NATIONAL WEATHER SERVICE

A New Operational Hurricane Prediction System for NOAA: UFS-based Hurricane Analysis and Forecast System (HAFS)

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Acknowledgement of ALL Active HAFS Developers

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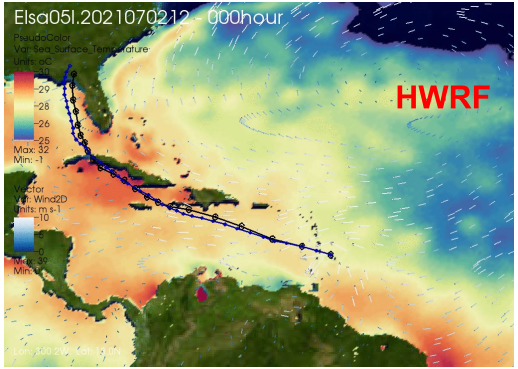
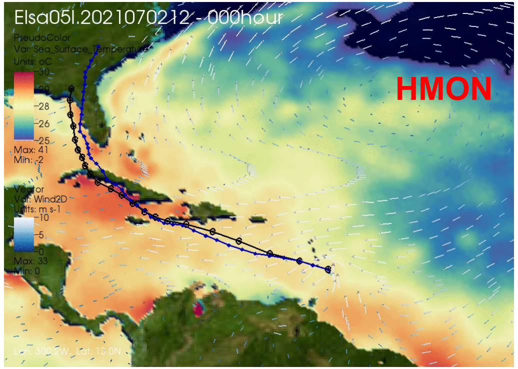
Existing Operational Tropical Cyclone Prediction Models at NCEP

	HWRF	HMON
Dynamic core	Non-hydrostatic, NMM-E	Non-hydrostatic, NMM-B
Nesting	13.5/4.5/1.5 km; 77°/18°/6°; 75 vertical levels; Full two-way moving	18/6/2 km; 75°/12°/8°; 71 vertical levels; Full two-way moving
DA and Initialization	Vortex initialization, Self-cycled hybrid EnKF-GSI with inner-core DA (TDR)	Modified vortex initialization, no DA
Physics	Updated surface (GFDL), GFS-EDMF PBL, Updated Scale-aware SAS, NOAH LSM, Modified RRTM, F-A MP	Surface (GFDL), GFS-EDMF PBL, Scale-aware SAS, NOAH LSM, RRTM, F-A MP
Coupling	MPIPOM, RTOFS, WaveWatch-III	HYCOM, RTOFS, No waves
Post-processing	NHC interpolation method, Updated GFDL tracker	NHC interpolation method, GFDL tracker
Operational forecasts	All global basins (NHC/JTWC), max. 7 TCs on-demand	NHC basins, max. 5 TCs, on-demand
Computation Resources	91 nodes in 98 mins	43 nodes in 100 mins

Hurricane Elsa, 05L, 2021





Note: Items in Green are similar/same; Items in Red are different

Hurricane Analysis and Forecast System (HAFS):

A collaborative project in UFS framework

Overview

- A UFS-based hurricane application
- An atmosphere-ocean-wave coupled TC forecast system with convection-allowing high-resolution, storm-following nests, vortex initialization, inner-core data assimilation, and physics calibrated by TC in-situ observations
- Established and funded jointly by NWS and OAR
- Scientists from NWS, OAR, NCAR, and universities participated in the HAFS development
- Real-time demo for the past three years (2020-2022)
- Two configurations (HAFS-A and HAFS-B) in operations since June 27, 2023
- UFS-R2O Extended to Phase 2 (FY24+)

Goals and Objectives

Based on HFIP strategic plan, HAFS goals and objectives are to

- **Reduce forecast guidance errors, including during RI, by 50% from 2017 baselines**
- **Produce 7-day forecast guidance as good as the 5-day forecast guidance in 2017**
- **Improve guidance on pre-formation disturbances, including genesis timing, and track and intensity forecasts, by 20% from 2017**
- **Improve hazard guidance and risk communication based on social and behavioral science, to modernize the TC product suite (products, information, and services) for actionable lead-times for storm surge and all other threats**

Summary of HAFS v1.0 Upgrades

System and Infrastructure Upgrades

- FV3 based dyn-core
- CCPP based physics suites
- ESG grids with moving nest
- Model Efficiency
- Workflow

Vortex Initialization Improvement

- Vortex Initialization modernized and leveraged from operational HWRF, cycling storm region only

Data Assimilation Improvement

- 4DEnVar with GDAS ensembles
- DA turned on for CPAC storms
- Leverage obs. used in GFS
- Additional meso-scale obs.

Post-process

- Upgraded GFDL Tracker

Model Physics Advancement

- GFDL/Thompson Microphysics
- Upgraded TKE-EDMF PBL
- Surface layer scheme (GFS vs GFDL)
- Upgraded scale-aware convection parameterization
- UGWPv1
- TC-specific mixing length scale adjustment

  TC-specific deep convection entrainment parameter in saSAS

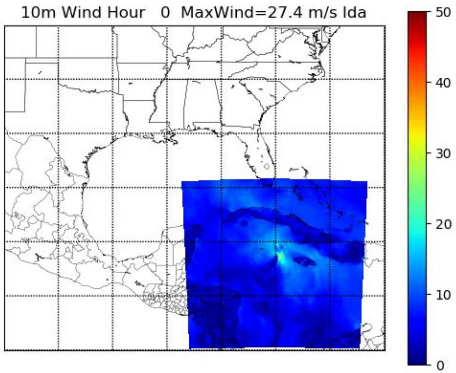
Ocean/Wave Coupling

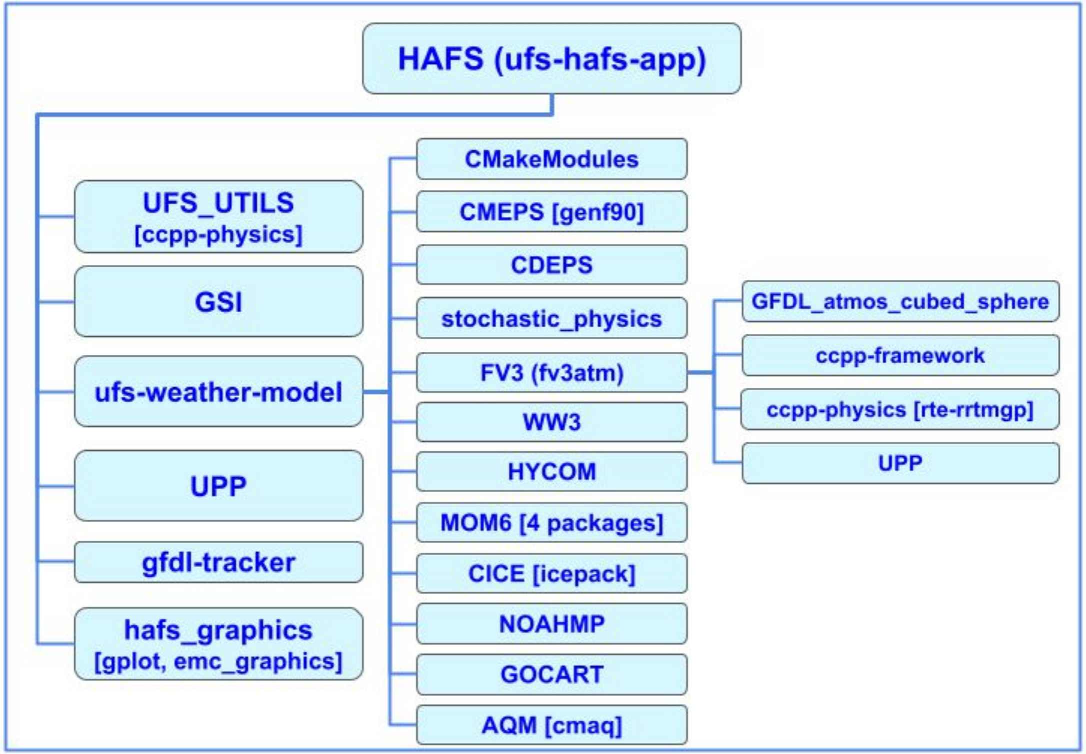
- CMEPS based coupling
- Coupled to HYCOM for all global basins
- Extended HYCOM domain to cover both NATL/EPAC basins, IC/BC from RTOFS

Items in red: Innovations implemented for the first time in Hurricane model operations

HAFS v1.0 System Upgrades

- **System and Infrastructure Upgrades**
  - FV3 based dyn-core
  - CCPP based physics suites
  - Moving nest
  - Model Efficiency
  - Workflow

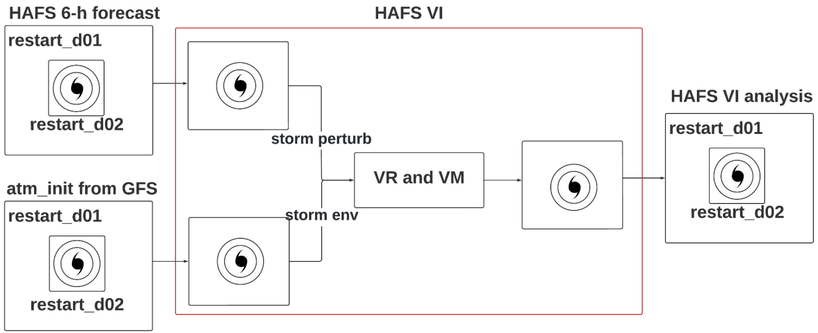


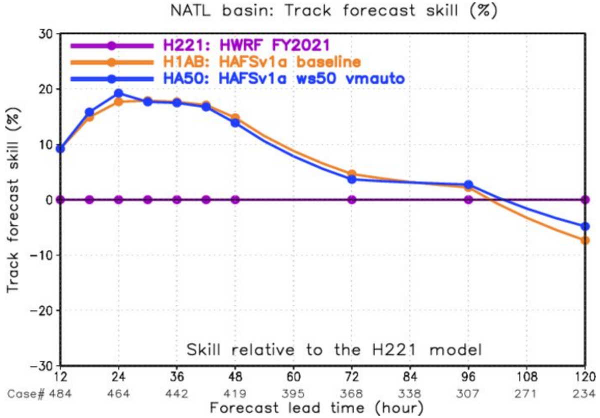


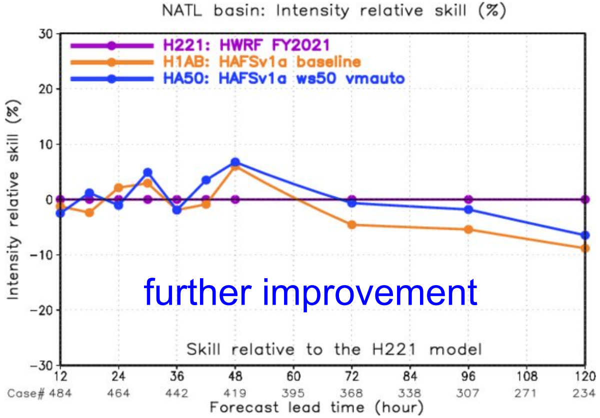
https://github.com/hafs-community/HAFS

HAFS v1.0 VI Upgrades

- **Vortex Initialization Improvement**
  - Sophisticated Vortex Initialization technique leveraged and modernized from operational HWRF and HMON,
  - Vortex Relocation and Vortex Modification
  - Cold-start from GDAS 6h forecasts if Vmax < 25 m/s (20 m/s, HFSB)
  - Warm-start by combining HAFS prior cycle's 6h forecast storm perturbation with GFS/GDAS environment if Vmax =>25 m/s (20 m/s, HFSB)
  - Cycling storm region only







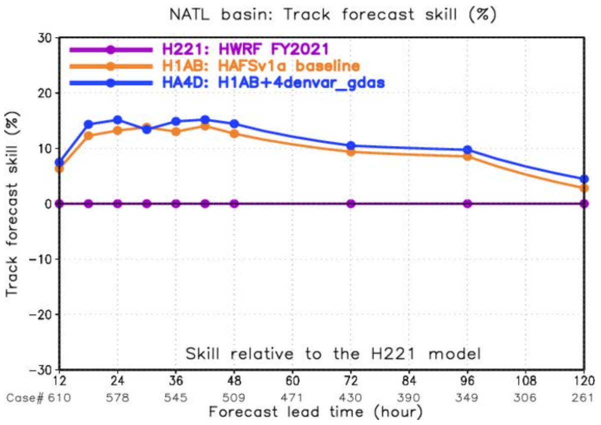
VI Threshold experiments

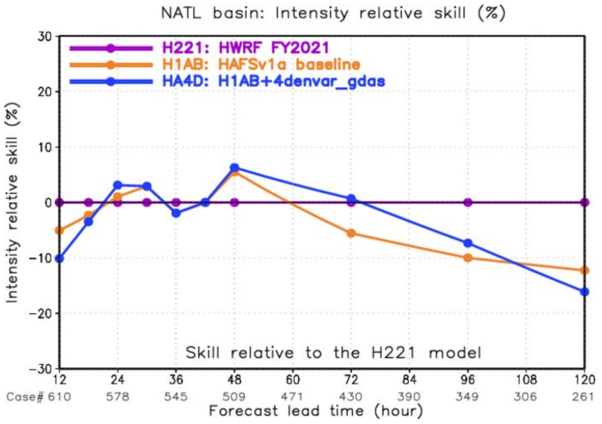
HAFS v1.0 DA Upgrades

- **Data Assimilation Improvements**
  - 6-hourly DA cycling in nested domain region, and use GFS analysis elsewhere in the parent domain
  - +/- 3-hour FGAT window
  - 3DEnVar to 4DEnVar with GDAS ensembles
  - Leverage obs. used in GFS
  - Additional meso-scale obs.

Additional obs. assimilated in Hurricane Models

- Tail Doppler Radar (TDR)
- Next Generation Weather Radar (NEXRAD)
- Dropsondes with drift corrections
- METAR observations

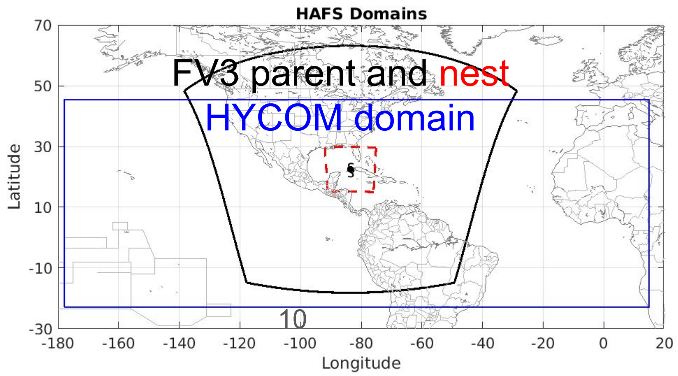




4DEnVar further improved intensity forecast skill over 3DEnVar

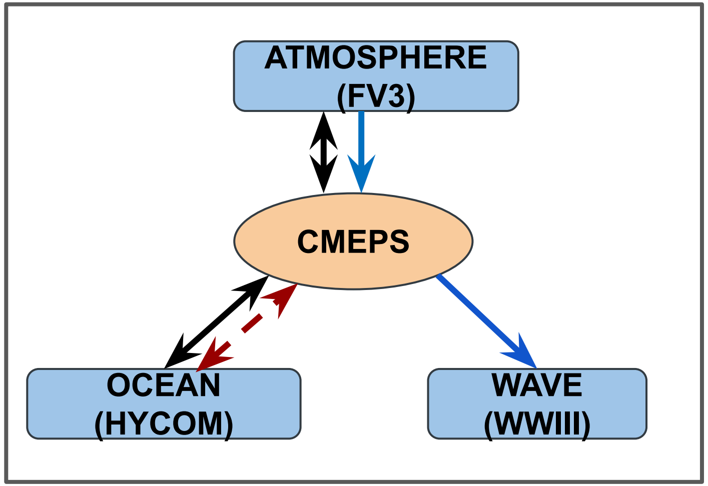
HAFS v1.0 Ocean coupling Upgrades

- **Ocean/Wave/LSM Coupling**
  - CMEPS based Coupling
  - Coupled to HYCOM for all global basins
  - Extended HYCOM domain to cover both NATL/EPAC basins
  - Use VIIRS veg type (vs MODIS)
  - One-way wave coupling



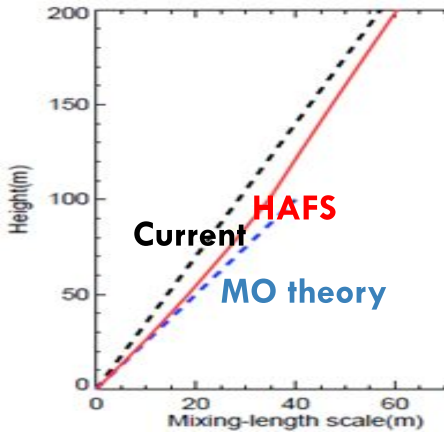
Ocean/Wave coupling with moving nest

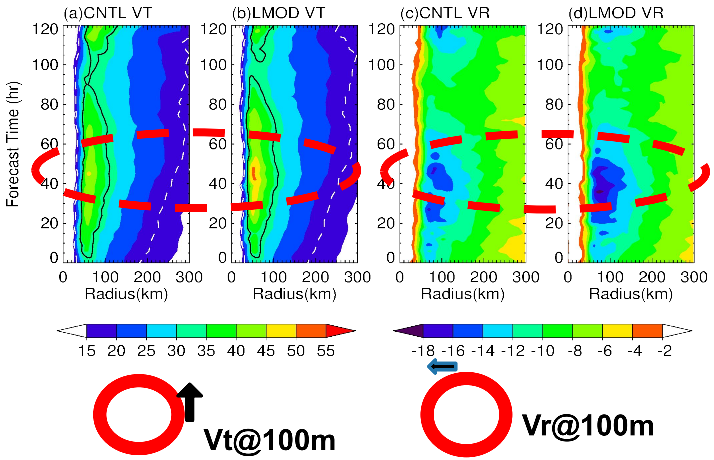
- HYCOM ocean coupled to HAFS parent, IC/BC from RTOFS
- Downscale HAFS parent SST for the nest domain
- One-way coupling with WW3: generate HAFS/wave IC/BC from GFS/wave



HAFS v1.0 Physics Upgrades

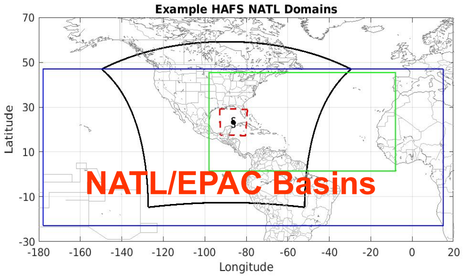
- **Model Physics Advancement**
  - Microphysics, (GFDL/Thompson vs Ferrier–Aligo in HWRF/HMON)
  - Upgraded PBL, TKE-EDMF
  - Surface layer scheme (GFS vs GFDL)
  - Upgraded scale-aware convection parameterization
  - Gravity wave drag scheme: UGWPv1
  - TC-specific mixing length scale adjustment
  - TC-specific deep convection entrainment parameter in saSAS

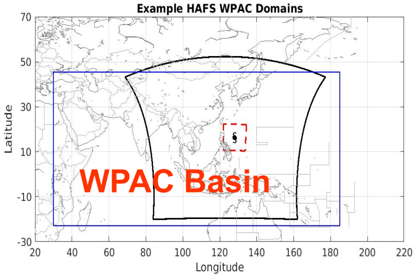


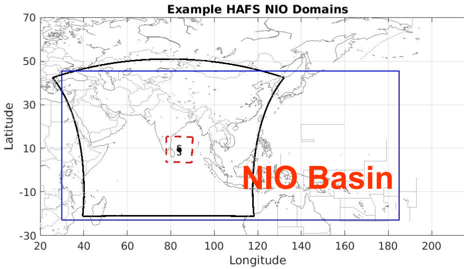


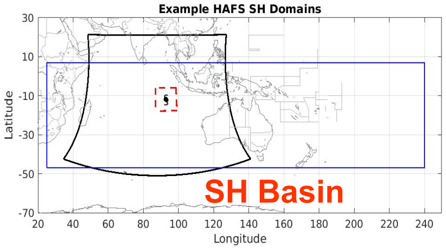
Two Configurations for Operational HAFS

HAFSv1.0	Domain	Resolution	DA/VI	Ocean/Wave Coupling	Physics	Basins
HFSA	Storm-centric with one moving nest, parent: ~78x75 deg, nest: ~12x12 deg	Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top	Vmax > 50 kt warm-cycled VI and 4DEnVar DA	Two-way HYCOM, one-way WW3 coupling for NHC/CPHC basins	Physics suite-1	All global Basins NHC/CPHC/JTWC Max 7 Storms similar to HWRF
HFSB	Storm-centric with one moving nest, parent: ~75x75 deg, nest: ~12x12 deg	Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top	Vmax > 40 kt warm-cycled VI and 4DEnVar DA	Two-way HYCOM No Waves	Physics suite-2	NHC/CPHC Max 5 Storms similar to HMON









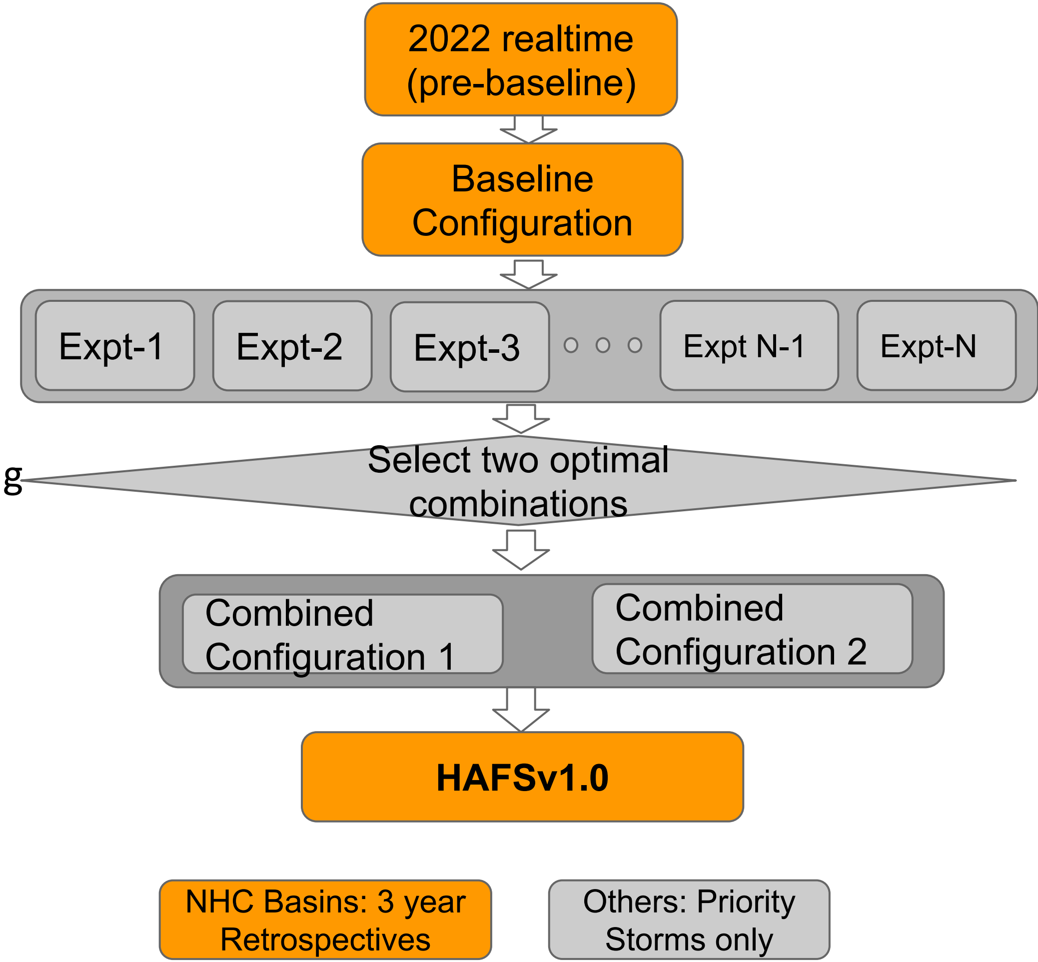
atmospheric domain, ocean domain, wave domain

HAFS Physics Schemes

	Suite 1	Suite 2	References
Land/ocean Surface	NOAH LSM VIIRS veg type, HYCOM	NOAH LSM VIIRS veg type HYCOM	Ek et al. (2003) …
Surface Layer	GFS, HWRF TC-specific sea surface roughnesses	GFS, HWRF TC-specific sea surface roughnesses	Miyakoda and Sirutis (1986); Long (1984, 1986)
Boundary Layer	Sa-TKE-EDMF, TC-related calibration, **mixing length adjustments**	Sa-TKE-EDMF, TC-related calibration, **tc_pbl=1, mixing length adjustments**	Han et al. (2019) Wang et al. (2022) Chen et al. (2022)
Microphysics	**GFDL single-moment**	**Thompson double-moment**	Lin et al. (1983) Chen and Lin (2013) Thompson et al (2008) Thompson and Eidhammer(2014)
Radiation	RRTMG Calling frequency **720 s**	RRTMG Calling frequency **1800 s**	Iacono et al. (2008)
Cumulus convection (deep & shallow)	Scale-aware-SAS, **calibrated deep convection entrainment**	Scale-aware-SAS	Han et al. (2017)
Gravity wave drag	uGWPv1	uGWPv1	Alpert et al. (1988)

HAFSv1 Development Strategy

- Use HWRF/HMON as benchmarks.
- Phase-1: Establish baseline (from pre-baseline, 2022 real time parallels). Conduct 3-year retrospective runs (2020-2022) for all storms in North Atlantic (NATL) and Eastern Pacific (EPAC) basins.
- Phase-2: Conduct experiments with upgraded dynamics, physics, vortex initialization, data assimilation, and coupling *separately* for a set of priority storms, including TCs in **NATL, EPAC**, CPAC*, WPAC, NIO and SH basins.
- Phase-3: Combine and select promising phase-2 upgrades to finalize HAFSv1.0 configurations.
- Final stage: Freeze HAFS development, and conduct 3-year retrospectives



*There have been no numbered/named storms in CPAC in the past 3 years, technical tests have been conducted, no T&E.

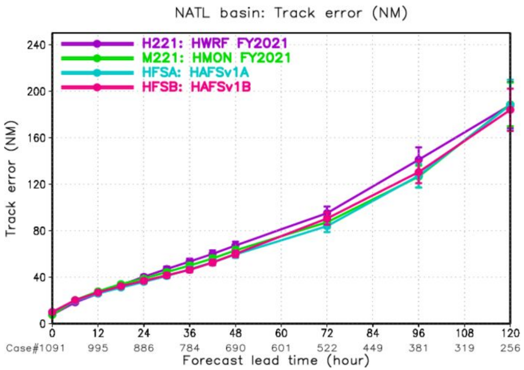
HAFS Verification for North Atlantic Storms (2020-2022)

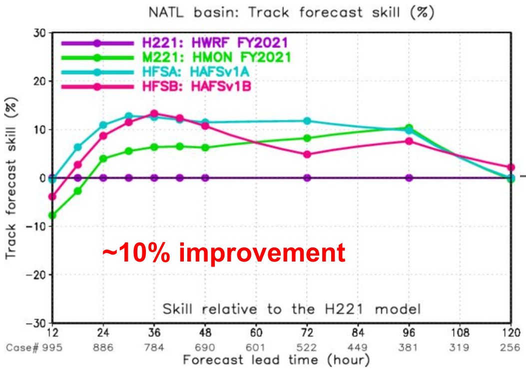
- **H221/H21I: Late/Early models of current operational HWRF**
- **M221/M21I: Late/Early models of current operational HMON**
- **HFSA/HFAI: Late/Early of proposed FY23 HAFS-A configuration**
- **HFSB/HFBI: Late/Early of proposed FY23 HAFS-B configuration**
- **Total 1279 cycles with 1091 verifiable cycles**

Late model guidance**:** the track/intensity forecast guidance from the current cycle
Early model guidance: the forecast guidance from the previous cycle and interpolated/shifted to the current cycle, which is typically used by NHC forecasters because the late dynamic model guidance is not yet available to hurricane specialists when preparing the official forecasts.

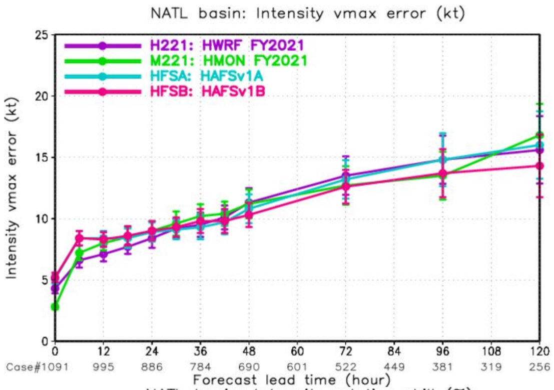
Track and Intensity Verification: NATL basin (2020-2022) (Late Model)

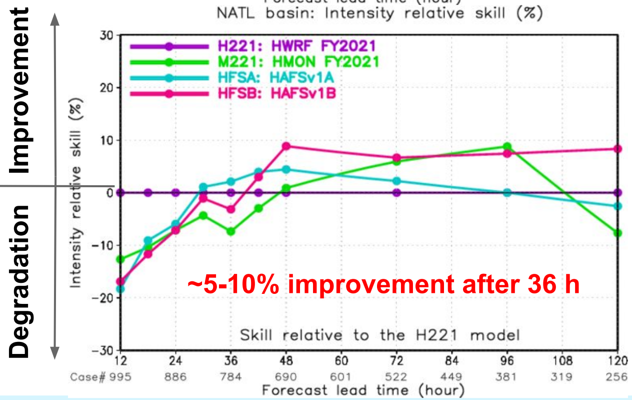
Track





Intensity

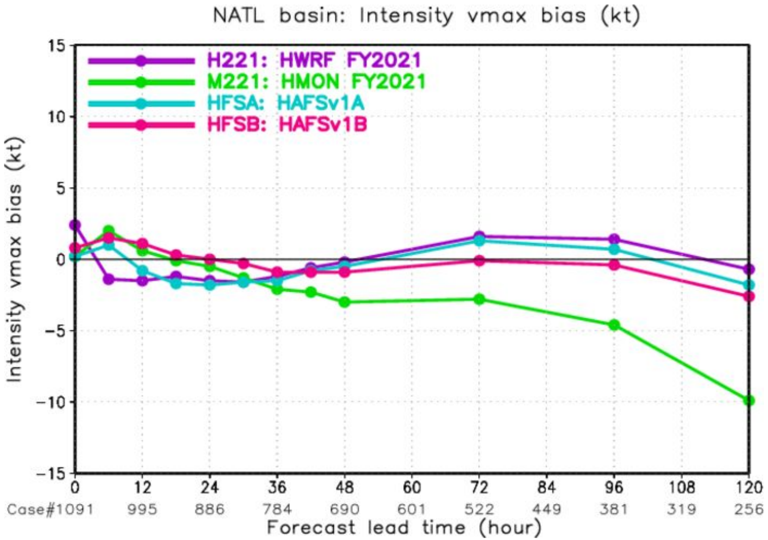




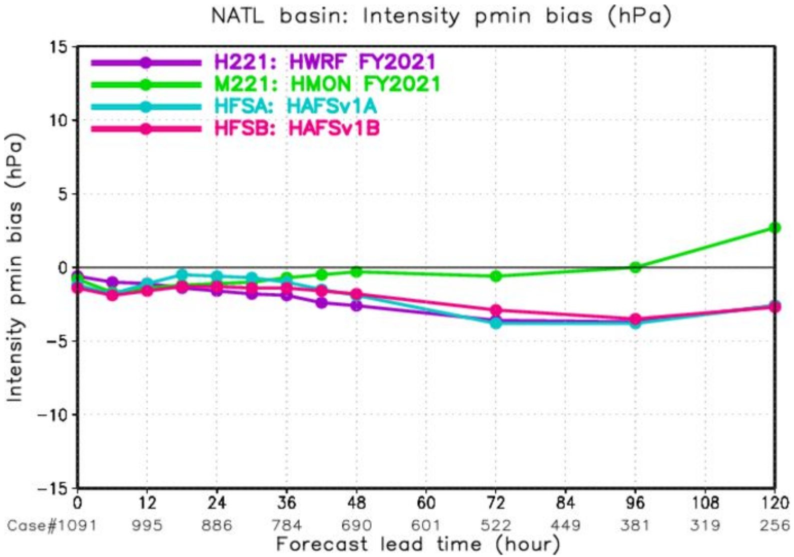
- Both HAFS configurations improved track forecast skill compared to HWRF at all lead times with more than ~10% between Days 1 and 4.
- Improvements in intensity skill are close to ~10% for lead times beyond Day 2 for HFSB, and ~5% maximum for HFSA.
- Initial intensity spin up/down issue is noted.

Vmax and MSLP bias: NATL basin (2020-2022) (Late Model)

Vmax

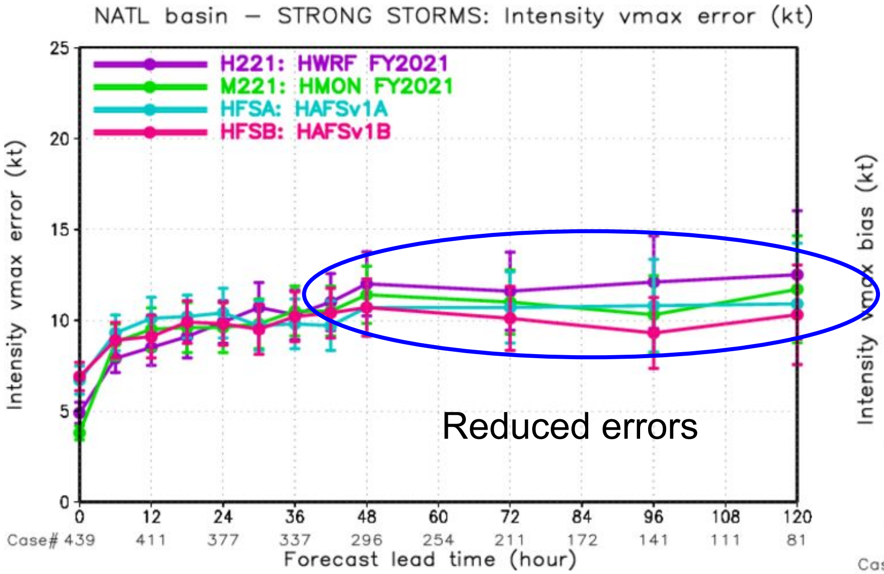


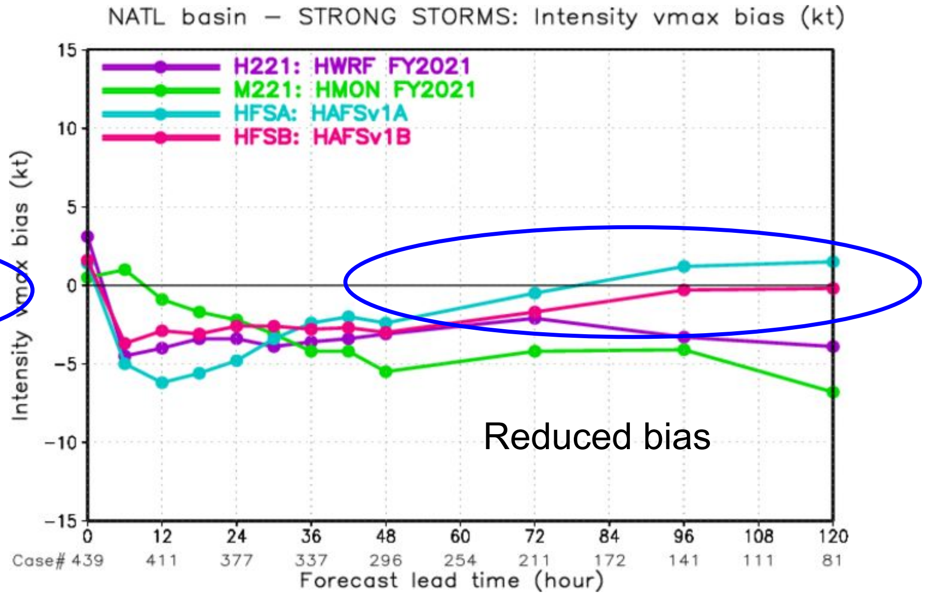
MSLP



There are modest improvements in Vmax and MSLP biases for the NATL basin with HFSA/HFSB.

Intensity Error Reductions: NATL basin (2020-2022)
(Strong Storms > 50 kt)

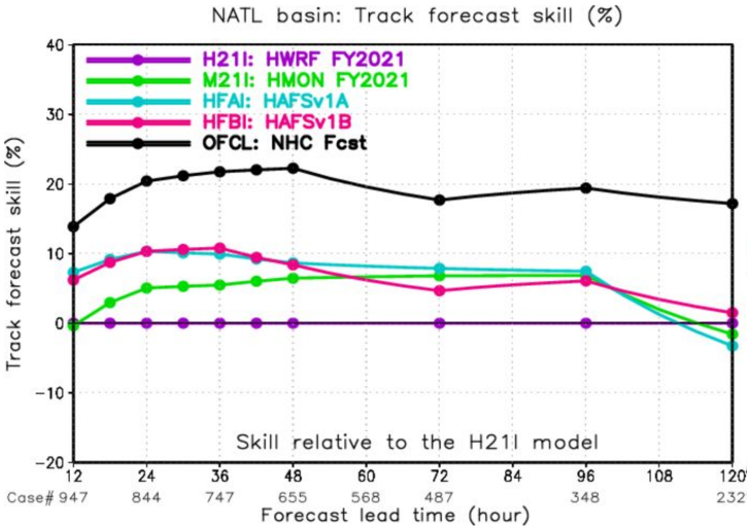




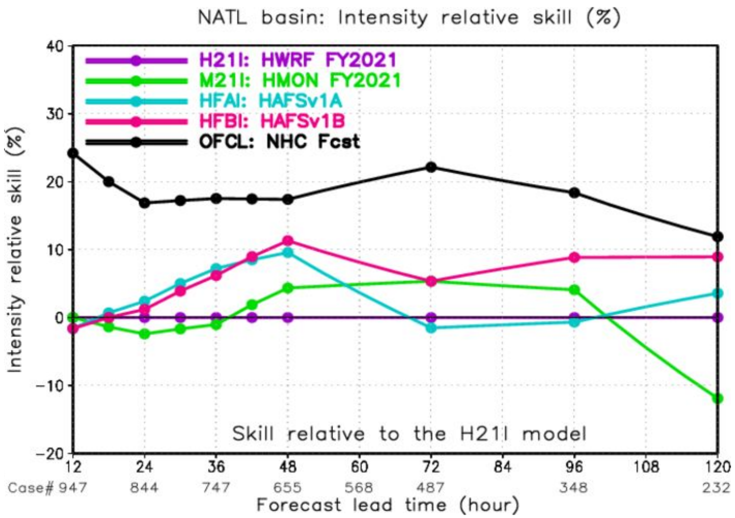
Both intensity errors and biases are reduced for HFSA/HFSB for strong storms after forecast 36 h as compared to H221 for the NATL basin.

Track and Intensity skill: NATL basin (2020-2022) (Early Model)

Track



Intensity



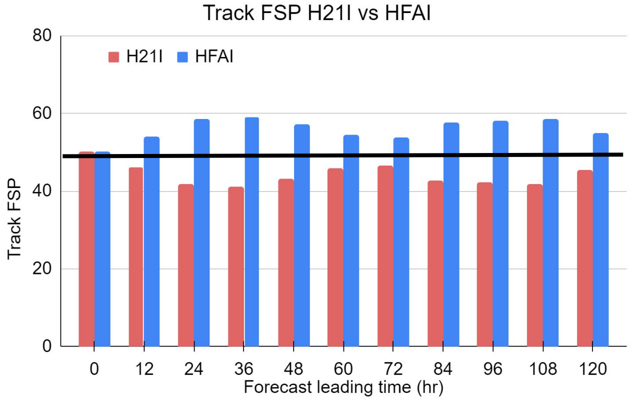
Early model results also show similar significant improvements in track skill as compared to H21I. While these improvements are impressive for track skill at almost all lead times, good improvements in intensity can be seen at most lead times.

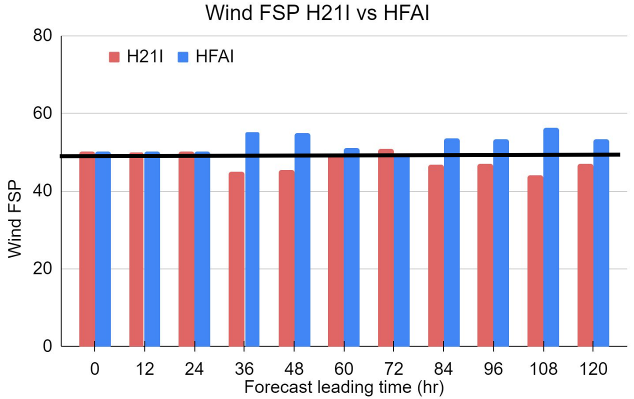
Frequency of Superior Performance: NATL basin

Track

Intensity

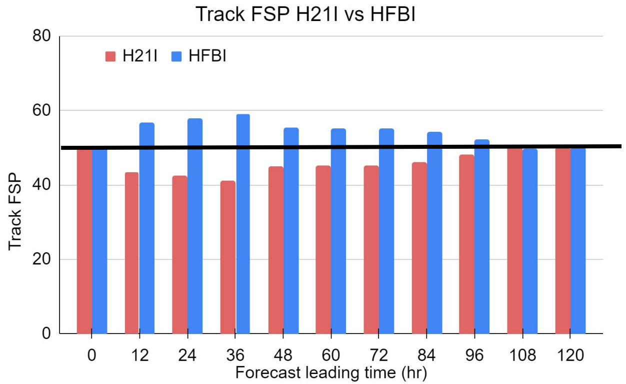
HFAI

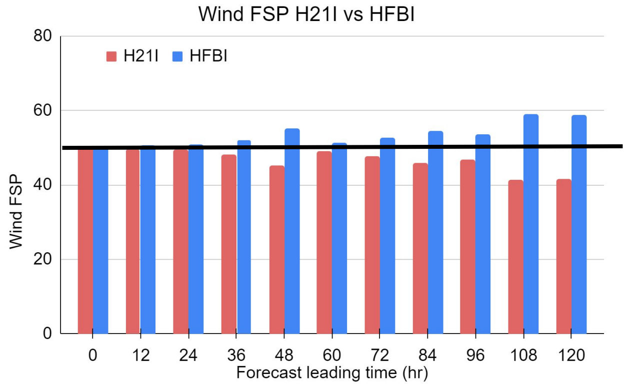




50%

HFBI

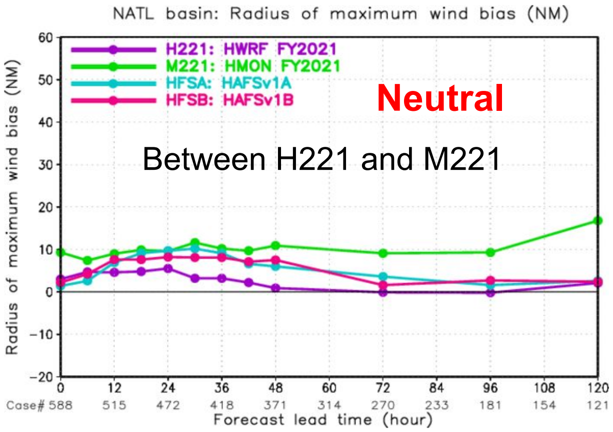




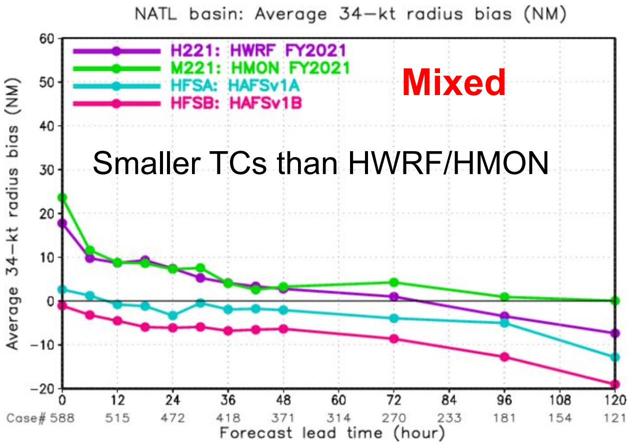
50%

Storm Size Biases: NATL basin (2020-2022)

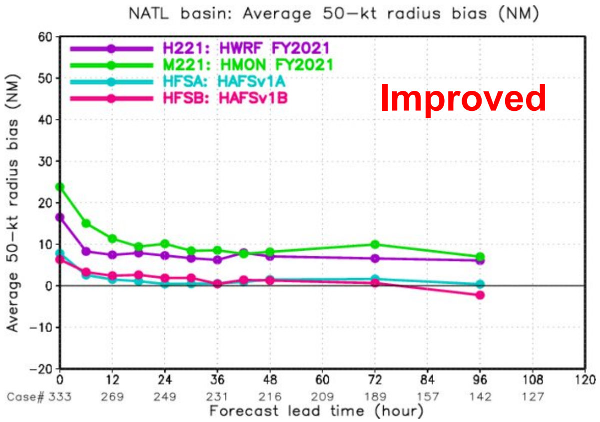
RMW



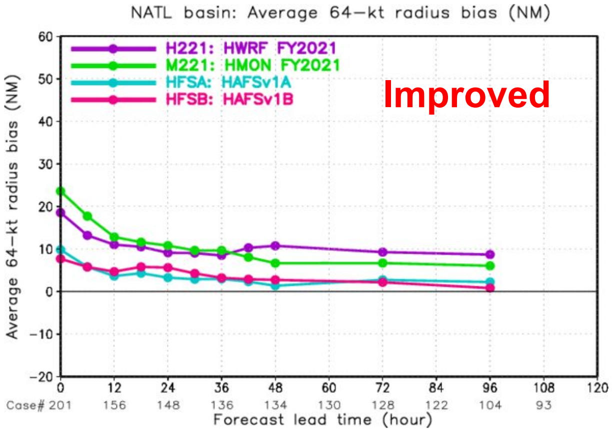
R34



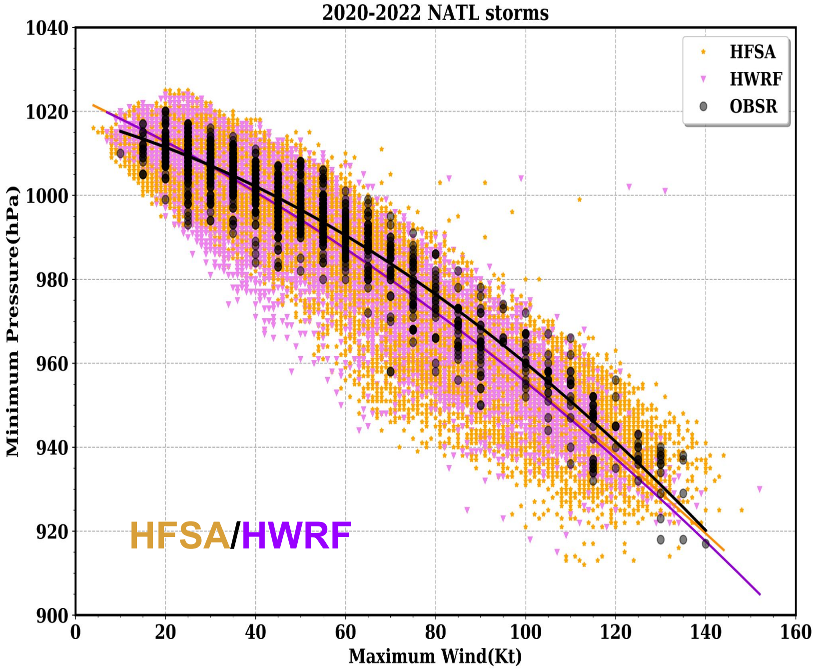
R50

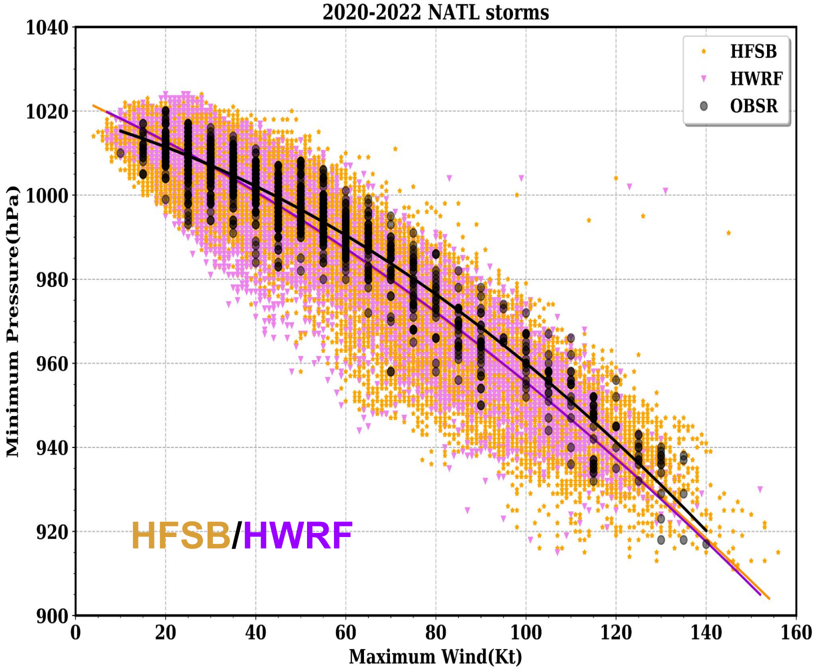


R64



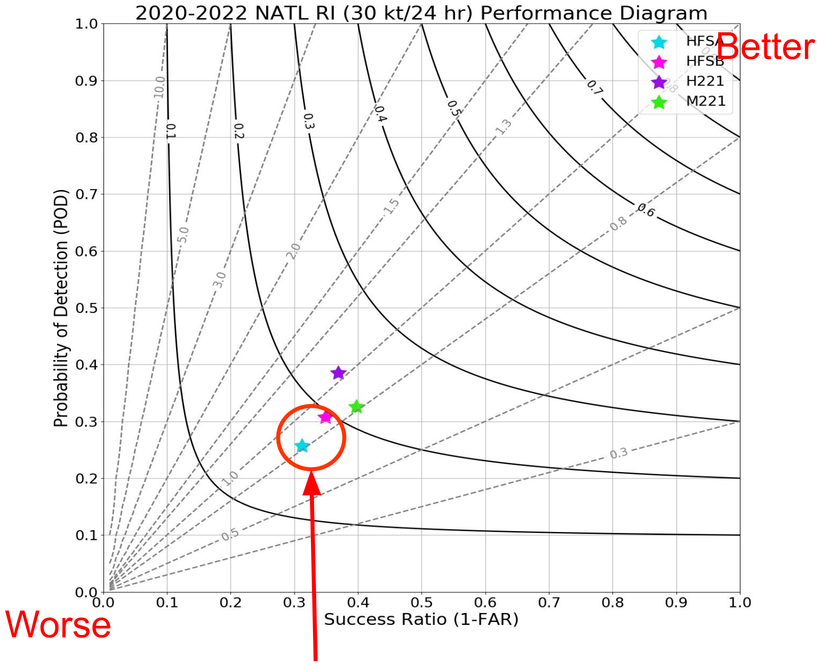
Pressure/Wind relationship: NATL basin (2020-2022)



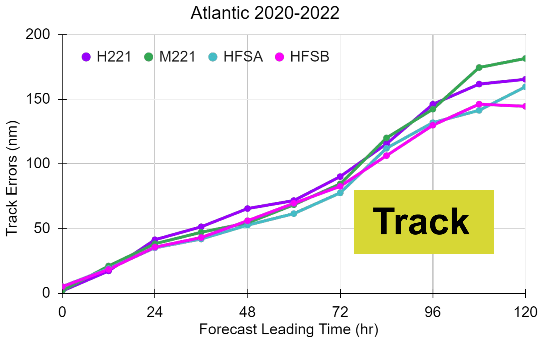


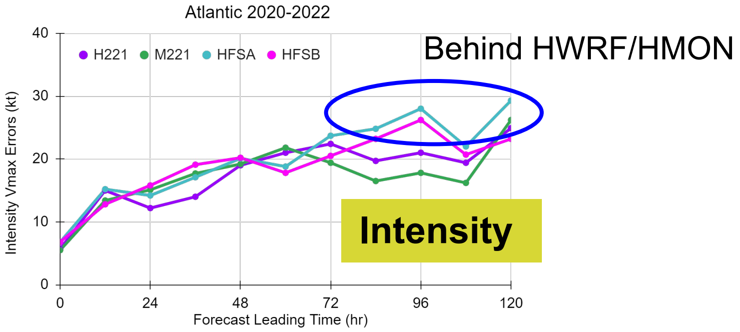
HFSA and HFSB produce similar W-P relationship compared to HWRF

Verification for Rapid Intensification Cycles: NATL Basin



HFSA/HFSB





Case# 40 102 89 87 43 33

verification algorithm from Mark DeMaria and James Franklin

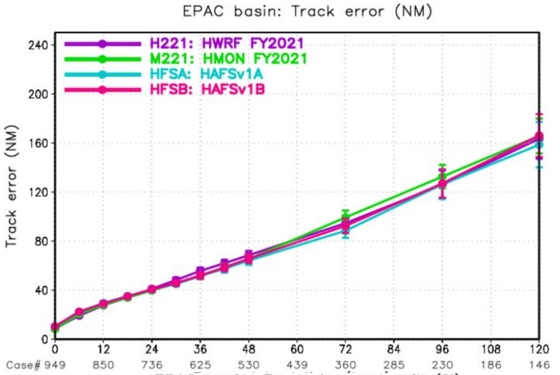
For RI cycles, both configurations of HAFS track forecast errors are lower than HWRF and HMON. HAFS intensity forecast skills for RI events are slightly behind HWRF and HMON.

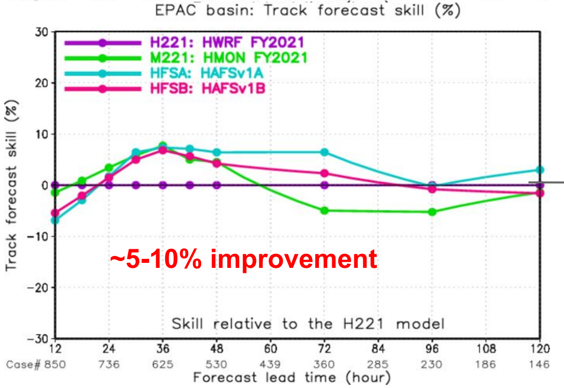
HAFS Verification for East Pacific Storms (2020-2022)

- H221/H21I: Late/Early of current operational HWRF
- M221/M21I: Late/Early of current operational HMON
- HFSA/HFAI: Late/Early of proposed FY23 HAFS-A configuration
- HFSA/HFAI: Late/Early of proposed FY23 HAFS-A configuration
- Total 1046 cycles with 947 verifiable cycles

Track and Intensity errors: EPAC basin (2020-2022) (Late Model)

Track

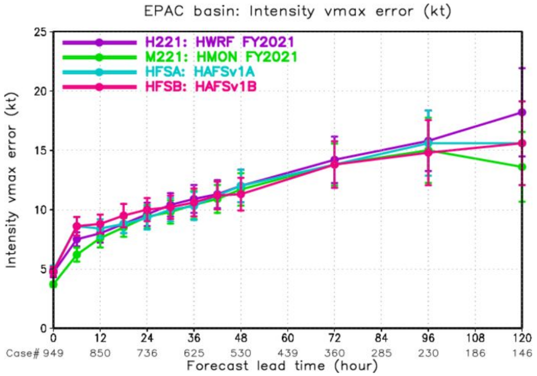


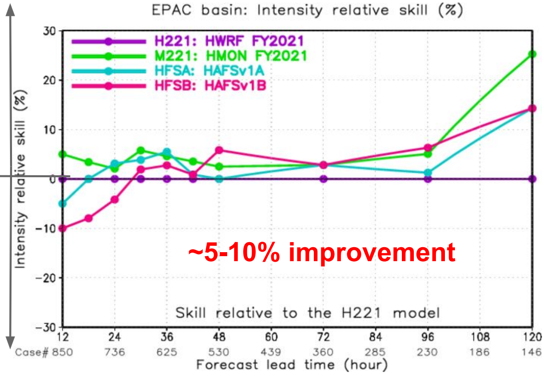


Improvement

Degradation

Intensity

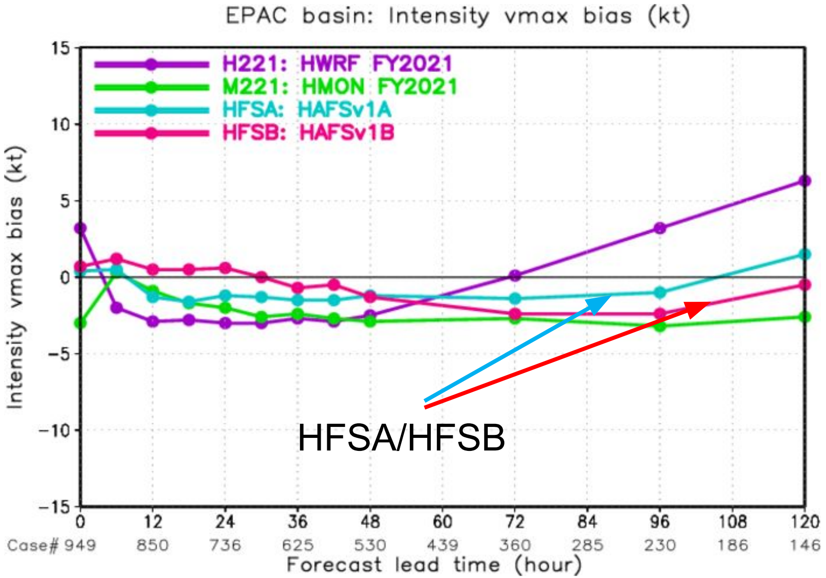




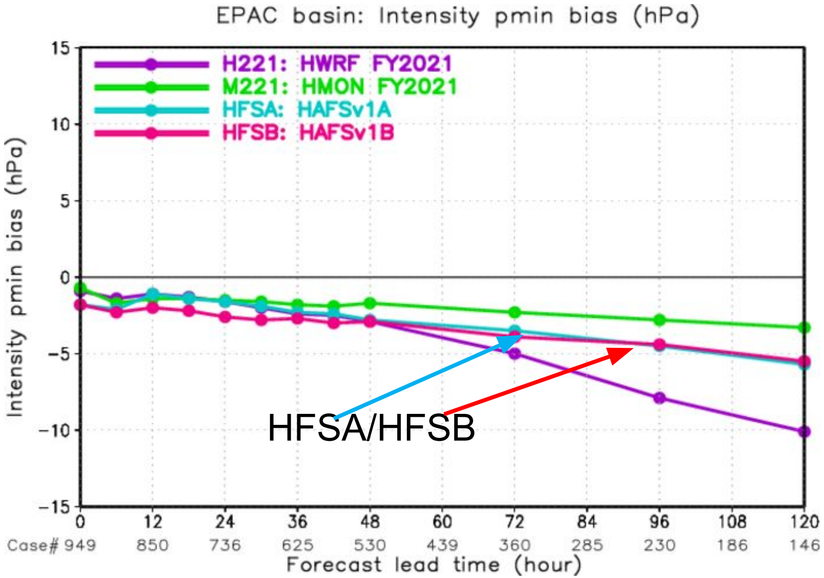
- Track skills are positive for almost all lead times, except at 12 h for both HAFS configurations and slightly negative at Day 5 for HFSB.
- Intensity skills become neutral and then turns positive after Day 1, and ~10% skillful than HWRF at Day 5 for both HAFS configurations.
- Both HAFS configurations are behind for Day 1 due to initial spin up/down issues.

Vmax and MSLP bias: EPAC basin (2020-2022) (Late Model)

Vmax



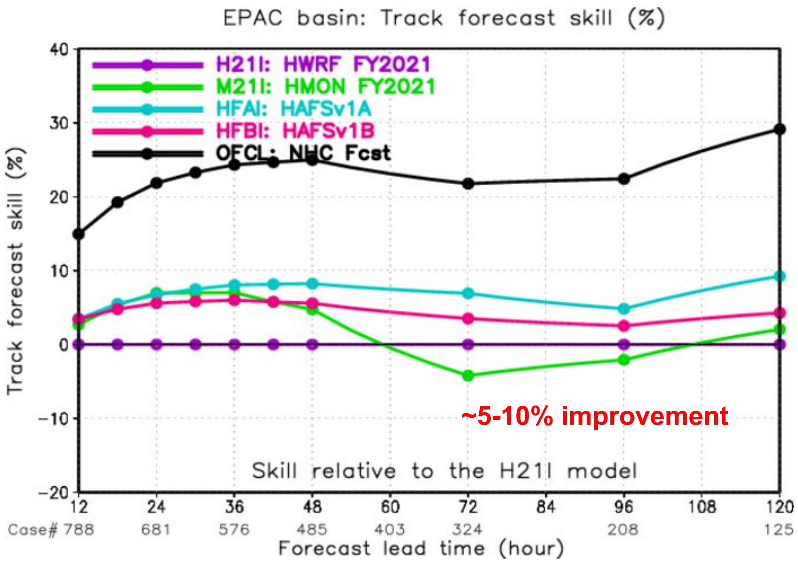
MSLP



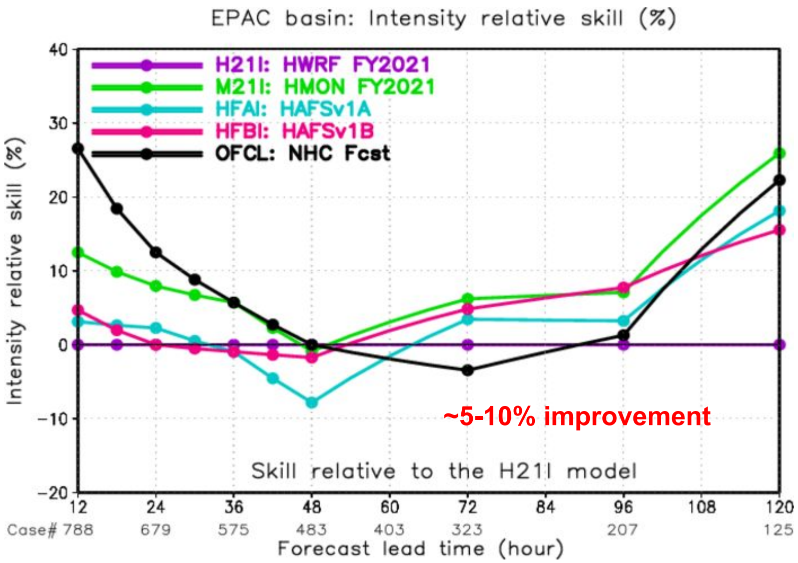
HFSA/HFSB Vmax biases are improved when compared with HWRF/HMON, while Pmin biases are also improved over HWRF, but are behind HMON.

Track and Intensity skill: EPAC basin (2020-2022) (Early Model)

Track



Intensity

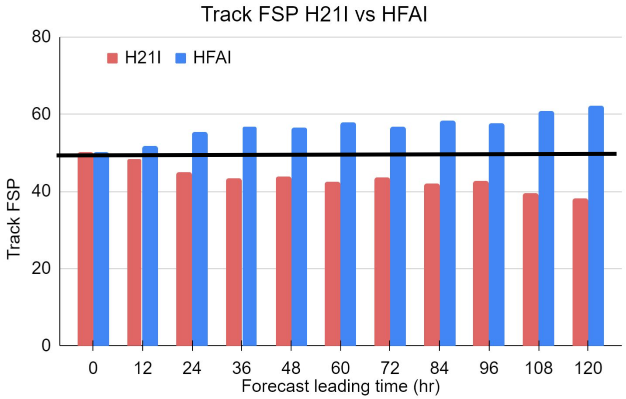


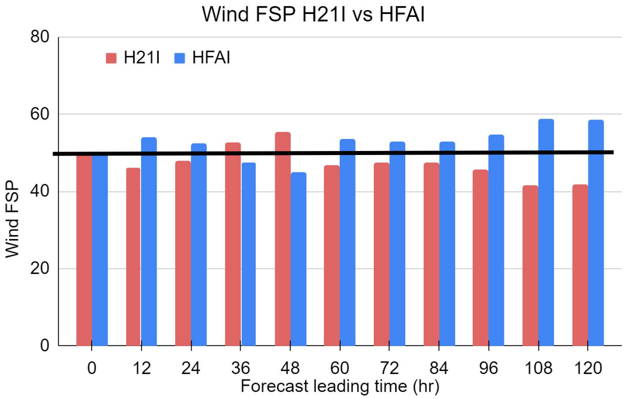
HFAI/HFBI track forecast are ~5-10% more skillful than H21I/M21I at all lead times. HFBI has neutral to positive impact on intensity forecast compared to H21I. HFAI intensity skills are better than H21I except at 48 h.

Frequency of Superior Performance Comparisons: EPAC basin

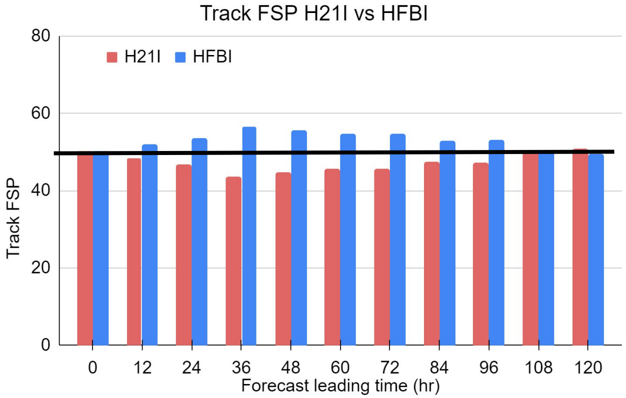
Track | **Intensity**

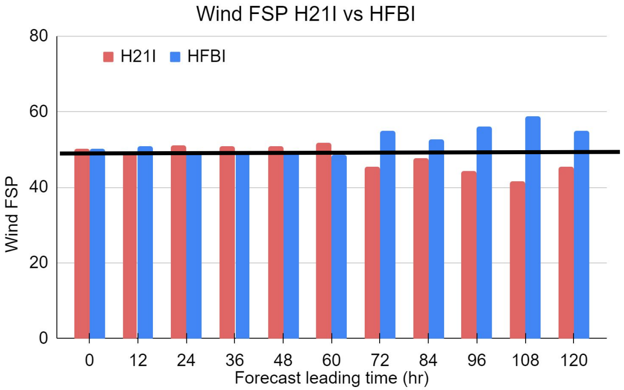
HFAI



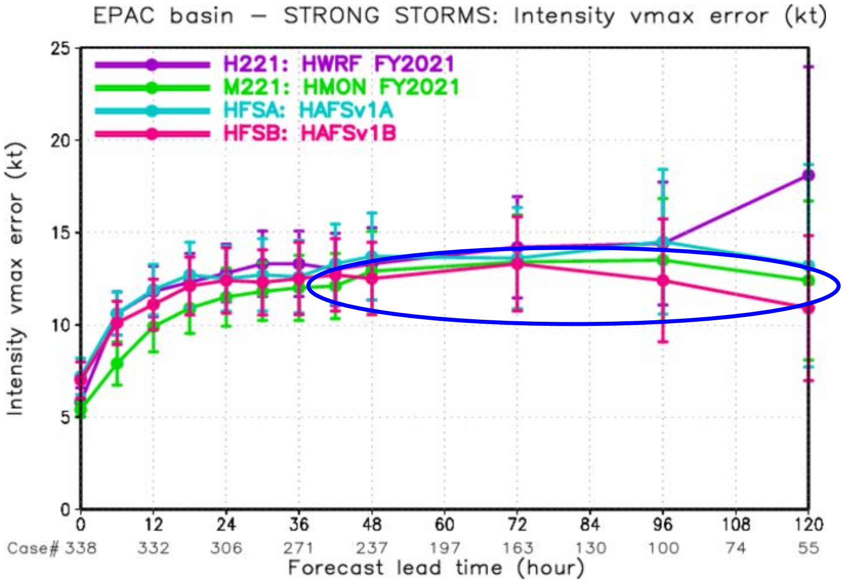


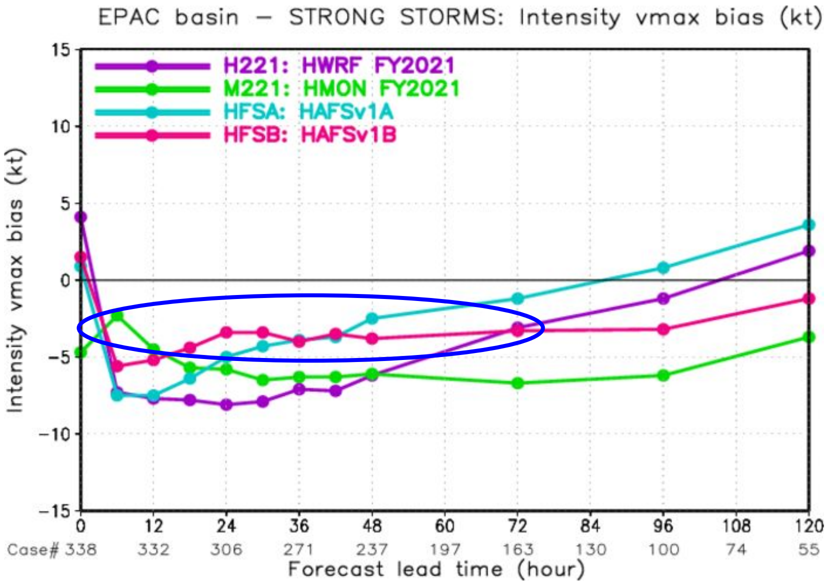
HFBI





Intensity Error Reductions: EPAC basin (2020-2022)
(Strong Storms > 50 kt)

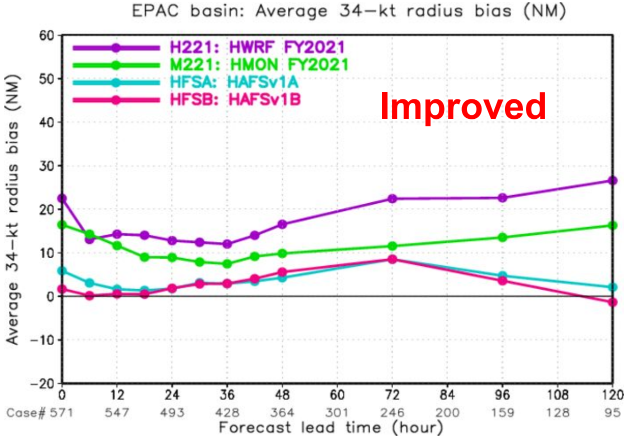




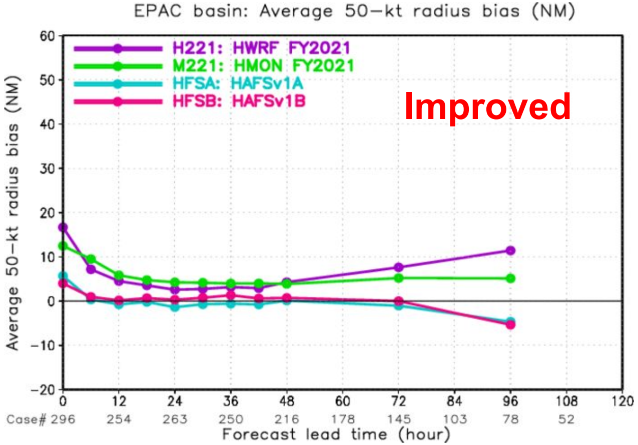
Intensity errors are reduced for HFSA/HFSB for strong storms at all lead times as compared to H221, same is true for intensity biases for HFSA. HFSB intensity biases are reduced before 72 h compared to H221, but degraded afterwards.

Storm Size Errors: EPAC basin (2020-2022)

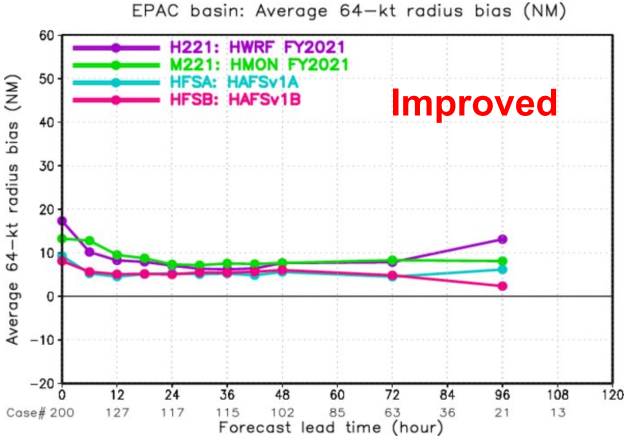
RMW



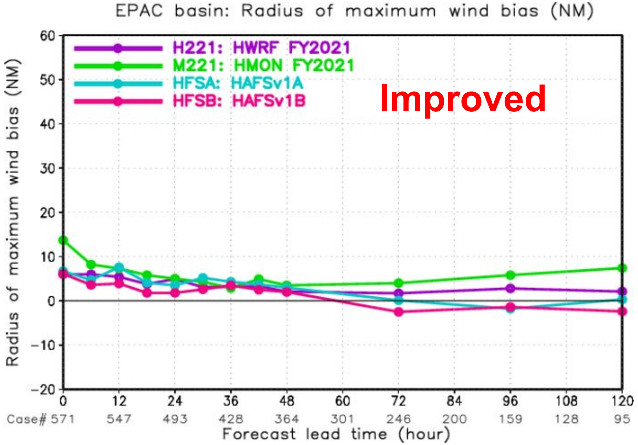
R34



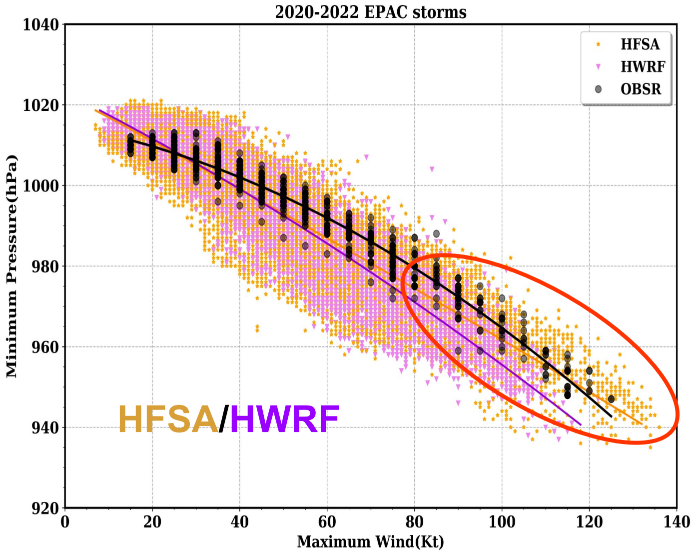
R50

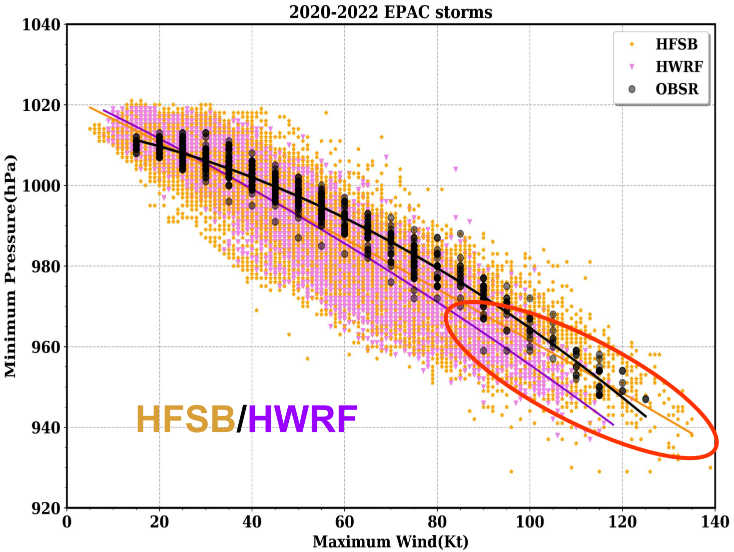


R64



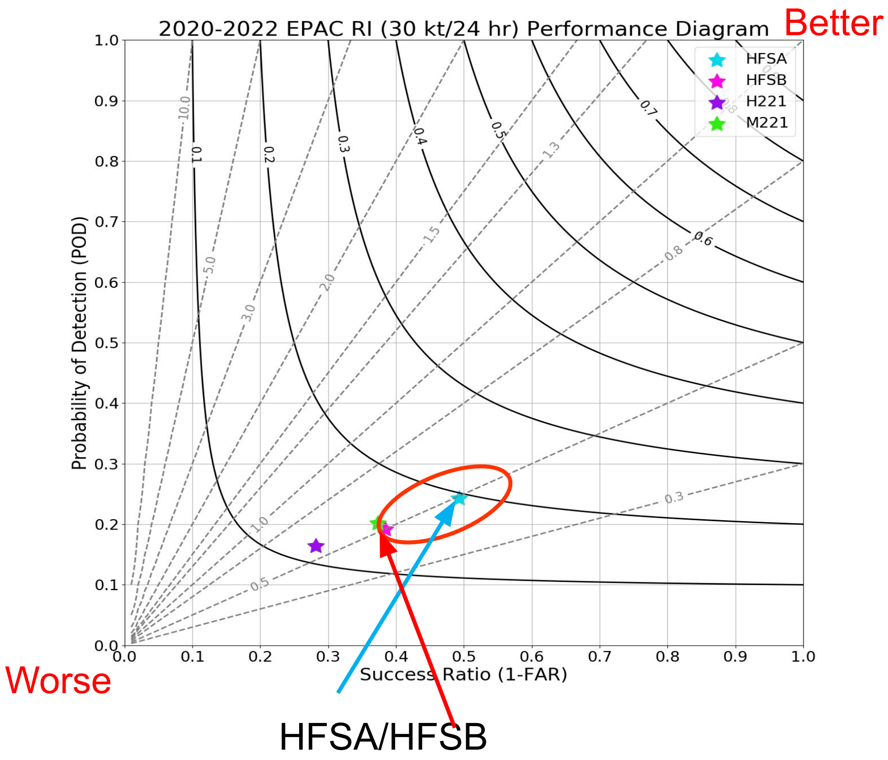
Pressure/Wind relationship: EPAC basin (2020-2022)

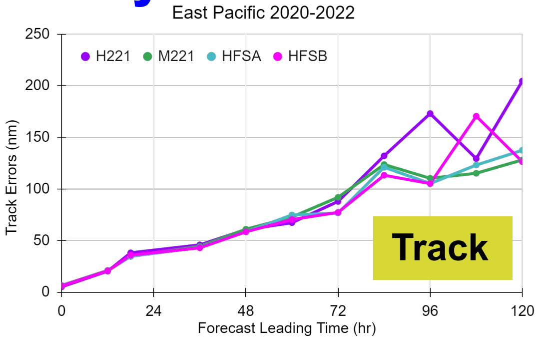


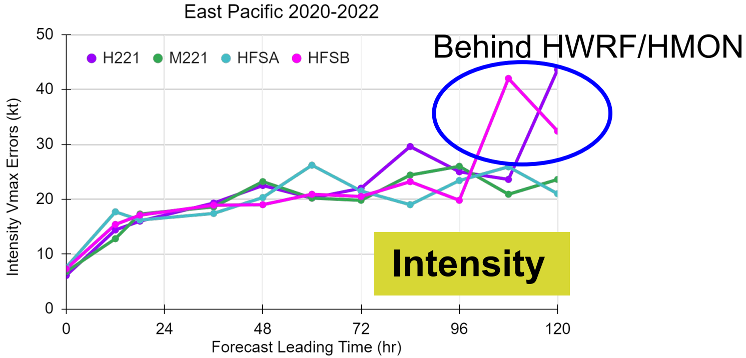


Both HFSA and HFSB have improved W-P relationship compared to HWRF, especially for strong storms.

Verification for Rapid Intensification Cycles: EPAC basin







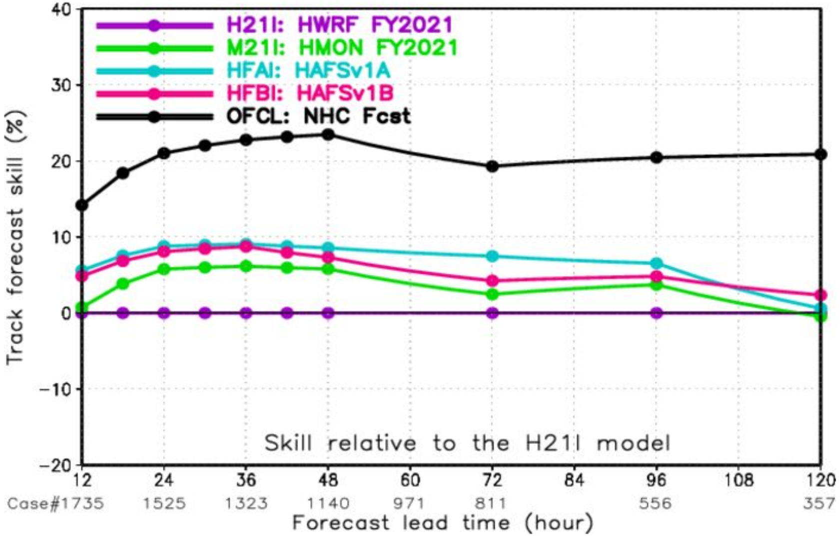
Case# 65 120 62 26 5 7

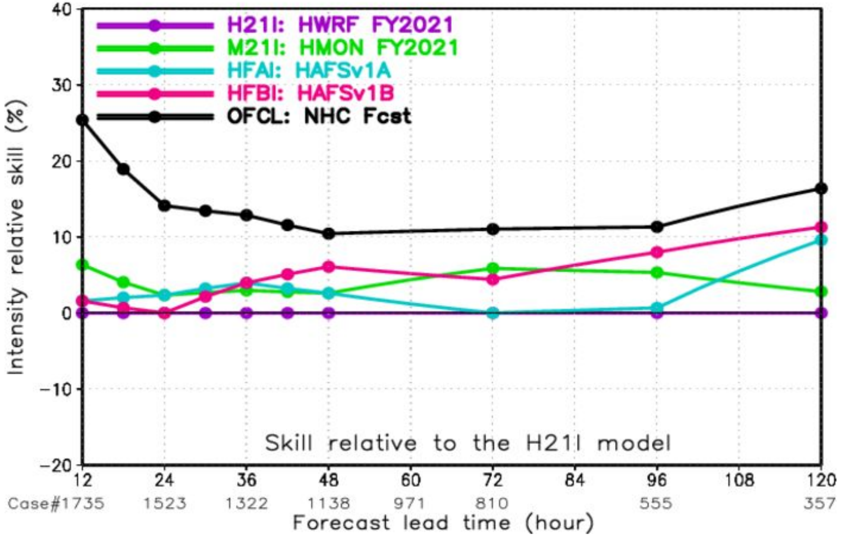
verification algorithm from Mark DeMaria and James Franklin

For RI cycles, HAFS configs. track forecast errors are lower than HWRF/HMON. HFSB intensity forecast errors are behind HWRF/HMON at later forecast hours. HFSA/HFSB improved POD/FAR over HWRF/HMON.

Track/intensity Forecast Skill

NATL+EPAC Cycles





For combined NHC basins, early model results show improvements in both track and intensity forecast skills as compared to H21I at all lead times. ~10% track skill improvements from HFAI, ~7-9% intensity skill improvements from HFBI

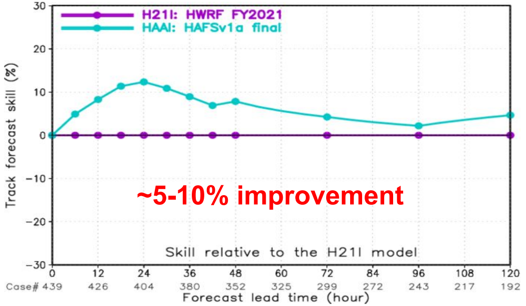
HFSA Verification: JTWC Storms (WPAC, SH and NIO basins for 2021-2022)

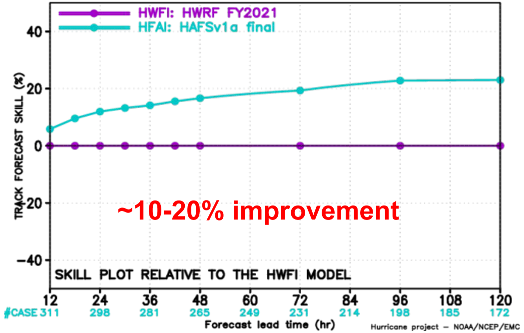
- **H221/H21I: Late/Early of current operational HWRF**
- **HFSA/HFAI: Late/Early of proposed FY23 HAFS-A configuration**
- **Storms included in retrospectives:**
  - **WPAC**: Total 477 cycles with 451 verifiable cycles for selected storms: 2022: 12W, 14W, 16W, 18W, 20W, 23W, 26W, 2021: 06W, 09W, 10W, 16W, 19W, 20W
  - **NIO**: Total 112 cycles with 93 verifiable cycles: 2021-2022 NIO storms
  - **SH**: Total 413 cycles with 311 verifiable cycles: 2022-2023 SH storms, including real time parallel for 11S to 16P

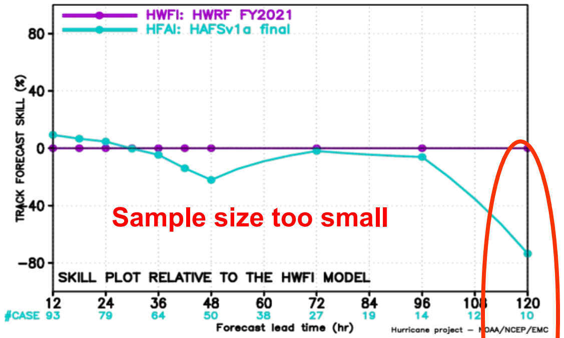
Track/intensity forecast skill: WPAC/NIO/SH basins (2021-2022)
Early Model Verification

WPAC | SH | NIO

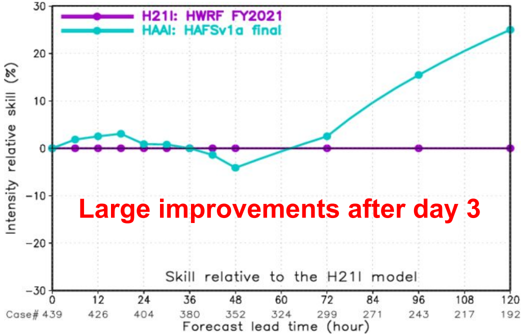
Track

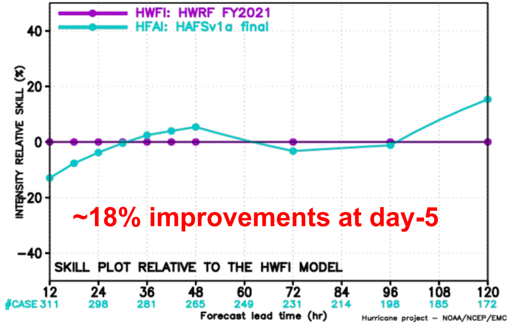


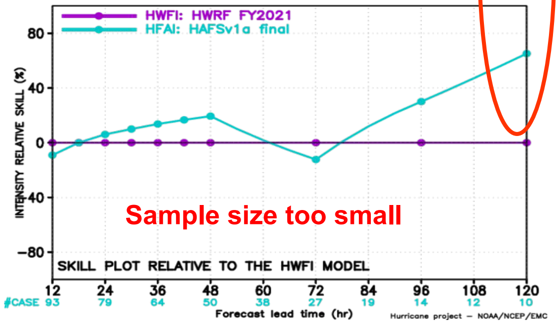




Intensity





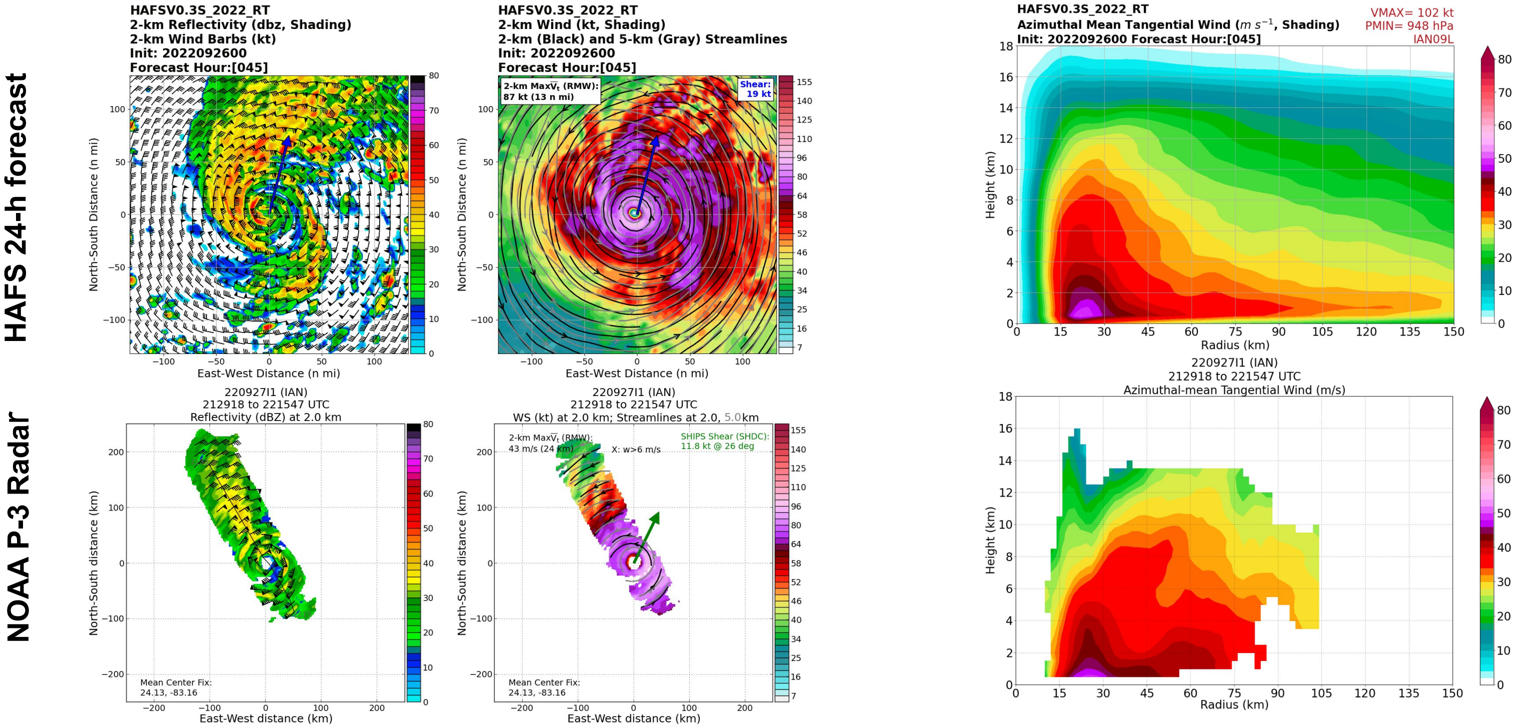


Data Assimilation is turned off for JTWC basins. For WPAC/SH storms, HFSA has improved track skill over HWRF for all lead times. Intensity forecasts are also largely improved especially after Day 3. NIO sample size is small.

Highlights of Case Studies

- Storm structure verification against TDR observations
- Storm-induced cold wake
- Ocean model output verified again Saildrone observations
- Wave model verification

Hurricane Ian: Model/Radar Comparisons for ERC

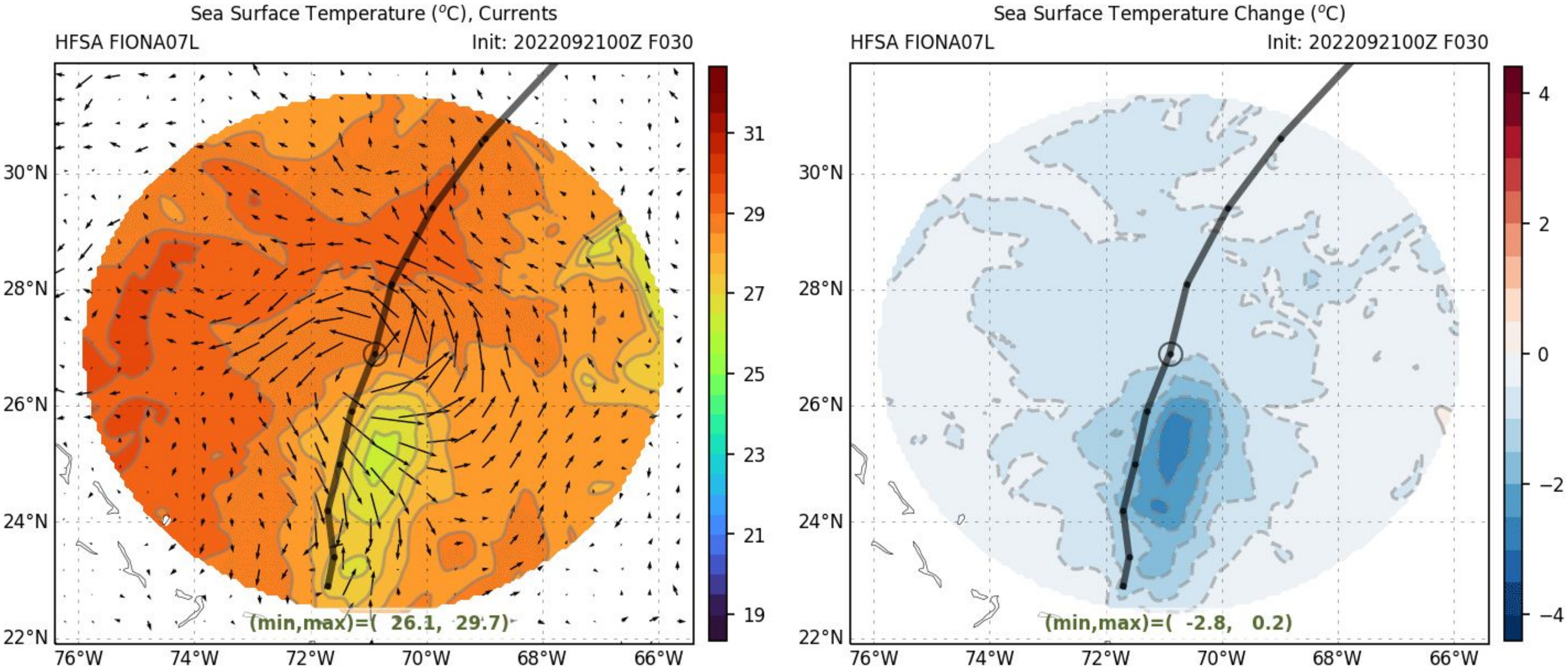


Several cycles of HAFS correctly captured the ERC that occurred near the Keys.

Courtesy of Andrew Hazelton

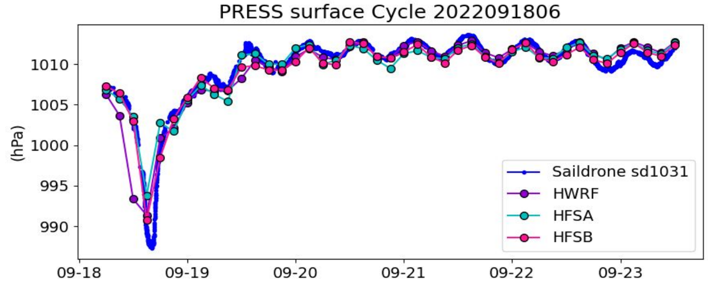
Ocean Response: Hurricane-induced cold wake

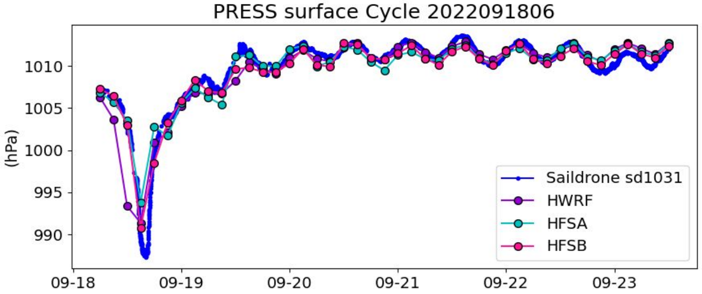
Hurricane Fiona, 20220921 00Z, fcst hour 30 h

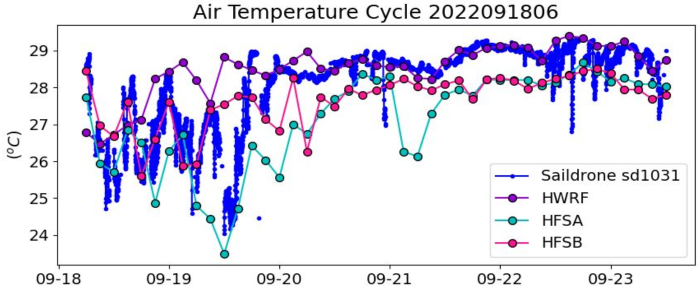


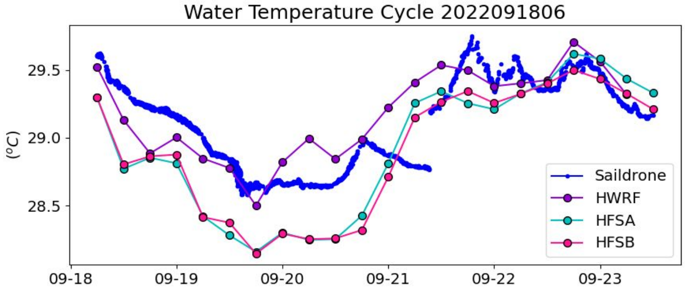
The cold wake induced by Hurricane Fiona track is captured in SST fields from coupled HYCOM.

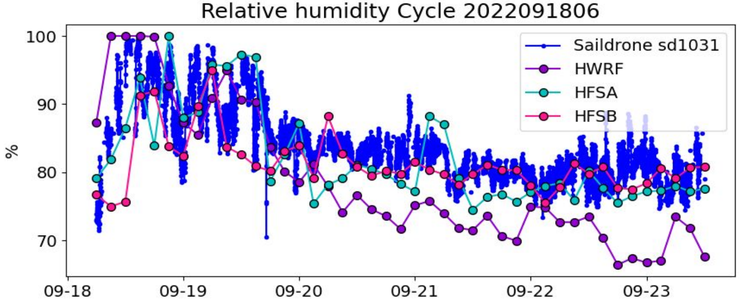
Comparison with Saildrone Data
Hurricane Fiona, 2022091806

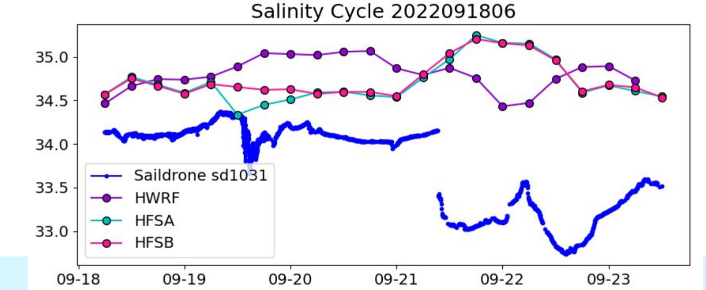






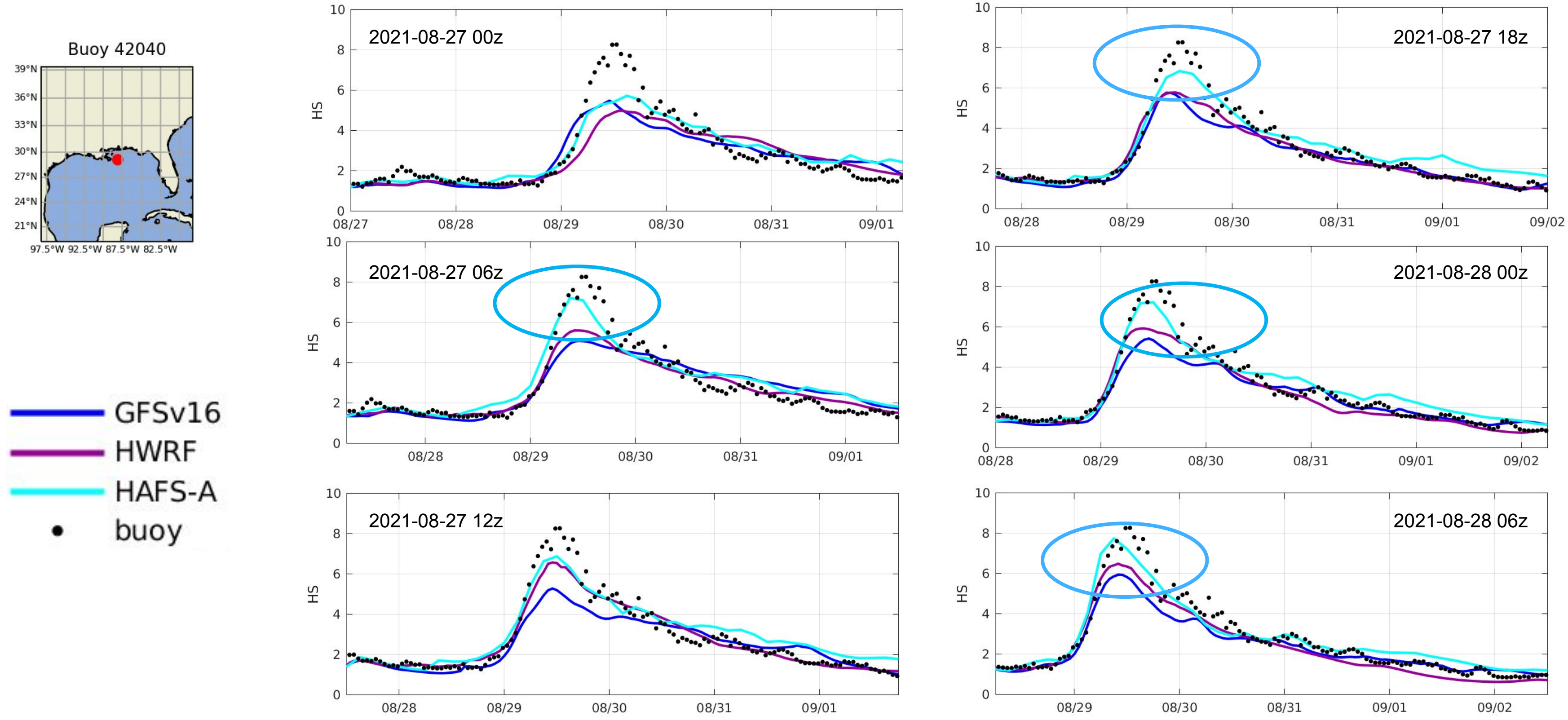






HFSA one-way Coupled WAVEWATCH III Results for Hurricane Ida (09L2021)

Compared with H221 (HWRF) and GFS v16 (Significant Wave Height)



Summary: Improvements for HAFS in Skill Space vs HWRF

Metric	NATL		EPAC	
	HAFS-A	HAFS-B	HAFS-A	HAFS-B
Track Skill	***Mostly improved***	***Improved***	***Improved***	***Improved***
Intensity Skill	Neutral to ***improved***	***Improved***	Neutral to ***improved***	***Mostly improved***
Storm Size Bias	RMW neutral, mixed for 34 kt, ***reduced*** for 50 kt and 64 kt radii	RMW neutral, increased for 34 kt, ***reduced*** for 50 kt and 64 kt radii	***Reduced*** for RMW, 34 kt, 50 kt and 64 kt radii	***Reduced*** for RMW, 34 kt, 50 kt and 64 kt radii
RI Cases	Track errors are ***reduced,*** intensity slightly behind	Track errors are ***reduced***, intensity slightly behind	Track errors are ***reduced***, neutral for intensity	Track errors are ***reduced***, intensity slightly behind
RI Metrics	Slightly behind HWRF	Slightly behind HWRF	***Improved***	***Improved***
P-W relationship	Neutral	Neutral	***Improved***	***Improved***
Waves	Neutral to ***Improved***	N/A	***Improved***	N/A

Negative	Mixed/Neutral	Positive

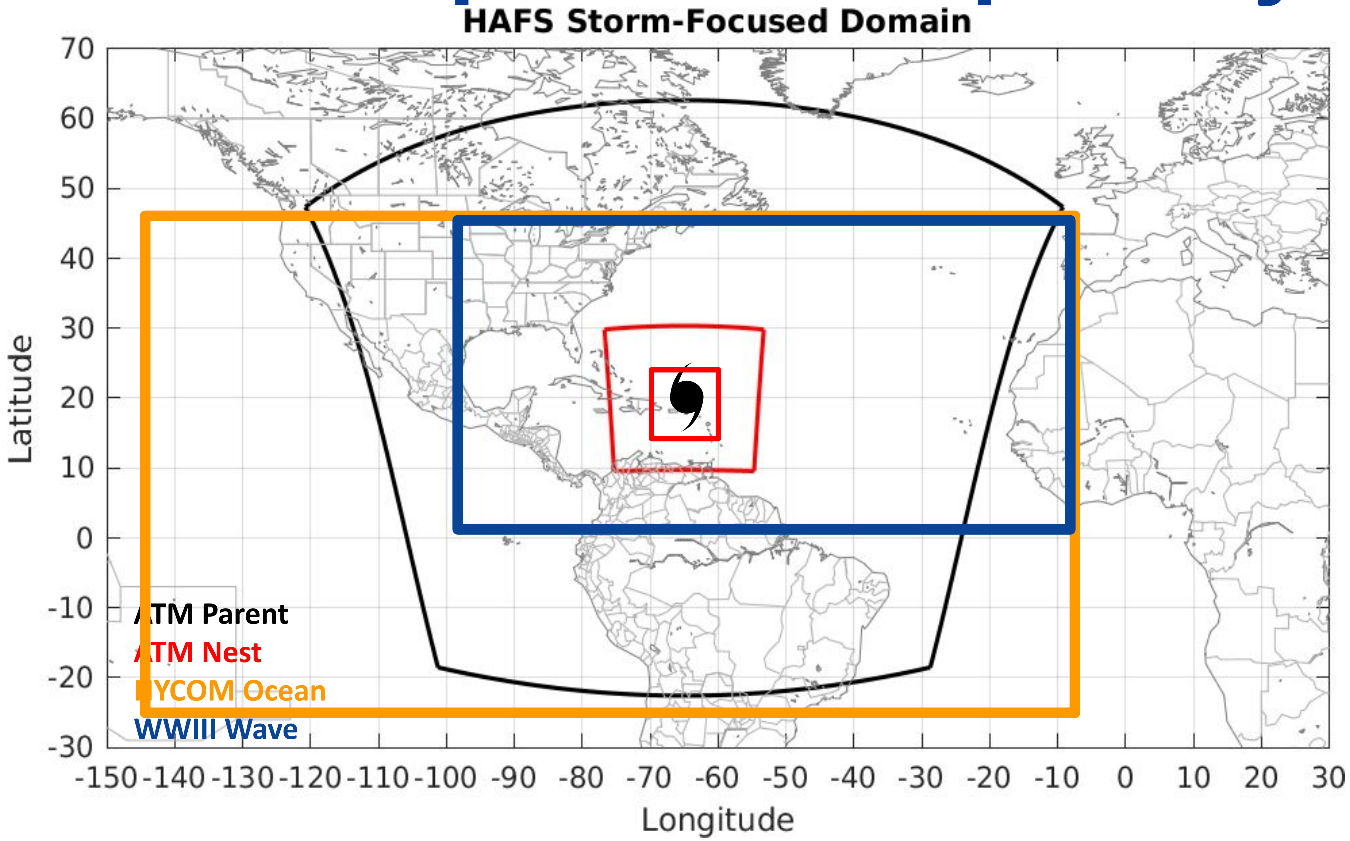
HAFS Development Priorities: after IOC

- **Moving nest**
  - Multiple storms
  - Flexible nesting refinement
  - Mass adjustment for fine topography consistency in blending zones
  - Code optimization
- **Data assimilation**
  - New data ingestion
  - Atmosphere/Ocean coupled DA
  - JEDI transition
- **Physics**
  - PBL for TC application
  - NOAH-MP transition and evaluation
  - CP upgrade, transition, & evaluation
  - Microphysics parameterization upgrade
- **Ocean and wave model transition**
  - HYCOM to MOM6 transition
- **Ensemble capabilities**
  - Stochastic physics ensemble capability
  - Ensemble on Cloud
- **Products**
  - Ensemble products
  - Product fidelities
  - 7-day forecast products

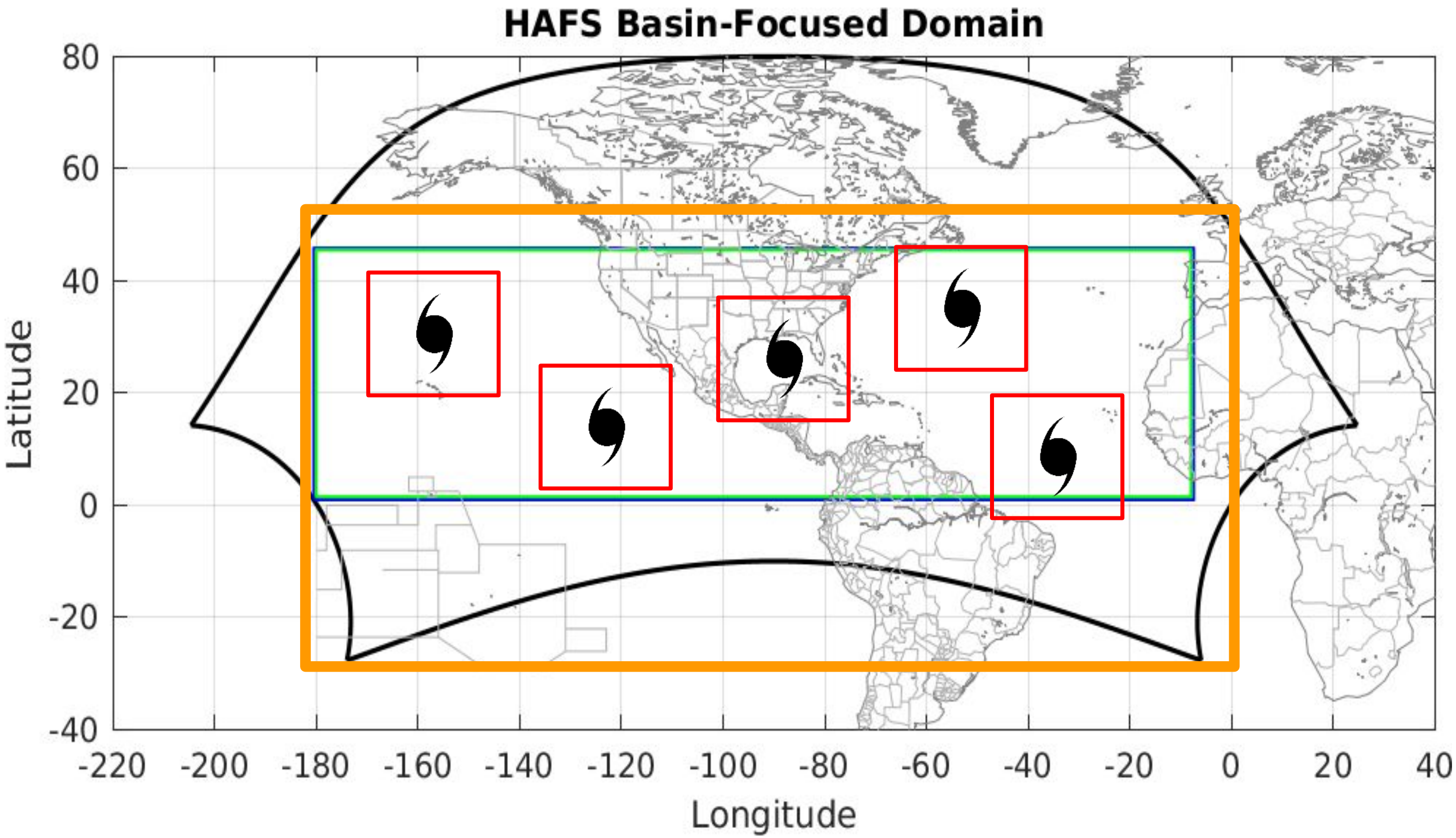
HAFS Development Priorities: future innovation

- **Moving nest**
  - Global moving nest
  - Telescopic moving nest for LES capability
- **Data assimilation**
  - AI/ML technology for DA
  - Atmosphere/Ocean coupled DA: strongly vs. weakly
  - All-sky radiance: CRTM vs. RRTMG
  - New DA methodology: scale-aware, particle filter, etc.
  - DA and physics parameterizations interaction
- **Observations**
  - New observations
  - Observation strategy
- **Ensemble**
  - Initial condition perturbation
  - Ensemble for DA
  - Ensemble on Cloud
- **Physics**
  - AI/ML for physics parameterizations
  - Sub-kilometer physics
  - Physics interactions
- **Ocean-Wave-Atmosphere coupling**
  - Three-way coupling
  - Coupling strategy
  - Ocean and wave model physics
  - Ocean and wave model initialization

Telescopic Nest Capability



Multiple Moving Nest Capability



Summary

- Target yearly upgrade using latest research
- Convection-resolving model resolutions
- Multimember HAFS ensemble based probabilistic forecasts
- Merge Hurricane forecast system within GFS
- Develop LES capability for dynamics and physics development
- Future release to the UFS community

Questions?