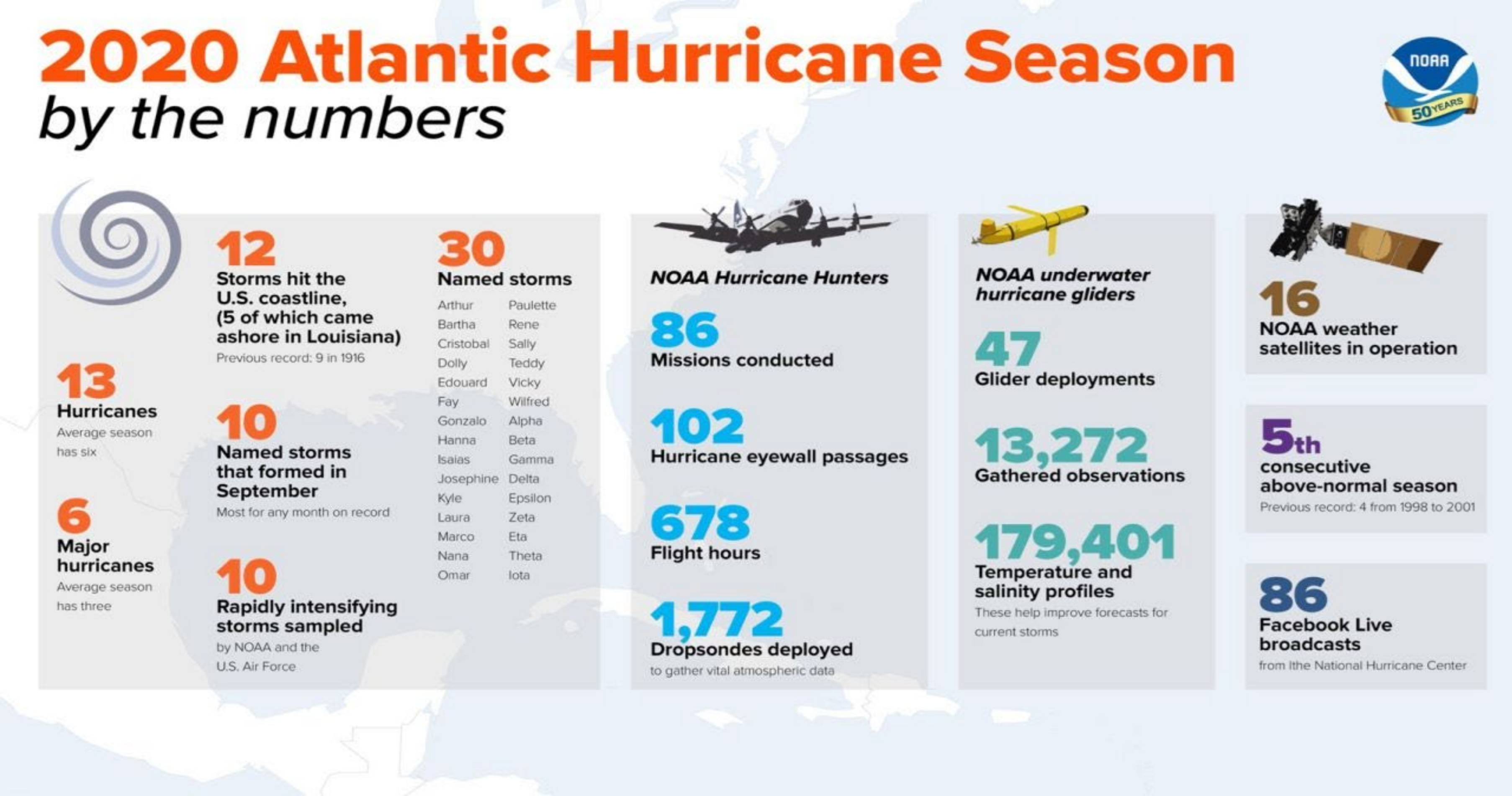
Hurricane Analysis and Forecast System (HAFS): A Unified Forecast System Hurricane Application

Avichal Mehra[1] and Xuejin Zhang[2]

[1]NWS/NCEP/EMC, [2]OAR/AOML/HRD

(with inputs from the EMC Hurricane team and our active collaborators at AOML, DTC, NCAR, NHC, GFDL, ESRL, FIU, OU, AER and others)

UFS Seminar, 3rd December 2020



2020 Atlantic Hurricane Season

by the numbers

13
Hurricanes
Average season has six

6
Major hurricanes
Average season has three

12
Storms hit the U.S. coastline, (5 of which came ashore in Louisiana)
Previous record: 9 in 1916

10
Named storms that formed in September
Most for any month on record

10
Rapidly intensifying storms sampled
by NOAA and the U.S. Air Force

30
Named storms

Arthur
Bartha
Cristobal
Dolly
Edouard
Fay
Gonzalo
Hanna
Isaias
Josephine
Kyle
Laura
Marco
Nana
Omar
Paulette
Rene
Sally
Teddy
Vicky
Wilfred
Alpha
Beta
Gamma
Delta
Epsilon
Zeta
Eta
Theta
Iota

NOAA Hurricane Hunters

86
Missions conducted

102
Hurricane eyewall passages

678
Flight hours

1,772
Dropsondes deployed
to gather vital atmospheric data

NOAA underwater hurricane gliders

47
Glider deployments

13,272
Gathered observations

179,401
Temperature and salinity profiles
These help improve forecasts for current storms

16
NOAA weather satellites in operation

5th
consecutive above-normal season
Previous record: 4 from 1998 to 2001

86
Facebook Live broadcasts
from Ithe National Hurricane Center

Hurricane Analysis and Forecast System (HAFS): A collaborative Project in UFS Framework

07 DTC

06 OFCM/AOC

05 ESRL/NESII

04 ESRL/GSD

NCEP/EMC 01

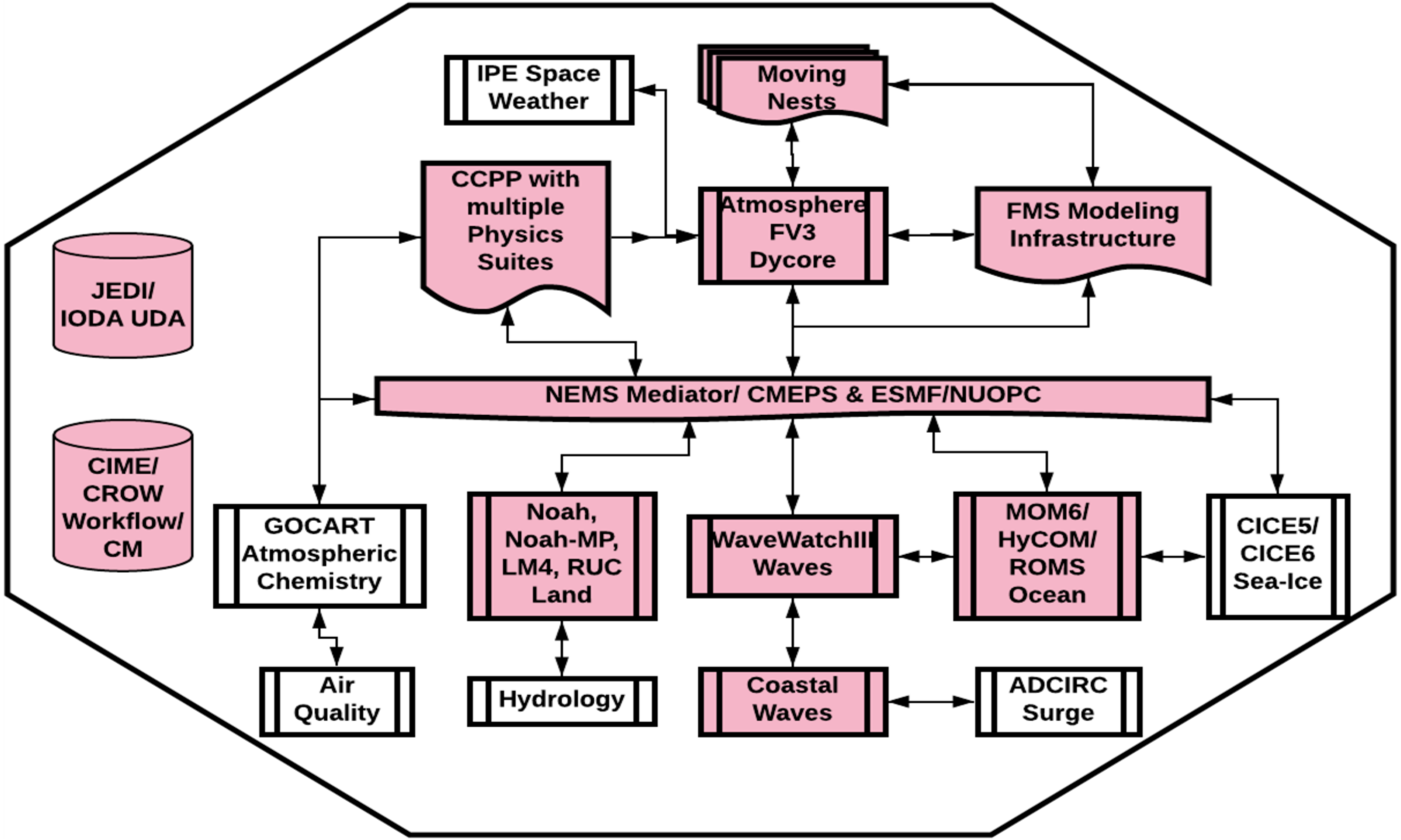
AOML/HRD 02

GFDL 03

Outline

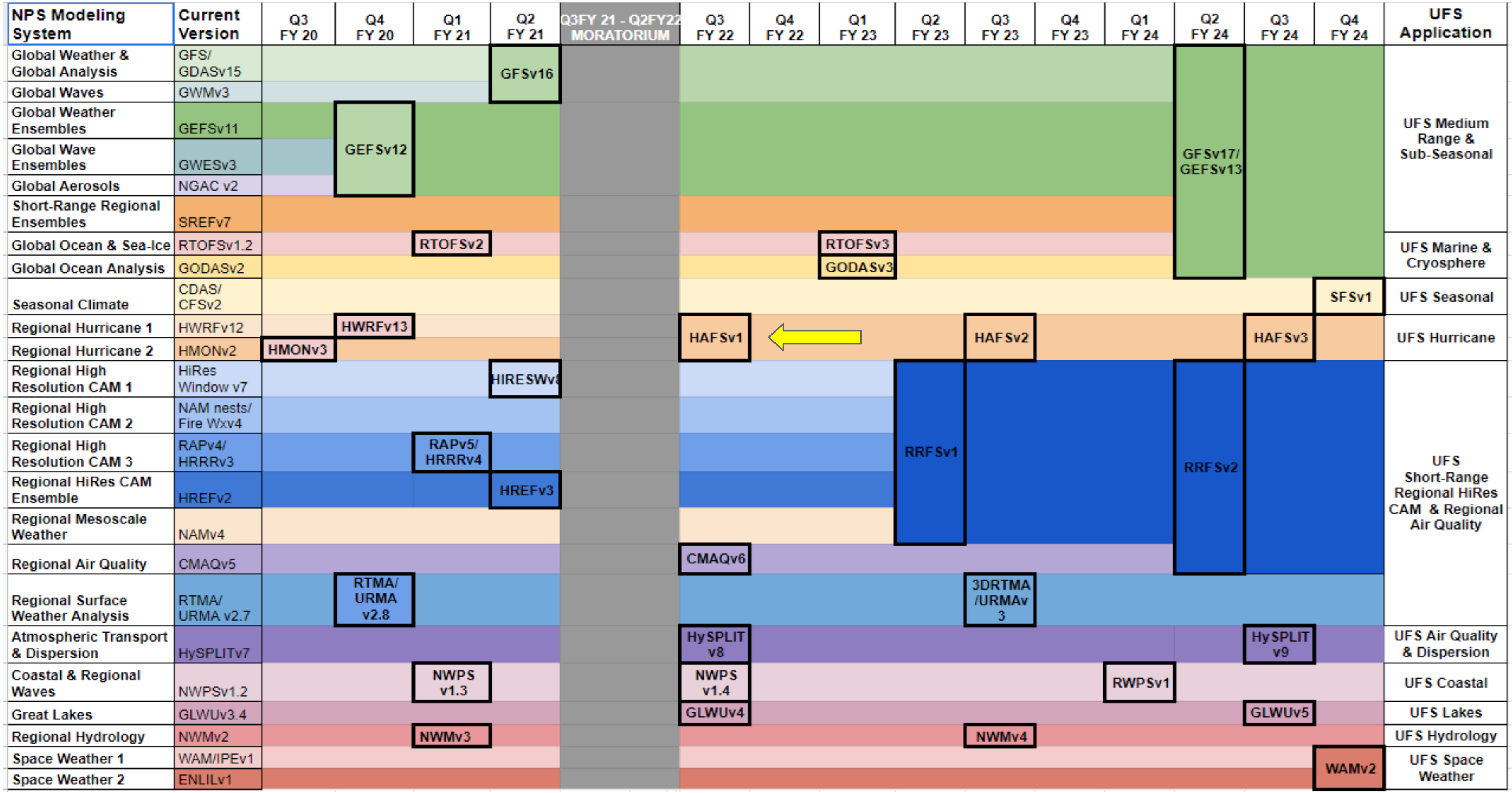
- HAFS – UFS Hurricane Application
- HAFS – Strategy and Science Objectives
- HAFS – Accomplishments in Years 1 & 2
- HAFS – Targeted Initial Operational Configurations
- HAFS – Ongoing Developments and Future Plans

UFS Hurricane Application (HAFS)



Ongoing Efforts at EMC Towards Simplified Production Suite

Modeling System	Current Status	Proposed Plans in the UFS Context
Global Deterministic	FY19: Transition FV3GFS into operations	Advancement of NGGPS/FV3GFS (biennial upgrades)
Global DA	4D-Hybrid En-Var using GSI	Migrate to JEDI
Global Ensembles (Sub-seasonal)	FV3/NEMS based reanalysis/ reforecasts	FY20: Implement FV3 GEFS for sub-seasonal weather forecasts (35 days)
Global Seasonal Climate	Develop coupled UFS and coupled DA	Implement FV3 SFS for seasonal climate forecasts (MOM6, CICE5, Noah-MP, WWIII, GOCART,JEDI)
Global Aerosols	NGAC V2 (NEMS/GSM + GOCART)	FY20: Merge with FV3 GEFS
Hurricanes	HWRF & HNMMB	FV3 GFS with multiple moving nests (HAFS)
Waves	Waves Multi2 merged with HWRF	FY20: Merge wave ensembles models with FV3GEFS FY21: Merge deterministic Waves with GFSv16
Ocean	RTOFS/HYCOM	MOM6 + NCODA + Marine JEDI
Meso-Scale	NAM V4 & NMMB frozen	Transition to FV3 CAM, NAM/RAP Parent domains subsumed by FV3GFS?
Short-range ens.	SREF V7.1 frozen	FY20: Replace SREF with FV3GEFS???
HREF	V2: HiRes Window + NAM Nests (SSEO)	FV3 SAR to replace poor performing HREF members
RAP/HRRR	V2/V3	FY20: V3/V4 UFS CAM (RRFS)
Products, V&V	UPP, VSDB/MET, MEG, NAWIPS	UPP+, MET+, MEG+
Collaborative Infrastructure	Various	NEMS/ESMF/NUOPC+; EE2+; CROW; Shared infrastructure and distributed development



NPS Modeling System	Current Version	Q3 FY 20	Q4 FY 20	Q1 FY 21	Q2 FY 21	Q3FY 21 - Q2FY22 MORATORIUM	Q3 FY 22	Q4 FY 22	Q1 FY 23	Q2 FY 23	Q3 FY 23	Q4 FY 23	Q1 FY 24	Q2 FY 24	Q3 FY 24	Q4 FY 24	UFS Application
Global Weather & Global Analysis	GFS/ GDASv15				GFSv16									GFSv17/ GEFSv13			UFS Medium Range & Sub-Seasonal
Global Waves	GWMv3																
Global Weather Ensembles	GEFSv11		GEFSv12														
Global Wave Ensembles	GWESv3																
Global Aerosols	NGAC v2																
Short-Range Regional Ensembles	SREFv7																
Global Ocean & Sea-Ice	RTOFSv1.2			RTOFSv2					RTOFSv3								UFS Marine & Cryosphere
Global Ocean Analysis	GODASv2								GODASv3								
Seasonal Climate	CDAS/ CFSv2															SFSv1	UFS Seasonal
Regional Hurricane 1	HWRFv12		HWRFv13				HAFSv1				HAFSv2				HAFSv3		UFS Hurricane
Regional Hurricane 2	HMONv2	HMONv3															
Regional High Resolution CAM 1	HiRes Window v7				HIRESWv8					RRFSv1				RRFSv2			UFS Short-Range Regional HiRes CAM & Regional Air Quality
Regional High Resolution CAM 2	NAM nests/ Fire Wxv4																
Regional High Resolution CAM 3	RAPv4/ HRRRv3			RAPv5/ HRRRv4													
Regional HiRes CAM Ensemble	HREFv2				HREFv3												
Regional Mesoscale Weather	NAMv4																
Regional Air Quality	CMAQv5						CMAQv6										
Regional Surface Weather Analysis	RTMA/ URMA v2.7		RTMA/ URMA v2.8								3DRTMA /URMAv 3						
Atmospheric Transport & Dispersion	HySPLITv7						HySPLIT v8								HySPLIT v9		UFS Air Quality & Dispersion
Coastal & Regional Waves	NWPSv1.2			NWPS v1.3			NWPS v1.4						RWPSv1				UFS Coastal
Great Lakes	GLWUv3.4						GLWUv4								GLWUv5		UFS Lakes
Regional Hydrology	NWMv2			NWMv3							NWMv4						UFS Hydrology
Space Weather 1	WAM/IPEv1															WAMv2	UFS Space Weather
Space Weather 2	ENLILv1																

HAFS Strategy and Science Objectives

- In order to address the Section 104 of *Weather Research and Forecasting Innovation Act of 2017*, the next generation of HFIP will build upon the original goals of the project through the following specific goals and metrics:
    - Reduce forecast guidance errors, including during RI, by 50% from 2017.
    - Produce 7-day forecast guidance as good as the 2017 5-day forecast guidance;
    - 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.

- Developing and advancing the Hurricane Analysis and Forecast System is one of the key strategies to address the next generation HFIP's science and R2O challenges.

HAFS Strategy and Science Objectives

- As a Unified Forecast System (UFS) application, HAFS is an FV3 (Finite Volume Cubed-Sphere Dynamical Core) based multi-scale model and data assimilation system capable of providing Tropical Cyclone (TC, a.k.a. Hurricanes in the Atlantic and East Pacific basins and Typhoons in the Northern West Pacific basin) analyses and forecasts of the inner core structure and the large-scale environment.
- The HAFS development targets an operational analysis and forecast system for TC forecasters with reliable, robust and skillful guidance on TC track and intensity (including rapid intensification), storm size, genesis, storm surge, rainfall and tornadoes associated with TCs.
- HAFS will provide an advanced analysis and forecast system for cutting-edge research on modeling, physics, data assimilation, and coupling to earth system components for high-resolution TC predictions within the Next Generation Global Prediction System (NGGPS)/Strategic Implementation Plan (SIP) objectives of the Unified Forecast System (UFS).

HAFS Strategy and Science Objectives

- Use cloud resolving resolutions with nesting (static, telescopic and moving) within global and basin-wide domains.
- Improve observations-based physics schemes by using existing and new observations to enhance the simulation of physical processes for TCs.
- Advance inner-core and satellite DA algorithm for TCs
- Ingest new observations and DA algorithm in a shared JEDI-based infrastructure

HAFS Forecast Priorities

- Improve the prediction of rapid intensity (RI) change and track of Hurricanes
- Improve the forecast and communication of surges from Hurricanes
- Incorporate risk communication research to create more effective watch and warning products

HAFS Accomplishments in Year 1

- HAFS Code Repository and Management
- HAFS Workflow Development
- HAFS Multiple Static Nests – towards Moving Nests
- HAFS Physics Suites
- Multiple HAFS configurations
  - Regional Static Nests
  - Regional Nests within Global FV3

HAFS Code Repository and Management

Incorporates the three-tier repository/fork structure

The authoritative HAFS repository:

- https://github.com/NOAA-EMC/HAFS
- Supports the main development activities and operational implementations.

Trusted community/organizational HAFS forks:

- e.g., https://github.com/hafs-community/HAFS
- Mainly provides community support and promotes organizational level collaborations.

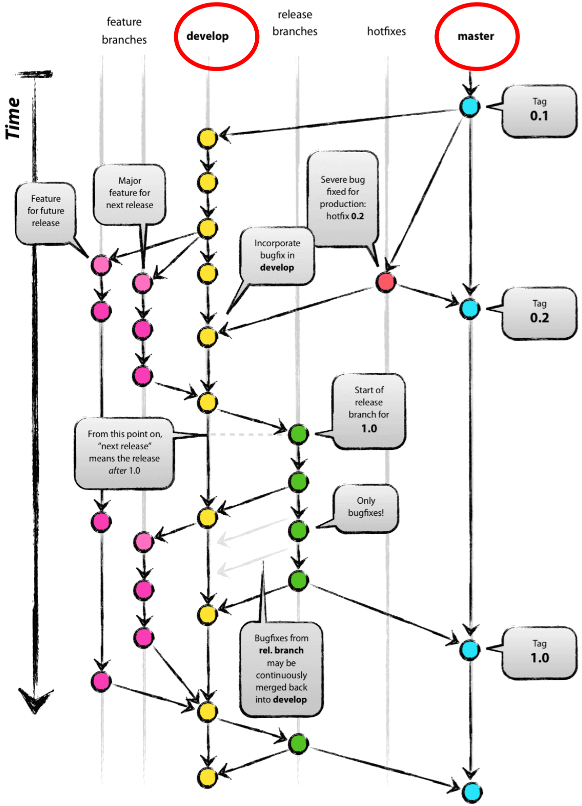
HAFS developer forks:

- Developer’s forks for individual feature (or capability) development.

Adopts the GitFlow rational

Branch naming convention:

- **develop** for the develop branch
- **master** for the master branch
- **feature/**[name] for feature branches



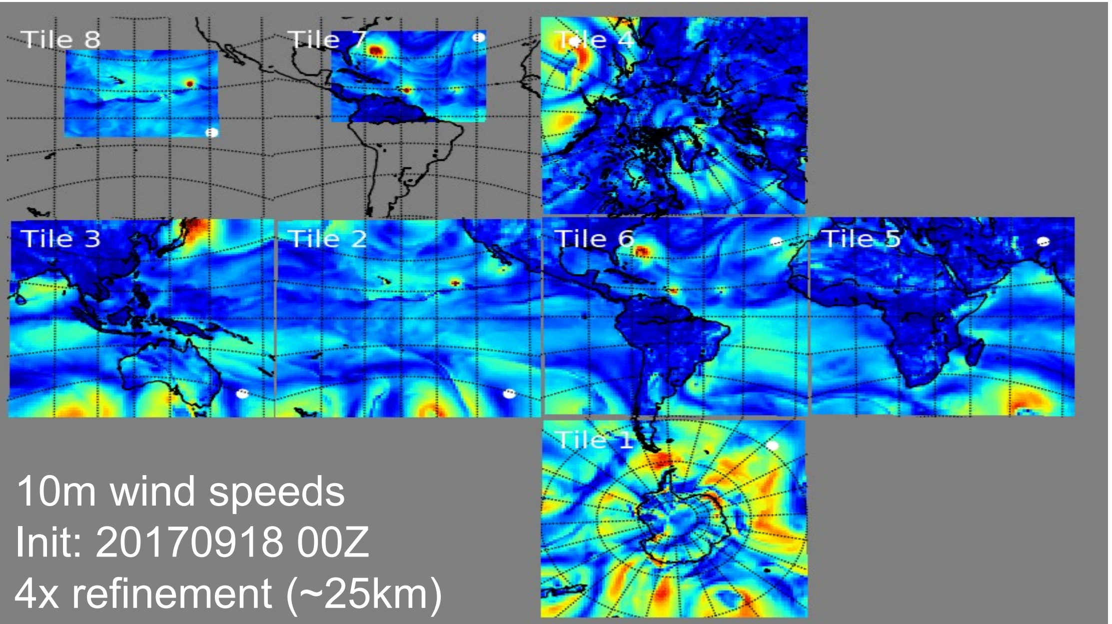
A GitFlow branching strategy (from Vincent Driessen’s blog)

From: Bin Liu & Jili Dong

HAFS -- Year 1: Two Static Nests on Two Tiles

Maria, Jose (NATL) and Otis (EPAC)

- Implementation of two static nests in FV3GFS completed
- Bitwise identical results with baseline FV3GFS code
- Successful 168 hour forecast run
- Second nest results also validated

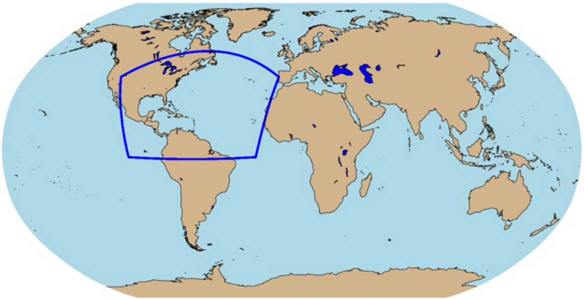


- 10m wind speeds
- Init: 20170918 00Z
- 4x refinement (~25km)

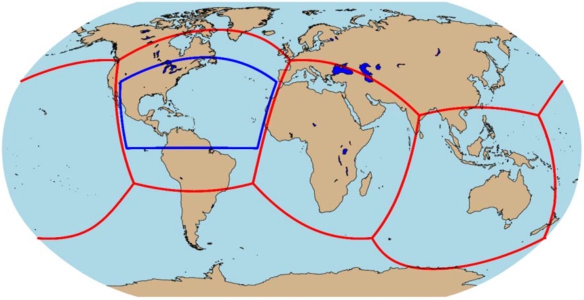
From: Xuejin Zhang

Year 1-- HAFS v0.A (SAR) and HAFS v0.B set ups: model grids

HAFS v0.A- SAR



HAFS v0.B- Global-nest



For FY19, both configurations ran in real time

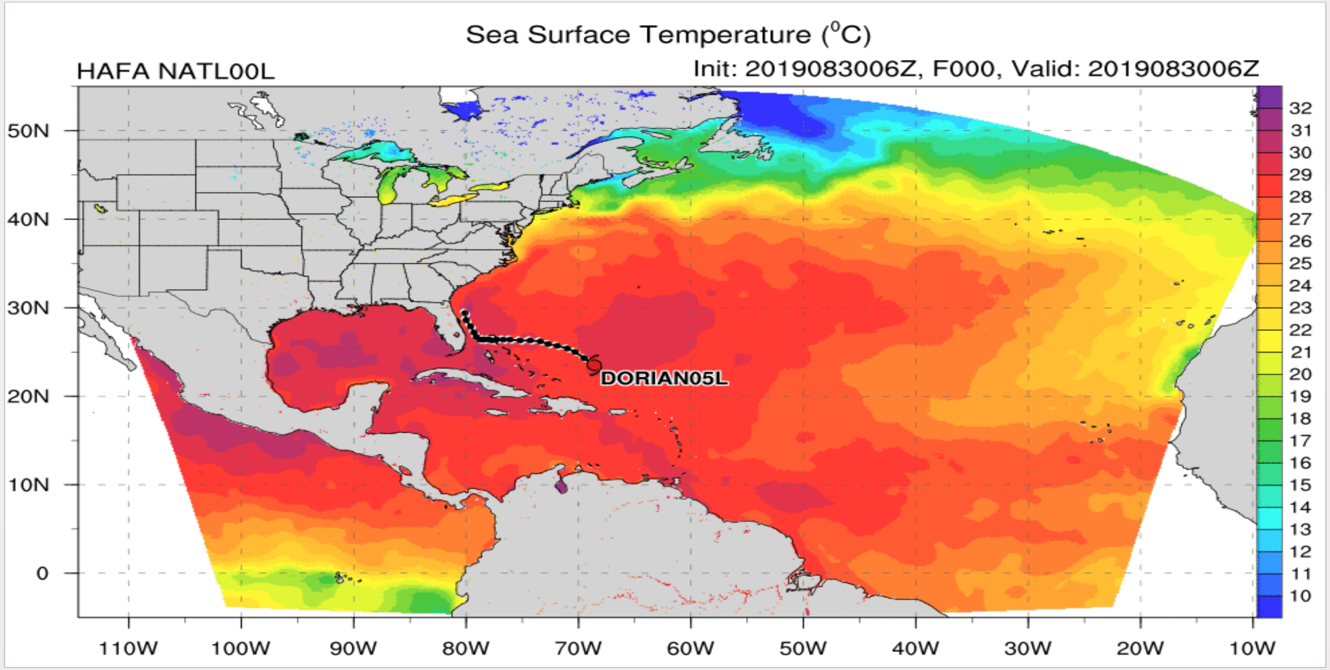
The NATL basin focused standalone regional (SAR) domain configuration (3km)

- C768 with a refinement ratio of 4
- the regional domain size: 2880x1920 (~85x56deg)

The NATL basin focused global-nesting domain configuration (3 km, global at 13 km)

- C768 with a refinement ratio of 4
- the nested domain size of 2880x1536 (~85x45deg)

Year 1: HAFS Experimental Configurations

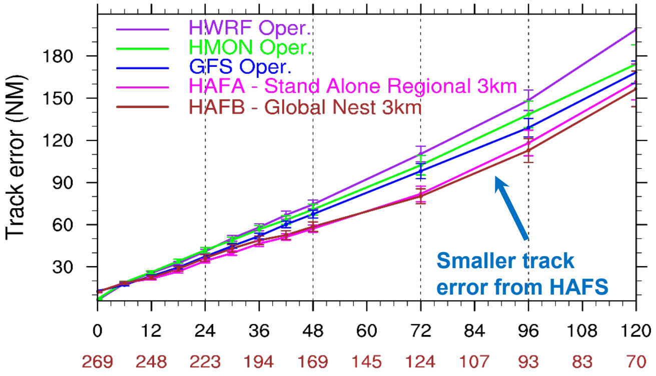


Hurricane Dorian forecasts using the HAFSv0.A configuration from HFIP real-time experiments.

Dorian track forecasts from HAFS picked up on the right turn before the operational models.

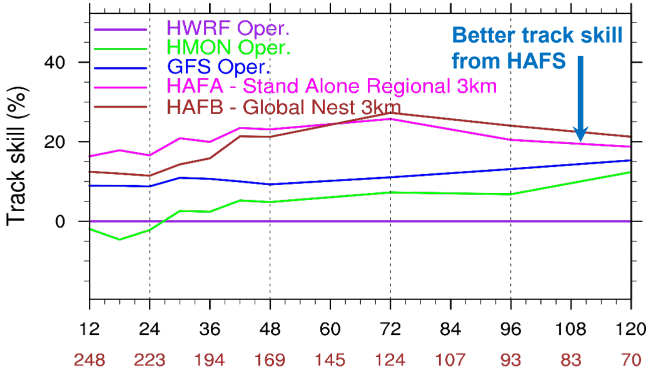
Year 1-- HAFS track forecasts for the NATL 2019 season

track error



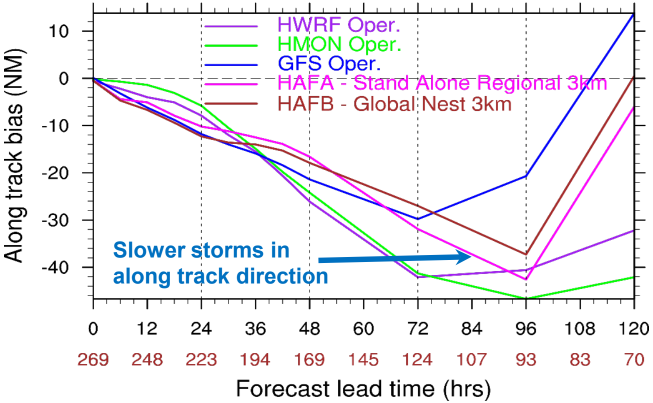
Smaller track error from HAFS

track skill



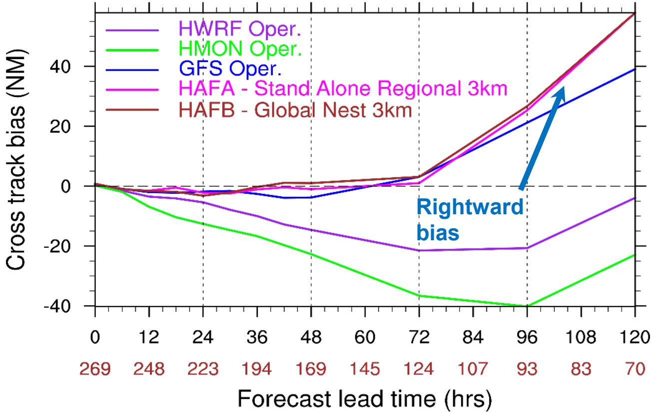
Better track skill from HAFS

along track bias



Slower storms in along track direction

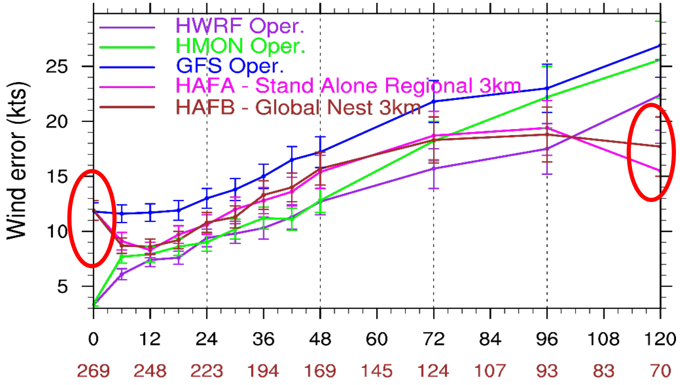
cross track bias



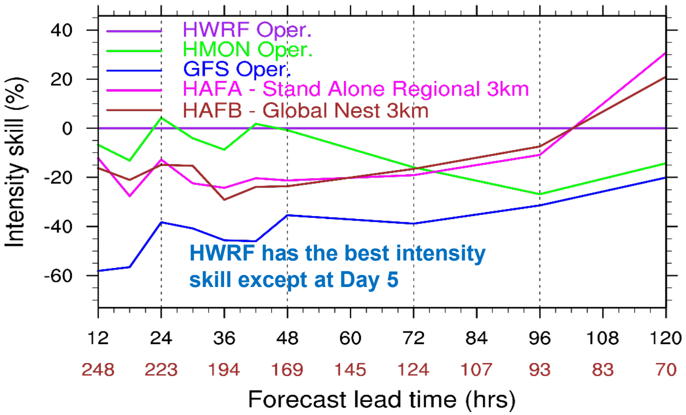
Rightward bias

Year 1-- HAFS intensity forecasts for the NATL 2019 season

wind error

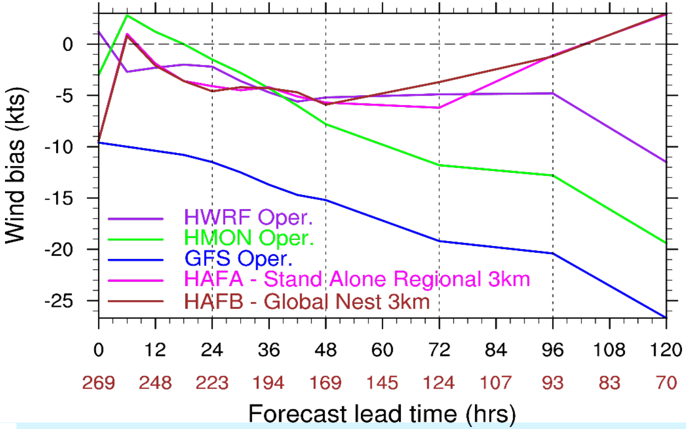


Intensity skill



HWRF has the best intensity skill except at Day 5

wind bias



- Large initial intensity errors in both HAFS models (spin down)
- Error reduced at 6 hours and increases afterwards till Day 3
- Relatively small errors at 120 hours
- Both HAFS models under-predict intensity in terms of maximum wind before Day 5
- HAFS v0.A and v0.B are comparable in intensity forecasts

HAFS Accomplishments in Year 2

- HAFS Coupling with Ocean

- HAFS Data Assimilation

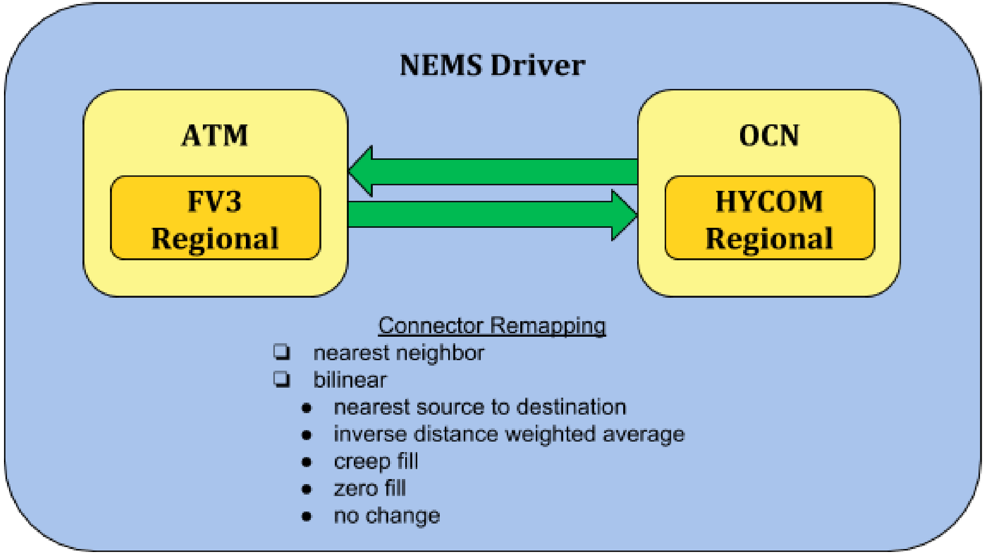
- HAFS Workflow Enhancements

- HAFS Moving Nests within FV3 Dycore

- Multiple HAFS Configurations
  - Regional Static Nest with Ocean Coupling (HAFS v0.1A)
  - Regional Nest within Global FV3 (HAFS v0.1B)
  - Regional Ensembles (HAFS v0.1E)
  - Alternate Regional Grid Projections (HAFS v0.1J)

ESMF/NUOPC Based HAFS-HYCOM Coupling

Direct coupling through the bilinear regridding method with the data merging for non-overlapped areas



Connector Remapping

- ❏ nearest neighbor
- ❏ bilinear
    - nearest source to destination
    - inverse distance weighted average
    - creep fill
    - zero fill
    - no change

Shapes	
▭	Component
⇨	Connector

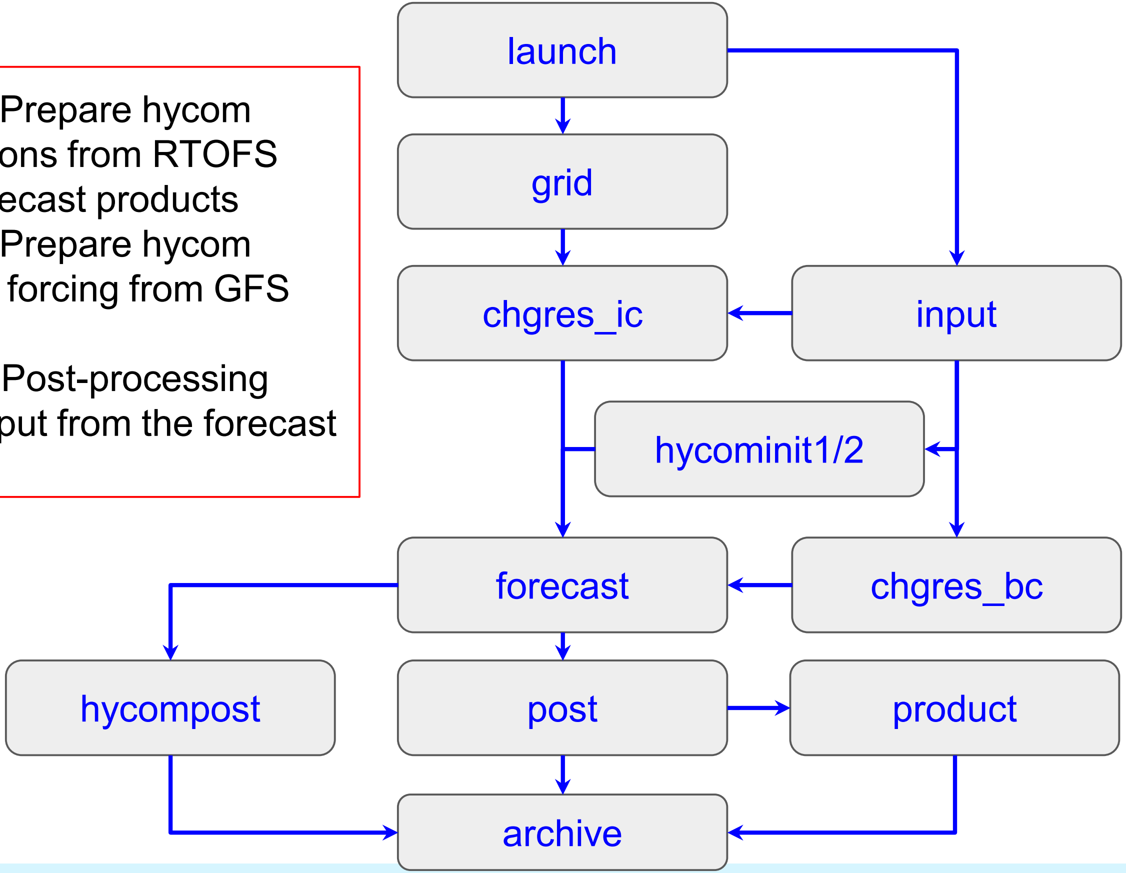
Color Code		
🟦	Blue	Driver
🟨	Yellow	Model
🟩	Green	Connector
🟧	Orange	Mediator
◼	Gray	Off

From ATM to OCN: 10-m wind, air-sea momentum flux, 2-m temperature, 2-m humidity, net short-wave and long-wave radiation fluxes, precipitation, surface pressure

From OCN to ATM: sea surface temperature

HAFS Workflow with Ocean Coupling

- hycominit1: Prepare hycom initial conditions from RTOFS restart or forecast products
- hycominit2: Prepare hycom atmospheric forcing from GFS forecasts
- hycompost: Post-processing HYCOM output from the forecast task



launch

grid

chgres_ic

input

hycominit1/2

forecast

chgres_bc

hycompost

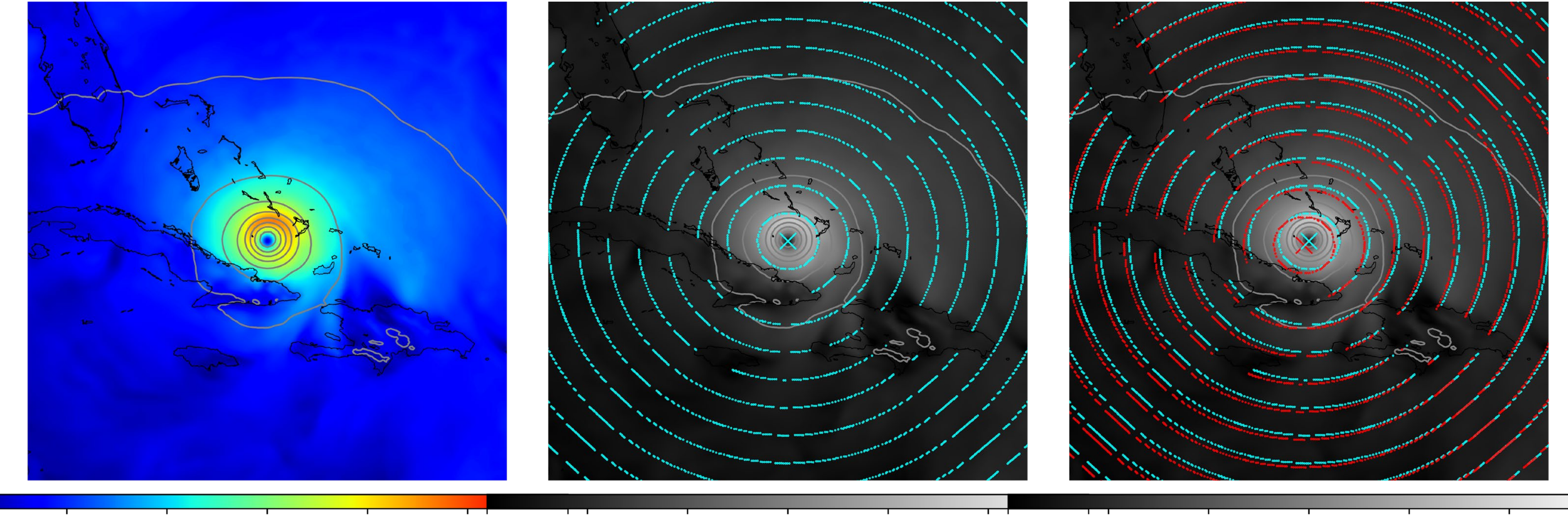
post

product

archive

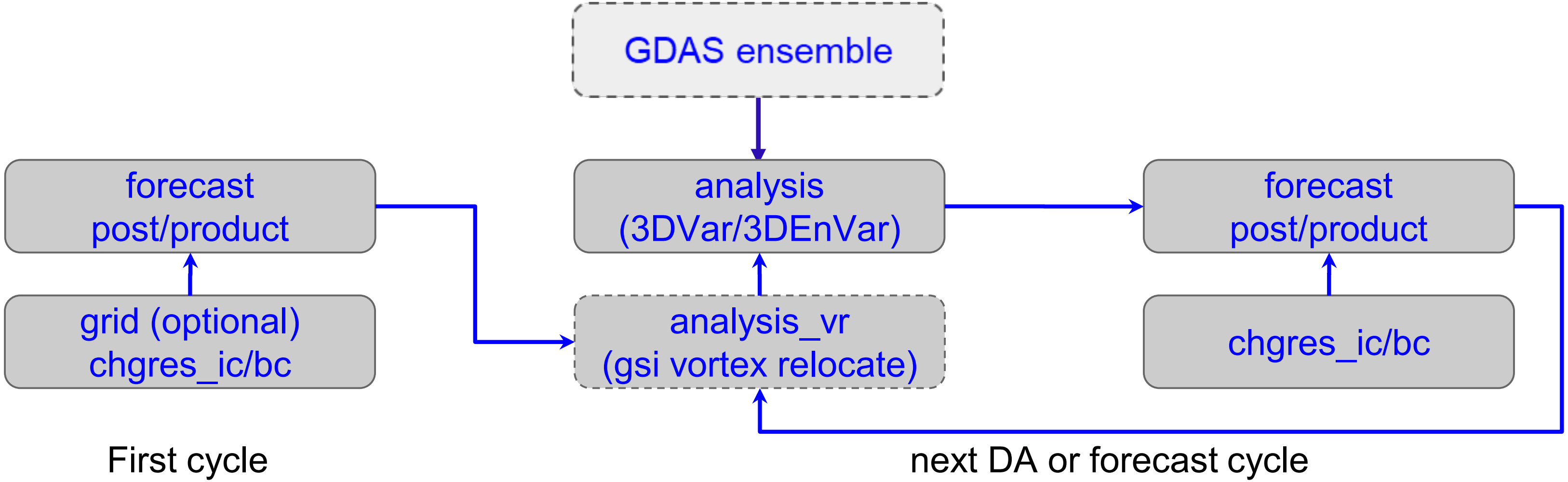
- run_ocean=yes or no
- ocean_model=hycom
- cpl_ocean:
  - 0: no coupling
  - 1: coupling through nearest point regridding
  - 2: coupling through bilinear regridding
- hafs_hycom.conf

HAFS: GSI-based TC Relocation Methodology



- The FV3 first-guess is used to create synthetic profile-type *observations*
- Ocean-relative observations are collected at radial intervals with respect to the forecast-time TC location (cyan points)
- The positions for the observations is updated to reflect their respective locations relative to the observed TC-vitals position (red points)
- The GSI assimilates these *observations* in order to relocate the TC

Current Status of HAFS-DA Development



GDAS ensemble

forecast
post/product

grid (optional)
chgres_ic/bc

analysis
(3DVar/3DEnVar)

analysis_vr
(gsi vortex relocate)

forecast
post/product

chgres_ic/bc

First cycle

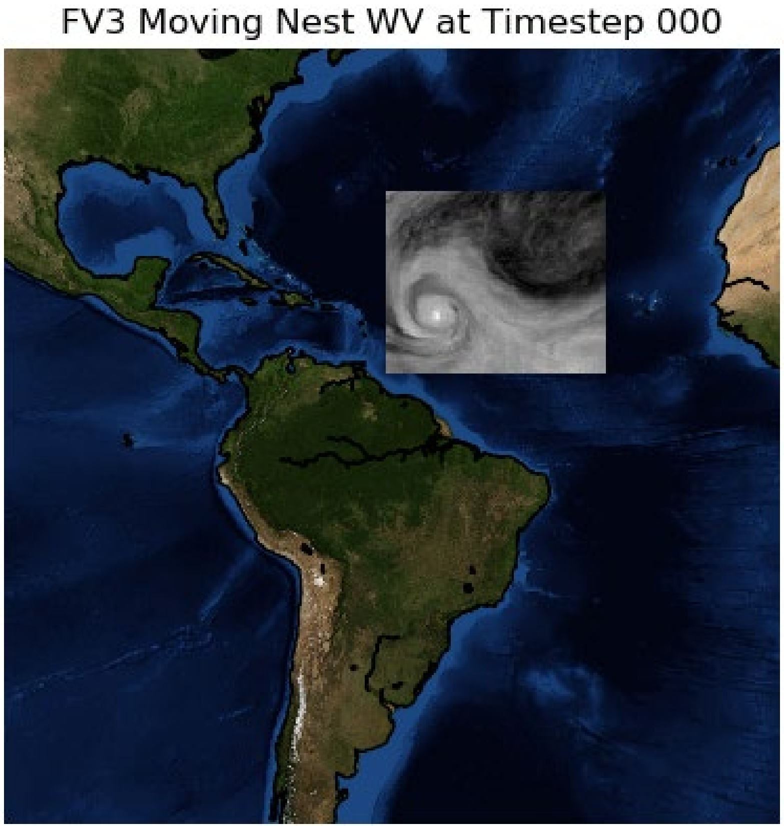
next DA or forecast cycle

Features:

- ➔ Cold start from GFS analysis (without DA)
- ➔ Warm start the current forecast cycle from its prior forecast cycle
- ➔ GSI-based TC relocation capability (configurable, on/off)
- ➔ 3DVar DA to assimilate observations
- ➔ 6-hourly hybrid 3DEnVar using GDAS ensemble

HAFS - Moving Nest Implementation

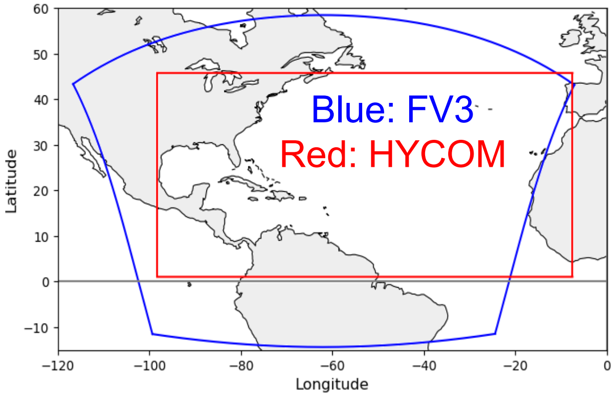
- Development of moving nests on global cubed sphere
- All prognostic variables moving
- Diagnostic variables recalculated
- Six-hour stable run with full physics and two-way feedback
- Physics run over open ocean



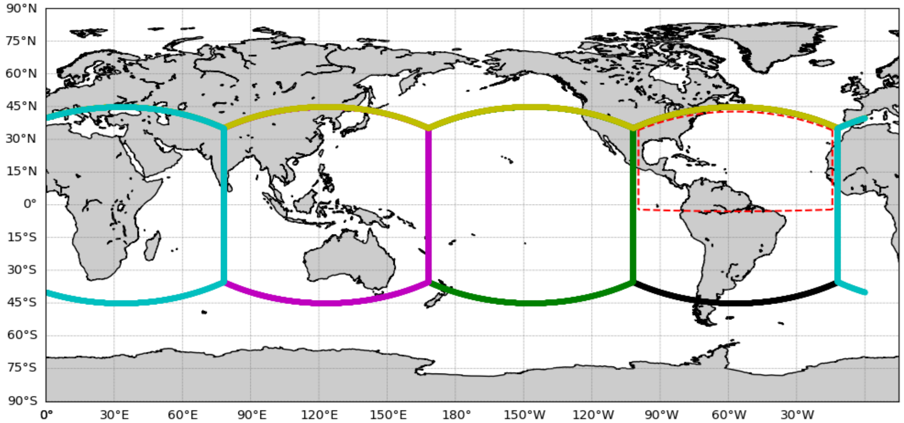
HAFS v0.1A Configuration

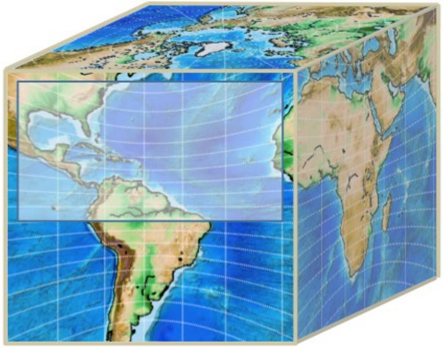
- The FV3 component (based on 2019 HAFS.v0.0A)
  - FV3 model domain (~85x72 deg)
  - 91 vertical levels from
  - Use the HAFS_V0_gfdlmp_nocpnsstugwd physics suite
    - GFDL microphysics; RRTMG radiation; No CP; Noah LSM; GFS surface layer with HWRF exchange coefficients; GFS EDMF PBL with HWRF modification; Both convective and orographic GWD are turned off; Turning off the NSST component
  - GFS NEMSIO file for IC; 3-hrly GFS grib2 files for LBC
  - 177 nodes, 5-day forecasts

- The HYCOM ocean model component
  - Cover NATL basin (1-45.78N, 261.8-352.5E) at a 1/12-degree resolution with 41 vertical layers
  - Ocean IC from RTOFS nowcast and/or forecasts
  - Use persistent oceanic LBC
  - Atmospheric forcing from 0.25-degree GFS grib2 files to cover non-overlapped area



HAFS v0.1B Configuration





- One static nest over the Atlantic.
- Use “tropical channel” global layout of FV3.
- Forecasts length of 174 hours (7.25 days) in order to provide 7-day interpolated forecast .
- Include results for the global domain, to allow for direct comparison with operational GFS; assess impact of the nest on the global domain through 2-way feedback.
- Physics and dynamics options similar to HAFS v0.B in 2019, upgrades to PBL physics.

Goal: In addition to facilitating comparisons with operational and experimental model guidance, assess impact of high-resolution nests in HAFS on the global circulation, as well as feedback of the nests on each other.

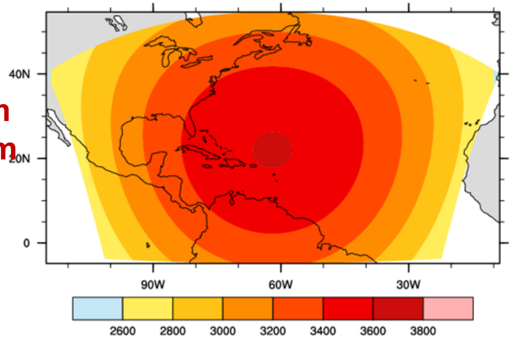
HAFS v0.1J Configuration

HAFS with ESG (Extended Schmidt Gnomonic) grid
- a more uniform grid for HAFS

- The default GFDL grid has non-uniform resolution over a large Atlantic domain: coarser resolution in the center; higher resolution over edges
- A more homogenous grid allows larger timestep; not necessarily limited by the minimum resolution in GFDL grid
- Easy design for large domains (e.g. basin-scale HAFS)
- 88 nodes, 7-day forecasts

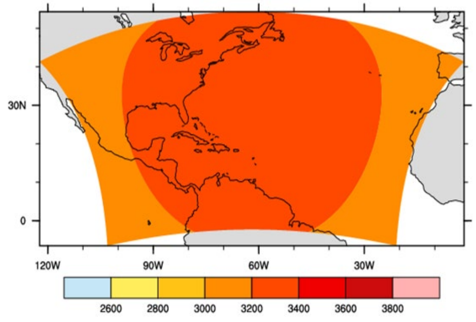
GFDL grid (default)

Min: 2.56 km
Max: 3.61 km



A more homogenous grid

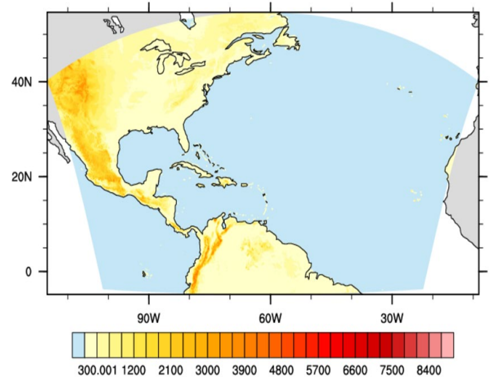
ESG grid



Min: 3.18 km
Max: 3.22 km

HAFS v0.1E Configuration

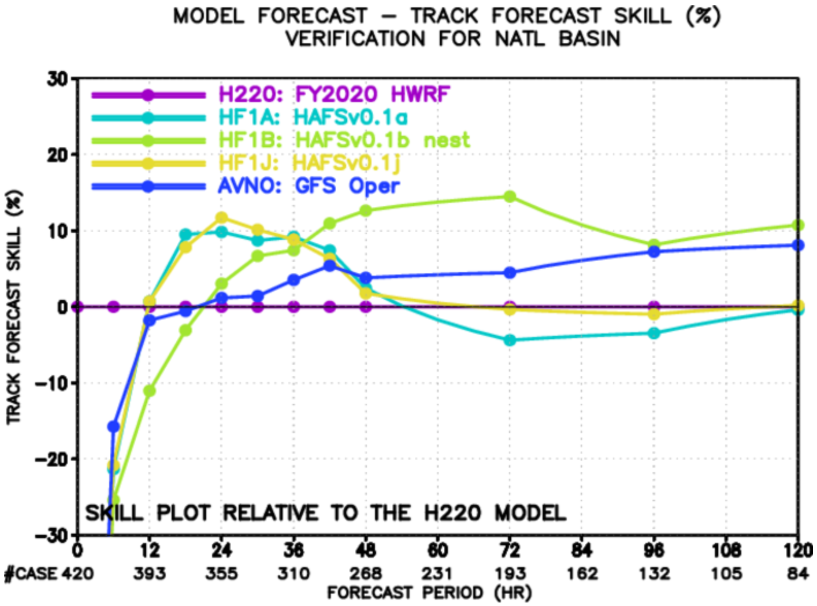
- Basic configuration, based on HAFSv0.1A
  - One control member plus 17 perturbed ensemble members
  - Coarser resolutions: ~6km vs. 3km; L64 vs. L91
  - Cumulus parameterization on
  - Twice a day (00Z and 12Z), Atlantic basin only
- IC/BC Perturbation:
  - IC/BC: GEFS grib2 (0.5x0.5)
- Model Physics:
  - Stochastic kinetic energy backscatter (SKEB)
    - Counteract excessive energy dissipation from numerical diffusion and interpolation, mountain and gravity wave drag, and deep convection
    - Stream function is randomly perturbed to represent upscale kinetic energy transfer
  - Stochastically perturbed physics tendencies (SPPT)
    - Represents uncertainties in physical parameterizations
    - Multiplicative noise modifies total parameterized tendency
  - Stochastically perturbed PBL humidity (SHUM)
    - Represents variability in the sub-grid humidity field
    - Similar to SPPT, but directly modifies low-level humidity field instead of tendency



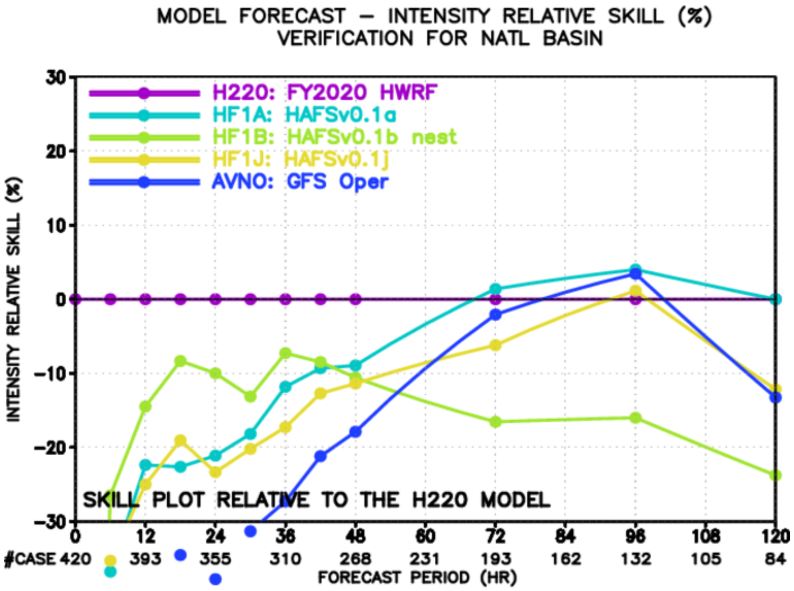
HAFS Performance for 2020 NATL Storms (03-30L)

HWRF
HF1A
HF1B
HF1J
AVNO

Track skill



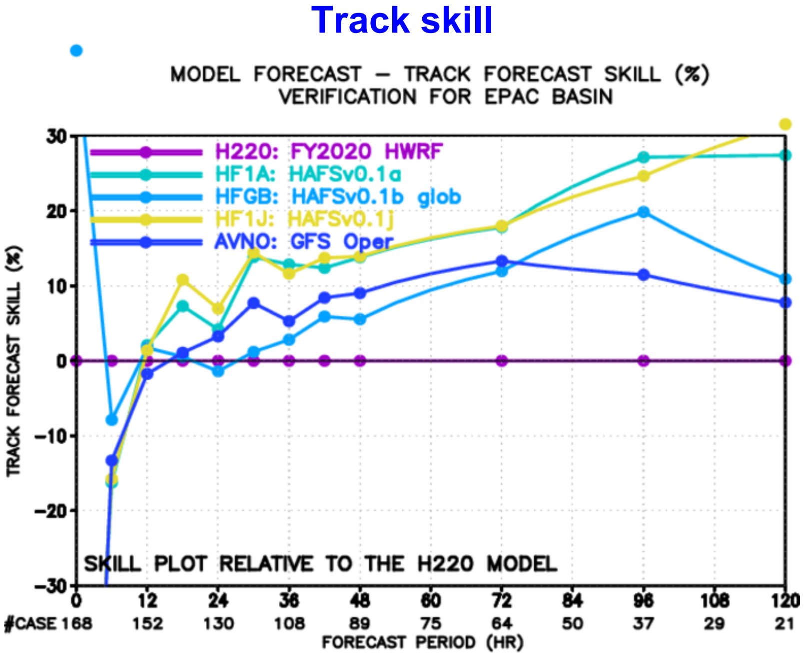
Intensity skill

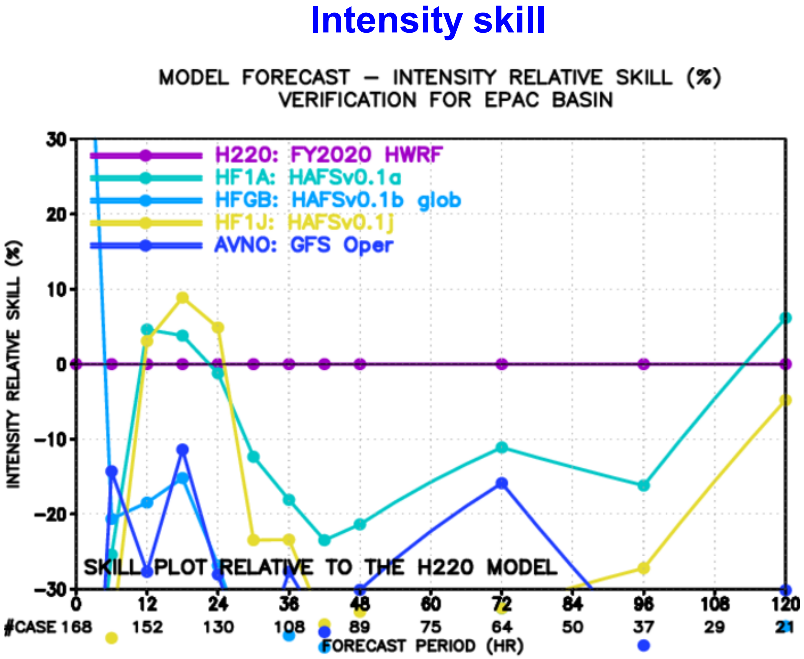


- HAFS-B (nest) had the best track skill overall followed by HAFS-J and HAFS-A.
- All HAFS configurations lag in intensity skill behind operational HWRF for early lead times. HAFS-A catches up to HWRF by Day 3.

HAFS Performance for 2020 EPAC Storms (03-19E)

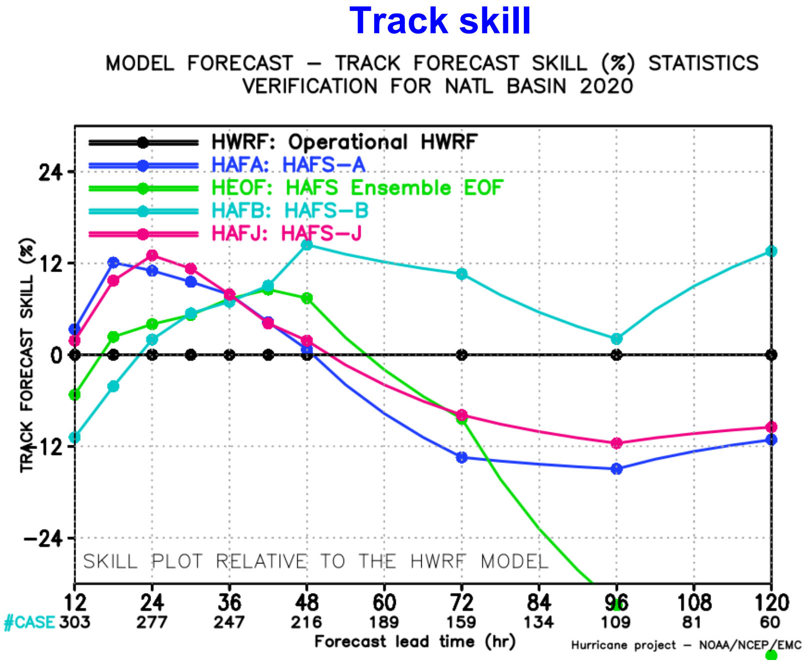
HWRF
HF1A
HF1B
HF1J
AVNO

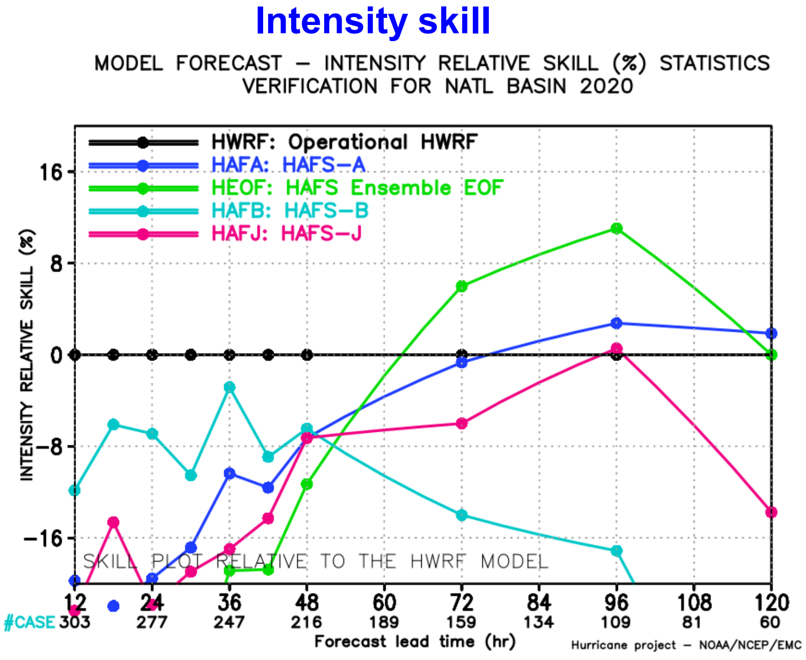




- HAFS-A and HAFS-J had the best track skill followed by HAFS-B (global).
- All HAFS configurations lag in intensity skill behind operational HWRF.

HAFS v0.1E Performance for 2020: NATL Basin





- HAFS-E has comparable track skill with HAFS-A and HAFS-J till Day-3, but lower thereafter.
- HAFS-E has lowest intensity errors for extended lead times for Days 3-5.

HAFS - Initial Operational Capability (IOC) in FY22

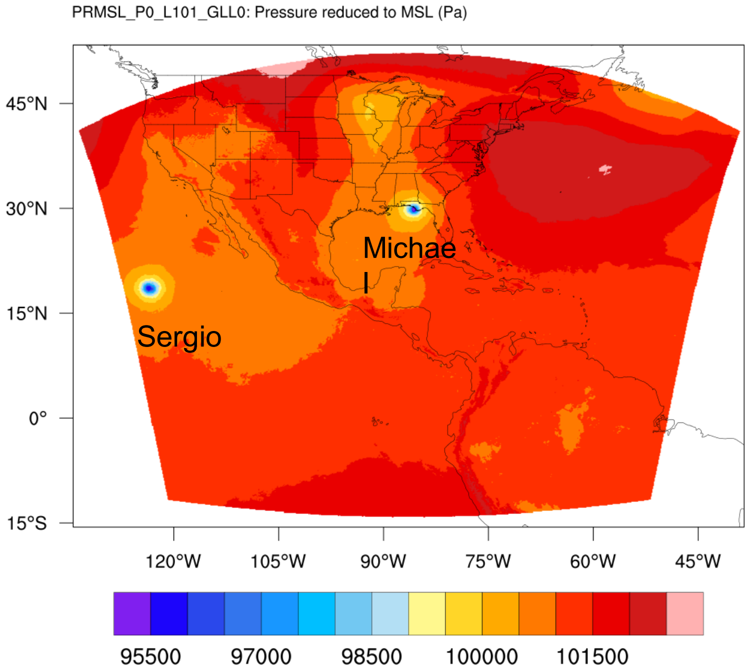
- Maintain current CONOPS: max 5 storms in NHC AOR for HWRF & HMON; max 7 storms for HWRF in all global basins (NHC, CPHC and JTWC) i.e. total max 12 storms.

- Functionality for 2021 Hurricane season:
  - Formal Vortex Initialization (VI/VM and/or GSI-based)
  - Coupling with ocean (2-way with HYCOM; 1-way with Waves)
  - GSI-based Data Assimilation capability
  - Workflow enhancements

All decisions on HAFS IOC based on EMC and NHC science evaluations

Target Option 1* (with single moving nests)

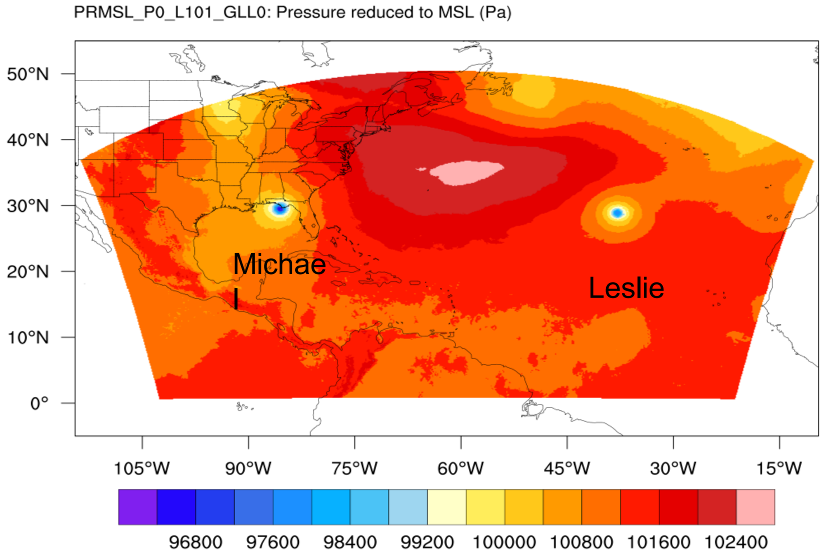
- Storm-centric with smaller outer domain at 4.5 km, embedded moving nests at 1.5 km; ~127L; (maximum **12/5**; two variants for NHC regions)
- Vortex Initialization
- Coupling with ocean (2-way with HYCOM;1-way with Waves), Use CMEPS
- Data Assimilation: dual-resolution; hybrid 3DEnVar; self cycled (similar to operational HWRF)



* **Primary for FY22; 12 domains replace both HWRF & HMON; 5 domains replace HMON**

Target Option 2* (static nests; with LAM domains)

- Two separate domains at 3 km – NATL and EPAC (bigger than HAFS v0.1A), ~127L
- Vortex Initialization
- Coupling with ocean (2-way with HYCOM; 1-way with Waves), Use CMEPS
- Data Assimilation: Hybrid 3DEnVar; self-cycled



* **Back-up for FY22**; **Replaces HWRF or HMON**

HAFS -- Ongoing Developments

- Integrate HAFS developments for improved analysis and forecasts:
  - Leverage UFS global and UFS-CAM DA developments
  - Build a modular DA workflow for HAFS
  - Moving Nest Algorithms in FV3 -- Dynamics and Physics

- Accelerate our ability to initialize Hurricane vortex and its environment with advanced DA methods (FY22 and FY23, development and evaluation)
  - New data ingestion and quality control methods
  - New DA algorithms and technologies for inner-core (vortex-scale) DA

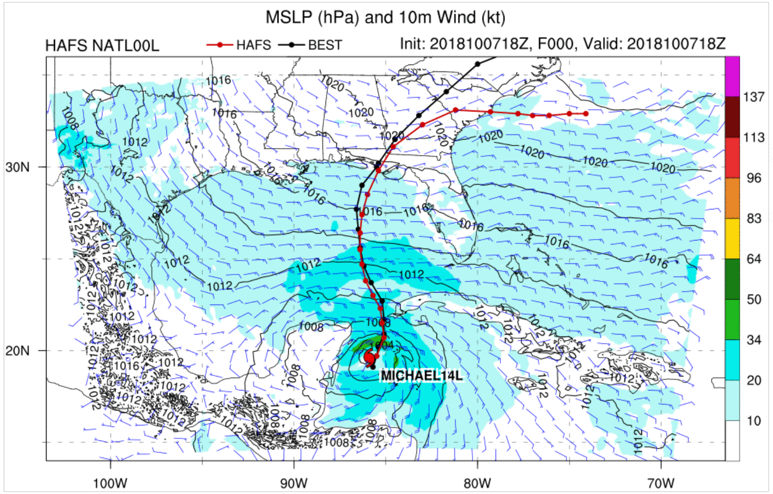
- Enhance physics for Hurricane Application
  - PBL, Microphysics, Radiation, Surface physics, and the interactions among schemes

- Conduct experiments with the above advancements for improved analysis and forecast skill

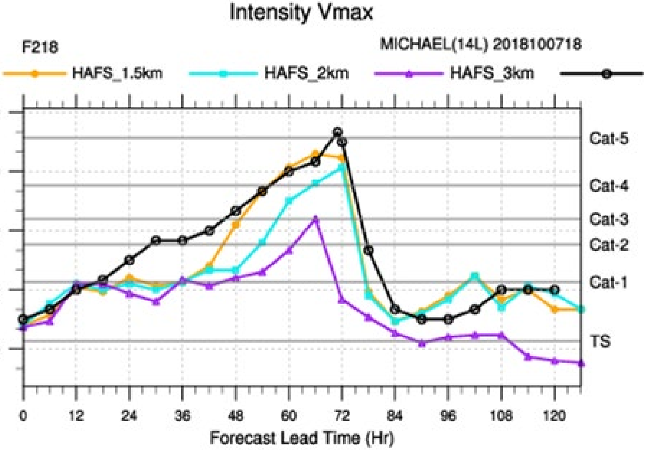
HAFS - Selected Physics Suites in CCPP

	GFSv15	GFSv16	GFSv17	HWRF	RAP (HRRR)
Cumulus	sa-SAS	sa-SAS	sa-SAS	sa-SAS	sa-GF
Microphysics	GFDL	GFDL	Thompson	SWSA-FA	Thompson
Radiation	RRTMG	RRTMG	RRTMGp	RRTMG	RRTMG
OGWD	GFS	GFS	uGWPv1	GFS	modified-GFS
NOGWD	off	uGWPv0	uGWPv1	off	off
Land	NOAH	NOAH	NOAH MP	NOAH	RUC
Surface Layer	GFS[1]	GFS	GFS	GFDL	MYNN
PBL	HEDMF[2]	sa-TKE-EDMF	sa-TKE-EDMF	modified-HEDMF	MYNN-EDMF

HAFS: Dynamics and Physics experiments



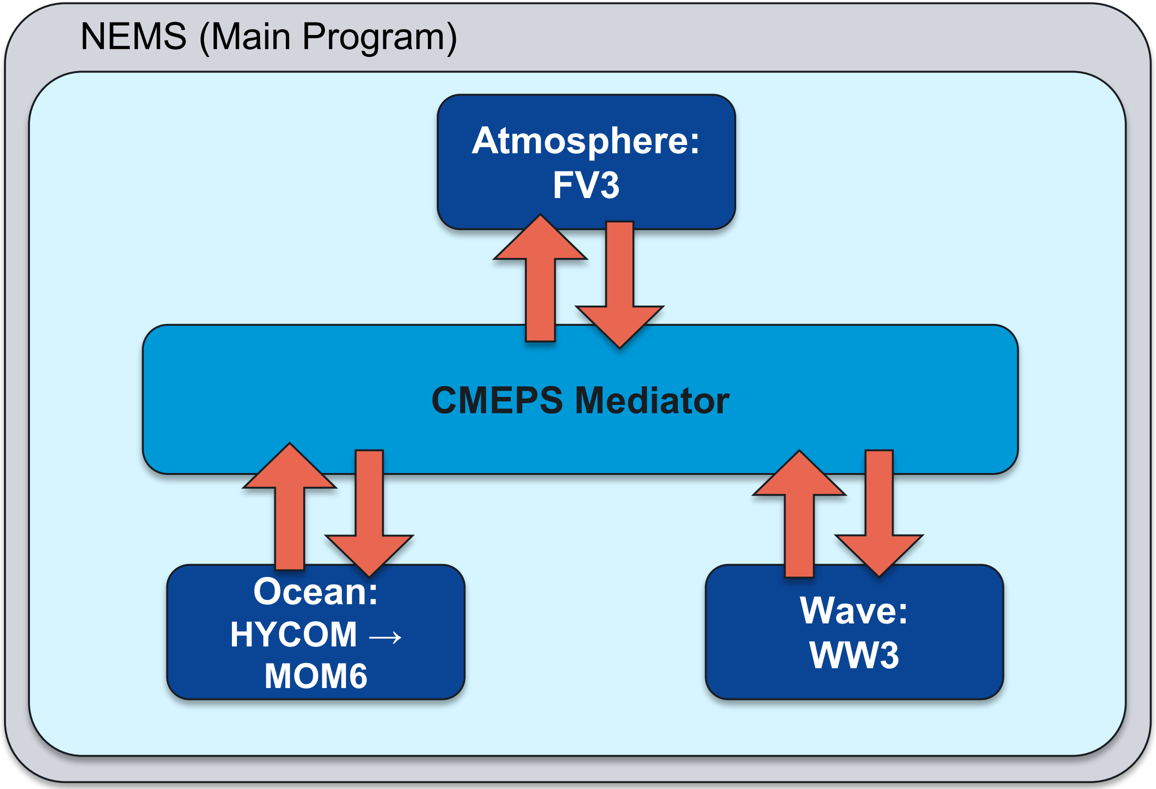
Hurricane Michael (2018) initialized on 2018/10/07/18



An animation (left pane) from an early cycle of HAFS - LAM showing landfall of Hurricane Michael as a strong category 5 storm along the Florida panhandle at 72 hr forecast.

Results from a horizontal resolution grid of 1.5 km (right panel, yellow line) show a much stronger storm as compared to lower resolution simulations (purple, cyan lines).

Future Coupled HAFS Configuration


NEMS (Main Program)

Atmosphere: FV3

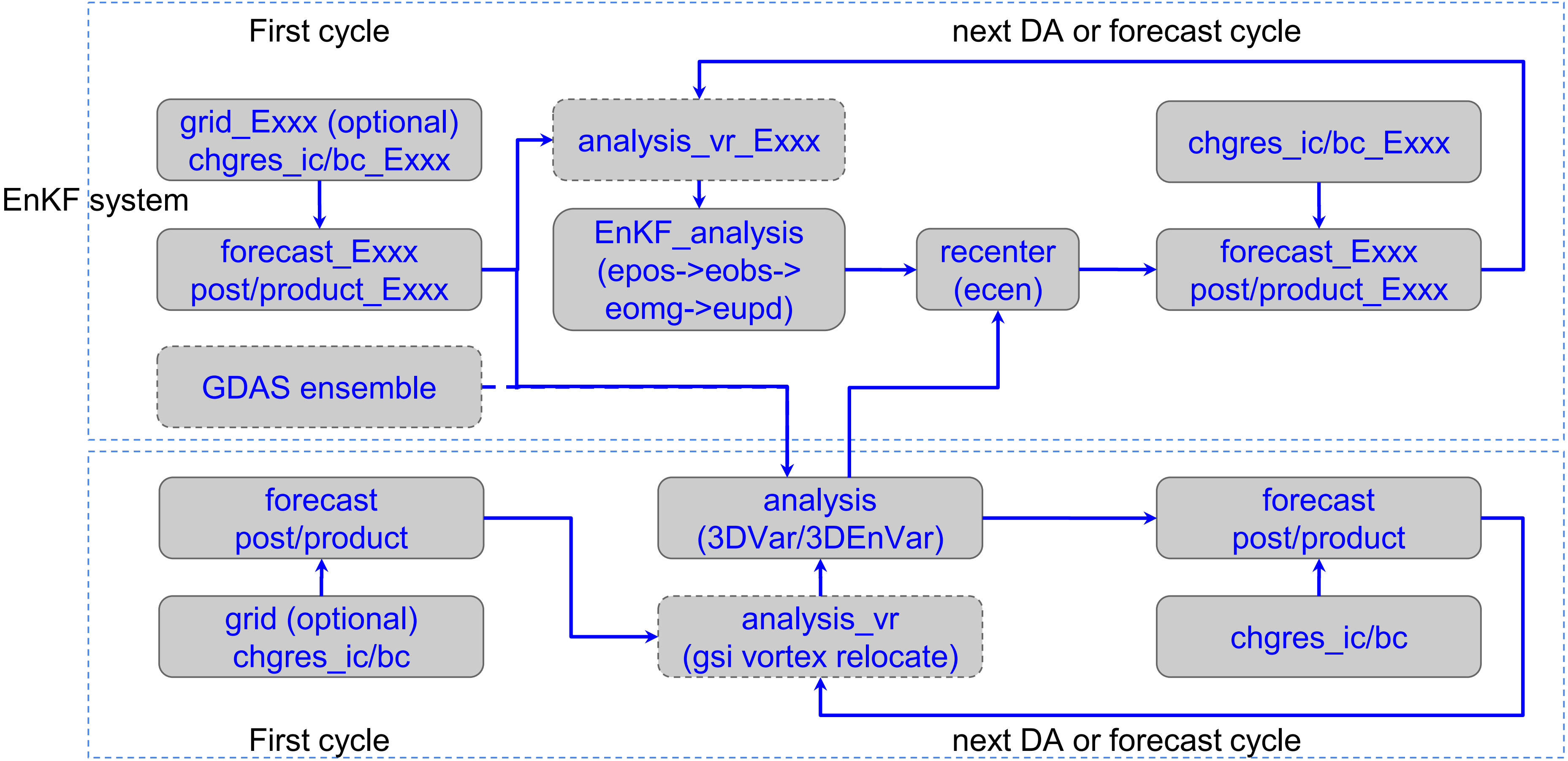
CMEPS Mediator

Ocean: HYCOM → MOM6

Wave: WW3

- Atm/Ocn fluxes are computed by atm model
- Atm/Ocn land/sea masks do not match
- SST is interpolated from ocean→atm using conservative interpolation followed by nearest neighbor fill
- Wave model sends z0 roughness length to atm, sends Stokes Drift (u,v) to ocean for sea-state dependent Langmuir mixing
- Ocean sends surface currents to Waves

Future: Schematic Workflow for HAFS ENSDA



EnKF system

First cycle

next DA or forecast cycle

grid_Exxx (optional)
chgres_ic/bc_Exxx

forecast_Exxx
post/product_Exxx

GDAS ensemble

analysis_vr_Exxx

EnKF_analysis
(epos->eobs->
eomg->eupd)

recenter
(ecen)

chgres_ic/bc_Exxx

forecast_Exxx
post/product_Exxx

forecast
post/product

grid (optional)
chgres_ic/bc

analysis
(3DVar/3DEnVar)

analysis_vr
(gsi vortex relocate)

forecast
post/product

chgres_ic/bc

First cycle

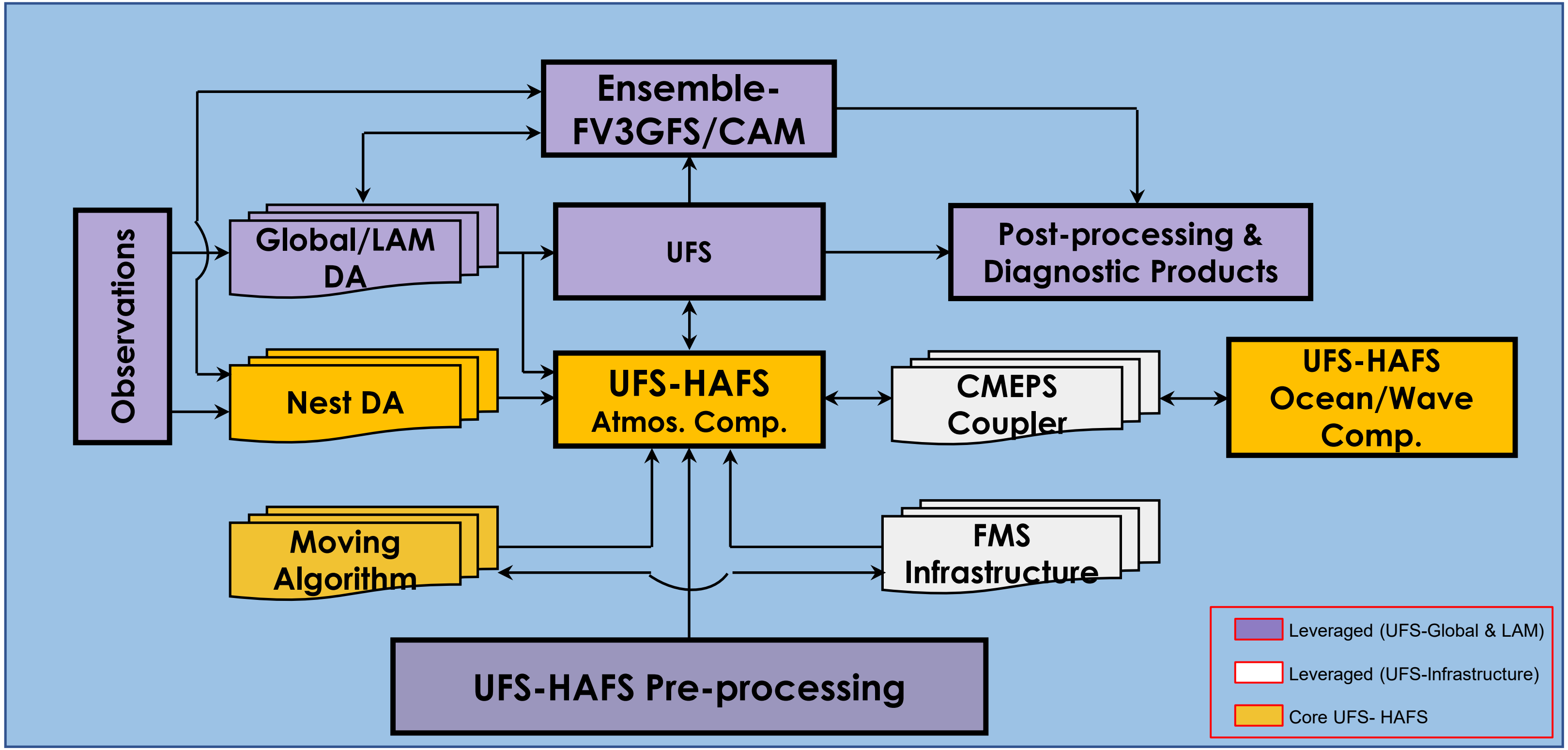
next DA or forecast cycle

Connections with other UFS projects

Connections and Dependencies

- IFAA-DRAS projects
  - 1A-4 (moving nest and SAR advancements)
  - 3A (HFIP & HAFS developments)
  - 3B (Observations)
  - 4A.2 (OSSE's)
  - 4B.2 (JEDI developments)
- UFS-R2O plans/projects
  - UFS-MER/S2S: DA, Physics, and Coupled model developments
  - UFS-CAM: SAR, WoF, 3DRTMA projects
  - UFS-CCI: Modeling infrastructure, Verification & Post-processing
  - EPIC
- Collaborations
  - CAM, MER, and CCI Application Teams
  - D&N, DA, Physics, Marine, Infrastructure, System Architecture and V&V SIP WGs
  - JCSDA

HAFS Strategic Roadmap in UFS-R2O



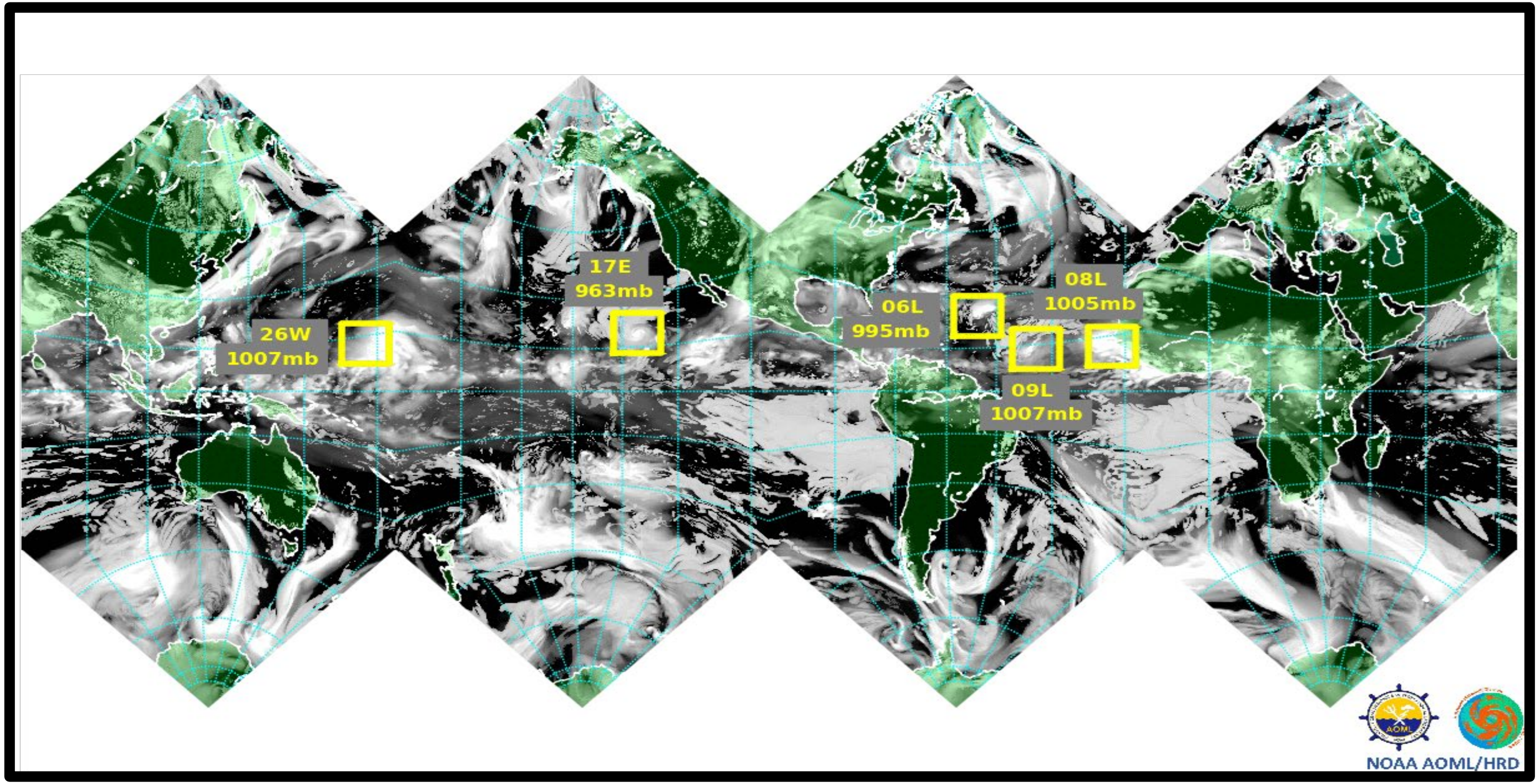
3-5 Year Vision

- Initial operational capability of the FV3-based Hurricane Analysis and Forecast System (HAFS) targeted for FY22. Replace existing operational HWRF and HMON systems with HAFS when performance and deliverables meet requirements of the relevant stakeholders

- Continue advancements in Vortex Initialization, Data Assimilation, Physics and Coupling for FY23 and beyond

- Future versions to embed moving nests/regions in the global Unified Forecast System with two-way feedback between the nests/regions and the parent domain

Long-term Target for HAFS/GFS



06L: Florence; 08L: Helene; 09L: Isaac; 17E: Olivia; 26W: Mangkhut

Thank You! Questions?