OSTI Perspectives and Current NOAA Development of Ensemble Systems

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NATIONAL WEATHER SERVICE

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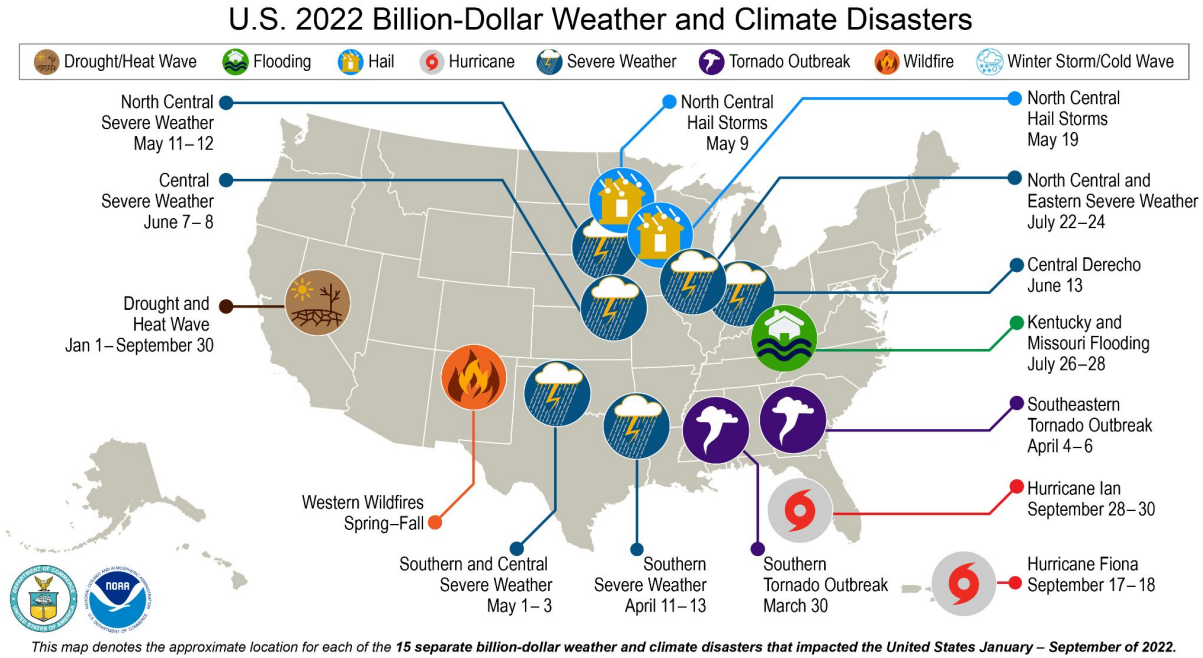
"An unbiased appreciation of uncertainty is a cornerstone of rationality – but it is not what people and organizations want. Extreme uncertainty is paralyzing under dangerous circumstances, and the admission that one is merely guessing is especially unacceptable when the stakes are high. Acting on pretended knowledge is often the preferred solution."

— Daniel Kahneman

"People want certainty; how do you present uncertainty in certain terms" … and lead them to the best decision?

w_{at}(Lead time) x w_{au}(Uncertainty) = Action/Preparedness$_a$

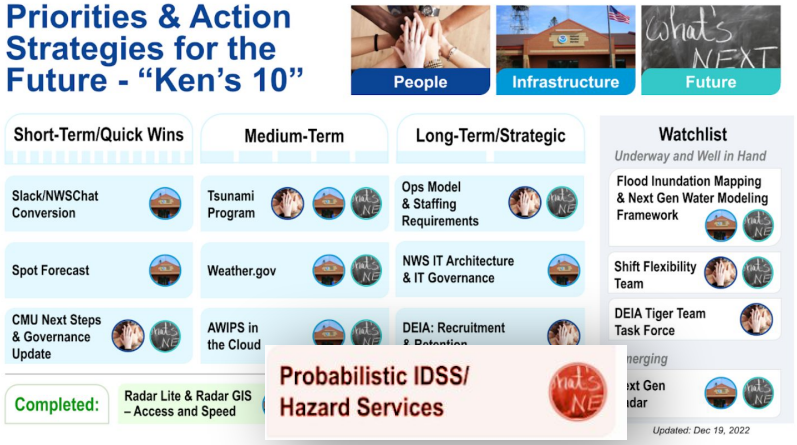
Where w is the weight for event type a



Types of extreme events require unique levels of certainty at various lead times to take action, e.g. increase preparedness/resiliency, or evacuation. Within some lead time, information is unactionable.

Ensembles key to mission and priorities

2.6: Build and Operate the world's best community-based and cross-platform numerical Earth modeling system, **with advanced ensemble prediction capabilities at all timescales**, through collaboration with our Enterprise partners, enabling increased seamless actionable warning and forecast accuracy in extended time frames.



Requirements: e.g. CaRDS 22-023 (PIC approval in progress)

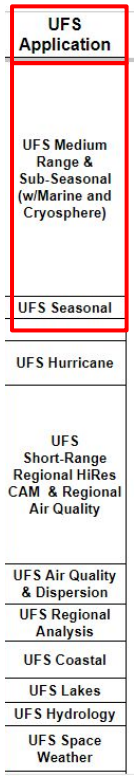
"Improve the ensemble spread in order to better capture extreme weather events"

	Priorities in Weather Research (PWR) Report Recommendations
ID-4	Prioritize research on equitable and effective use of hazardous weather information - **to better understand and inform diverse hazard and risk assessment needs, protective decisions and action**
ID-5	**Develop and evaluate probabilistic and deterministic hazard information delivery capabilities for diverse end-users -for rapid dissemination of useful products and to strengthen decision support**
ID-6	Build capacity to collect and analyze baseline and event-specific social and behavioral data -**to learn what weather information is needed when, by whom, and how it can and will be used**
FE-3	Accelerate the NOAA Artificial Intelligence (AI) Strategy and **expand artificial intelligence research -to provide higher quality and more timely products** and services for societal benefits
FE-6	Immediately invest and develop plans for substantially **more computing resources** -in order to achieve the goals recommended in this report that are vital to enhance the U.S. Weather Enterprise
FE-7	**Convert, prepare for, and leverage emerging high performance computing architectures** -to keep pace with technological advances and develop the software tools and IT workforce for the future

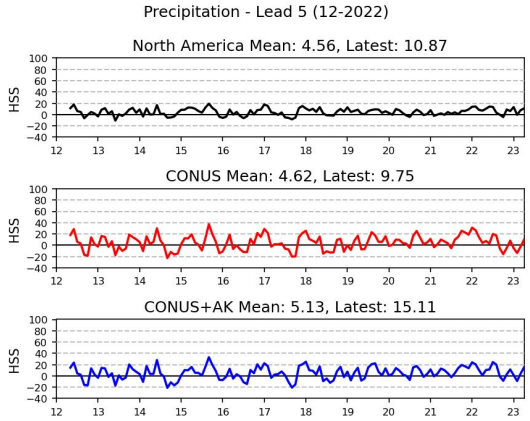
Emphasis added

Modeling/supplemental program activities

Global coupled land, ocean, sea-ice, atmosphere, *waves, and aerosol*



	GEFS v13	SFSv1
Ens size	31 or 90 members	12, 36, or 100 members
Res	25 or 35 km	25, 35 or 50 km
ICs	Coupled GDAS/Stoch phys.	EnKF/phys. tendencies/phys. param perturbations
Schedule	Daily (00/06/12/18)	1-2 times/month
Lead Times	16 days (45 at 00Z)	96 days-1 year
Compute	1.3M core/hrs at 25 km	4M core/hrs at 25 km
Implementation	Q1FY26	>FY27



North American Multi-Model Ensemble (NMME) Precipitation scores (HSS) 2012-2023
https://www.cpc.ncep.noaa.gov/products/NMME/verif/seasindex.html

Modeling/supplemental program activities

UFS Application

UFS Medium Range & Sub-Seasonal (w/Marine and Cryosphere)

UFS Seasonal

UFS Hurricane

UFS Short-Range Regional HiRes CAM & Regional Air Quality

UFS Air Quality & Dispersion

UFS Regional Analysis

UFS Coastal

UFS Lakes

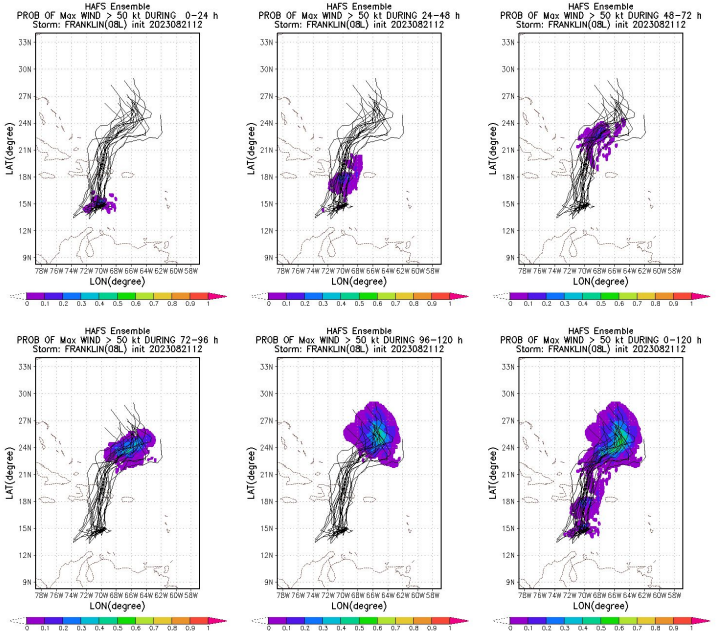
UFS Hydrology

UFS Space Weather

Development of high resolution HAFS Ensemble based on operational HAFS

HFIP 2017 Strategic Goal: Incorporate risk communication research to create more effective watch and warning products.

- 21-member ensemble with two-way ocean coupling,
- 120h forecast length 4x per day (00Z/06Z/12Z/18Z),
- Physics perturbations chosen for ability to project onto TC track, intensity, and/or structural diversity.
- Testing in 2023 near-real time experiments, alternate config (static 6km domain)



Tropical Storm Franklin HAFS Ensemble probability of wind speed > 50 kts 0-120 hrs https://www.emc.ncep.noaa.gov/HAFS/HAFSEPS/tcall.php

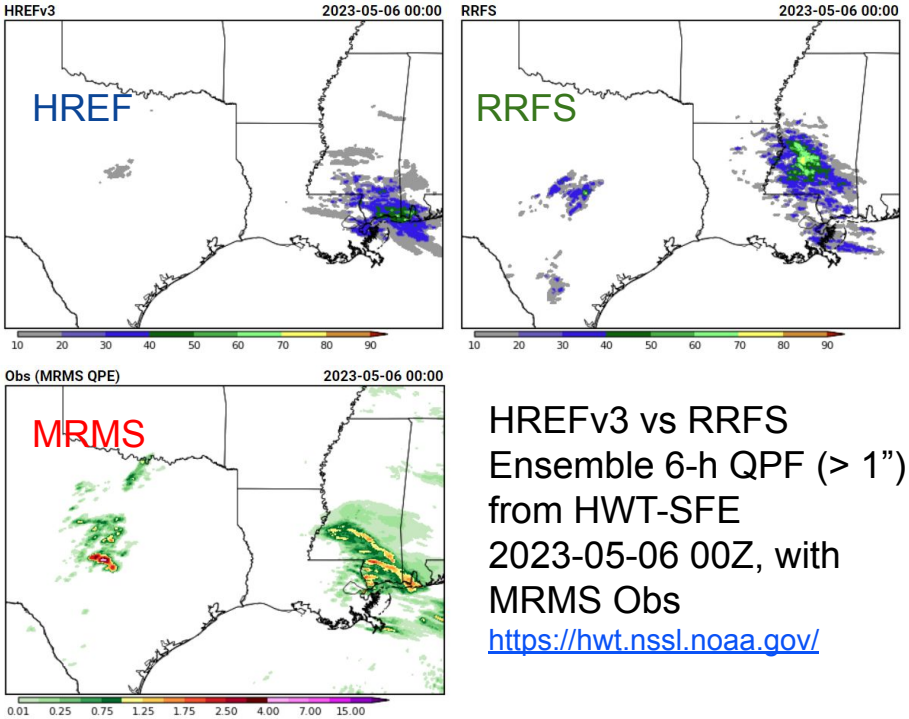
Modeling/supplemental program activities

UFS Application

- UFS Medium Range & Sub-Seasonal (w/Marine and Cryosphere)
- UFS Seasonal
- UFS Hurricane
- UFS Short-Range Regional HiRes CAM & Regional Air Quality
- UFS Air Quality & Dispersion
- UFS Regional Analysis
- UFS Coastal
- UFS Lakes
- UFS Hydrology
- UFS Space Weather

Development of the Rapid Refresh Forecast System (RRFS) Ensemble

- Replace all CAM guidance with a single North American domain forecast ensemble running at 3 km grid spacing
- ~ 10-member ensemble including time-lagged members + deterministic forecast
- 60h forecast length 4x per day (00Z/06Z/12Z/18Z)
- IC perturbations subset from ~30 member EnKF; Stochastic physics and (possibly) multiphysics; LBC perturbations from GEFS
- Current development focused on improving ensemble spread



HREFv3 vs RRFS Ensemble 6-h QPF (> 1”) from HWT-SFE 2023-05-06 00Z, with MRMS Obs
https://hwt.nssl.noaa.gov/

Other thoughts

- Mixed program oversight (OSTI/WPO through UFS-R2O, HSUPs, BIL/IRA etc) but the bottom line is UFS advancement is a community effort
- Ensemble spread should represent actual model uncertainty. Should the spread naturally reduce over time (upgrade-to-upgrade)?
- Utility of calibrating/weighting members for post-processing vs. improving ensemble approach/design (algorithms/AI can learn systematic underperformers, but why waste the CPU to generate them?)
- HPC barriers: limited operational compute means more compute needed to optimize ensemble approach (size, resolution, lead time, etc). Explore AI/emulation of ensembles
- Improving communication and understanding of probabilities: remove perceptions, biases of decision makers/stakeholders. Transform messaging

BACKUP

Key Messages (HREF, SREF, RRFS)

- Current ensemble capabilities (By system, HREF, SREF, GEFS. Provide details: Resolution, number of members, lead time, initialization time, strategy/schemes e.g. configurations and/or perturbations)
  - HREF
    - Combines multiple ~3 km models (HiresW + HRRR + NAM nest) and their time-lagged runs into an 10-member system for ensemble product generation
    - Provides guidance to 48 h for severe weather, aviation, QPF, winter weather, and general forecasting applications
    - Initialized twice a day (00Z/12Z for CONUS and Hawaii, 06Z/18Z for Alaska and Puerto Rico)
  - SREF
    - Used to assess the mesoscale environment for hazardous weather
    - Ensemble members are constructed using either a single model with different initial conditions or different models with the same initial conditions
    - 16 km horizontal grid spacing, 26-member ensemble, initialized every 6 hours (03Z/09Z/15Z/21Z)
    - Output is available at 3h intervals through 87 hours
- Current ensemble development (RRFS, HAFS/surge, GEFS, SFS).
  - RRFS
    - Replace all CAM guidance with a single North American domain forecast ensemble running at 3 km grid spacing
    - ~ 10-member ensemble including time-lagged members + deterministic forecast
    - 60h forecast length 4x per day (00Z/06Z/12Z/18Z)
    - IC perturbations subset from ~30 member EnKF; Stochastic physics and (possibly) multiphysics; LBC perturbations from GEFS
    - Requires 184K cores / 6.6 PFlops for operations and x6 for R&D (rough estimates)

Rapid Refresh Forecast System (RRFS)

- Replace all CAM guidance with a single North American domain forecast ensemble running at 3 km grid spacing
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- 60h forecast length 4x per day (00Z/06Z/12Z/18Z)
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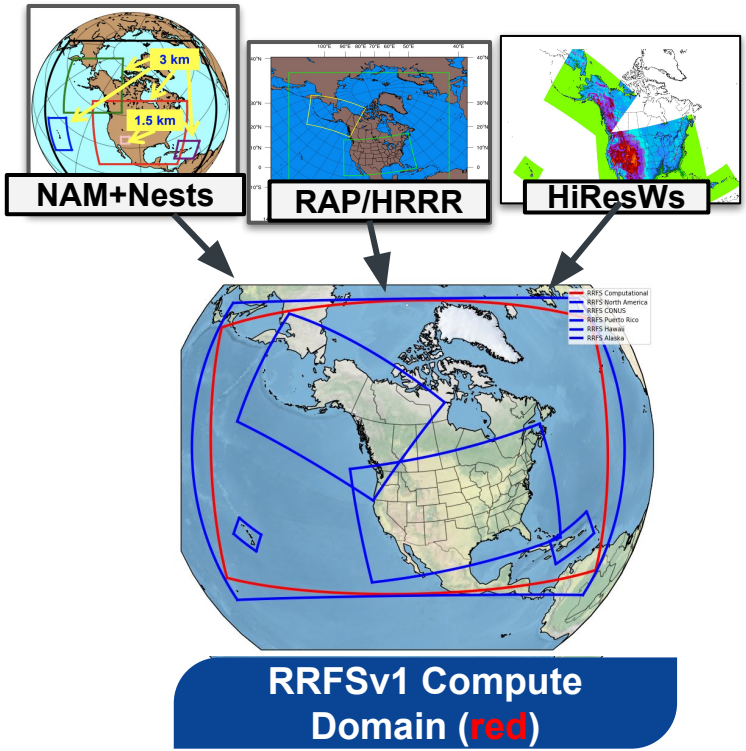
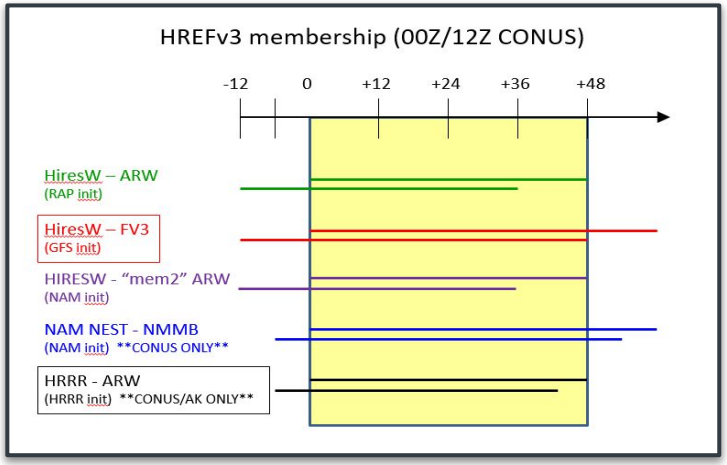
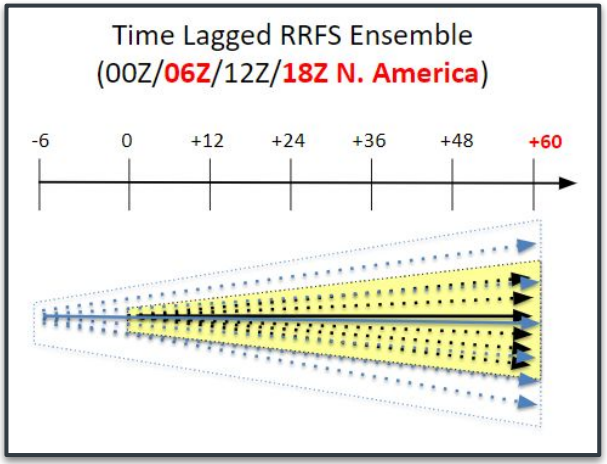


RRFSv1 Forecast Ensemble Design



- 5 on time members + 5 time lagged
- 48H forecast length 2x per day
- Multi-dycore (3)
- ICs from NAM + nests, RAP, HRRR, GFS
- Multiphysics



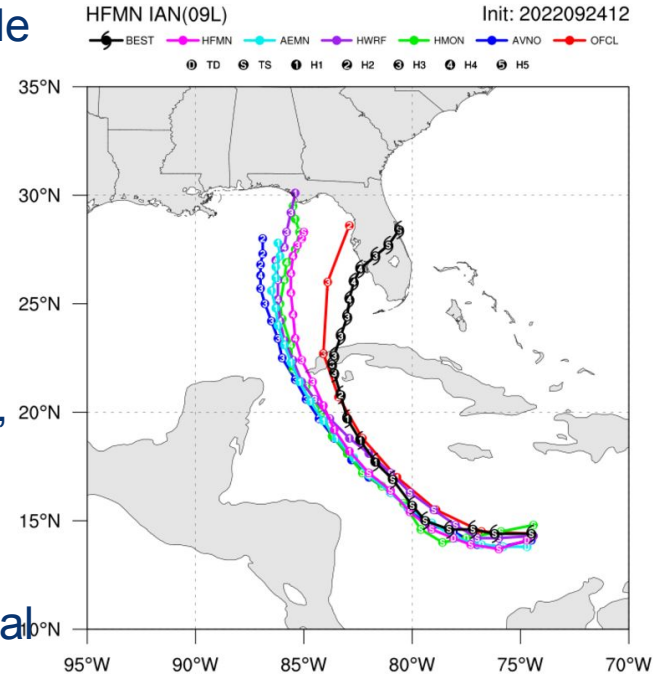
- 12 Time lagged members (complete N. America coverage)
- 60H forecast length 4x per day (54H w/ time lagging)
- Single dycore
- IC perturbations subset from ~30 member EnKF
- Stochastic physics and (possibly) multiphysics
- LBC perturbations from GEFS

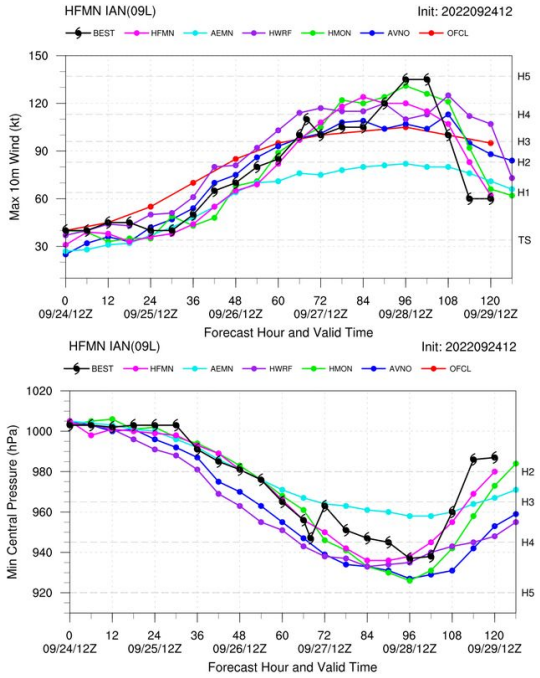
- RRFSv1 ensemble design leveraging HRRRE development and HIWT, UFS-R2O projects to incorporate methods of representing uncertainty (multiphysics, SPP, etc.)
- *Testing is ongoing to determine if v1 will have multiphysics membership*

[Jacob Carley (2023, 28th NWP Conf.)]

Hurricane Analysis and Forecast System (HAFS)
HAFS Ensemble Real-time on Cloud (HERC)

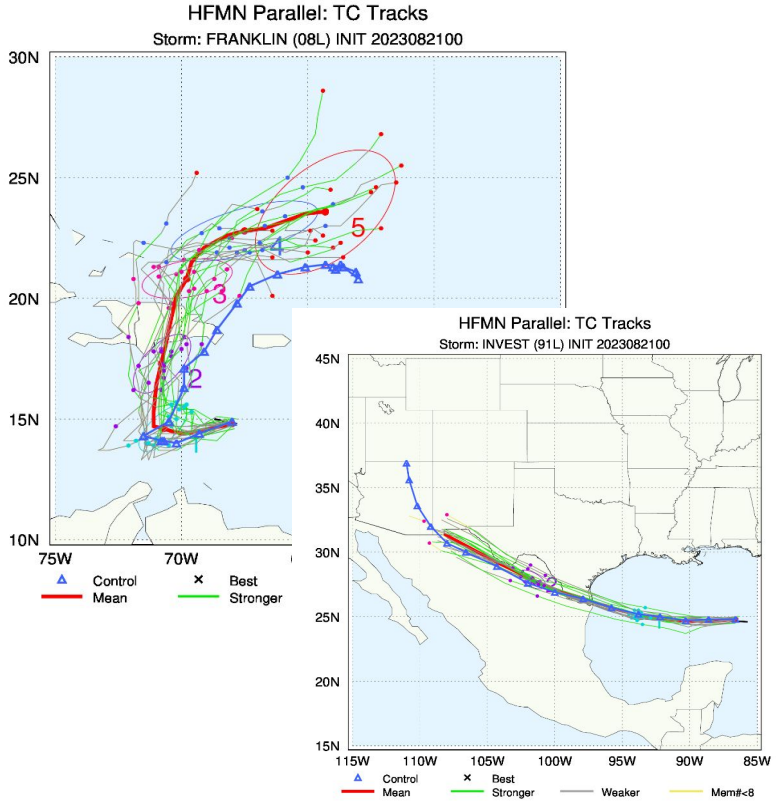
- High resolution ensemble developed from operational HAFS,
- 21-member ensemble with two-way ocean coupling,
- 120h forecast length 4x per day (00Z/06Z/12Z/18Z),
- Physics perturbations chosen for ability to project onto TC track, intensity, and/or structural diversity.





Hurricane Analysis and Forecast System (HAFS) Real-time DA experiment on Jet

- Plan: Self-cycled DA system on a static 6-km domain
- 20 ensemble members, 10 running 6h forecasts for EnKF only, 10 run 5-day forecasts.
- Possible pivot due to limited compute resources on jet real-time:
  - Run the DA system only (6 h forecasts for 20 members) within jet reservation, and run 5-day, 10-member ensemble forecasts option on other rdhpcs.
- If resources insufficient, will evaluate the 5-day ensembles after season, rather than real-time.



Subseasonal Global Ensemble Forecast System (GEFS)

- **GEFSv12:**
  - **Implementation 2020**, **atmos-land-waves** (FV3, Noah, WW3), 2-tiered SST + NSST, atmos-land (25km, 64 vertical levels); **31-year (1989-2020) reforecast**: IC from FV3 reanalysis (CFSR) after (before) 2000. Real-time: 31 members, 16 days lead time from 06/12/18UTC, 35 days lead time from 00UTC, EnKF initial perturbations, stochastic physics.
- **GEFSv13:**
  - **Implementation Q1FY26**, **atmos-land-ocean-sea ice-waves (possibly aerosols)** (FV3, Noah-MP, MOM6, CICE6, WW3, GOCART), atmos-land-aerosols (25km, 127 vertical levels), ocean-sea ice (0.25-deg), unstructured waves; **31-year (1994-2023) reforecast**: IC from replay to ERA5, ORAS5, snow DA. Real-time: 31 members, 16 days lead time from 06/12/18UTC, 45 days lead time from 00UTC, coupled GDAS initial perturbations, stochastic physics.
  - **Trade Space: Ensemble Size vs Resolution:**
    - **~1.3M core hours** per 45-day forecast with 127 vertical levels, 0.25-deg ocean/sea ice and

25-km resolution
31 members

or

35-km resolution
90 members

- **Challenges:**
  - **Test & evaluation**: currently 3 year period, 11-member ensemble, insufficient to represent full uncertainties
  - **Reanalysis & reforecast**: 30 year reforecast requires model been frozen about 1 year earlier
  - **Upgrade cadence:** R&D, stakeholder needs and feedbacks
- **Opportunities:** Cloud HPC, UFS community modeling, AI

Climate Forecast System (CFS) and Seasonal Forecast System (SFS)

- **CFSv2:**
  - **Implementation 2011**, **atmos-land-ocean-sea ice** (**Spectral GFS** +Noah, MOM4, SIS), atmos-land (100km, 64 vertical levels), ocean-sea ice (0.5-deg); **29-year (1981-2010) reanalysis & reforecast**: Climate Forecast System Reanalysis (CFSR), 4 members, every 5 days, lead times out to 9 months; Real-time: IC from CFSR, 4 members, every day.
- **SFSv1:**
  - **Implementation TBD, atmos-land-ocean-sea ice (possibly waves, aerosol)** (**FV3**+Noah-MP, MOM6, CICE6, possibly WW3, GOCART)**,** atmos-land (25-50 km, 127 vertical levels), ocean-sea ice (0.25-deg), 11-100 members, lead times out to 12 months, initialization 1x or 2x per month (e.g. on the 1st and 15th), cycled EnKF perturbations, physics tendency perturbations, physics parameterization perturbations, **40+ years coupled reanalysis & reforecast**
  - **Trade Space: Ensemble Size vs Resolution**
    - **~4M core hours** per 12 month forecasts with 127 vertical levels, 0.25-deg ocean/sea ice and:

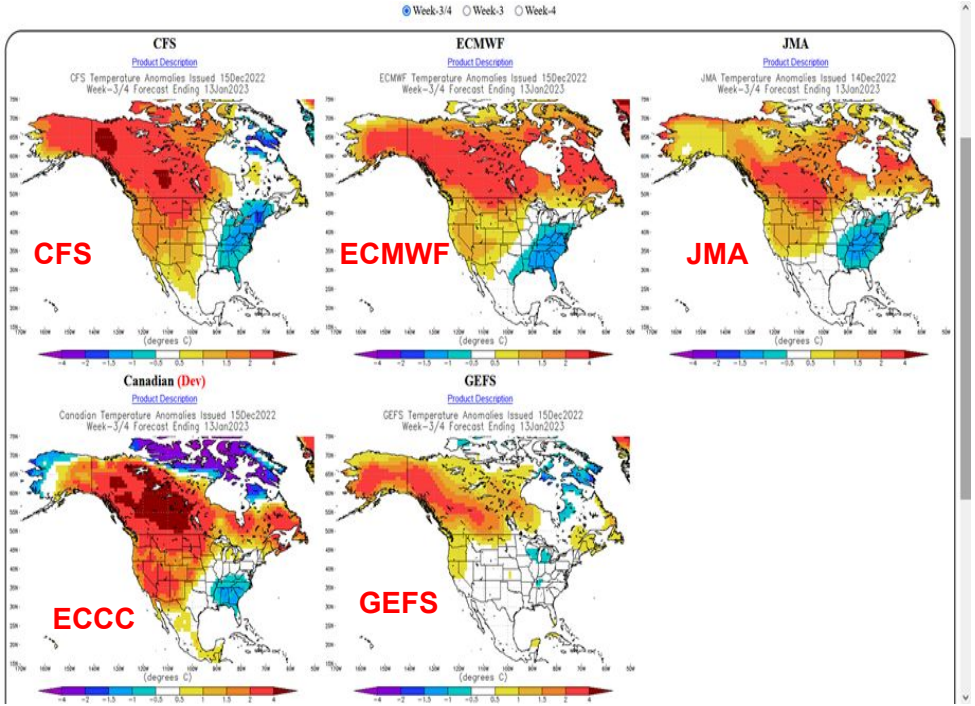
25-km resolution 12 members	or	**35-km resolution 36 members**	or	**50-km resolution 100 members**

- **Challenges:**
  - **Test & Evaluation**: 20+ years period, 11-member ensemble, to establish a baseline skill
  - **Earth modeling complexity**: represent physical processes, cross-component interactions, and reduce model biases
  - **Reanalysis & reforecast:** represent initial state in ocean, sea ice and land, 40+ years coupled reanalysis & reforecast

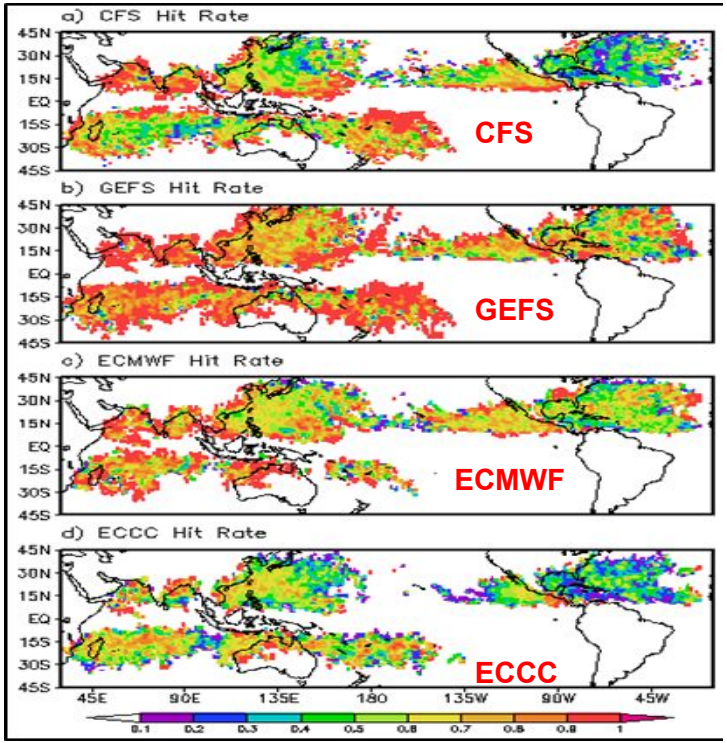
- **Opportunities:** Cloud HPC, UFS community modeling, AI

GEFSv12 and CFSv2: Probabilistic IDSS for Weeks 2-4 Forecast

Week 3-4 Temperature Forecast



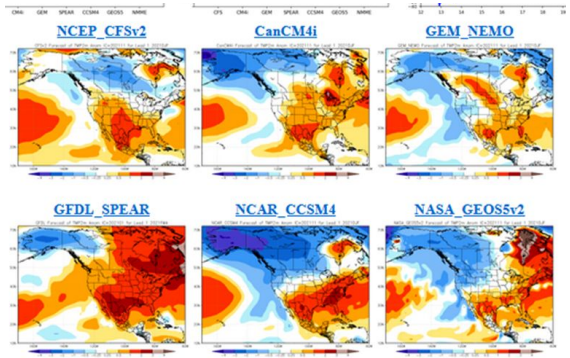
Week 2 Tropical Cyclone Hit Rate

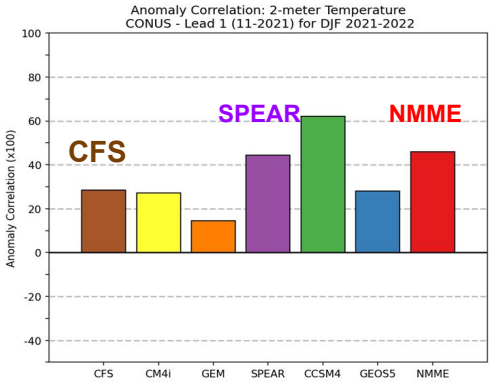


CFSv2: Probabilistic IDSS for Monthly and Seasonal Forecast

Seasonal Mean Forecast for DJF, 1 Month Lead

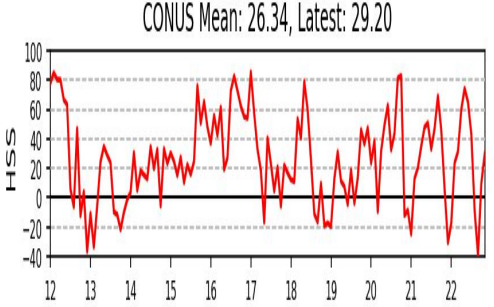
Temperature



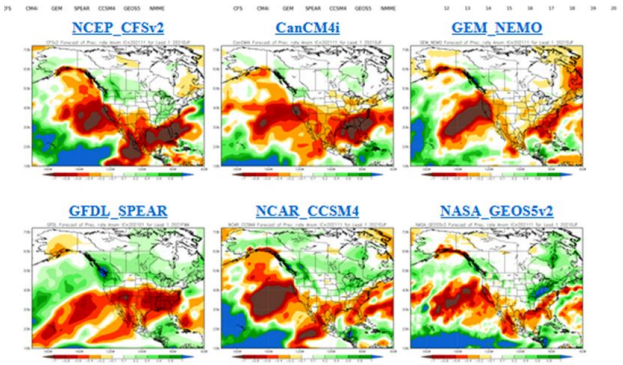


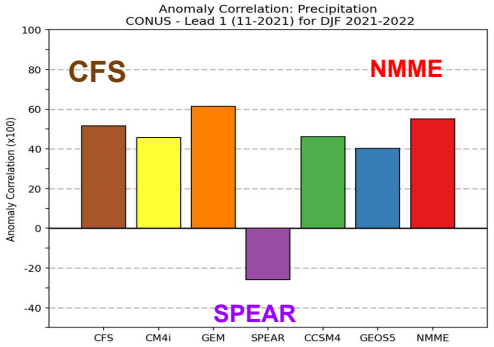
T2m, Mean HSS = 26

HSS= 29 for DJF 2021-2022



Precipitation





Prec, Mean HSS = 8

HSS= 18 for DJF 2021-2022