The Rapid Refresh Forecast System: Looking Beyond the First Operational Version

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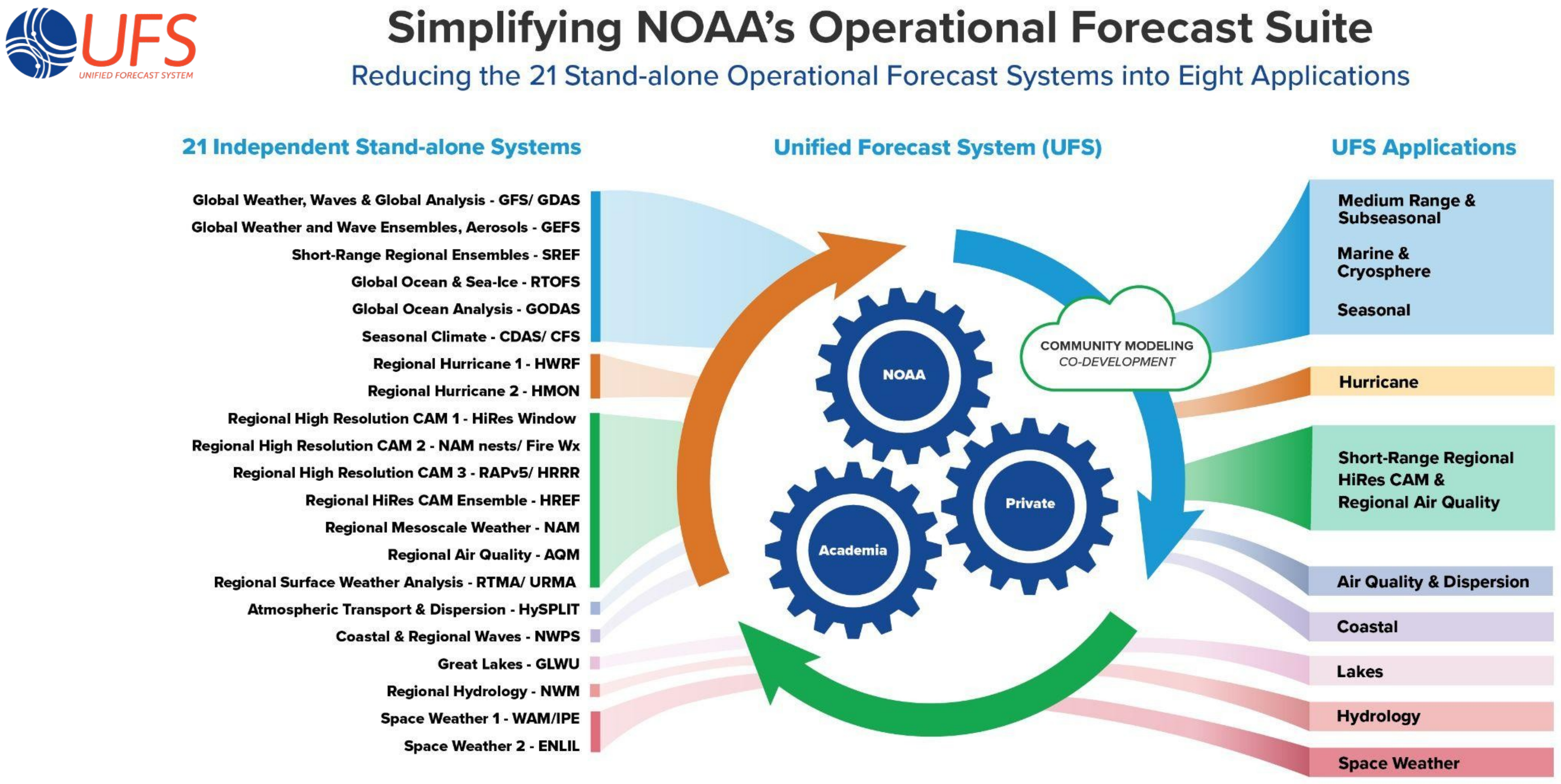
Curtis Alexander[1], Jacob Carley[2], Matt Pyle[2]

and many developers from NOAA/GSL and NOAA/EMC

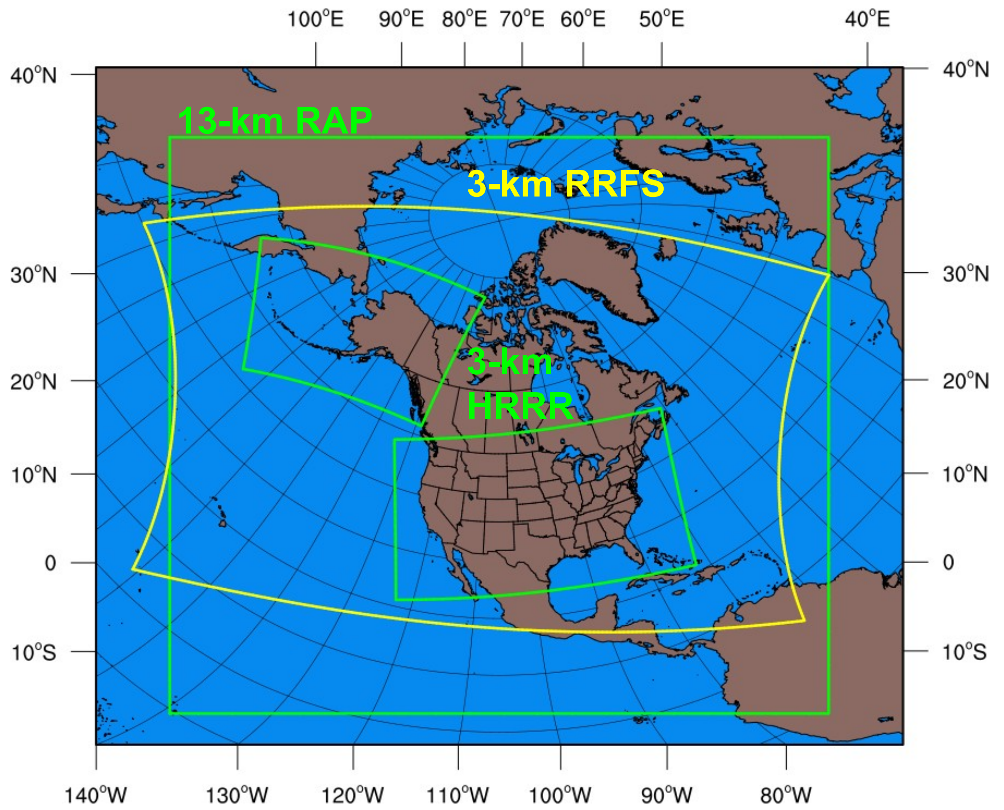
[1]NOAA/OAR/GLOBAL SYSTEMS LABORATORY

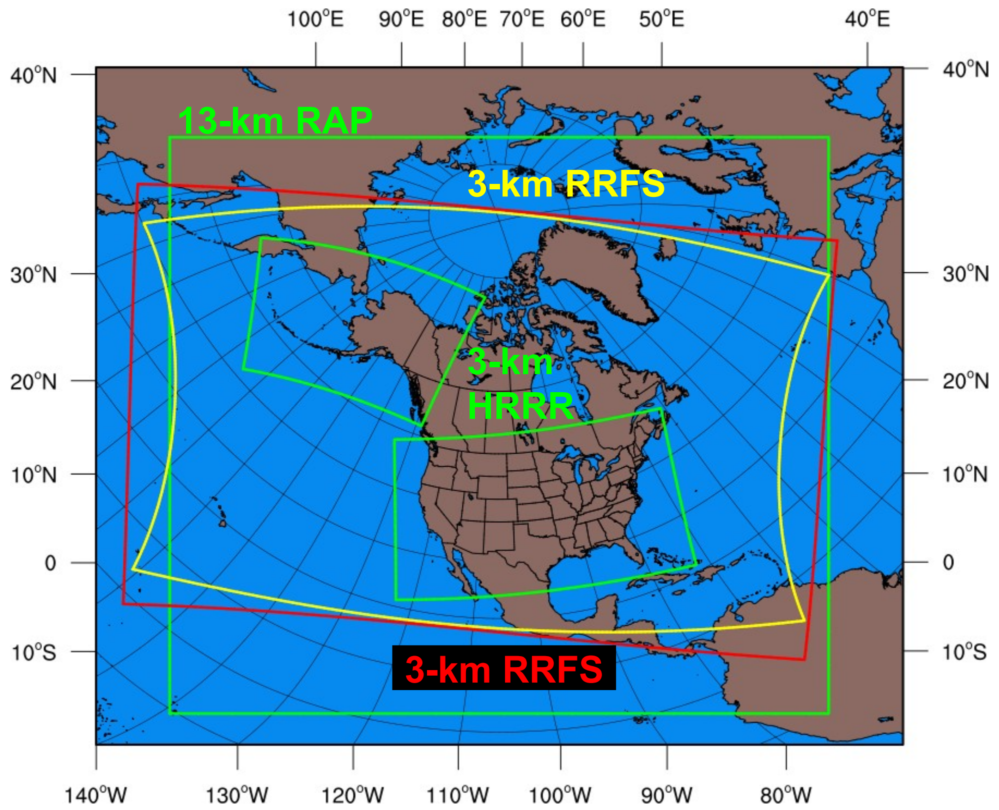
[2]NOAA/NWS/NCEP/ENVIRONMENTAL MODELING CENTER

Unified Forecast System Forecast Suite



FV3 “ESG” Grid: The RRFS Domain





- ESG map projection (yellow) is comparatively new and requires transformation to familiar rotated lat-lon projection (red) for post-processing etc…
- RRFS grid is very large compared to RAP/HRRR:

RAP 13-km	**HRRR-CONUS 3-km**	**HRRR-AK 3-km**	**RRFS 3-km**
953x834x50	1799x1059x50	1299x919x50	4881x2961x65
(794,802)x50	(1,905,141)x50	(1,193,781)x50	(14,452,641)x65
300MB/3Dnative file	800MB/3Dnative file	500MB/3Dnative file	10GB/3Dnative file
Rotated Lat-Lon	Lambert Conformal	Polar Stereographic	Rotated Lat-Lon

7.6 times as many 2-D gridpoints
9.7 times as many 3-D gridpoints

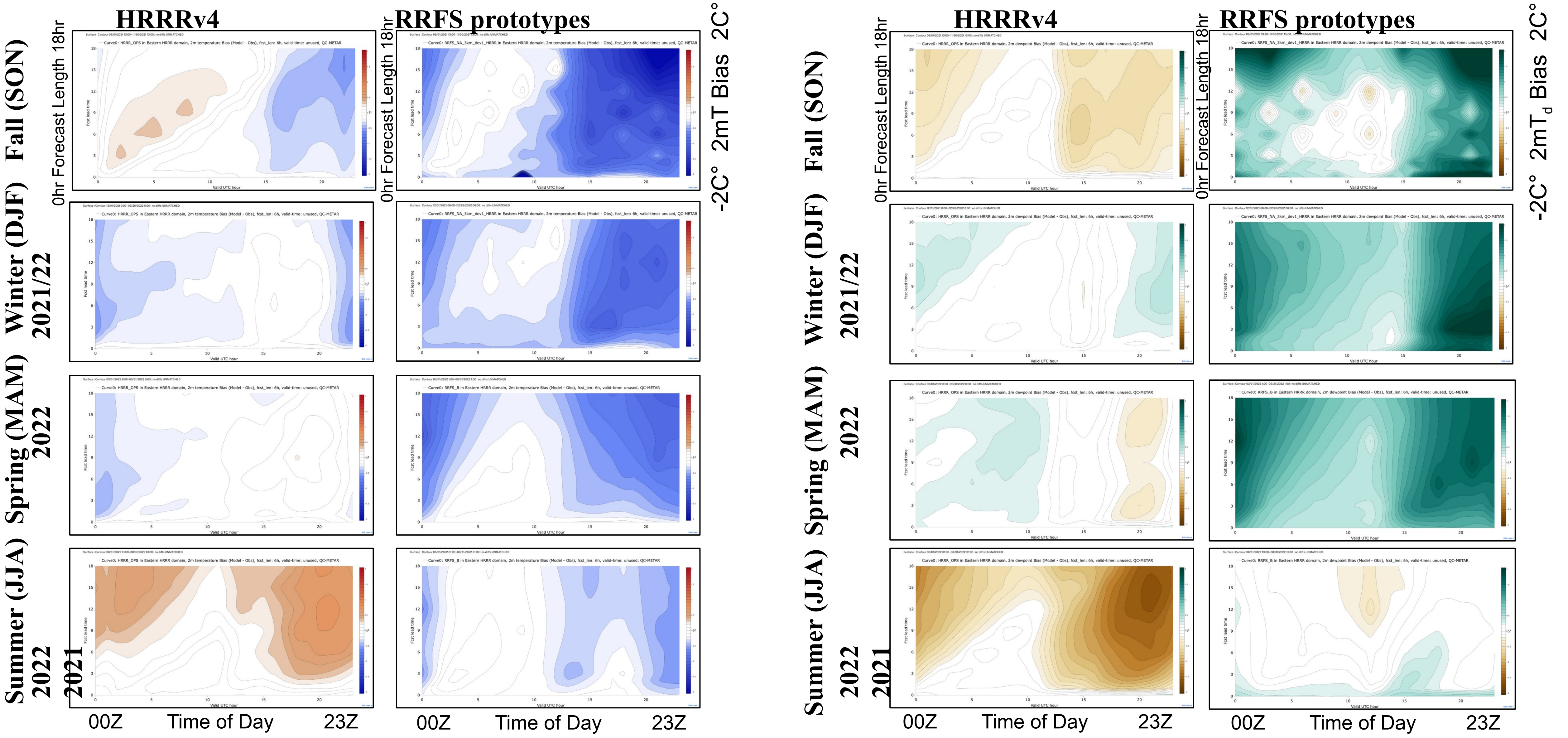
925 million 3-D forecast grid points and 2-3 times 13-km GFS

RRFSv1 Development and Testing Progress

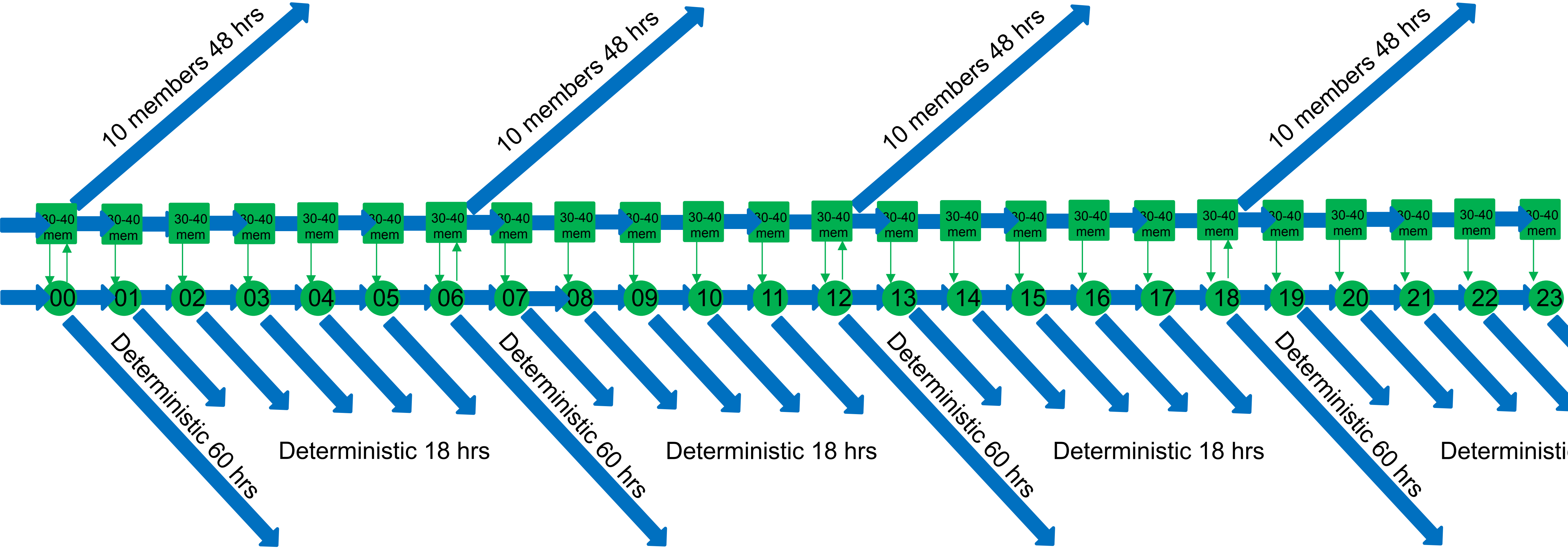
	Model Infrastructure	Dynamics/Physics	Data Assimilation	Testing/Eval/T2O
2018-19	• FV3LAM established • ESG grid • GFS IC/LBC option	• CCPP ready	• GSI FV3LAM interface	
2020	• RAP/HRRR IC/LBC option • Initial dynamics options	• RRFSv1 alpha suite • Thompson/RRTMG • UGW/MYNN/GFS SL	• Conventional DA	• SFE/FFaIR/WWE • RAPv5/HRRRv4
2021	• SRWv1.0 app release • N. America domain • Cloud HPC deployment • 65 vertical layers set • VGF/IMS snow/ice updating	• MYNN SL • RUC/Noah LSM • SPPT • SPP • Smoke	• Partial cycling design • Soil temp/moisture adj • Radar reflectivity LH DA • Satellite clear radiances	• SFE/FFaIR/WWE • HREFv3 • DTC benchmark • MEG Alpha Eval
2022-23	• SRWv2.0/2.1 app releases • FVCOM Great Lakes • Ensemble ICs • UPP read ESG grid	• 8th order damping • Inner loop MP • Semi-Lag Mp • Ensemble physics • CLM Lake • GF Convective Param	• Soil temp/moisture adj • EnKF ensemble • Cloud analysis • Stoch phys in EnKF mems • EnKF recentering/coupling	• SFE/FFaIR/AWT/WWE • Agile prototyping

•Tested in real-time experiment **• Some testing** **• More development needed**

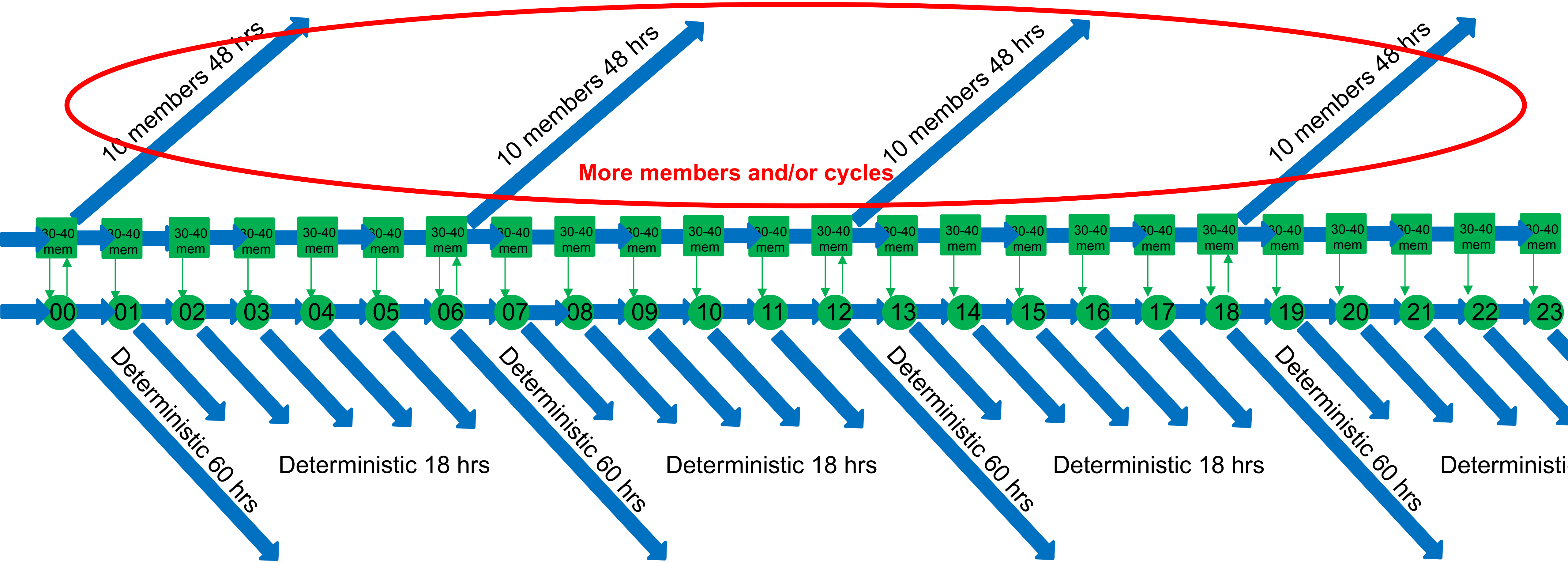
RRFS Seasonal 2m Bias Reduction



RRFSv1 Initial Operational Capability for Forecasts



RRFSv2+ Forecasts



Physics

RRFSv1 Physics

“HRRR physics” fully implemented and further optimized within RRFS

Component	Scheme	Features/Status
Land-Surface:	RUC	9-layer soil model, 2-layer snow
Lake Model	CLM (small lakes)	FVCOM for Great Lakes
Surface Layer:	MYNN	Adding fractional sea-ice capability
PBL:	MYNN-EDMF	Includes SGS partial cloud component Updated diffusion
Convection:	Grell-Freitas	Final testing
Drag:	Unified Drag Suite	Minor changes from HRRR
Radiation:	RRTMG	Update to provide qc, qi, qs as in-cloud means
Microphysics:	Thompson Aerosol-aware	Small adjustments for reflectivity bias

RRFSv2+ Physics

Component	Scheme	Features/Status
Land-Surface:	NoahMP	9-layer soil model?, 2-layer snow? Tuning for land assimilation VIIRS VGF update consistency IMS snow update consistency Variable density snowfall consistency
Lake Model	CLM (small lakes)	
Surface Layer:	MYNN	
PBL:	MYNN-EDMF	
Convection:	Grell-Freitas	
Drag:	Unified Drag Suite	
Radiation:	RRTMGP?	
Microphysics:	Thompson Aerosol-aware	

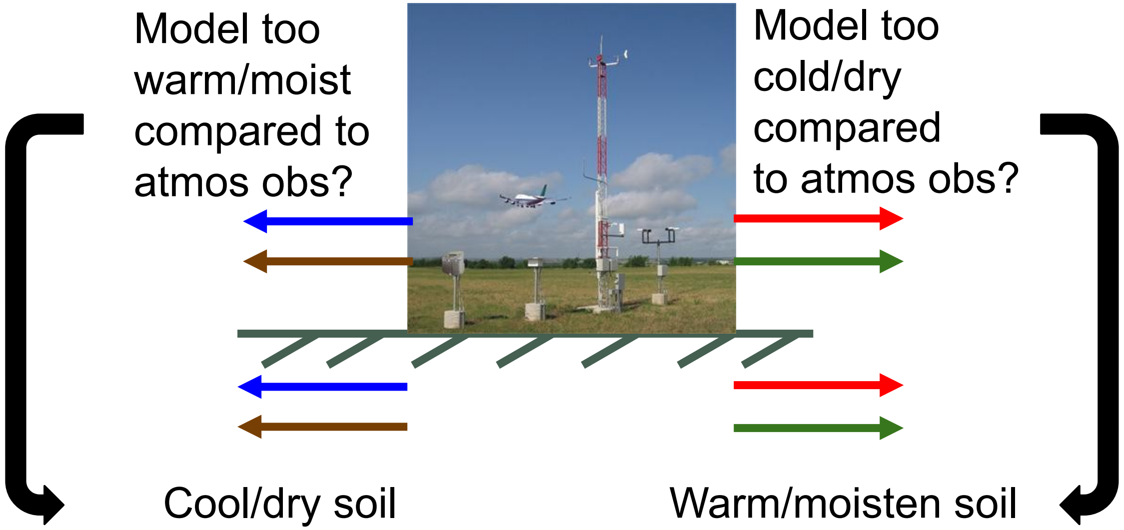
Data Assimilation

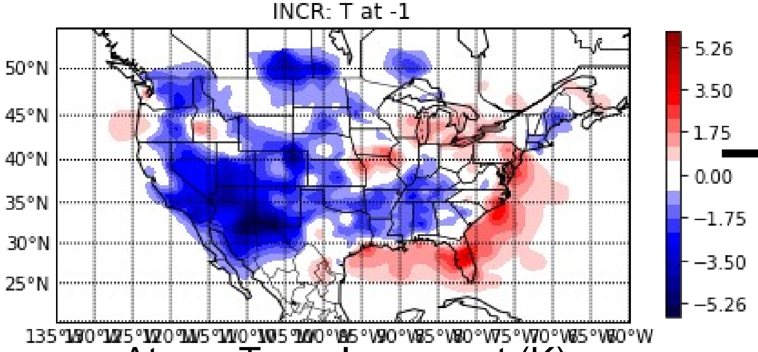
Data Assimilation Software Framework RRFSv2+

GSI Gridpoint Statistical Interpolation → Joint Effort for Data assimilation Integration (JEDI)

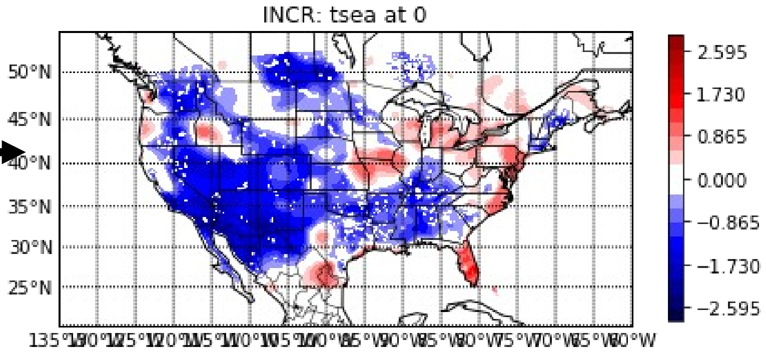
RRFSv2+: Land-Atmosphere DA

RRFSv1 one-way (moderately) coupled DA Soil Adjustment





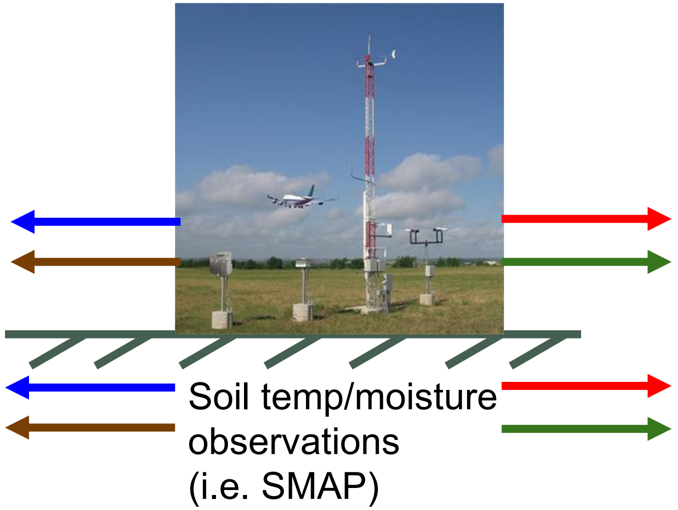
Atmos Temp Increment (K)



Soil Temp Increment (K)

- Leverages experience with RUC/RAP/HRRR soil DA in GSI (see Benjamin et al 2022: https://doi.org/10.1175/JHM-D-21-0198.1)
- Attribution of some model error to incorrect latent/sensible fluxes to/from ground
- No soil observations used (one-way adjustment into soil)

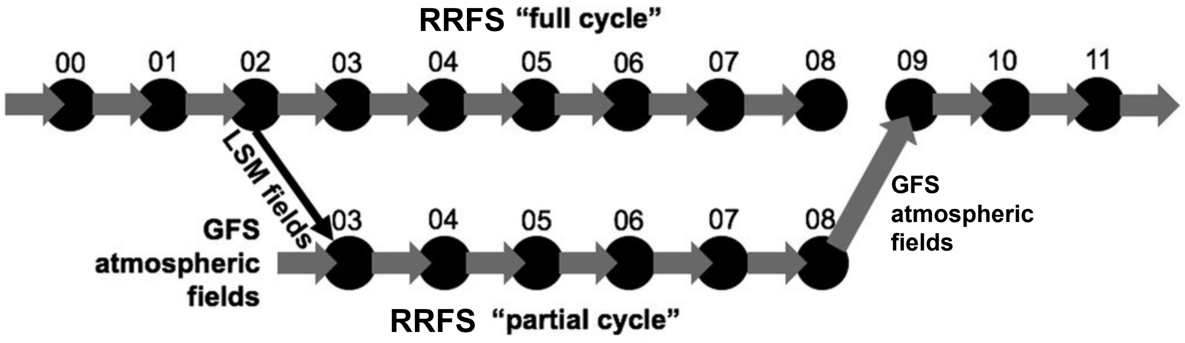
RRFSv2+ strongly coupled land/atmosphere DA



- Leverage soil temp/moist observations (SMAP)
- Cross-covariances between land and atmosphere
- JEDI EnKF using RDAS ensemble for BECs
- Leveraging with global DA

RRFS Design: Atmospheric DA/Cycling

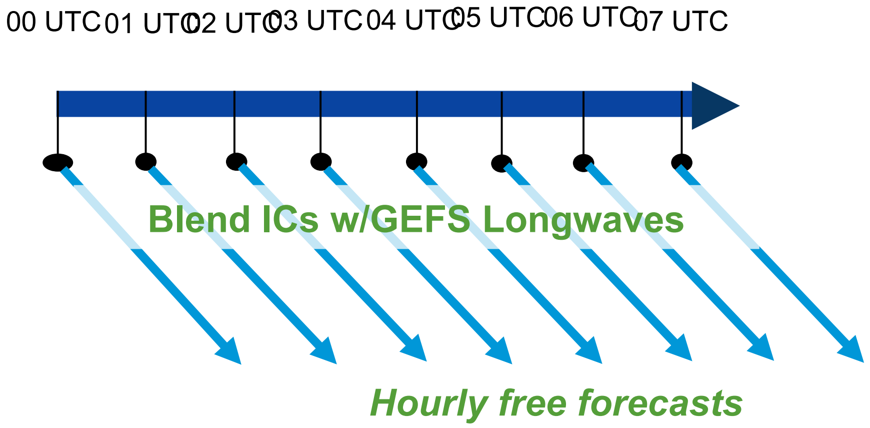
GFS/RRFSv1 dependencies



RRFSv1 Partial Cycling

- Mitigates risk with familiar LAM cycling design (e.g. RAP)
- Ensures inclusion of longer wavelength information limiting drift
- Collects latent observations
- Partial cycling still more expensive than continuous cycling
- Workflow is more complex than continuous cycling

GFS/RRFSv2 dependencies



RRFSv2 Full Cycling

- Blending GDAS/GEFS longwave perturbations into ICs
- Overlapping windows to collect latent observations
- Reduced computation cost compared to partial cycling
- Simplified workflow
- More development needed prior to operational transition

Schwartz, et al. , 2022: Comparing Partial and Continuously Cycling Ensemble Kalman Filter Data Assimilation Systems for Convection-Allowing Ensemble Forecast Initialization. *WAF*, **37**, 85-112.

RRFSv2+ Design: Atmospheric DA/Cycling

Future Approach: Overlapping windows to update every hour assimilating observations that have arrived within the past hour and are valid within the past 3 hours

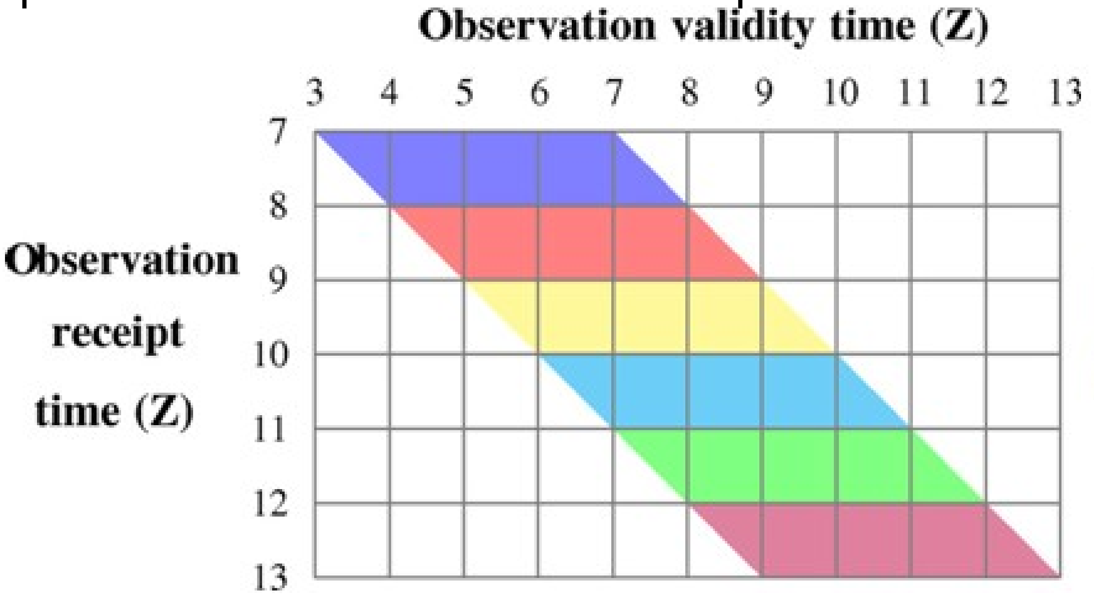
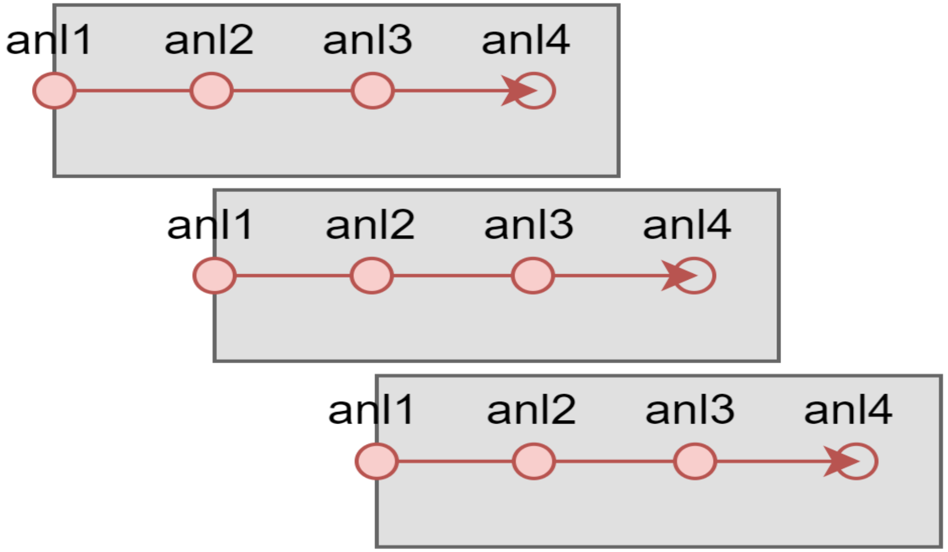


Figure 3 of Payne (2017)



Figures courtesy D. Lippi and NOAA collab on HSUP 1-A5

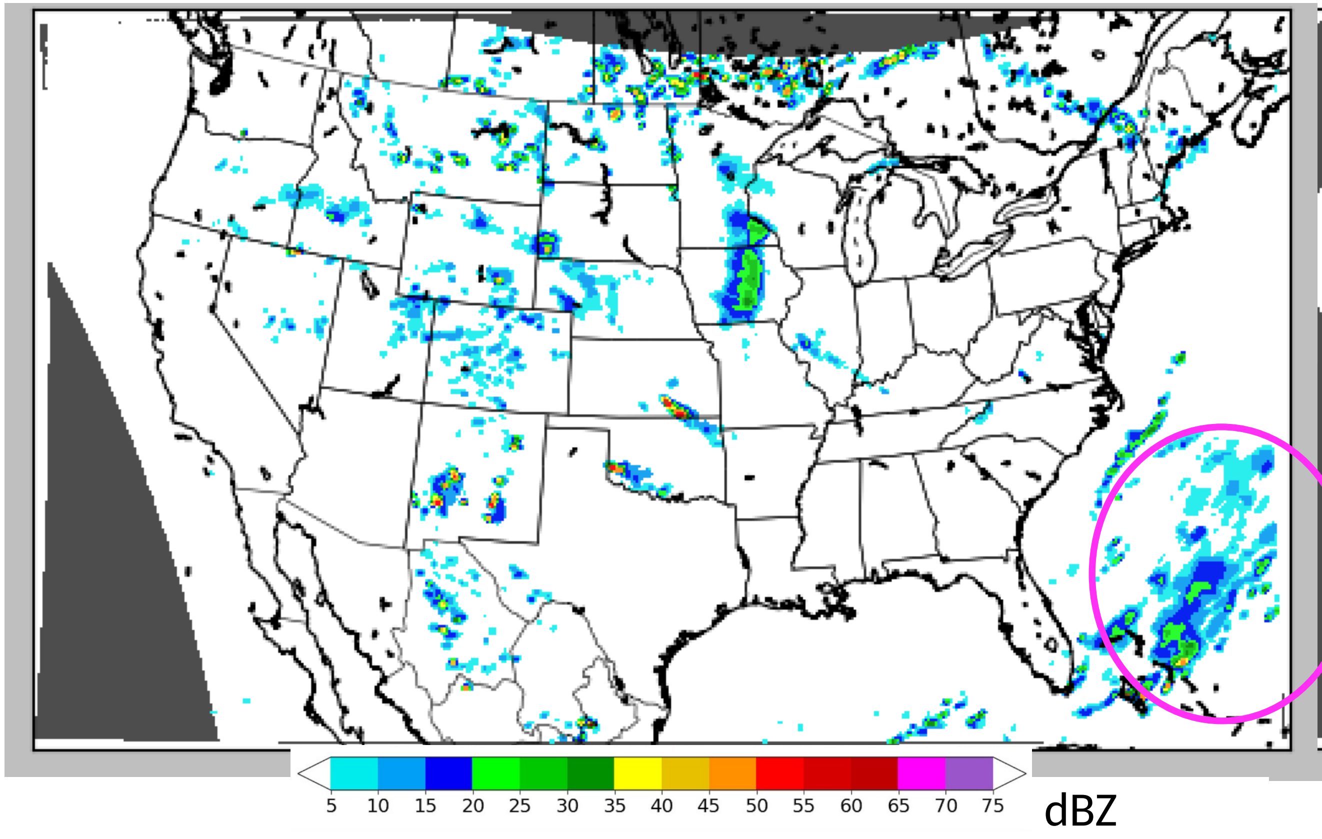
Slivinski, L. C., D. E. Lippi, J. S. Whitaker, G. Ge, J. R. Carley, C. R. Alexander, and G. P. Compo, 2022: Overlapping Windows in a Global Hourly Data Assimilation System. Mon. Wea. Rev., 150, 1317–1334, https://doi.org/10.1175/MWR-D-21-0214.1.

RRFSv2+: GOES-based Synthetic Radar Imagery

GREMLIN (GOES Radar Estimation via Machine Learning to Inform NWP)

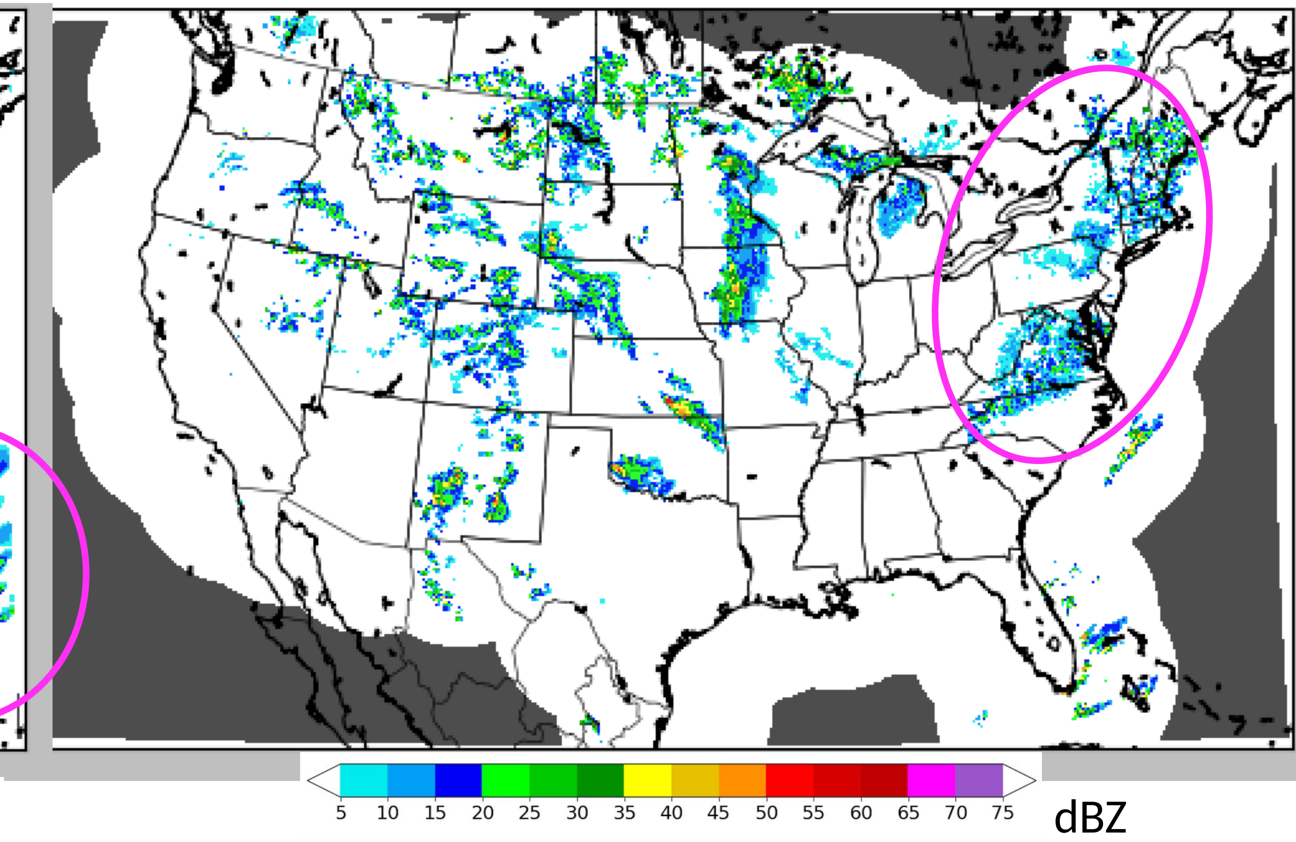
Experimental CSU CIRA product (Hilburn et al.)
Neural net synthesizes radar from GOES-East ABI & GLM
Intended to supplement MRMS coverage; test in place of MRMS

GREMLIN SYNTHETIC CREF



GREMLIN column-max reflectivity at 19Z, 5/14/2021

MRMS CREF OBSERVATIONS

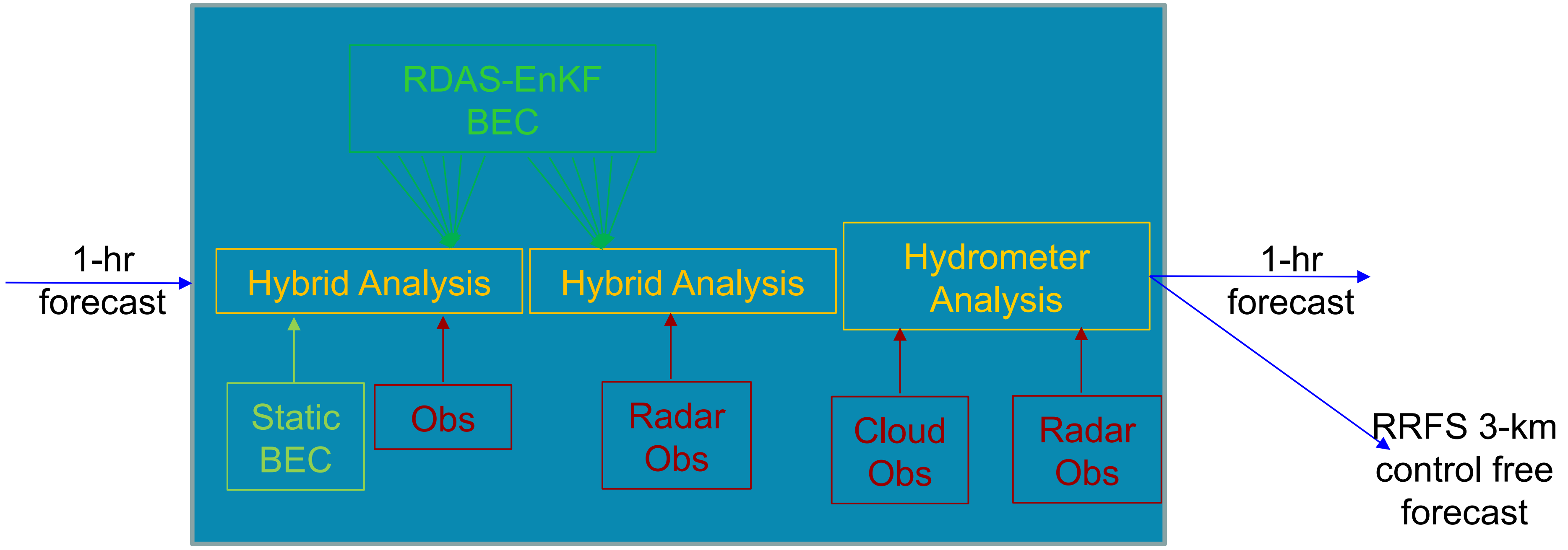


MRMS column-max reflectivity at 19Z, 5/14/2021

RRFSv2+ Design: Analysis Stages

RDAS Methodology

Components of Each Assimilation Cycle

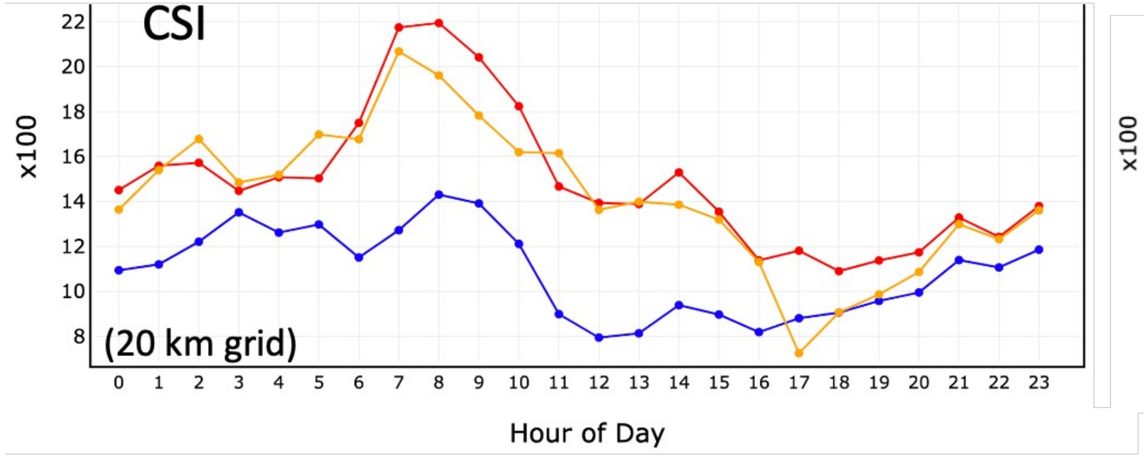


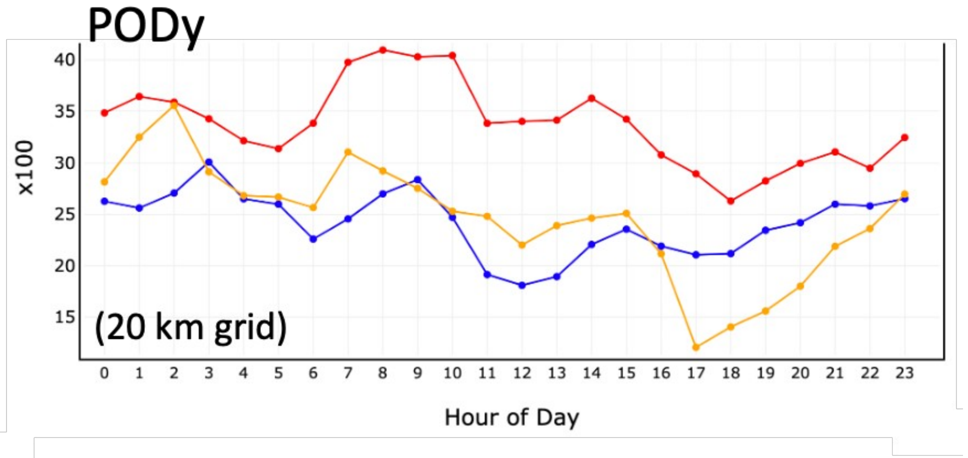
Multiscale DA can simplify these components while improving the analysis

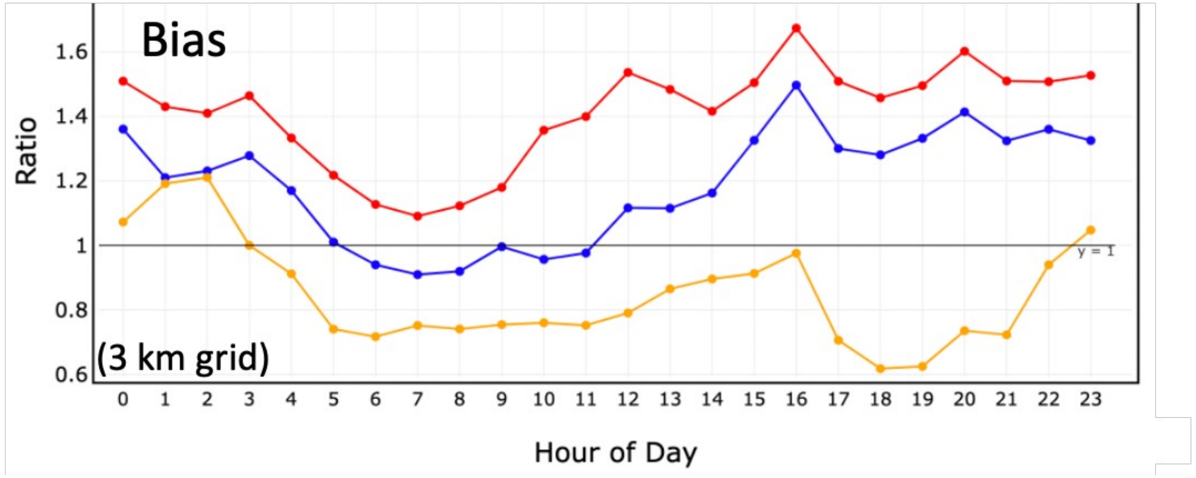
RRFSv1 Design: Radar DA

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 cumulus scheme

RRFSv2+ Highlights

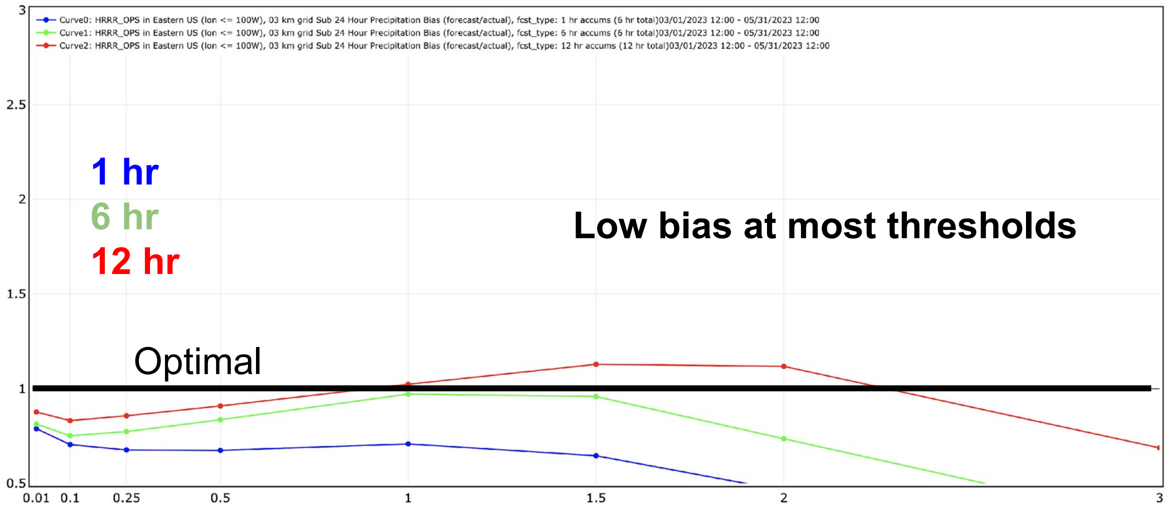
Dynamic Core

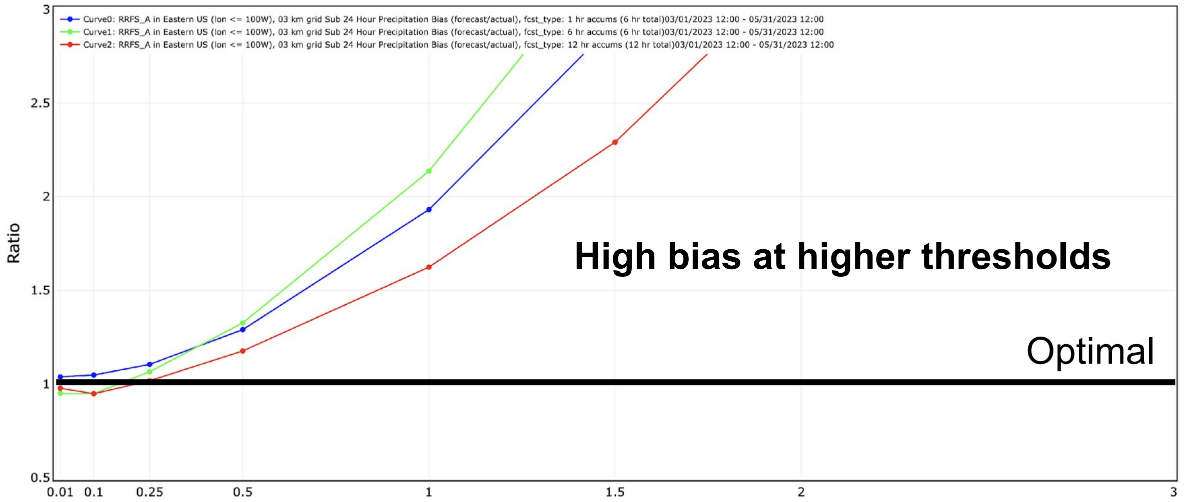
RRFSv1 Challenges: QPF Warm Season Bias

3 km Eastern CONUS QPF Frequency Bias 2023

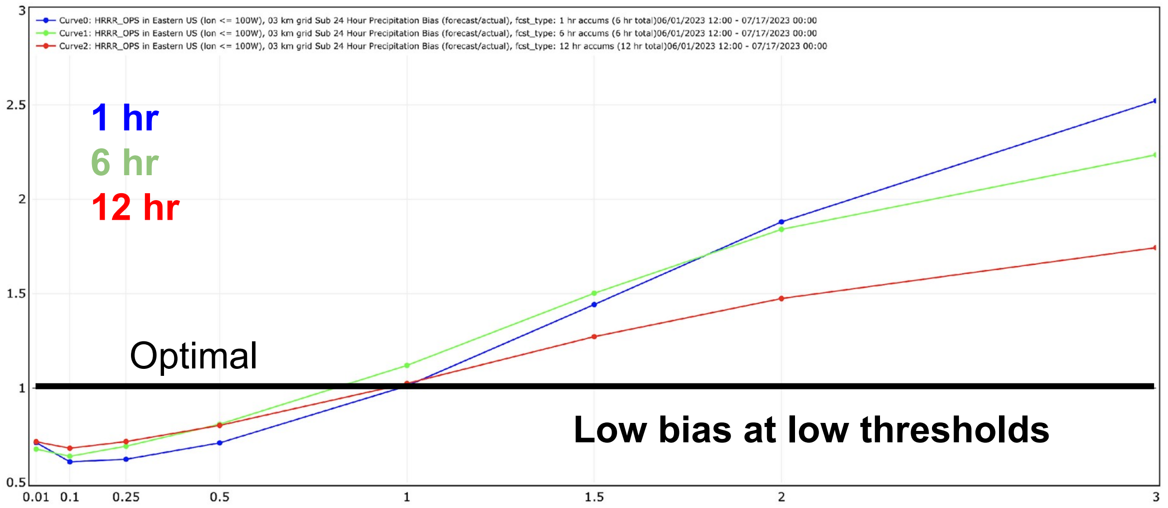
HRRRv4 | **RRFS_Prototype**

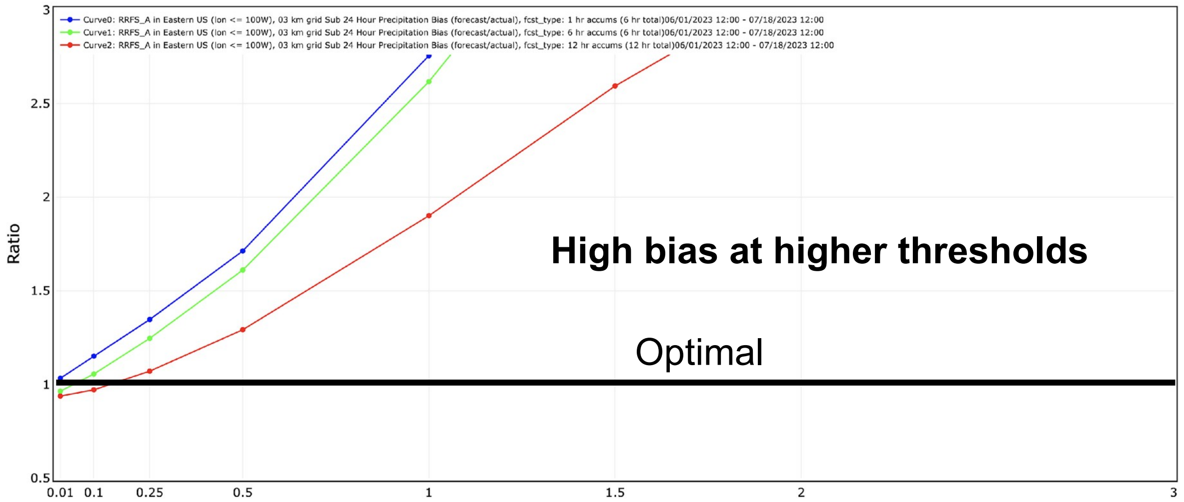
Spring 2023 (MAM)





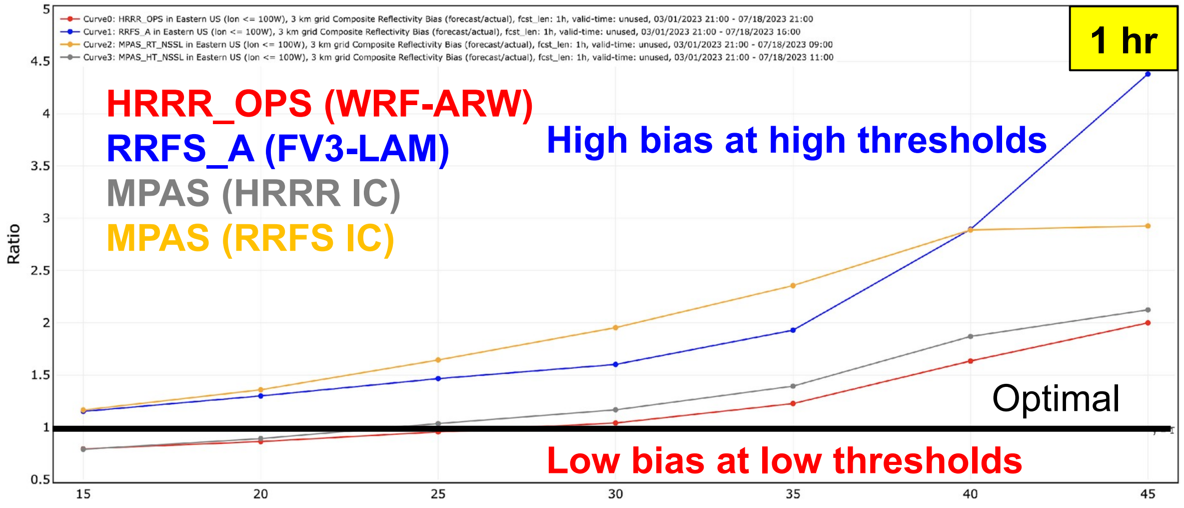
Summer 2023 (JJ)

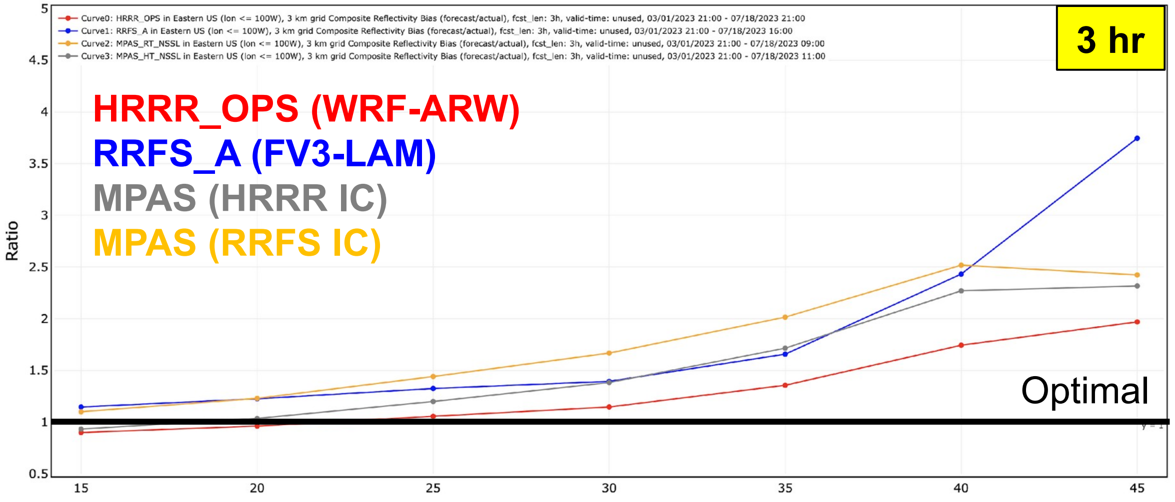


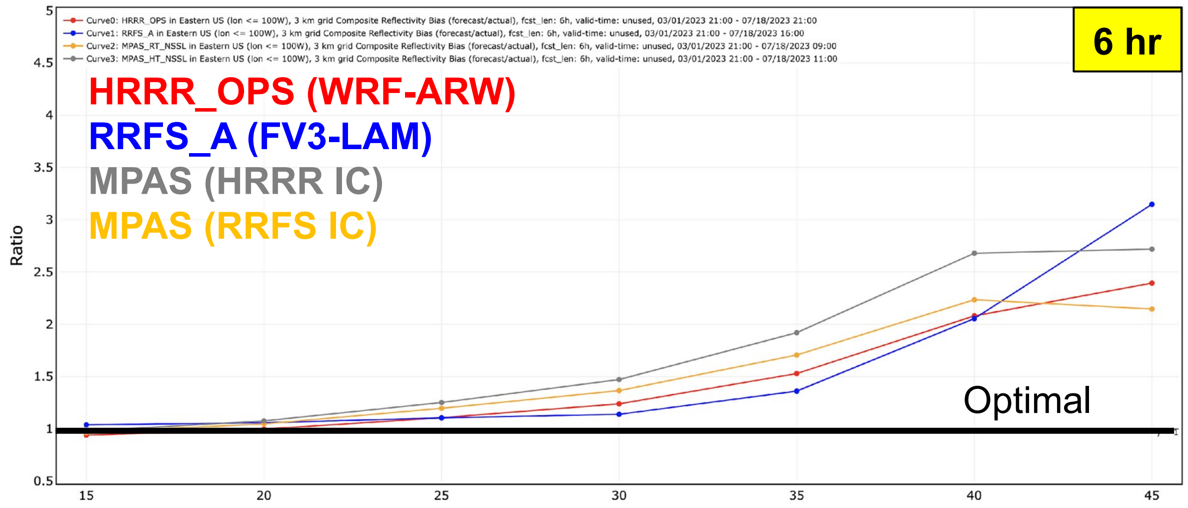


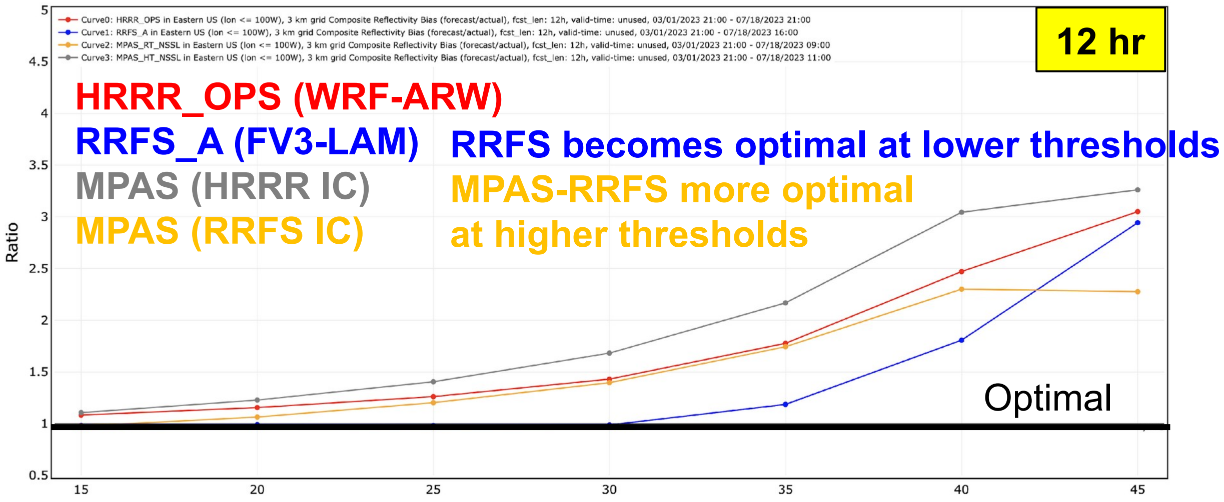
RRFSv1 Challenges: Reflectivity Warm Season Bias

3 km Eastern CONUS Composite Reflectivity Frequency Bias (Mar-Jul 2023)



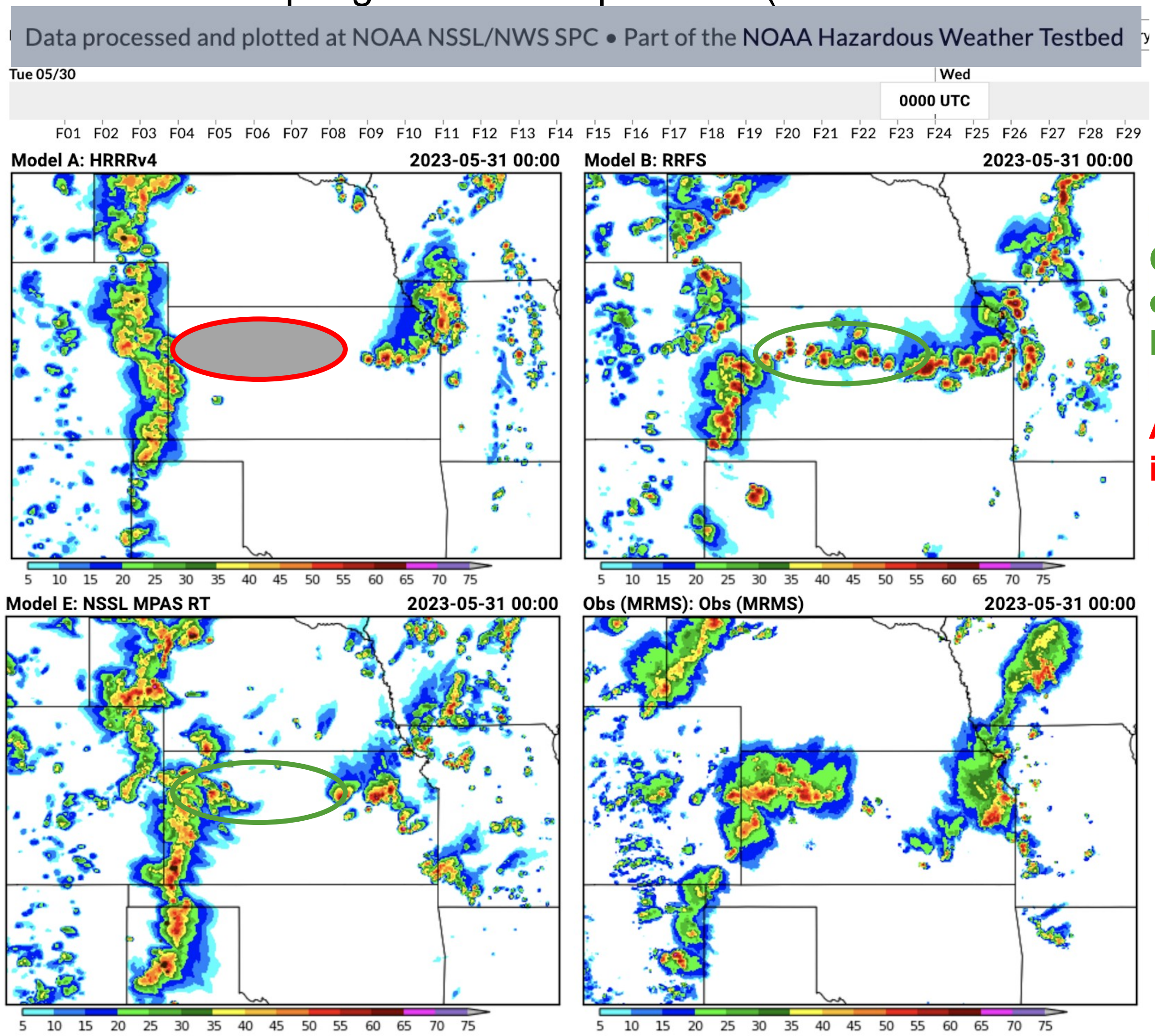






RRFSv1 Challenges: Warm Season Convective Biases

Hazardous Weather Testbed 2023 Spring Forecast Experiment (24 hr forecasts valid 00z 31 May 2023)



HRRR_OPS

Does not capture new convection along old outflow boundary in northern Kansas

RRFS_A

Captures convection along old outflow boundary in northern Kansas

All convection appears very intense with larger cells

MPAS (RRFS_A IC)

Captures convection along old outflow boundary in northern Kansas

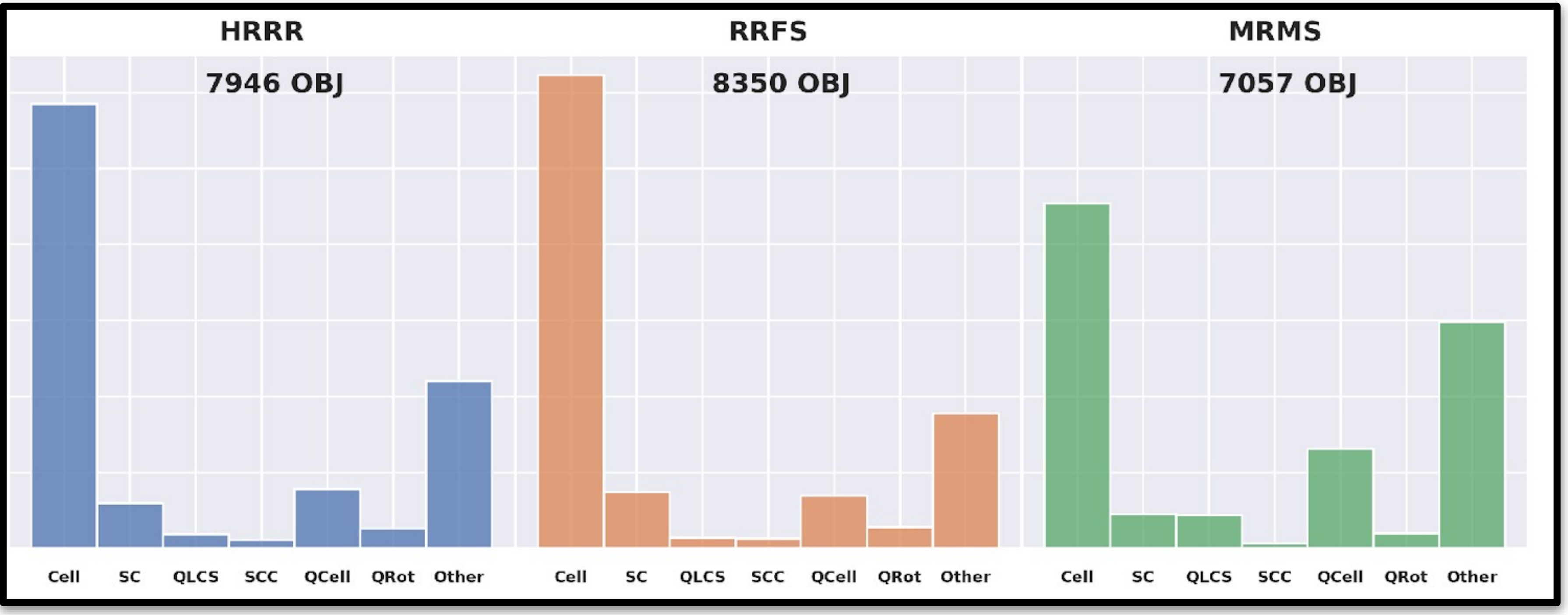
Greater diversity of cell intensity and sizes

Still slight overforecast (TX)

Truth (MRMS Radar)

RRFSv1 Challenges: Storm type differences

Similar Overall Distributions

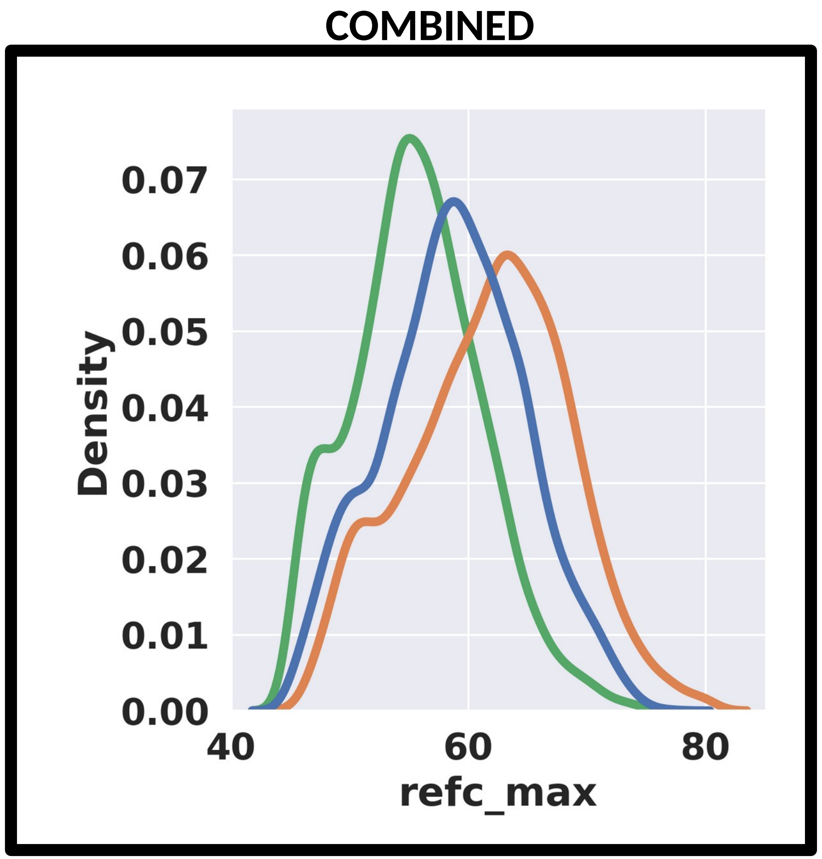


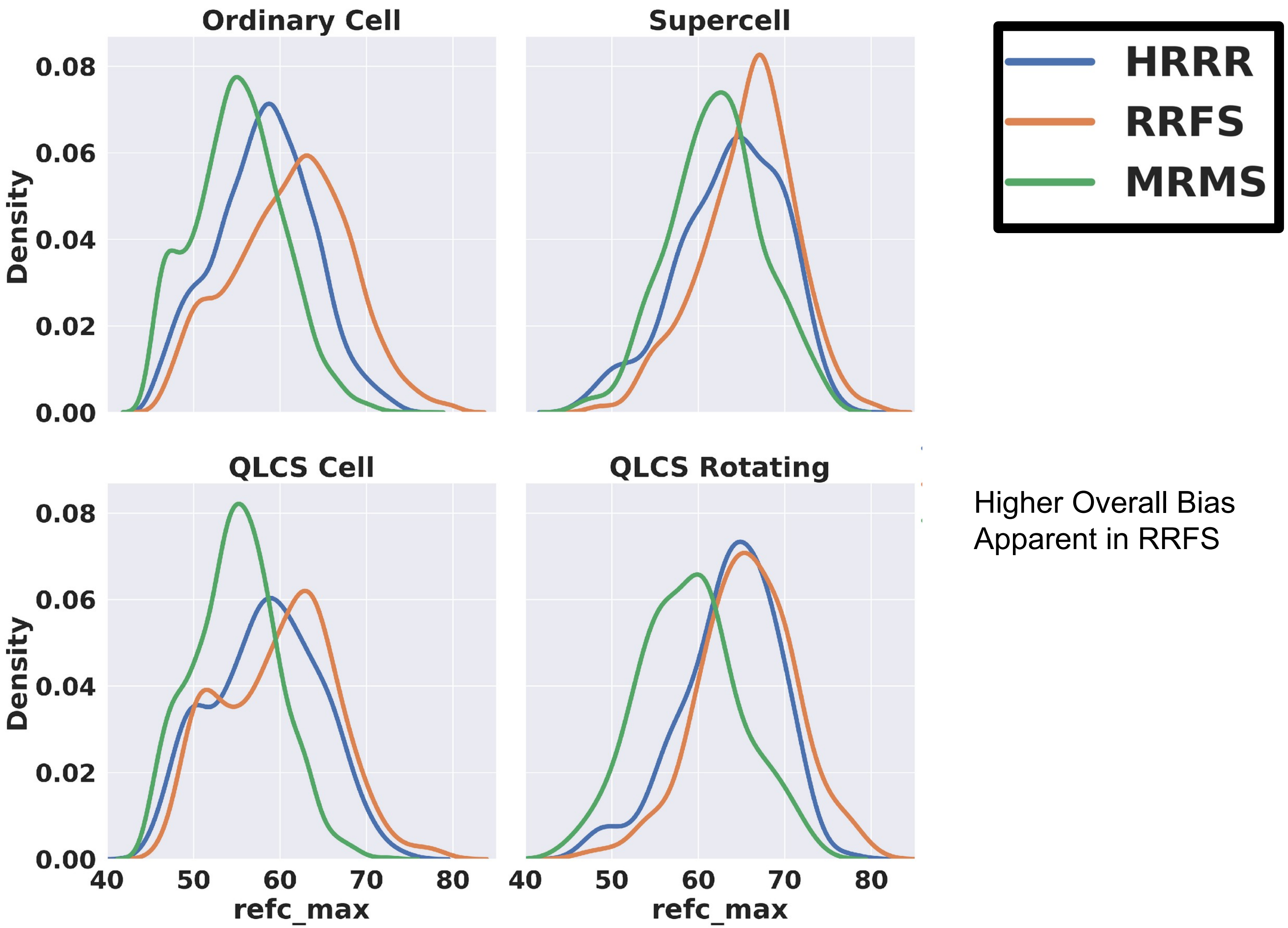
Class	Description
ORDINARY	Single storm cell lacking sustained intense rotation; not embedded in QLCS convective line (see QLCS_MESO); may be embedded in QLCS stratiform region or be one of a cluster of storms
SUPERCELL	Single storm cell containing sustained intense rotation; not embedded in QLCS convective line (see QLCS_MESO); may be embedded in QLCS stratiform region or be one of a cluster of storms
QLCS	Convective line of a quasi-linear convective system that exhibits systemwide organization
SUP_CLUST	Multiple storms in close proximity, of which *two or more* are supercells; not a QLCS
QLCS_ORD	QLCS-line-embedded cell lacking sustained intense rotation
QLCS_MESO	QLCS-line-embedded cell containing sustained intense rotation (either a supercell, or a mesovortex-bearing cell)
OTHER	Cluster of ordinary cells (or one ordinary cell and one supercell), *or* a convective segment lacking systemwide organization, *or* noncanonical storm mode (e.g., amorphous blob of convection not associated with a single strong updraft)

Analysis courtesy of NSSL/CIWRO
Larissa Reames and Lou Wicker

- 10 cases from May, June 2022, 6-12 forecast hours each (total 92 hr)
- RRFS_B (GSL), HRRR, and MRMS data all interpolated to same ECONUS domain
- Over 23,000 total objects – 7000-8000ish objects per dataset
- Mostly ordinary cell, “other”
- Models have more ordinary cells, less “other” and QLCS Cells

RRFSv1 Challenges: Storm type differences

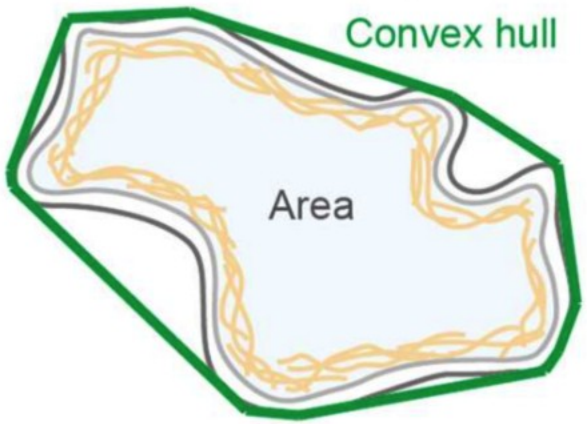




Higher Overall Bias
Apparent in RRFS

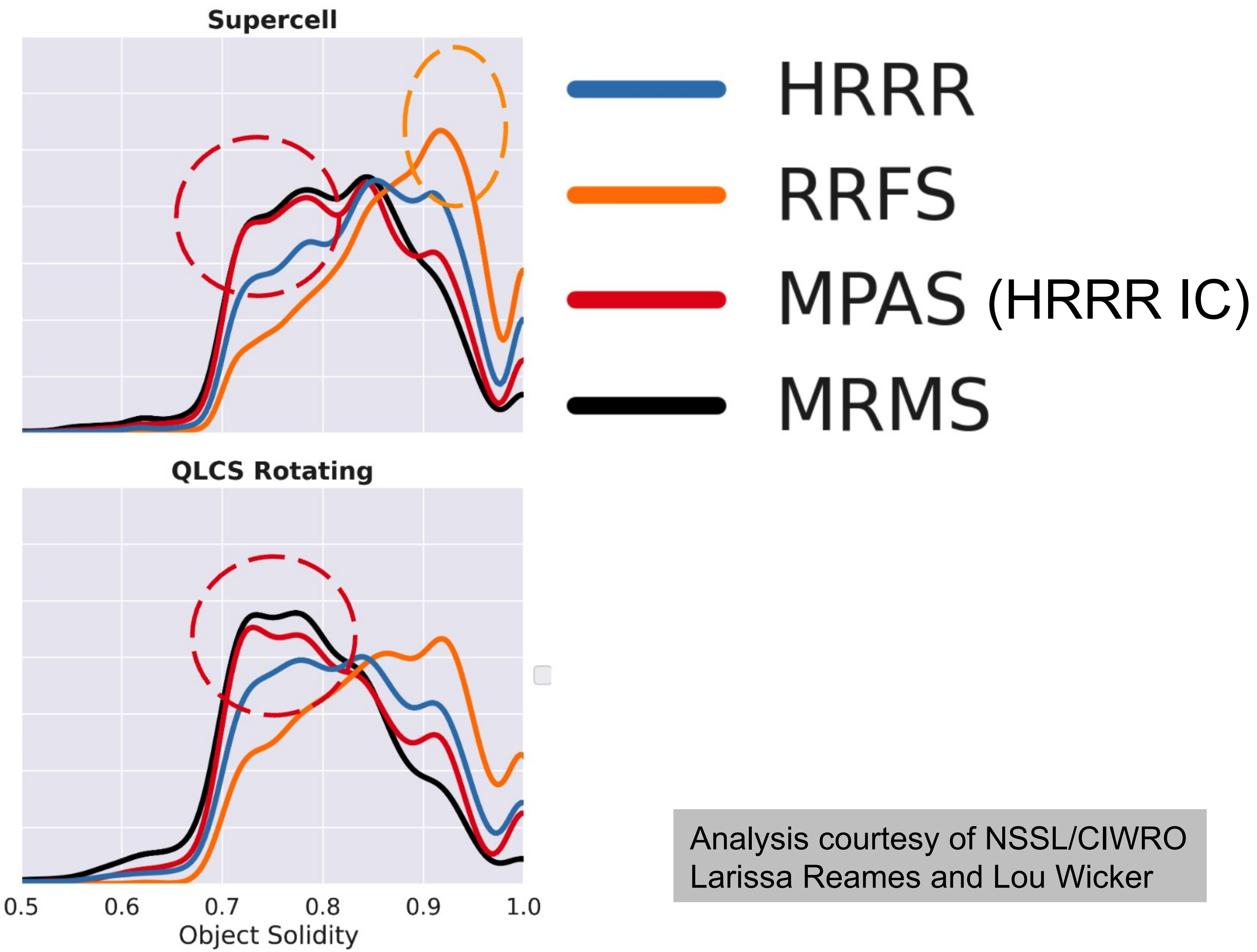
Analysis courtesy of NSSL/CIWRO
Larissa Reames and Lou Wicker

RRFSv1 Challenges: Storm structure differences



$$\text{Solidity} = \frac{\text{Area}}{\text{Convex hull area}}$$

Solidity ⇒ 1 == Concentrated shape



- Up to 61 forecasts from May-June 2023
- 36 forecast hours each
- RRFSA, HRRR, MPAS, & MRMS data all interpolated to same 3km ECONUS domain
- Removed objects over water

Analysis courtesy of NSSL/CIWRO
Larissa Reames and Lou Wicker

RRFSv1+ Status Summary

RRFSv1

- RRFSv1 is a major upgrade over HRRR (bigger domain, longer forecast length, ensemble forecasts)
- Scheduled for **September 2024-March 2025** operational implementation (FY25)
- Code freeze fall 2023 to spring 2024, science evaluation 2024
- Deterministic forecasts (hourly to 18h, 6-hourly to 60h), ensemble forecasts (6-hourly to 48h)
- Advanced scale-aware physics, two-way coupled storm-scale ensemble data assimilation
- Significant improvement in RRFS forecast skill over past two years, now close to HRRR and HREF
- RRFS forecast bias characteristics somewhat different than HRRR

RRFSv2+ (highlights, not exhaustive)

- RRFSv2 estimated implementation **FY27**
- Expanding support for Pacific Region (American Samoa, Micronesia, etc…)
- Expanding ensemble forecast membership/cycles
- Transition from GSI to JEDI data assimilation software/infrastructure
- Transition to strongly-coupled land-atmosphere DA
- Inclusion of more blending/overlapping-windows/multi-scale information for analysis
- Addition of new observations: DPQC radial velocities, GREMLIN, PBL height, all-sky radiances, etc…
- Transition to Noah-MP LSM, RRTMGP?, Air Quality/Chemistry?
- Explore transition to MPAS dynamic core

RRFSv2+

- FV3 fundamental design emphasis on vorticity dynamics is good for large scales
- Numerical design of the dycore for 3D divergent motions results in a loss of precision for CAM applications
- Difficulty in tuning model filtering to both:
  - (1) represent convection
  - (2) prevent spurious storms that produce excessive precipitation and contamination of the environment
- Data assimilation, which can generate spurious motions due to imbalances, also triggers excessive convection
- Increasingly difficult to mitigate this problem as the frequency of data assimilation increases (sub-hourly DA):
  - Warn on Forecast (WoFS)
  - Land-falling TCs
  - Fire prediction
- The moving vertical coordinate, while shown useful in non-convective applications to increase efficiency, becomes much more problematic at CAM scales:
  - Lagrangian surfaces can collapse even within the small time step cycling
  - Between remapping steps in the presence of strong updrafts
- Physics tendencies from the model are implemented in a way not used in other operational models
  - Also introduces imbalances
  - Can be improved but would require non-trivial effort

Explore MPAS for RRFSv2+

RRFSv2+ Status Summary

Why not just jump straight to RRFSv2?

- Schedule
  - NAMv4: 2017 (now more than 6 years ago)
  - RAPv5/HRRRv4: December 2020 (now more than 2.5 years ago)
  - HREFv3: May 2021 (now more than 2 years ago)
  - RRFSv1 best case: September 2024-March 2025 (~4 years after last CAM upgrade)
  - WCOSS2 implementation moratorium coming during FY26
  - Need to retire legacy systems before moratorium less code porting be needed without SME
- Data Assimilation
  - GSI-MPAS development limited with no direct interface to unstructured grid
  - Continued investment in GSI development not viable with needed resources moving to JEDI
  - JEDI-MPAS only practical option
- Physics
  - Need full CCPP framework/suite integration into MPAS
  - Stochastic physics not currently available in MPAS for RRFS ensemble

Given needed DA, physics, infrastructure development with MPAS and scheduling factors:

- RRFSv2 best case implementation: FY27 (6-7 years after last legacy CAM upgrade)
- RRFSv1 has a lot of (equitable) benefits with increased domain size, direct radar DA, advanced physics, smoke/dust, two-way coupling with ensemble, etc…

HRRRv4 References

Benjamin, S. G., James, E. P., Hu, M., Alexander, C. R., Ladwig, T. T., Brown, J. M., Weygandt, S. S., Turner, D. D., Minnis, P., Smith, W. L., Jr., and Heidinger, A. K. (2021). Stratiform Cloud-Hydrometeor Assimilation for HRRR and RAP Model Short-Range Weather Prediction. Monthly Weather Review 149, 8, 2673-2694, https://doi.org/10.1175/MWR-D-20-0319.1

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