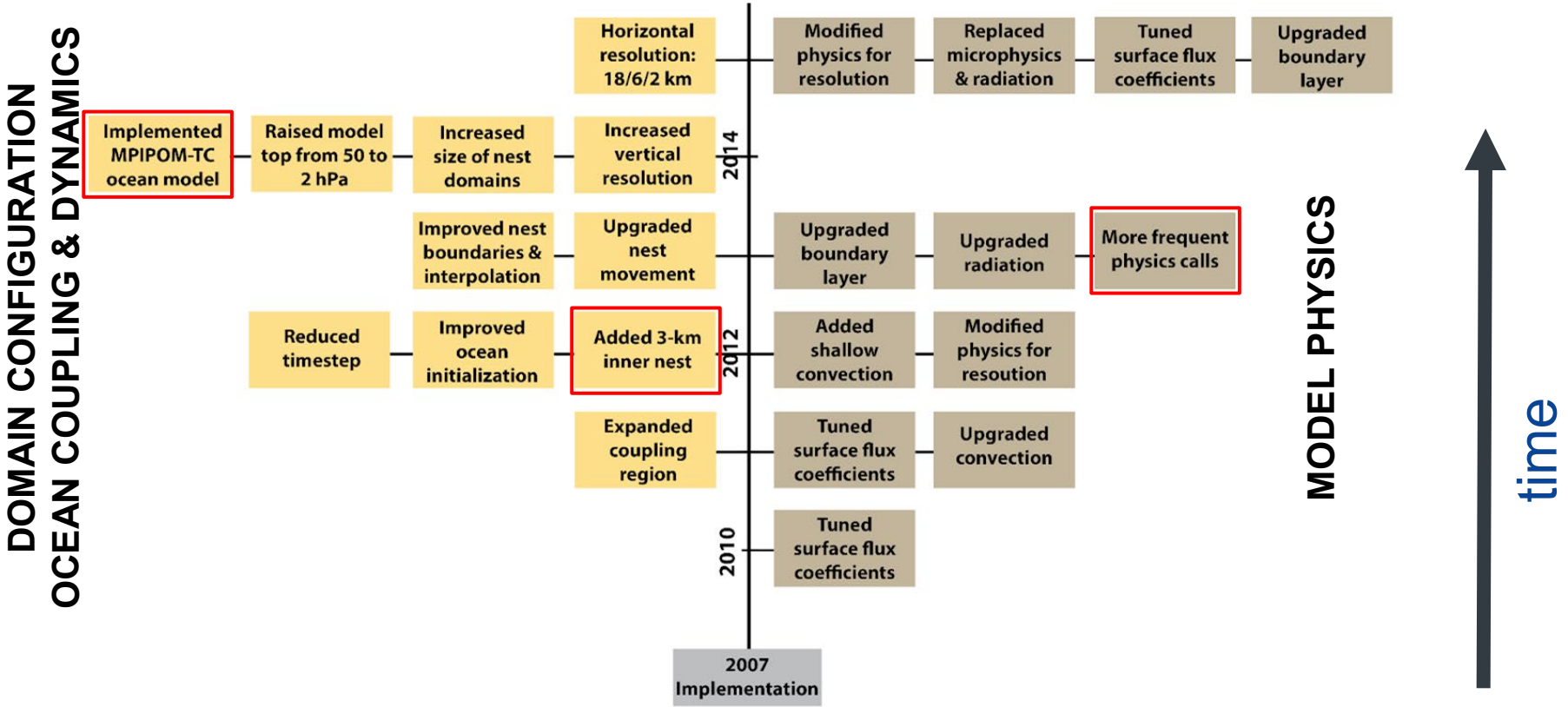
Abstract/Excerpt Full Text PDF

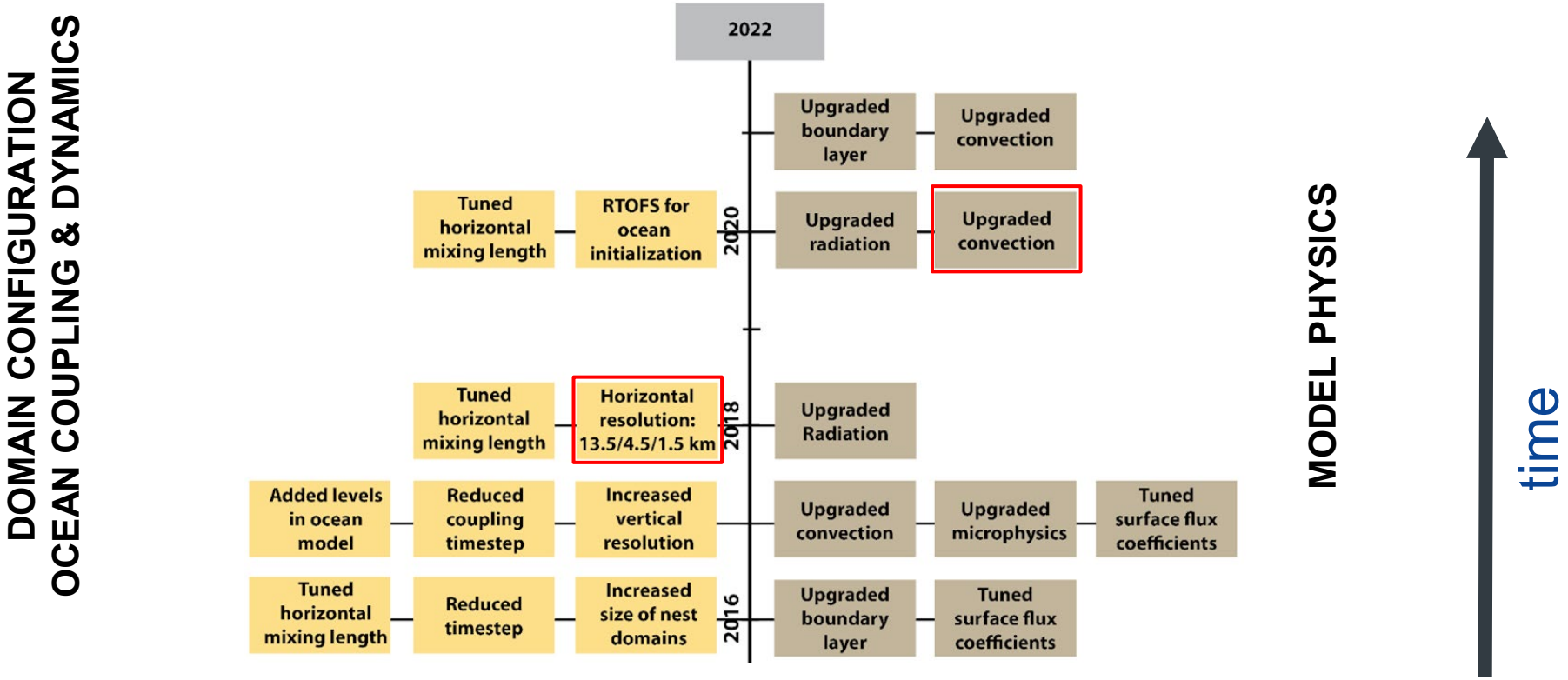
Abstract

The Hurricane Weather Research and Forecasting (HWRF) model was the flagship hurricane model at NOAA's National Centers for Environmental Prediction for sixteen years and a state-of-the-art tool for tropical cyclone (TC) intensity prediction at the National Weather Service and across the globe. HWRF was a joint development between NOAA research and operations, specifically the Environmental Modeling Center and the Atlantic Oceanographic and Meteorological Laboratory. Significant support also came from the National Hurricane Center, Developmental Testbed Center, University Corporation for Atmospheric Research, universities, cooperative institutes, and the TC community. In the North Atlantic basin, where most improvement efforts focused, HWRF intensity forecast errors decreased by 45-

HWRF Upgrade History in NATL Basin



HWRF Upgrade History in NATL Basin



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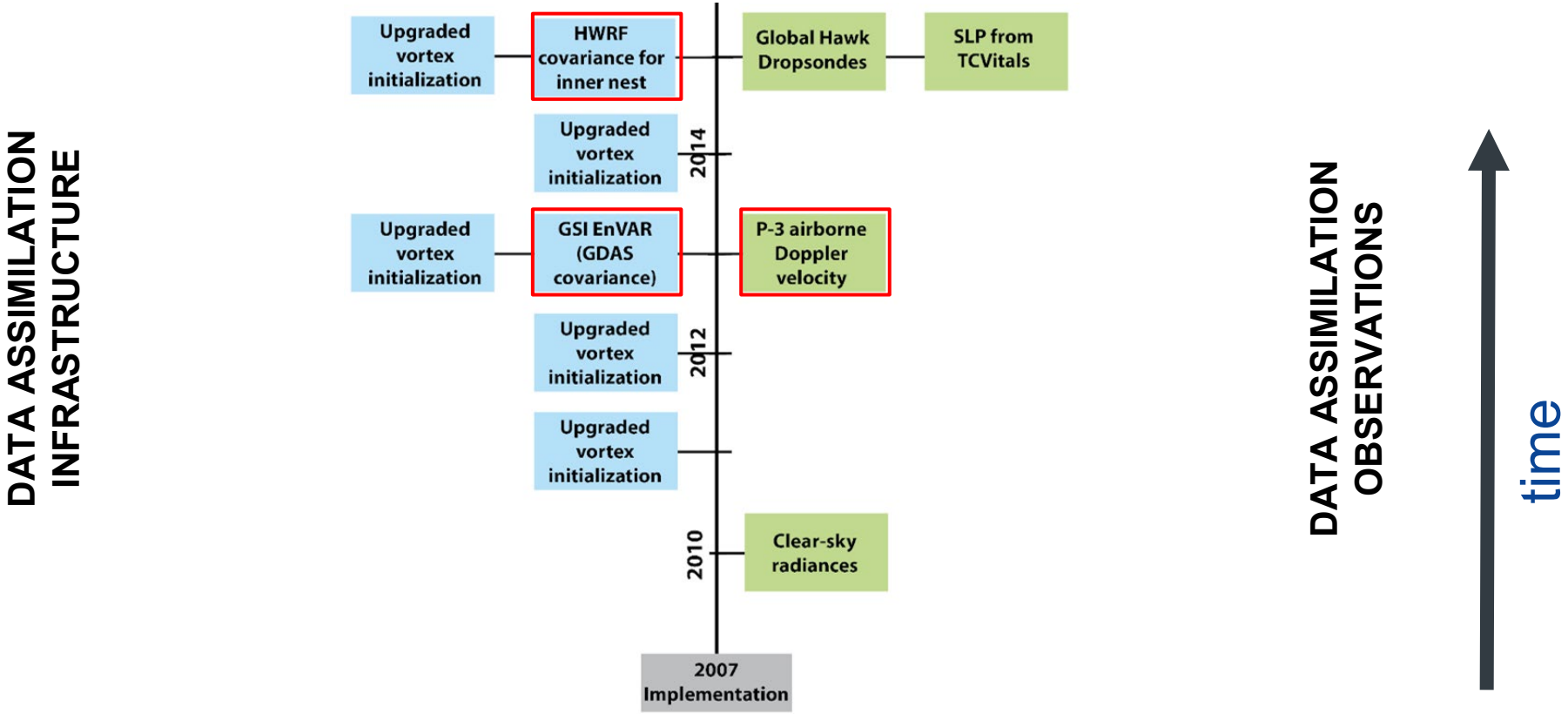

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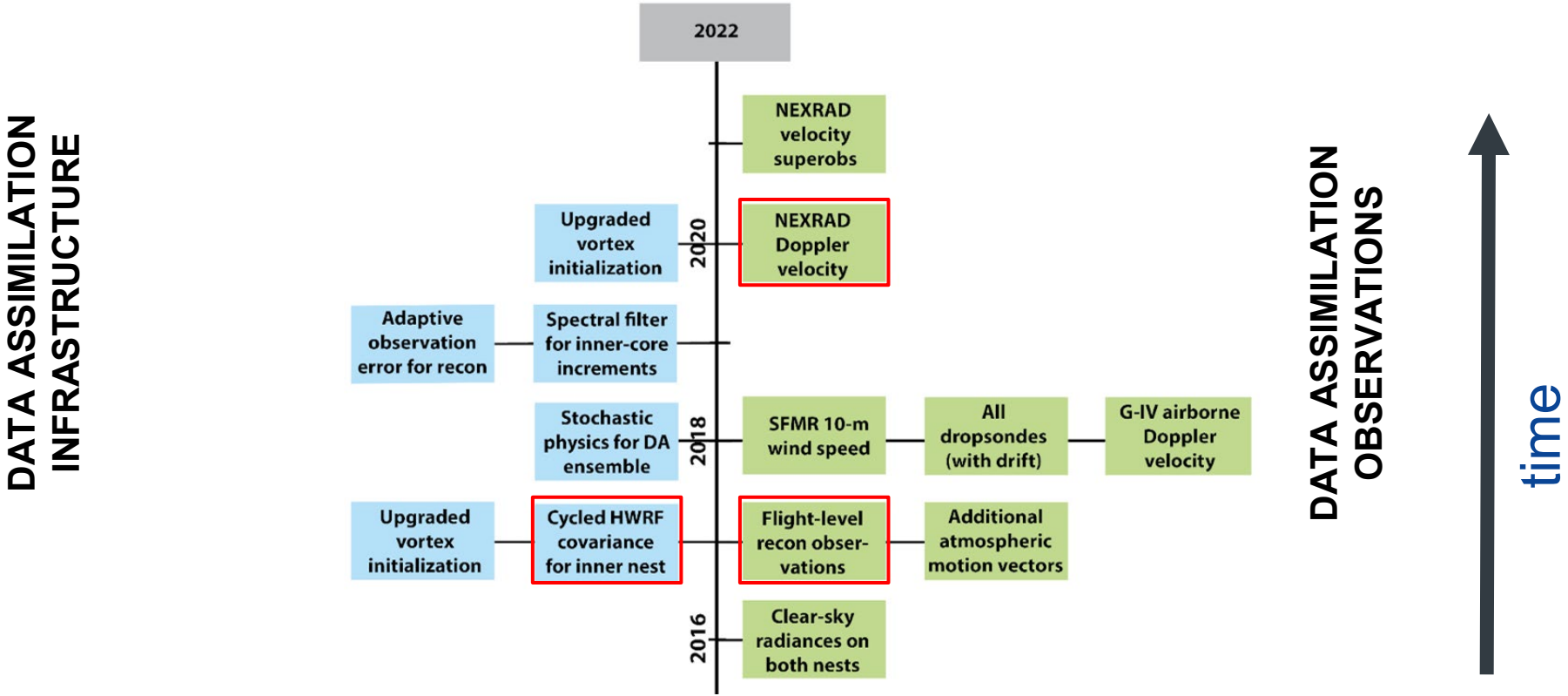

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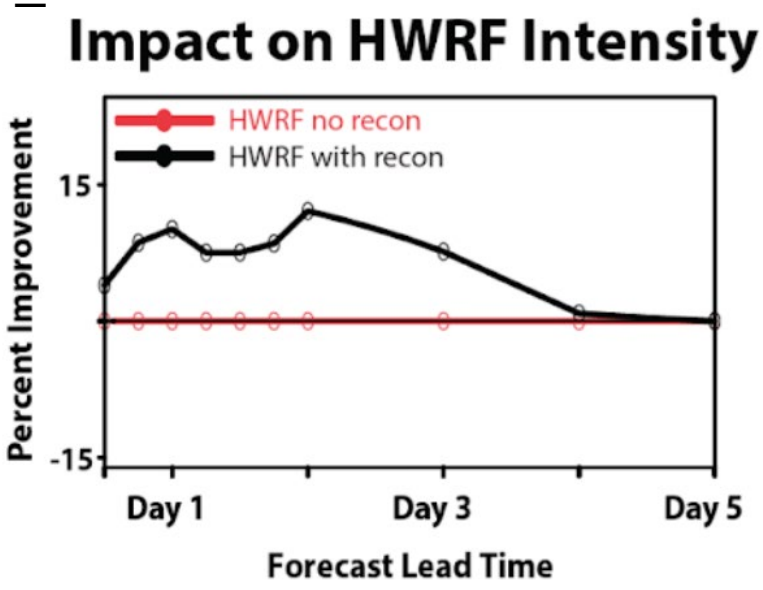
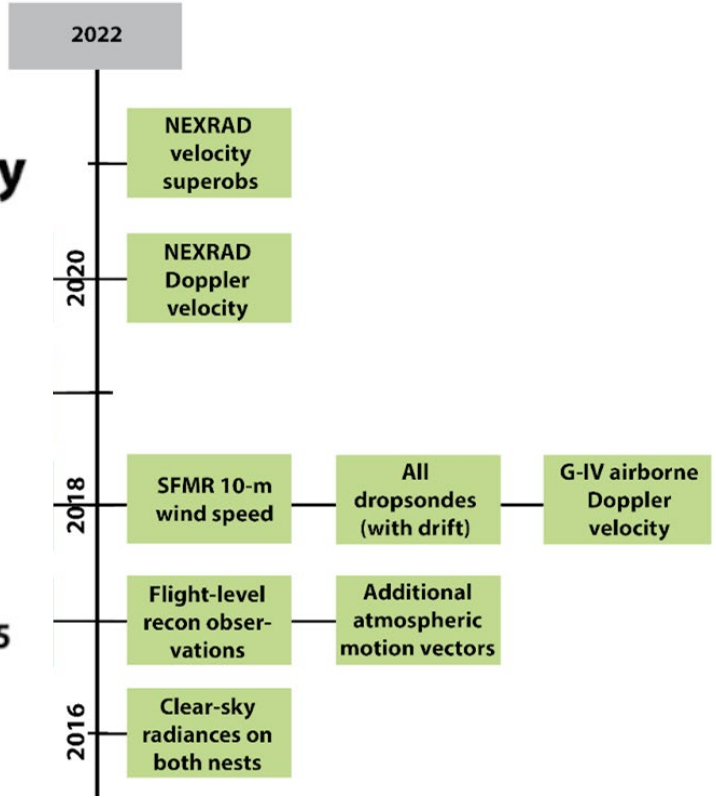
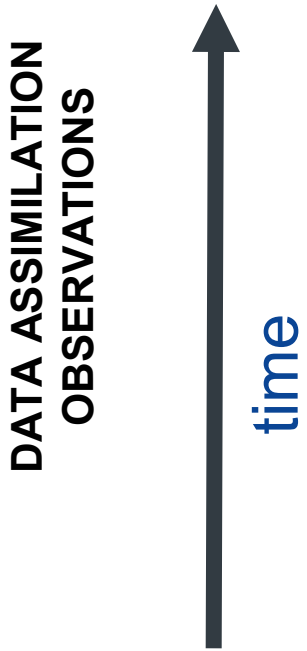
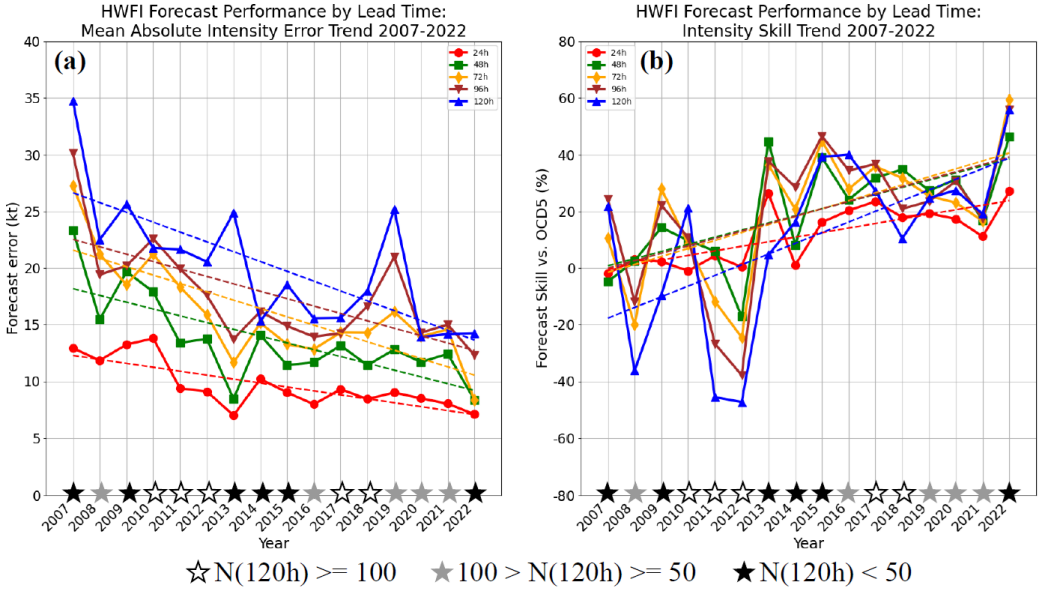






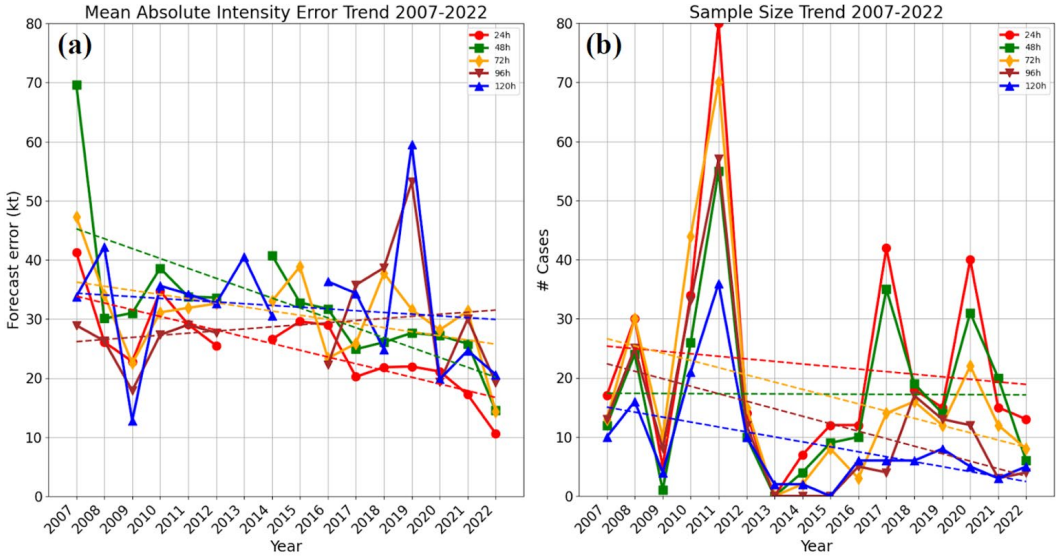
HWRF Error/Skill Trends: Intensity

- Intensity errors reduced and skill increased for all major lead times
- VMAX errors fell by 45-50% at all lead times
- VMAX skill improved ~40% at 96 h and ~60% at 120 h

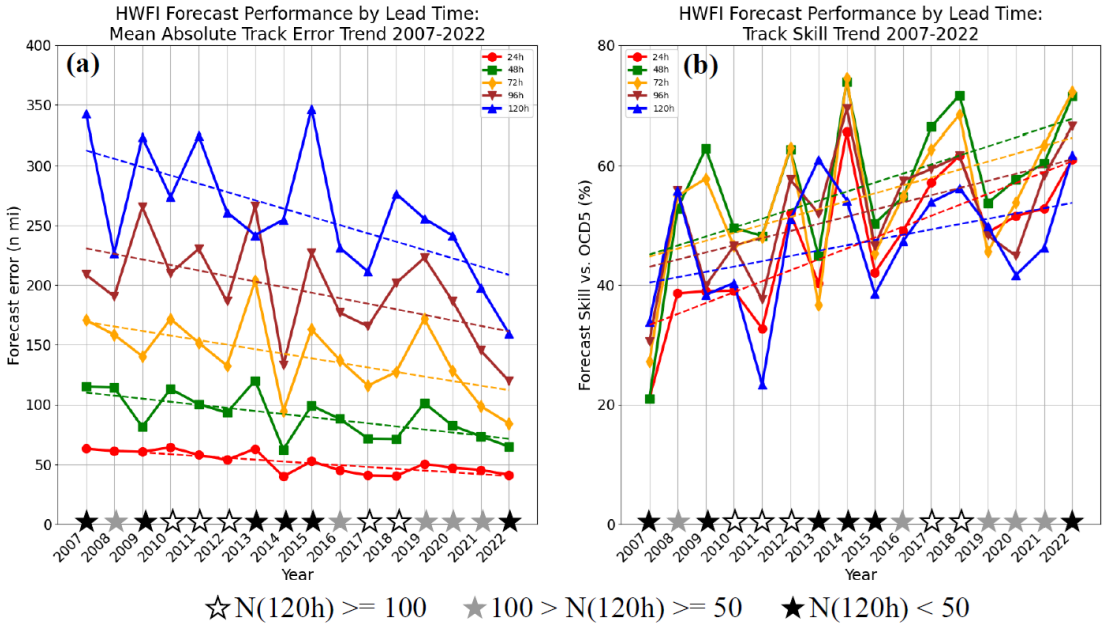


HWRF Error/Skill Trends: Rapid Intensification

- Before 2017, VMAX errors for RI were 20-40 kt and had no trend
- After 2017, errors reduced by ~50%
- Due to finer resolution and improved DA

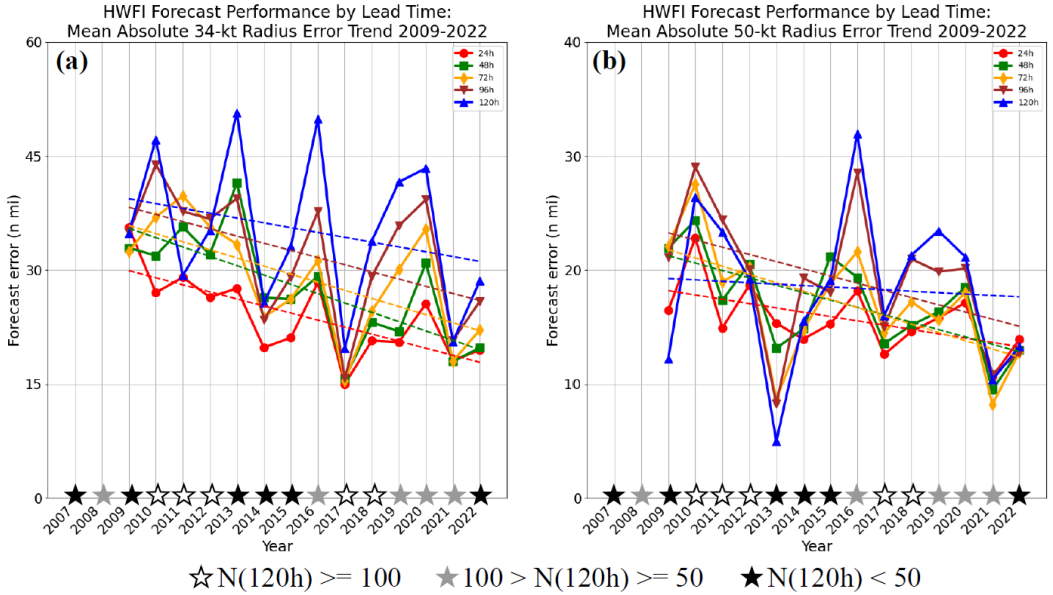


HWRF Error/Skill Trends: Track



- Track errors reduced and skill increased for all major lead times
- Track errors fell by 30-40% at longer lead times
- Track skill increased by ~30% at 24 h and ~20% at longer lead times

HWRF Error Trends: Storm Size

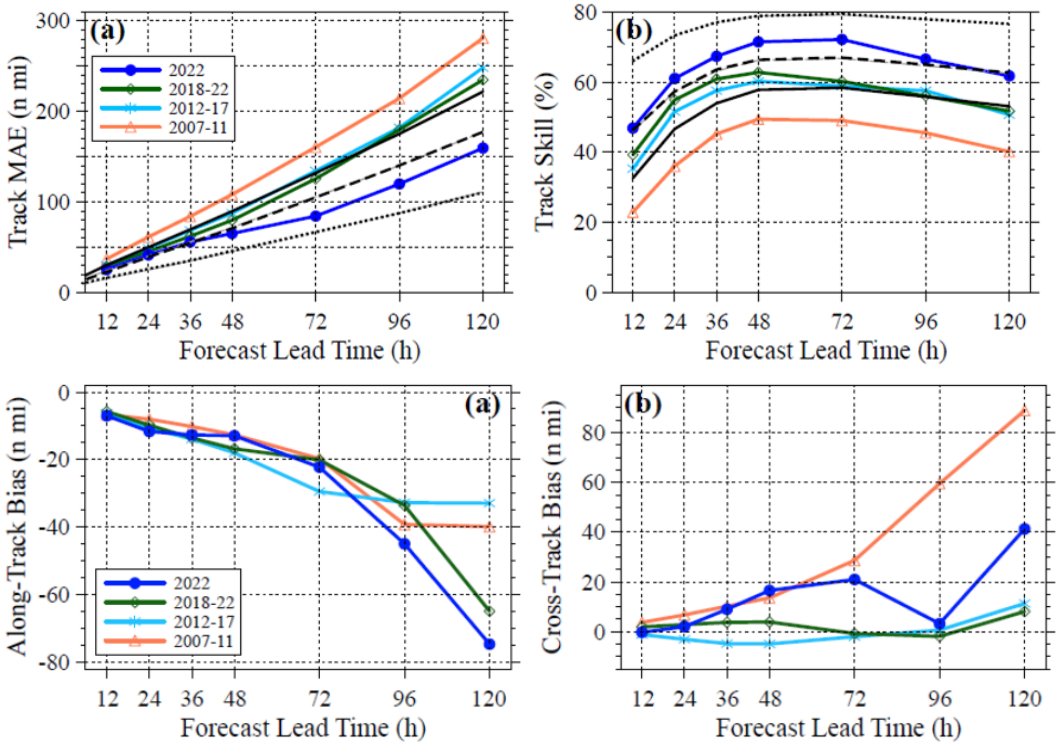


- Wind radii errors reduced for all major lead times
- R34 errors decreased by ~30-35%
- R50 errors decreased by ~25%

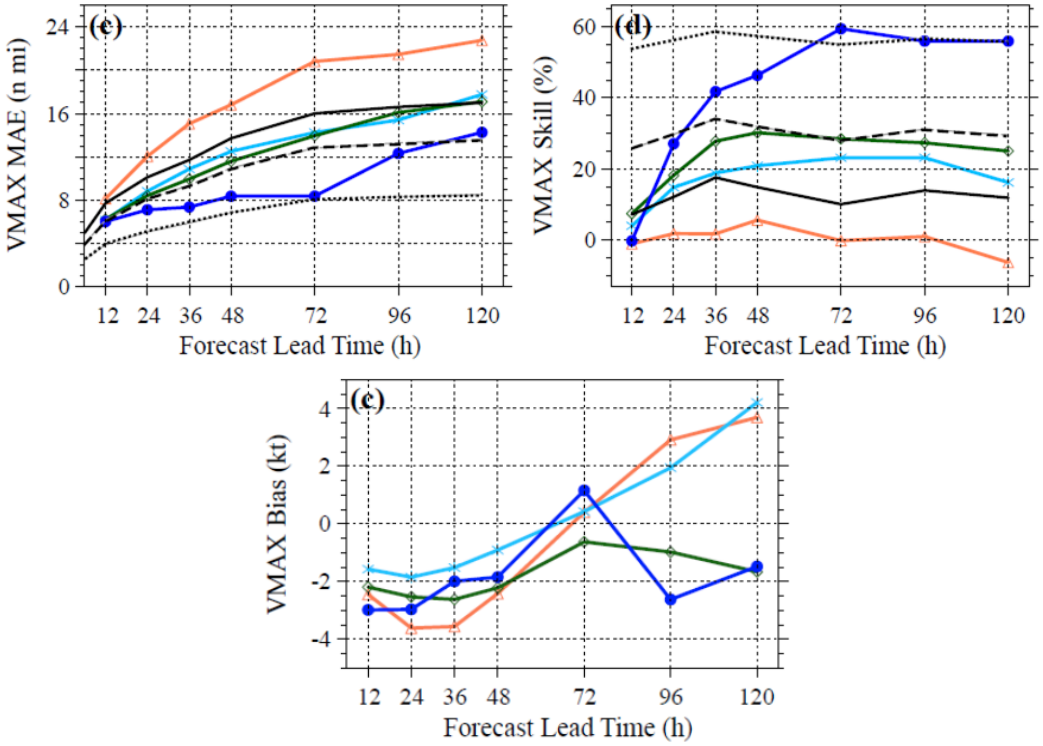
HWRF Errors by Period: Track

(1) Preliminary period (07-11)
(2) Maturing period (12-17)
(3) Modern period (18-22)

- Substantial improvements from **prelim period** to **maturing period**
- Slower improvements after that
- **2022** forecasts were excellent



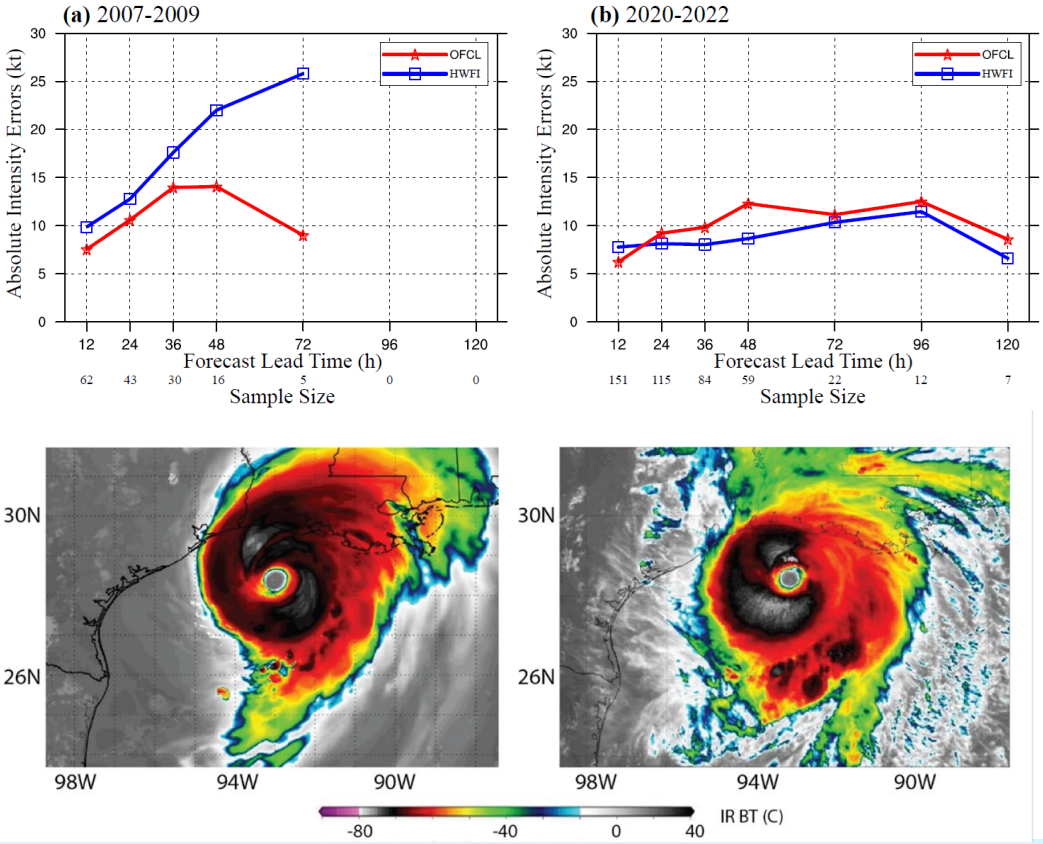
HWRF Errors by Period: Intensity



(1) Preliminary period (07-11)
(2) Maturing period (12-17)
(3) Modern period (18-22)

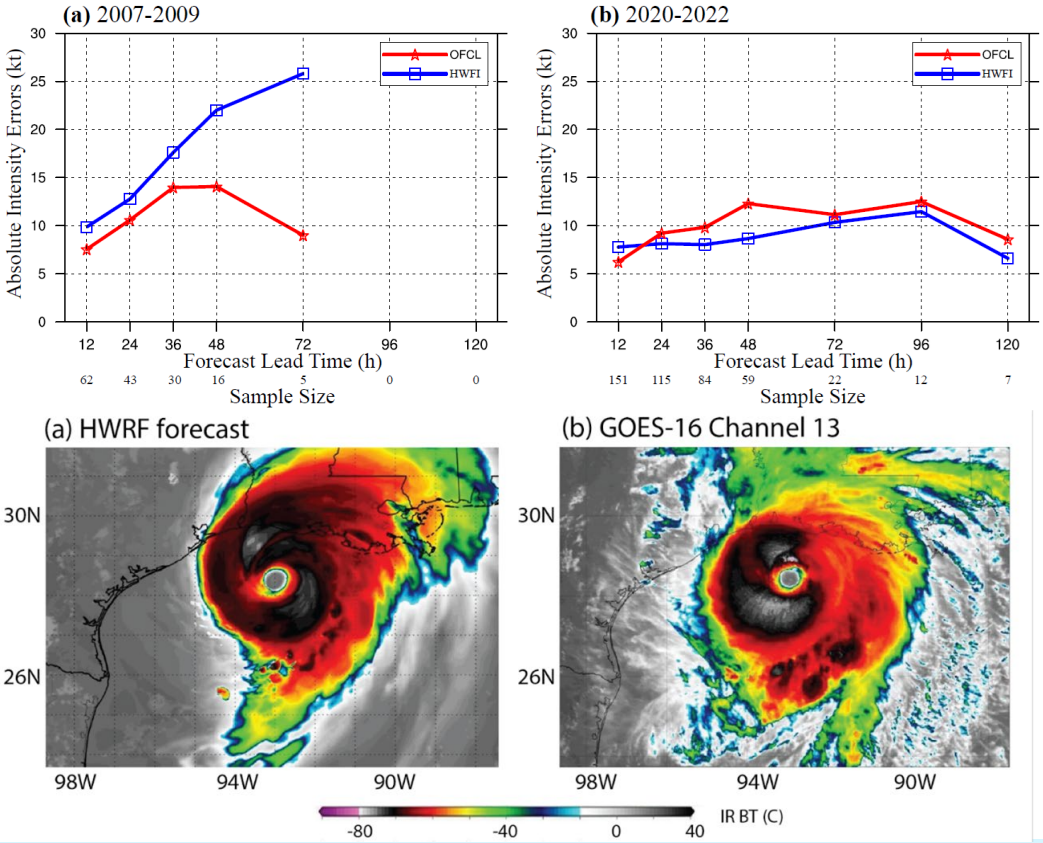
- **Prelim period** had very large errors that were reduced over time
- Bias generally improved over time
- **2022** forecasts were excellent

HWRF in the Gulf of Mexico



- Intensity errors in the Gulf of Mexico improved dramatically from the first 3 years to the last 3 years
- 2020-22: HWFI errors were consistent with NHC OFCL errors
- Very realistic forecasts, e.g., simulated IR imagery. *Which one is the forecast?*

HWRF in the Gulf of Mexico



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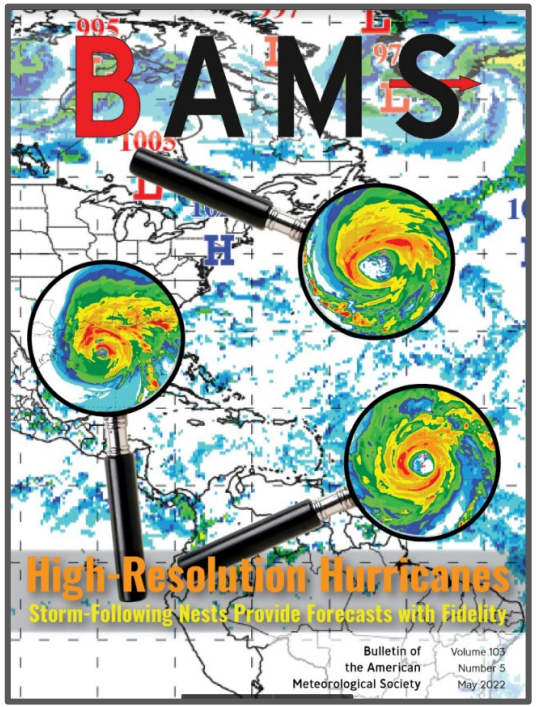
Multiple Moving Nests Improve Forecasts!

Basin-Scale HWRF (HWRF-B)



Alaka et al. 2022

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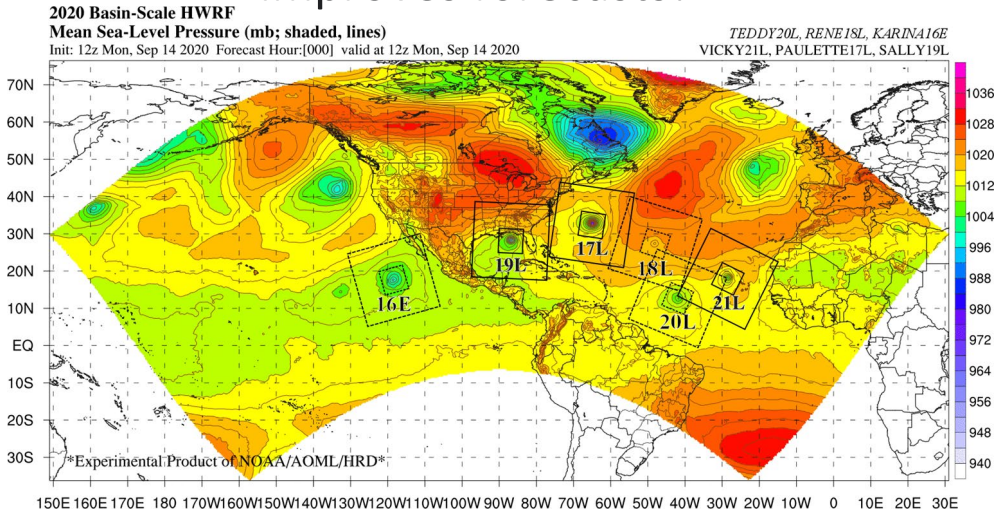
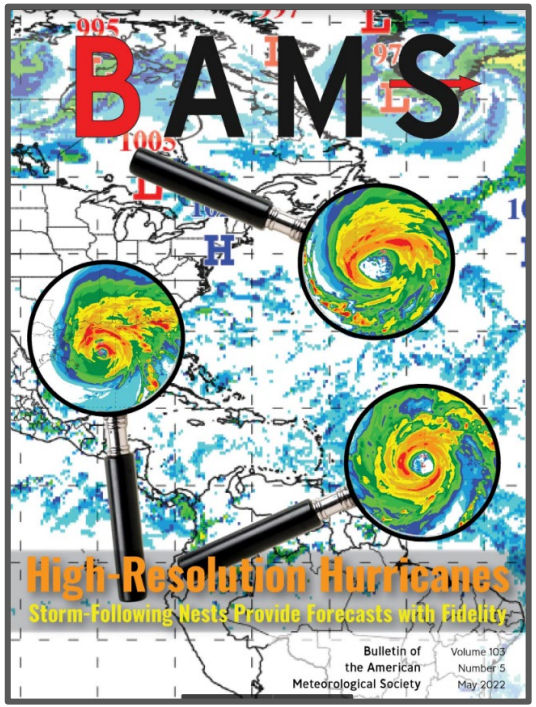
Simply adding more moving nests improves forecasts!



Multiple moving nests in action

Multiple Moving Nests Improve Forecasts!

Basin-Scale HWRF (HWRF-B)



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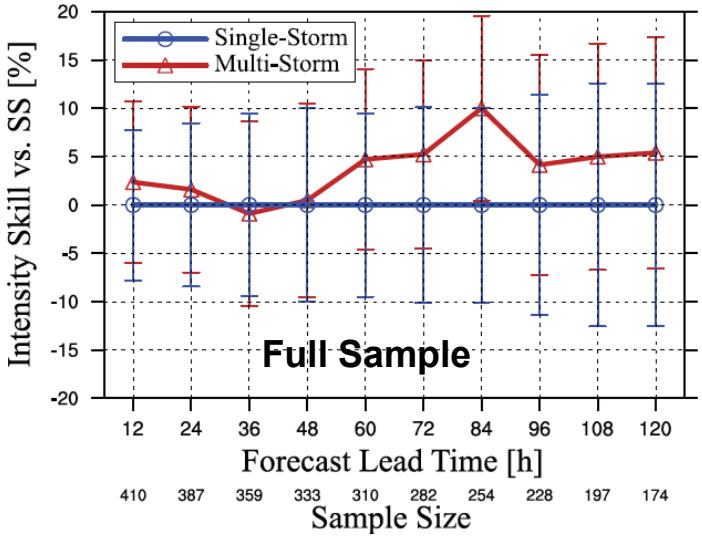

Improved intensity predictions

Outline

- Background: Improving hurricane predictions & HFIP
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- HAFS: NOAA's flagship hurricane prediction model
- HAFS Research and Potential Transitions

All HAFS credit goes to the UFS-R2O Hurricane Application Integration Team

Atmospheric model dynamics/configurations/workflow NCEP/EMC Bin Liu, Dusan Jovic, Avichal Mehra, JungHoon Shin,Vijay Tallapragada, Biju Thomas, Jun Wang, Zhan Zhang, Yangxing Zheng AOML/HRD Ghassan Alaka, S. Gopalakrishnan, Mu-Chieh Ko, William Ramstrom, Xuejin Zhang DTC Mrinal Biswas, Kathryn Newman, Linlin Pan GFDL Rusty Benson, Lucas Harris, Joseph Mouallem GSL Samuel Trahan	**Ocean/Wave coupling through CMEPS** NCEP/EMC Maria Aristizabal, Matthew Masarik, Jessica Meixner, John Steffen AOML/HRD Lew Gramer AMOL/PhOD HeeSook Kang, Hyun-Sook Kim NCAR/ESMF Dan Rosen, Gerhard Theurich, Ufuk Turuncoglu	**Data Assimilation** NCEP/EMC Jing Cheng, Daryl Kleist, Ting Lei, Shun Liu, Yonghui Weng AOML/HRD Altug Aksoy, Sarah D. Ditchek, Jason Sippel, Dan Wu OU Xu Lu, Xuguang Wang UM/CIMAS UMD Joseph Knisely, Kenta Kurosawa, Jonathan Poterjoy SUNY/U at Albany Ryan Torn, Eun-Gyeong Yang
Model Pre- and Post-processes **NCEP/EMC** George Gayno, Hui-Ya Chuang, Nathalie Rivera-Torres, Qingfu Liu, Chuan-Kai Wang, Wen Meng, Lin Zhu **GFDL** Timothy Marchok	**Atmospheric Physics** **NCEP/EMC** Jongil Han, Ruiyu Sun, Xu Li, Weiguo Wang, Fanglin Yang **AOML/HRD** Andrew Hazelton **UAH** Xiaomin Chen	**Verification/Evaluation** **NCEP/EMC** Olivia Ostwald, Hananeh Jafary, Jiayi Peng **NHC** Michael Brennan, Jon Martinez, Ben Trabing, David Zelinsky, Wallace Hogsett **JTWC** Brian Strahl, Levi Cowan

Majority of the development supported through FY18/FY19/FY22 HSUP/DSUP, JTTI, and UFS-R2O Projects

The Hurricane Analysis and Forecast System

- NOAA's new hurricane modeling system within the Unified Forecast System (UFS) framework
- HFIP strategic implementation plan supporting 2017 Weather Act
- Multi-year R2O collaboration (EMC + AOML)
- Two versions "A" & "B" to provide high-resolution TC forecasts w/ uncertainty information

NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
United States Department of Commerce

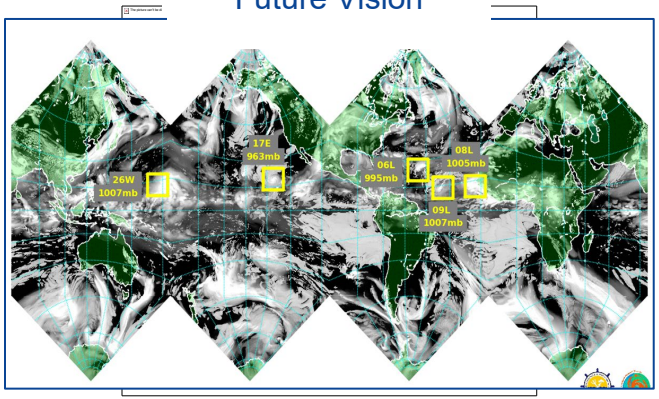
NOAA HURRICANE FORECAST IMPROVEMENT PROJECT

Hurricane Forecast Improvement Program Five-Year Plan: 2019-2024

Proposed Framework for Addressing Section 104 of the Weather Research Forecasting Innovation Act of 2017

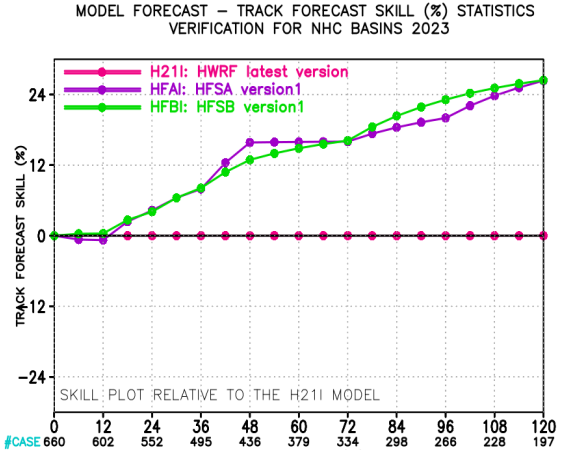
22 June 2018
Updated 25 June 2019

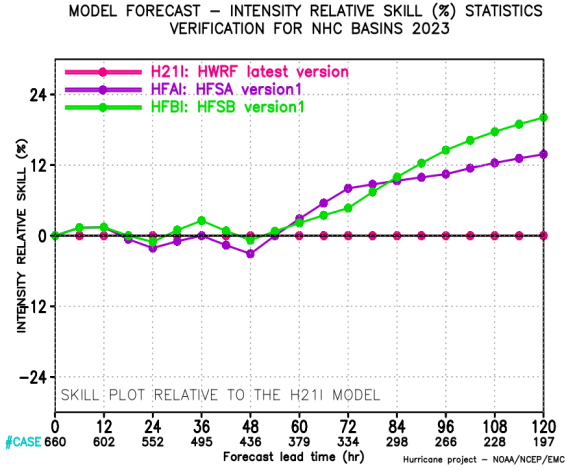
Future Vision



HAFS is now operational!

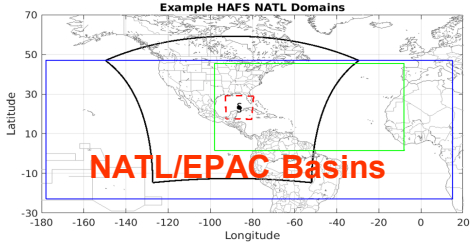
Hurricane Paulette, 2020

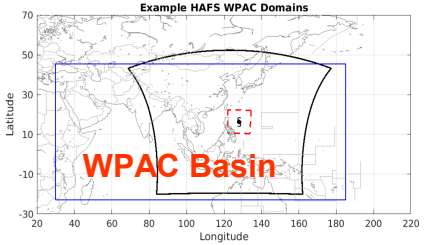


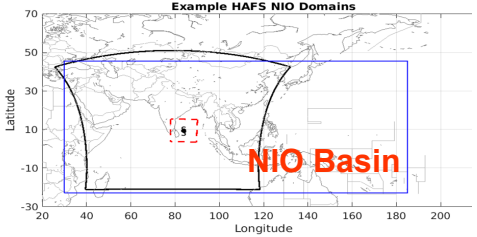


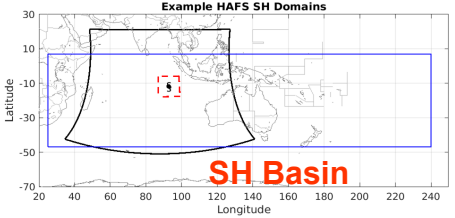
HAFS v2 just accepted for 2024 operations!

HAFSv 2.0	Domain & Dynamics	Resolution	DA/VI	Ocean/Wave Coupling	Physics	Basins
HFSA	parent: 77x74 deg. nest: 11.8x11.8 deg. dt_atmos=90s hord_mt/vt/tm/dp/tr=1 /1/1/1/-5 with lim_fac of 3.1 (AL), 2.9 (EP)	Regional (ESG), ~5.4/1.8 km, L81, ~2 hPa model top	Vmax > 40 kt warm-cycled VI Updated comp. vortex vi_cloud=1 Vmax adj: always 4DEnVar DA,SDL on	Two-way MOM6 (L55, KPP, Ri=0.2, updated CEMPS, SST(t) in non-overlapping atms domain, SSC) one-way WW3 coupling for NHC/CPHC basins	suite-1	All global Basins NHC/CPHC/JTWC Max 7 Storms
HFSB	parent: 75x75 deg nest: 12x12 deg dt_atmos=72s hord_mt/vt/tm/dp/tr=1 /1/1/1/-5 with lim_fac of 2.8	Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top	Vmax > 40 kt warm-cycled VI V1 comp. vortex vi_cloud=0 Vmax adj: auto 4DEnVar DA,SDL on	Two-way HYCOM (L41, KPP, Ri=0.25, CMEPS-based regional coupling, SST(t0) in non-overlapping atms domain, no SSC) No Wave coupling	suite-2	NHC/CPHC Max 5 Storms







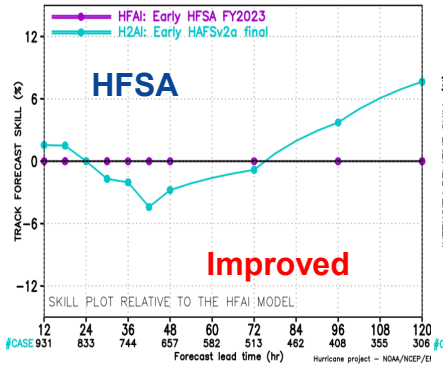


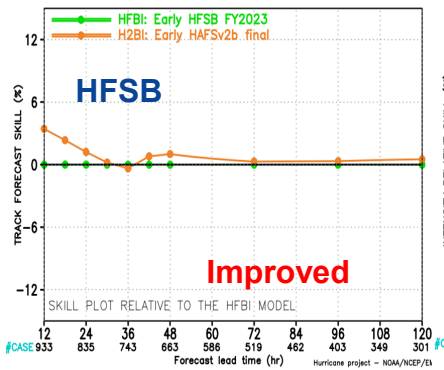
atmospheric domain, ocean domain, wave domain

Courtesy of EMC

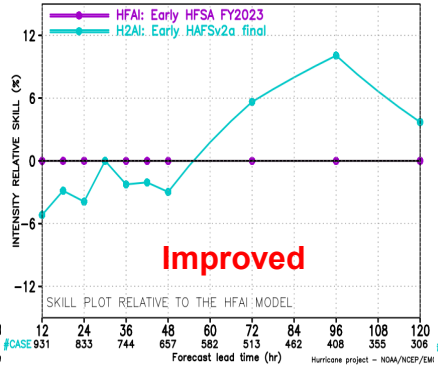
HAFS V2: Early Model Verification, NATL 2021-

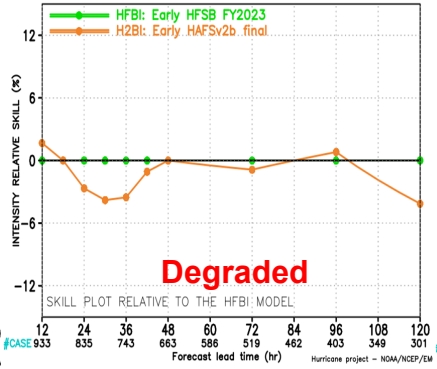
Track Skill



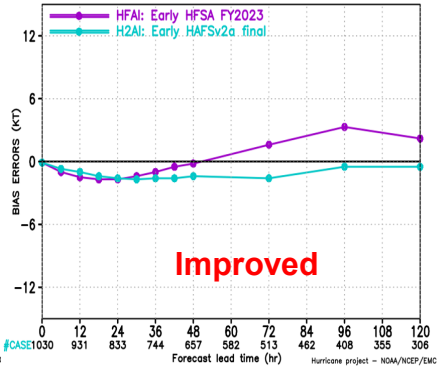


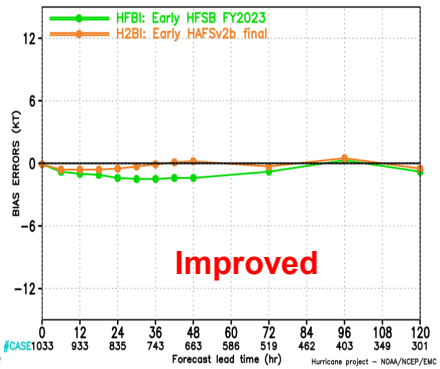
Vmax Skill





Vmax Bias





- **HFSA/HFAI: Late/Early models of current operational HAFS-Av1**
- **HFSB/HFBI: Late/Early models of current operational HAFS-Bv1**
- **HV2A/H2AI: Late/Early of proposed HAFS-Av2**
- **HV2B/H2BI: Late/Early of proposed HAFS-Bv2**
- **Total 1183 cycles with 1059 verifiable cycles**

Courtesy of EMC

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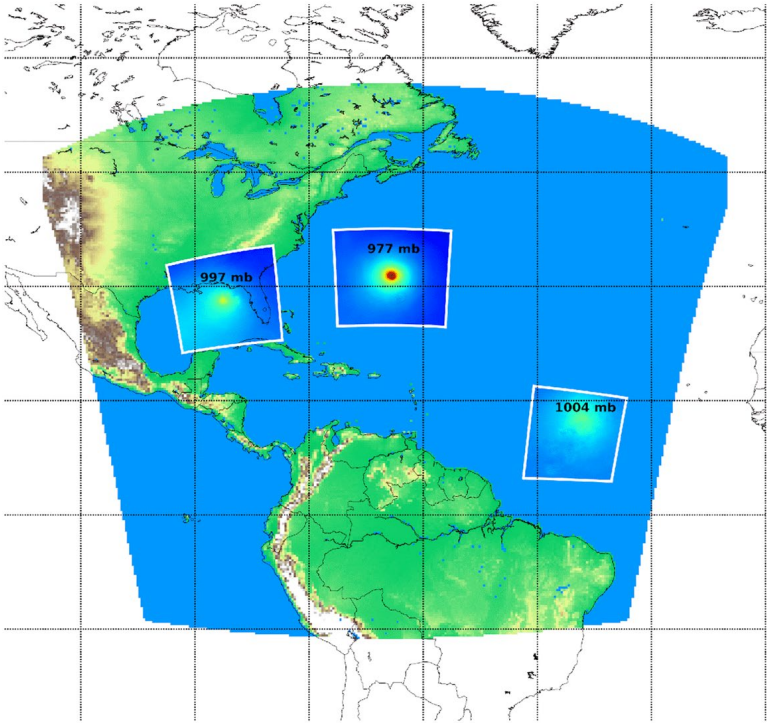
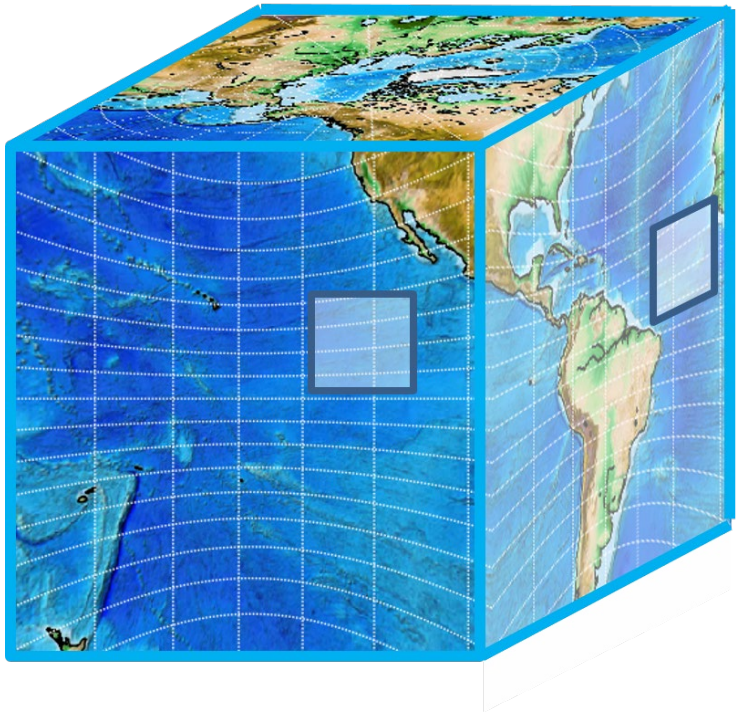
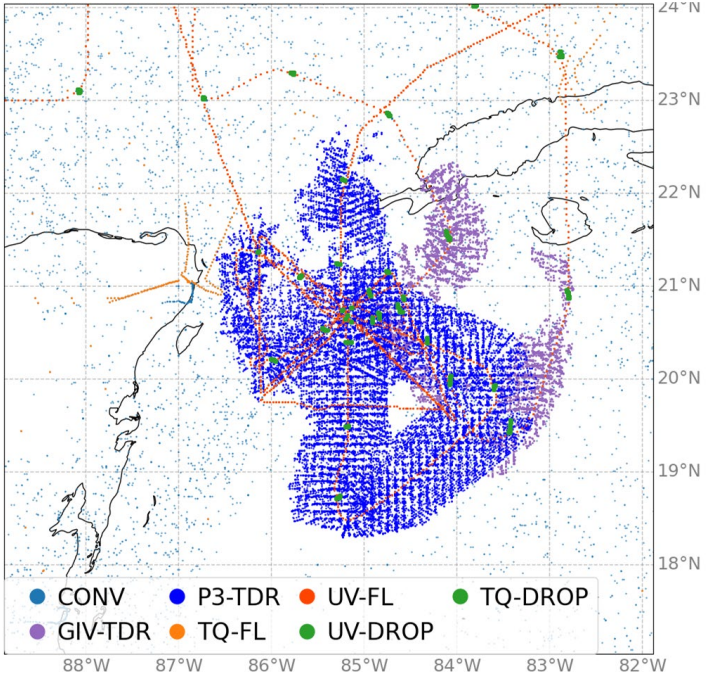
Multiple Moving Nests in HAFS



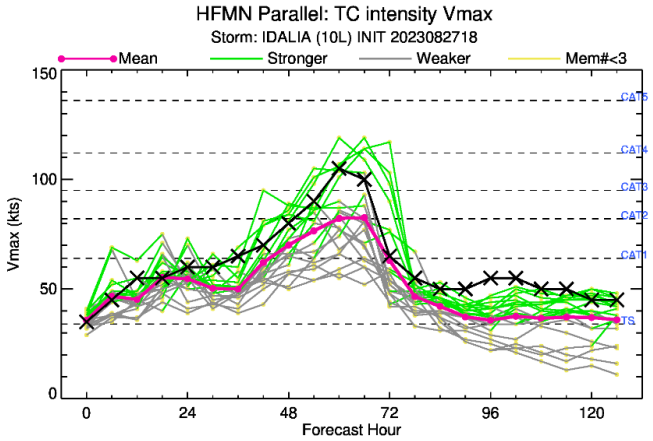


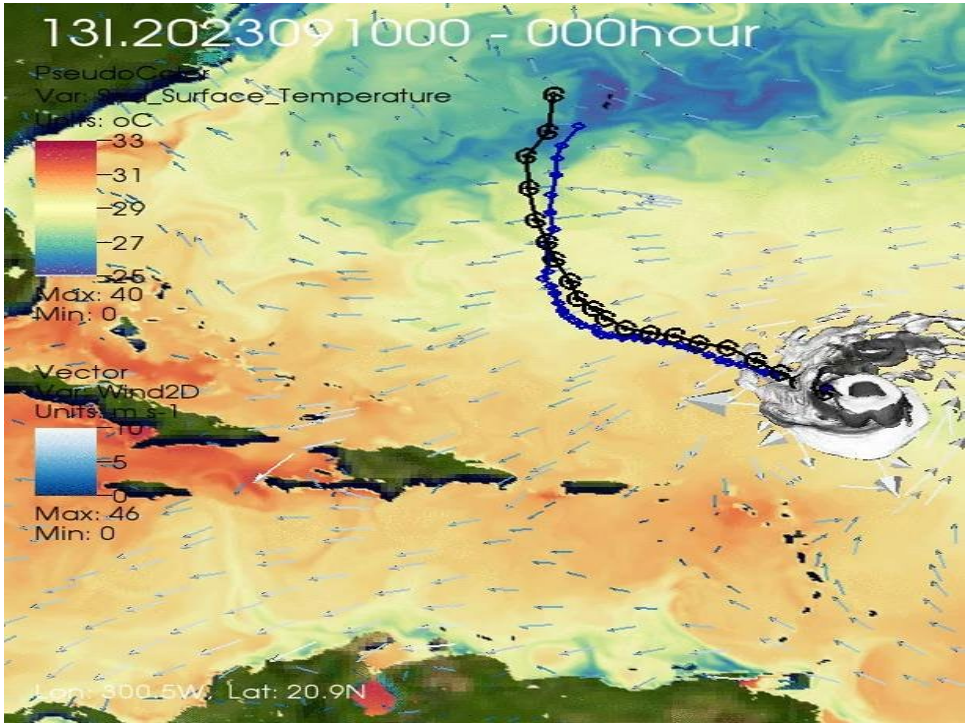
Data Assimilation: Recon in HAFS

- Preliminary impact in HAFS mostly positive for 2023 season
- Looking forward to further DA system advances going foward

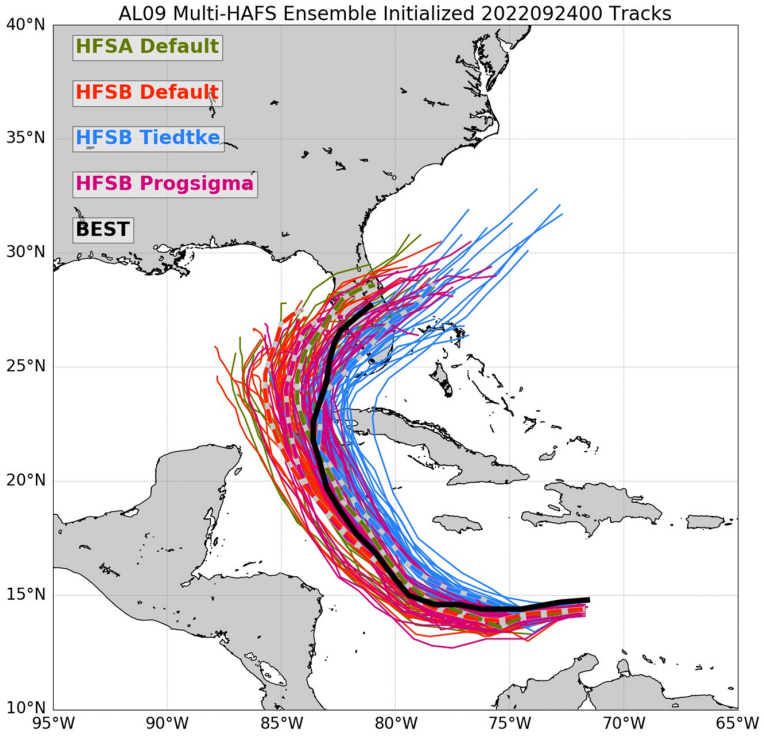


HAFS Ensemble in Real-time on the Cloud (HERC)



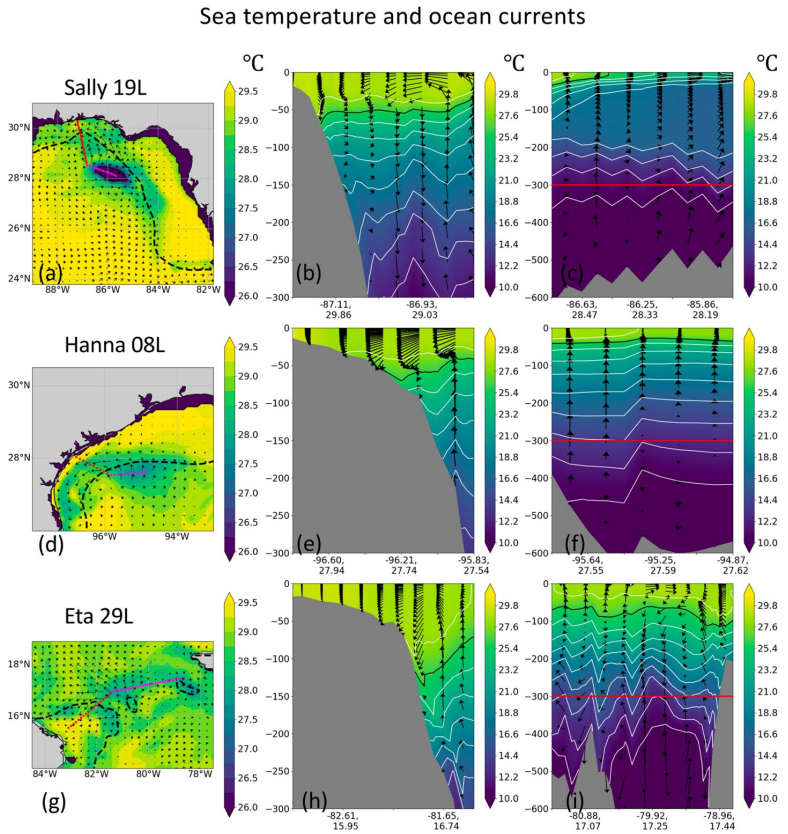


HAFS Multi-Physics Ensemble

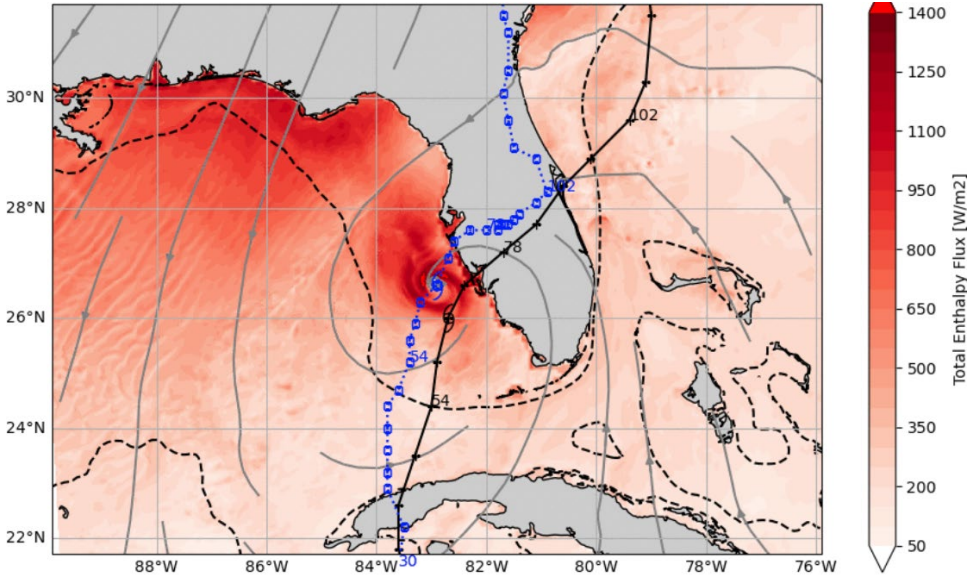


- Differences based on physics suite
  - HFSB default: left bias
  - HFSB w/ Tiedtke: right/fast bias
- Ensemble tracks are fairly dispersive and include the observed track (black)
- Dashed lines show control members

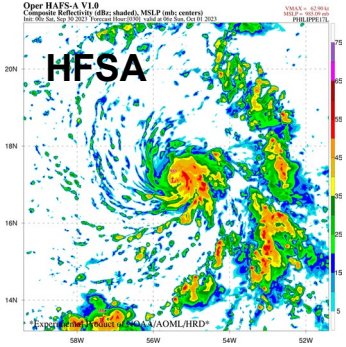
Ocean & Coastal Impacts

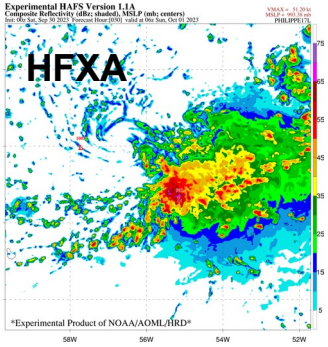


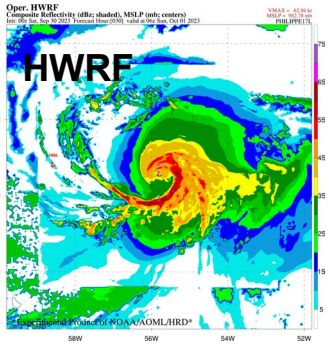
- Enthalpy flux increased as Ian moved onto FL shelf
- Downwelling maintains or increases SST over the shelf

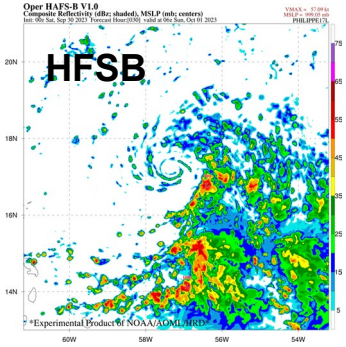


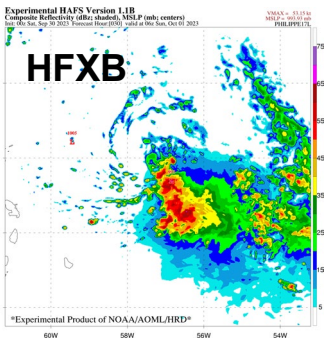
Multi-Model Evaluations

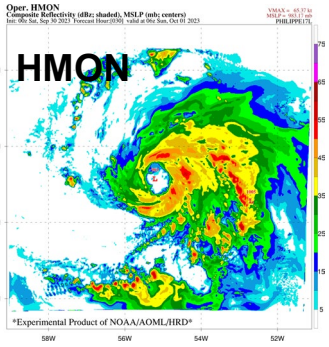




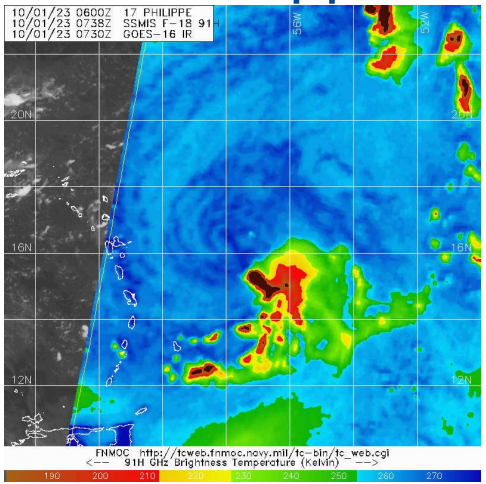






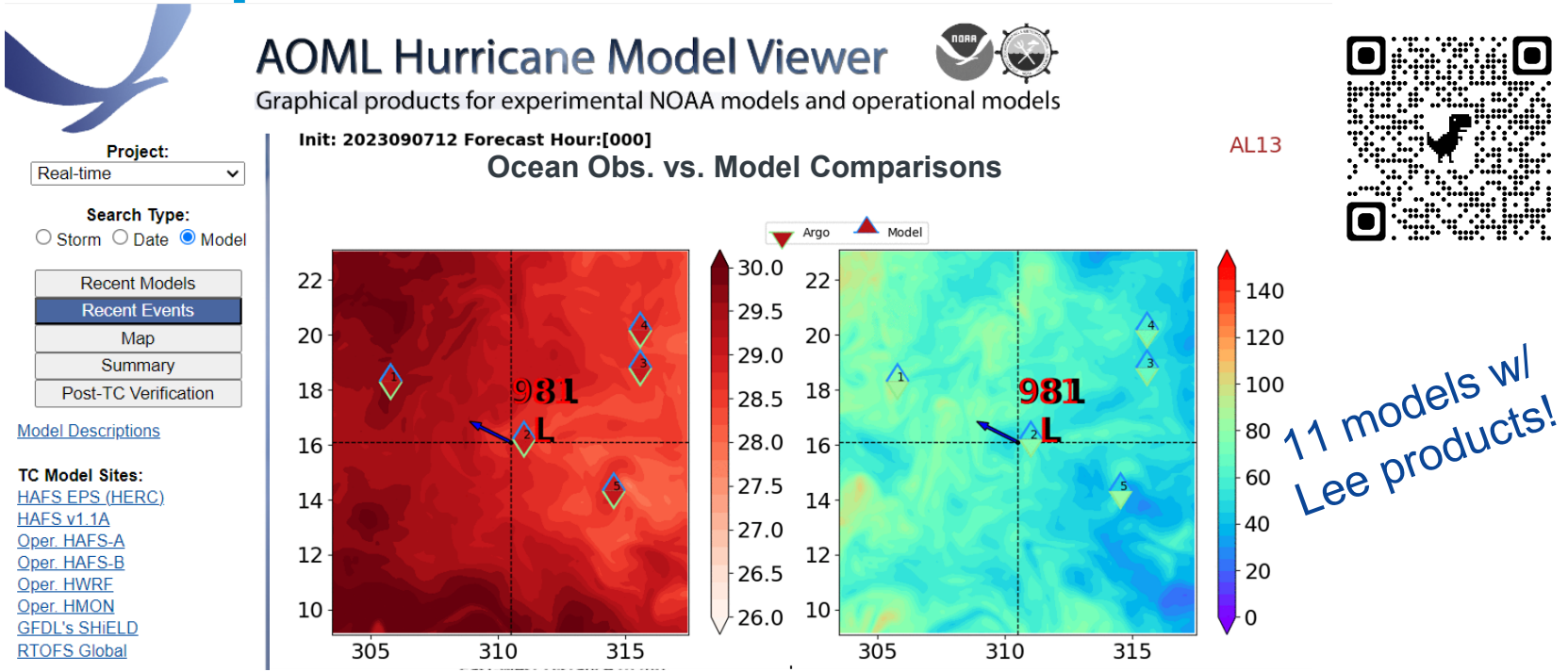


TS Philippe



SSMIS observations

HFIP Experimental Real-Time Products

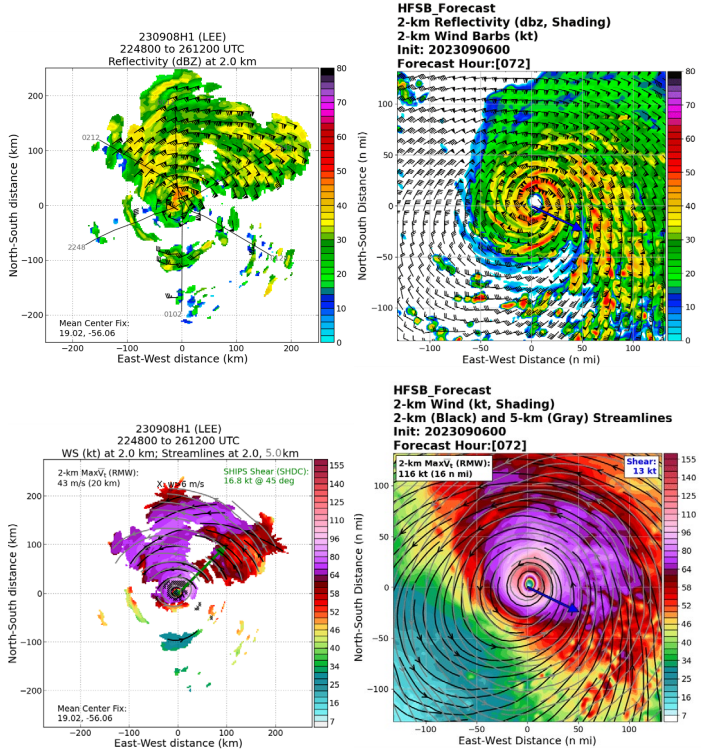


Millions of products for experimental & operational models

https://storm.aoml.noaa.gov/viewer

Hurricane Lee: Rapid Intensification

P3 TDR

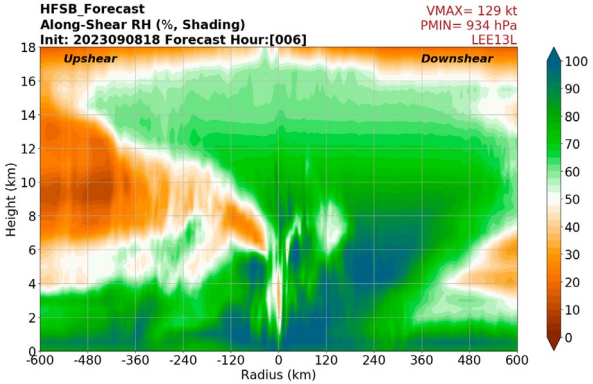


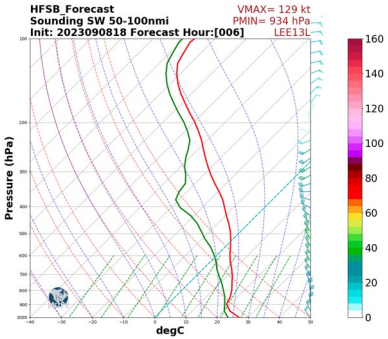
HFSB

- Inner core differences
  - **HAFS**: inner core was too symmetric
  - **TDR**: inner core was smaller and more asymmetric
- Environmental differences
  - **HAFS**: weaker shear from NW
  - **TDR**: stronger shear from SW
  - HAFS errors coming from GFS?

Hurricane Lee: Rapid Weakening

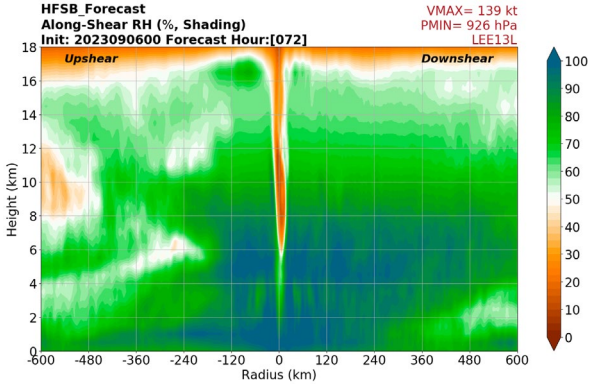
Later forecast: 6h

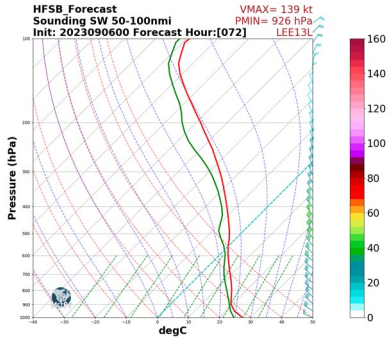




Same valid time

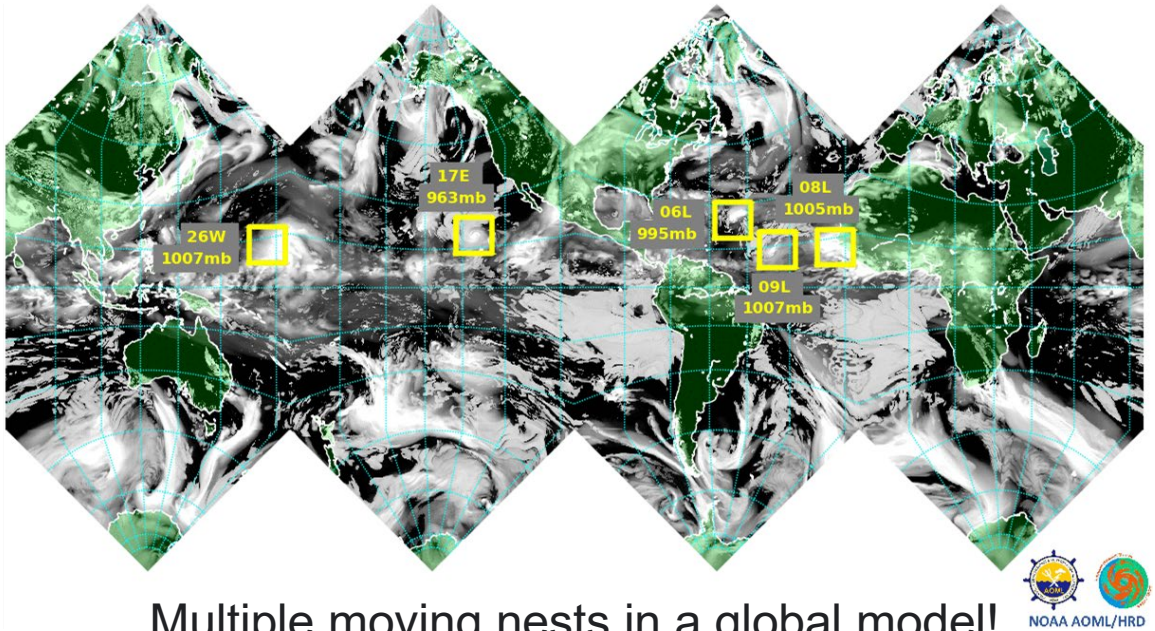
Earlier forecast: 72h





- 3-day forecasts missed shear-induced erosion/ ventilation of the core
- Early forecasts missed the dry SW inflow around ~300-400 hPa undercutting the outflow layer

Future Vision of UFS/HAFS



Multiple moving nests in a global model!

Check out these HRD Modeling Team papers

Thank you! Ghassan.Alaka@noaa.gov