Design and Development of NOAA's State-of-the-Art Seasonal Forecast System (SFS) for Research and Operations

NATIONAL WEATHER SERVICE

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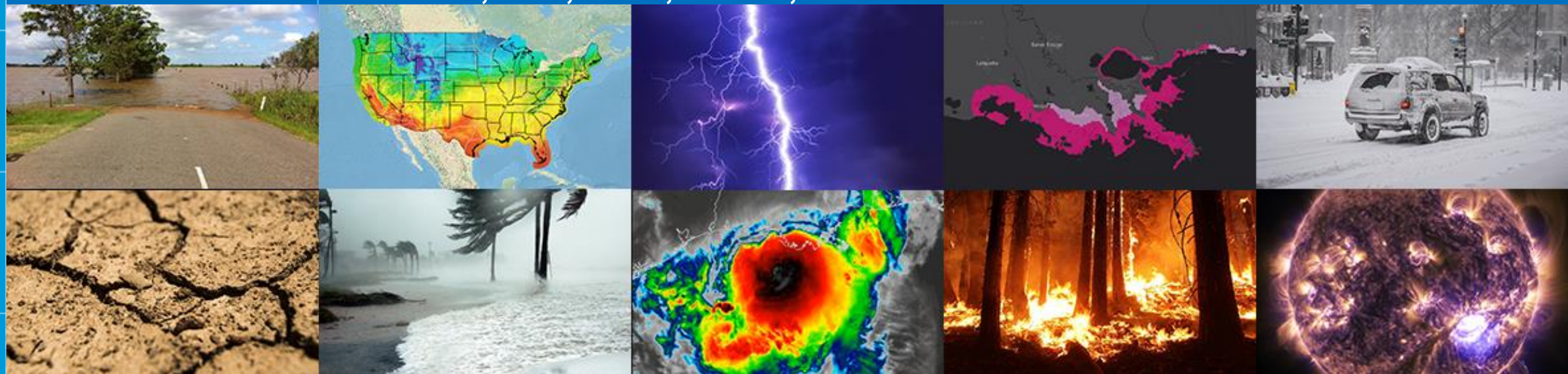
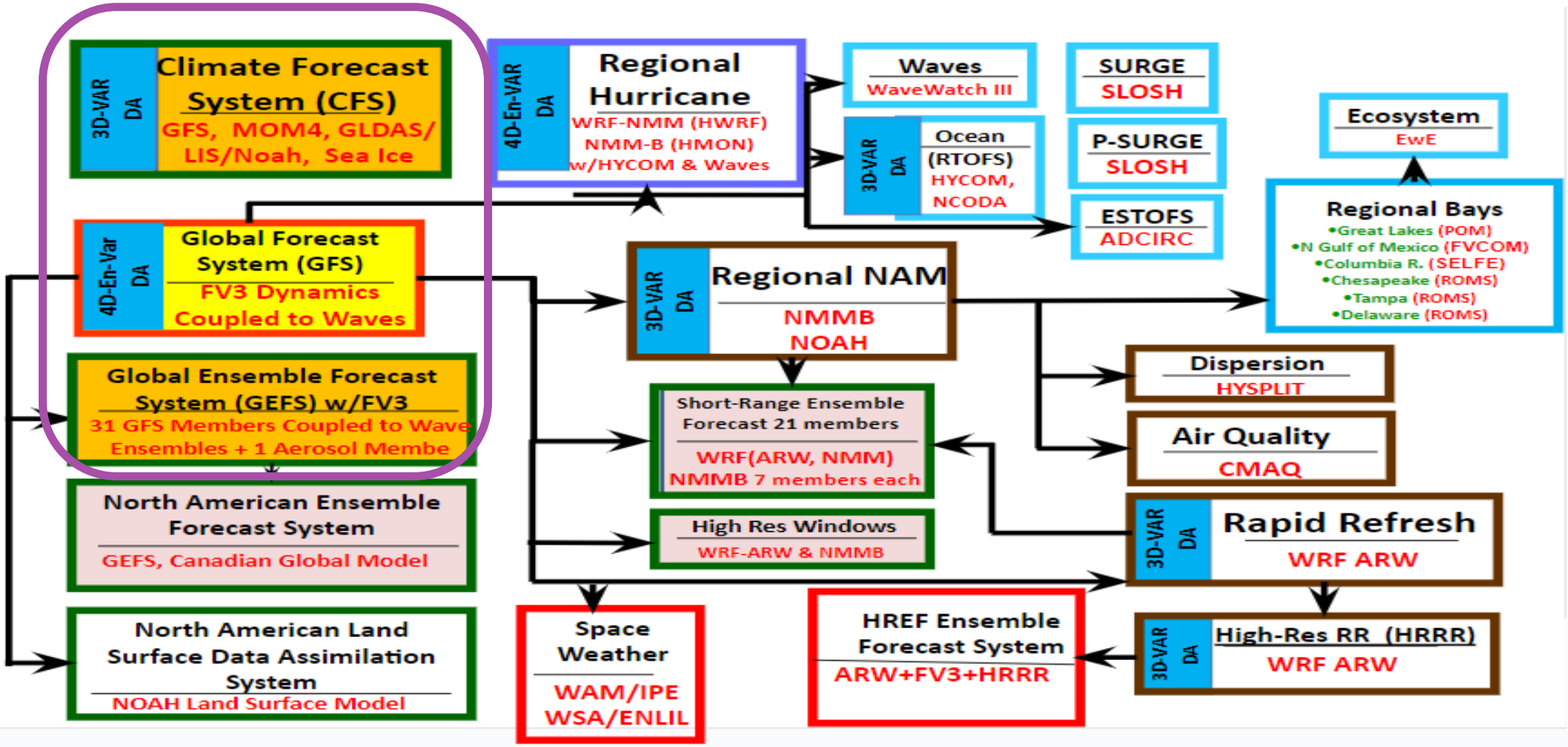


- **Acknowledgements**
  - All of the outstanding scientists and engineers at the Environmental Modeling Center, and Collaborators within NOAA, at other Federal agencies, International Collaborators, Academia, and the Private Sector
- **Reference**
  - EMC 5-Year Implementation Plan

NOAA's Current Production Suite: The "quilt"



Unified Forecast System

The Unified Forecast System (UFS) is a community-based coupled Earth modeling system, designed to support the Weather Enterprise and also be the source system for NOAA's operations.

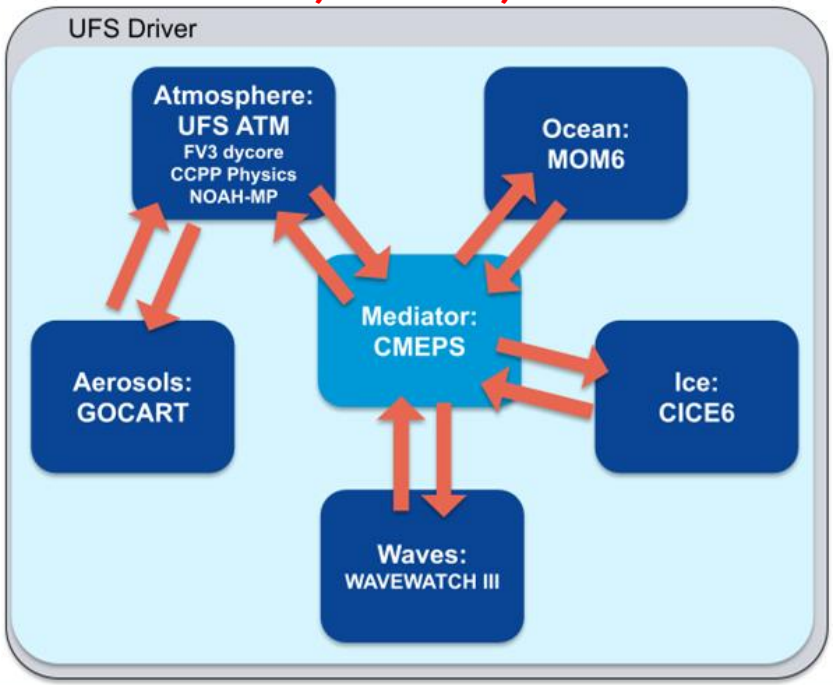
- Community components in UFS
  - Model infrastructure: ESMF, NUOPC, CMEPS
  - Atmosphere model: FV3 dycore, CCPP Physics
  - Ocean model: MOM6
  - Ice model: CICE6
  - Wave model: WW3
  - Aerosol model: GOCART
  - Land model: Noah-MP (currently)
  - Data assimilation: Joint Effort for Data assimilation Integration (JEDI)
- Each component has its own authoritative repository.

UFS Research-to-Operations (UFS R2O) Project

Developing the next-generation global and regional forecast systems and transition to NOAA operations in FY23 and beyond

Jointly supported by NOAA NWS and OAR

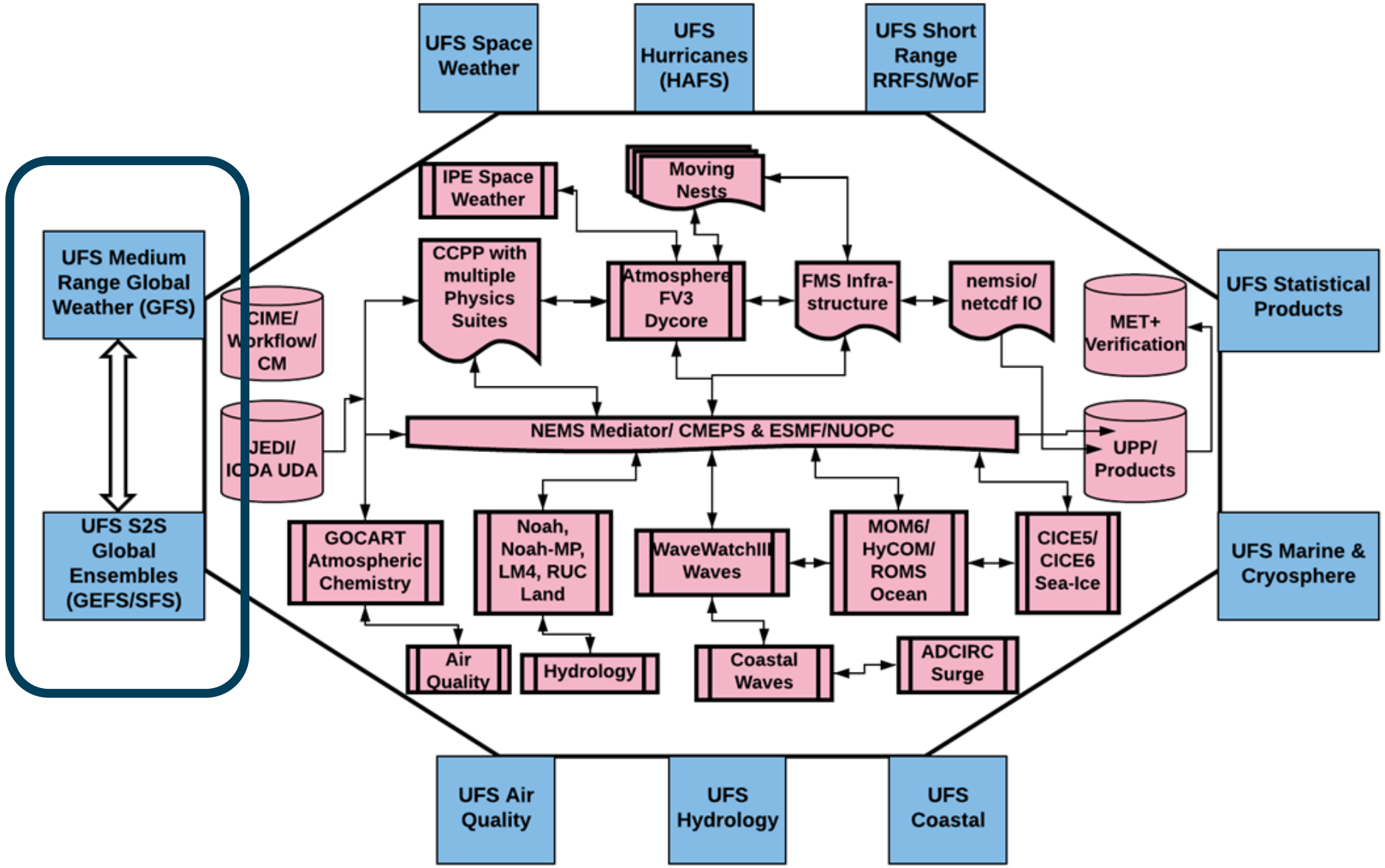
MRW/S2S Applications: GFSv17, GEFSv13, SFSv1



NPS Transitioning to UFS Applications

"UFS is configurable into multiple applications that span local to global domains and predictive time scales from less than an hour to more than a year."

Conceptual UFS applications in production covering all NPS applications, maintaining the dependencies between the applications and products.



Global UFS-Coupled Model Development Objectives

1. **Establish** forecast priorities spanning the Medium-Range (0-2 weeks) to S2S (3 weeks to 2 years) time scales, within the NOAA mission space.

2. **Identify** scientific goals that will ensure that the Medium-Range Weather(MRW) and S2S applications will meet identified forecast priorities with increased forecast skill.

3. **Design and conduct** an evaluation of MRW/S2S applications to improve performance on forecast priorities, in coordination with users and stakeholders.

NWS Global Weather to Seasonal Forecast Systems: Current and Future Implementations

Current Systems

GFSv16.3 (since November 2022)
Weather scales, deterministic,
no coupling with ocean/ice. FV3

GEFSv12 (since September 2020)
Weather to subseasonal, ensemble,
no coupling with ocean/ice. FV3

CFSv2 (***since March 2011***)
Subseasonal to seasonal, ensemble,
coupled with ocean & sea ice.
Spectral Atm/MOM4 Ocean/SIS1 Sea ice

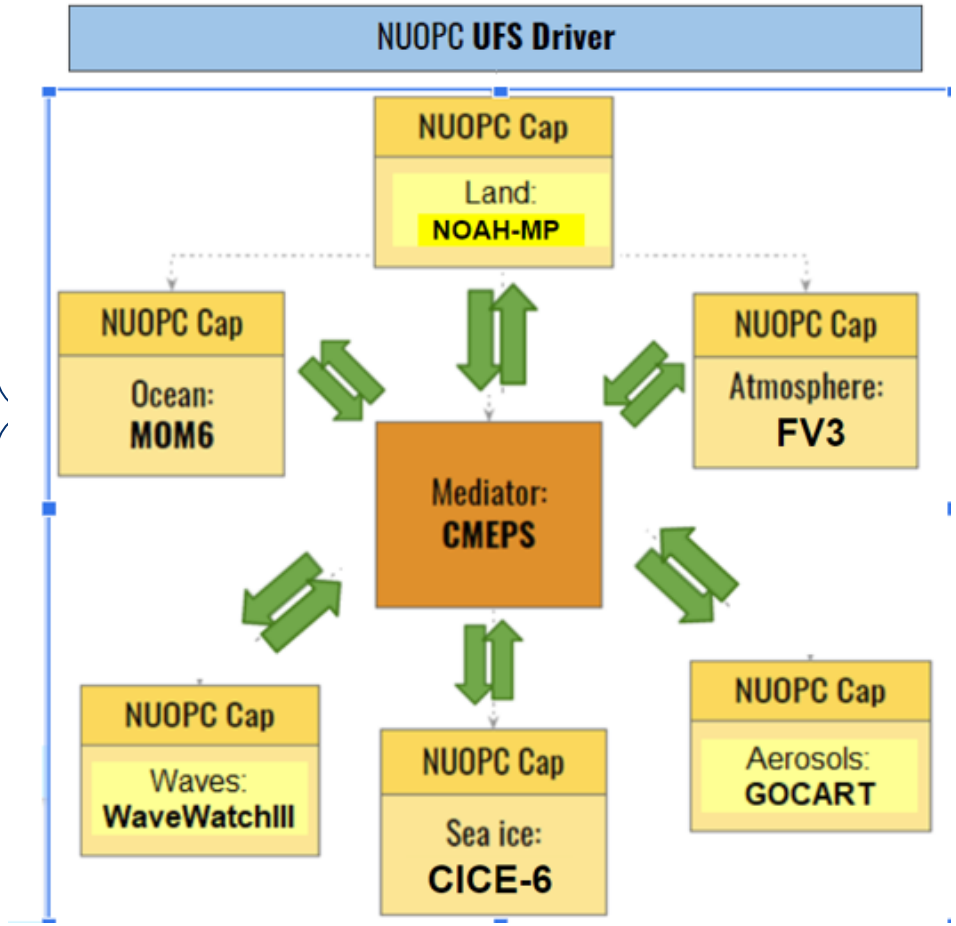
Future UFS Systems

GFSv17 (FY 2026)

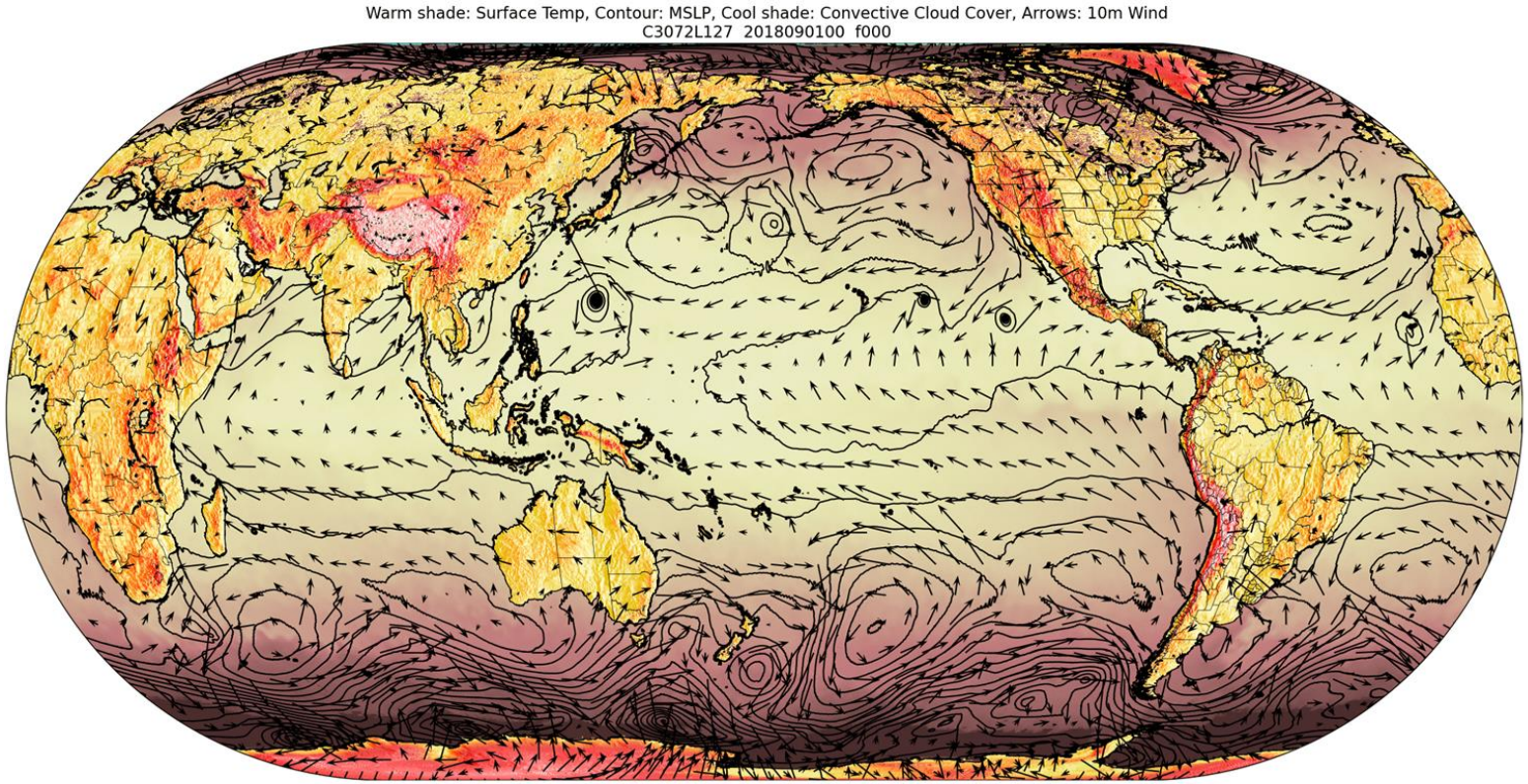
GEFSv13 (FY 2026)

SFSv1 (FY 2028+)

UFS System Configuration



MRW/S2S: Building a Six-Way Global Coupled Unified Forecast System For future GFS, GEFS and SFS

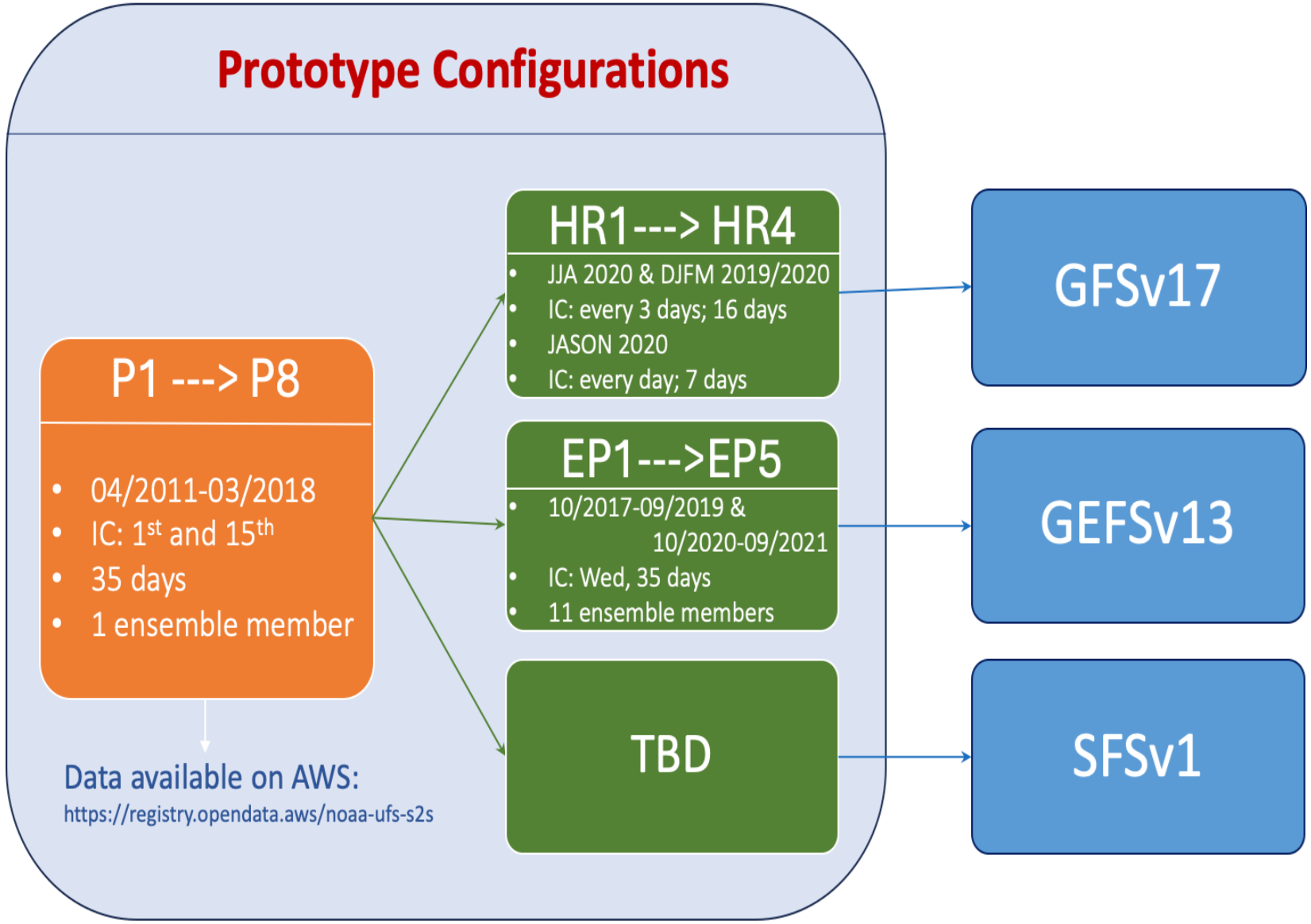


UFS Earth System Model Components:

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

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.

MRW/S2S Applications Prototype Testing and Evaluation

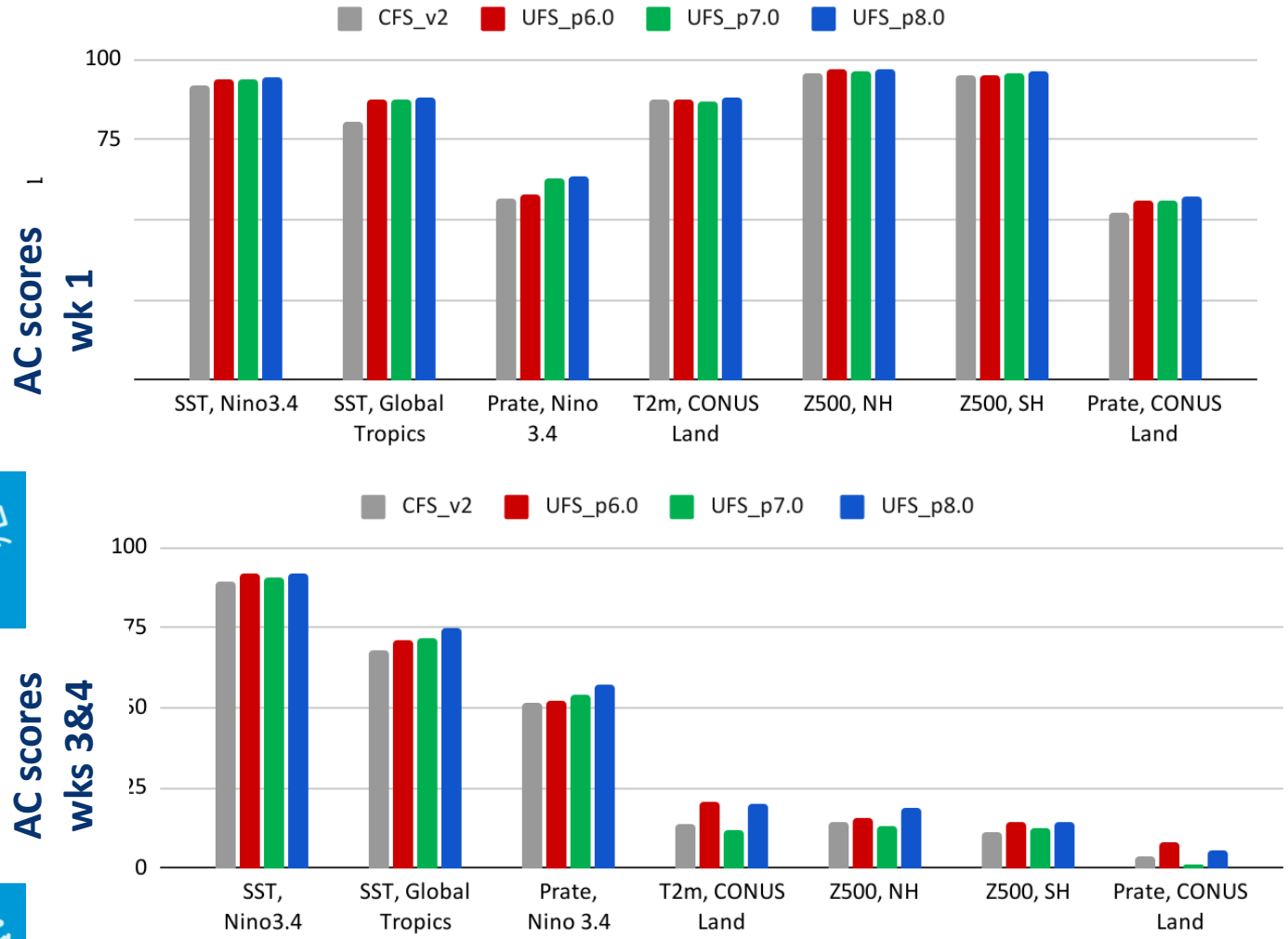


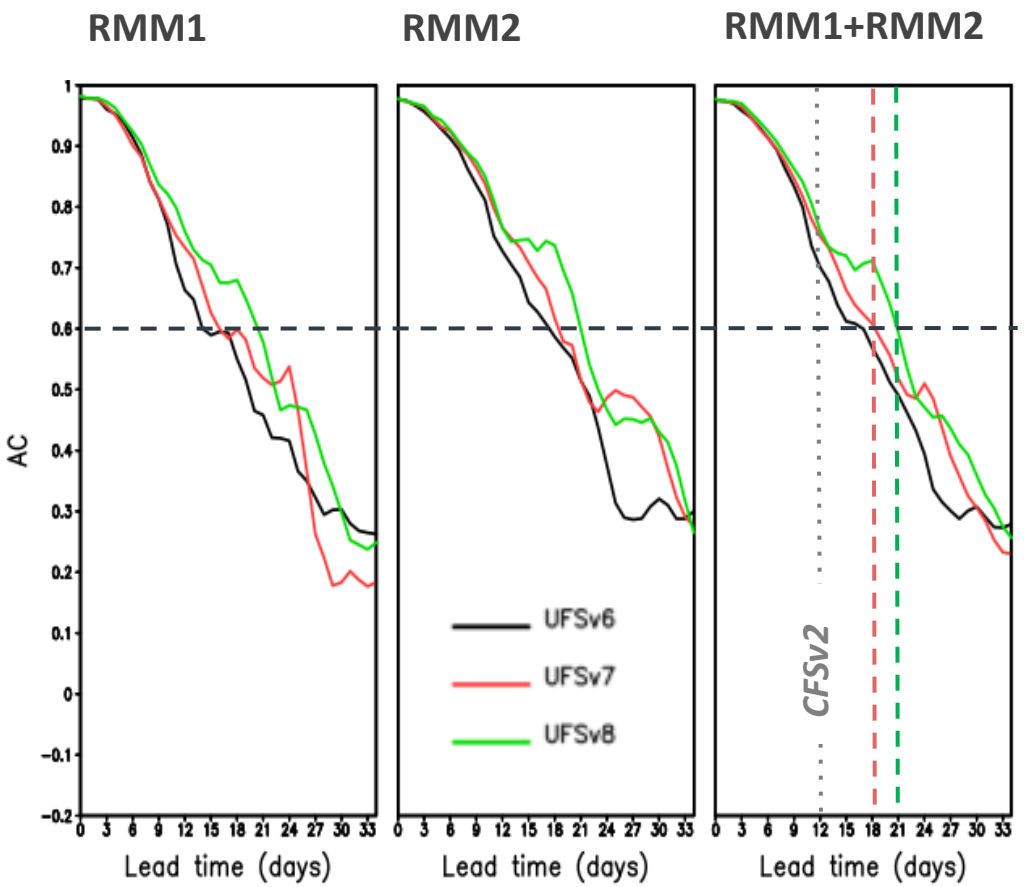
Coupled UFS Prototypes 1–8

Prototype	Atmospheric Model C384 (~0.25 degree) horizontal resolution			Ocean Model Tripolar ~0.25 degree horizontal resolution	Wave Model Regular lat/lon 0.5 degree grid	Ice Model Tripolar ~0.25 degree horizontal resolution	Mediator
	Dynamical Model	Physics Settings & Driver	Land Model				
P1	FV3 64 layers, Non-Fractional grid (model top at 54km)	GFSv15.2, IPD driver	Noah LSM	MOM6	N/A	CICE5	NEMS
P2							
P3.1							
P4		GFSv15.2, CCPP driver			WW3		
P5						CICE6 (Mushy TD not turned on)	CMEPS
P6	FV3 127 layers, Fractional grid (model top at 80km)	GFSv16					
P7		Modified GFSv16	Noah-MP LSM			CICE6 (Mushy TD turned on)	
P8		Further Modified GFSv16	Modified Noah-MP LSM				

(P8+ includes one-way coupled aerosols)

P8 Benchmark AC scores and MJO AC





Courtesy of Wei Li, EMC

- **Benchmark AC scores clearly improved**
- **MJO skill highest of all prototypes**

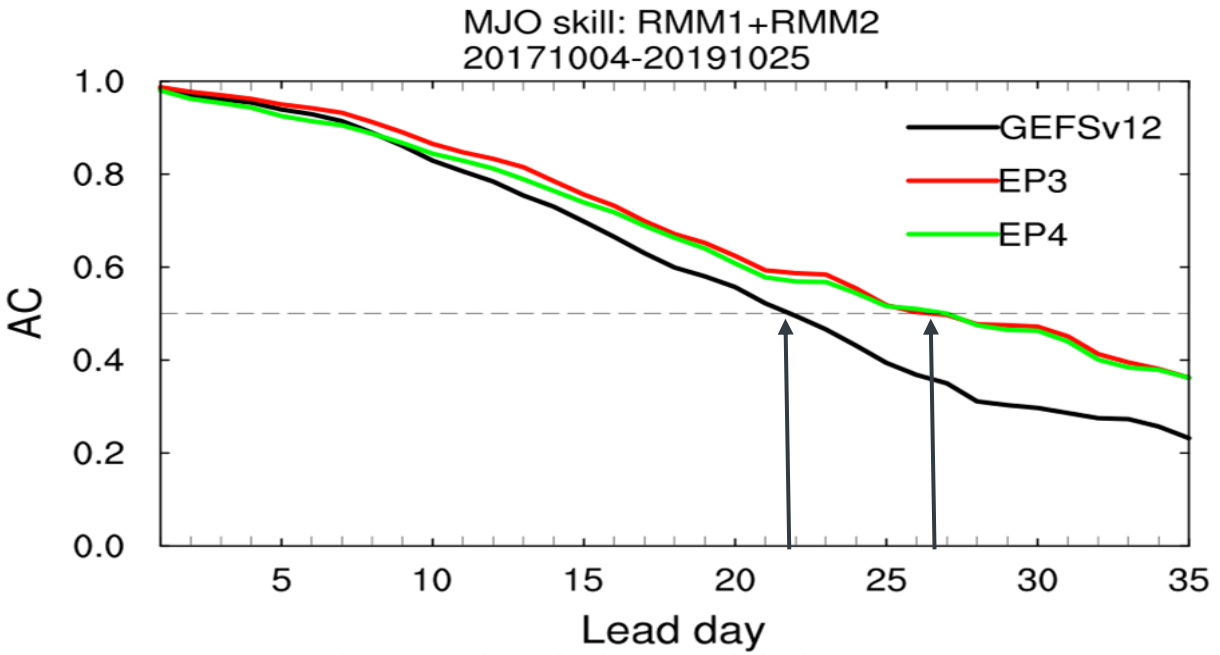
Coupled UFS Ensemble Prototypes 0–5

	Code tag of determinstic	General Description of Updates (include ensemble's configurations)	Initial Conditions								Model Perturbations			
			FV3		MOM6		CICE		WW3		FV3	MOM6	CICE6	WW3
			ANL	PERT	ANL	PERT	ANL	PERT	ANL	PERT				
EP0	Prototype-5.0	Early UFS-P5 version (Sep 2020) F	GFSv15	GFSv15 EnKF	CFSR (SST & Salinity)	N/A	CPC ice anl	N/A	N/A	N/A	SPPT = 0.56,0.28,0.14,0.056,0.028 SKEB = 0.7	N/A	N/A	N/A
EP1	Prototype-5.0	Later UFS-P5 version (Feb 2021) FV3 (C384); MOM6 (0.25d); CICE6 (0.25d); WW3 (0.5d) 11 members CTB project (shared meeting notes)	GFSv15	GFSv15 EnKF	CFSR (SST & Salinity)	N/A	CPC ice anl	N/A	Generated with GFSv15 forcing	N/A	SPPT = 0.56,0.28,0.14,0.056,0.028 SKEB = 0.7	N/A	N/A	N/A
		Subset 1 - update of SPPT experiments (shared notes)												
		Subset 2 - land perturbation experiments (shared notes)												
		Subset 3 - ocean stochastics experiments (shared notes)												
EP2	Prototype-7.0	UFS-P7 FV3 (C384L97); MOM6 (0.25dL41); CICE6(0.25d); WW3(0.5d)	GFSv15	GFSv15 EnKF	CFSR (SST & Salinity)	N/A	CPC ice anl	N/A	Generated with GFS forcing (later WW3 version)	N/A	SPPT = 0.56,0.28,0.14,0.056,0.028 SKEB = 0.7	OSPPT = 0.8,0.4,0.2,0.08,0.04 ePBL = 0.8,0.4,0.2,0.08,0.04	N/A	N/A
EP3	Prototype-8.0	UFS-P8 FV3 (C384L97); MOM6 (0.25dL41); CICE6(0.25d); WW3(0.5d)	GFSv15	GFSv15 EnKF	ORAS5	combinaion from 4 ocean analysis	CPC ice anl	N/A	Generated with GFS forcing (later WW3 version)	N/A	SPPT = 0.6,0.3,0.15,0.06,0.03 SKEB = 0.8	OSPPT = 0.8,0.4,0.2,0.08,0.04 ePBL = 0.8,0.4,0.2,0.08,0.04	N/A	N/A
EP4	HR1+ (C384)	HR1 + stoch fix and others FV3 (C384L127); MOM6 (0.25dL75); CICE6(0.25d); WW3(0.25d, latlon grid)	GFSv15/16	GFSv15/16 EnKF	ORAS5	combinaion from 4 ocean analysis	CPC ice anl	N/A	GEFSv12 wind/ice forcing	GEFS v12 (4/10) perts repeatly use	SPPT = 0.56,0.28,0.14,0.056,0.028 SKEB = 0.8	OSPPT = 0.8,0.4,0.2,0.08,0.04 ePBL = 0.8,0.4,0.2,0.08,0.04	N/A	N/A
EP5	HR3 (C384)	HR3 FV3 (C384L127); MOM6 (0.25dL75); CICE6(0.25d); WW3(0.25d, latlon grid)	replay IC	replay IC	replay IC	replay IC	replay IC	replay IC	replay IC	replay IC	SPPT = 0.56,0.28,0.14,0.056,0.028 SKEB = 0.8	OSPPT = 0.8,0.4,0.2,0.08,0.04 ePBL = 0.8,0.4,0.2,0.08,0.04		

Fully Coupled Global Ensemble Forecast System (GEFS, Sub-X)

- 1st fully-coupled global ensemble forecast system including coupling between ATM-LSM-OCN-ICE-CHM-WAV
- Model vertical resolution increase from 64 to 127 layers with a model top of 80km.
- Thompson microphysics scheme replacing GFDL microphysics scheme, NOAH-MP replacing NOAH LSM and other ATM physics updates
- Adding ocean stochastic physics to represent uncertainties from ocean prediction
- Forecast length increases from 35 days to 48 days

Four Ensemble Prototypes (EP1 - EP4) completed, results are encouraging.



EP3 and EP4 both have higher MJO skill (RMM1+RMM2) than GEFSv12 for longer lead times (extend skill for 4-5 days).

NOAA's Seasonal Forecast System (SFS) to replace CFS

GOALS:

- **Balanced initializations across interfaces**
- **Minimize systematic drift from initial conditions**
- **Best estimation of uncertainties in ensemble forecasts**
- **Reduce systematic biases and improve forecast skill**
- **SFS infrastructure should provide critical support**

SFS will be:

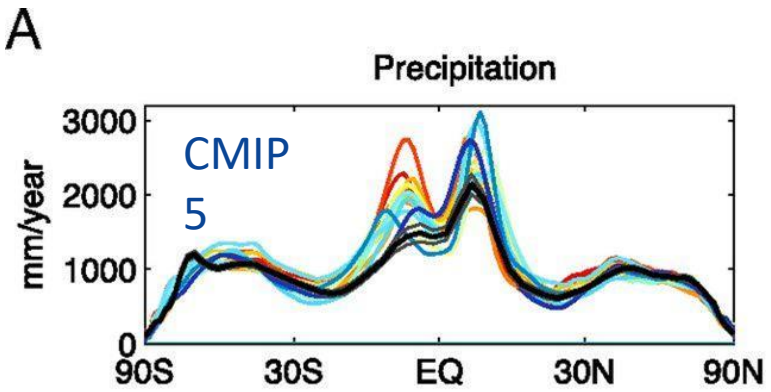
- **Enabled to run in the cloud**
- **Incorporated into UFS repositories**
- **Provided to community through the Earth Prediction Innovation Center (EPIC)**

- Develop SFSv1 as a **replacement** of Climate Forecast System version 2 **(CFSv2)**, a decade-old system
- **Address common errors** in CFSv2 and NMME
  - MJO propagation across Maritime Continent
  - False ENSO alarms
  - Positive SST trend errors in tropical Pacific
  - Too frequent above-normal temperature forecast
  - Too infrequent below-normal temperature forecast

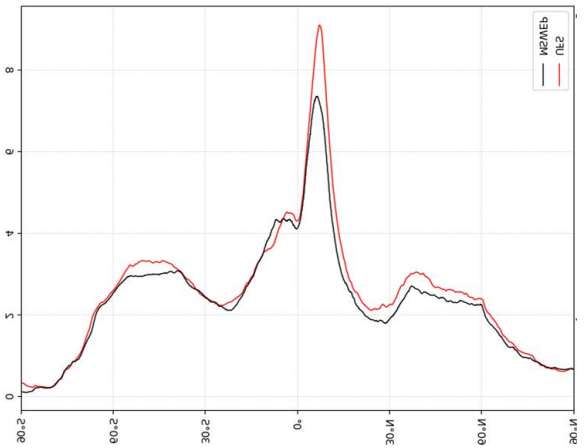
SFS Development Plan: UFS Components for SFSv1

1) Finite Volume Cubed Sphere (FV3) dynamical core
2) Common Community Physics Package (CCPP)
3) Noah-Multi Parameterization Land Surface Model (Noah-MP LSM)
4) Modular Ocean Model (MOM),
5) Los Alamos Sea ice model (CICE)
6) WAVEWATCH III wave model (WW3)
7) Goddard Chemistry Aerosol Radiation and Transport (GOCART)
8) Community Mediator for Earth Prediction System (CMEPS)
9) Joint Effort for Data Assimilation Integration (JEDI)
10) Enhanced Model Evaluation Tools (METplus)

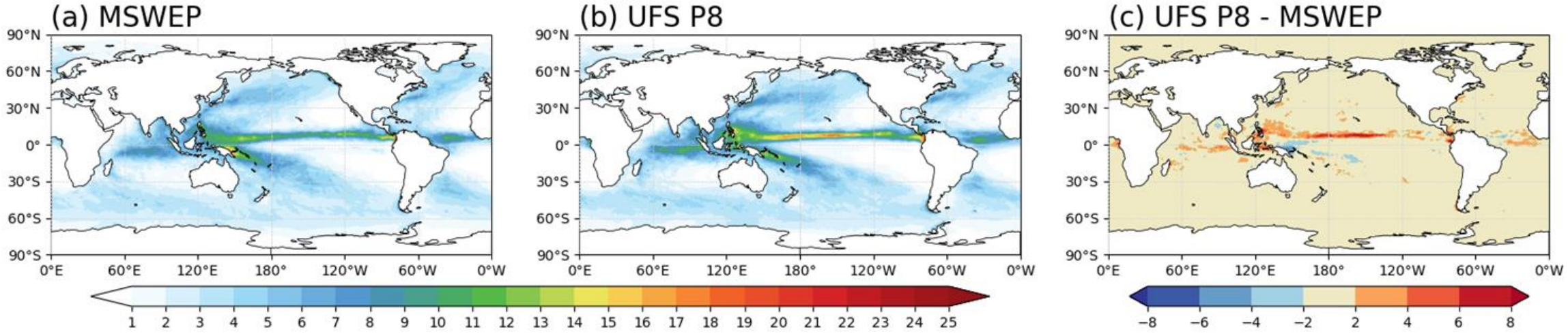
Early Results: No Double ITCZ in UFS climate run



[Hwang and Frierson, 2013, PNAS]



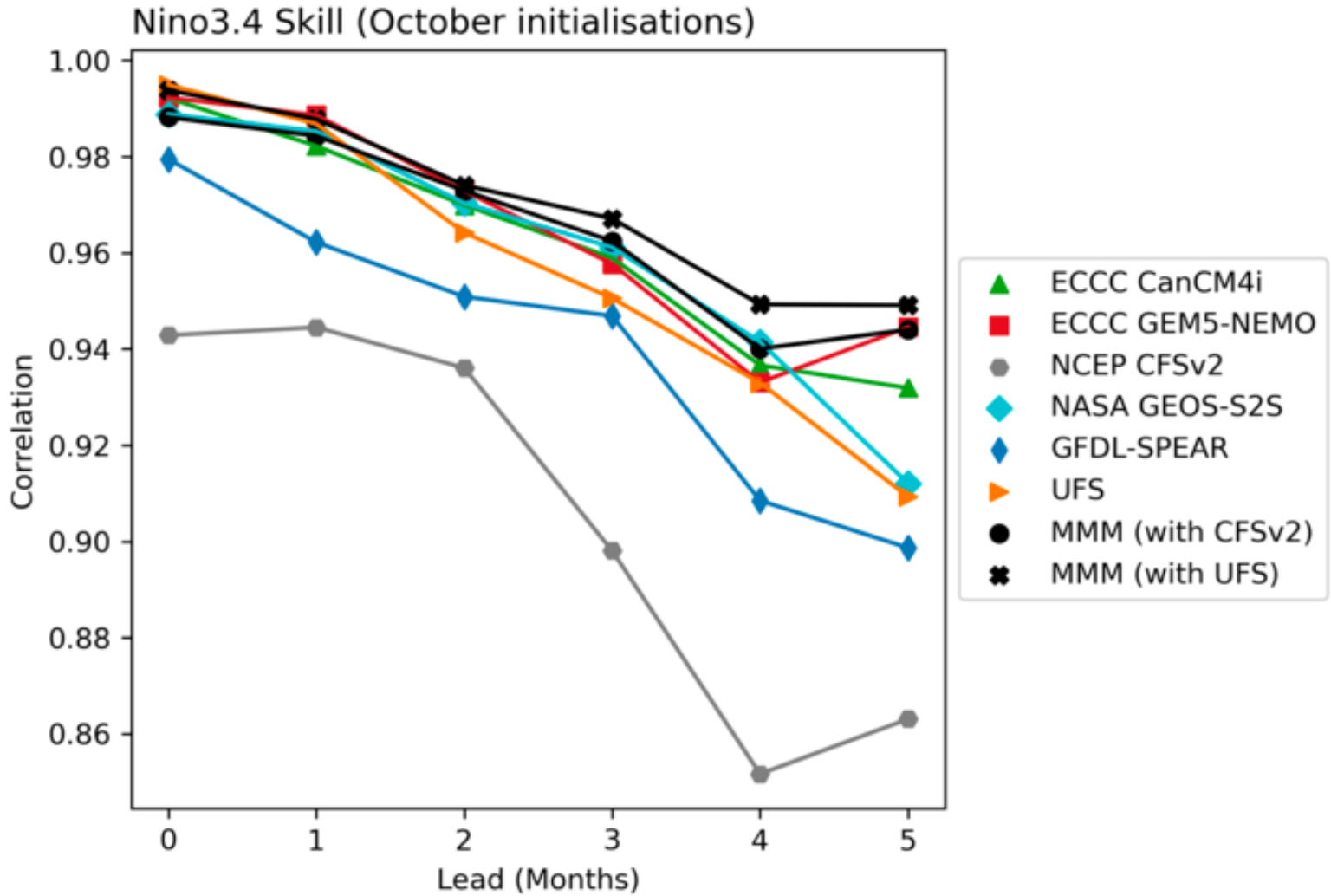
UFS P8 overestimates ITCZ, but doesn't show double ITCZ



Seasonal Prediction with Coupled UFS – Preliminary Prototypes

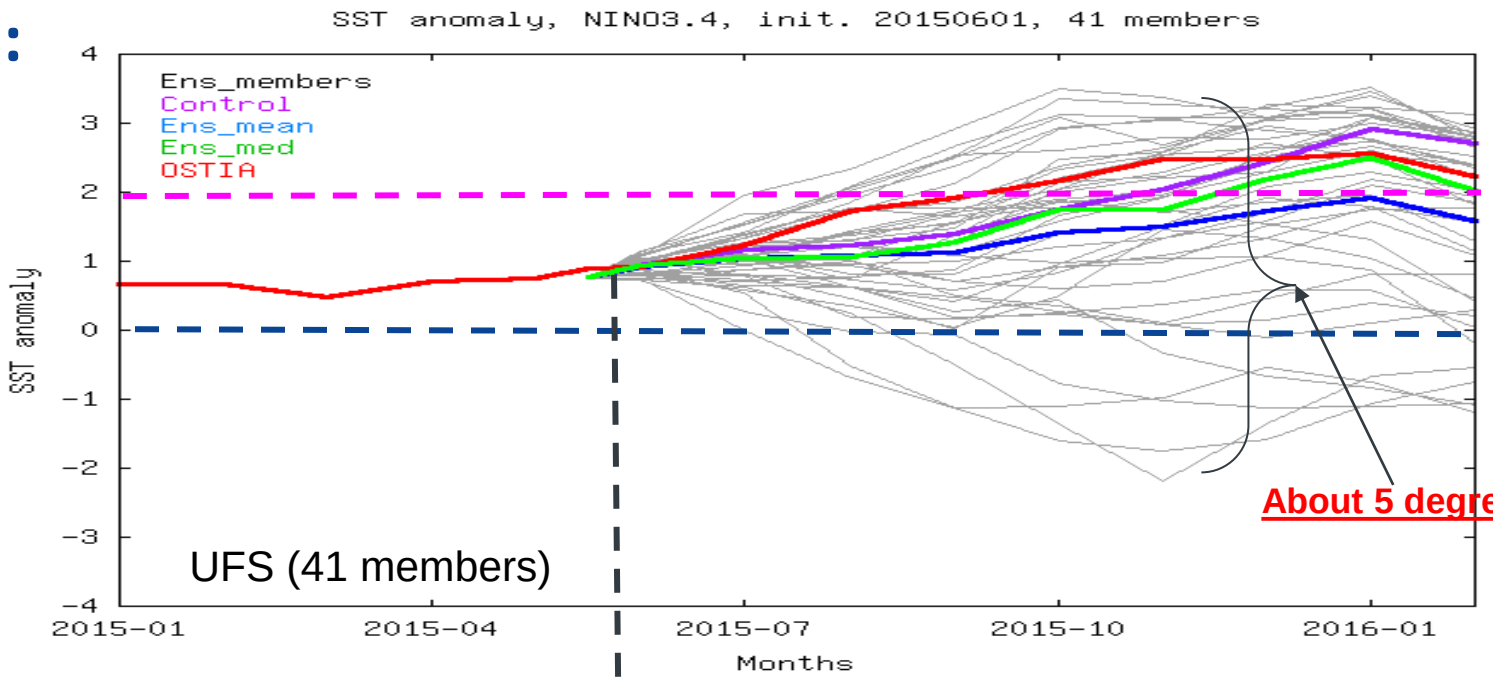
- **Models**
  - Atmosphere - C192L64 (P5, GFSv15, GEFSv12)
    - Retain NSST to assimilate SST diurnal variability, expect to reduce cold SST bias
  - Ocean - MOM6 (0.5d)
  - Seaice - CICE6 (0.5d)
  - Wave - WW3 does not include in this experiment
- **Stochastics**
  - Atmosphere: 5-scale SPPT (30% off); SKEB (0.7)
    - They are the same as CGEFS-H and CGEFS-L.
  - Ocean:
    - ePBL perturbations (perturbed TKE generation and dissipation)
    - Perturbed SST, salinity and layer of thickness.
    - All 5 scales, [0.8,0.4,0.2,0.08,0.04]
- **Initial conditions**
  - June 1st 2012 (neutral case); June 1st 2015 (El Nino case); June 1st 2017 (La Nina case)
  - Atmosphere - GFSv15 retrospective analysis (and perturbations)
  - Ocean - GODAS interpolated to 0.5d including ocean current (full fields)
  - Ice - CPC's analysis
- **Members and forecast length**
  - 41 members; out to 9 months

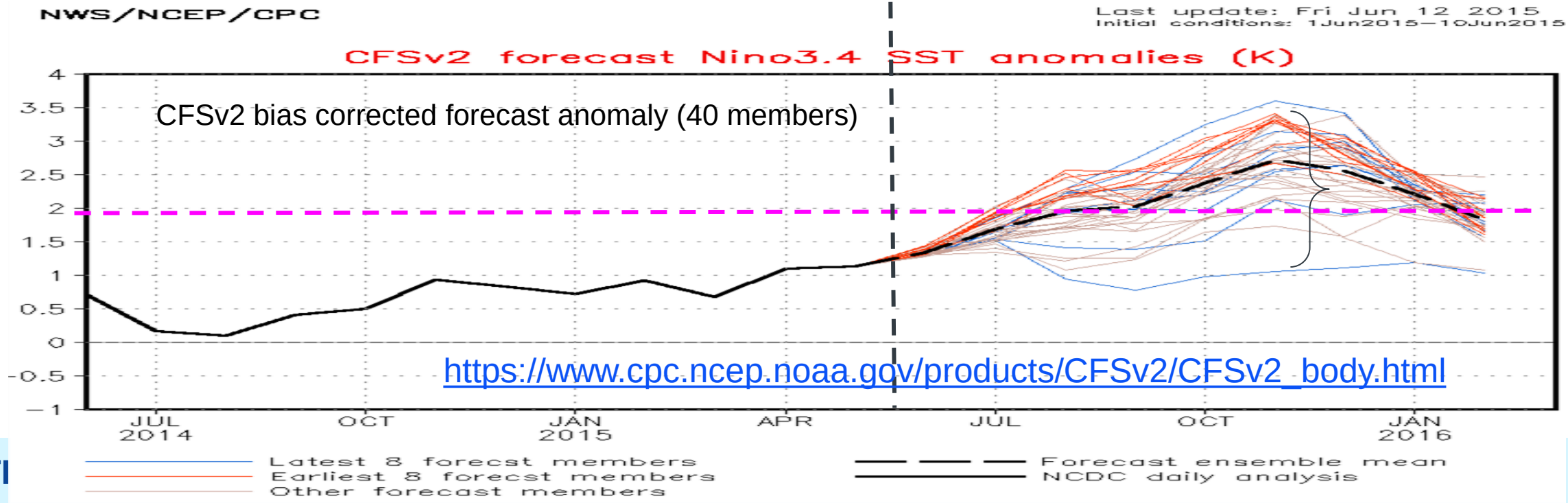
Nino3.4 Reforecast Skill



Nino 3.4 indexes comparison: "El Nino Case"

- Right plume is coupled UFS seasonal run, no bias correction
- Bottom plume is CFSv2 seasonal run, with bias correction
- Initial state of SST: ~1 degree for both systems
- CFSv2 demonstrated a good forecast in terms of trend and peak
- Coupled GEFS is very well either even without bias correction, but spread is too large.

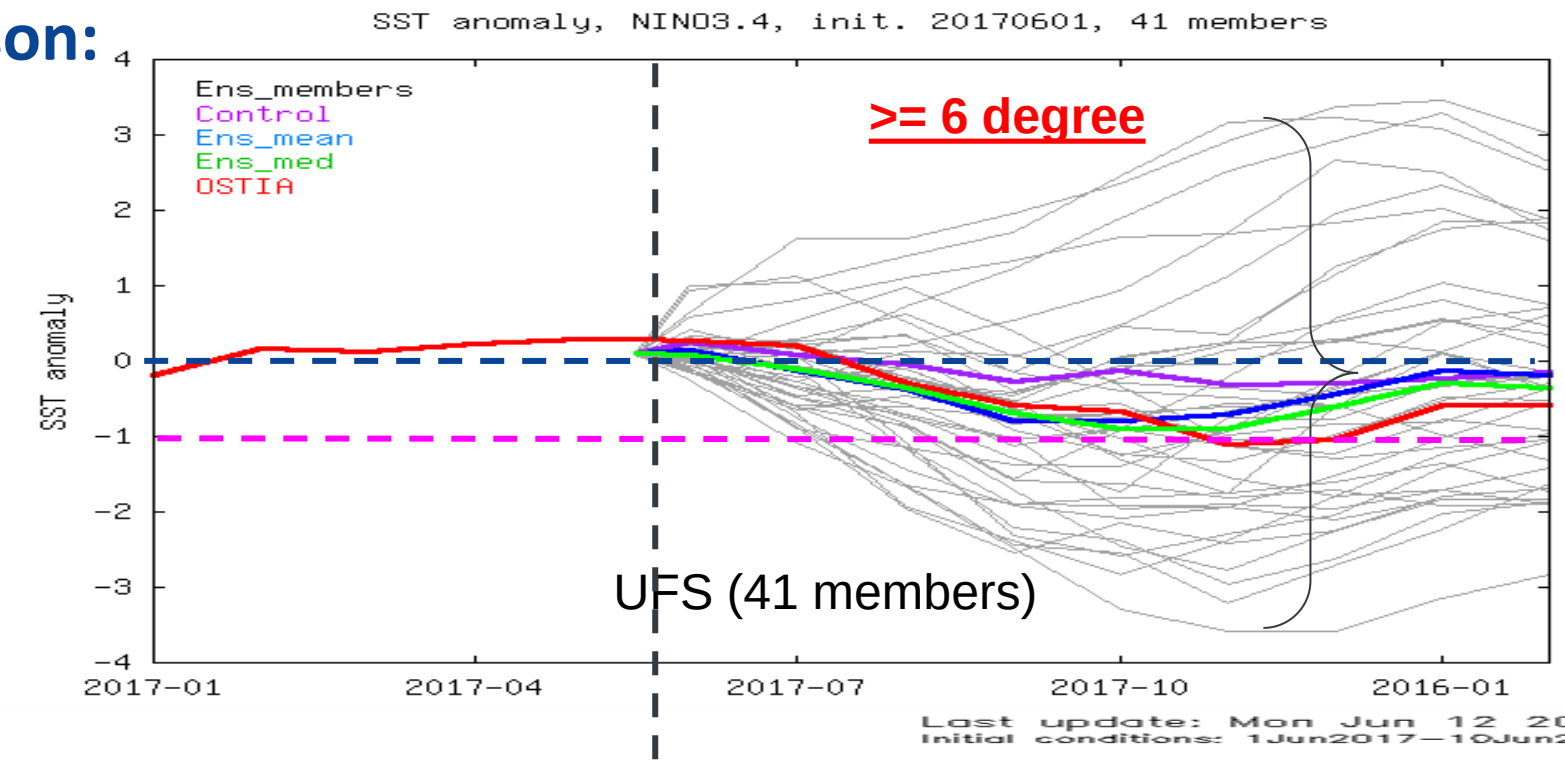




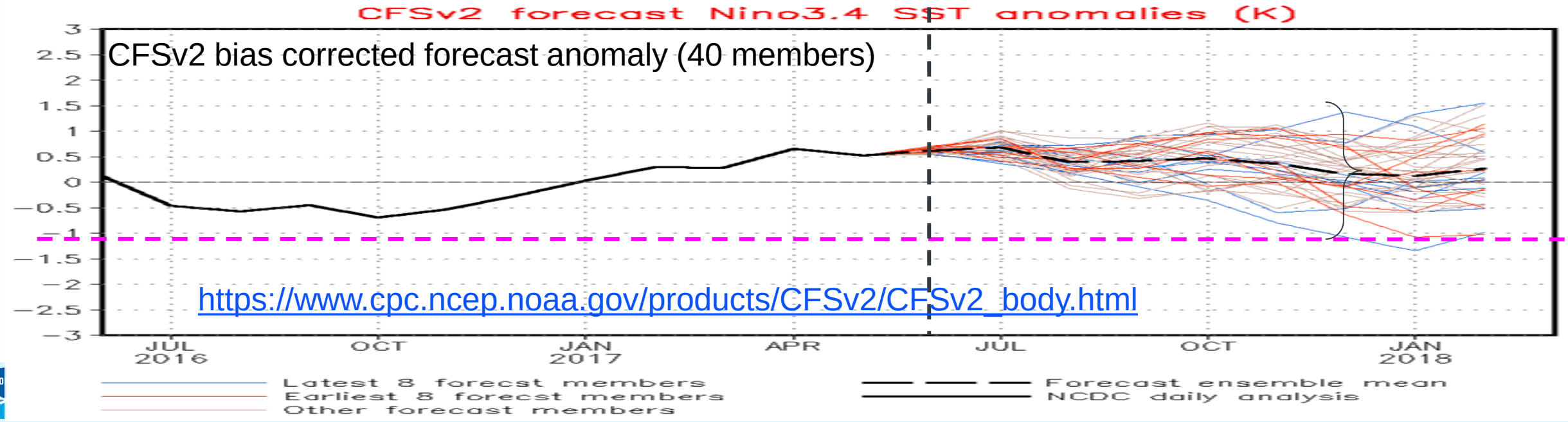
Nino 3.4 indexes comparison:

“La Nina Case”

- Right plume is coupled UFS seasonal run, no bias correction
- Bottom plume is CFSv2 seasonal run, with bias correction
- Initial state of SST: 0.2 (UFS); 0.6 (CFSv2)
- CFSv2’s prediction tends to very weak, no indication of La Nina event
- Coupled UFS captures the trend in the summer-fall time, but return to normal SST earlier, which could be a winter warm bias.

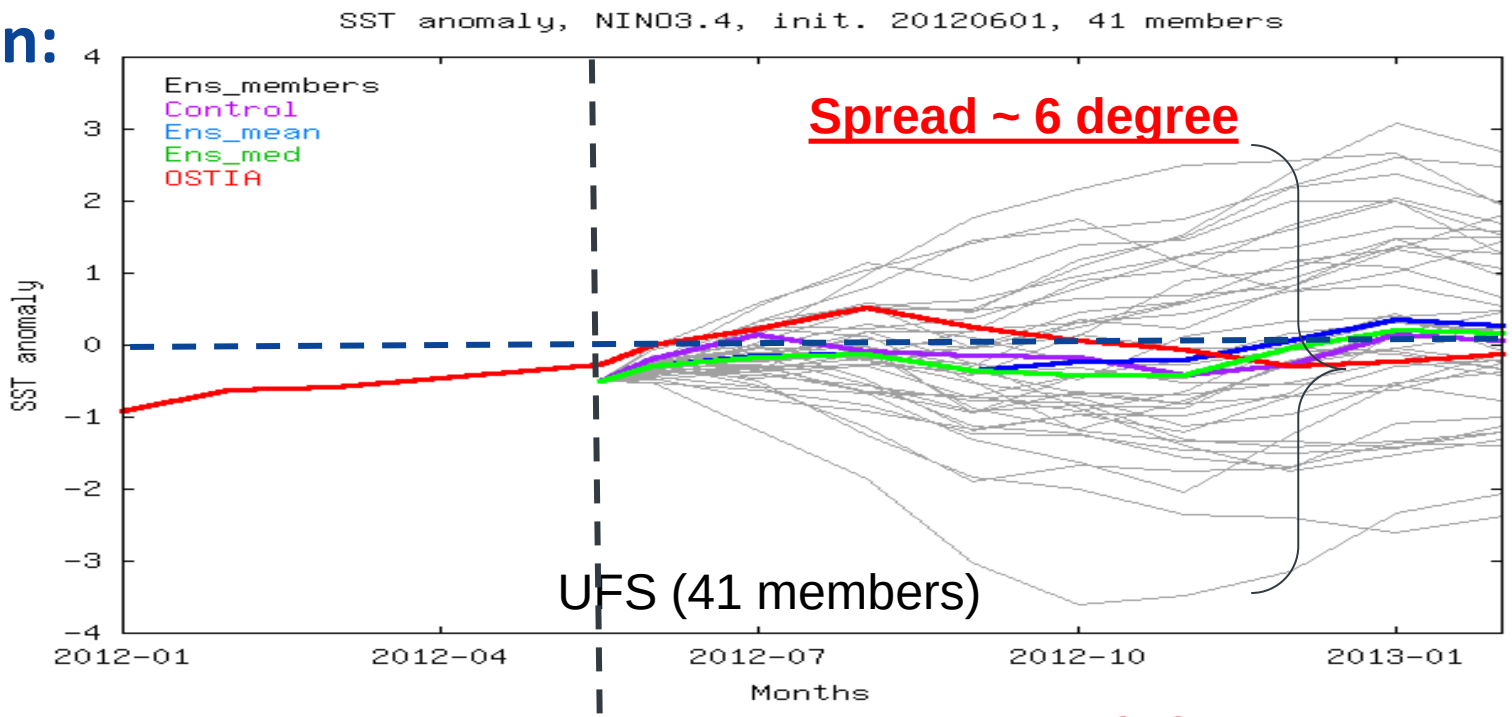


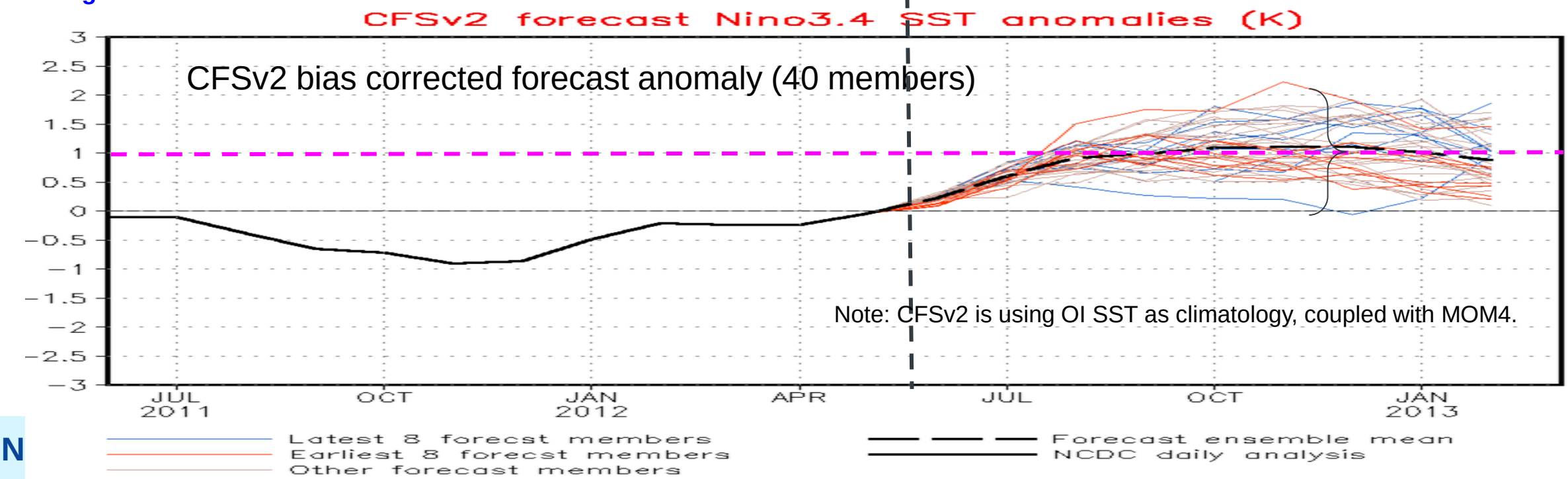
NWS/NCEP/CPC



Nino 3.4 indexes comparison: "Neutral Case"

- Right plume is coupled UFS seasonal run, no bias correction
- Bottom plume is CFSv2 seasonal run, with bias correction
- Initial state of SST: -0.3 (UFS); 0.2 (CFSv2)
- CFSv2's prediction tends toward positive anomaly, reached 1d around fall (El Nino?).
- Coupled UFS has a good prediction for this neutral case, but the spread is still large.





Note: CFSv2 is using OI SST as climatology, coupled with MOM4.

Development of Hydrostatic SFS

Courtesy: Kate Zhou & Fanglin Yang

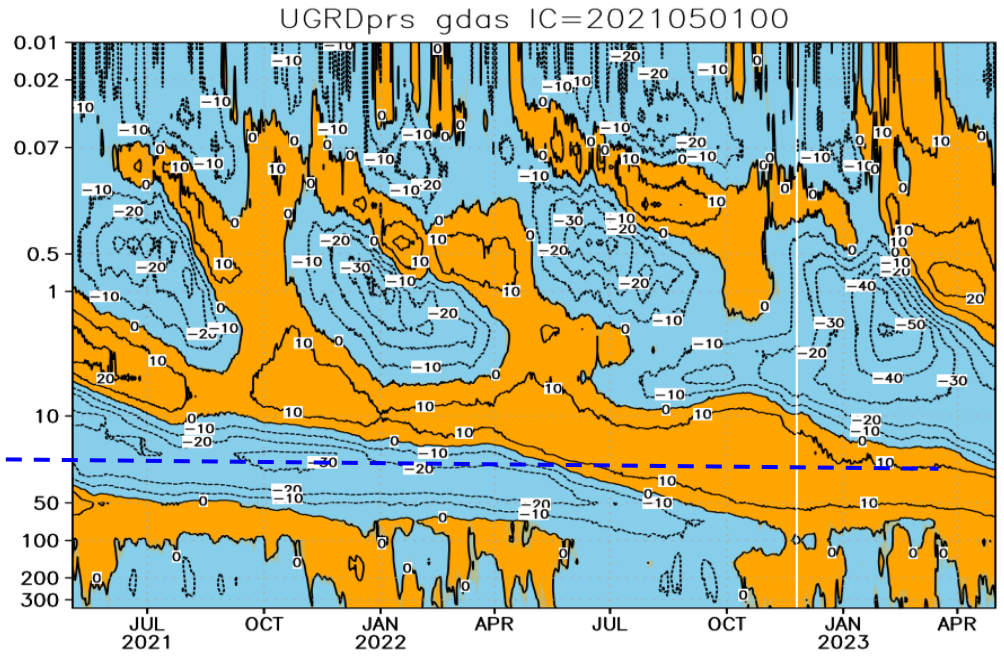
- All current UFS-based applications have been non-hydrostatic
- Why hydrostatic for SFS
  - Suitable for the seasonal to interannual (and longer) time scales
  - Proven Performance and Reliability
    - Long history of application with hydrostatic FV3 in GFDL climate models
  - Reduced Computational Costs
    - reduce ~12% computing cost for C192 with same settings
  - Potential for Longer Time Step (47% computational cost saving)

dt_atmos	Acoustic time step	NH	HYD	-C192L127 -atmos-only -8x8 layout -2 threads
600s	75	4.5 mins/day	4 mins/day	
900s	75	unstable	2.4mins/day	

QBO: Zonal mean U-Comp (5S-5N)

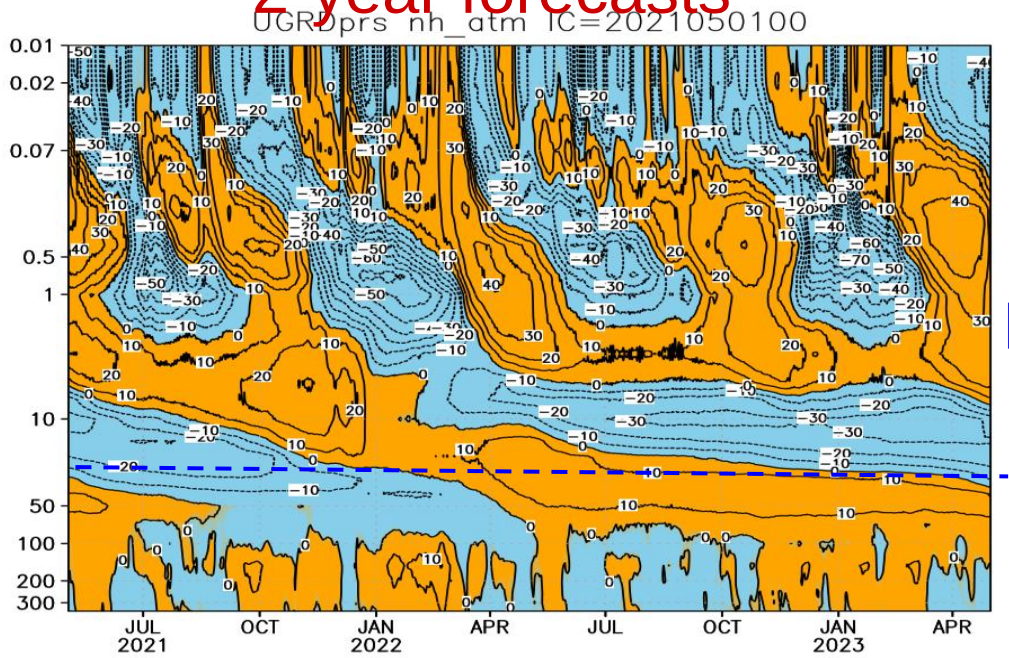
Courtesy: Kate Zhou &
Fanglin Yang

GDAS

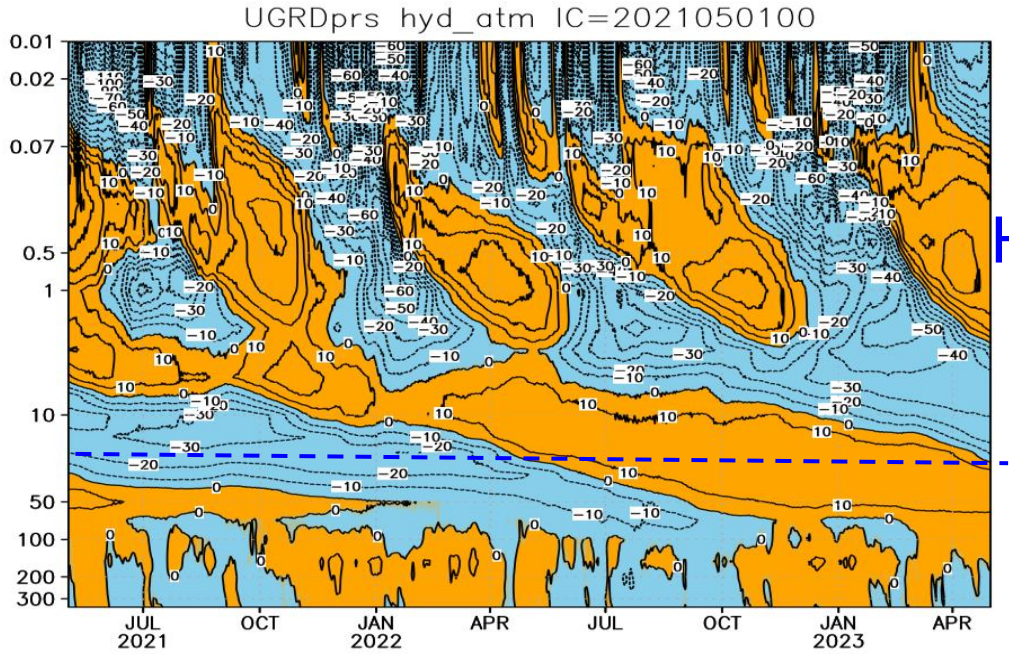


*QBO in NH faster than HYD

2-year forecasts



NH_atm

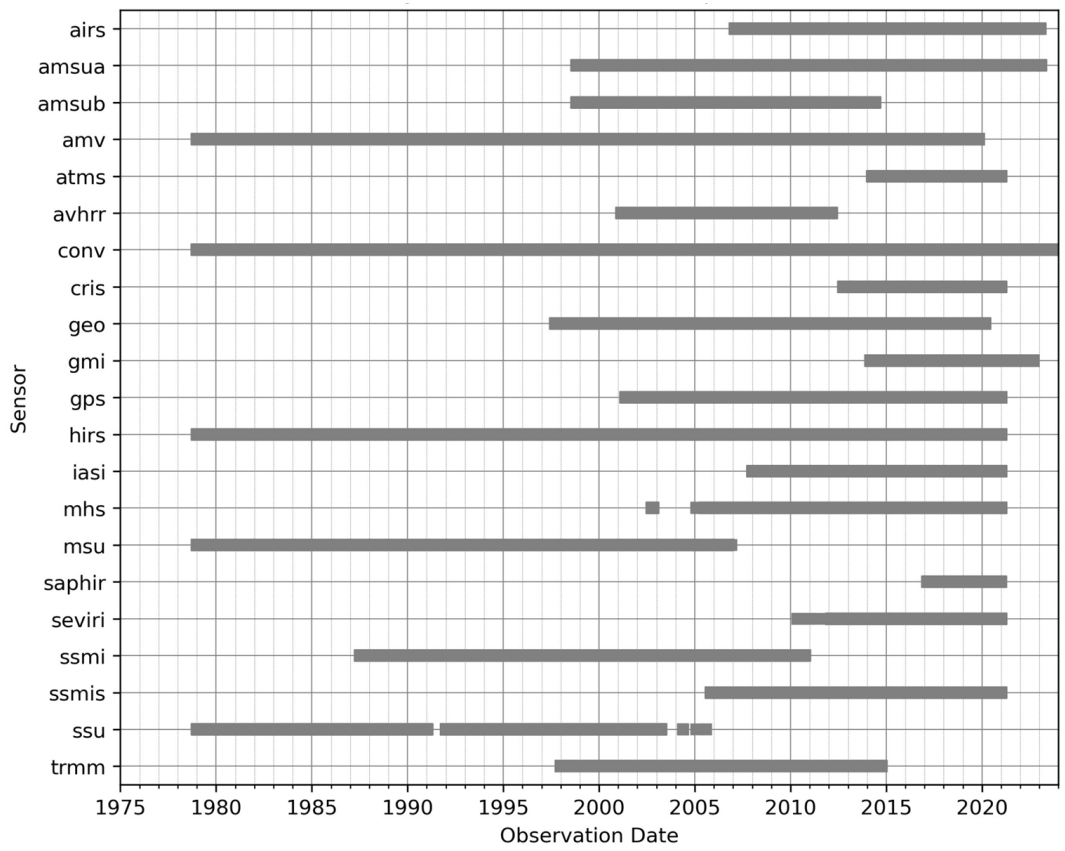


HYD_atm

Coupled Data Assimilation and Reanalysis (Leads: D Kleist, S Frolov, J Whitaker, P Pegion)

- Completion of 30 year replay to ERA5 and ORA5 reanalysis from 1993-2023
  - Balanced coupled initial conditions for GEFSv13 reforecast, and also one-degree “proof-of-concept” SFS reforecasts
  - Dataset publicly available at NODD https://noaa-ufs-gefsv13replay-pds.s3.amazonaws.com/index.html
- Development of a 50+ year publicly available observational database for coupled reanalysis
- Low resolution "scout run" in progress (in preparation for upcoming full resolution ensemble coupled reanalysis)

Inventory of ATM observations in the NNJA (NOAA-NASA Joint Archive of Observations for Reanalysis)



Joint Effort for Data assimilation Integration

Infrastructure for Unified Data Assimilation & Reanalysis

GSI in operations since 2007, but portions of the code are 30+ years old

JEDI is a project within the Joint Center for Satellite Data Assimilation (JCSDA)

JEDI provides a software infrastructure for DA that:

- is model agnostic (but requires an interface to models!)
- is generic and portable
- does not impose specific methodologies or algorithms
- allows to share efforts (new observation types, etc.) across different orgs.

JEDI will allow us to have one shared codebase for all DA,
from global to regional, and for all Earth-system components

Weakly Coupled Data Assimilation for Coupled UFS

FV3

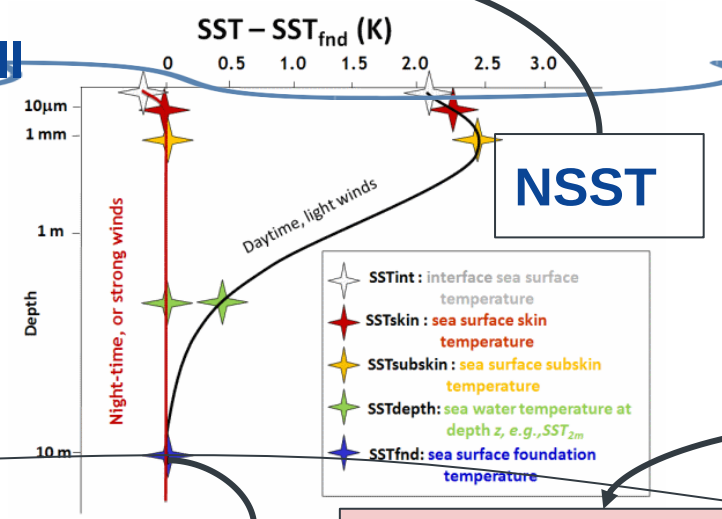
GSI, hybrid 4D EnVAR
80 members
LETKF pert.

GOCART

JEDI/FV3-JEDI 3DVAR

JEDI/FV3-JEDI LETKF
(ens. OI)

WAVEWATCHIII



NSST

CICE6

Noah-Mp
LSM

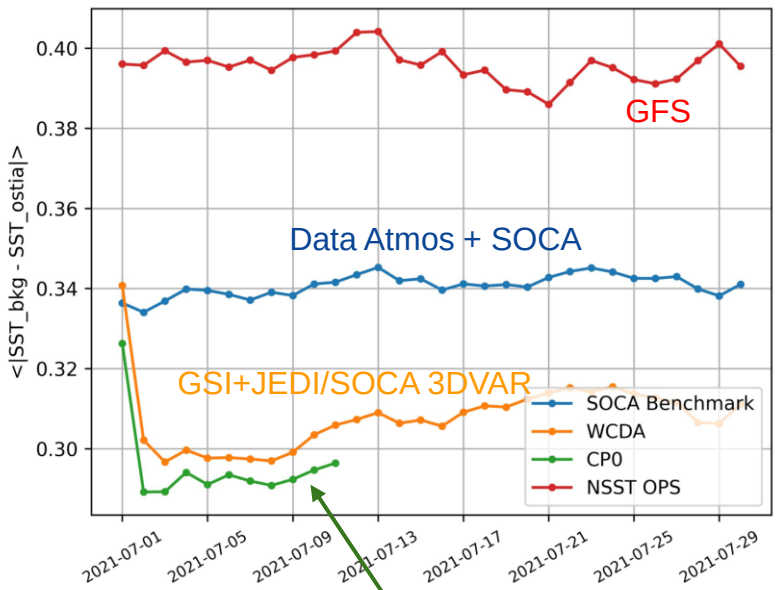
MOM6

JEDI/SOCA, hybrid EnVAR
80 members
LETKF pert.

Foundation Temperature

Advances in JEDI based Weakly Coupled Data Assimilation

comparison against OSTIA

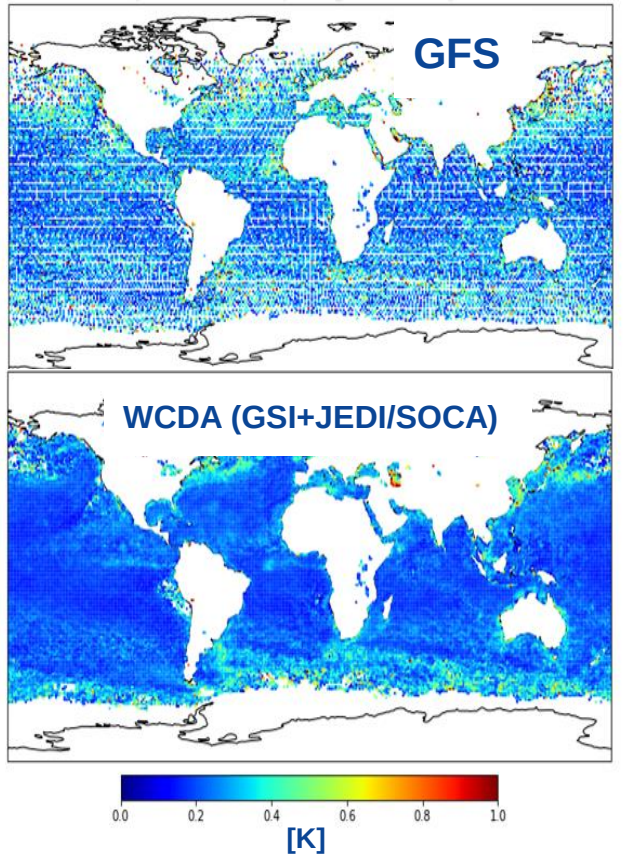


GSI+JEDI/SOCA Hybrid EnVAR

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



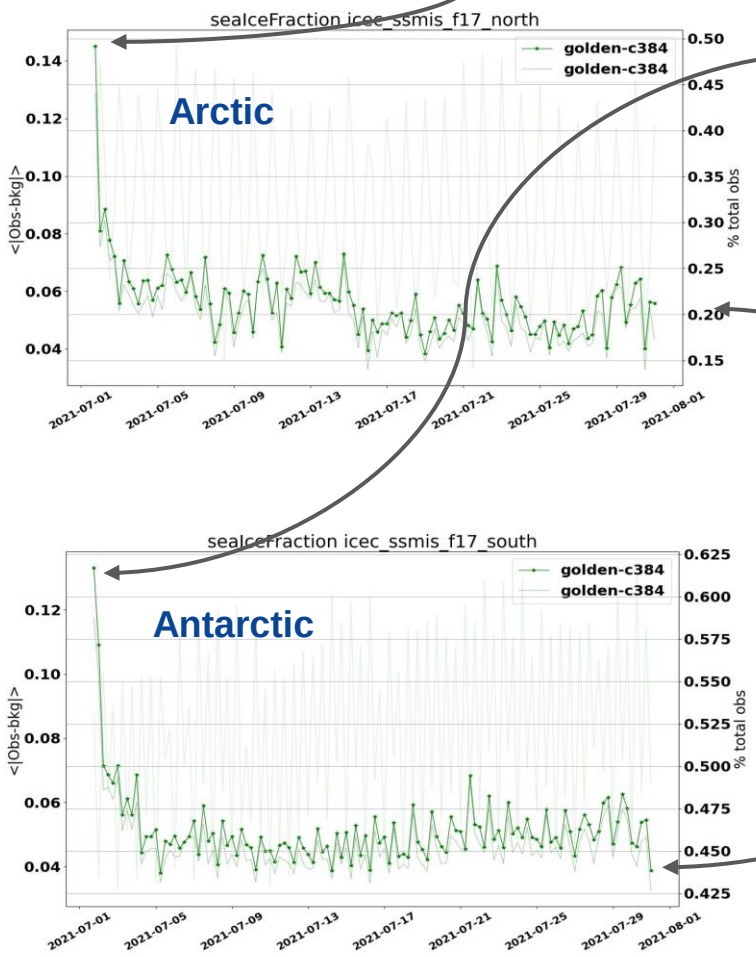
- More obs passed the GSI QC
- Smaller O-B almost everywhere

Weakly Coupled Data Assimilation preliminary results: SST

WCDA status: Preliminary Results

Seaice DA: in OK shape

Seaice concentration OMB statistics

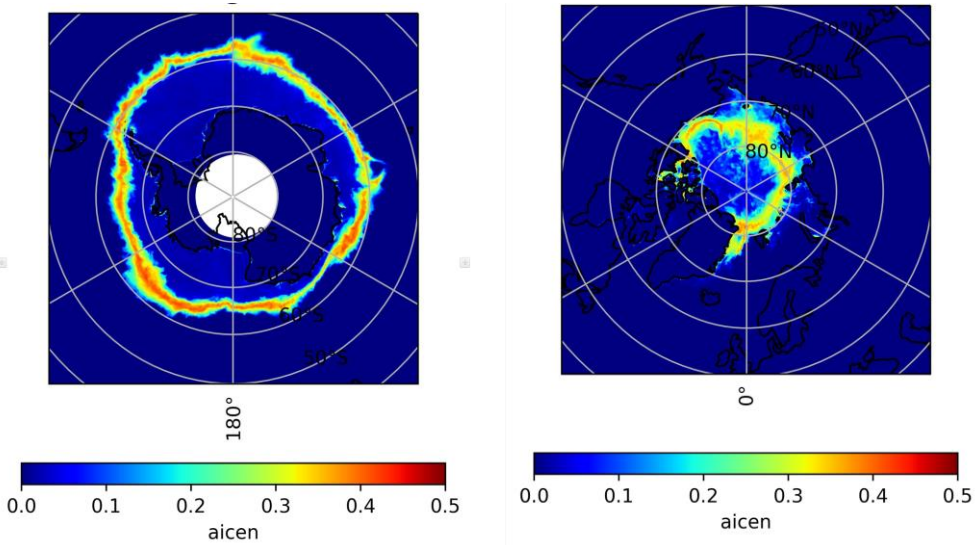


Started from a benchmark SOCA based short reanalysis (~6 months)

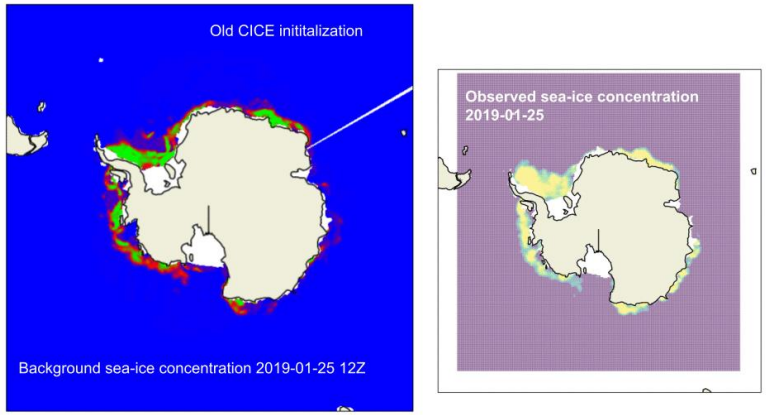
Significant error reduction in the WCDA system

Major updates (besides WCDA):

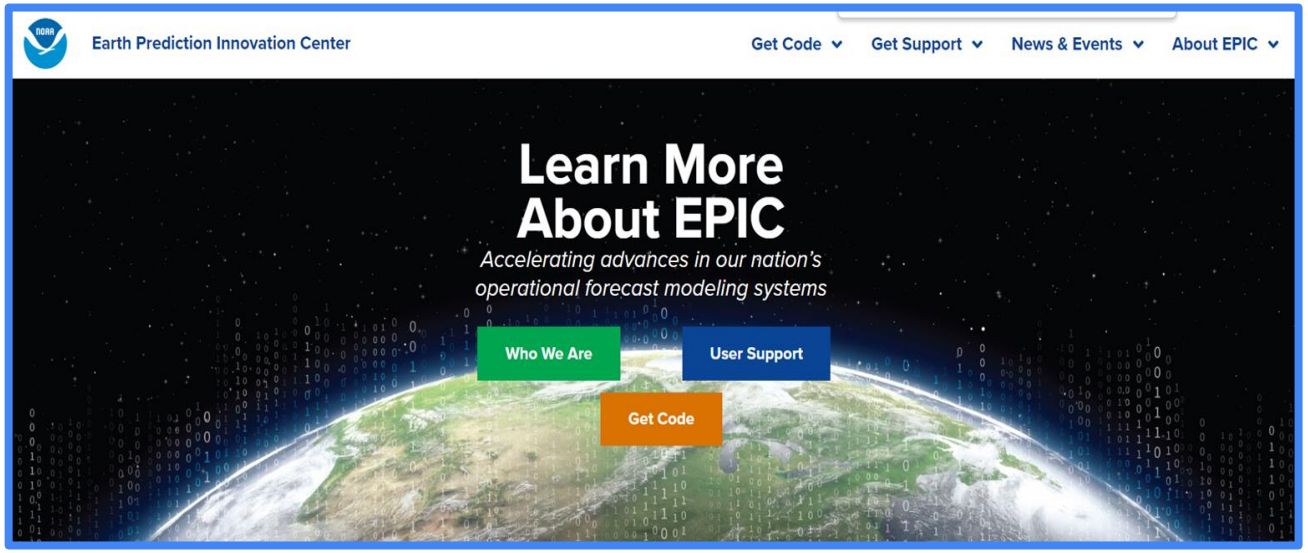
- Background error



- CICE6 initialization



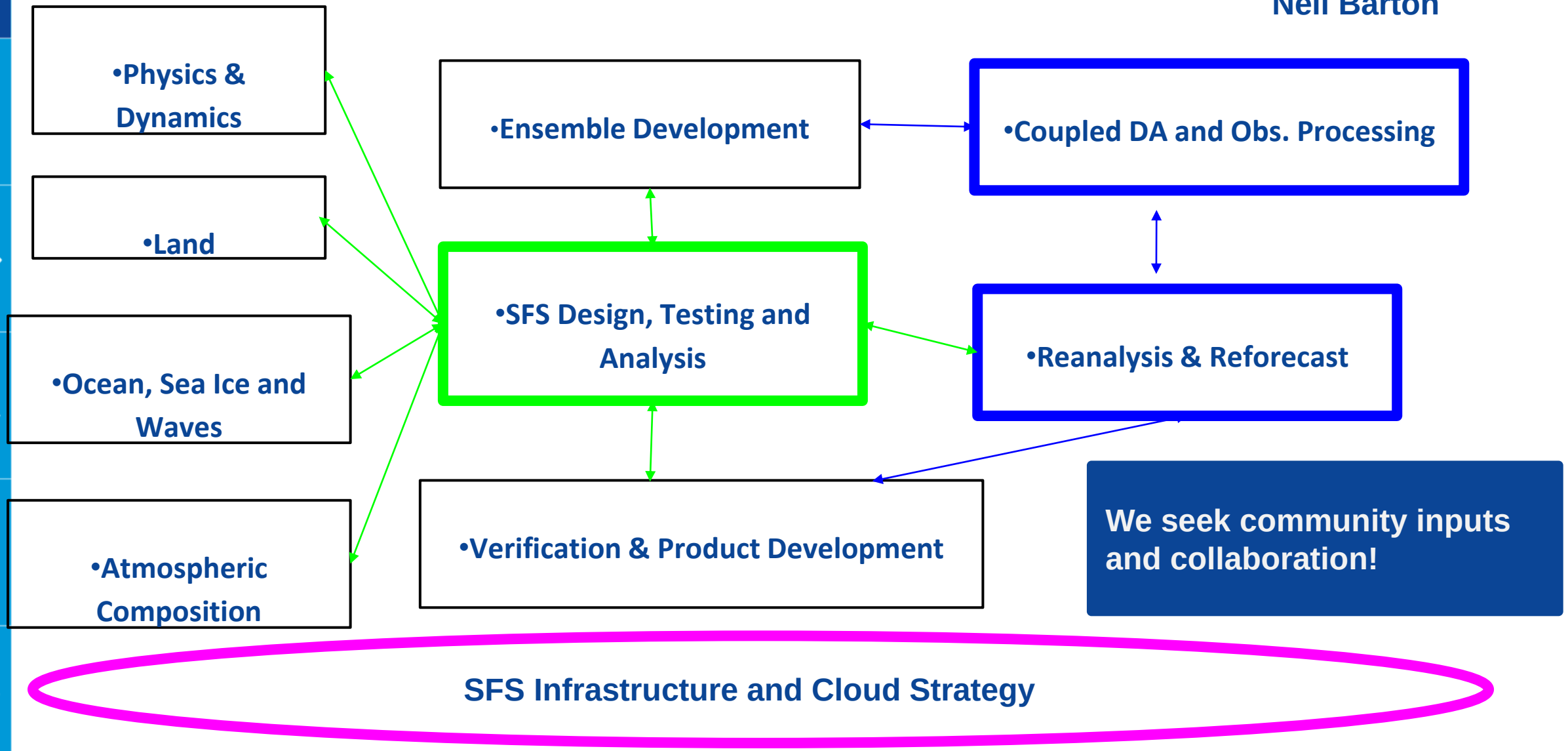
EPIC Community Portal and UFS User Support



- Quarterly code sprints and hackathons;
- **3rd Unifying Innovations in Forecasting Capabilities Workshop, Jul 22-24, 2024, Jackson, MS**
- Release additional UFS capabilities: RRFS-on-cloud, Land-DA, UFS Use Cases;
- Incorporate support for fire weather, S2S and coastal applications;

Seasonal Forecast System Focus Areas

Co-Leads: Avichal Mehra, Phil Pegion, Neil Barton



How to engage with UFS Community?

https://epic.noaa.gov/ → User engagement (support)

https://github.com/ufs-community → Developer engagement (open source, open access)

https://registry.opendata.aws/noaa-ufs-s2s/ → Data access and products from prototypes (open access)

Questions?