Status of Hurricane Analysis and Forecast System (HAFS) Development: Initial Operational Capabilities and Future Priorities

Xuejin Zhang[1], Zhan Zhang[2], and Avichal Mehra[2]

Vijay Tallapragada[2], S. Gopalakrishnan[1], and Frank D. Marks, Jr.[1]

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

Contributed by Hurricane Application Team

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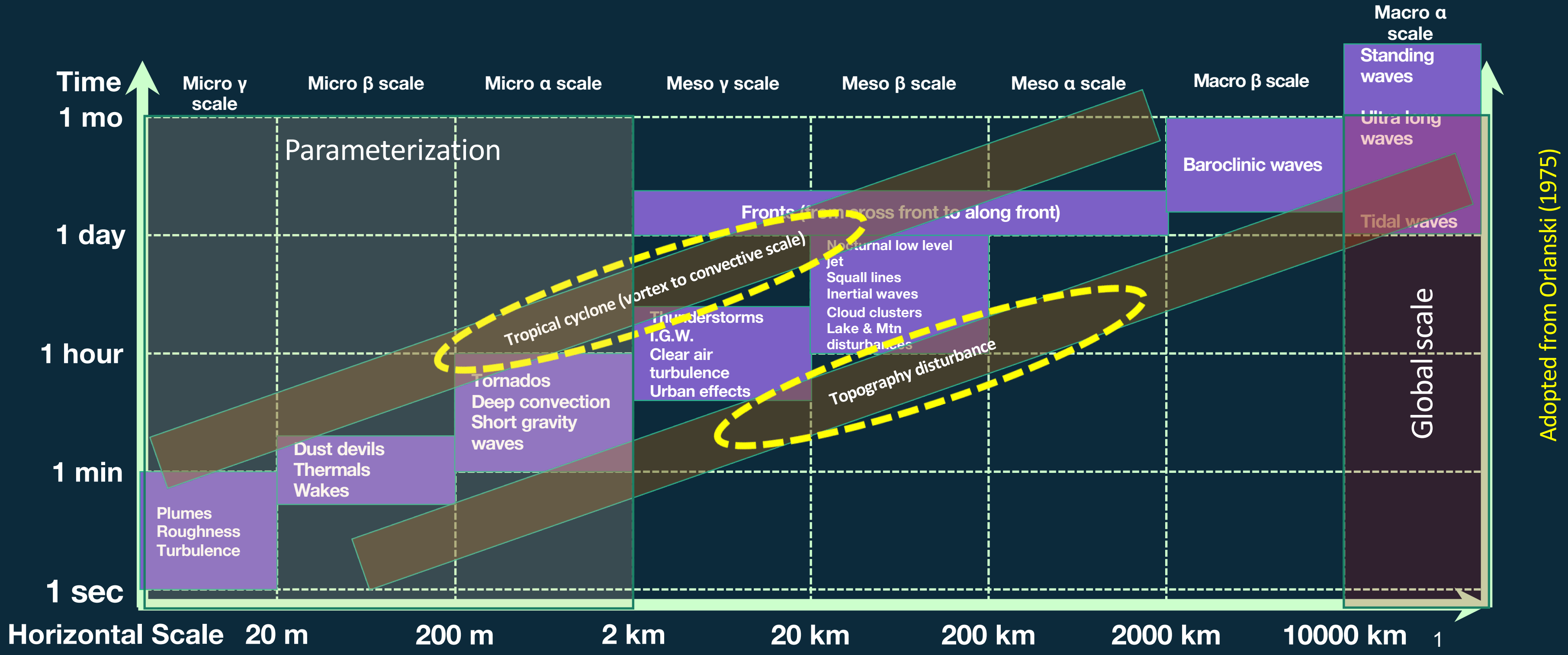
Spatial-Temporal Scales of Atmospheric Processes



Energy Spectrum

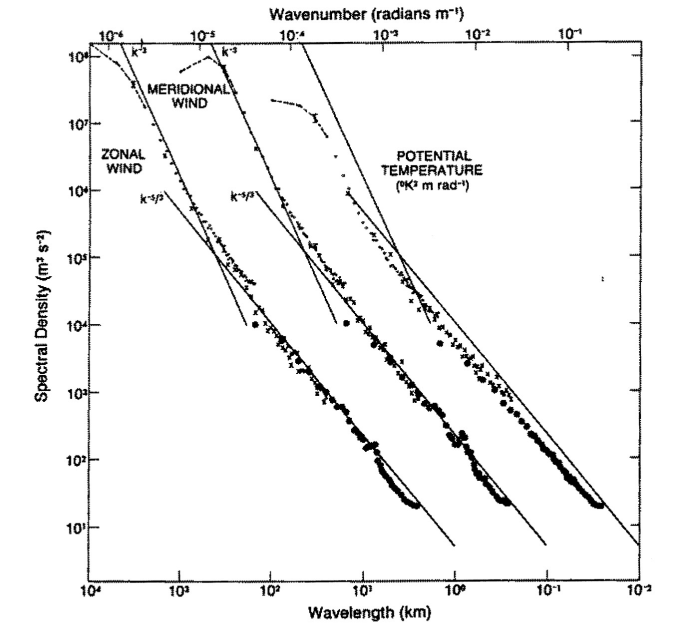
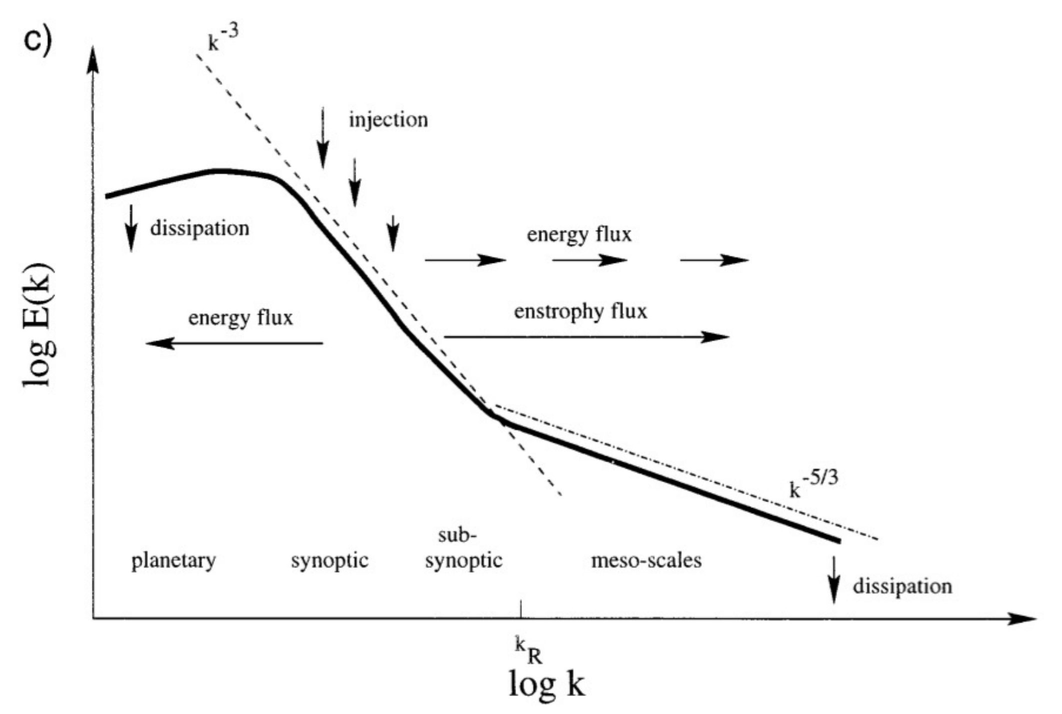
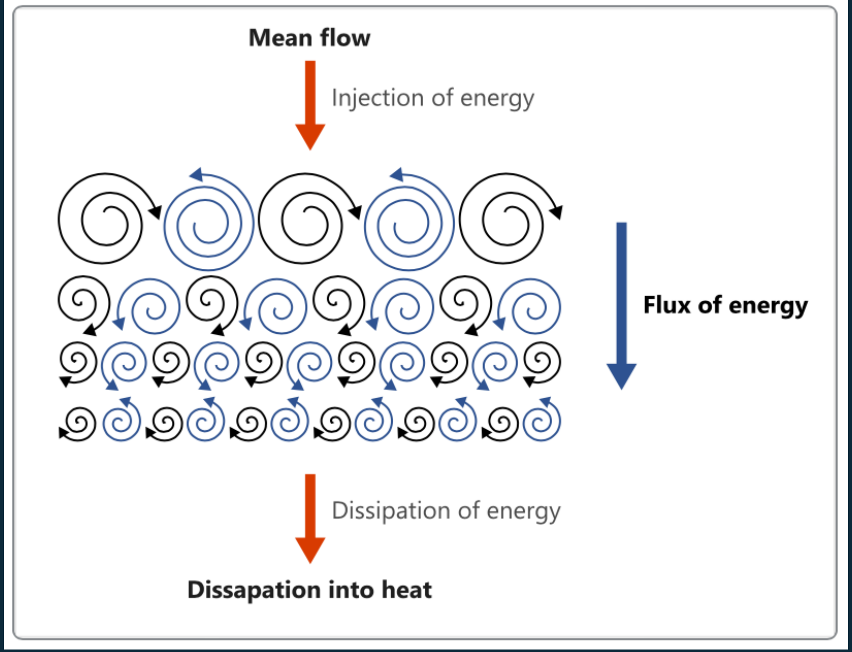


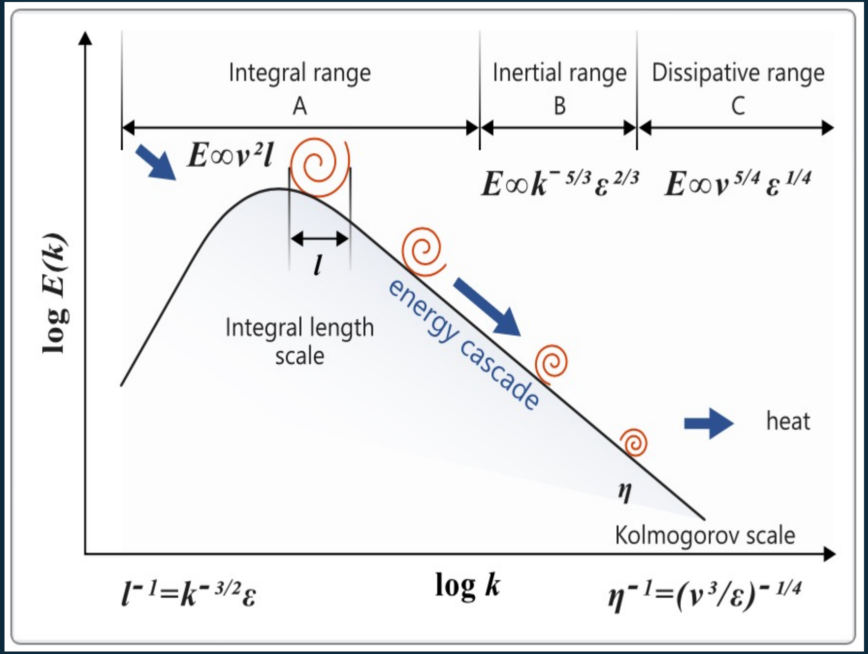
FIG. 1. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes -3 and $-5/3$ are entered at the same relative coordinates for each variable for comparison. [Reproduced with permission from Nastrom and Gage (1985).]



Tung & Orlando (JAS, 2003)

Energy Cascade





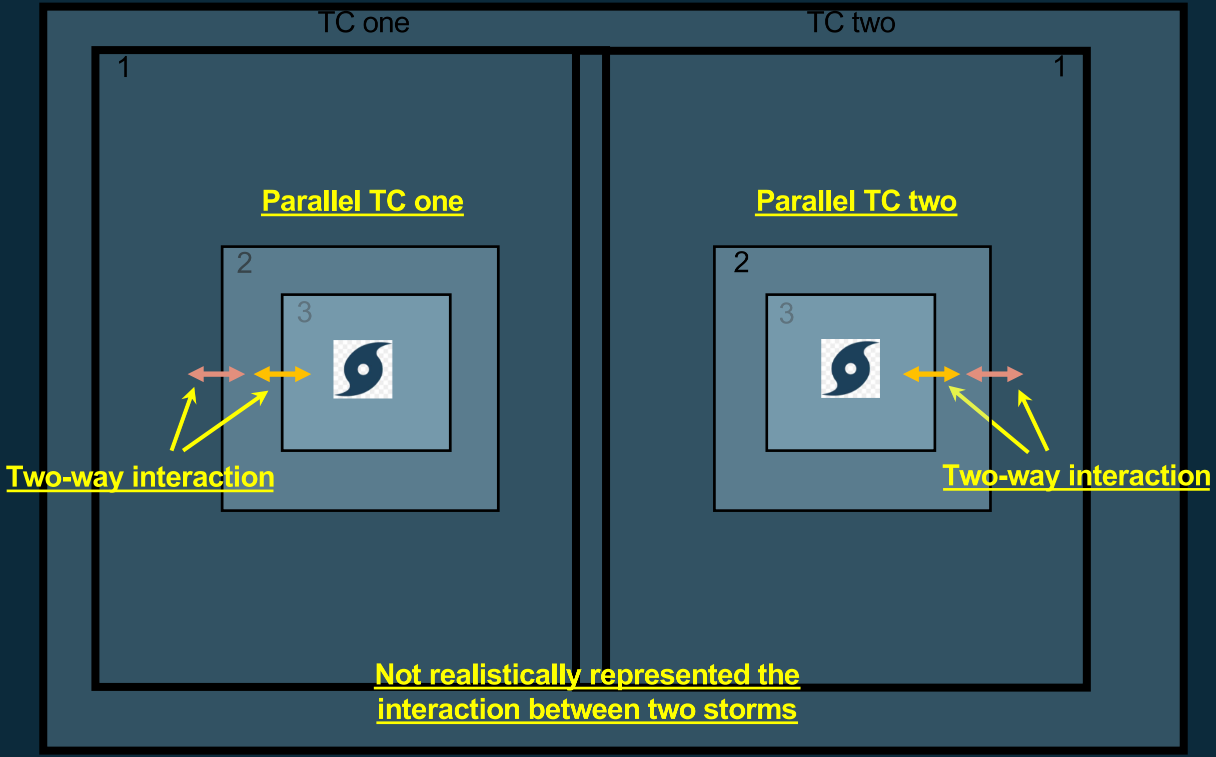
Scientific Rationale and Approach

- Preserve full-scale processes
  - Resolving better on both ends of the scale spectrum
  - Representing better on multi-scale interactions
    - Wave-wave interactions
    - Wave-mean interactions
    - Dissipation

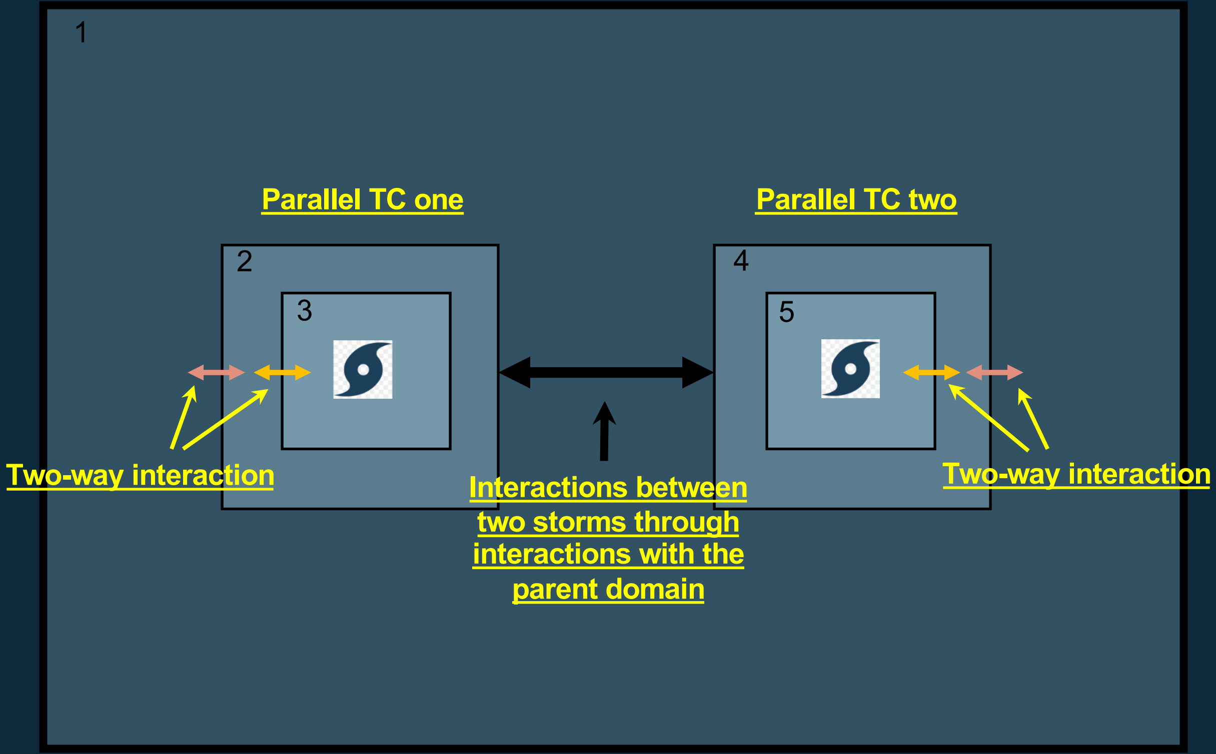
Operational Modeling System Requirements

- Quantify model bias and errors
- Facilitate coherent capacity of cycling and initialization
- Tailor a feasible tool suitable for operational forecasts
- Advance science through modeling and observations

Storm-Centric Configuration



Multiple-Storm Configuration



Zhang et al. (2016, WAF)

HAFS Development Goals

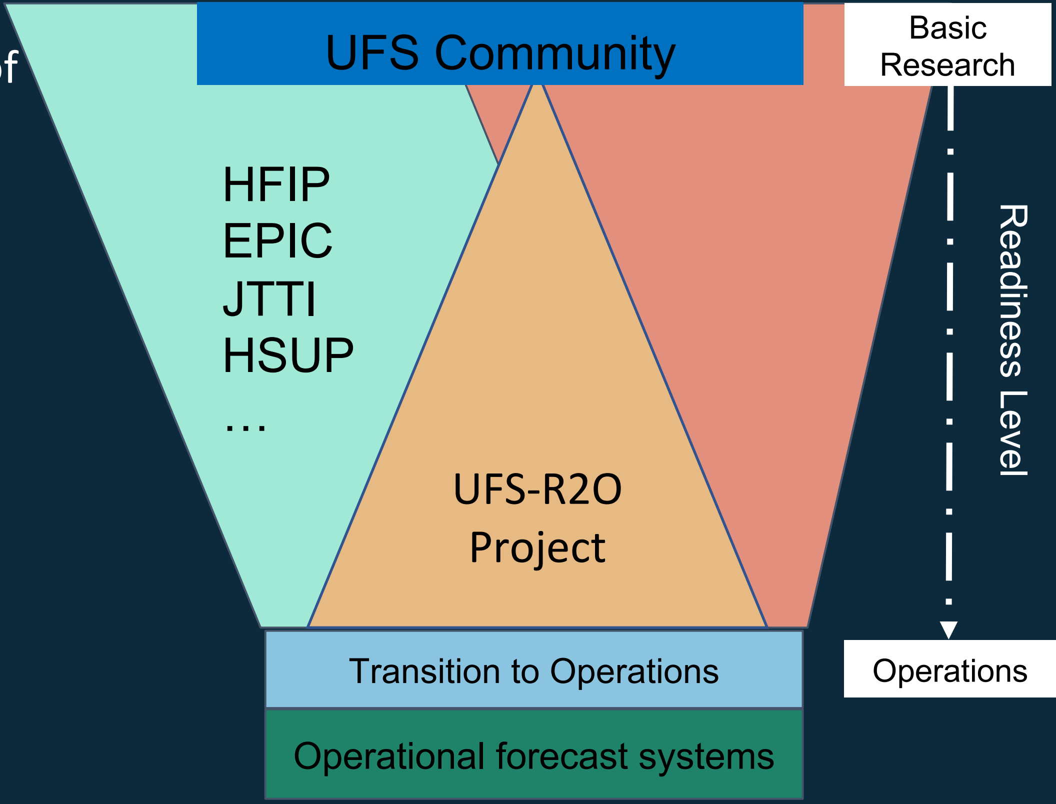
HAFS development is aligned with the latest HFIP strategic plan. Its development goals are to:

- Improve forecast accuracy
  - Hurricane impact areas (track): 50% in 5 years
  - Severity (intensity): 50% in 5 years
  - Special focus: Rapid intensity change
- Extend forecast reliability out to 7 days
- Quantify, bound and reduce forecast uncertainty
- Improve the downstream forecasts

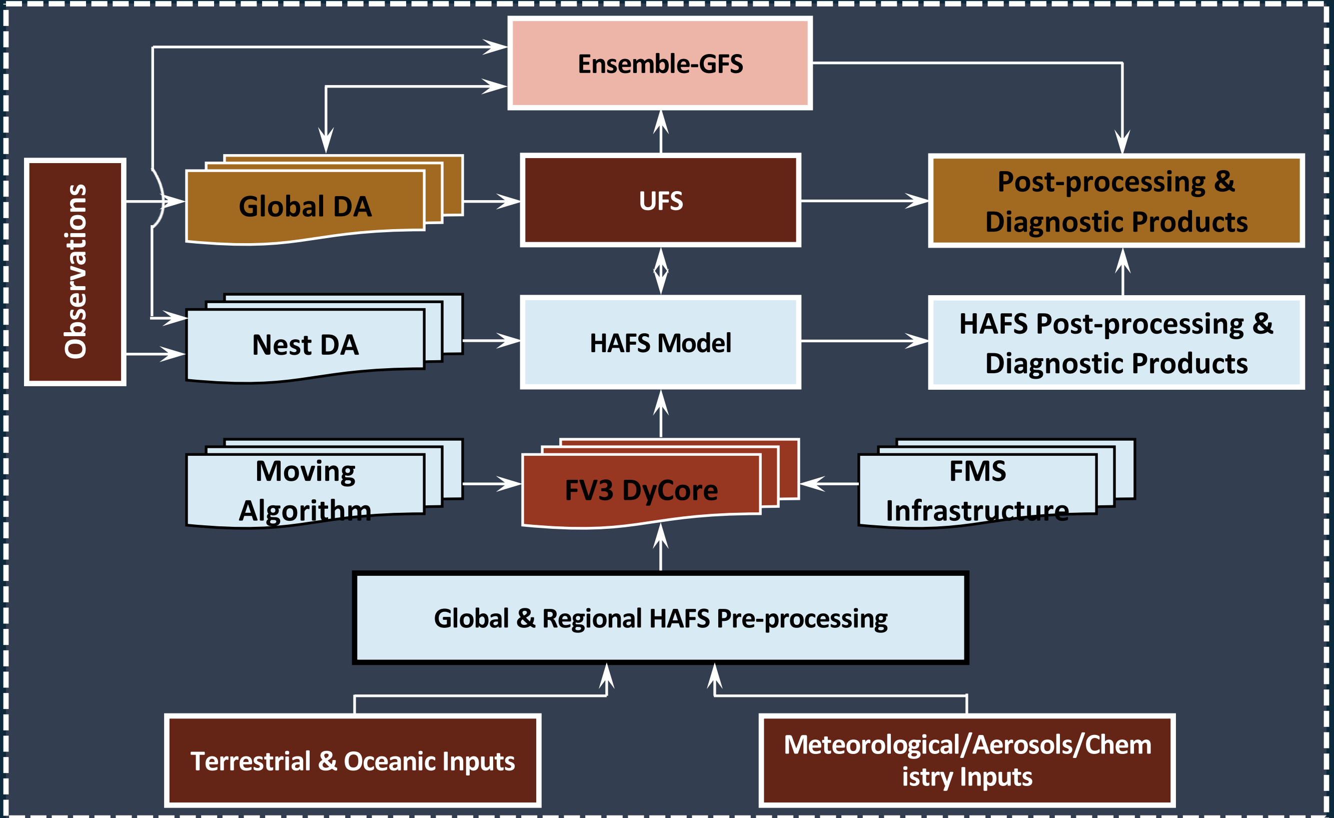
HAFS Development Approach

HAFS is a hurricane application, one of three applications in the UFS-R2O Project. Its development follows the same approach of the UFS-R2O project:

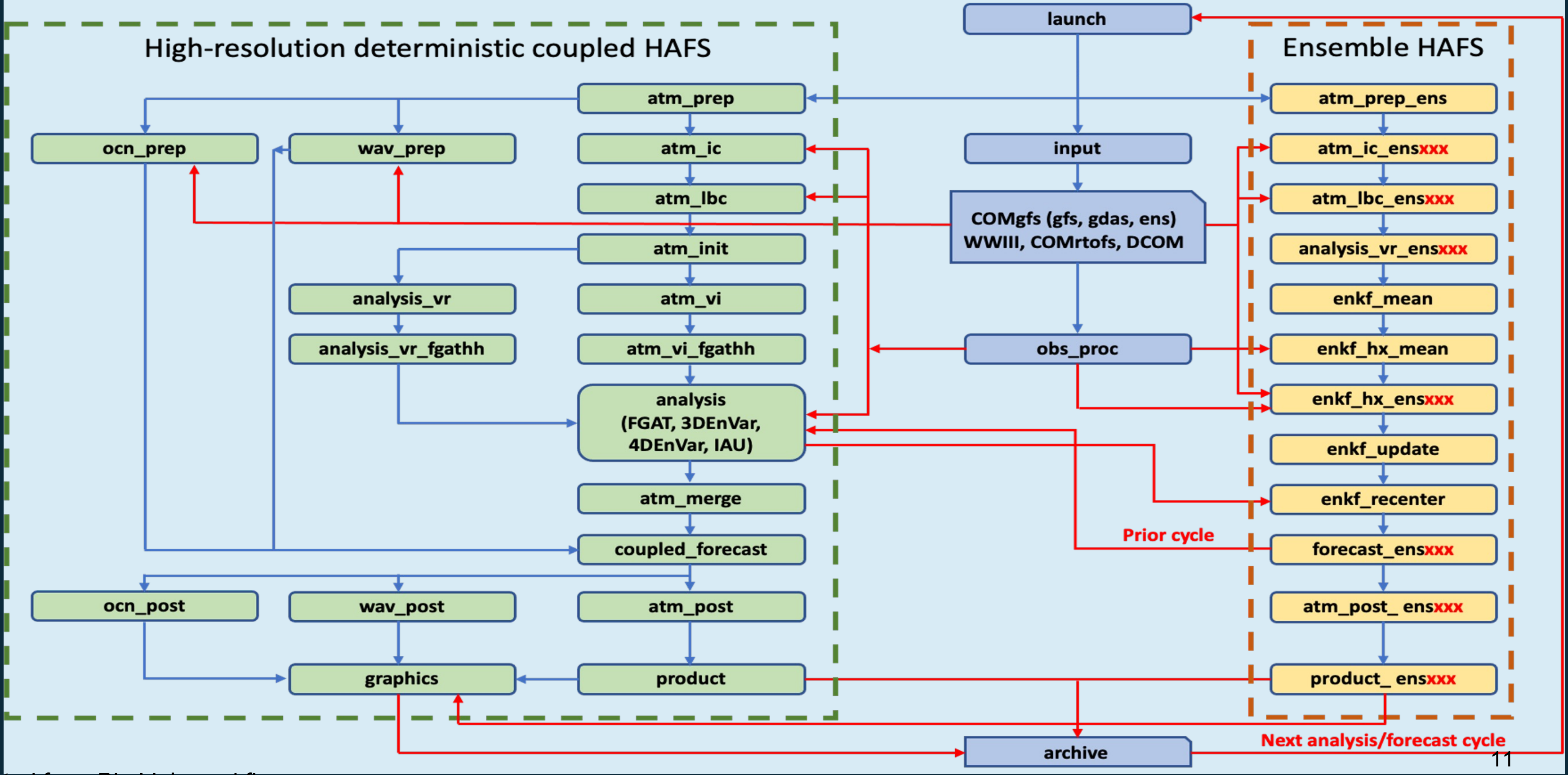
- Develop innovations into operations
- Ensure lower Readiness Level (RL) research in the R2O pipeline
- Leverage other research and development programs and projects
- Transfer high RL research into operations



Roadmap to Hurricane Analysis and Forecast System (HAFS)



HAFS Overarch Framework



Adopted from Bin Liu's workflow

HAFS Current Status

Workflow

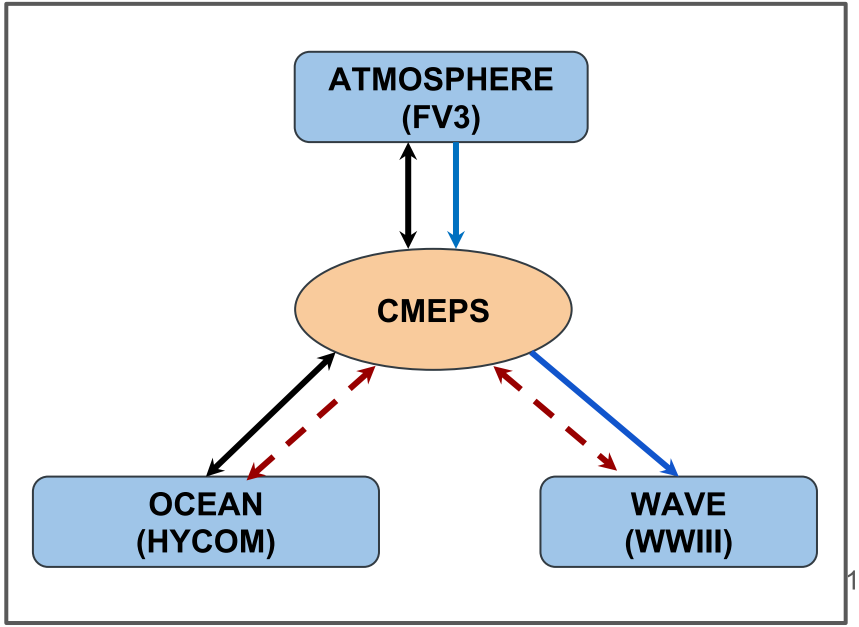
- Configurable moving nest capability
- Optional vortex initialization
- Configurable storm-region and/or entire domain data assimilation
- Post-process both parent and nest domain
- Research and forecast products
- ESG configuration

Moving nest

- Single-storm following nest
- Full physics nest motion
- Auto storm tracking
- Namelist option for moving nest
- Optimized running moving nest

Ocean/Wave coupling with moving nest

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

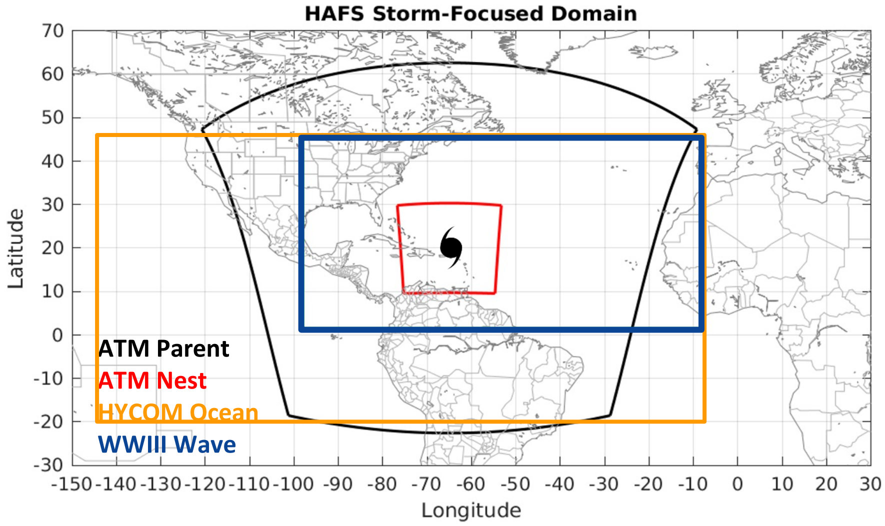


HAFS Current Status

Utilities for DA and VI
- Interpolating/remapping functions
- Merging domains
- Interface to Data Assimilation
- Vortex consistency
- First Guess at Appropriate Time (FGAT)

Data Assimilation
- 6-hourly DA cycling in nested domain region
- +/- 3-hour FGAT window
- 4DEnVar with GDAS ensembles
- Leverage observation used in GFS
- Additional observations assimilated
  - Tail Doppler Radar (TDR)
  - Next Generation Weather Radar (NEXRAD)
  - Drifting corrected Dropsondes
  - Metar observations
  - High resolution GOES-16 AMVs

Infrastructure
- WriteGrid component for multiple domains
- FMS support telescopic & multiple nests



Timelines for HAFS T2O

08/01-10/31, 2021 Complete	11/01-07/31, 2022 Ongoing	08/01-10/31, 2022 Planned	11/01-03/30, 2023 Planned	03/31-06/30, 2023 Planned	07/01, 2023 Planned
HAFSv0.2 real time experiments	Evaluation and development	HAFSv0.3 real time Experiments	We are here Evaluation and developments	HAFSv1.0 implementation	NCO implementation

Prepare New configurations (HAFSv0.3):

- High resolution moving nest
- Updated model physics
- Vortex initialization and Inner-core data assimilation
- T&E to select optimal configurations

Finalize HAFSv1.0

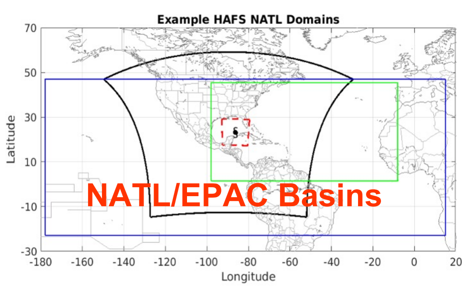
- New GFSv16.3 input
- ESG grid with Dynamic core diffusion tuning
- Vortex initialization threshold
- 4DEnVar using GDAS ensemble
- Enhanced GOES-R AMVs and GOES-18
- NOAH MP LSM with VIIRS Veg Type
- Ocean coupling bug fix
- Unified Gravity Wave Drag, uGWP
- Code modernization and optimization
- Model instability
- JTWC basins T&E

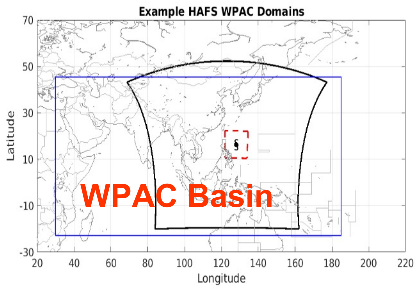
HAFS Physics Schemes

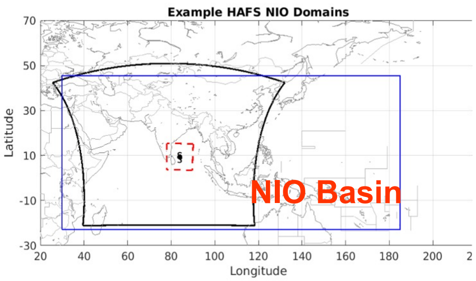
	Suite 1	Suite 2	References
Land/ocean Surface	NOAH LSM VIIRS veg type, HYCOM	NOAH LSM VIIRS veg type HYCOM	Ek et al. (2003) …
Surface Layer	GFS, HWRF TC-specific sea surface roughnesses	GFS, HWRF TC-specific sea surface roughnesses	Miyakoda and Sirutis (1986); Long (1984, 1986)
Boundary Layer	Sa-TKE-EDMF, TC-related calibration, **mixing length adjustments**	Sa-TKE-EDMF, TC-related calibration, **tc_pbl=1*, mixing length adjustments**	Han et al. (2019) *Chen et al. (2022)
Microphysics	**GFDL single-moment**	**Thompson double-moment**	Lin et al. (1983) Chen and Lin (2013)
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	Improved UGWPv1 (orographic on/convective off)	Improved UGWPv1 (orographic on/convective off)	Alpert et al. (1988)

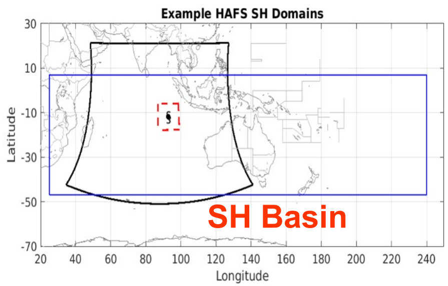
Two Configurations for HAFS IOC

HAFSv1.0	Domain	Resolution	DA/VI	Ocean/Wave Coupling	Physics	Basins
HAFS-A	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 to replace HWRF
HAFS-B	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 to replace HMON



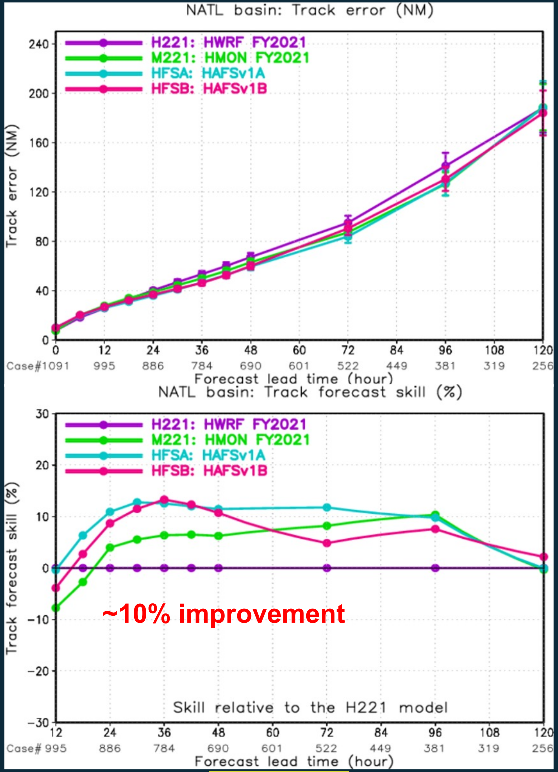




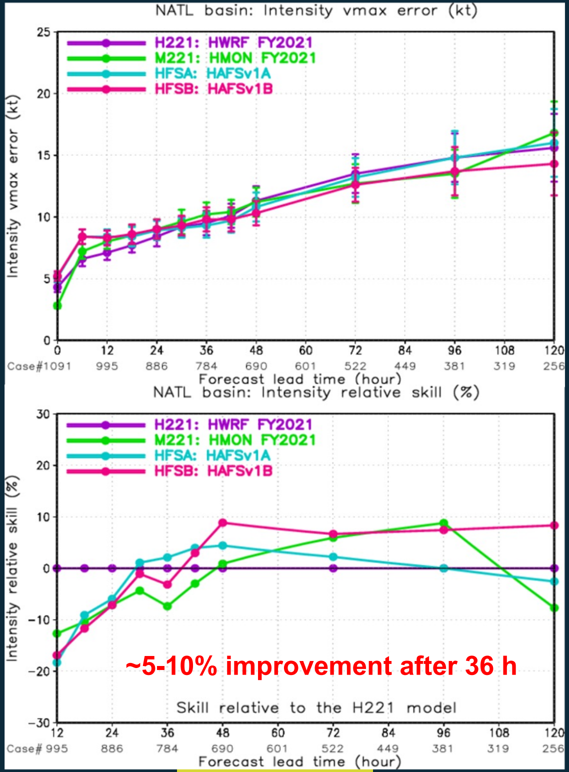


atmospheric domain, ocean domain, wave domain

There-Year Late Model Verification (NATL)



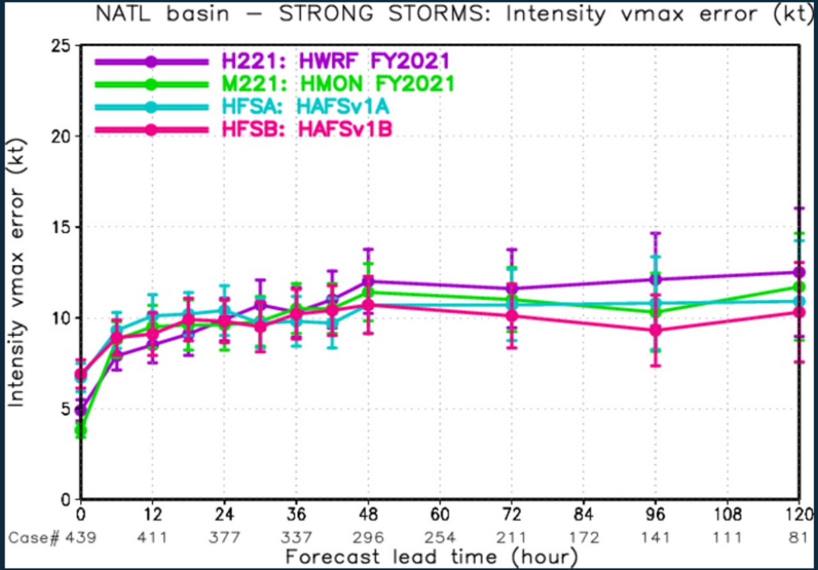
Track

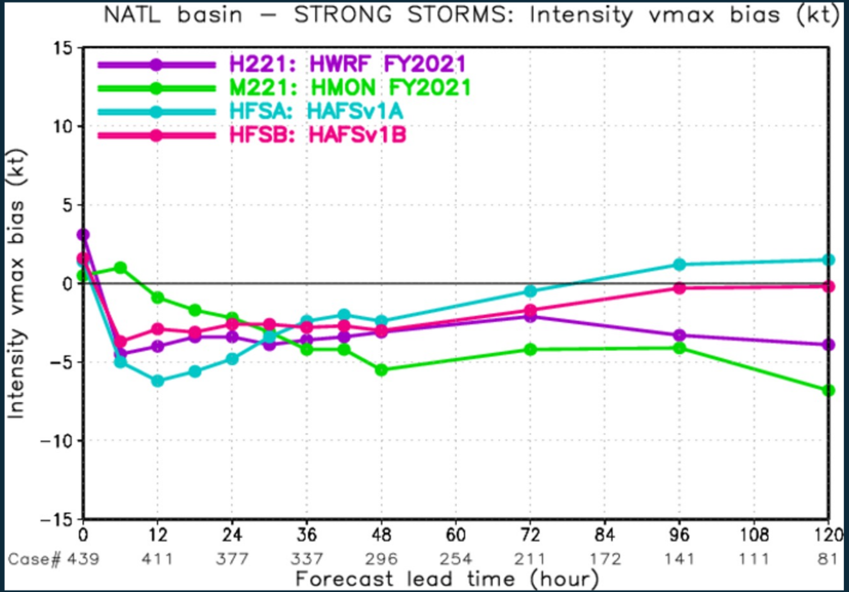


Intensity

- Improved track forecast skills at all lead times with > 10% between Days 1 and 4.
- Improved intensity skills ~10% for lead times beyond Day 2 for HFSB, and ~5% max for HFSA.
- Initial intensity spin up/down issue is noted.

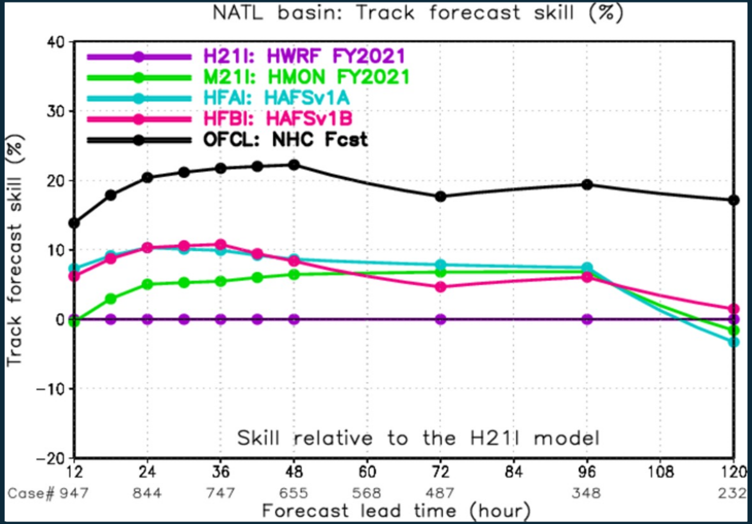
There-Year Late Model Verification (NATL)



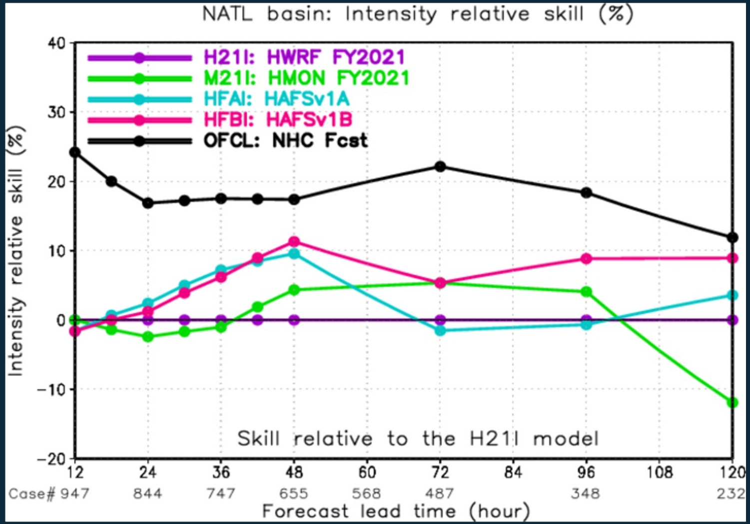


Intensity errors and biases both are reduced for strong storms after 36 hr forecast

There-Year Early Model Verification (NATL)



Track



Intensity

- Significant improvements in track at almost all lead times
- Moderate improvements in intensity at all lead times for HAFS-B and at most of lead times for HAFS-A

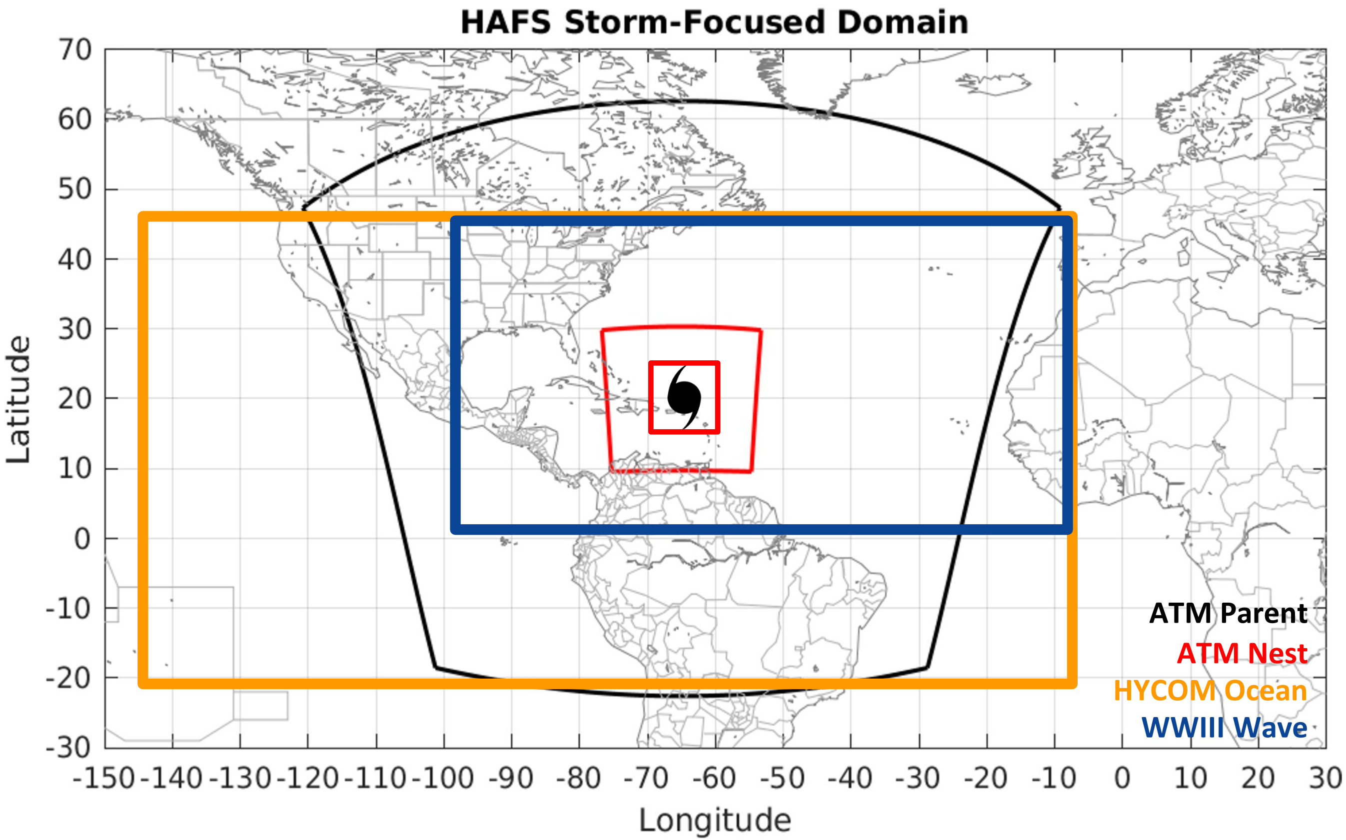
HAFS Development Priorities: after IOC

- **Moving nest**
  - Multiple storms
  - Flexible nesting refinement
  - Mass adjustment for fine topography consistency in blending zones
  - Code optimization
- **Data assimilation**
  - New data ingestion
  - 4DEnVar
  - Atmosphere/Ocean coupled DA
  - JEDI infrastructure
  - JEDI transition
- **Physics**
  - PBL for TC application
  - NOAH-MP evaluation
  - saSAS upgrade, transition, & evaluation
  - Microphysics parameterization upgrade
- **Ocean and wave model transition**
  - HYCOM to MOM6 transition
  - Atmosphere-MOM6-Wave three-way coupling
  - Coupling scheme

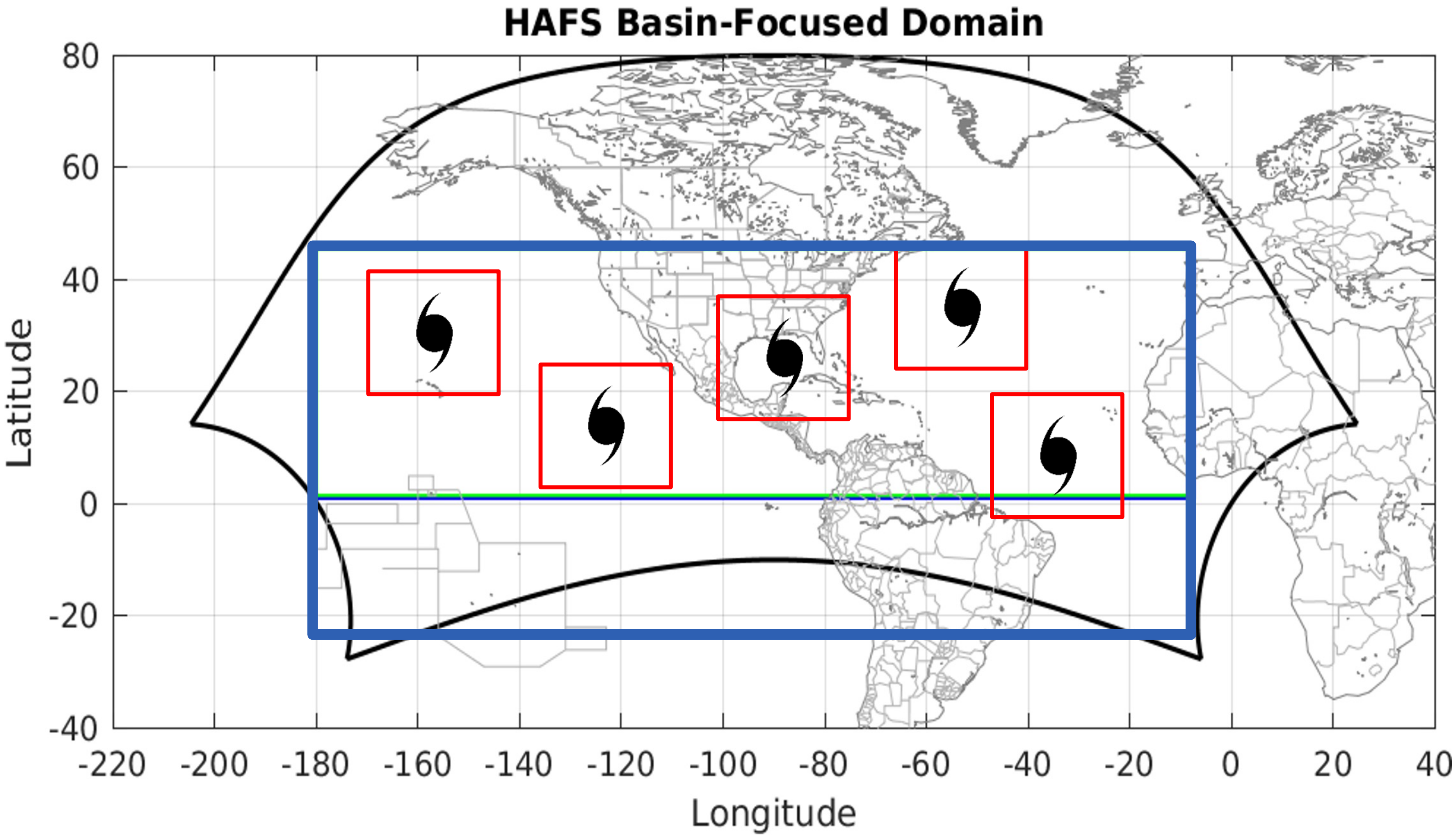
HAFS Development Priorities: future innovation

- **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
- **Products**
  - Ensemble products
  - Product fidelities
  - 7-day forecast products
- **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 (DA)

Telescopic Nest Capability



Multiple Moving Nest Capability



Summary

- HAFS completed for 2022 real-time demo and 2020-21 retrospective forecasts
- HAFS was approved for initial operational implementation in 2023 hurricane season
- HAFS development and operational implementation will prioritize the following aspects:
    - Moving nest capabilities
    - New DA capabilities, methodologies and data
    - New physics ready for high-resolution
    - Synchronize development to NOAA’s Unified Forecast System (UFS)
- Some statistics
    - AMS annual meeting (incomplete)
        - Participating six conferences
        - 35+ presentations related HAFS
        - Involving 50+ participants from public sectors, academia, and private sectors
    - Peer-reviewed HAFS related publications
        - 24+ publications before 2022
        - 26 manuscripts under review or preparation)

Opportunities and Engagement

- EPIC
  https://epic.noaa.gov/
- OAR/WPO and NWS/OSTI Notice of Funding Opportunity announcements
- OSTI UFS R2O project
- Student Opportunities
  https://epic.noaa.gov/wings-dissertation-fellowship/
- Unifying Innovations in Forecasting Capabilities Workshop (Abstract due on May 19)
  https://epic.noaa.gov/eventsposts/uifcw-2023/
- AOML modeling, DA, and observation teams welcome your visit and collaboration

List of HAFS-related Presentation (35 presentations)

13th Conference on Transition of Research to Operations

- 1B.2 - Progress Report on The Unified Forecast System Research to Operations (UFS R2O) Project: A Collaborative and Coordinated Development of MRW/S2S, CAM/SRW and Hurricane Applications
- 1B.3 - Development of UFS-based Coupled Global and Regional Operational Forecast Systems at NWS/NCEP
- 1B.5 - Advancing NOAA's Hurricane Modeling Systems: Operational Implementation of UFS-Based HAFS for 2023 and Beyond
- 2B.2 - Impacts of Different Physics Suites on the Hurricane Analysis and Forecast System Performances
- 7A.1 - The Hurricane Analysis and Forecast System: From Plan to Reality!
- 7A.2 - Development of the Regional Moving-Nesting and Ocean-Coupled HAFS Configuration for Tropical Cyclone Forecasting
- 7A.3 - Real-Time and Retrospective Evaluation of the Hurricane Analysis and Forecast System (HAFS-S Version)
- 7A.4 - Diagnosing the Relationship Between Biases in the Hurricane Analysis and Forecast System Using Innovation Statistics
- 7A.5 - Modeling Ocean Mechanisms That Improve Hurricane Forecasts
- 7A.6 - Case Studies Demonstrating the Potential Benefits of the NOAA Next-Generation Enterprise Ocean Heat Content Algorithm for Tropical Cyclone Intensification Forecasting in the Gulf of Mexico

List of HAFS-related Presentation (cont')

13th Conference on Transition of Research to Operations

- 8A.1 - Hurricane Forecast Improvement Program (HFIP): Transition to Operational Improvement of Tropical Cyclone Forecasting
- 8A.2 - Moving Nest Implementation for the Hurricane Analysis and Forecast System (HAFS)
- 8A.3 - An Improved PBL Scheme in Hurricane Conditions using Large-Eddy Simulations and Its Impact on Hurricane Forecasts from Hurricane Analysis and Forecast System
- 8A.4 Developing a Multi-Storm Configuration of the Hurricane Analysis and Forecast System
- 8A.5 - Developing the Hurricane Analysis and Forecast System: Future Priorities
- 8B.4 - Transitioning Research Innovations into the Unified Forecast System Hurricane Application
- 9B.1 - Toward the Development of Coherent Modeling Requirements that Systematically Address the Effects of Upstream Systems on Downstream Systems for NWS Analysis and Forecast Systems
- V7 - An Overview of HAFS Physics Parameterizations and Their Performance
- V102 - Using MODE to Calculate the WPC, NBM, and HAFS QPF Displacement Error for Landfalling Tropical Cyclones During the 2021 Hurricane Season
- V142 - The Use of Composite GOES-R Satellite Images to Evaluate TC Forecast By an Operational Hurricane Forecast Model

List of HAFS-related Presentation (cont’)

Second Symposium on Community Modeling and Innovation

- JointJ13A.1 - The Common Community Physics Package: Supporting Research and Operational Needs of the Unified Forecast System

Fifth Special Symposium on Tropical Meteorology and Tropical Cyclones

- 5.5 - Parameterization of Environmental Wind Shear Effect in the NCEP GFS Planetary Boundary Layer and Convection Schemes and its Impact on Hurricane Intensity and Track Forecasts
- 6.3 - Improvements in the Assimilation of Tropical Cyclone Inner-core Observations in NOAA's Next-Generation Hurricane Analysis and Forecast System (HAFS)
- 6.4 - Evaluation of the Coupled Ocean Response in the Hurricane Analysis and Forecast System (HAFS) during the 2022 Hurricane Season
- 10.4 - Evaluating and Post-processing HAFS version A QPF over the Tropical Atlantic for the 2020 and 2021 hurricane seasons
- 667 - Case Studies of Hurricane Landfalls in the Hurricane Analysis and Forecast System Moving-nest Configuration
- 670 - Improving Hurricane Forecasting Through Supplemental Program Projects
- 664 - Evaluating the Skillfulness of High Resolution Model Forecasts of Tropical Cyclone Precipitation using an Object-Based Methodology

List of HAFS-related Presentation (cont')

27th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS)

- 6B.2 - Impacts of CyGNSS v3.1 L2 Winds on Analyses and Forecasts of Tropical Cyclones in Regional OSEs
- 8B.2 - Assimilation of TROPICS Pathfinder Radiance Observations from Ida (2021) in HAFS
- 11th AMS Symposium on the Joint Center for Satellite Data Assimilation (JCSDA)
- 8ii.2 - A JEDI-Based Regional Ocean Data Assimilation System for HAFS
- 8ii.3 - Current Capabilities and Future Plans for SOCA: The JEDI Based Marine Data Assimilation System
- 11B.2 - Tropical Cyclone Hazards Evaluated using Recent Advancements in Ensemble Data Assimilation

22nd Conference on Artificial Intelligence for Environmental Science

- 904 - The Development of a Tropical Cyclogenesis Index with a Consensus Machine Learning Model using the HAFS Dataset

22nd Annual Student Conference

- S244 - Applying the Method for Object-based Diagnostic Evaluation (MODE) to Precipitation Associated with Tropical Cyclones