The Status of the First Version of the Rapid Refresh Forecast System

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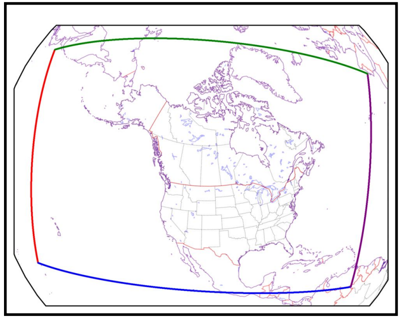
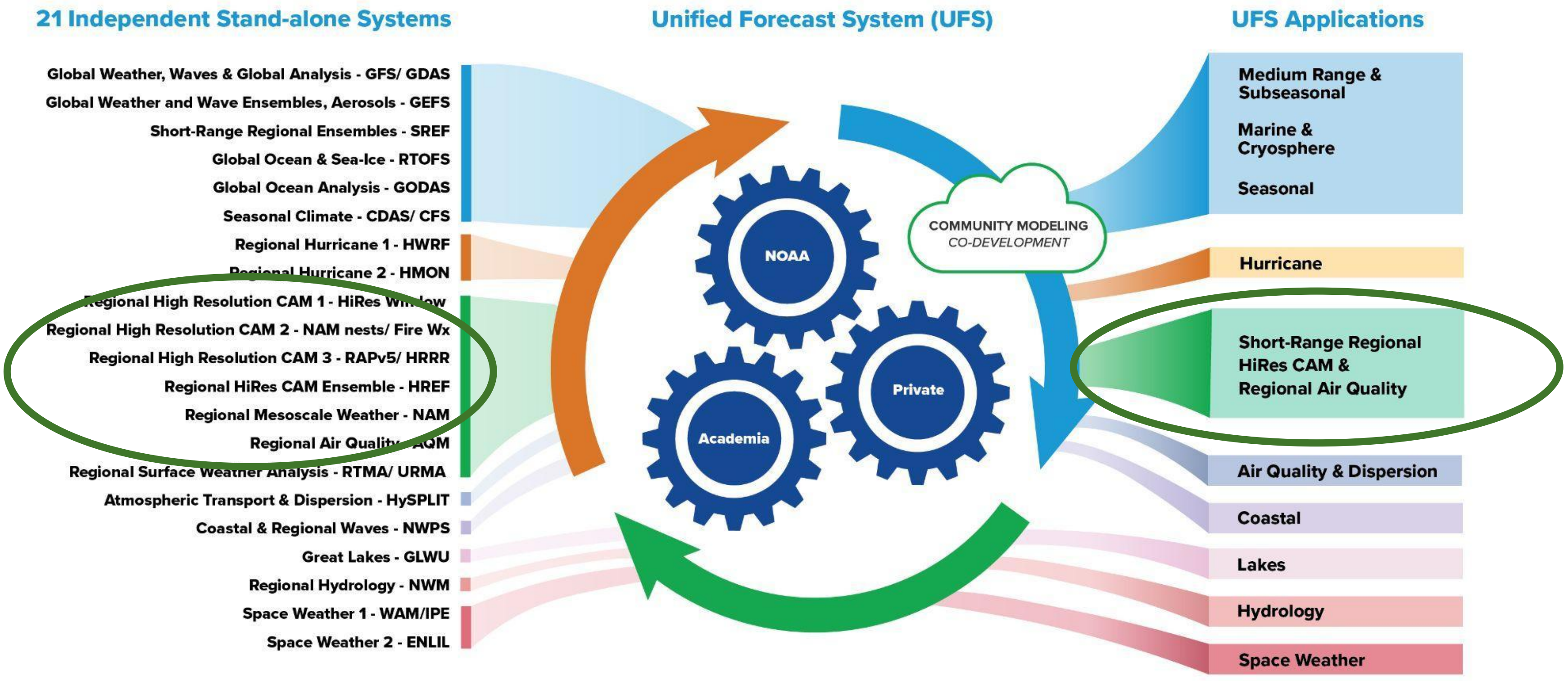
And many developers across EMC, GSL, NSSL, GFDL, NCAR/DTC, and our academic partners

[1]NOAA/NWS/NCEP/EMC
[2]NOAA/OAR/GSL



Simplifying NOAA's Operational Forecast Suite

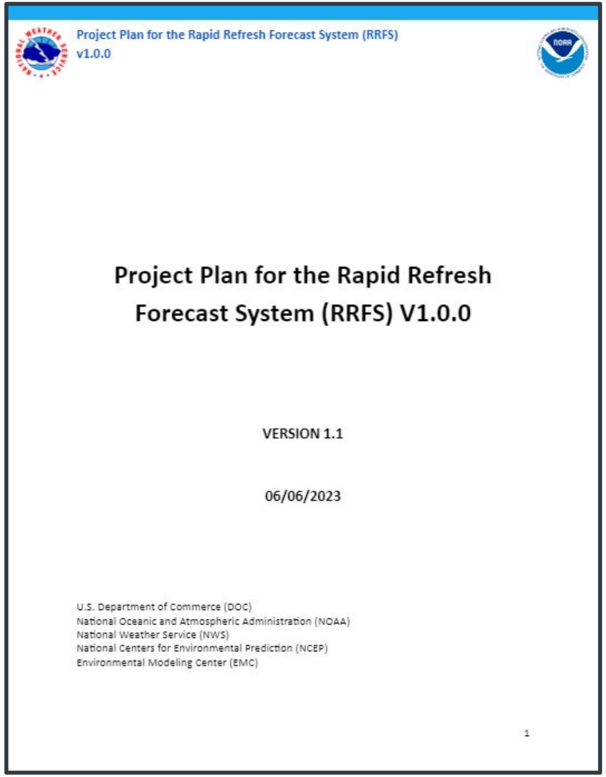
Reducing the 21 Stand-alone Operational Forecast Systems into Eight Applications



RRFSv1 Project Plan

Informed by Stakeholder Feedback and Requirements

1. HRRRv4 Implementation & Evaluation (2020)
2. HREFv3 Implementation & Evaluation (2021)
3. UFS Forecaster priority workshops (2020-2021)
4. UFS Metrics Workshops (2021)
5. NOAA Testbed reports from HWT and HMT (2020-Now)
6. CaRDS 21-012
7. CaRDS CAM Ensemble


Project Plan for the Rapid Refresh Forecast System (RRFS) v1.0.0

Project Plan for the Rapid Refresh Forecast System (RRFS) V1.0.0

VERSION 1.1

06/06/2023

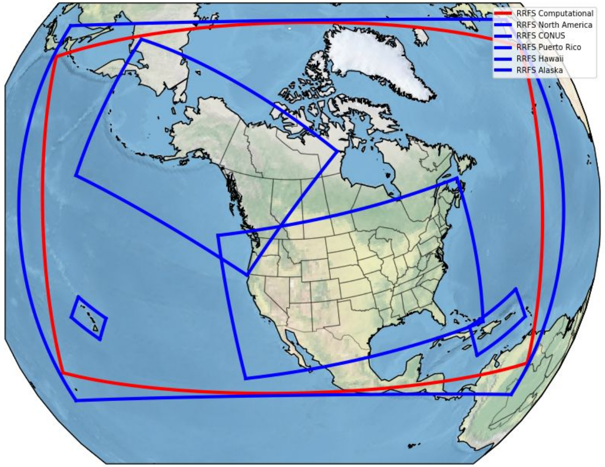
U.S. Department of Commerce (DOC)
National Oceanic and Atmospheric Administration (NOAA)
National Weather Service (NWS)
National Centers for Environmental Prediction (NCEP)
Environmental Modeling Center (EMC)

1

Rapid Refresh Forecast System (RRFS)

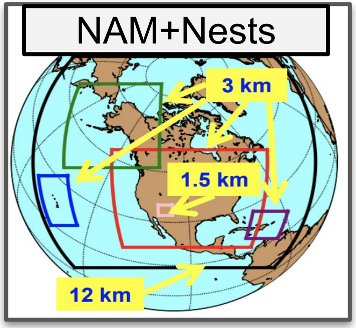
A UFS Application

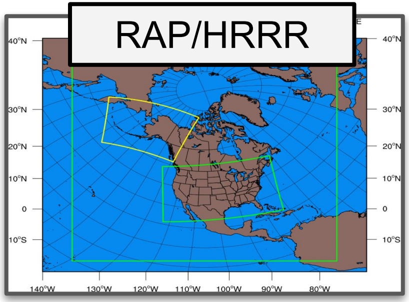
- **Based on the FV3 dynamical core Limited Area Model (LAM) capability**
- **Rapidly updated**
- **Convection-allowing (~3 km grid spacing)**
- **65 vertical layers**
- **Hybrid 3DEnVar assimilation (30 members)**
- **Deterministic forecasts to at least 18h every hour**
- **Deterministic & Ensemble forecasts to 60h every 6 hours**
  - 12 Time Lagged Members
    - 6 on-time + 6 t-6h

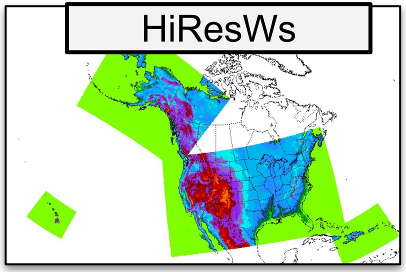


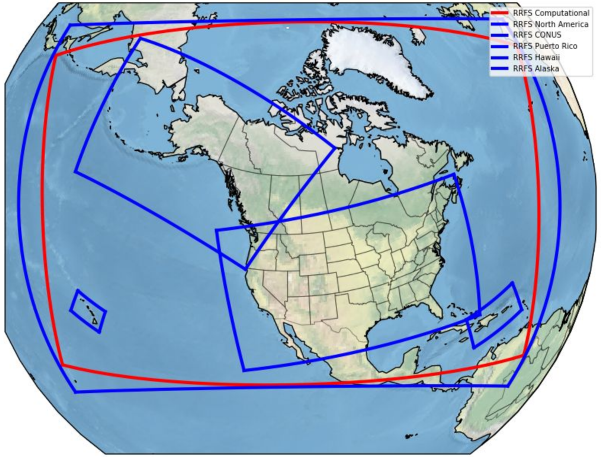
RRFSv1 Compute Domain (red)

Unifying Regional Domains







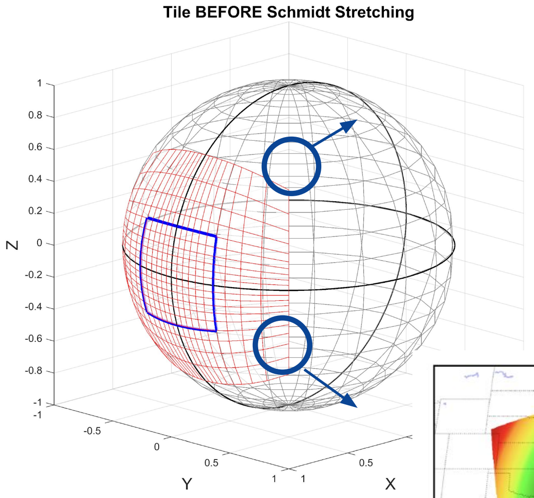


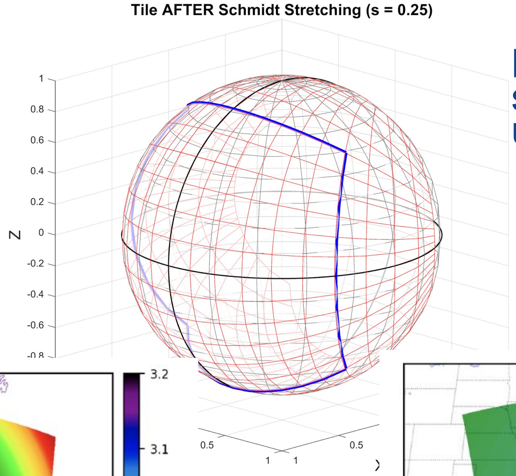
~10.7 million cells per layer

3-km RRFSv1 Domain

Novel Computational Grid

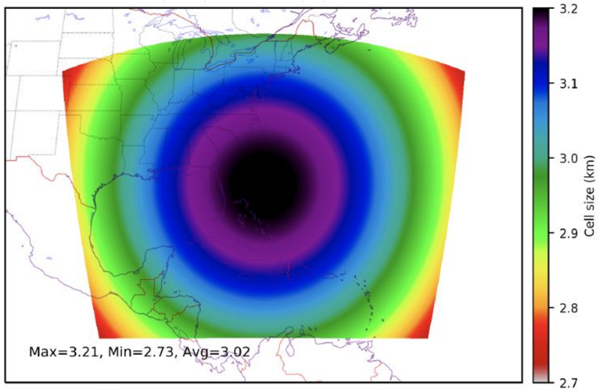
The Extended Schmidt Gnomonic Grid



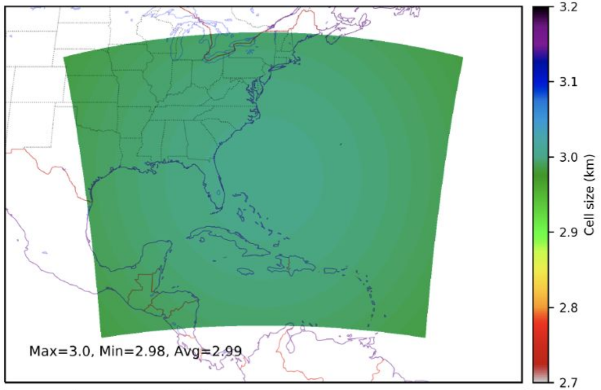


Minimizes variance of cell sizes for an exceptionally uniform mesh

Allows for a larger domain with minimal distortion

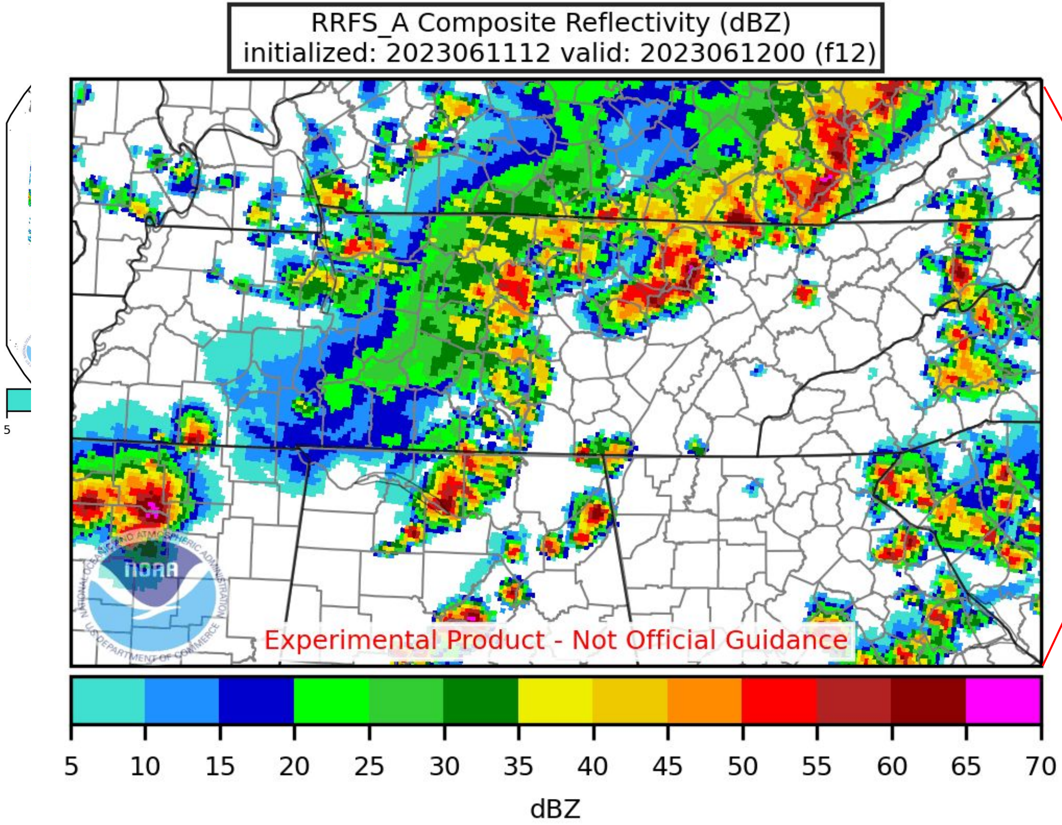


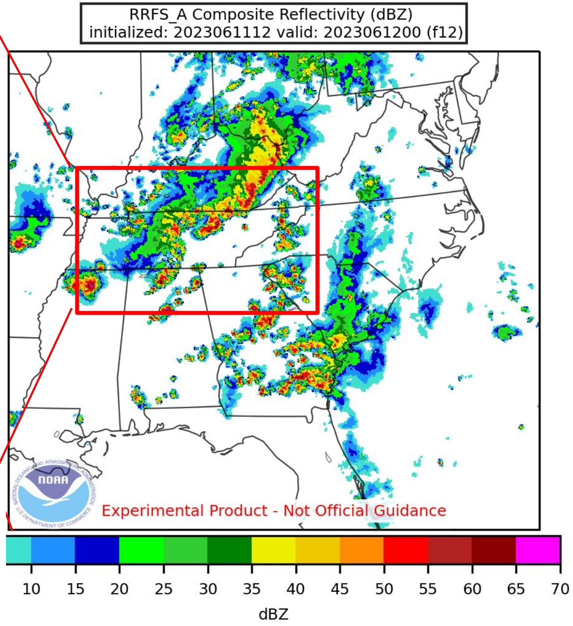
ordinary gnomonic grid



extended Schmidt gnomonic grid

North America 3 km Domain



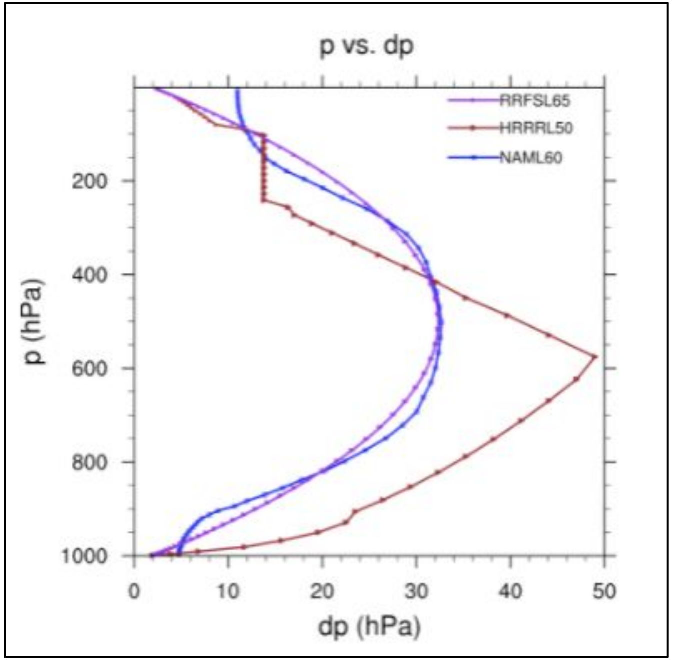


RRFS Physics and Vertical Resolution

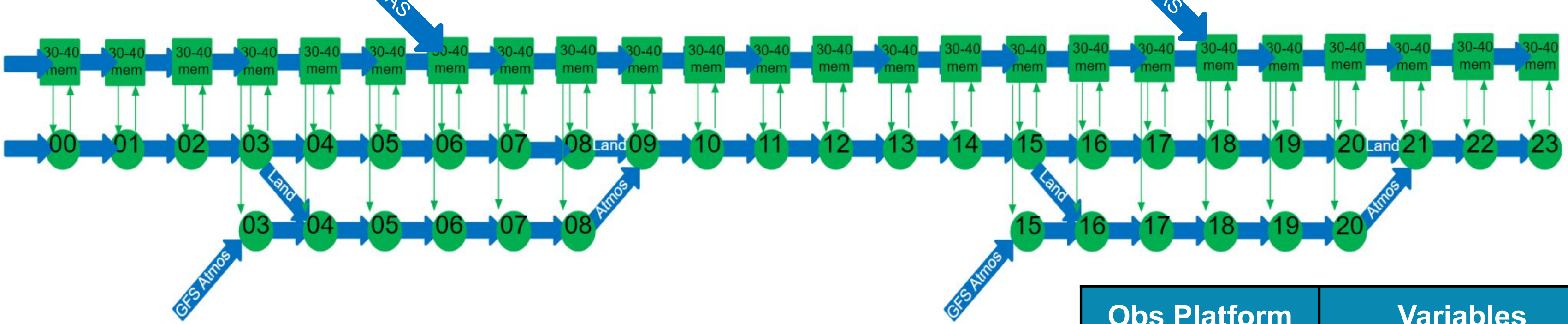
Physics	SCHEME	REFERENCE
PBL/Turbulence	MYNN-EDMF	Olson et al. (2019)
Surface Layer	MYNN	Olson et al. (2021)
Microphysics	Thompson-Eidhammer	Thompson and Eidhammer (2014)
Climatological Aerosols	Thompson-Eidhammer	Thompson and Eidhammer (2014)
Smoke and Dust	RAVE fire data, FENGSA scheme for dust	Ahmadov et al., Freitas et al., 2010
Shallow Convection	MYNN-EDMF	Olson et al. (2019) Angevine et al. (2020)
Gravity Wave Physics	Small Scale and Turbulent Orographic Gravity-Wave & Form Drag	Beljaars et al. (2004) Tsiringakis et al. (2017) Toy et al. (2021)
Land Model	RUC LSM	Smirnova et al. (1997, 2000, 2016)
Large Lakes	FVCOM	Fujisaki-Manome et al. (2020)
Small Lakes	CLM Lake	Subin et al. (2012), Mallard et al. (2015), Benjamin et al. (2022)
Long and Short Wave Radiation	RRTMG	Iacono et al. (2008), Mlawer (1997)

Tested L65 and L70 configurations for 30 cases

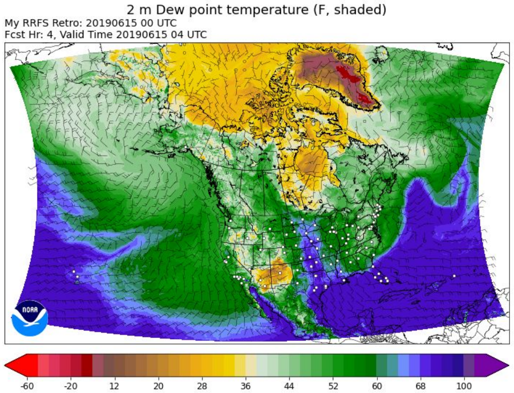
- Performance similar between L65 and L70
- Both improved over NAM's L60



RRFSv1 Data Assimilation



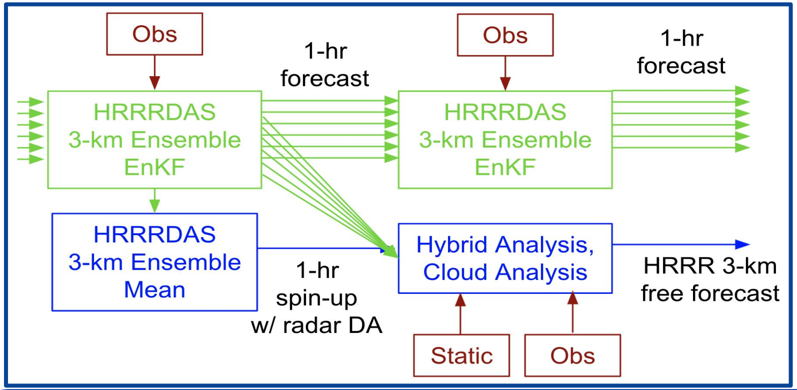
- Two-way interaction between 30 member 3-km DA ensemble (■) and 3-km deterministic RRFS hybrid 3DEnVar analysis(●)
- Partial cycle spin-up of atmosphere from GFS twice per day (RAP like), land states fully cyc'd



- All ensemble members (in square) and deterministic/control (circle) on 3-km NA grid

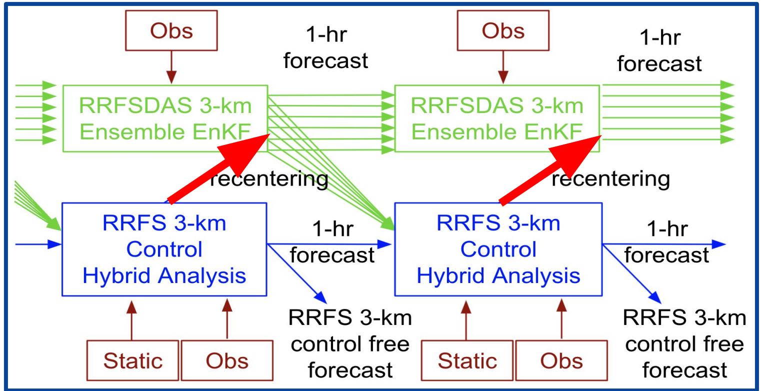
Obs Platform	Variables
METAR, Mesonet, Buoy, C-Man, Ship	T, moisture, W, ps, ceiling, vis
Rawinsonde	T, moisture, W
NEXRAD Radar	dBZ, rw, VAD W
Lightning	Flash Extent Density
Aircraft	T, moisture, W
GOES-16/18	ABI, AMVs, cloud top pres. & T
Polar Orbiters	Radiances (AMSUA, MHS, ATMS, CRIS, IASI, SSMIS)

RRFSv1 Data Assimilation



Operational HRRRv4 HiRes Ensemble DA

- Ensemble covariances in deterministic analysis
- Leverages ensemble mean for deterministic forecast
- *One-way* information from ensemble to deterministic forecast
- Deterministic atmospheric forecast *not* hourly cycled
- *Non*-var/*non*-hybrid cloud/radar DA in deterministic HRRR
- Deterministic forecast can fall *outside* ensemble solutions



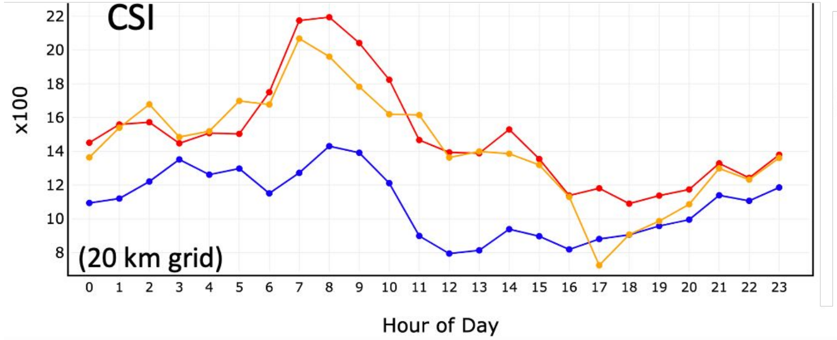
RRFSv1 HiRes Ensemble DA

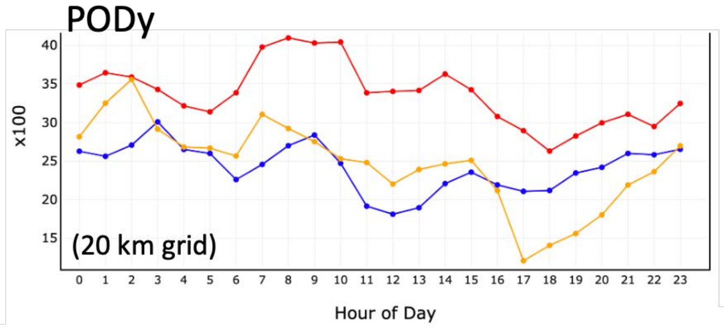
- Ensemble covariances in deterministic analysis
- Ensemble mean recentered from deterministic analysis
- ***Two-way* information between ensemble and control member**
- **Deterministic atmospheric forecast *hourly* cycled**
- **Hybrid cloud/radar DA in deterministic RRFS**
- Deterministic/control forecast *within* ensemble solution space

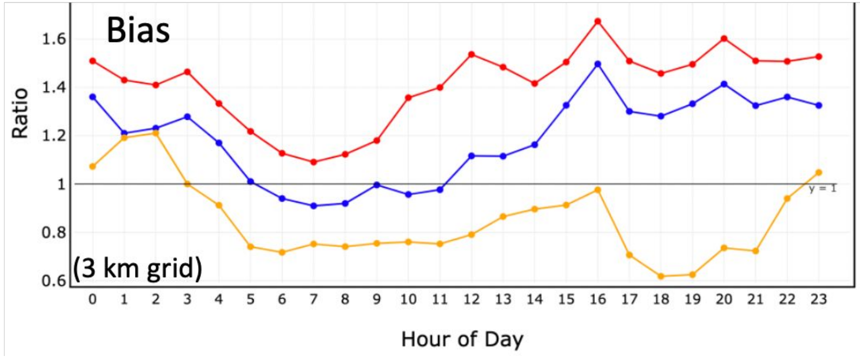
RRFSv1 Design: Radar DA

Time of Day Verification of Reflectivity > 30 dBZ
3-hour forecasts

BaseE_Ens06Z18Z_300km_RTPS1.0
BaseE_1
HRRR_OPS







Inclusion of radar assimilation in RRFS

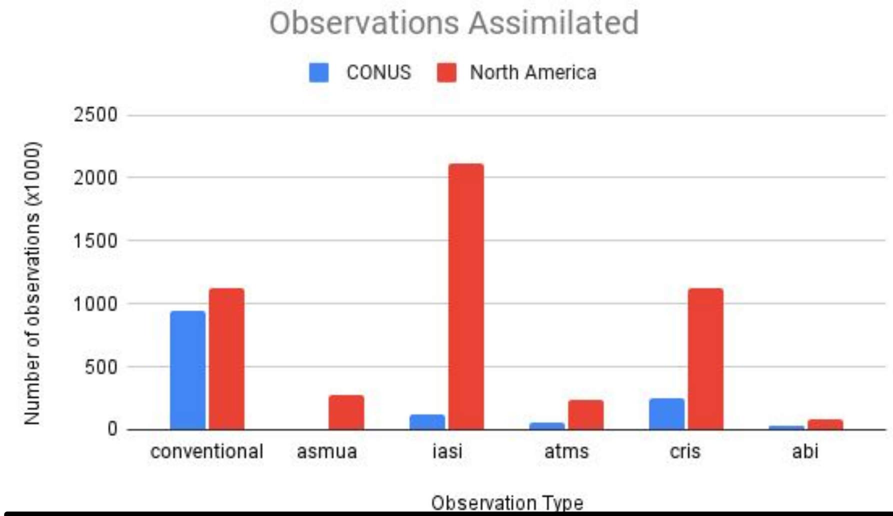
- Overall better than without radar
- Improves skill, comparable to HRRR
- Improves probability of detection, better than HRRR
- Increases high bias, potential improvement from with multiscale algorithm (more later in talk)

Direct radar reflectivity assimilation for hybrid EnVar follows the approach of Wang and Wang 2017 (direct dBZ assimilation from OU/MAP)

RRFSv1 Data Assimilation

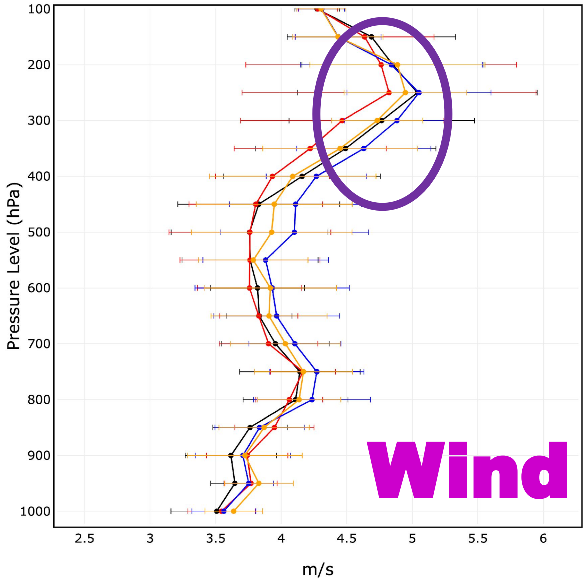
Satellite Data

- Moving to the North American domain increases the number of observations available for assimilation for the RRFS (by 250%) - particularly those from satellites



Total assimilated observations over CONUS (blue) and prototype North America domains (red) for an arbitrary cycle

18h fcst. radiosonde verification



NA 3km Control run (conventional data only)

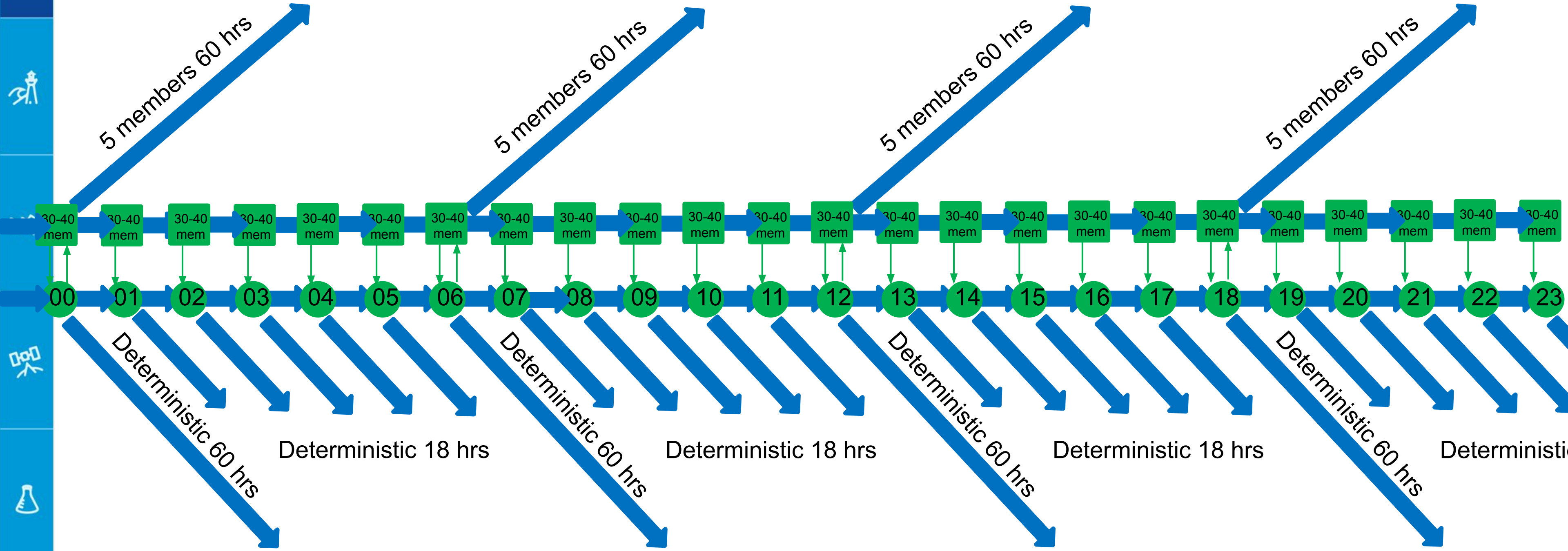
NA 3km Radiance run

NA 13km Control run (conventional data only)

NA 13km Radiance run

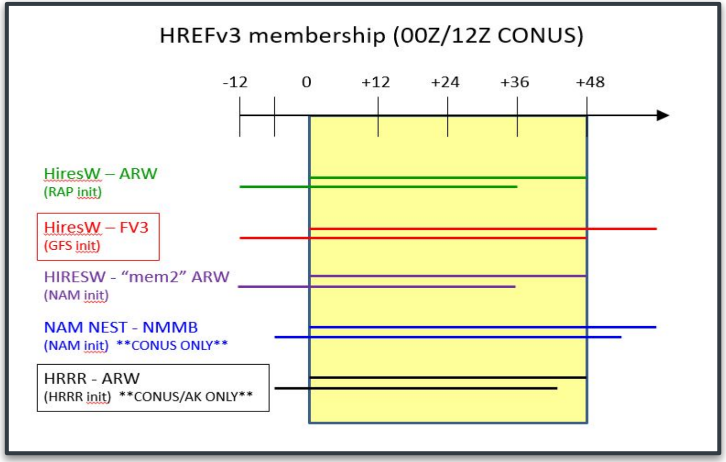
From Zhang (EMC) and Lin (GSL)

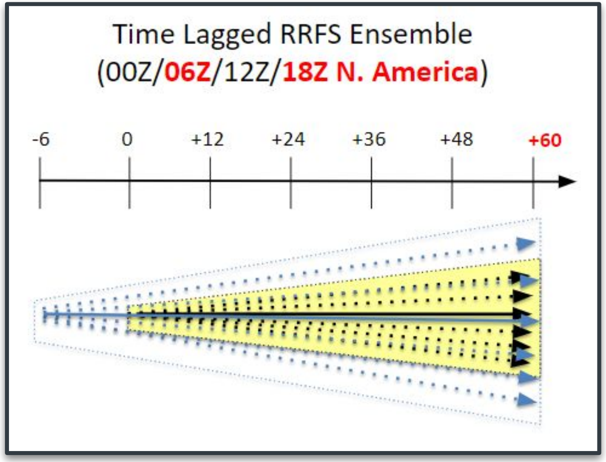
RRFSv1 Initial Operational Capability for Forecasts



With Time Lagging we have 12 ensemble members

RRFSv1 Forecast Ensemble Design





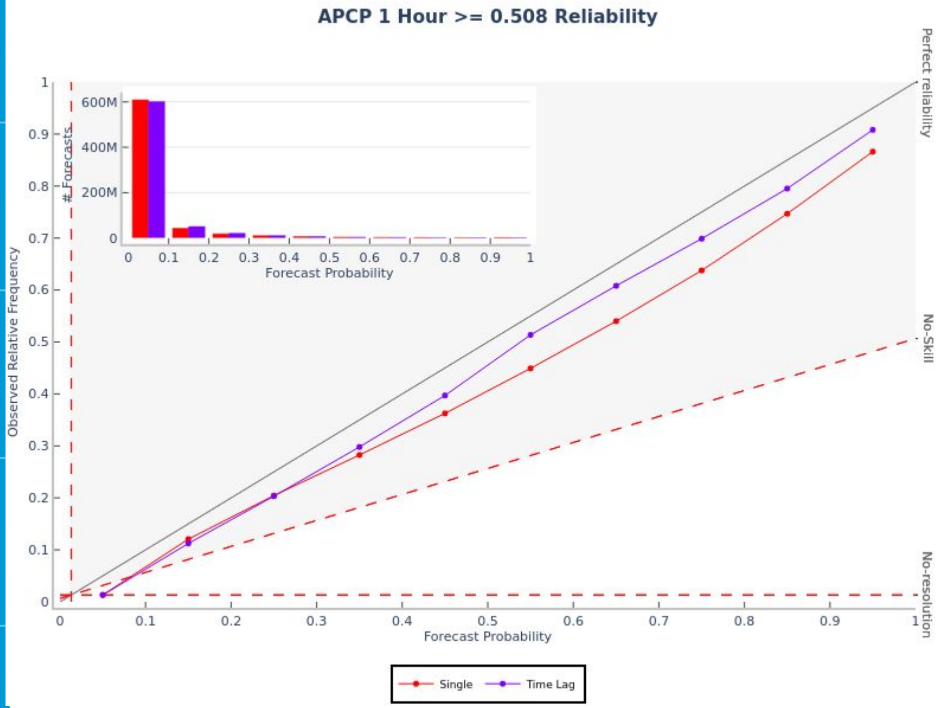
- 5 on time members + 5 time lagged
- 48H forecast length 2x per day
- Multi-dycore (3)
- ICs from NAM + nests, RAP, HRRR, GFS
- Multiphysics

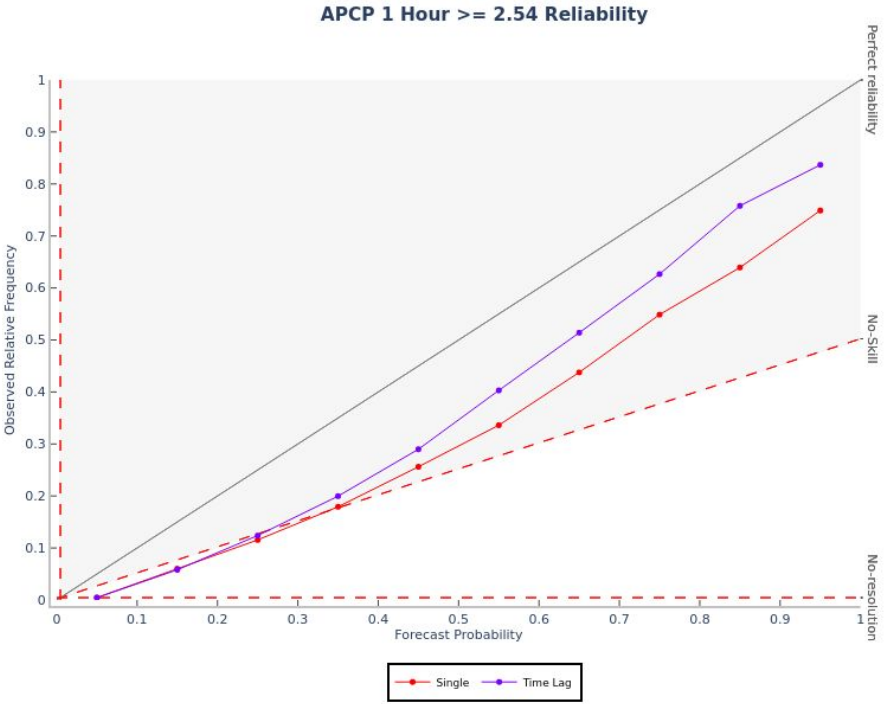
- 12 Time lagged members (complete N. America coverage)
- 60H forecast length 4x per day
- Single dycore
- IC perturbations subset from ~30 member EnKF
- Stochastic physics and (possibly) multiphysics
- LBC perturbations from GEFS

- Single core & physics CAM ensembles designed *to date* have typically been are under-dispersive vs. HREF
- RRFSv1 ensemble design leveraging HRRRE development and HIWT, UFS-R2O projects to incorporate methods of representing uncertainty (multiphysics, SPP, etc.)
- Goal: Skillful spread & error relationship.

Precipitation Accumulation Reliability for Time-Lagged/Single Init

9 member RRFS Ensemble forecasts from 2021 HWT SFE





- Time-lagging improves reliability of these precip forecasts

Acknowledge DTC for this analysis

Ensembles at FFaIR

Single Physics

Members	ICs	LBCs	Microphysics	PBL/SFC	LSM	Radiation	Shallow Cumulus
*RRFSp1 (cnt)	RRFS hybrid 3DEnVar	GFS	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
*RRFS01	enkf1	GEFS m1	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
*RRFS02	enkf2	GEFS m2	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
*RRFS03	enkf3	GEFS m3	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
*RRFS04	enkf4	GEFS m4	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
*RRFS05	enkf5	GEFS m5	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
RRFS06	enkf6	GEFS m6	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
RRFS07	enkf7	GEFS m7	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
RRFS08	enkf8	GEFS m8	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
RRFS09	enkf9	GEFS m9	Thompson	MYNN/MYNN	RUC	RRTMG	n/a

Multi-Physics

Members	ICs	LBCs	Microphysics	PBL/SFC	LSM	Radiation	Shallow Cumulus
*RRFSp1 (cnt)	RRFS hybrid 3DEnVar	GFS	Thompson	MYNN/MYNN	RUC	RRTMG	n/a
*RRFSphys01	enkf1	GEFS m1	Thompson	H-EDMF/GFS	RUC	RRTMG	saSAS Shal
*RRFSphys02	enkf2	GEFS m2	Thompson	TKE-EDMF/GFS	RUC	RRTMG	saSAS Shal
*RRFSphys03	enkf3	GEFS m3	Thompson	MYNN/MYNN	RUC	RRTMG	saSAS Shal
*RRFSphys04	enkf4	GEFS m4	Thompson	TKE-EDMF/GFS	RUC	RRTMG	saSAS Shal
*RRFSphys05	enkf5	GEFS m5	NSSL	MYNN/MYNN	RUC	RRTMG	saSAS Shal
RRFSphys06	enkf6	GEFS m6	NSSL	H-EDMF/GFS	RUC	RRTMG	saSAS Shal
RRFSphys07	enkf7	GEFS m7	NSSL	TKE-EDMF/GFS	RUC	RRTMG	saSAS Shal
RRFSphys08	enkf8	GEFS m8	NSSL	MYNN/MYNN	RUC	RRTMG	saSAS Shal
RRFSphys09	enkf9	GEFS m9	NSSL	TKE-EDMF/GFS	RUC	RRTMG	saSAS Shal

- At FFaIR we are effectively evaluating 4 ensembles
- 10 Member Single Physics
- 10 Member Multi Physics
- 12 Member Time Lagged Single Physics
- 12 Member Time Lagged Multi Physics

Past FFaIR Experiments

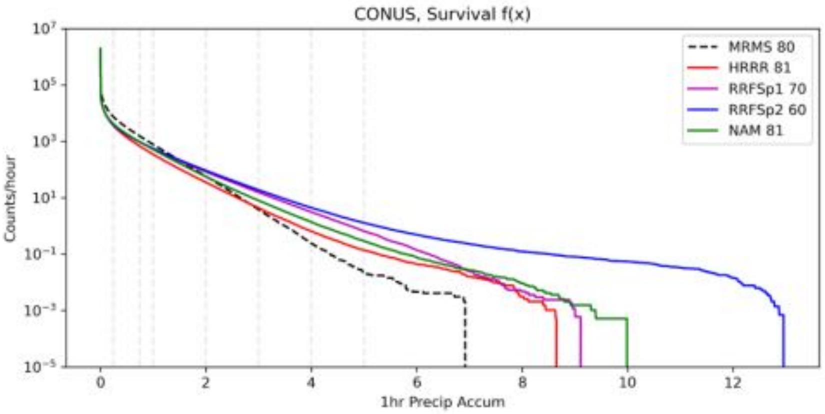
From the 2022 FFaIR Final Report

"The RRFSs generally performed similar to the NAM. They both had pros and cons. One thing that stuck out for me was that while the NAM has high rain rates, the RRFSs have even higher rain rates."

"One bias I generally noticed from the RRFSp1 and p2 was the tendency to over forecast coverage and rainfall maxima pockets for the pulse thunderstorm convection over the Texas/Louisiana/Arkansas Gulf Coast area. Otherwise it handled the northeast CONUS convection and southwest convection fairly well."

"RRFS seemed to really overdo precip accums, especially in moist air masses like with the tropical system or the southeast."

"Overall, I thought it was too popcorny and wasn't showing enough more organized thunderstorm clusters."



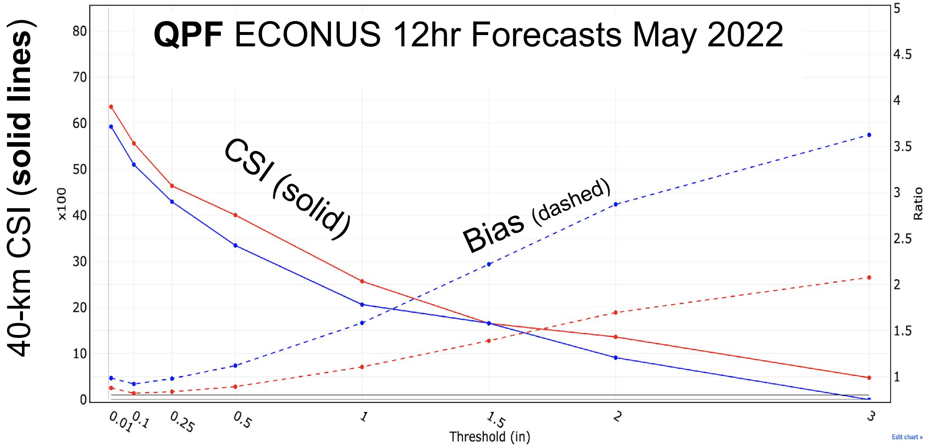
RRFS Precipitation Verification

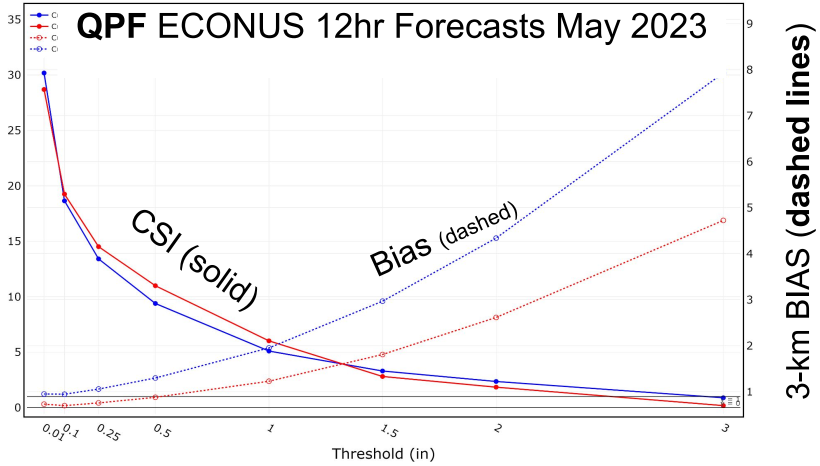
May 2022 vs May 2023

2022

RED = Op. HRRR
BLUE= RRFS_A

2023





- CSI performance gap is closing between RRFS and HRRR
- May 2023 has lower CSI and higher bias for both models
- *RRFS still has a high precipitation bias problem*

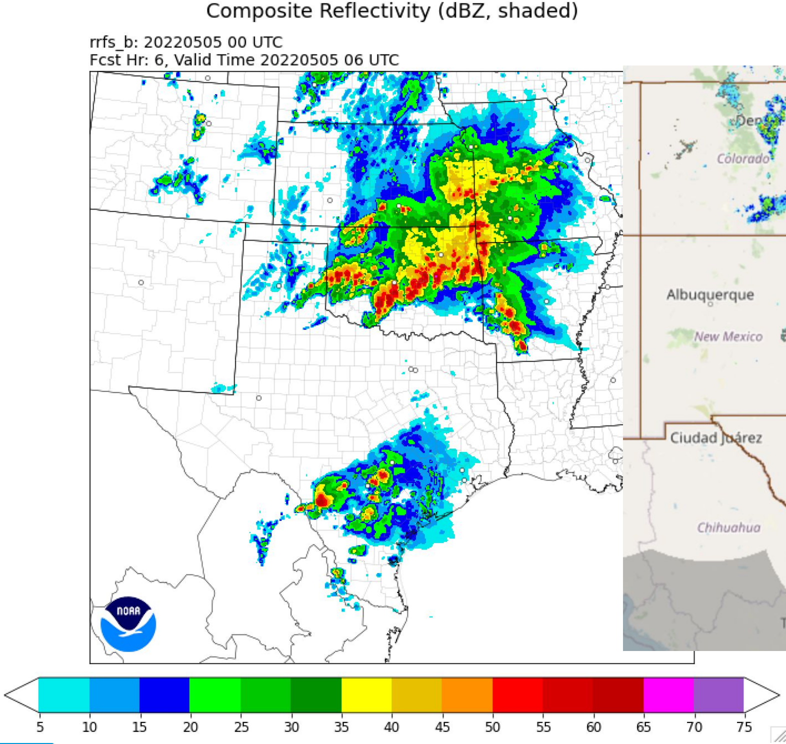
This is an Ongoing Challenge

- No changes are yet mature enough to be included in the RRFS prototypes seen at 2023 FFaIR
  - You will still see this bias, generally in the following areas:
    - Conditionally unstable airmass without strong forcing
    - Weak vertical wind shear
  - We do not see issues in the cool season
- So what have we been doing?
  - Established an R2O agreement with GFDL signed by GSL and EMC - drafted last fall in response to 2022 FFaIR feedback
  - Evaluate dampening condensational heating from microphysics
  - Enhancing connection between model physics and dynamics
  - Evaluating parameterized deep convection
  - Introducing vertical subgrid mixing
  - Multiscale DA to improve assimilation of radar data and subsequent model balance

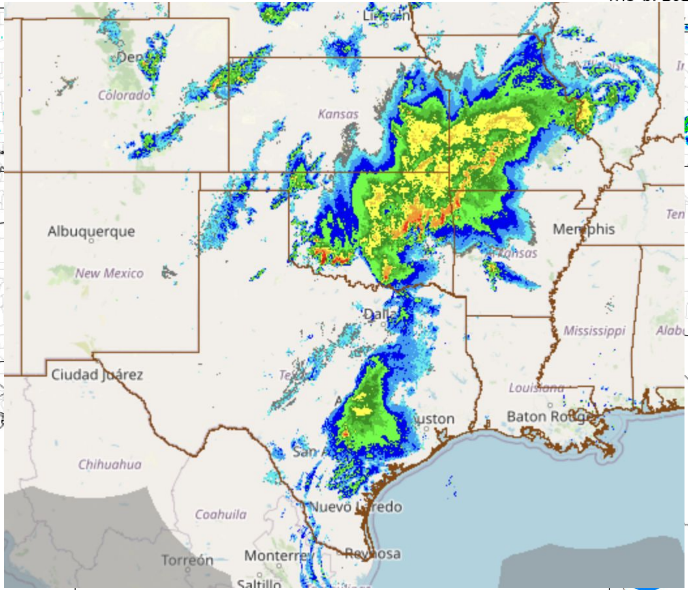
Parameterized Deep Convection w/ Grell-Freitas

[Not in official RRFS Prototype System]

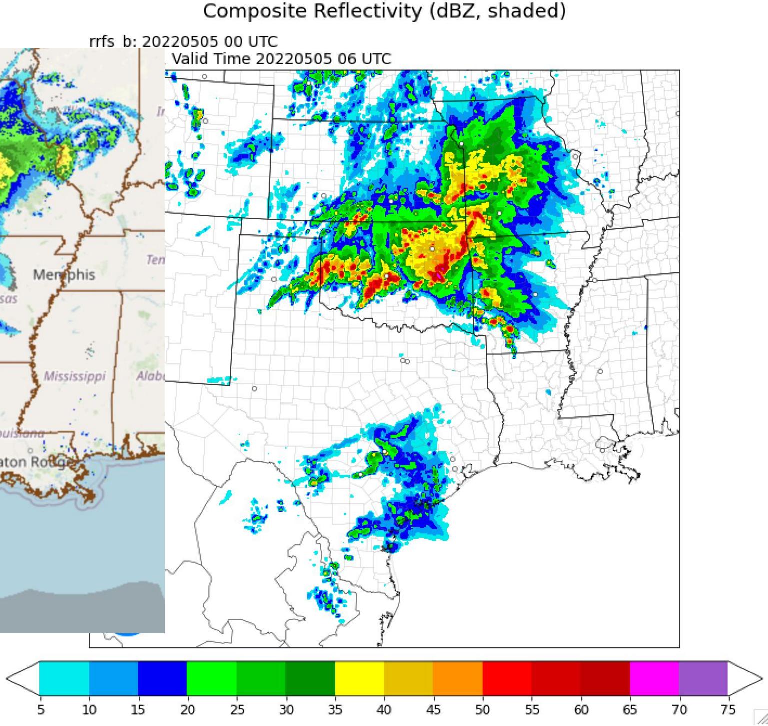
No GF scheme



MRMS - observations

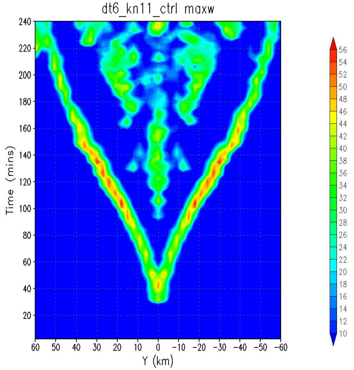


With GF scheme

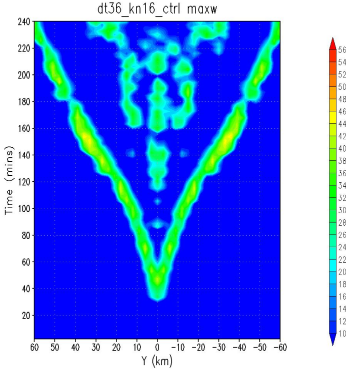


Acknowledge Georg Grell and Haiqin Li at GSL

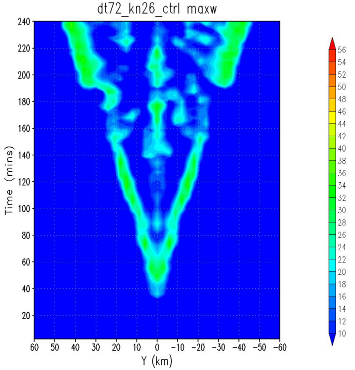
Updated Physics-Dynamics Coupling
[Not in official RRFS Prototype System]



6 second coupling/physics frequency



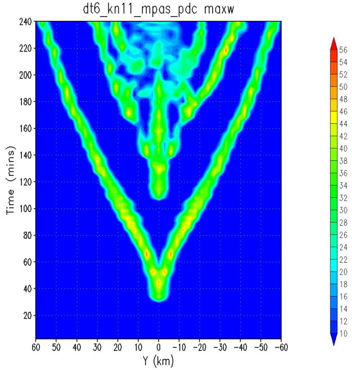
36 second coupling/physics frequency



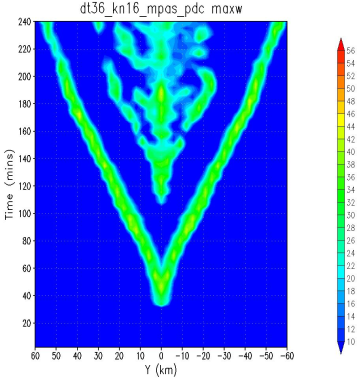
72 second coupling/physics frequency

Hovmoeller of maximum vertical velocity over the convective region for idealized splitting supercell

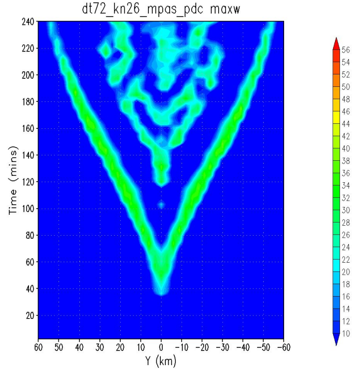
Current FV3 coupling has significant sensitivity of solution to choice of physics time-step



6 second coupling frequency,
6 second physics frequency



6 second coupling frequency,
36 second physics frequency



6 second coupling frequency,
72 second physics frequency

Modified FV3 coupling greatly reduces sensitivity of solution to physics time-step

Acknowledge Kevin Viner (EMC) for this work

Introducing Subgrid Vertical Transport Scheme

[Not yet in official RRFS Prototype System]

- JMA and other centers have noticed challenges with excessive grid point storms in their modeling systems
- To address this they have introduced a scheme to account for unresolved vertical transport of heat and moisture in deep convection
  - Known as The Leonard Term
- EMC is coding this scheme up now

$$L_{\phi w} = \frac{K_L}{12}\left(\Delta_x^2 \frac{\partial \bar{\phi}}{\partial x}\frac{\partial \bar{w}}{\partial x} + \Delta_y^2 \frac{\partial \bar{\phi}}{\partial y}\frac{\partial \bar{w}}{\partial y}\right)$$

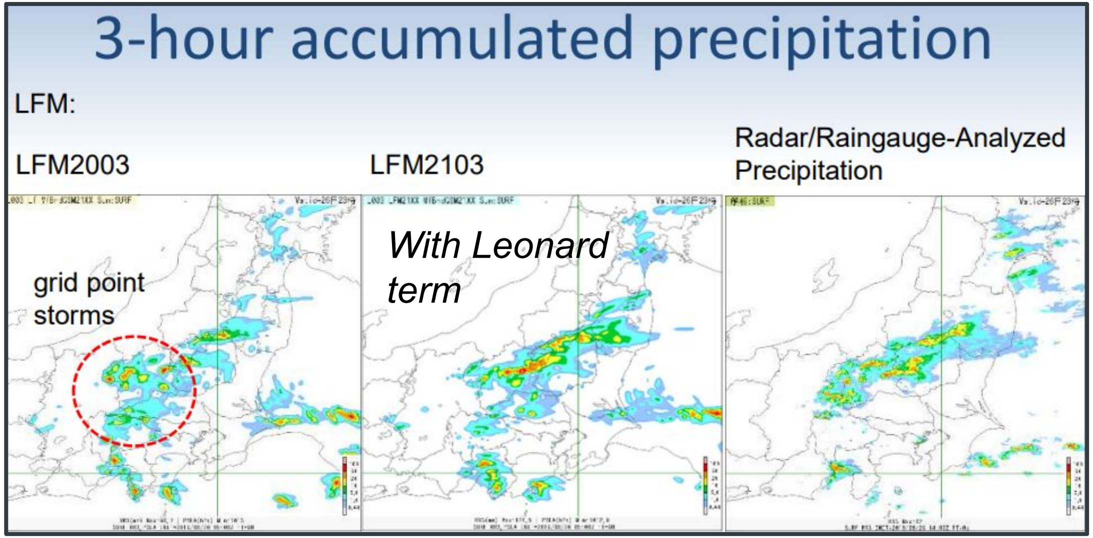
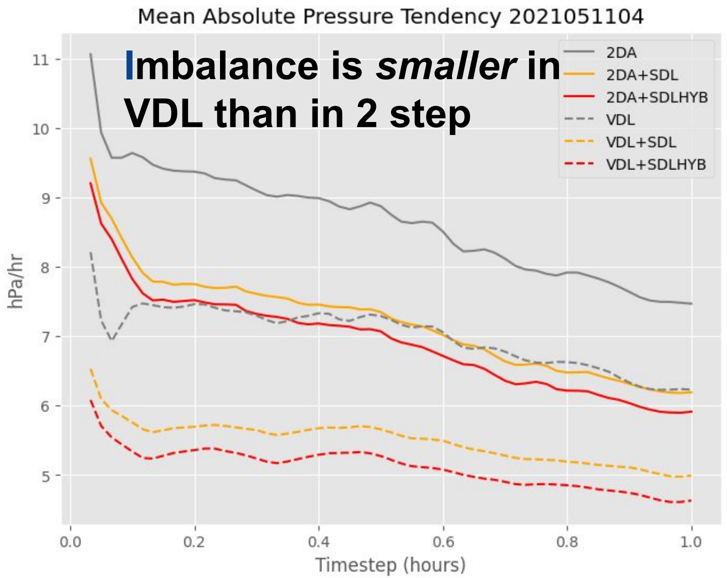


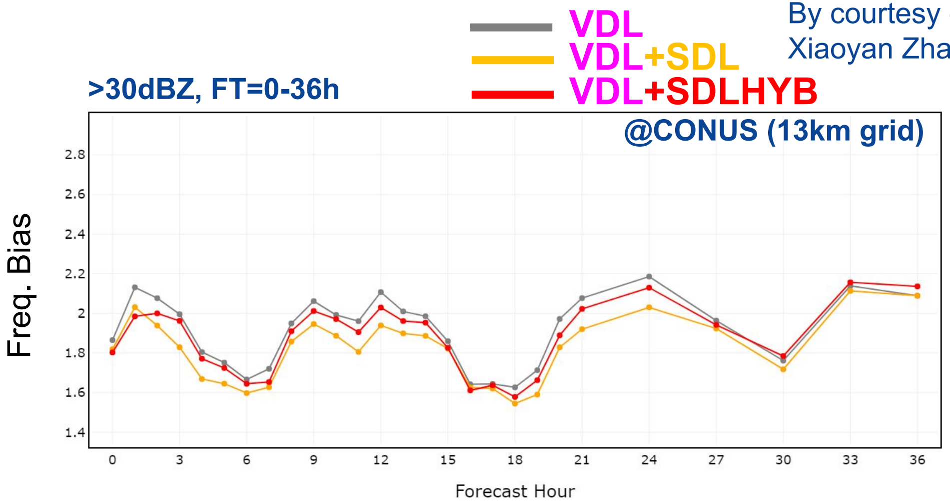
Figure obtained from presentation by Hiroshi Kusabiraki et al. (2021) demonstrating impact at JMA

Multiscale DA Algorithm

[Not yet in official RRFS Prototype System]

- Scale and variable dependent localization employed in the EnVar DA algorithm
  - Ensemble covariances undergo scale-selective filtering (short, medium, & long waves)
  - Localization radii appropriate for each scale are used
- Allows for *all* observations to be assimilated simultaneously
  - Eliminates 2 step implementations with ad-hoc separation of observations (sondes vs radar)





By courtesy of Xiaoyan Zhang

Acknowledge JMA visiting scientist Sho Yokota, OU/MAP group, and T. Lei (EMC)

Products and Computing

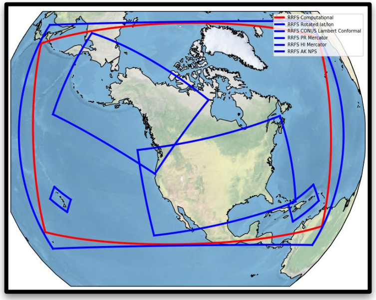
Products

RRFS will provide functionally equivalent products currently on NOMADS and the SBN (NOAAport/AWIPS)

- e.g., covering the following systems HRRR, NAM nests, HREF and HiResW members
  - **SBN (AWIPS)**:
    - Deterministic
      - CONUS: 227 deterministic variables on 2 unique grids.
      - Alaska: 231 deterministic variables on 3 unique grids.
      - Hawaii, Puerto Rico, Guam: 110 deterministic variables.
    - Probabilistic HREF output
      - CONUS: 193 probabilistic variables.
      - Alaska, Hawaii, Puerto Rico: 190 probabilistic variables.
  - **NOMADS:**
    - Deterministic
      - CONUS: 4000+ deterministic variables on 4 unique grids.
      - Alaska: 2800+ deterministic variables on 3 unique grids.
      - Hawaii: 1300+ deterministic variables on 2 unique grids.
      - Puerto Rico: 1300 deterministic variables on 4 unique grids.
      - Guam: 390 deterministic variables on 2 unique grids.
    - Probabilistic HREF output
      - CONUS: 305 probabilistic variables.
      - Alaska, Hawaii, Puerto Rico: 294 probabilistic variables

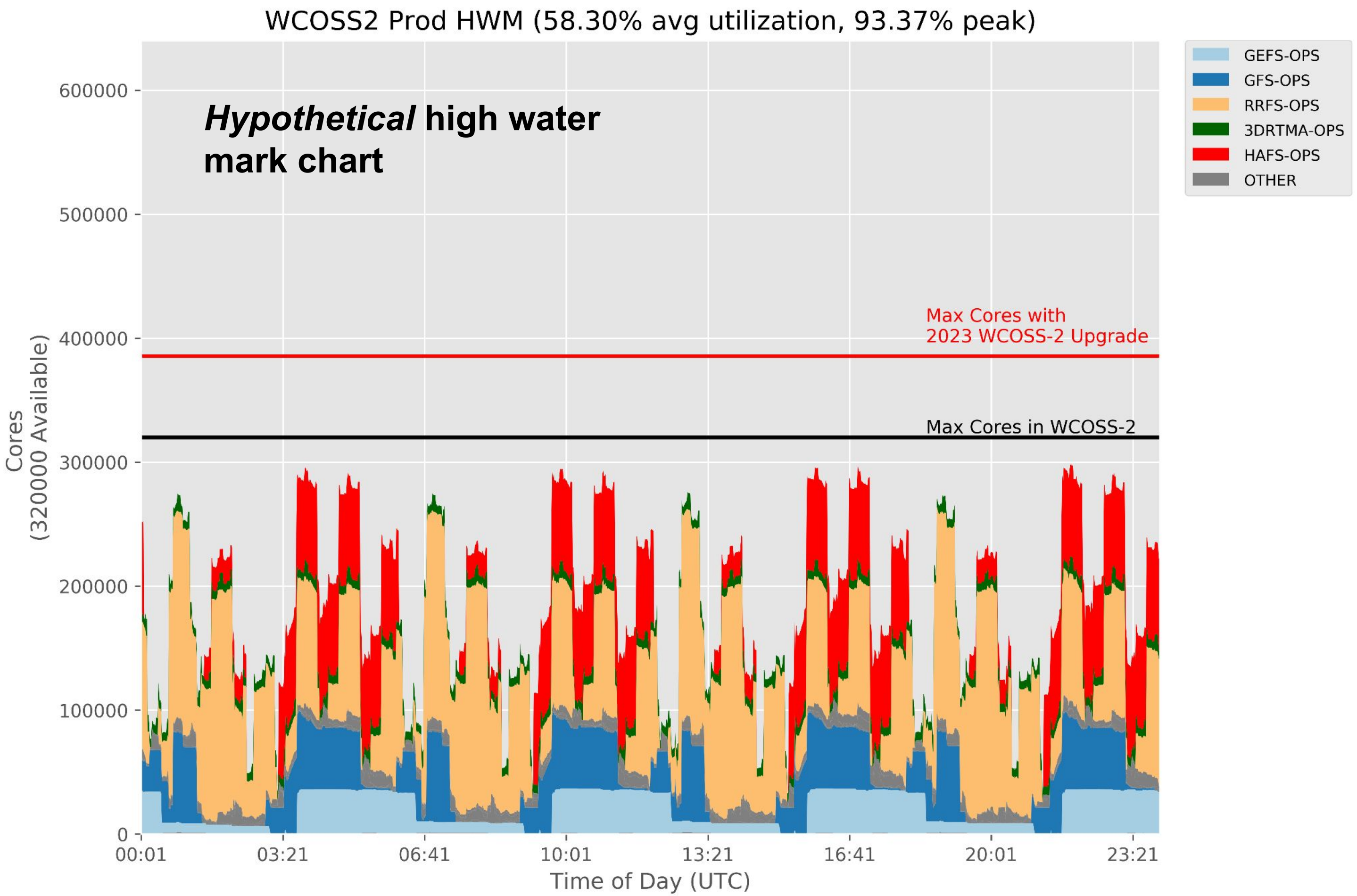
Table depicting planned output grids for distribution from RRFS.

Region	Projection	Approx. Grid-spacing	Corresponding existing grid (if applicable)	Notes
North America [coarse-res]	Rotated Lat-Lon	13 km	-	
North America [hi-res]	Rotated Lat-Lon	3 km	-	
CONUS	Lambert Conformal	3 km	HRRR CONUS	
CONUS [legacy]	Lambert Conformal	13 km	Office Note 388 Table B Grid 130	Legacy grid with select aviation products for FAA Weather Aviation and Radar system (WAR targeted to be retired in 2027) - *not for NOMADS distribution (and not pictured below).*
Alaska	Polar Stereographic	3 km	NAM AK nest	
Hawaii	Mercator	2.5 km	NAM HI nest	
Puerto Rico	Mercator	2.5 km	NAM PR nest	



*Thanks to Andrew Benjamin for this material

HPC



WCOSS2 Prod HWM (58.30% avg utilization, 93.37% peak)
Hypothetical high water mark chart
Max Cores with 2023 WCOSS-2 Upgrade
Max Cores in WCOSS-2
Cores (320000 Available)
600000
500000
400000
300000
200000
100000
0
00:01
03:21
06:41
10:01
13:21
16:41
20:01
23:21
Time of Day (UTC)
GEFS-OPS
GFS-OPS
RRFS-OPS
3DRTMA-OPS
HAFS-OPS
OTHER

Summary

- RRFS will be a *major* change:
  - Looking to replace wide swath of operational CAM guidance with a single, unified 3 km system covering North America

- Still have challenges to overcome, both scientific and technical, but targeting a science freeze this Fall, and an implementation about a year later.

Thank you!
Questions?