Overview: State of the Science of UFS

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With many thanks for inputs from UFS-R2O Team Leads

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Outline

- UFS as a community forecast system for research and operations
- UFS-R2O Project: Community of UFS Developers
- Three Years of Science Infusion
- Where do we stand compared to other systems?
- What is still needed to realize the vision?

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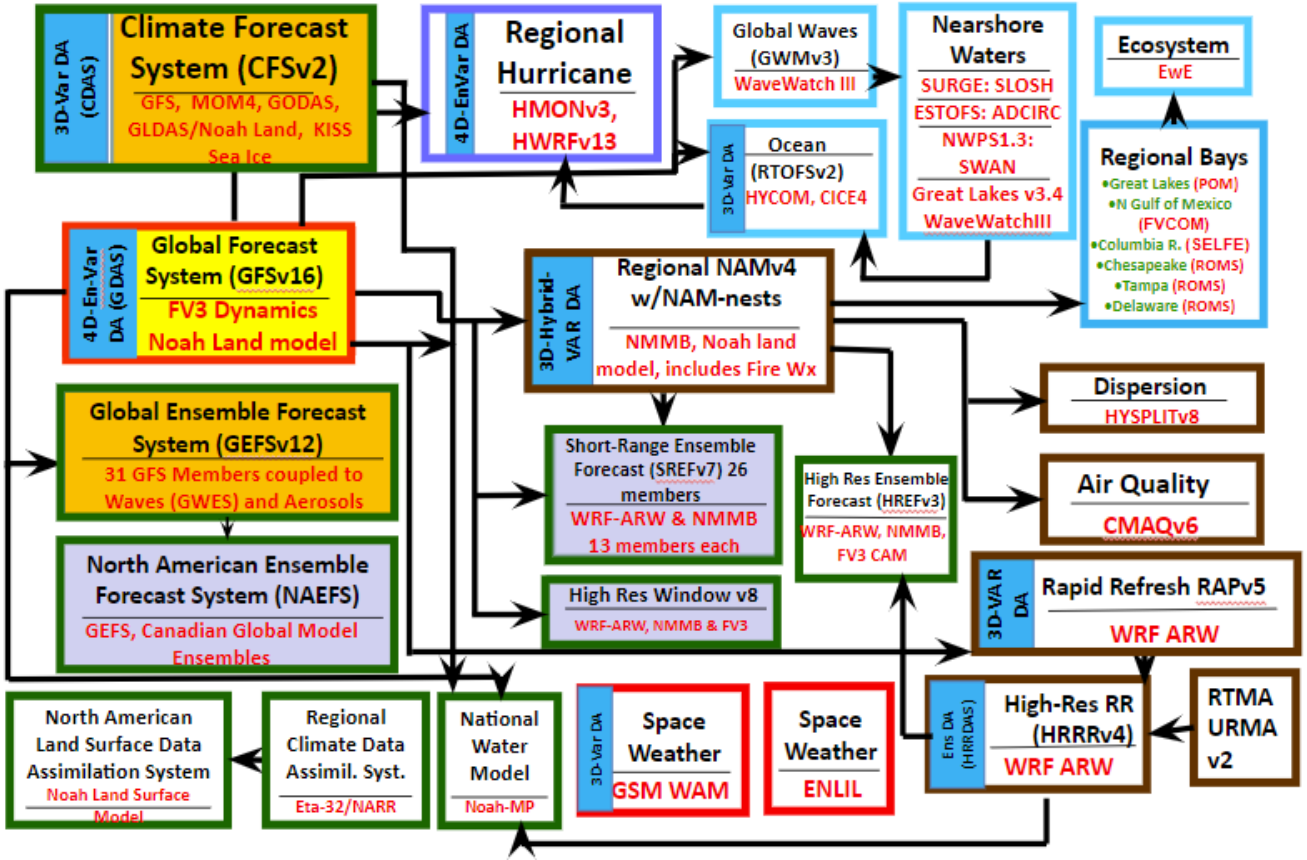
Inspiration

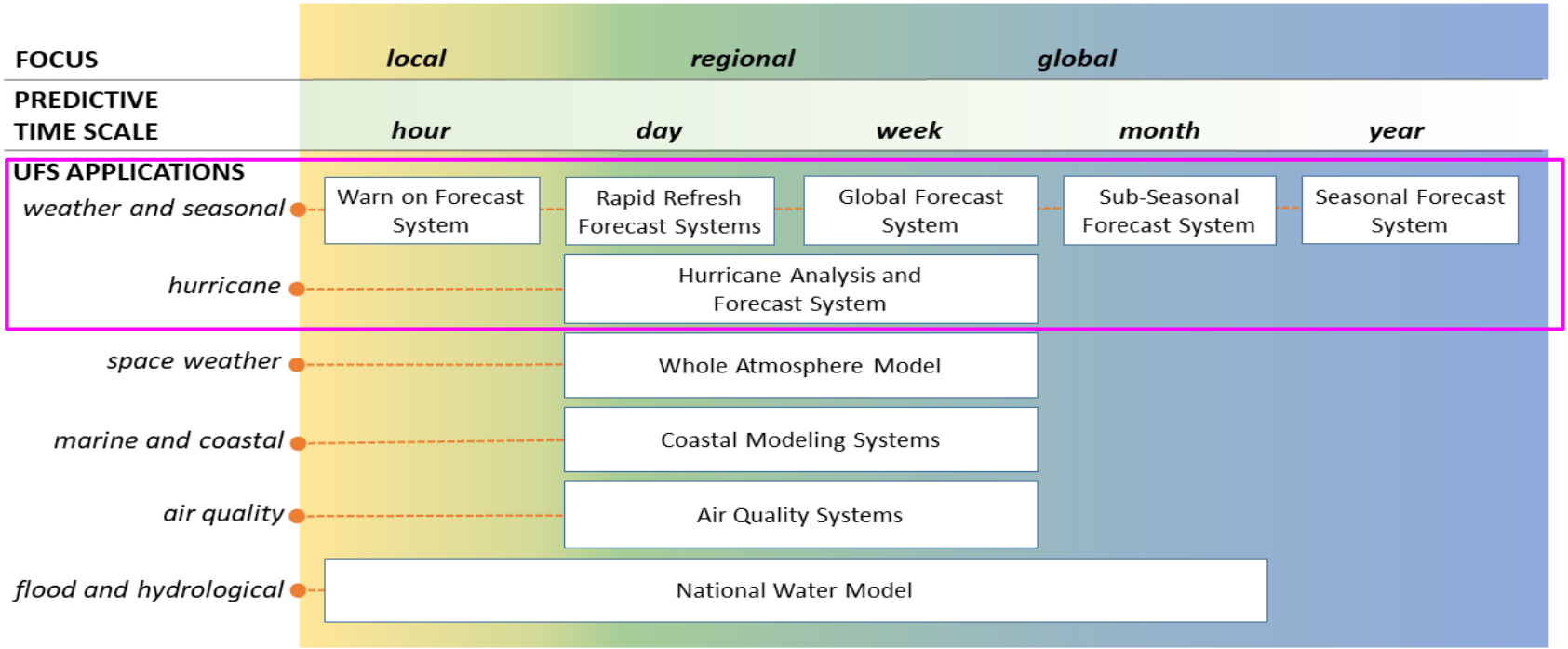
- From UCAR Modeling Advisory Committee (2018 report):
  - NOAA must be “all-in” in developing and deploying a unified community model, with a unified collaborative strategy
  - NOAA Modeling & Data Assimilation needs to be integrated and collectively managed
- NGGPS selection of FV3 dynamical atmospheric core
- Establishment of Unified Forecast System (UFS)
- From EPIC Vision and Mission:
  - Accelerate scientific research and modeling contributions through continuous and sustained community engagement to produce the most accurate and reliable operational modeling system in the world.
- Status quo ante: Unmanageable/costly-to-maintain “quilt” of forecast applications

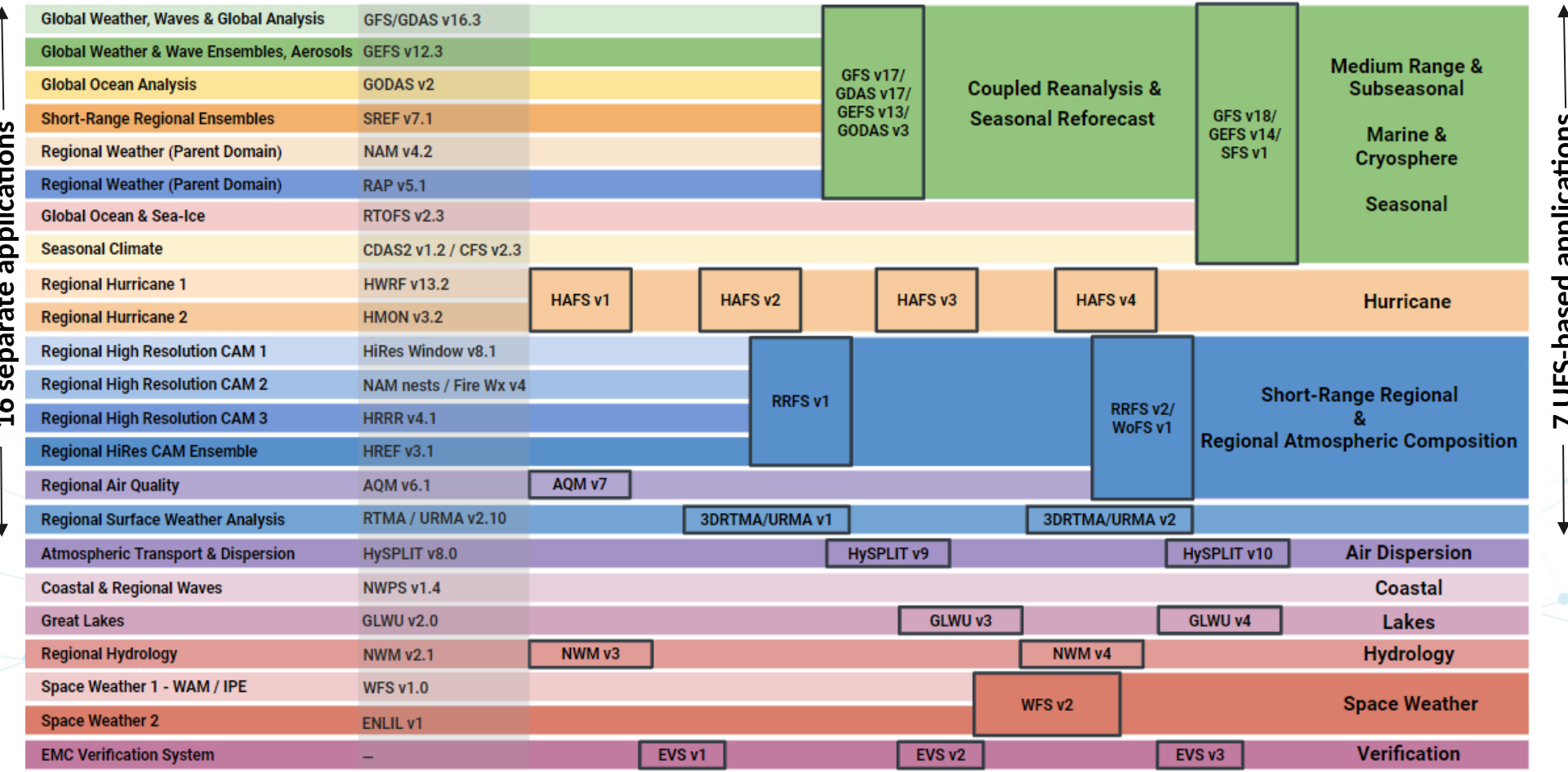
Current State of NCEP Production Suite



- NCEP operates more than 38 distinct modeling systems to meet the stakeholder requirements
- Quilt of Models developed to meet the service needs over a long period of time
- Simplification of NCEP Production Suite is critical to reduce redundancy and improve efficiency

The Goal: Transition to UFS Applications and Simplify NCEP Production Suite

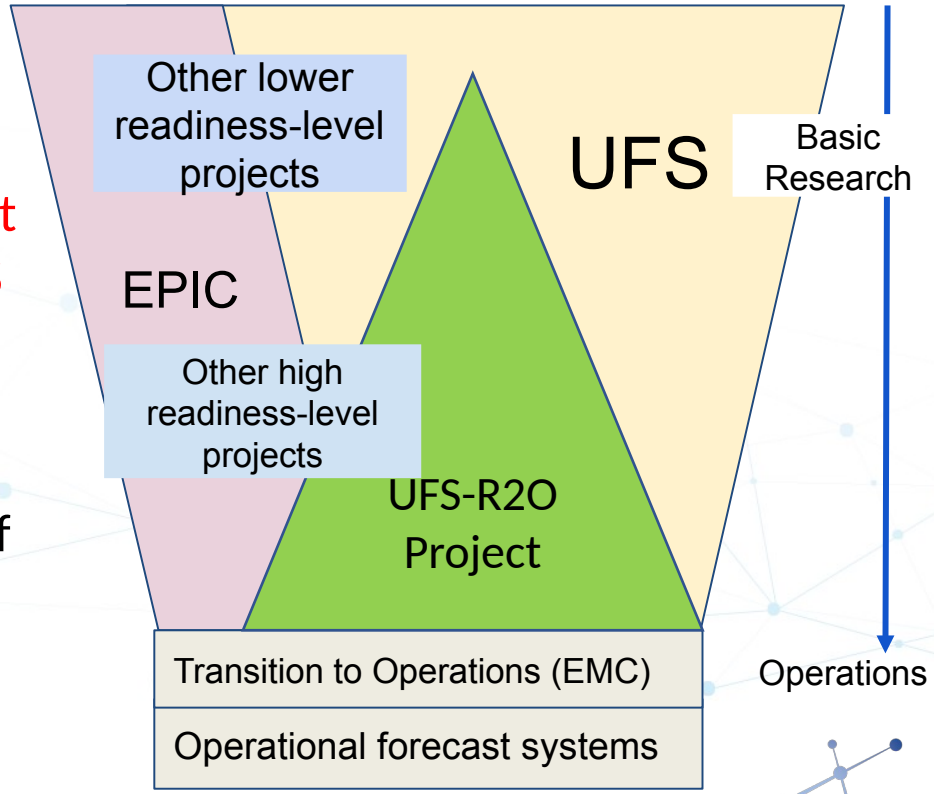




EMC Migration Plan to UFS-based Modeling Suites

The UFS-R2O Project

Launched in 2020, the UFS-R2O project is a broad collaboration within the UFS community intended to accelerate innovations into NOAA operational modeling for weather and climate prediction. It focuses on the transfer of innovations into operations based on priorities drawn from both forecasters and scientific developments.

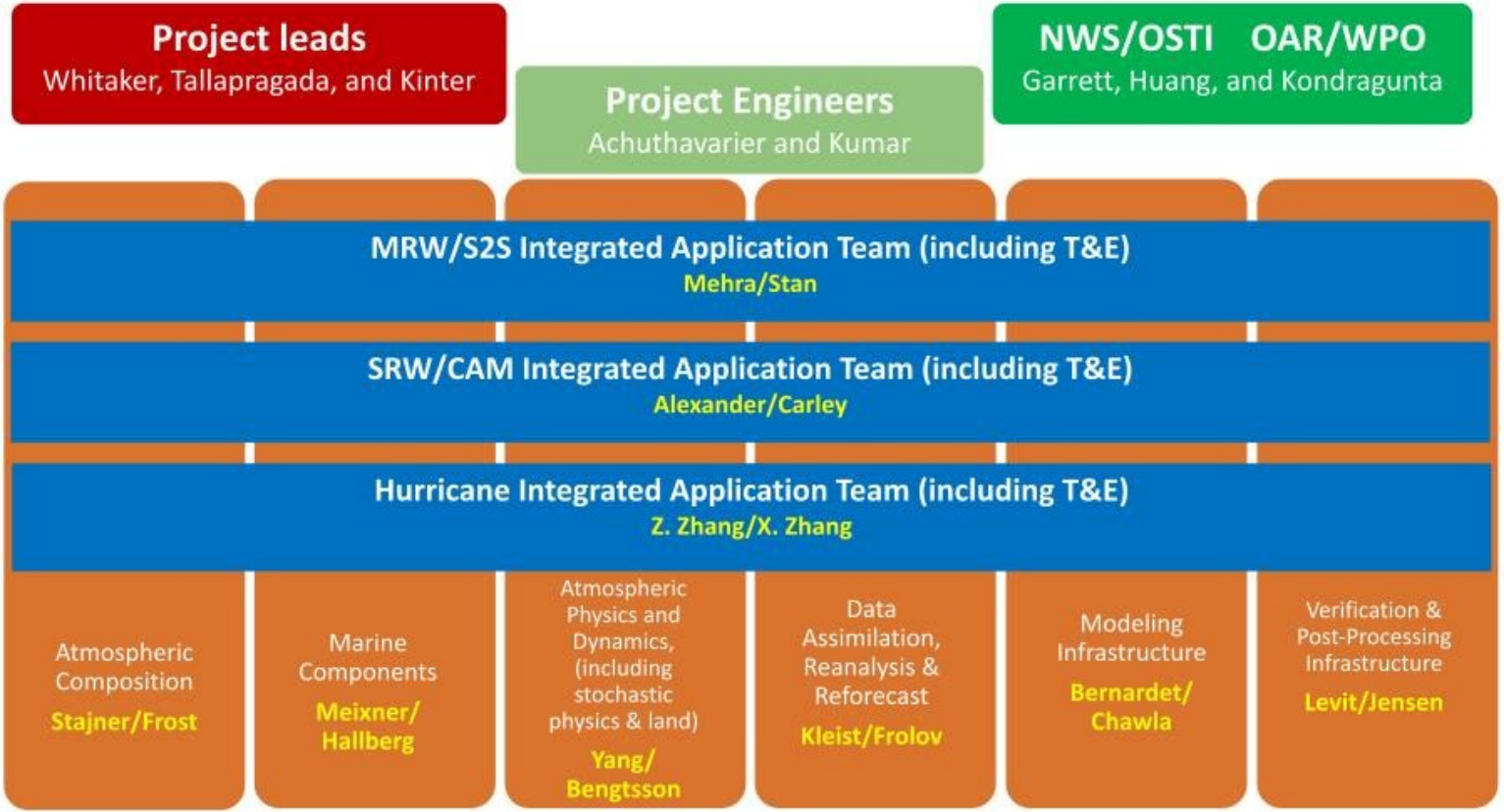


Scientific Priorities

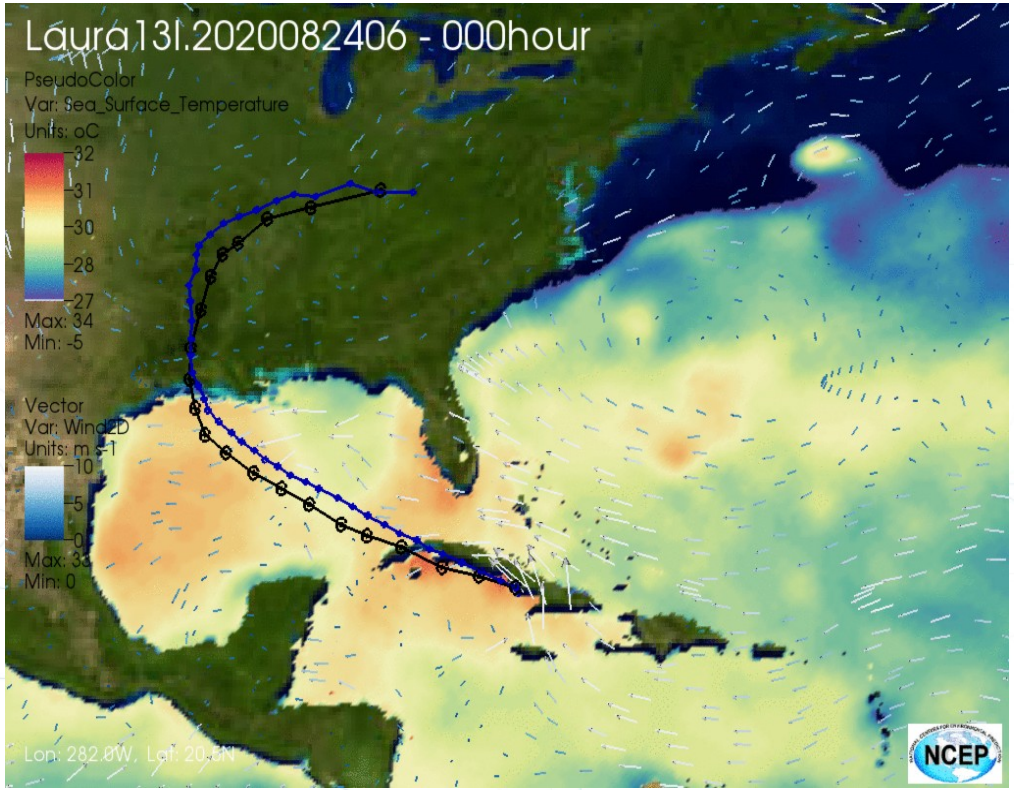
Motivated by forecast priorities collected from stakeholders/testbeds

- Reduce coupled model biases
- Improve representation of key modes of variability (e.g. MJO)
- Optimally combine Earth system observations and model forecasts using an advanced data assimilation system to initialize coupled ensembles (land-ocean-sea ice-atmosphere-aerosols).
- Develop a convection-allowing ensemble forecast capability for short-range prediction of severe weather and hurricanes
- Improve initialization at all scales (convective to global), through improved use of observations and advances in data assimilation algorithms.
- Improve quantification of model uncertainty in ensembles, especially near model component interfaces.

Project Structure



Hurricane Application Team



Hurricane Analysis and Forecast System (HAFS): ***to create more accurate high-resolution forecast guidance for tropical cyclones across the globe.***

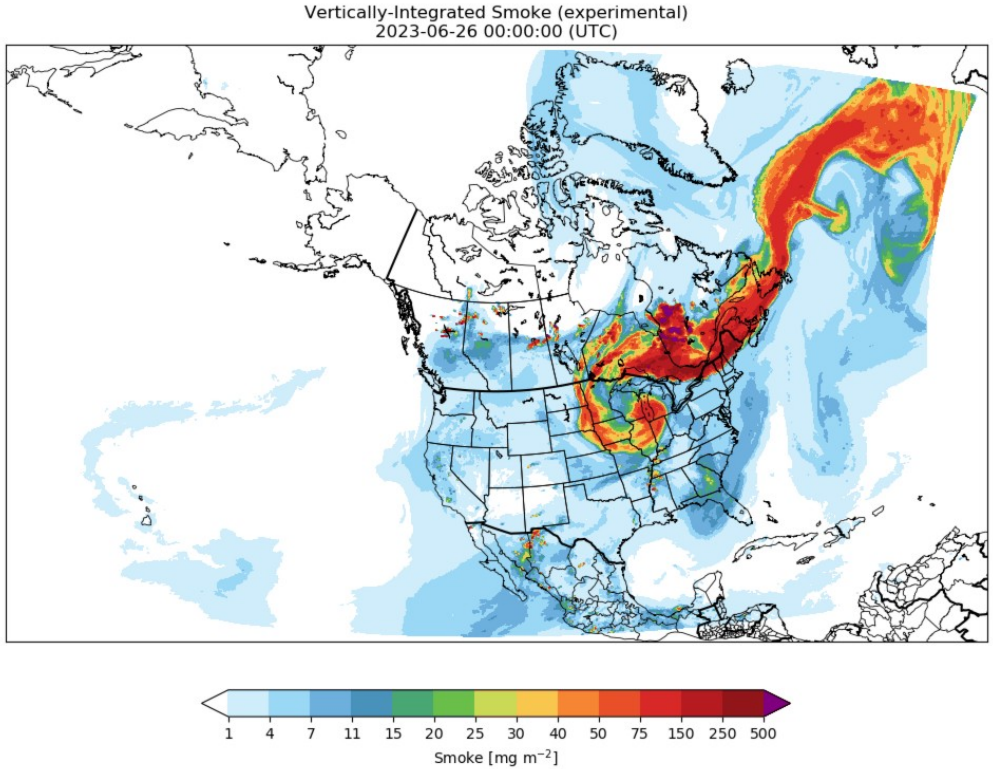
- **Coupled ATM/OCN with cloud resolving nests and coupled domains**
- **Improved physics schemes for tropical cyclones**
- **Advanced inner-core and satellite data assimilation**

HAFSv1 implemented into operations on 27 June 2023

Hurricane AT Achievements

- Developed a coupled forecast system based on FV3-LAM (ATM) and HYCOM (OCN) with moving nests
- Finalized two configurations (HAFS-A and HAFS-B) for implementation to replace operational HWRF and HMON in FY23
- Both configurations have **demonstrated significant improvement in track forecasts, and comparable performance for intensity forecasts** relative to HWRF and HMON, based on ~2,500 cycles in 3 years of retrospective forecasts

Short-Range Weather / Convective-Allowing Models AT



3 km vertically integrated smoke forecast from 26 June 2023 depicting impact from Canadian wildfires

Develop a Rapid-Refresh Forecast System (RRFS) based on UFS to replace existing hi-res modelling suite, and a 3-Dimensional Real Time Mesoscale Analysis (3DRTMA) system to support National Digital Forecast Database operations.

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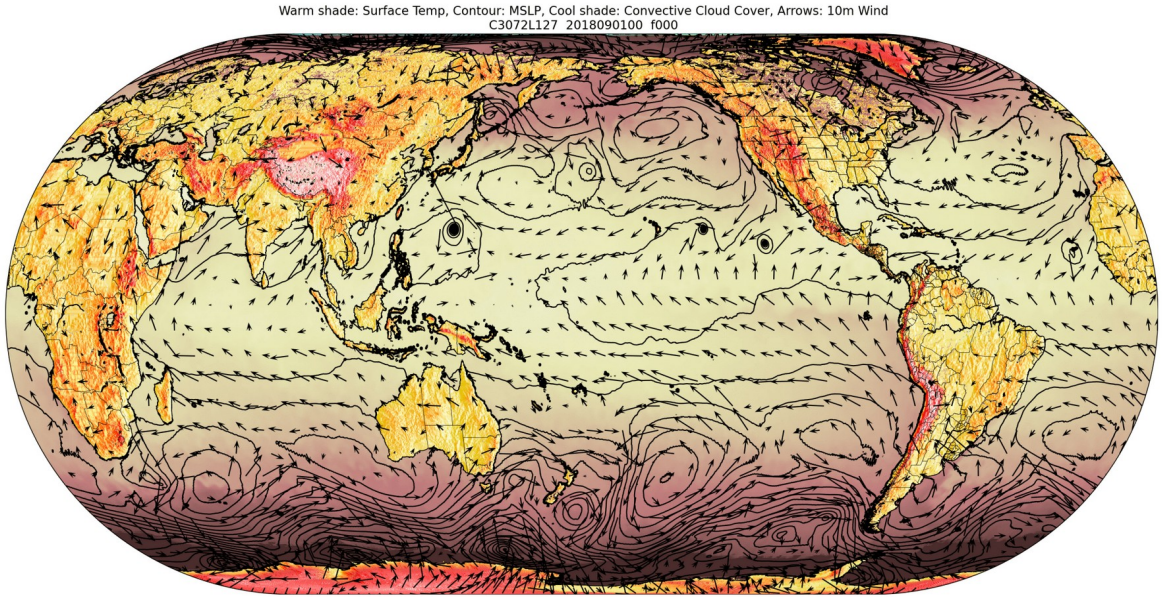
SRW/CAM AT Achievements

- Brought together regional NWP development teams across NOAA and academia
- Regional **convective-allowing, hourly-updating, ensemble system** developed based on FV3-LAM with 18-hour, 9 member forecasts (out to 60-h every 6-h)
  - Hybrid ensemble-variational assimilation (30 members).
  - Stochastic and multi-physics ensemble
- 15-minute 2.5-to 1.25 km analysis system to support NDFD operations using 1-h RRFS forecast as background
- First versions of RRFS and 3DRTMA to be implemented operationally in FY25
- **Successful real-time demonstration of a cycling ensemble-DA based RRFS in 2022/2023 NOAA testbed experiments**

Medium-Range Weather / Subseasonal to Seasonal AT



UFS Earth System Model Components:

- FV3 (Atmosphere)
- MOM6 (Ocean)
- CICE6 (Sea Ice)
- WW3 (Waves)
- NOAH-MP (Land)
- GOCART (Aerosols)

A Six-Way Global Coupled Unified Forecast System (UFS)

A fully coupled UFS serves as a foundation for future operational global forecast systems at NOAA/NWS/NCEP ranging from weather to subseasonal to seasonal scales. Coupled DA for atmosphere, ocean, sea-ice, aerosol and land components.

MRW/S2S AT Achievements

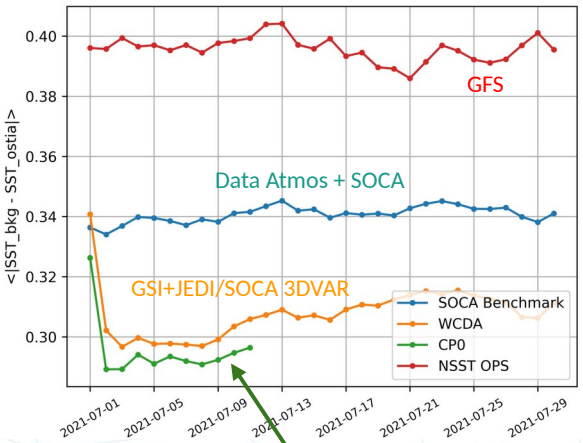
- Pre-operational testing for **implementation in GEFSv13 and GFSv17 in FY26**
- Next-gen DA system based on JEDI
  - Initially for ocean/land/aerosols, ATM in next upgrade
  - ‘Weakly coupled’ GDAS for GFSv17
- **New ATM physics package** with many community innovations
- **Ensemble system with stochastic physics** in ATM, land and ocean
- Reanalyses and reforecasts for GEFSv13
- Interactive aerosols based on GOCART
- Prototype data available in AWS

Data Assimilation, Reanalysis and Reforecast Cross-Cutting Development Team

- Accelerating non-atmospheric, JEDI-based assimilation capabilities
  - Initial OI-like snow assimilation
  - Coupled ocean/sea-ice
  - Initial capabilities for composition assimilation (in-kind)
- Produced 40-year, prototype marine reanalysis based on JEDI-SOCA
- Initial demonstration of weakly coupled assimilation prototype
  - GSI-atmosphere, JEDI-marine
- Continued improving use of observations in operational GFS/GDAS
  - All-sky microwave to include precipitating fields of view, MP-specific scattering
- Significant preparatory work for future coupled reanalysis

Weakly Coupled Data Assimilation preliminary results: SST

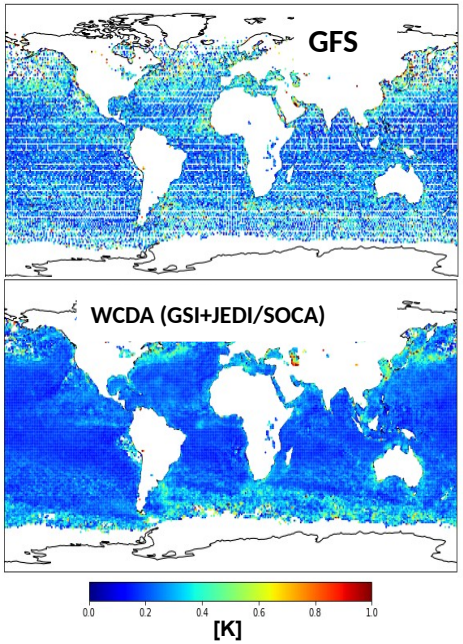
comparison against OSTIA



cp0: Status as of 07-11-2023. Ocean & sea ice hybrid EnVAR with 30 offline members

Better estimate of the foundation temperature leads to better simulation of radiances sensitive to SST.

AVHRR NOAA-18, channel 3 <|Obs-Bkg|> from SI/CRTM h(x)



- More obs passed the GSI QC
- Smaller O-B almost everywhere

Modeling Infrastructure Development Team: Common Community Physics Package (CCPP)

- Designed, developed, and implemented the Common Community Physics Package (CCPP) for the UFS and community models
- Operational transition of the CCPP to the newest UFS Hurricane Analysis and Prediction System (HAFS)
  - See the DTC lead story about this point at: https://dtcenter.org/news/lead-story
- CCPP version 6 public release (June 2022)
  - Released standalone (with Single Column Model, SCM) and as part of UFS SRW App
  - 23 supported schemes in 6 supported suites
  - Online tutorial and documentation updates (SciDoc, TechDoc, and User's Guide)
  - Support provided via GitHub discussions
  - See Heinzeller et al., 2023, GMD

CCPP Advantages

- Updated physics packages in a **centralized authoritative code repository** (CCPP-Physics) shared among research and operational communities.
- Runtime configuration of physics suites and physics packages through the CCPP Framework.
- Agile test beds and workflows enabled by the CCPP.
- **Hierarchical system development** capability enabled by the CCPP.
- Testing and evaluation capability enabled by the **CCPP Single Column Model** (SCM).

Modeling Infrastructure Development Team: ESMF

- **ESMX**, Earth System Model eXecutable layer: simplifies standing up and maintaining NUOPC-based systems and promotes hierarchical model component testing
- **Spack-based build of ESMF in UFS**, (https://spack.io/) provides more portability and flexibility
- Multi-tile Arrays and Fields (e.g., six-tile cubed sphere grid) in Read and Write operations: simplifies grid manipulations
- **ESMF-managed UFS threading**, allowing different threading levels for different components
- **Exchange grid** implemented as an option for flux calculations in UFS via CMEPS / CCPP
- Efficient writing of fields with moving nests
- Various enhancements to performance, profiling and regridding

Atmospheric Physics & Dynamics Development Team

- **Unified processes across scales**
- Upgraded or improved practically every aspect of atmospheric physics
  - First implementation of a **scale-aware convective parameterization**
  - Upgraded **two-moment microphysics** scheme
  - Enhanced **gravity wave physics**
  - Improved **PBL and convection** schemes
  - Adopted advanced land model (**NOAH-MP**)
  - Incorporated convective gray-zone considerations
- Enhanced tropical variability prediction
- Attained world-class skill in shallow cumulus cloud prediction in RRFS

Atmospheric Composition Development Team

- UFS-Aerosol: **prognostic aerosol component** of the UFS 6-way S2S coupled system
- Strong foundation for NOAA's next-generation subseasonal and seasonal forecast systems
- Fully NUOPC-compliant aerosol application, **based on NASA's GOCART aerosol model**
- Incorporates improved aerosol process descriptions (e.g., **fire emissions, dust sources, wet scavenging, and aerosol precipitation flux**)
- Includes **aerosol direct/semi-direct radiative feedback** and satellite aerosol optical depth DA
- Developed a **biomass burning emission climatology** for longer forecast times
- EMC aims to incorporate UFS-Aerosol in GEFSv13, and its performance is being tested in EP4
- Collaboration partners: NWS, OAR, NESDIS, and others

UFSR2O Project Phase 2 - Planning and Priorities

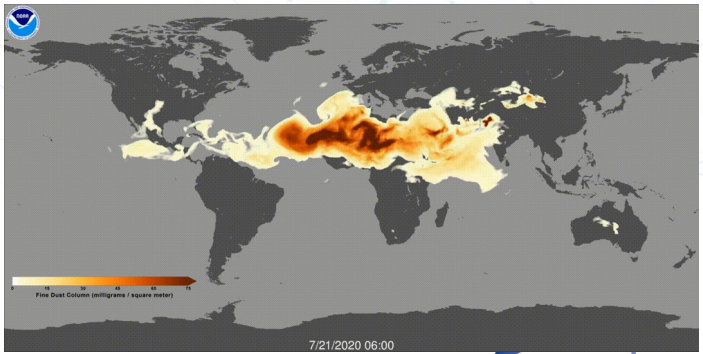
- **Phase 2: July 2023 - June 2026**
- Support multiple upcoming transitions
  - **HAFSv2 and beyond**
  - **RRFSv1 & 3D-RTMAv1**
  - **GFSv17 and beyond**
  - **GEFSv13 and beyond**
- Prioritize activities supporting **transition of externally funded projects** (Disaster supplementals, JTTI, NOFOs)
- Ensure transition of capabilities that address **forecasters feedback on model performance**
- Integrate UFSR2O with **new Seasonal Forecast Application Team**

UFSR2O Project Phase 2 - Planning and Priorities

- **MRW/S2S Application Team**
  - Produce a **fully coupled extended reanalysis and reforecast** set
- **SRW/CAM Application Team**
  - Address **long-standing convective storm structure issues** and related biases in RRFS
  - Address RRFS ensemble tendency to be under-dispersive
  - Transition to **JEDI DA**
- **HAFS Application Team**
  - Develop **multiple nest** capability
  - Transition to **JEDI DA**
  - Transition from HyCOM to MOM for ocean component
  - **Ensembles**: stochastic physics, enhanced probabilistic products, consider 7-day extension
- **Integrate new science and infrastructure from the Development Teams**

UFSR2O Project Phase II - Planning and Priorities

- **Physics and Dynamics Dev Team**
  - Enhance atmospheric physics for HAFS
  - Address challenges with gray-zone convection, 3D turbulence, scale-adaptive physics, non-stationary gravity wave drag
  - Improve physics-dynamics coupling
  - Adopt NOAH-MP across all UFS applications; hydrology
  - Tuning, tuning, tuning!
- **Atmospheric Composition Dev Team**
  - Evaluate performance of aerosol predictions and impacts on meteorological predictions in ensemble prototypes
  - Improve aerosol DA approaches
  - Extend UFS-Aerosol to seasonal scales
  - Implement UFS-Aerosol cloud microphysics
  - Incorporate simplified gas phase chemistry

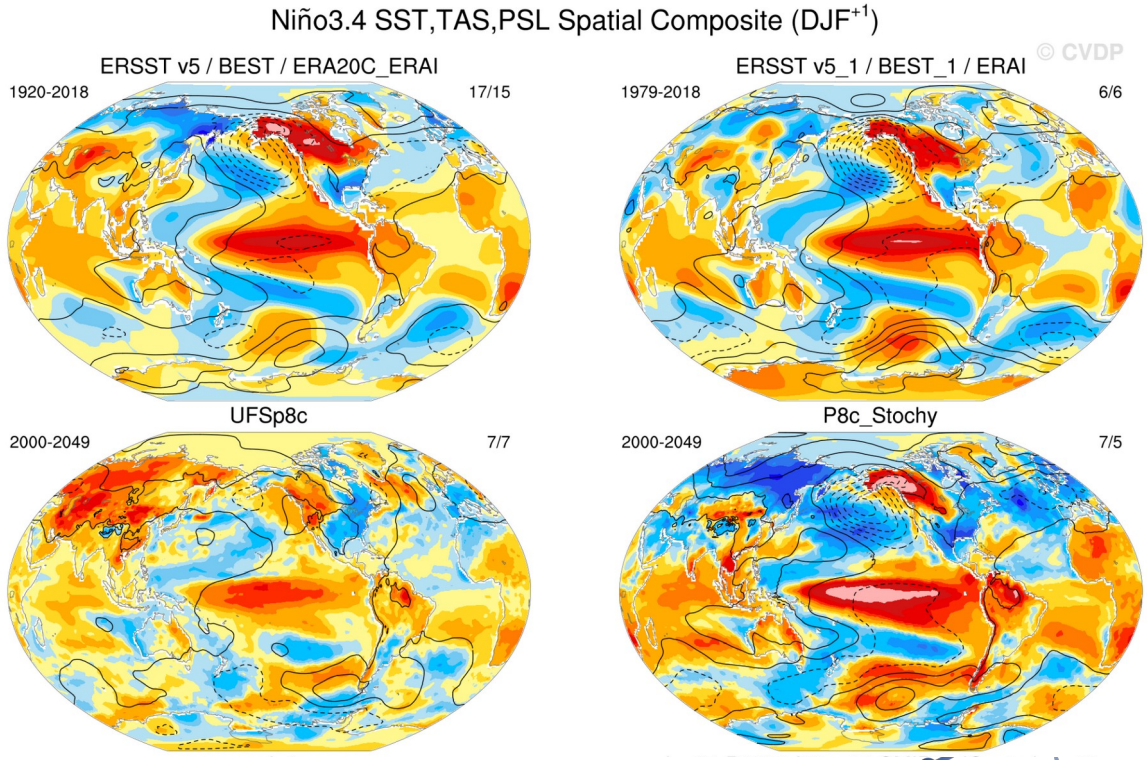


UFSR2O Project Phase II - Planning and Priorities

- **DA, Reanalysis and Reforecast Dev Team**
  - Full JEDI-based capabilities for unified DA across UFS-based applications
  - Coupled assimilation across UFS-based applications
  - Embrace and integrate new technologies, e.g., AI/ML, continuous assimilation, new/novel observations
- **Modeling Infrastructure Dev Team - CCPP**
  - Implement/include/organize new CCPP contributions in coordination with community partners
  - Single precision, GPU acceleration, improve interoperability
  - Hierarchical development: data component model and “replay” mode in Single Column Model
- **Modeling Infrastructure Dev Team - ESMF**
  - Support hierarchical model development and testing
  - Implement spherical vector regridding
  - Support developers and users of the UFS

Preparing for Seasonal Forecast AT: UFS simulates ENSO better with stochastic physics

- UFS P8 run at 1 deg w/ & w/out stochastic forcing for 50 years, the first 20 having observed CO_2 for 2000-2020, and the last 30 years with CO_2 fixed at 2020 levels.
- The stochastic physics includes both SPPT and SKEB active, using the EP3 values.
- ENSO teleconnections match observations better with stochastic physics (although ENSO SST signal too strong).



Current State of the UFS: Where do we stand compared to other systems?

- **UFS is unique in the world right now**
  - Capabilities to do operationally relevant prediction science
  - NB: There is a long way to go to realize the vision
- UFS has **end-end forecast capabilities** (data assimilation) that are lacking in other open development modeling systems that are used in the research community, e.g. CESM and WRF
- **Capabilities lag behind other operational systems** (e.g., ECMWF Integrated Forecast System and MetOffice Unified Model), but none of these have the open development model we seek.

What Is Still Needed to Realize the Vision?

- **Computing resources** (See Priorities in Weather Research)
- **Operational transitions** for all applications and **JEDI DA**
- Advance UFS as **Earth system model** to include new applications like seasonal, coastal, space weather, hydrology (See Priorities in Weather Research)
- **Reimagine the Production Suite** to enable more agile and flexible process for T2O
- **Portable systems and workflow**, with supporting datasets with capability to reproduce operational applications (EPIC).
  - Entrain wider development community working on non-NOAA systems (NSF, cloud etc.)
- **Community-driven, well-defined rules of engagement** (stages and gates) in R2O funnel
- Well defined **governance and accountability**

Questions?

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