

# Review of NOAA's Operational Hurricane Prediction Systems and HAFS



NATIONAL  
WEATHER  
SERVICE

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HFIP/NCAS-M HAFS Summer Colloquium  
28-30 May 2024





# Outline



- **Overview of NOAA's operational hurricane prediction systems**



- Evolution of the legacy operational hurricane prediction model systems: HWRF and HMON



- Development of the new generation of operational hurricane prediction Model: HAFS

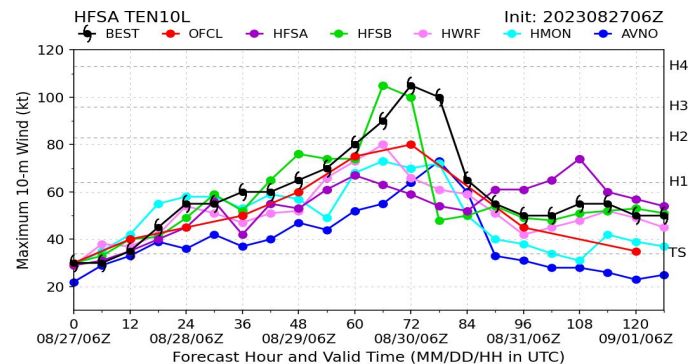
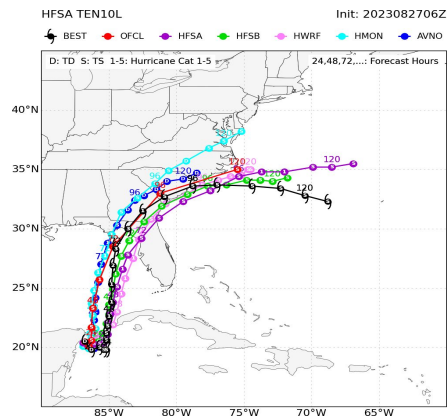


- Future Plans



# Basic Info of NOAA's Operational Hurricane Modeling Systems

- There are four operational hurricane prediction models in NOAA's modeling suites:
  - Hurricane Weather Research and Forecasting (HWRF)\*
  - Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic model (HMON)\*
  - Hurricane Analysis and Forecast System (HAFS), two configurations, HFSA and HFSB
- The systems are on-demand forecast systems that are run at the requests from NHC, CPHC, and JTWC whenever there are TCs in any global oceanic basins.
- The systems provide 3-hourly **TC track and intensity forecast guidance** out to 5-days initiated at each synoptic times (0000 UTC, 0600 UTC, 1200 UTC, 1800 UTC)



<https://www.emc.ncep.noaa.gov/hurricane/HFSA/index.php>

\* subsetting on Nov. 30, 2024



# Hurricane Prediction System

## Input files

TCVital  
Used for TC relocation

RTOFS  
Used to generate ocean IC

GFS Analysis & 0-129hr fcst  
Used to generate atm/wave  
IC/BC

Prior GDAS forecasts at  
03,06,09 h  
Used to FGAT files

80 GDAS member Ens.  
forecasts at 03,06,09 h  
Used for 4DEnVAR DA

## Components

Pre-process

Vortex Initialization

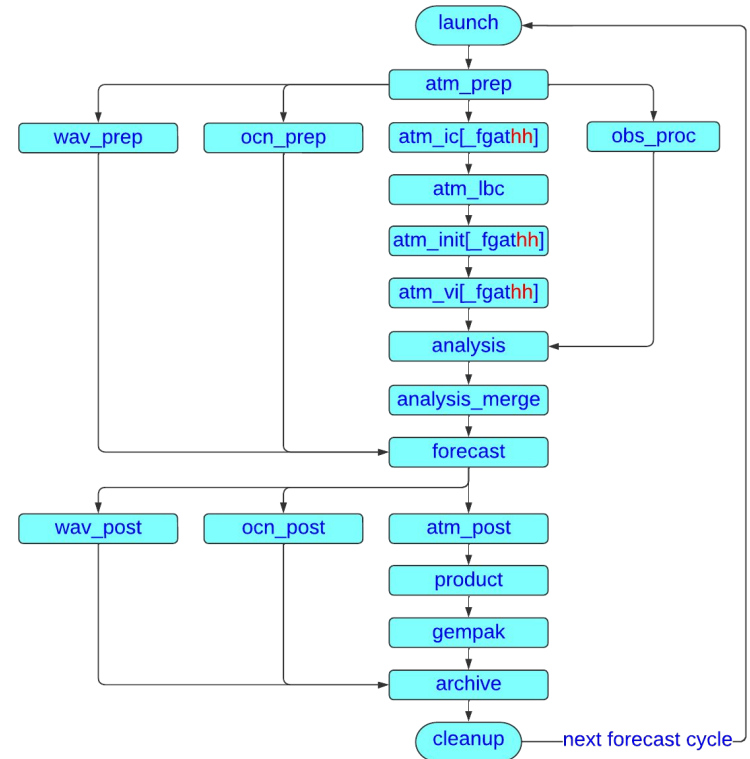
Data Assimilation

Forecast Systems:  
Atms/Ocean/Wave  
Coupled through  
CMEPS

Post-process:  
Grid/Tracker

Archive

## Flowchart





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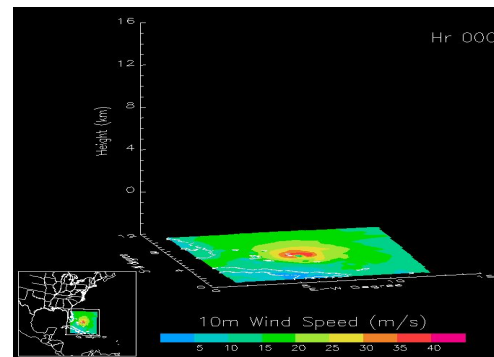
- Future Plans



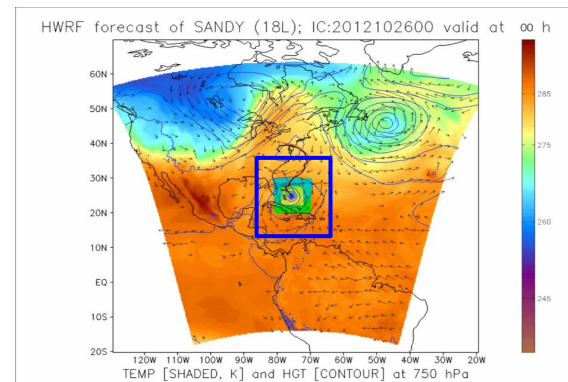
# Milestones of NOAA's Legacy Operational Hurricane Models

- **2007: HWRF Initial Operational Capability; 27/9 km, L43**; Coupled with Princeton Ocean Model (POM)
- 2010: Assimilate clear-sky radiation in the hurricane environment
- **2012: Introduce triple nest; first time operational cloud-permitting resolution; 27/9/3 km**
- **2013: Assimilate P3 Tail Doppler Radar in inner-core**
- 2014: Increase vertical resolution from **L43 to L61** and model top from 50 hPa to **2 hPa** for NHC basins **POM to MPIPOM**
- **2015: Increase resolution to 18/6/2 km for NHC basins; TC forecasts for JTWC basins; Flow-dependent covariance**
- 2016: Clear-sky radiation DA for both nests
- **2017: Increase atmospheric vertical level to L75 with 10 hPa model top for NHC basins; Increase ocean model vertical levels L24 to 41; Self-cycled DA; GFDL sunset, replaced by HMON**
- 2018: Unified resolutions for global basins: **13.5/4.5/1.5km, L75**
- 2019: Adaptive observation error for recon; Spectral filter for inner-core increment
- 2020: RTOFS for ocean init globally; NEXRAD radial wind assimilation

Continuously Upgrades of Physics Schemes

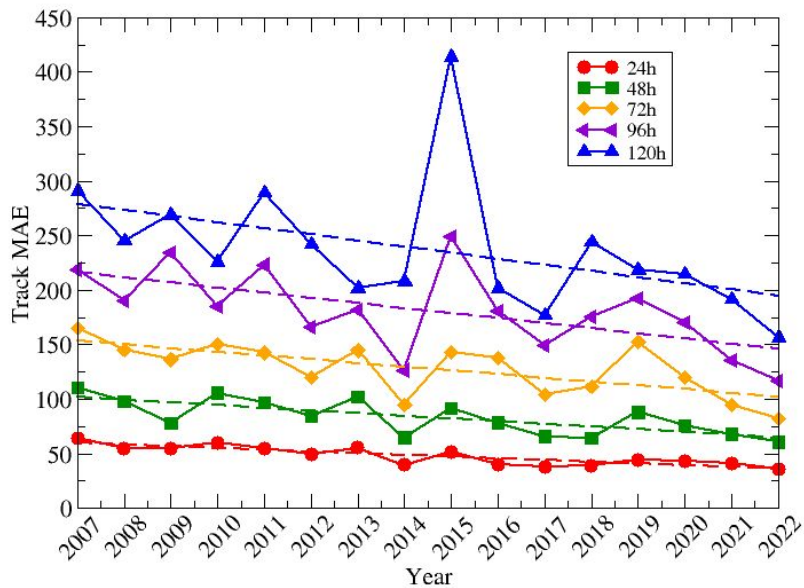


**Telescopic domain: 27km: 75x75°; 9km  
~11x10° 3km inner-most nest 6x5.5°**

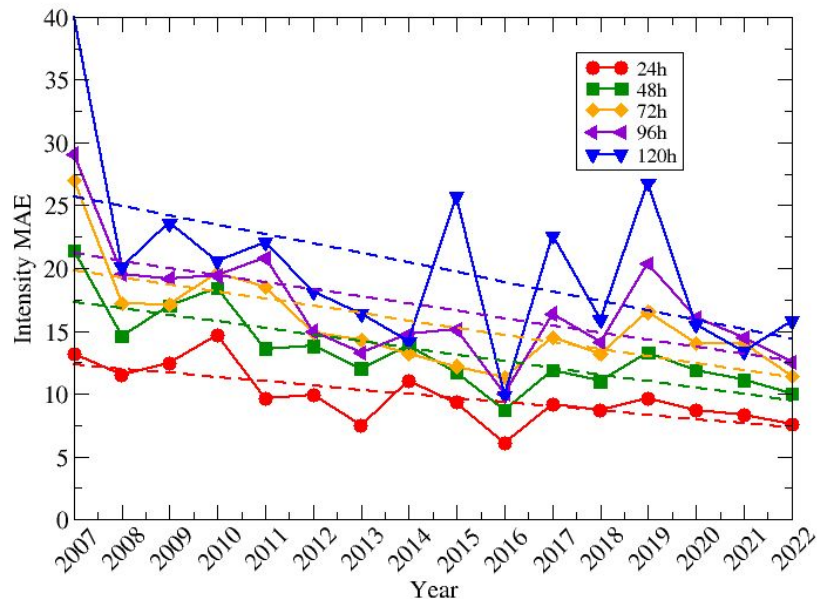


# HWRF Track/Intensity Forecast Error Trend

HWRF Performance: Lead Time Error Evaluation 2007-2022



HWRF Performance: Lead Time Evaluation 2007-2022





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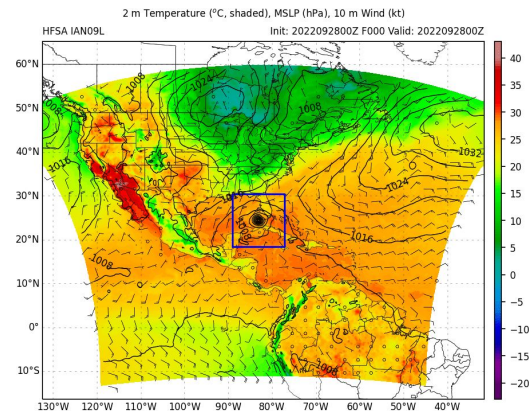
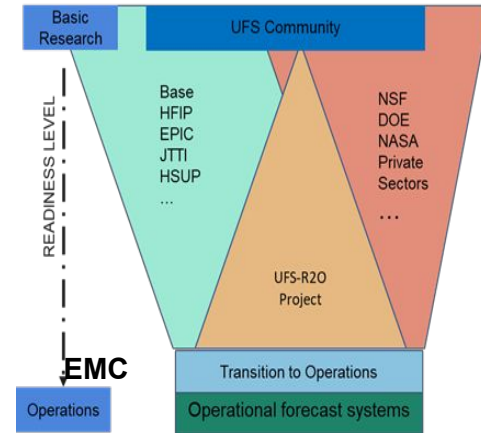
- Future Plans





# Operational HAFS (Hurricane Analysis and Forecast System)

- HAFS is one of the UFS-R20 projects under UFS, focusing on transitioning tropical cyclone modeling research to operation
- As a result of multi-year collaboration among NOAA agencies, research and operational communities, HAFSv1 was implemented operationally on June 27, 2023, providing improved forecast skills compared HWRf
- HAFSv1 is the first major UFS based regional operational system, consisting of
  - FV3 based dyn-core
  - Cloud-allowing high resolution moving nest
  - Improved vortex initialization
  - 4D-EnVar inner-core data assimilation with high res. recon mission
  - TC-specific model physics
  - CEMPS based ocean/wave coupling
  - Two-way coupled to ocean models in all global basins
  - One-way coupled to wave model (WW3) in NHC basins



# Evolution of HAFS Development and Operational Transition

- 2018: HFIP Annual Meeting; HAFS development planned and started
- 2019: **~3-km resolution, L75**; two configs: regional standalone (HAFS-A), global-nesting (HAFS-B); cold start from GFS, no ocean coupling, no vortex initialization, no data assimilation
- 2020: Similar resolutions as 2019, one regional with **ESG grid**, one global-nest, **HYCOM ocean coupling**
- 2021: Similar resolutions as 2020, ESMF/CMEPS based HYCOM ocean coupling, **Data Assimilation**
- 2022: **Regional moving-nesting (~6/2km, L81), VI, inner-core DA, two model physics suites**
- **2023: HAFSv1 Initial Operational Capability (IOC) 06/27/2023**
- **2024: HAFSv2 upgrade and operational implementation (07/16/2024, Planned)**

# Scope of HAFS v1.0 Upgrades

## System and Infrastructure Upgrades

- FV3 based dyn-core
- CCPP based physics suites
- Moving nest with ESG grid in FV3 framework
- Model Efficiency
- Workflow

## Vortex Initialization Improvement

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

## Data Assimilation Improvement

- 3DEnVar to 4DEnVar with GDAS ensembles
- DA is turned on for CPAC storms
- Leverage obs. used in GFS
- Additional meso-scale obs.

## Post-process

- Latest version of UPP
- Upgraded GFDL Tracker

## Model Physics Advancement

- Microphysics (GFDL/Thompson vs Ferrier–Aligo)
- Upgraded TKE-EDMF GFS 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

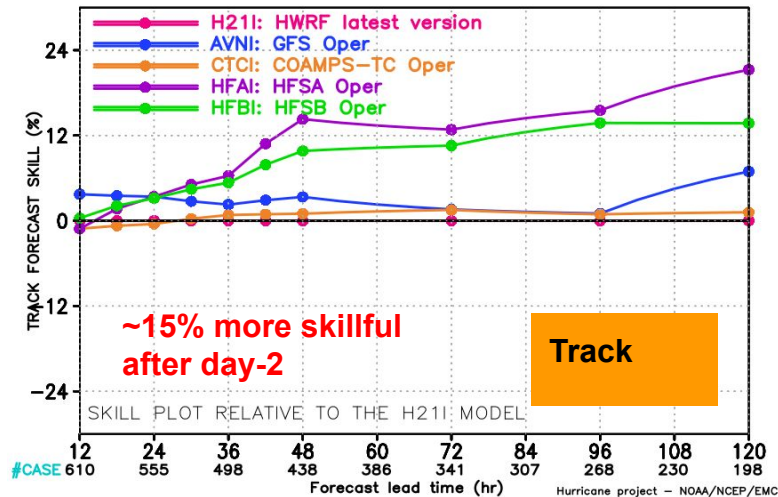
## Ocean/Wave Coupling

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

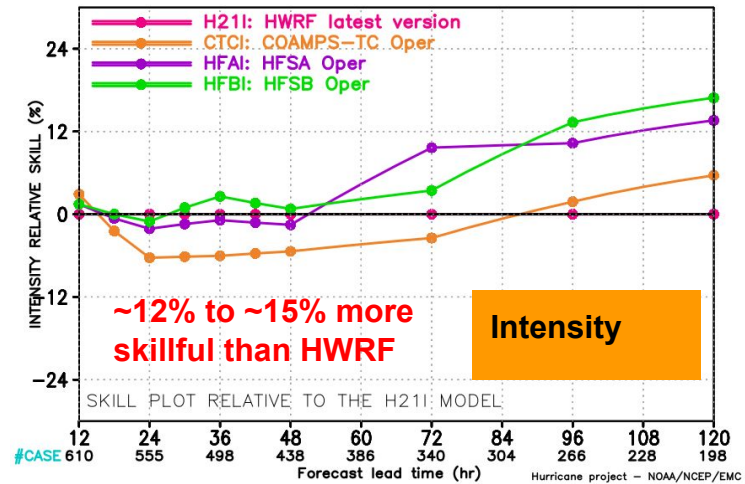
Items in red: Innovations implemented for the first time in Hurricane model operations

# HAFSv1 Performance in 2023 Hurricane Season for NHC Basins

MODEL FORECAST – TRACK FORECAST SKILL (%) STATISTICS  
VERIFICATION FOR NHC BASINS 2023



MODEL FORECAST – INTENSITY RELATIVE SKILL (%) STATISTICS  
VERIFICATION FOR NHC BASINS 2023



# Scope of HAFS v2.0 Upgrades

## System and Infrastructure Upgrades

- Latest version of UFS, HAFSv2 final scientific configuration freeze on 20240208
- Increase horizontal resolution from 2 to 1.8 km
- Reduce model time step from 90 to 72s
- Updated horizontal advection options
- Improved model stability and runtime efficiency

## Data Assimilation Improvement

- Ingest new high-resolution GOES-R mesoscale AMVs
- Scale-Dependent Localization for innercore DA
- Refine GPS RO (Radio Occultation) DA

## Vortex Initialization Improvement

- Enhance vortex initialization to cycle hydrometeor variables and vertical velocity
- Update composite vortex and reduce warm-cycling v<sub>max</sub> threshold from 50 to 40 kt

## Model Physics Advancement

- Upgrade Thompson MP with bug fixes
- Thompson/GFDL Microphysics
- Update TKE EDMF PBL and SASAS CP schemes with vertical wind shear impacts
- Reduce radiation time step from 1800 to 720s
- Update CO2 fix files

## Ocean/Wave Coupling

- MOM6 ocean model coupling
- CMEPS with inline-CDEPS coupling

## Post-processing

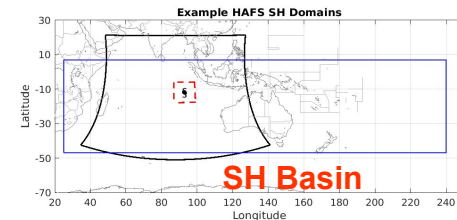
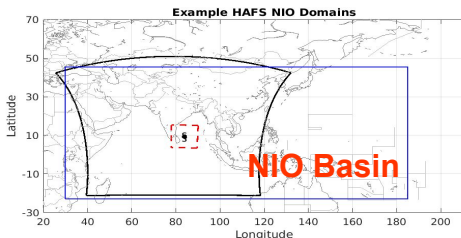
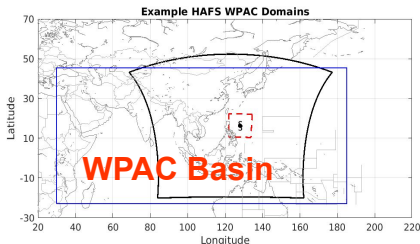
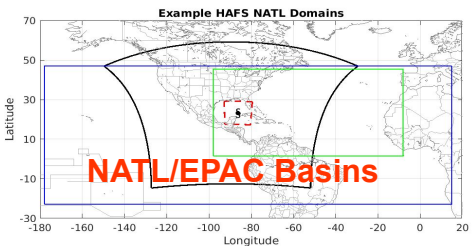
- Upgrade GFDL Tracker

Blue: HFSA only, Green: HFSA only

Black: Both HFSA and HFSA

# Two Proposed Configurations for HAFS v2

HAFSv2.0	Domain & Dynamics	Resolution	DA/VI	Ocean/Wave Coupling	Physics	Basins
<b>HFSA</b>	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	<b>suite-1</b>	All global Basins NHC/CPHC/JTWC Max 7 Storms
<b>HF SB</b>	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	<b>suite-2</b>	NHC/CPHC Max 5 Storms



atmospheric domain, ocean domain, wave domain

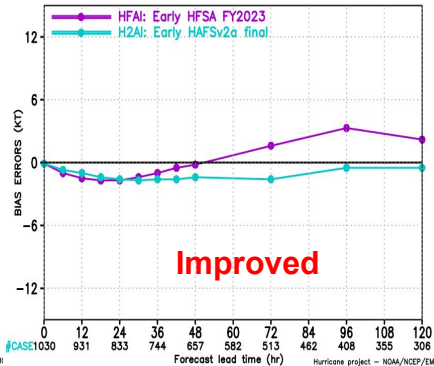
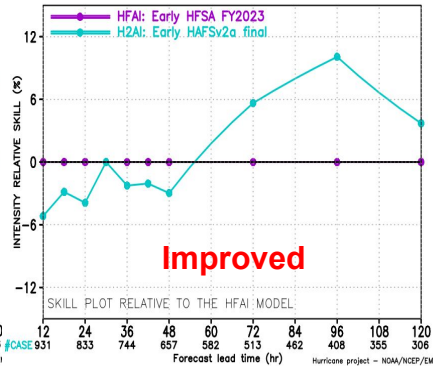
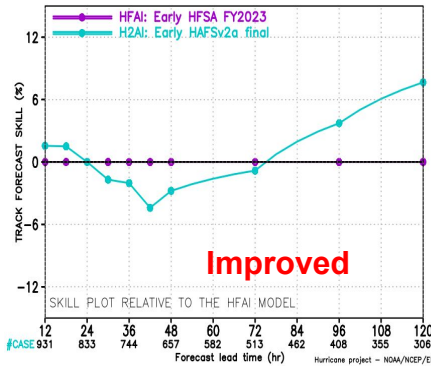
# Early Model Verification, NATL 2021-2023

## Track Skill

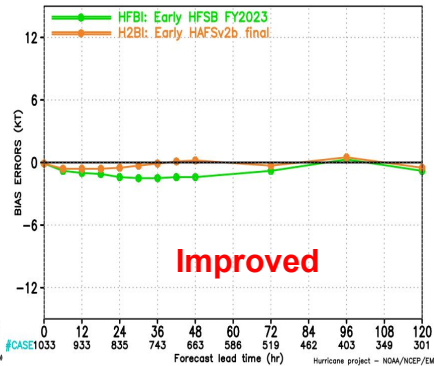
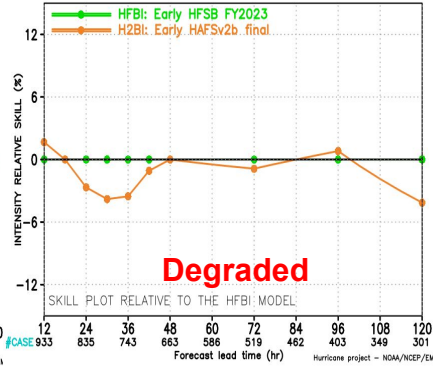
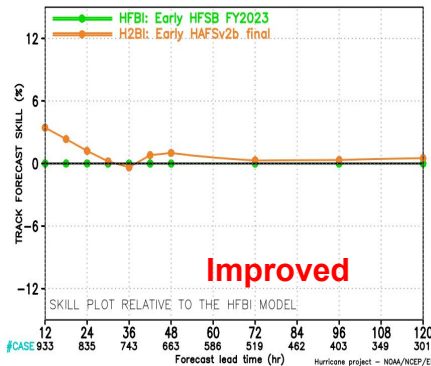
## Vmax Skill

## Vmax Bias

HFSA



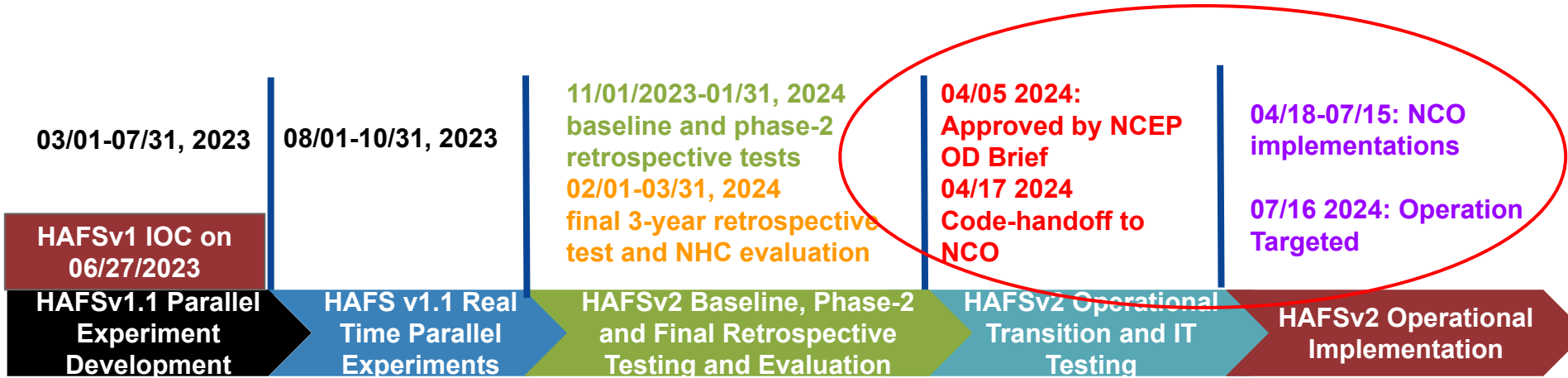
HFSB



- **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**



# HAFSv2 Development and Operational Transition Timeline





# Components the HAFS Modeling system

- Pre-processing
- Vortex Initialization
- Data assimilation system based on community GSI
- Atmospheric Model: Dynamical Core and physics
- Ocean Initialization, Ocean Models
- Wave Initialization, Wave model
- Community Mediator for Earth Prediction System (CMEPS)
- Unified Post-Processing (UPP)
- GFDL Vortex tracker
- Advanced applications

# Options of HAFS Pre-processing System

## Start-run

- Storm-triggered (on-demand)
- Continuously cycling (w/ or w/o storms)

## Domains

- Basin-focused regional
- Basin-focused global-nesting
- Storm-focused single regional
- Storm-focused regional with nest
  - Moving
  - Static
- Basin-scale multiple nests

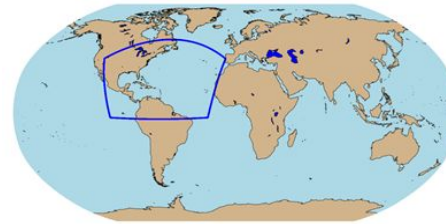
## Grids

- Extended Schmidt Gnomonic (ESG) grids
- Regular Schmidt Gnomonic grids

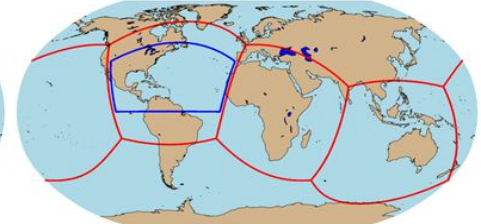
## GFS/GDAS input format

- NetCDF for IC Grib2 for LBC
- NetCDF for both IC/LBC
- Grib2 files for both IC/LBC

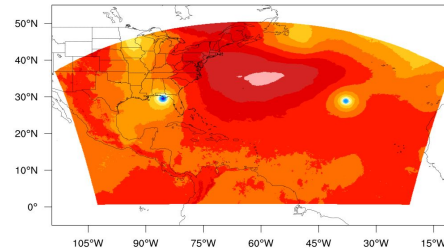
regional



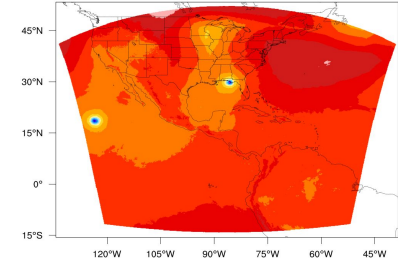
global-nested



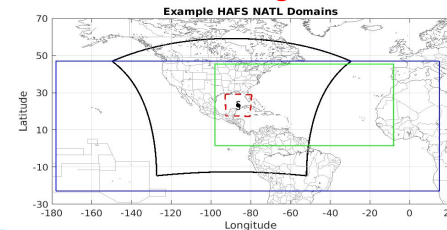
basin-focused



storm-focused



With moving nest



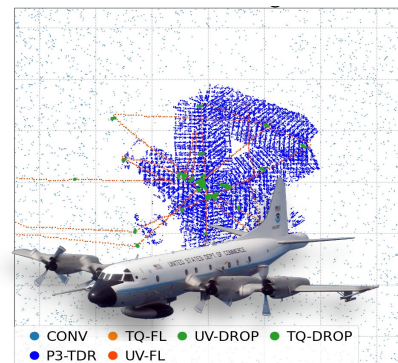
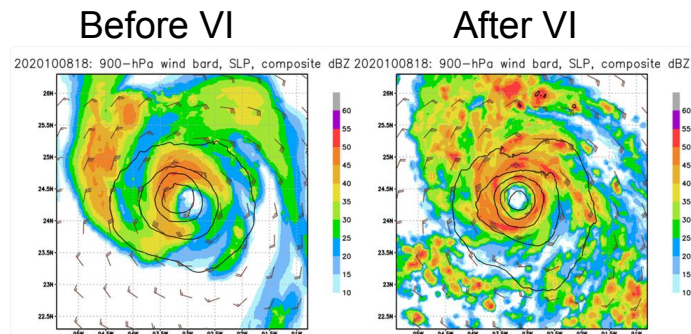
# Vortex Initialization and Data assimilation Options

## Vortex Initialization

- Vortex initialization **on** or off
- **Warm-cycle threshold specification**
- **Hydrometeor/vertical velocity relocation**

## Data assimilation system based on community GSI

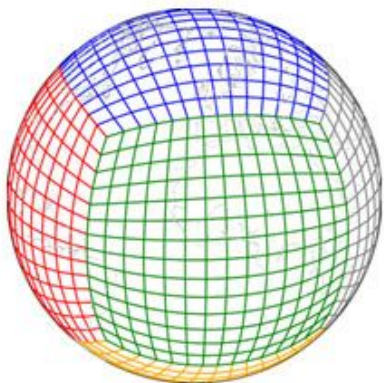
- DA domain
  - Parent, **Nest**, Parent and nest
- **First Guess at Appropriate Time (FGAT)**
- Background
  - 3DVar, 3DEnVar, **4DEnvar**
  - **GDAS**, HAFS ensembles
- Dual-resolution self-cycled DA
- Incremental Analysis Update (IAU)
- Scale- and Variable- Dependent Localization (**SDL/VDL**)



# HAFS Atmospheric Model

## Finite-Volume Cubed-Sphere Dynamical Core (FV3)

- Horizontal/vertical resolutions
- Time step
- Dynamic parameters



## Physics Scheme Options (for NATL Basin)

	Suite 1 (HFSA)	Suite 2 (HFSA)
Land/ocean Surface	NOAH LSM VIIRS veg type	NOAH LSM VIIRS veg type
Surface Layer	GFS, HWRF TC-specific sea surface roughnesses	GFS, HWRF TC-specific sea surface roughnesses
Boundary Layer	Sa-TKE-EDMF sfc_rlm=1 tc_pbl=0 elmx/rlmx=250 (nest)	Sa-TKE-EDMF: sfc_rlm=0 tc_pbl=1 elmx/rlmx=75 (nest)
Microphysics	Thompson, dt_inner=45s (AL) GFDL MPv1 (EP)	Thompson, dt_inner=36s
Radiation	RRTMG Calling frequency 900 s	RRTMG Calling frequency 720 s
Cumulus convection (deep & shallow)	sa-SAS progsigma=false (AL), true (EP) entrainment: clam_deep=0.15	sa-SAS progsigma=false (AL), true (EP) entrainment: clam_deep=0.1
Gravity wave drag	Improved UGWPv1 (orographic on/convective off)	Improved UGWPv1 (orographic on/convective off)

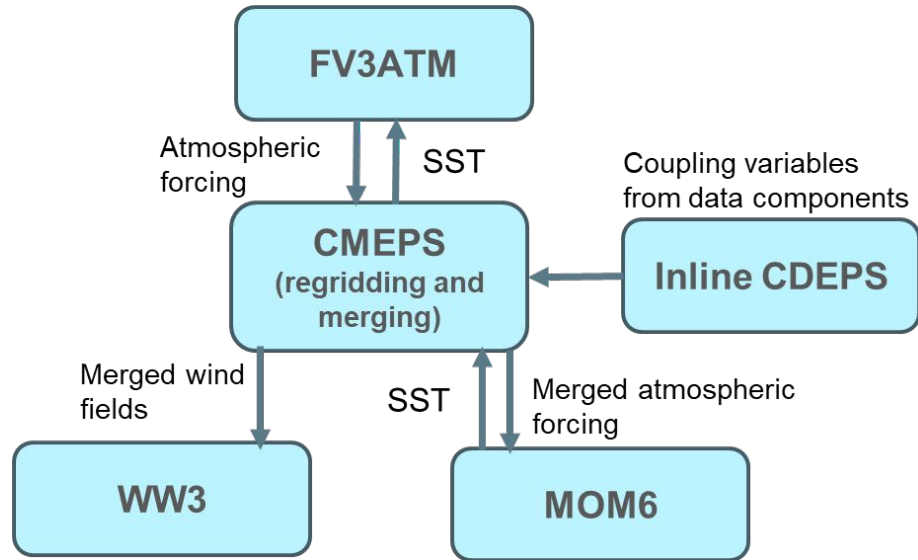
# Ocean/Wave model Coupling

## Ocean Initialization, Ocean Models

- MOM6 (HAFS-A)
- HYCOM (HAFS-B)

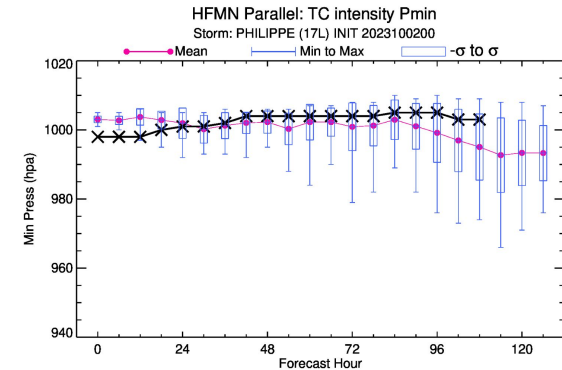
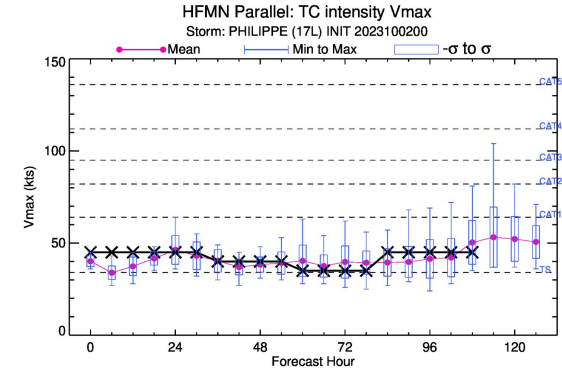
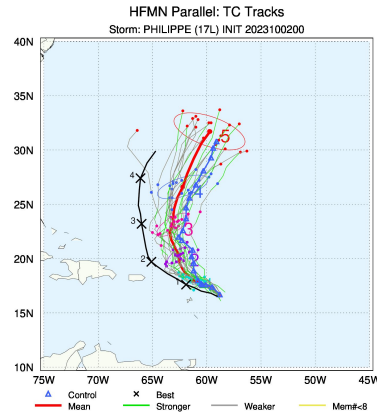
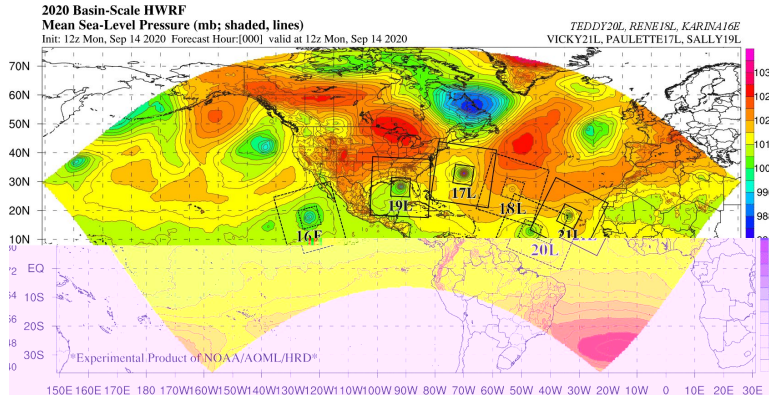
## Wave model: *Wave Watch III*

## Community Mediator for Earth Prediction System (CMEPS)



# Advanced Applications

- Basin-scale multiple storms
- Hurricane ensemble prediction
- Idealized hurricane simulation



# What to expect from practical hands-on sessions

## Students will learn

- How to obtain and build the HAFS software
- How to initialize HAFS model, pre-process, vortex initialization, and DA
- How to configure and run HAFS modeling system (uncoupled and coupled; w/ and w/o moving nest; cold/warm start, different physics options)
- How to post-process HAFS model output
- How to generate track forecast files, run graphic package



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- **Future Plans**





# HAFS Development Priorities: Future Innovation

- **Moving nest**

- Multiple moving nests in basin-scale and global domain
- Telescopic moving nest with LES capability

- **Data assimilation**

- Transition to JEDI based DA
- AI/ML technology for DA
- Atmosphere/Ocean coupled DA: strongly vs. weakly
- All-sky radiance
- New DA methodology: fully scale-aware, particle filter, etc.
- DA and physics parameterizations interaction

- **Observations**

- New observations
- Higher spatial and temporal observation

- **Products**

- Ensemble products
- 7-day forecast products

- **Physics**

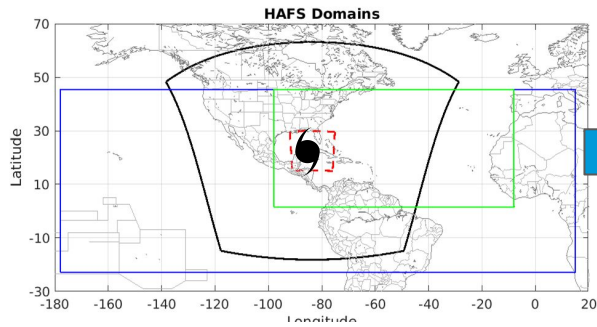
- AI/ML and physics parameterizations
- Sub-kilometer physics
- Scale-aware and unified physics package

- **Ocean-Wave-Atmosphere coupling**

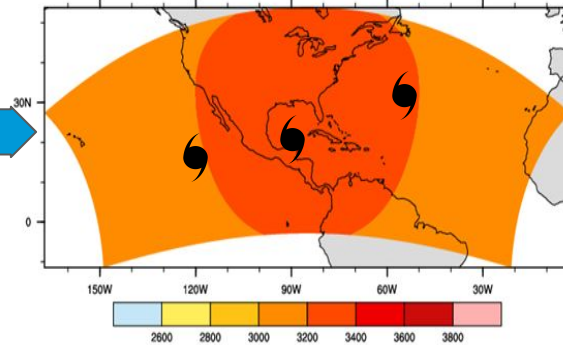
- Three-way coupling
- Coupling strategy
- Ocean and wave model physics
- Ocean and wave model initialization

# Future Plan for Hurricane Modeling System

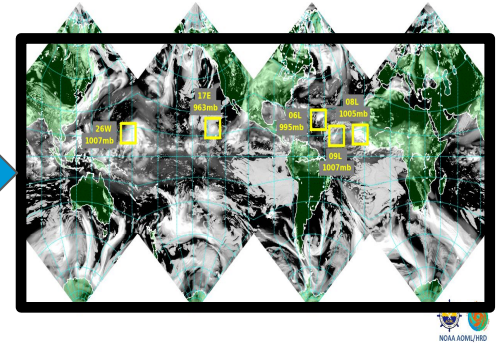
## Annual Upgrade after IOC



**Storm-centric**



**Basin domain**



**Multiple moving nests in GFS**