The Operational Future of the Rapid-Refresh (RAP) and High-Resolution Rapid Refresh (HRRR)

14 June 2018

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NOAA/ESRL/GLOBAL SYSTEMS DIVISION

RAP/HRRR: Hourly-Updating Weather Forecast Suite

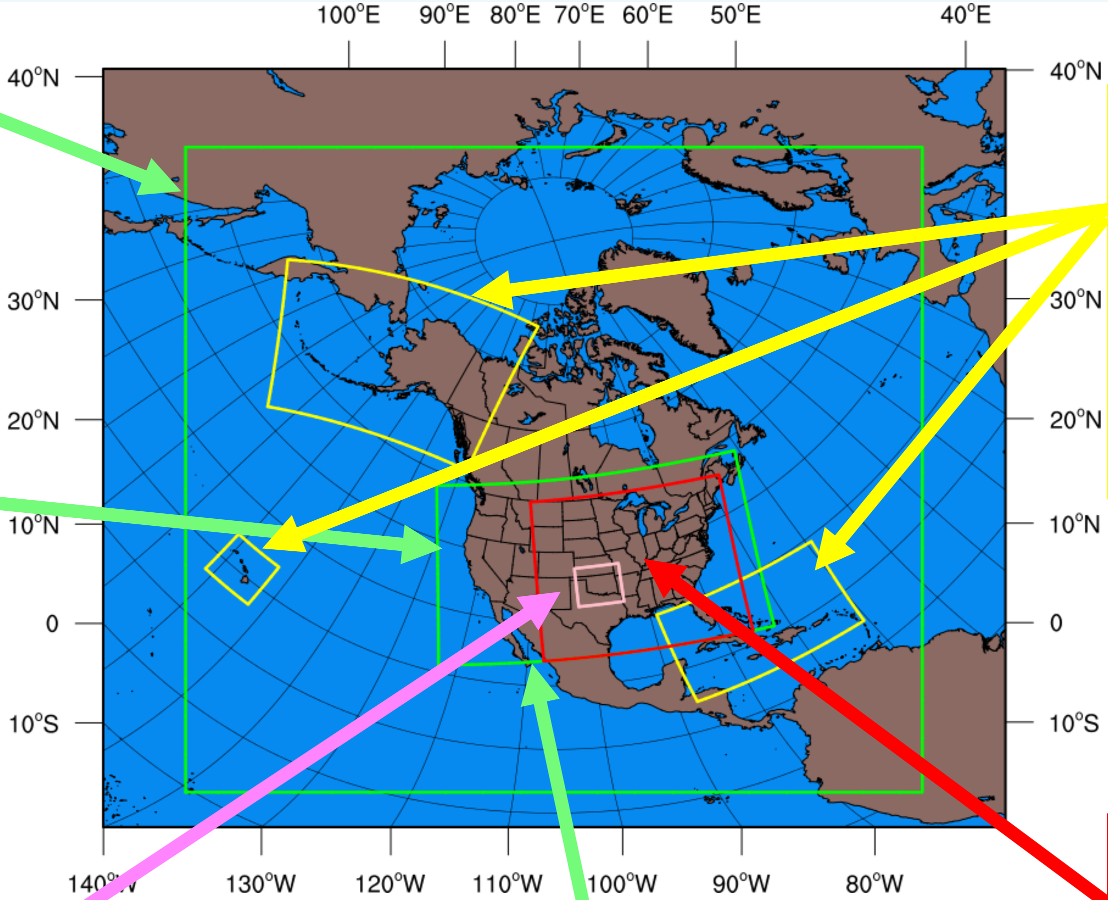
13-km Rapid Refresh (RAPv4) – to 39h (July 2018)

Boundary Conditions

3-km High-Resolution Rapid Refresh (HRRRv3) – to 36h (July 2018)

Initial & Lateral Boundary Conditions

750-m HRRR nest Scale-aware Physics Testing (ongoing)



3-km High-Resolution Rapid Refresh Alaska, Hawaii and Puerto Rico Testing (HRRR-AK, HRRR-HI, HRRR-PR) Experimental (ongoing)

3-km High-Resolution Time Lagged Ensemble (HRRR-TLE)

3-km HRRR-Smoke (VIIRS fire data)

3-km Storm-Scale Ensemble Analysis and Forecast (HRRRE) 55% CONUS HRRR Experimental (ongoing)

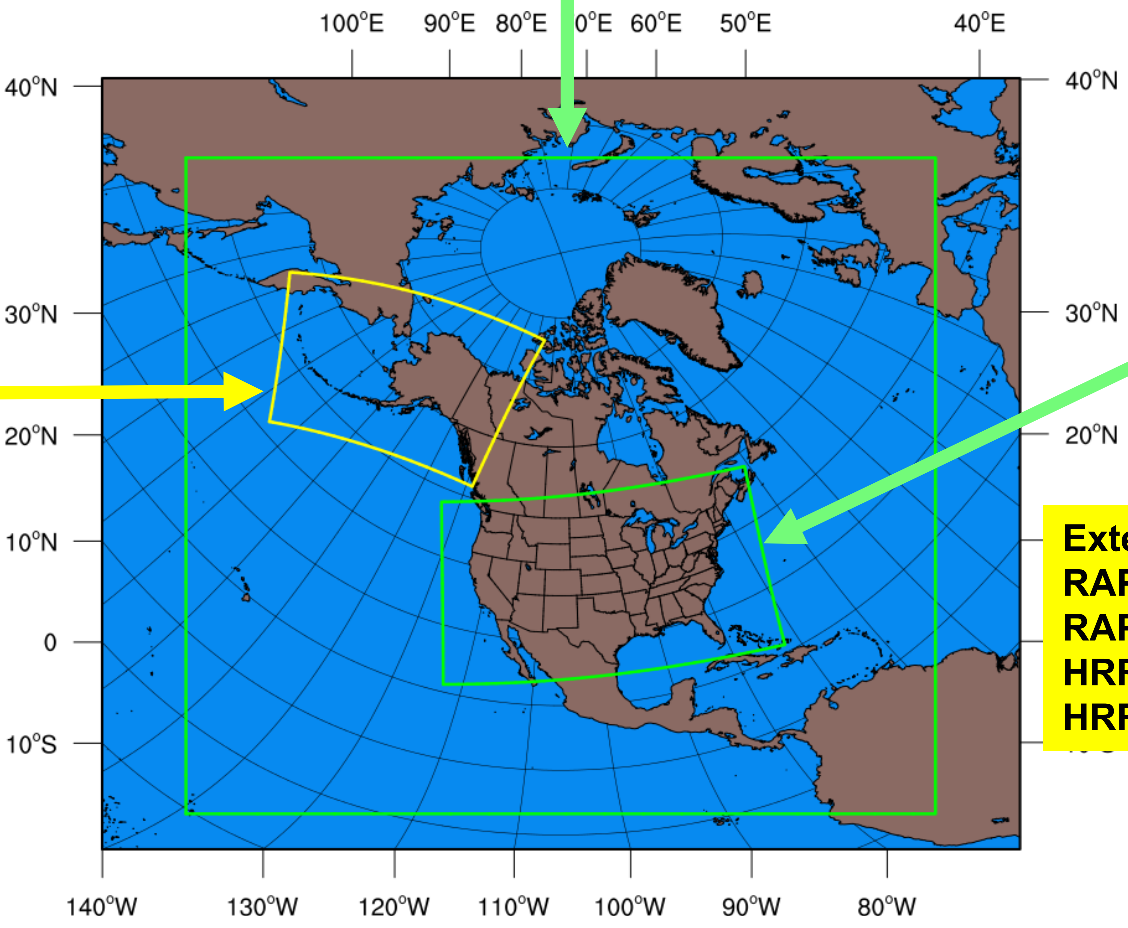
RAPv4/HRRRv3 Model Forecast Changes

13-km Rapid Refresh (RAPv4) – to 39h (July 2018)

Initial & Lateral Boundary Conditions

Initial & Lateral Boundary Conditions

3-km High-Resolution Rapid Refresh Alaska (HRRR-AK) 36 hr (July 2018)



3-km High-Resolution Rapid Refresh (HRRRv3) – to 36h (July 2018)

OCONUS Domains
HRRR-Alaska:
Every 3 hrs to 18 hrs
Every 6 hrs to 36 hrs

Extended Forecast Lengths
RAP: 03z, 09z, 15z, 21. 21 hrs → 39 hrs
RAP: All other hourly cycles remain 21 hrs
HRRR: 00z, 06z, 12z, 18z 18 hrs → 36 hrs
HRRR: All other hourly cycles remain 18 hrs

RAP/HRRR Transition to Operations

ESRL RAPv5/HRRRv4 What:	When:
Begin ESRL RAPv5/HRRRv4	Mid-March 2018
Spring Freeze ESRL RAPv5/HRRRv4	30 Apr 2018

Shortest Term Changes:
Fractional lake ice-concentrations (GFS-based)
Assimilation moisture observations above 300mb
Change to revised albedo/land use from MODIS
Remove mosaic snow building/trimming for 2mT < -2C
Update cloud water number concentration from RAP to HRRR initialization (default value that is too low)

Up Next:
Transition to WRFv3.9.1
Updated MYNN PBL and LSM (gravity wave drag, etc…)

NCEP RAPv4/HRRRv3 What:	When:
~~GSD-EMC Package Briefing~~	~~14 April 2017~~
~~GSD-EMC Package Briefing~~	~~30 May 2017~~
~~GSD code hand-off to EMC~~	~~26 Jun 2017~~
~~NCEP EE2 Meeting~~	~~06 Jul 2017~~
~~EMC 24x7 parallel~~	~~21 Aug 2017~~
~~EMC Evaluation Begins~~	~~20 Nov 2017~~
~~EMC Evaluation Ends~~	~~20 Jan 2018~~
~~EMC CCB Meeting~~	~~26 Jan 2018~~
~~NCEP Director Briefing~~	~~02 Feb 2018~~
~~EMC code hand-off to NCO~~	~~15 Feb 2018~~
~~NCO 24x7 parallel~~	~~Mar 2018~~
NCO 30-day start	25 May 2018
NCO Management Meeting	25 June 2018
NCEP Implementation	11 July 2018

RAPv4/HRRRv3 Summary of Changes

Operational RAPv3/HRRRv2

Model	Run at:	Domain	Grid Points	Grid Spacing	Vertical Levels	Vertical Coordinate	Pressure Top	Boundary Conditions	Initialized
RAP	GSD, NCO	North America	953 x 834	13 km	50	Sigma	10 mb	GFS	Hourly (cycled)
HRRR	GSD, NCO	CONUS	1799 x 1059	3 km	50	Sigma	20 mb	RAP	Hourly (pre-forecast hour cycle)

Model	Version	Assimilation	Radar DA	Radiation LW/SW	Microphysics	Cumulus Param	PBL	LSM
RAP	WRF-ARW v3.6+	GSI Hybrid Ensemble to 0.75	13-km DFI	RRTMG/ RRTMG	Thompson Aerosol v3.6	GF + Shallow	MYNN v3.6	RUC v3.6
HRRR	WRF-ARW v3.6+	GSI Hybrid Ensemble to 0.75	3-km 15-min LH	RRTMG/ RRTMG	Thompson Aerosol v3.6	None	MYNN v3.6	RUC v3.6

Model	Horiz/Vert Advection	Scalar Advection	Upper-Level Damping	Diffusion Option	6th Order Diffusion	SW Radiation Update	Land Use	MP Tend Limit	Time-Step
RAP	5th/5th	Positive-Definite	w-Rayleigh 0.2	Simple (1)	Yes 0.12	20 min	MODIS Seasonal	0.01 K/s	60 s
HRRR	5th/5th	Positive-Definite	w-Rayleigh 0.2	Simple (1)	Yes 0.25	15 min with SW-dt	MODIS Seasonal	0.07 K/s	20 s

RAPv4/HRRRv3 Summary of Changes

Upcoming RAPv4/HRRRv3

No Change in CONUS Domains

Model	Run at:	Domain	Grid Points	Grid Spacing	Vertical Levels	Vertical Coordinate	Pressure Top	Boundary Conditions	Initialized
RAP	GSD, NCO	North America	953 x 834	13 km	50	Sigma-Isob Hybrid	10 mb	GFS	Hourly (cycled)
HRRR	GSD, NCO	CONUS	1799 x 1059	3 km	50	Sigma-Isob Hybrid	20 mb	RAP	Hourly (pre-forecast hour cycle)

Newer Model Version
More Ensemble Weight
Advanced "Physics Suite"

Model	Version	Assimilation	Radar DA	Radiation LW/SW	Microphysics	Cumulus Param	PBL	LSM
RAP	WRF-ARW v3.8.1+	GSI Hybrid Ensemble to 0.85	13-km DFI, ½ Strength	RRTMG/ RRTMG	Thompson Aerosol v3.8.1	GF + Shallow	MYNN v3.8.1	RUC v3.8.1
HRRR	WRF-ARW v3.8.1+	GSI Hybrid Ensemble to 0.85	3-km 15-min LH	RRTMG/ RRTMG	Thompson Aerosol v3.8.1	None	MYNN v3.8.1	RUC v3.8.1

Seasonal Vegetation Fraction/Leaf Area Index

Model	Horiz/Vert Advection	Scalar Advection	Upper-Level Damping	Diffusion Option	6th Order Diffusion	SW Radiation Update	Land Use	MP Tend Limit	Time-Step
RAP	5th/5th	Positive-Definite	w-Rayleigh 0.2	Full (2)	Yes 0.12	20 min	MODIS Seasonal	0.01 K/s	60 s
HRRR	5th/5th	Positive-Definite	w-Rayleigh 0.2	Full (2)	Yes 0.25	15 min with SW-dt	MODIS Seasonal	0.07 K/s	20 s

2018 RAPv4/HRRRv3 Change Highlights

Data Assimilation	Model	Land-surface/post
Merge with GSI trunk – Mar 2017 *New Observations for assimilation:* Add AMVs over land and TAMDAR NCEP new VAD wind retrievals Add IASI, CrIS, SEVIRI radiances Use direct readout radiances (larger volume) *Assimilation Methods:* Revised PBL pseudo-obs –better winds/RH More ens weight in hybrid DA (0.85/0.15) Cloud building - smaller qc/qi, cloud CCN now specified - GOES/METAR build <1200m Radar reflectivity assimilation - Latent heating reduced by 50% - RAP only - also affects HRRR – reduces high precip bias	WRF-ARW v3.8.1+ incl. phys changes *Physics changes:* Thompson microphysics – improved ice clouds (not excessive) MYNN PBL update – better sub-grid clouds, EDMF (local/deep) mixing Land-sfc model update – mosaic snow, 2m temp diagnostic Revised Grell-Freitas cumulus (RAP) Eclipse-ready short-wave radiation *Numerics changes:* Hybrid vertical coordinate from NCAR Low-level subgrid wind drag Diffusion – horiz only, not on slopes	MODIS higher-res 15” land-use data VIIRS real-time greenness veg fraction Revised roughness length 10m wind (not ~8m) Wind gust diag fixed (stronger at night) Visibility diag improved

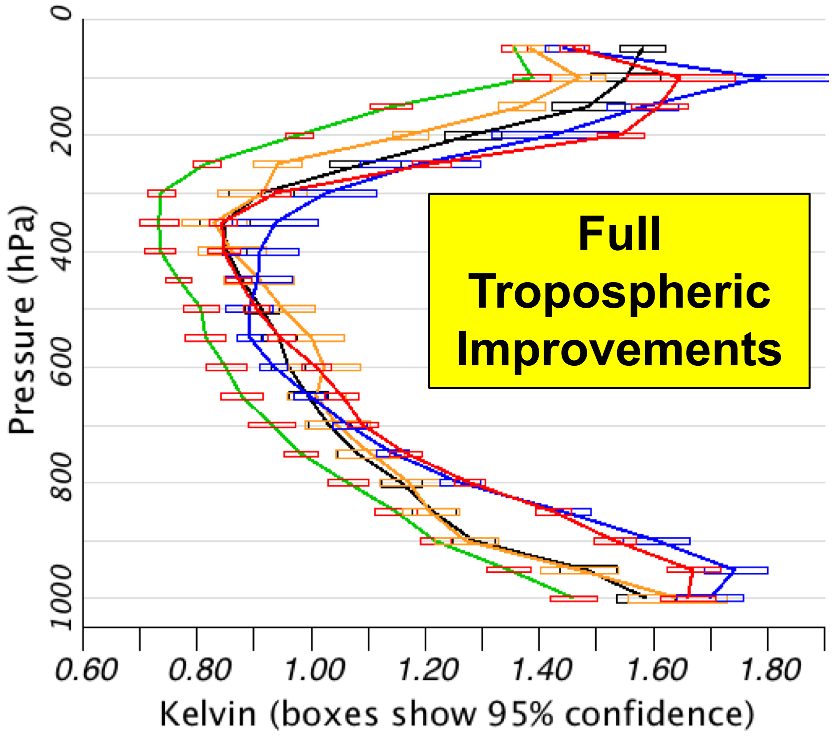
RAP/HRRR Performance History

- 2013 (v2)
- 2014
- 2015 (v3)
- 2016
- 2017 (v4)

Experimental RAP RMSE
6-hr Forecasts – June-July

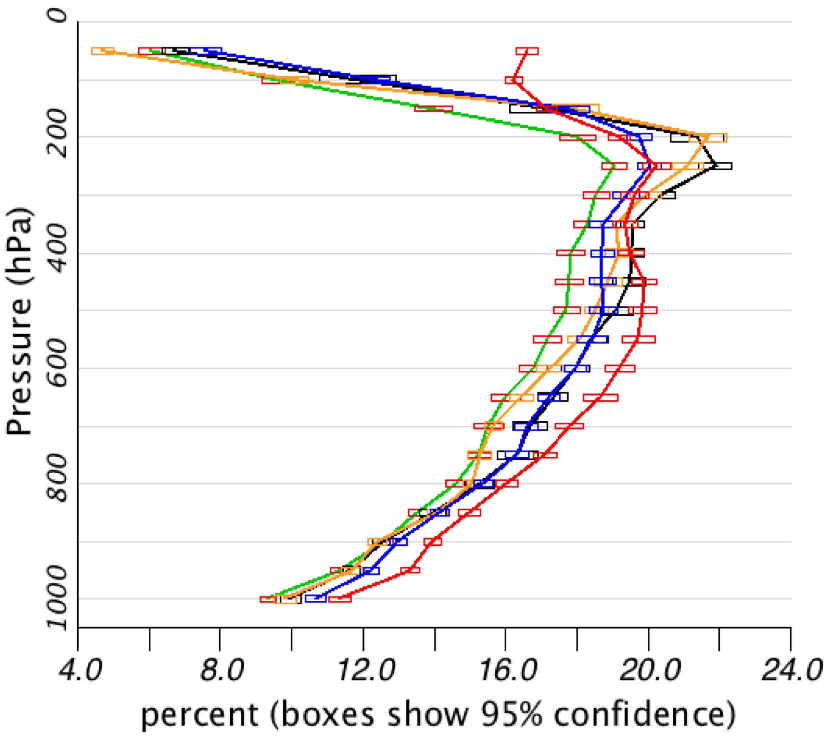
~25% RMSE Reduction in 5 years

Temperature



← More Skill

Humidity



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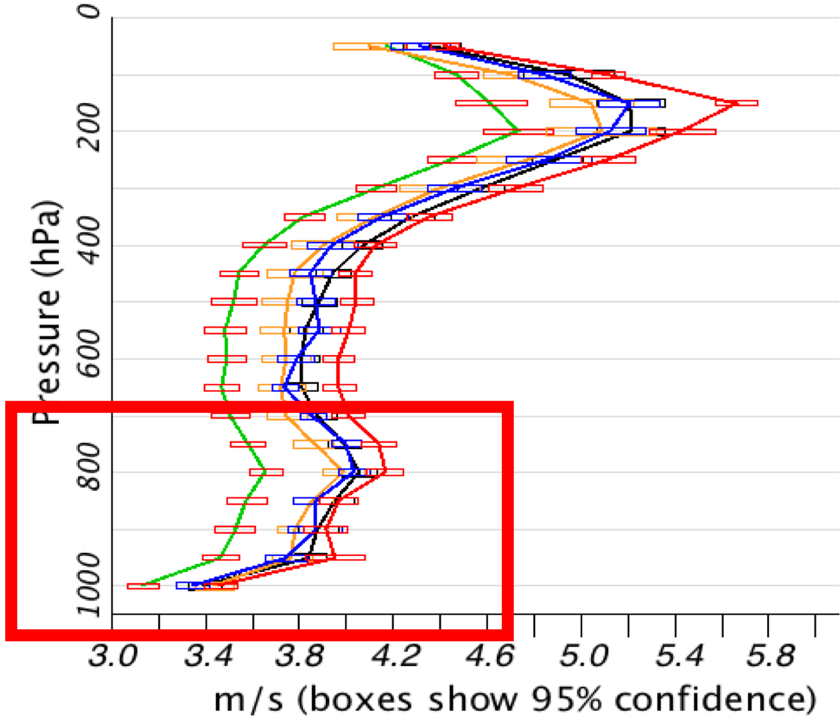
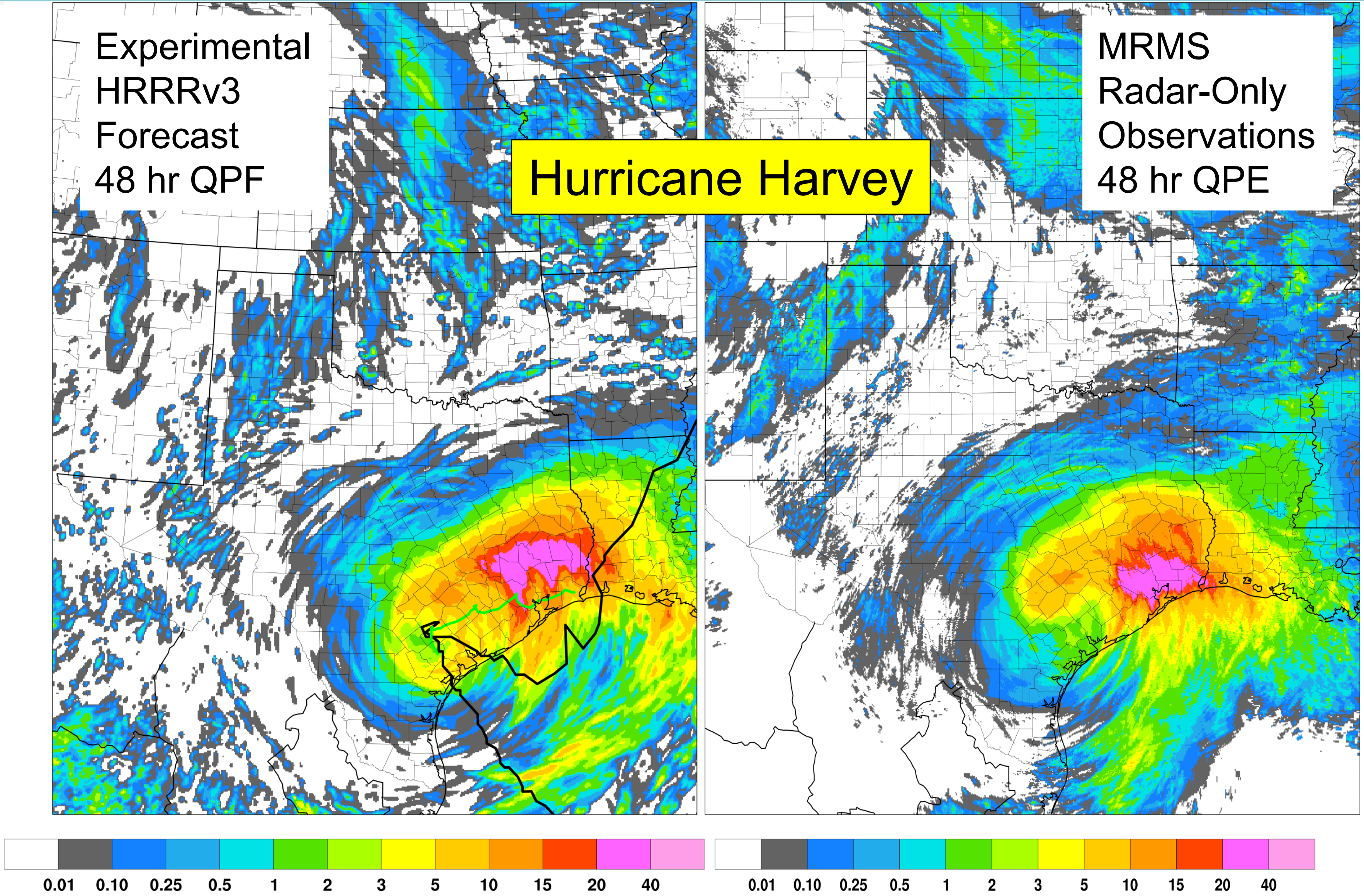
Wind



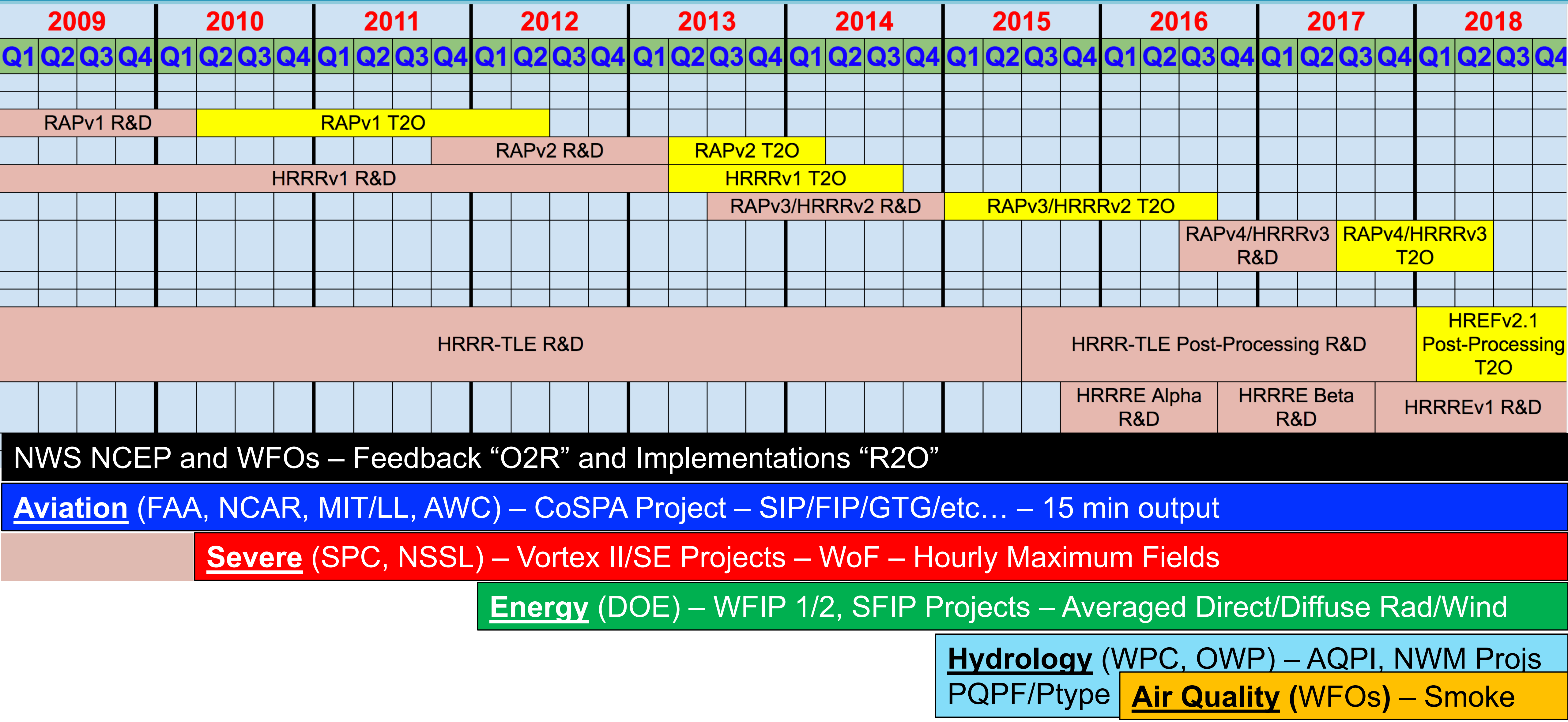
← More Skill

Landfalling Tropical Cyclones

- **2017 hurricanes in operational and experimental HRRR domains**
- **Realistic structures and impacts but some errors in track forecasts**
- **Future improvements to RAP/HRRR/regional FV3 data assimilation (e.g., tcvitals, radar, satellite)**



ESRL/GSD Regional Model Projects



Downstream Applications

Operational Downstream Dependencies from RAP/HRRR

1. Real-Time Mesoscale Analysis (RTMA/URMA/smartinit) (analysis)
2. National Blend of Models (NMB) (general forecasting)
3. National Water Model (NWM) (hydrology)
4. Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) (air quality)
5. Local Aviation MOS Program (LMP/GLMP) (aviation)
6. Graphical Turbulence Guidance (GTG) (aviation)
7. High-Resolution Ensemble Forecast (HREF/HIRESW) (CAM ensemble)
8. Short Range Ensemble Forecast (SREF/NARRE) (mesoscale ensembles)
9. Surface Objective Analysis (SurfaceOA) (severe)
10. National Ocean Service (NOSOFS) (ocean)

GSD-EMC-NCO Implementation Efficiency

Model Systems	Year	Number of Quarters (3 is minimum)	Quarters/System	% Improvement
RAPv1	2012	9	9	-
RAPv2 and HRRRv1	2014	10	5	45%
RAPv3/HRRRv2	2016	7	3.5	30%
RAPv4/HRRRv3 (CONUS and AK)	2018	4	1.3	63%

Average 46% improvement (each implementation ~2x faster)

Increasing T2O efficiency from:

- More familiarity with the model system software (GSI, ARW, UPP)
- More familiarity with the target high performance computer (WCOSS) and O2R optimizations
- More developer involvement at GSD and EMC

T2O challenges remain:

- Heterogeneity of R&D and operational HPC environments
- Increasing sophistication/complexity of model system components

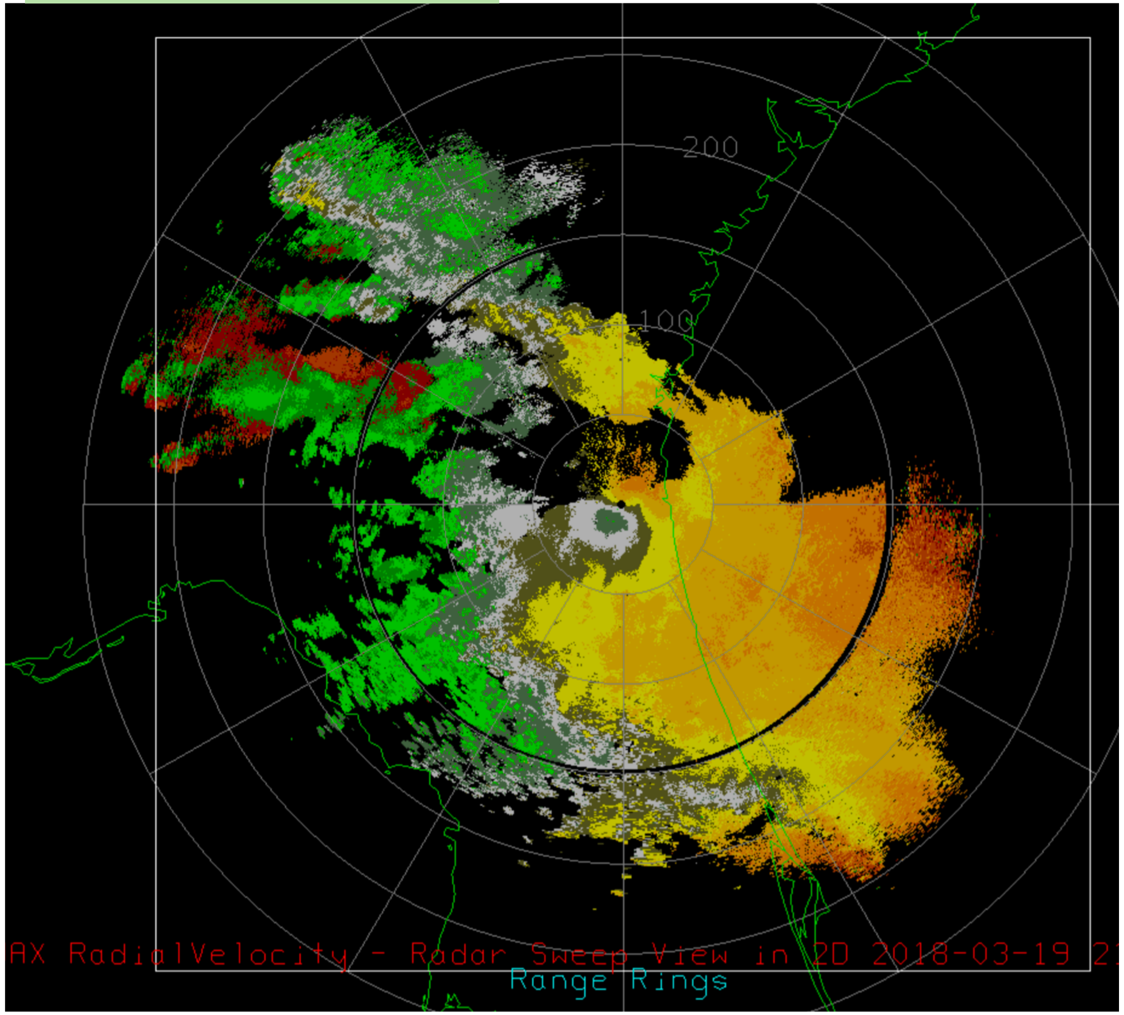
2020 RAPv5/HRRRv4 Change Highlights

Model	Data Assimilation	Land-surface / post
WRF-ARWv4.0+ incl. phys changes *Physics changes:* MYNN PBL update – yet better sub-grid clouds, improved EDMF mixing length, goal: retaining stable layers Aerosols sources/sinks – fire/smoke, dust - Add smoke with VIIRS fire radiative power Improved land-surface/snow model including better 2m T/Td diagnostics - no snow mosaic for T<271K Latest Grell-Freitas conv (RAP only) Lake model for small lakes Enhanced gravity-wave drag	Merge with GSI trunk – 2018 *New Observations for assimilation:* GOES-16 radiances, GLM lightning MRMS dual-polarization radar mosaics Extra mesonet data incl. anemometer hgt TC vitals for trop cyclone location/ strength Satellite-based AOD (aerosol optical depth) Aircraft/raob moisture obs for p<300 hPa *Assimilation Methods:* HRRR - 3km ensemble DA (40 mems out to 1h) – effective in 2017/18 tests. Reduced LH for radar assim in HRRR Cloud/hydrometeor assim within ens DA DA for subgrid cloud fraction/cloud water w/ METAR, satellite cloud fraction	Switch to MODIS albedo (higher), replace 1-deg albedo. Add zenith-ang albedo adj Fractional sea/lake ice concentration ? – FVCOM SST/ice VIIRS/MODIS/GOES fire radiative power HRRRE prob products Full cycle RAP land-sfc

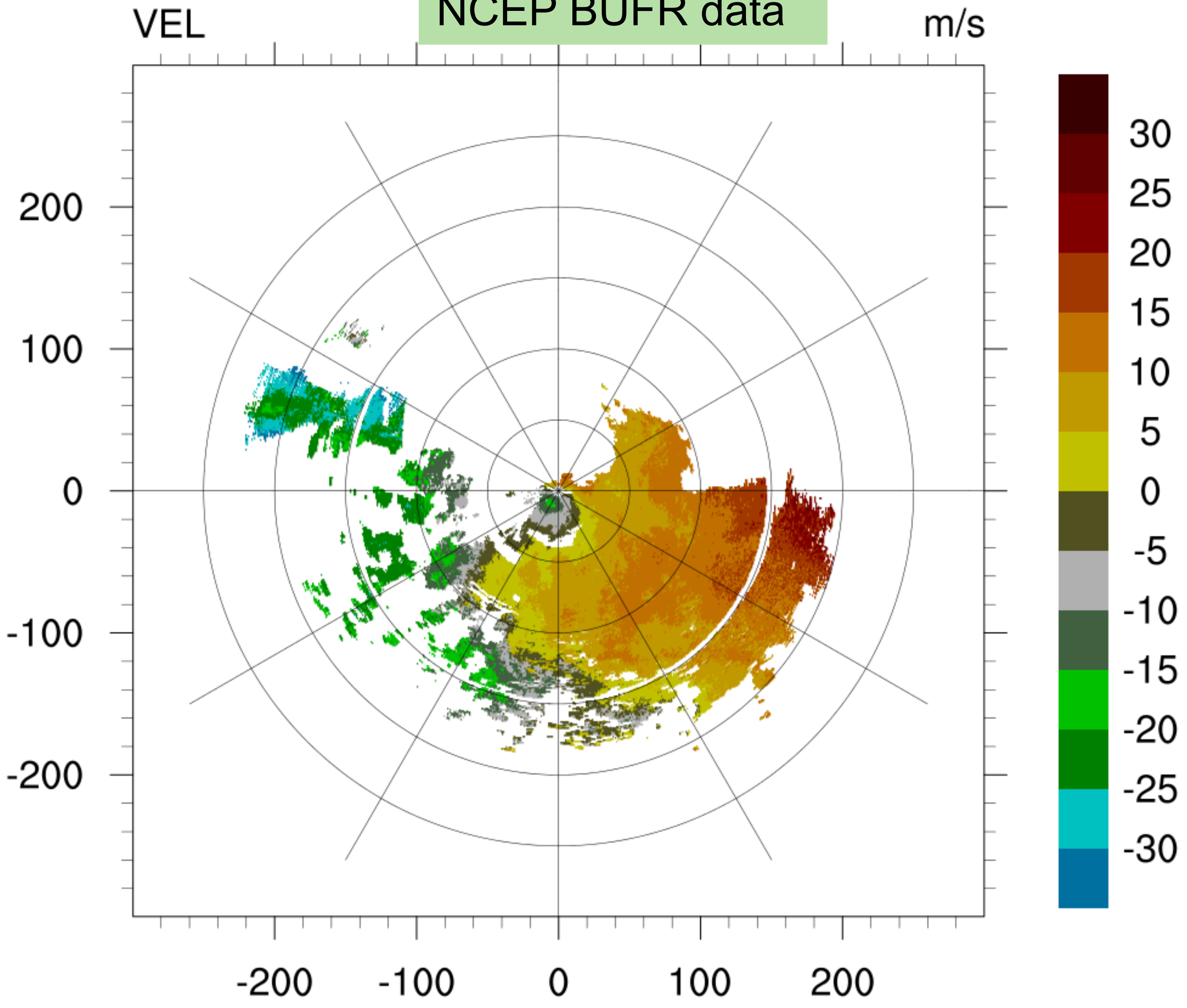
Exploring Dual-Polarization QC of Radial Velocities

KJAX 20180319-215242z 1.3° (Jacksonville, FL) void=192152 scid=3

NEXRAD raw data



NCEP BUFR data



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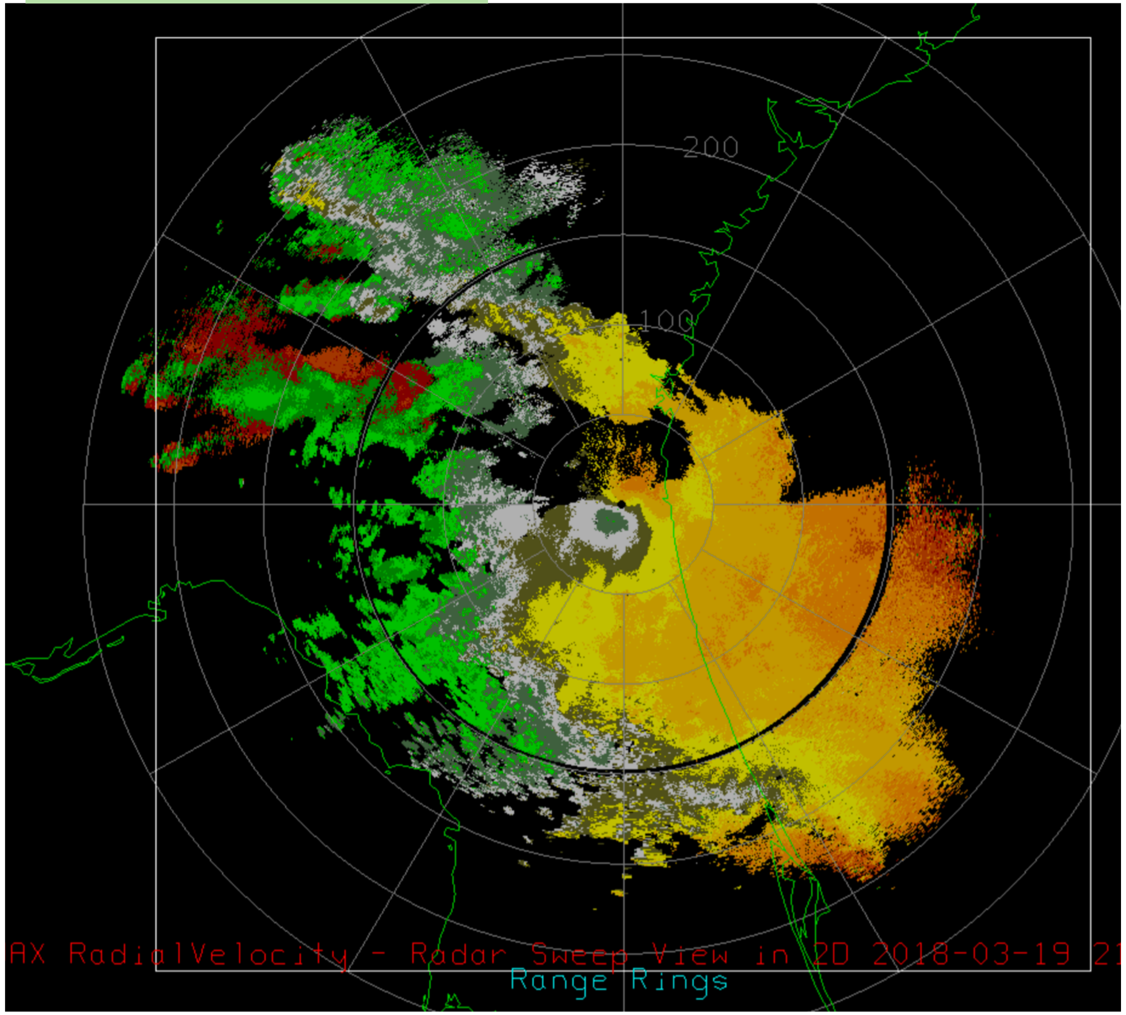
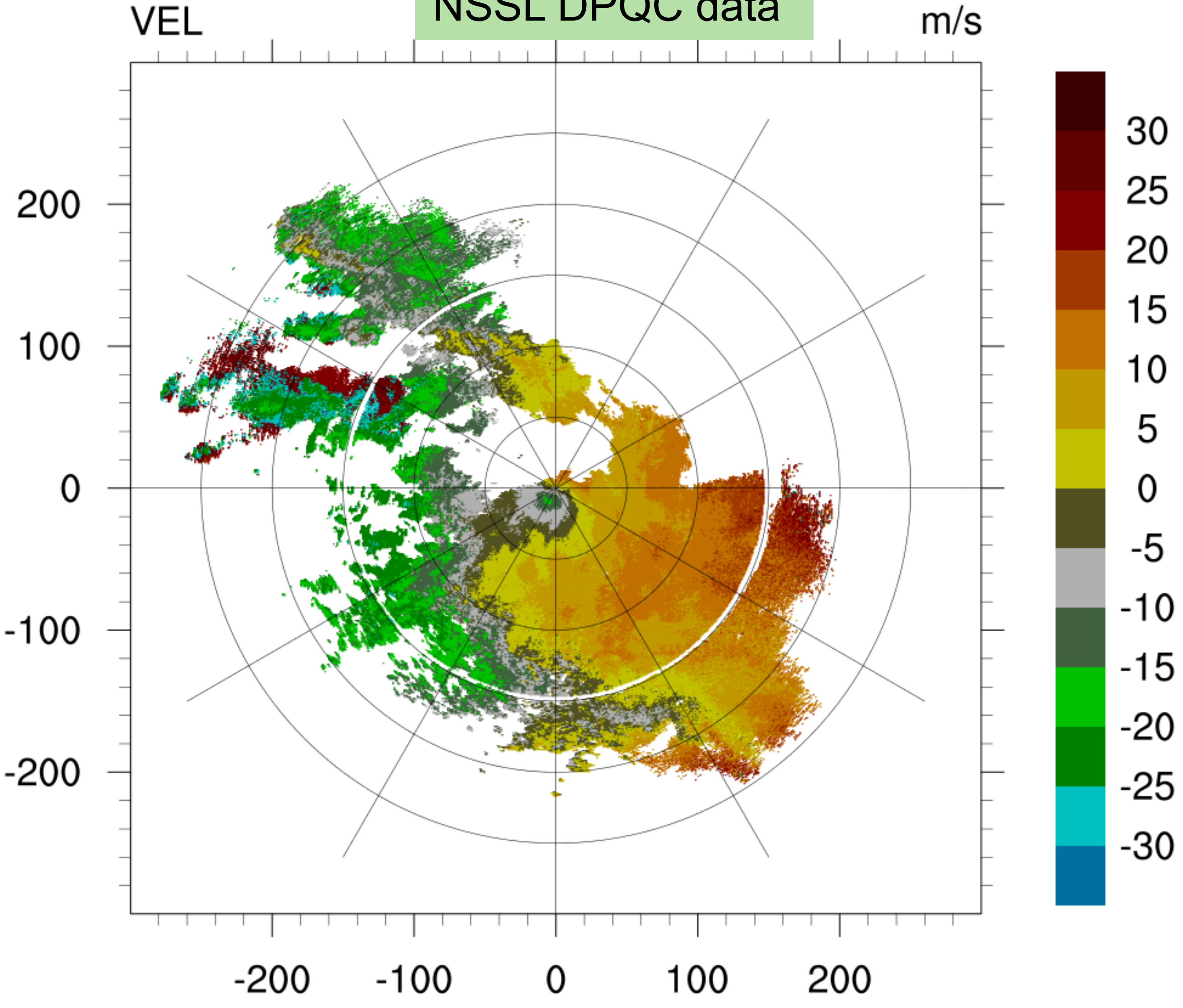
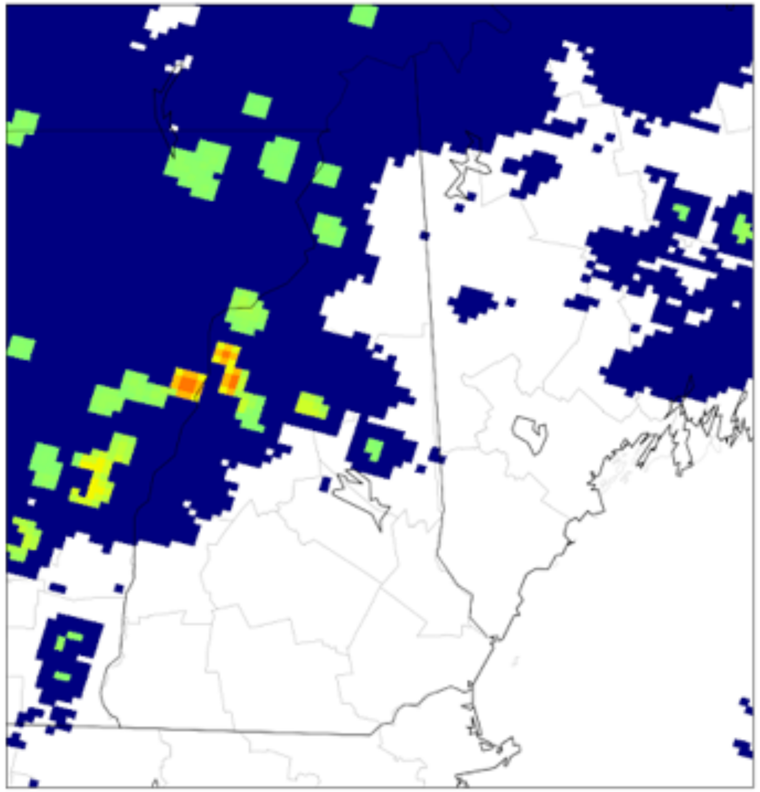


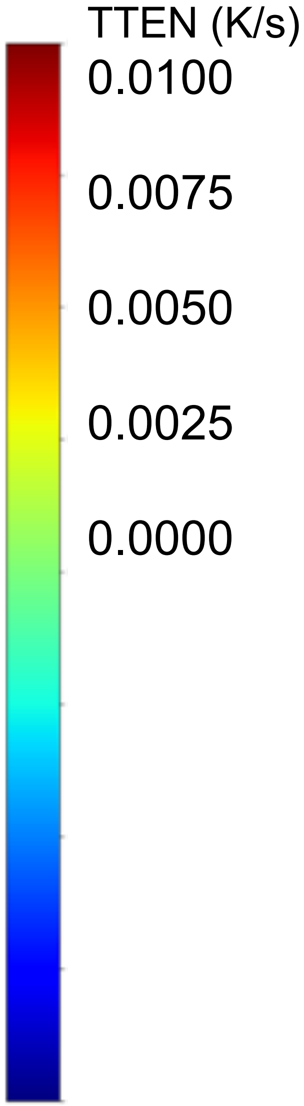
NSSL DPQC data



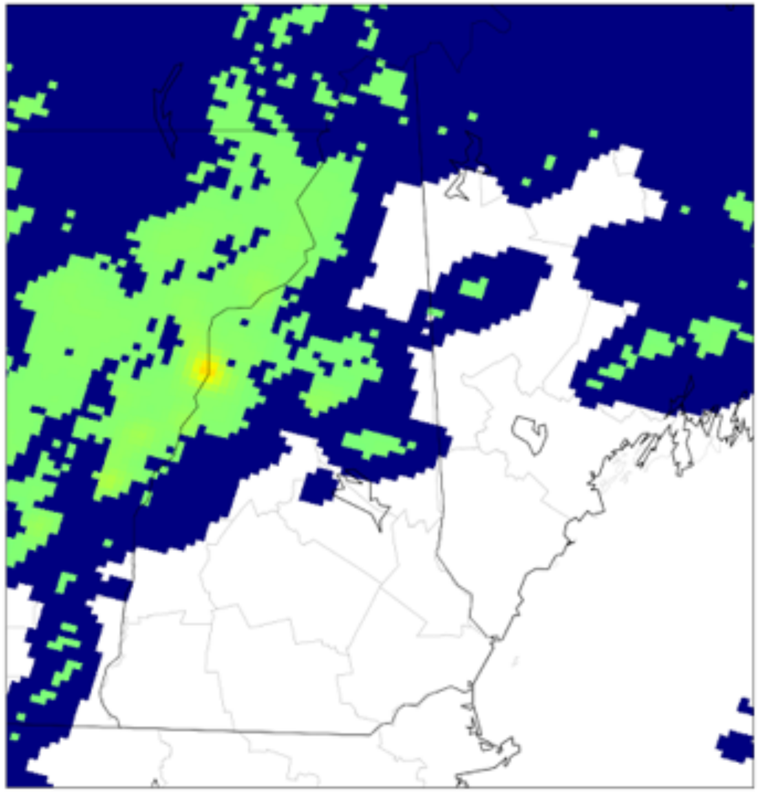
HRRR Dual-Polarization Radar Data Assimilation

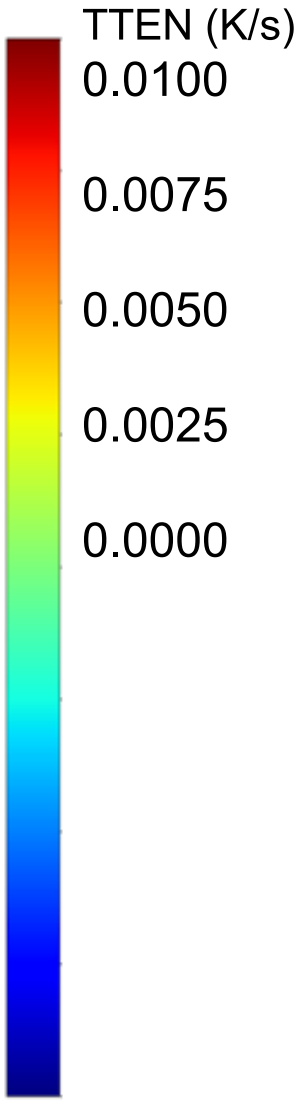
Z_{DR} column-located temperature tendencies using Z_H derived rate





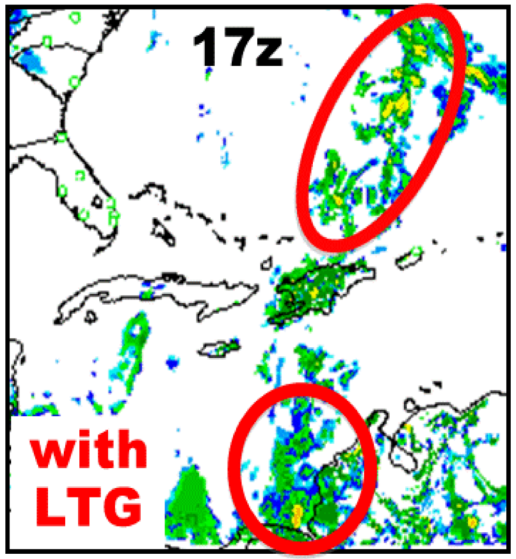
Temperature tendencies from current Z_H HRRR scheme

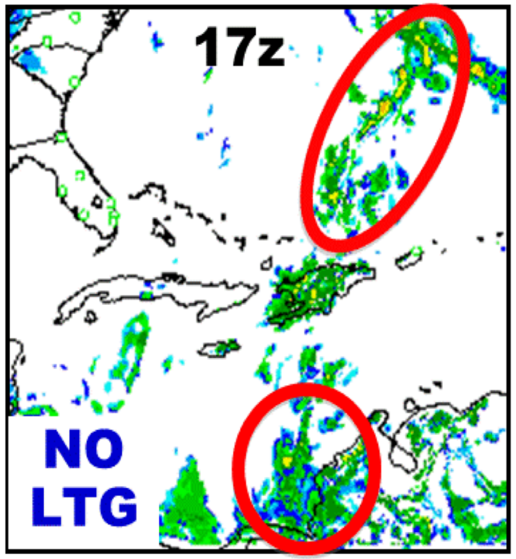




RAP/HRRR GOES Lightning Assimilation

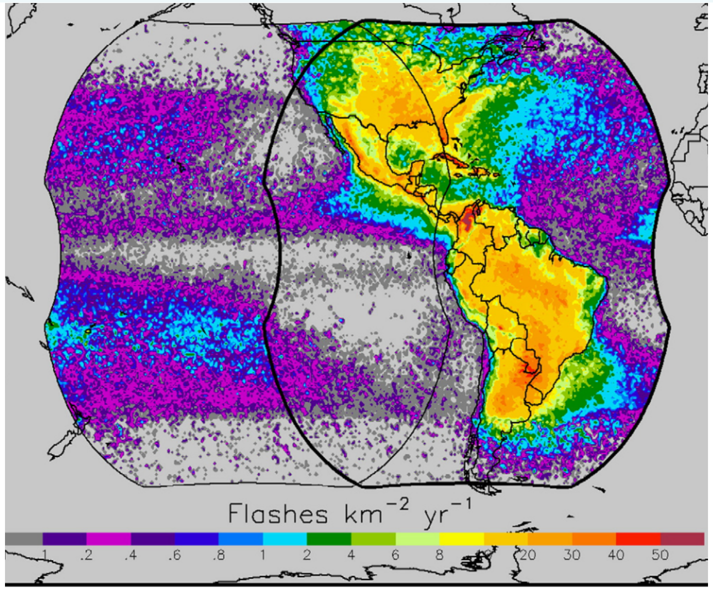
Rapid Refresh oceanic lightning assimilation example





16z +1h GSD RAP forecasts

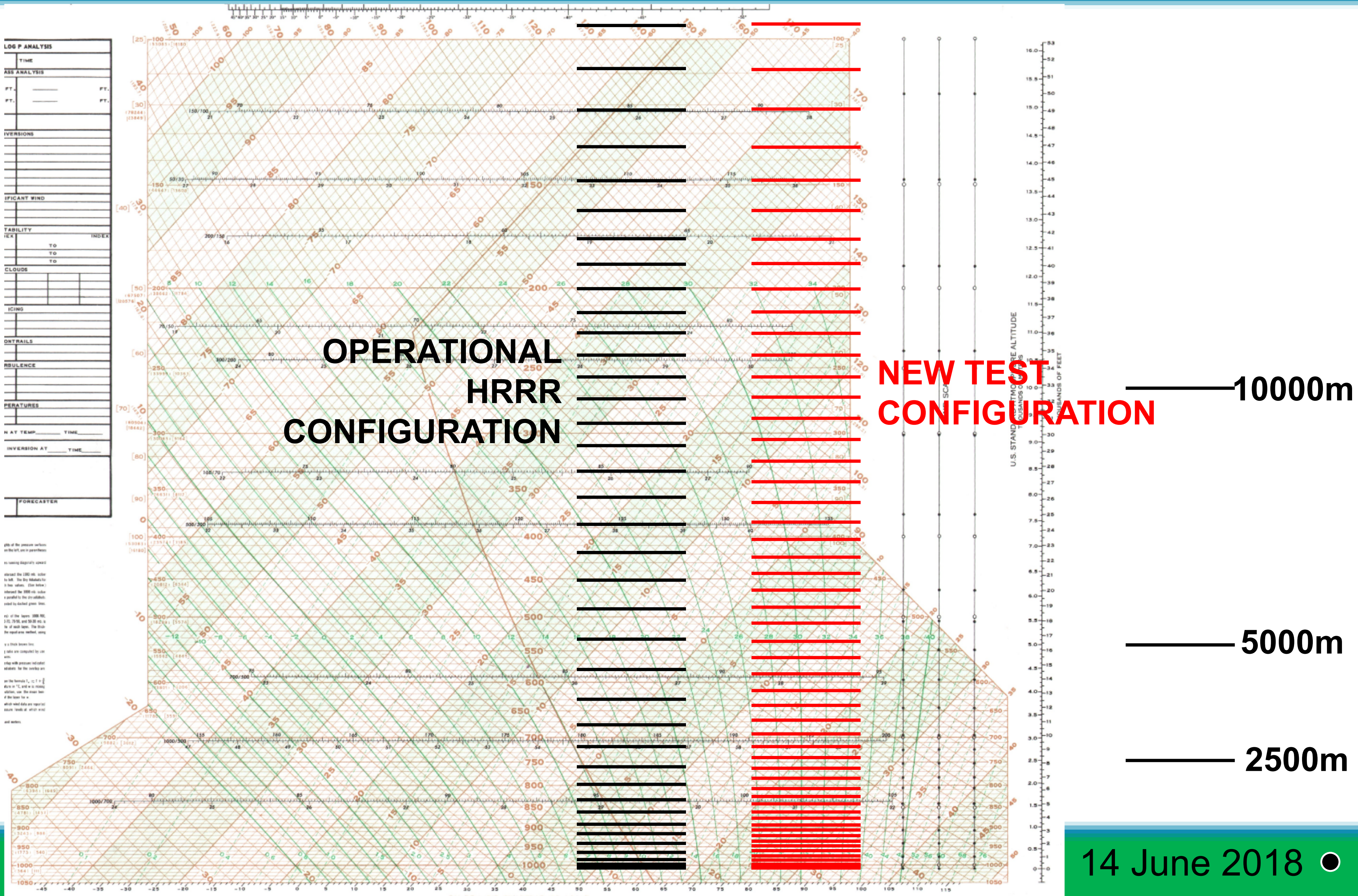
LTG DA → slight impact on RAP forecast storm clusters



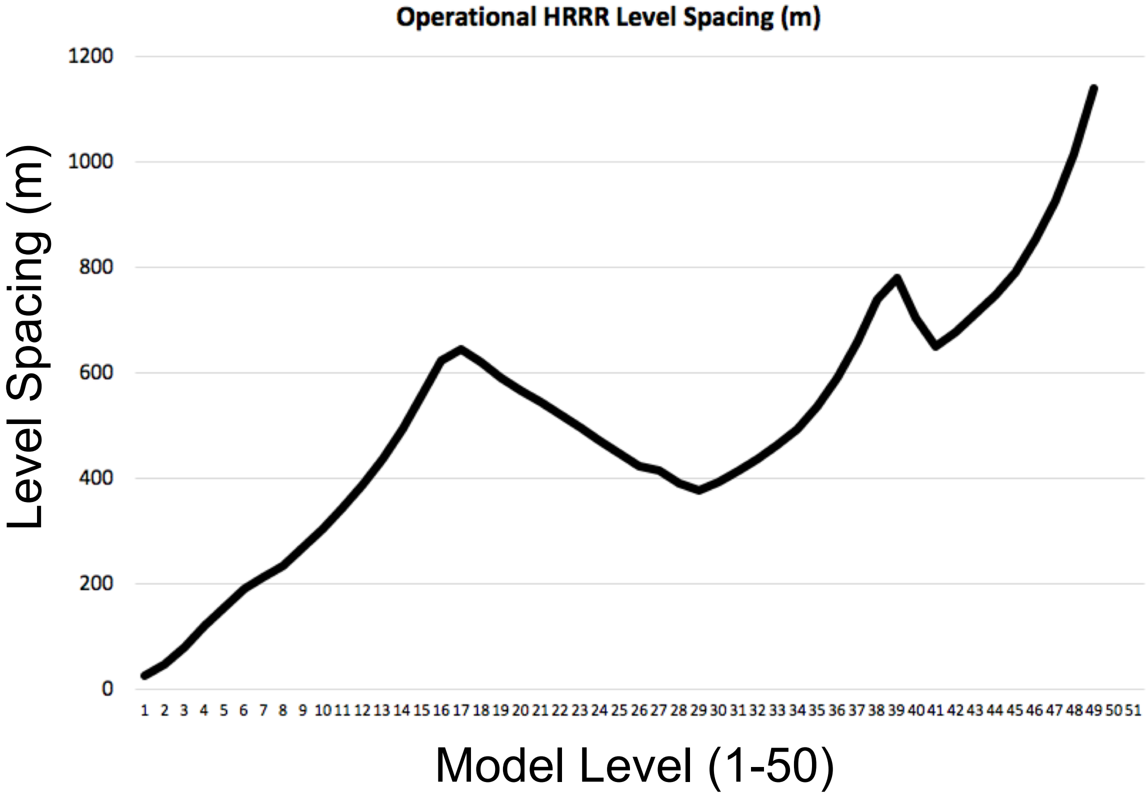
Mean annual lightning flash densities. The bounding curves indicate the extensive coverage of the GLM data (including many regions with no other convective indicator coverage),
while the color shading indicates the frequency of lightning occurrence.

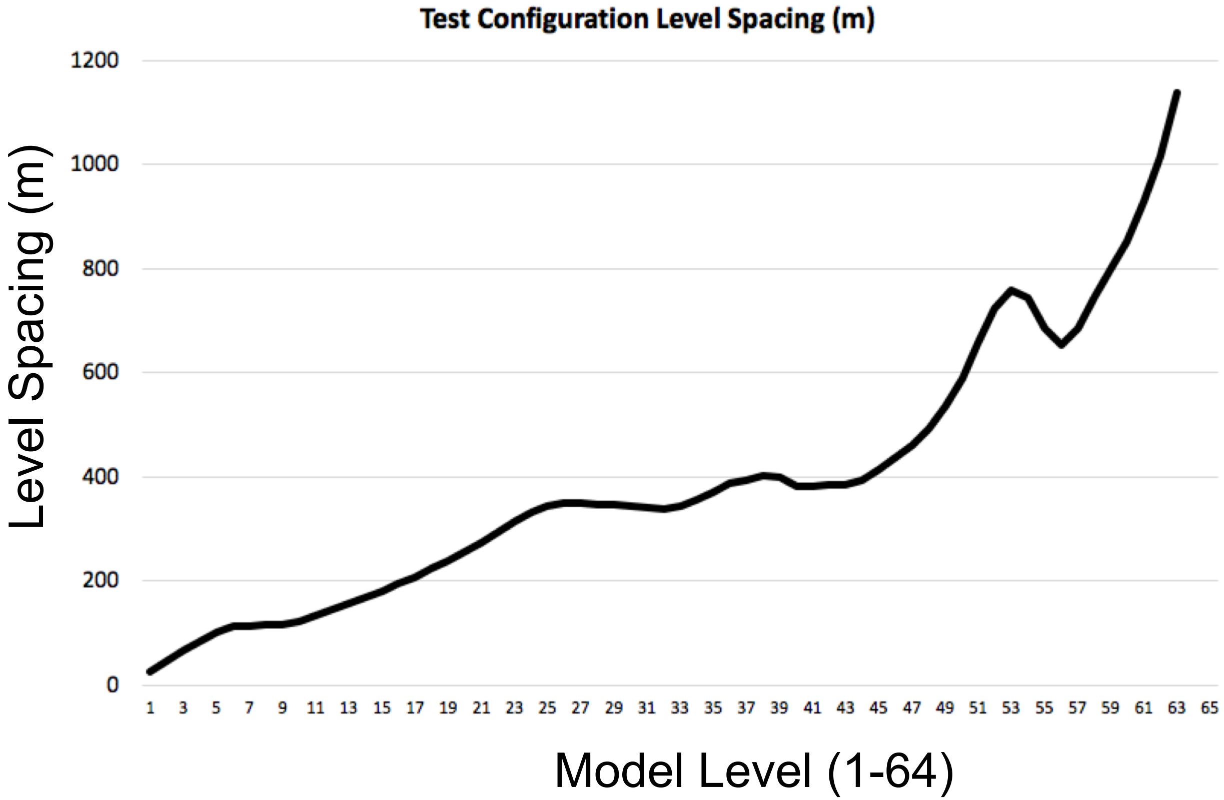
RAP/HRRR More Vertical Levels?

WRF run time cost (compared to operational configuration): **15%-25%**



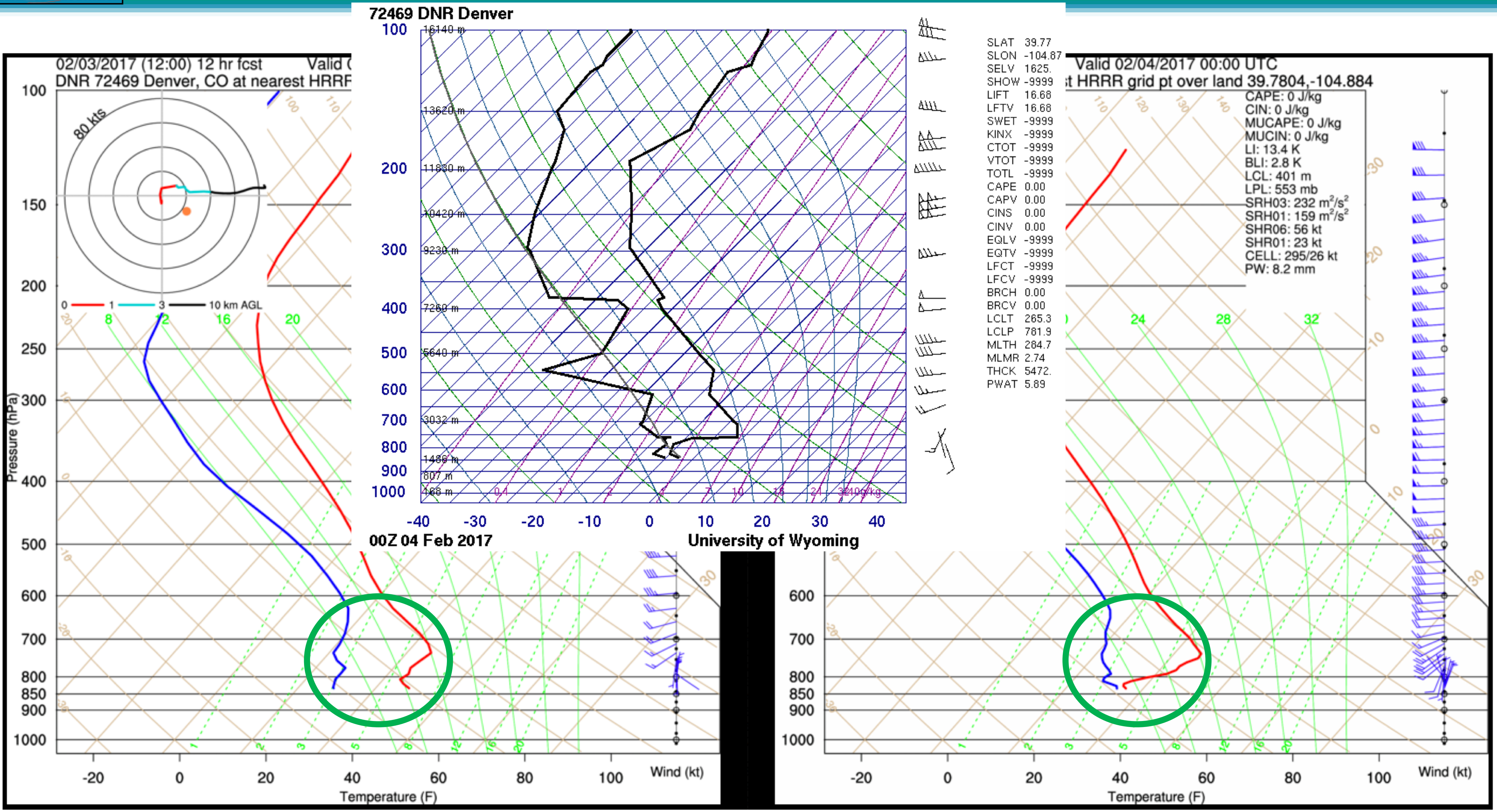
RAP/HRRR More Vertical Levels?





- Vertical level spacing is shown in these figures.
- The new configuration keeps the spacing below 400m all the way up to approximately level 45.

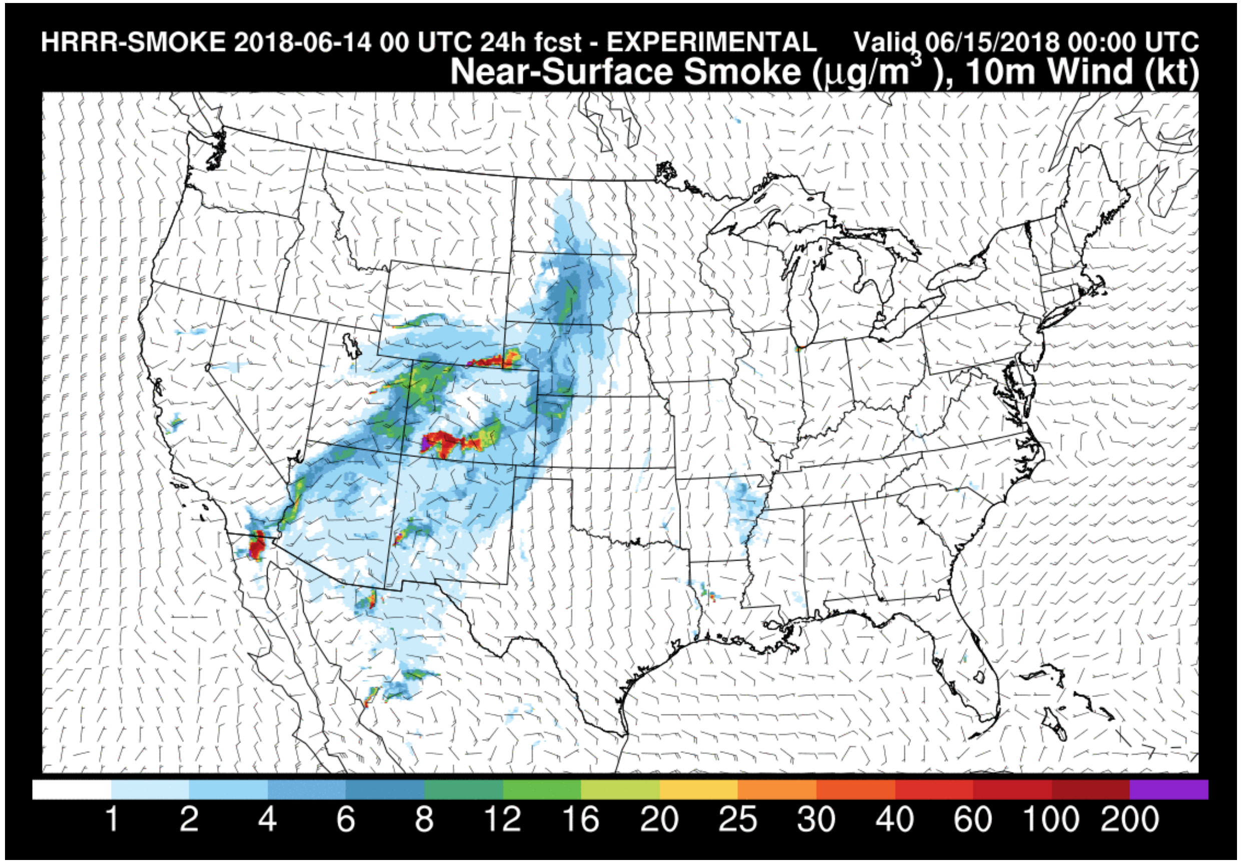
More Vertical Levels: Shallow Airmass Retention



12 hr Forecasts

Smoke Forecasting in RAP and HRRR

- **Single tracer (smoke)** added to experimental RAP and HRRR versions
- Smoke from Alaska, Canada, Mexico, and elsewhere simulated in RAP and provided to HRRR through boundary conditions
- Biomass burning emissions and inline plume rise parameterization based on satellite (VIIRS, MODIS) FRP data
- Full coupling: feedback of smoke on predicted radiation, cloudiness, and precipitation
- Candidate for operational implementation in 2020



Experimental smoke forecast for 14 June 2018 (rapidrefresh.noaa.gov/hrrr/HRRRsmoke/)

Ravan Ahmadov and Eric James

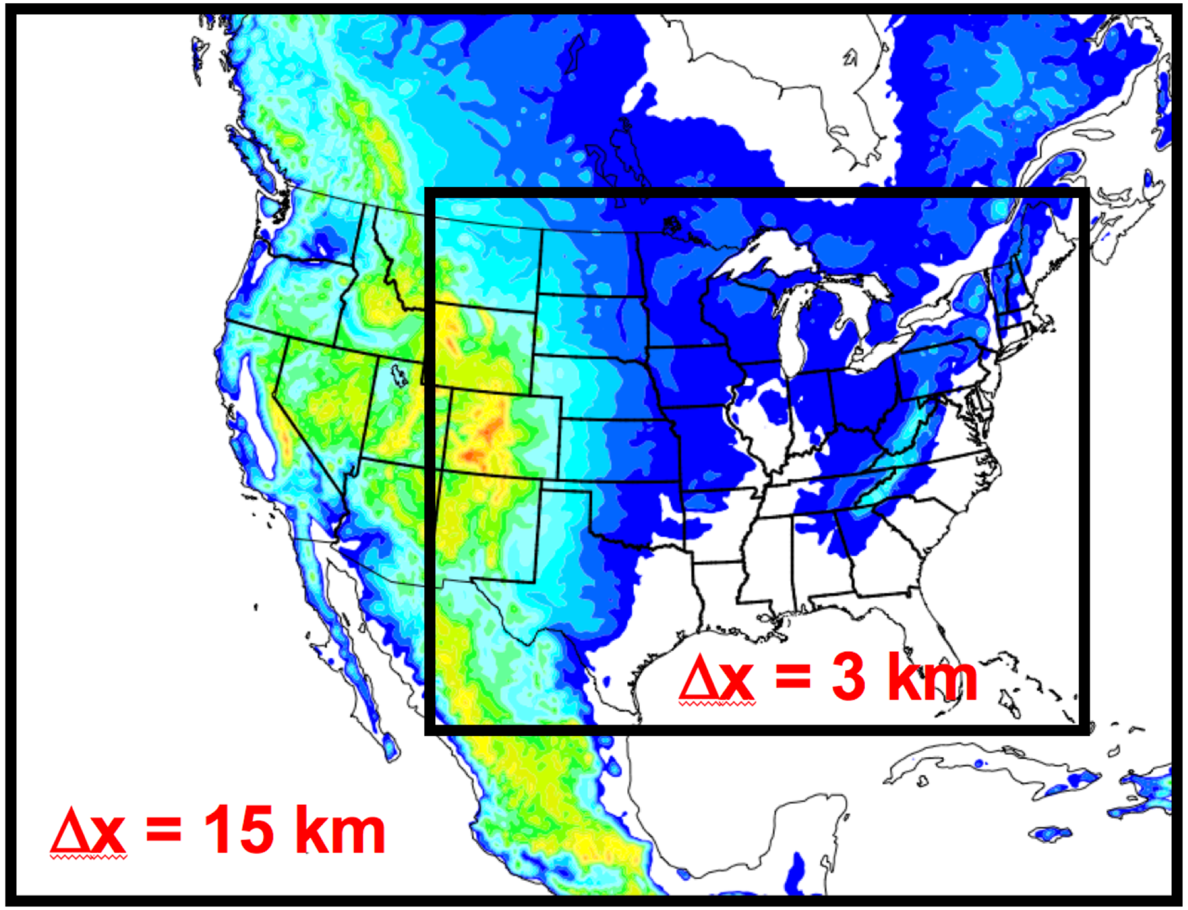
HRRRE Analysis and Forecast System

36-member ensemble analysis system

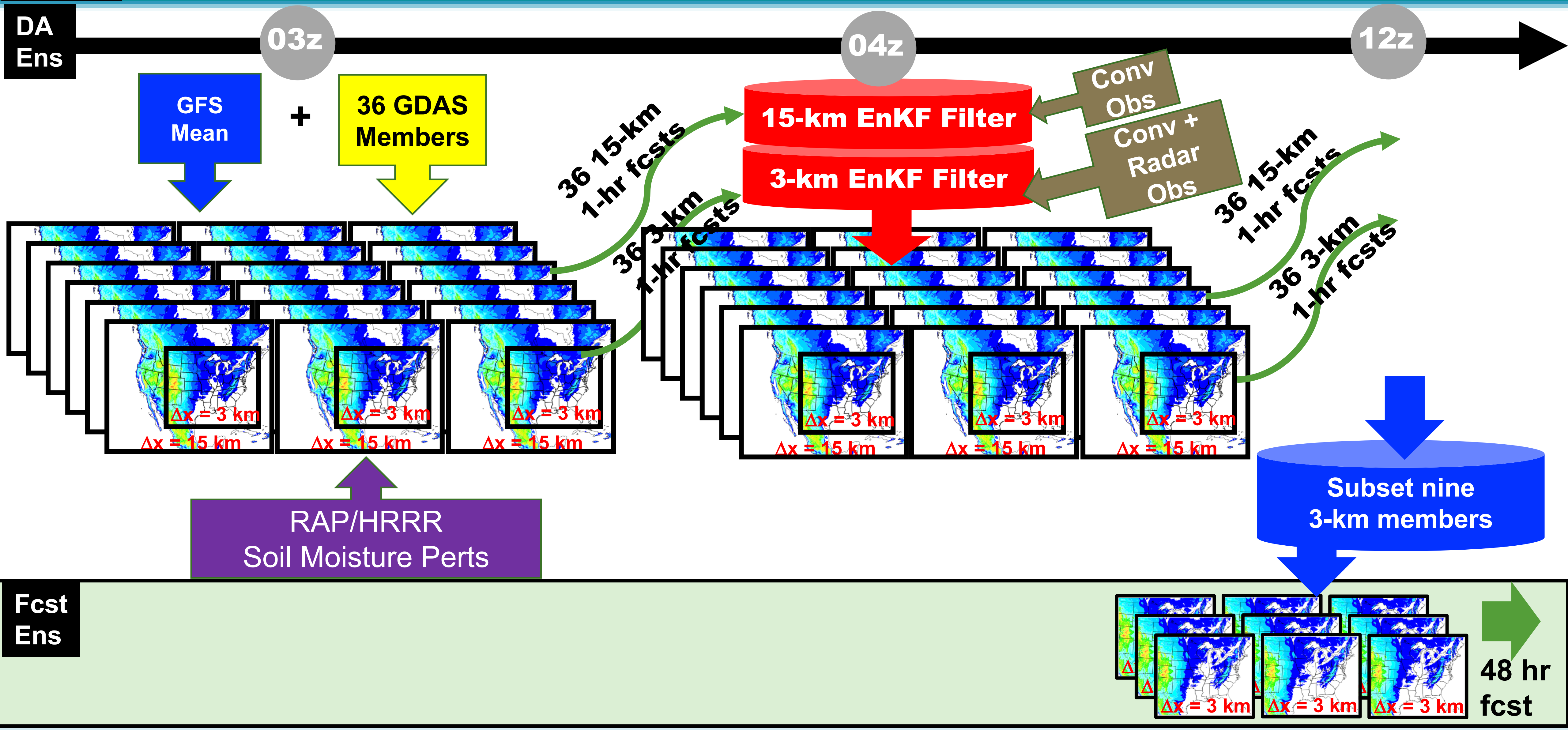
- Daily initialization of nested WRF-ARW system from GFS+GDAS, followed by hourly cycling
- GSI for ob preprocessing and ensemble priors
- EnKF data assimilation
  - conventional observations both domains
  - radar reflectivity 3-km domain
- Analysis variables: U, V, PH, T, MU, QVAPOR, QCLOUD, QICE, QRAIN, QSNOW
- Posterior inflation

Ensemble forecasts

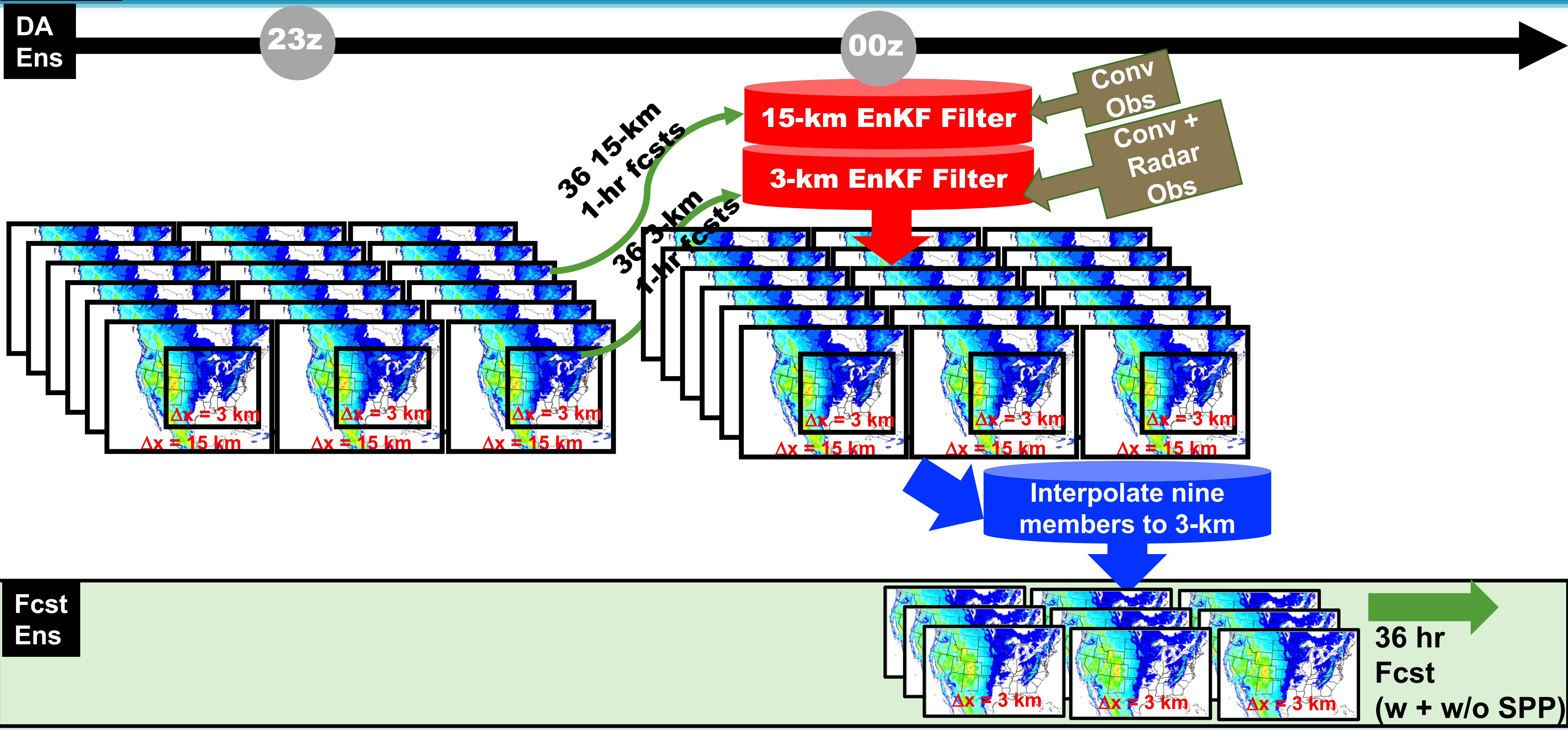
- 9 members out to ~36 hours
  - 0000 UTC, 1200 UTC, and other selected times
- Graphics for 3-km domain
  https://rapidrefresh.noaa.gov/hrrr/HRRRE/



03z-21z HRRRE 2018 Design



00z HRRRE 2018 Design



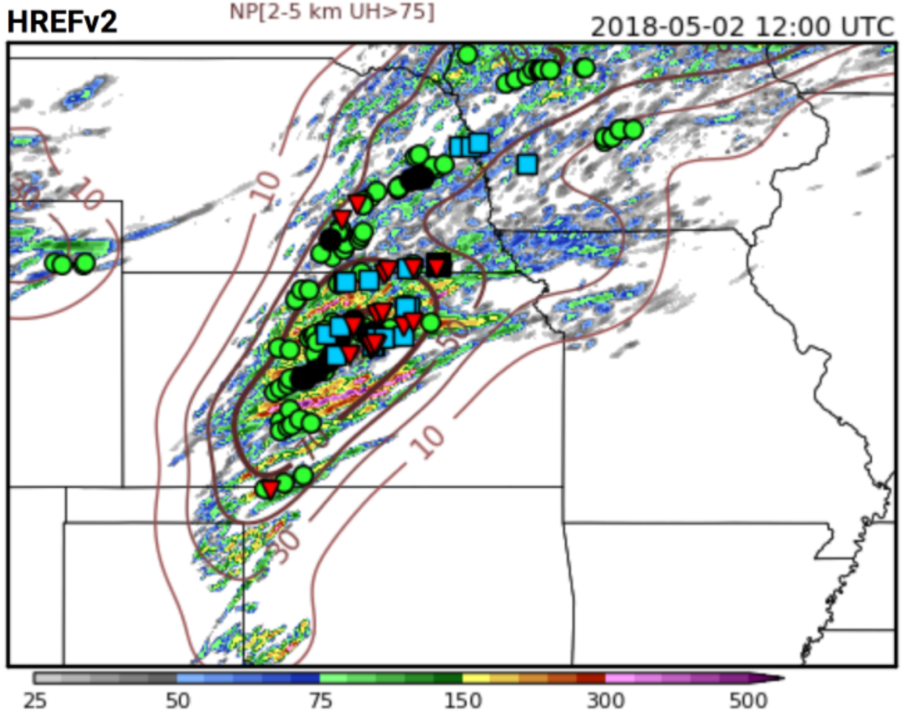
Convective-Allowing Ensemble Configurations

Attribute	HRRRE	NCAR Ensemble	HREF
Dynamic Core	ARW	ARW	ARW and NMMB
Physics	RAP/HRRR Suite	RAP/HRRR Suite	Mixed
Initial Condition Atmos	GFS + GDAS once-daily restart	Continuous cycle	RAP and NAM
Initial Condition Soil	RAP/HRRR soil + perturbations	Continuous cycle	RAP and NAM
Hourly DA Cycling	EnKF w/posterior inflation	EnKF w/posterior inflation	None (6 of 8 members)
Lateral Boundary	Perturbations	Perturbations	RAP and NAM
Stochastic Physics	None (or LSM, PBL, MP, Cu)	None	None
Number of DA Members	36	80	None
Number of Fcst Members	9	10	8 (4 time-lagged)

Real-time Demos Spring 2018 "May Day" Forecast

- Forecasts from HREF, HRRRE, NCAR Ensemble, CAPS EnKF, and OU (MAP) were evaluated recently during Hazardous Weather Testbed "Spring Experiment".

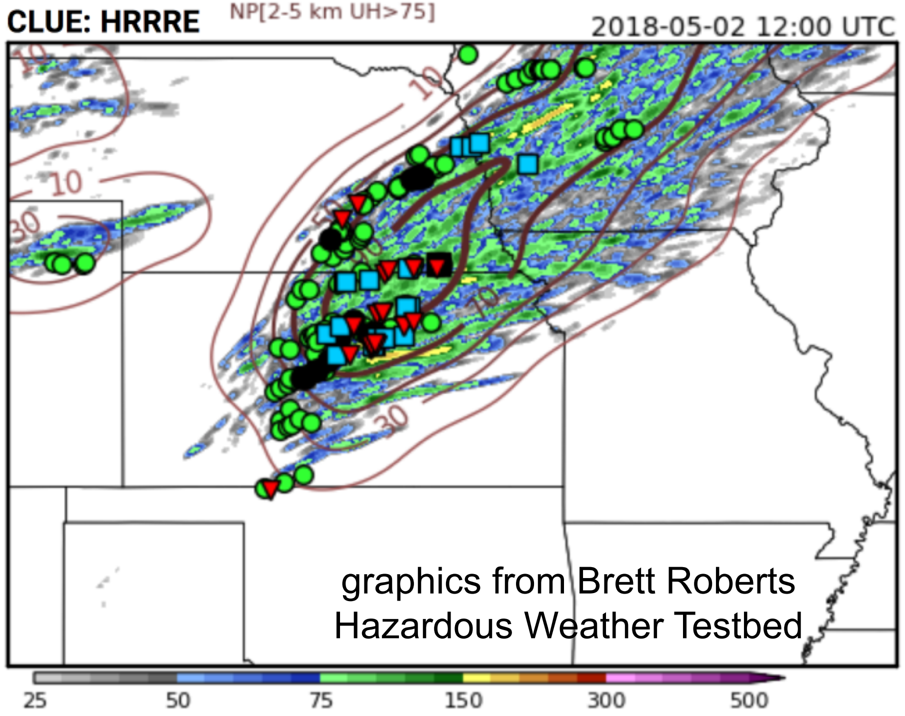
HREF: multi-model system



HREF (left)
HRRRE (right)
Updraft Helicity
0-24 h forecast
8 members

tornado, hail,
and wind reports

HRRRE: single-model system

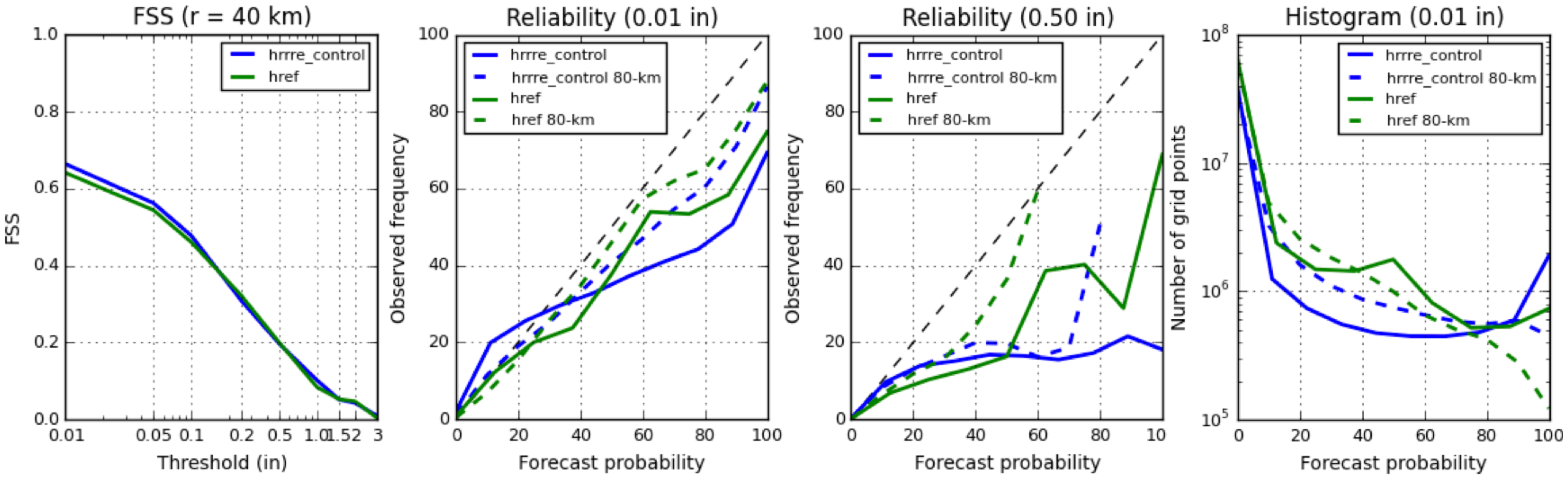


Probabilistic Verification: 12-18 h Precipitation

April 2018

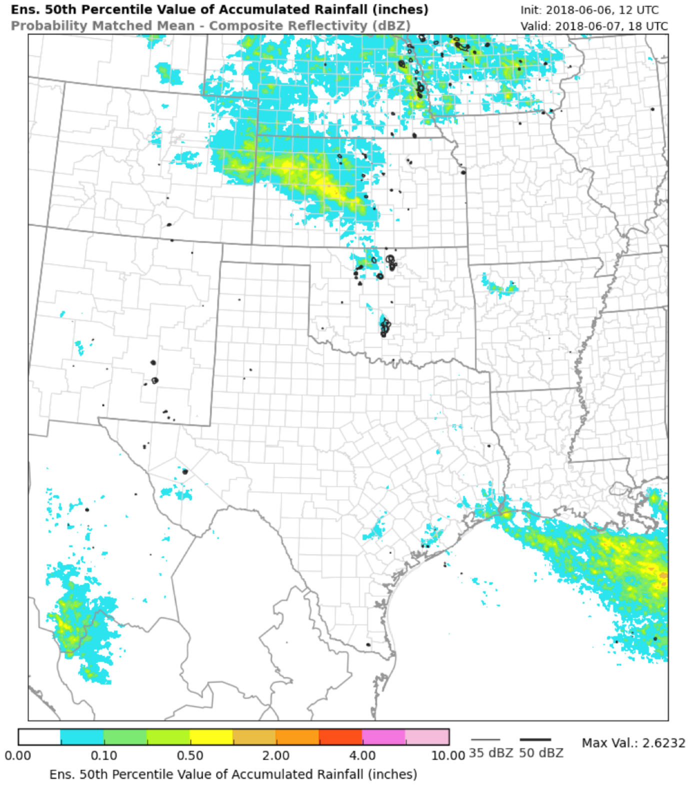
HRRRE: single-model system

HREF: multi-model system

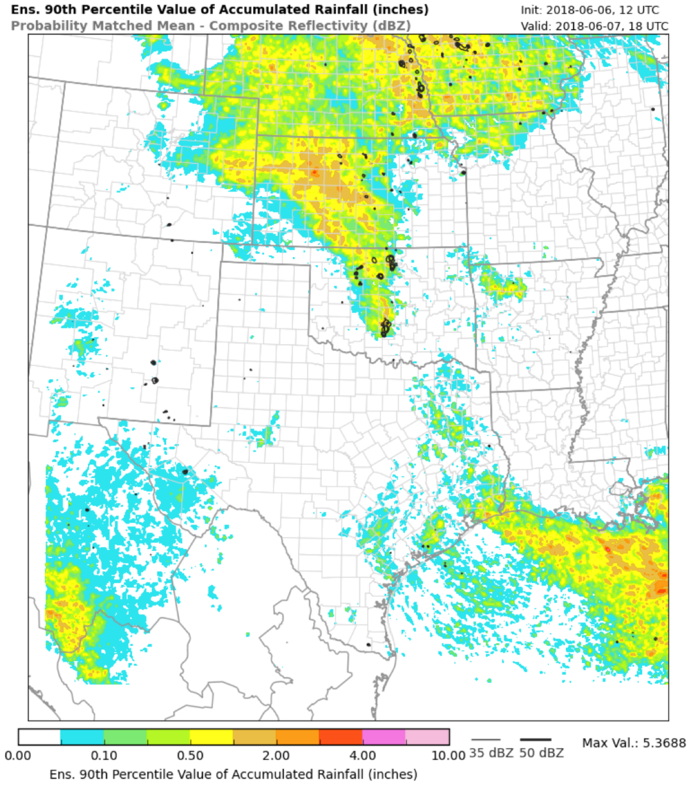


HRRRE Init 12 UTC 06 June 2018: 24-30 hr forecasts

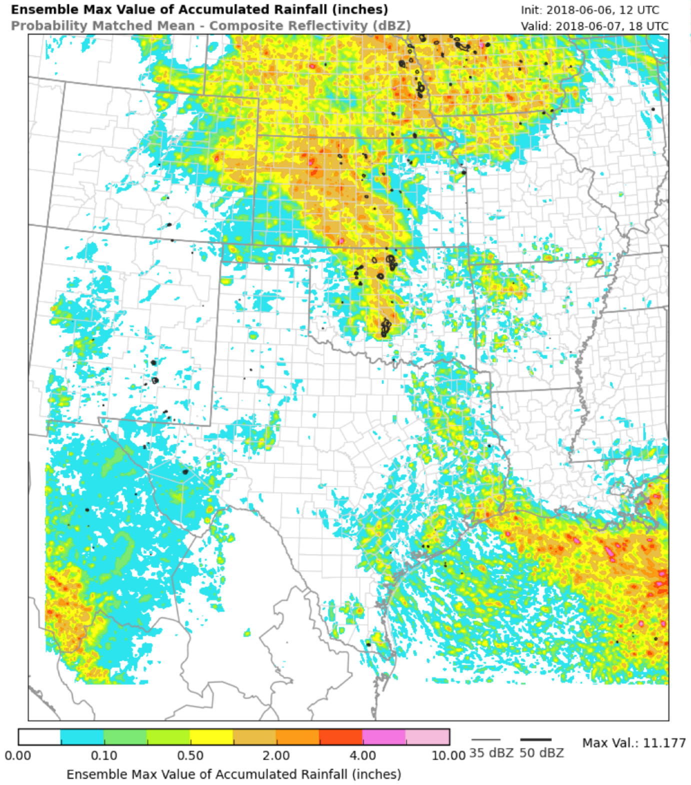
50th Percentile 6hr QPF

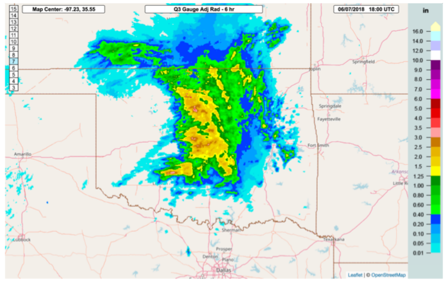


90th Percentile 6hr QPF

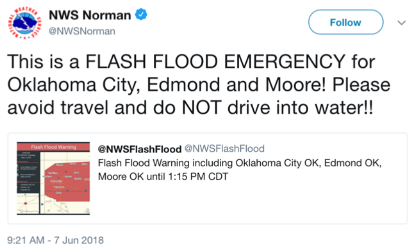


Ensemble Max 6hr QPF

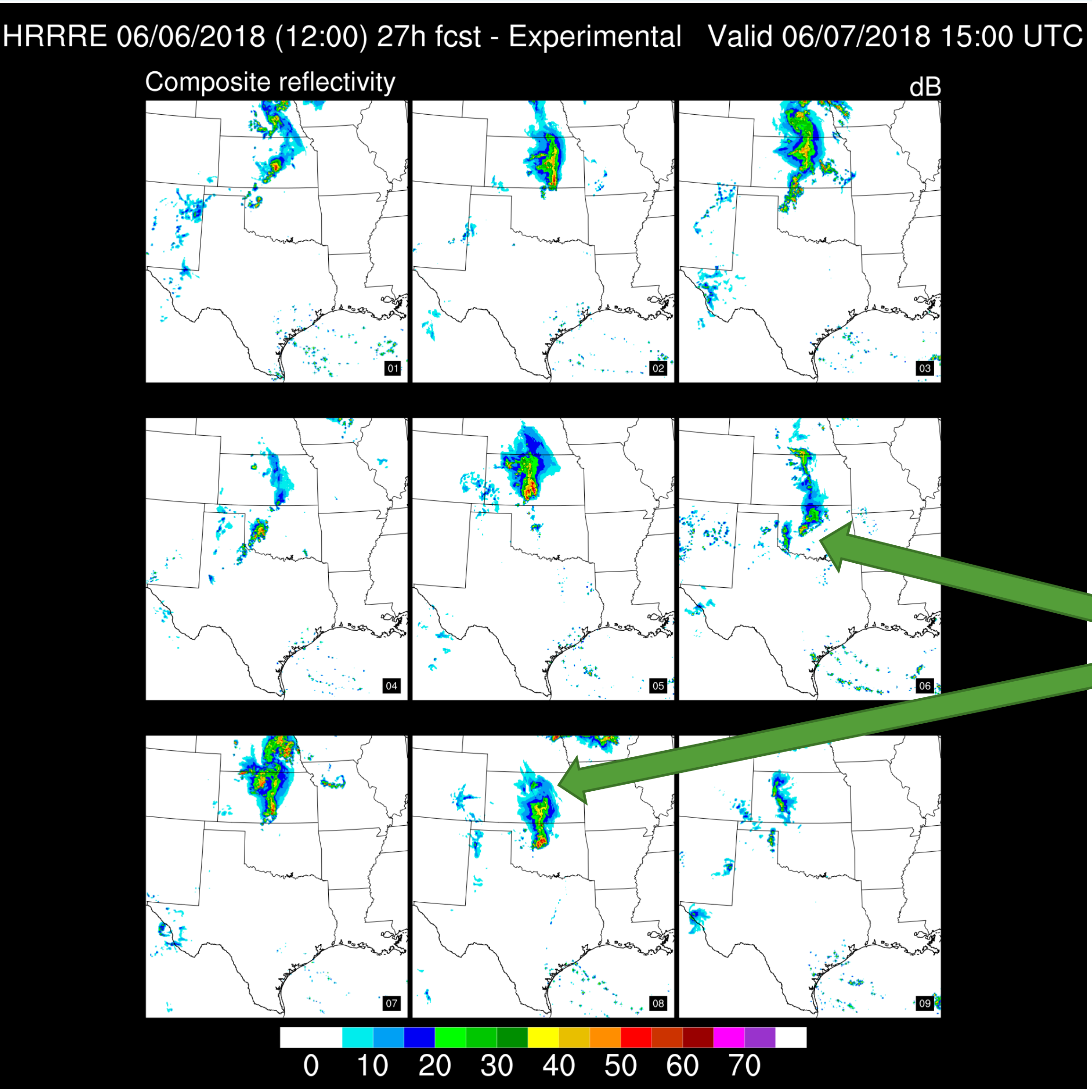




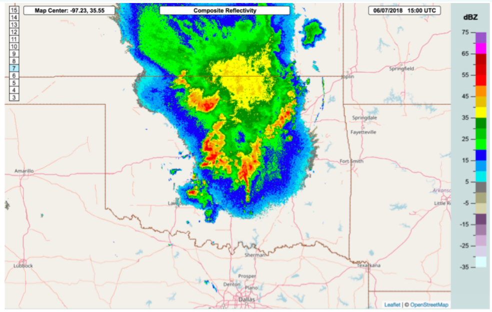
MRMS 6hr QPE
18 UTC 07 June



HRRRE Init 12 UTC 06 June 2018: 27 hr forecasts



HRRRE Nine Members
27 hr forecasts
Valid 15 UTC 07 June 2018

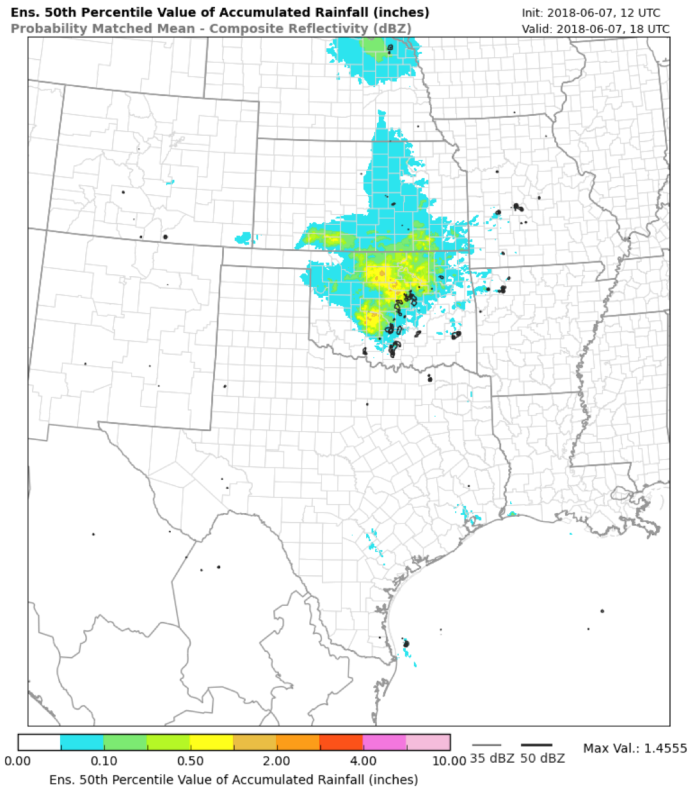


MRMS CREF
15 UTC 07 June

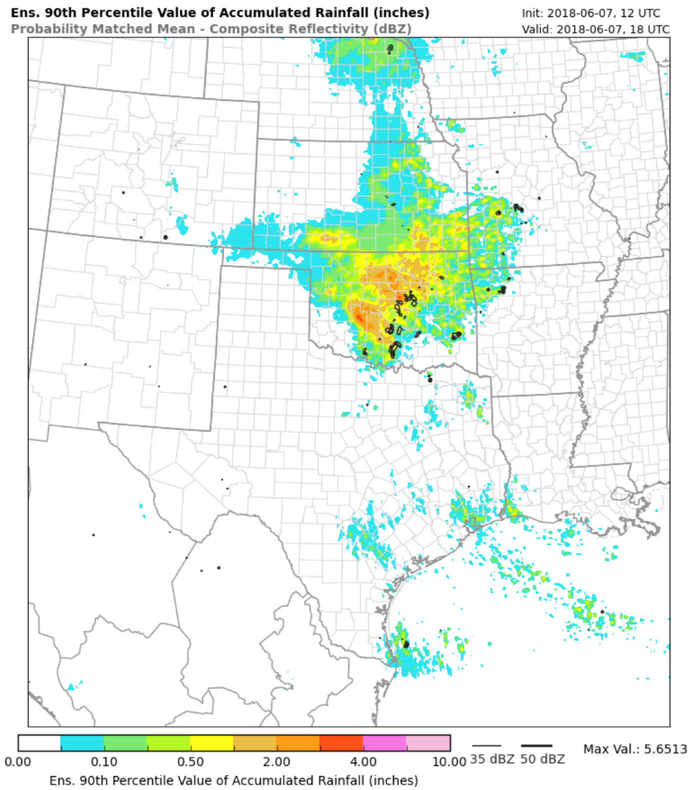
A few members depicted a scenario with sustained convection in OK

HRRRE Init 12 UTC 07 June 2018: 00-06 hr forecasts

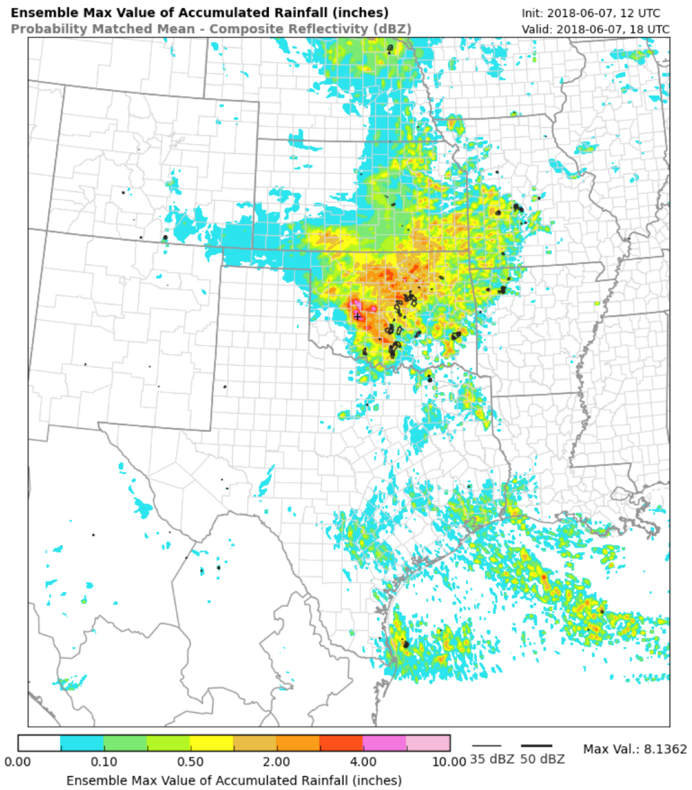
50th Percentile 6hr QPF

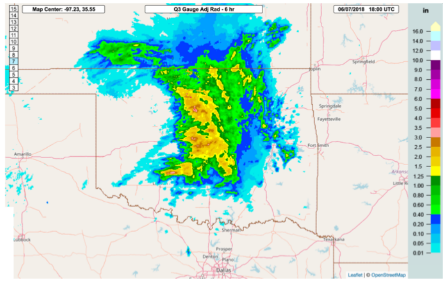


90th Percentile 6hr QPF



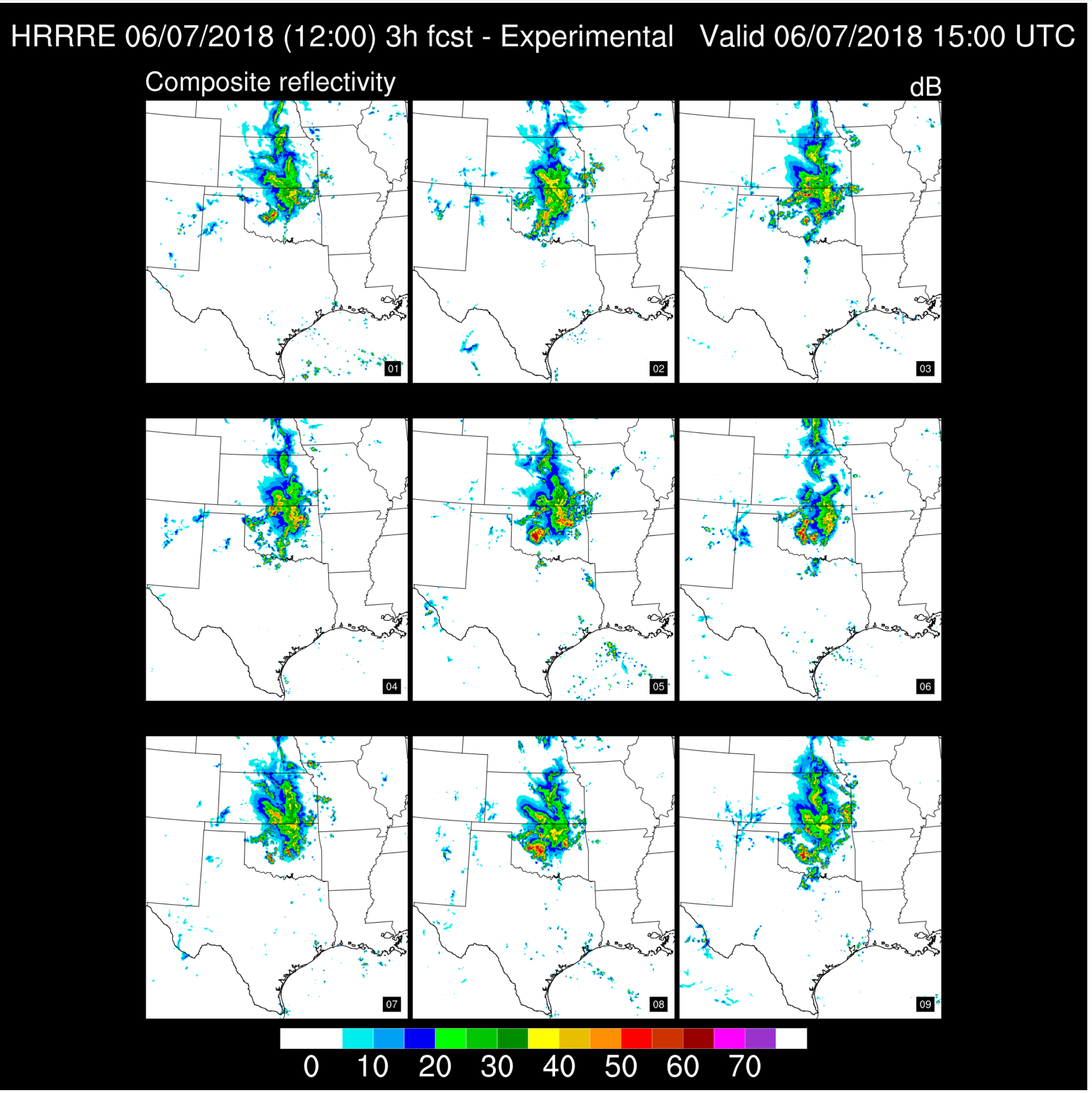
Ensemble Max 6hr QPF



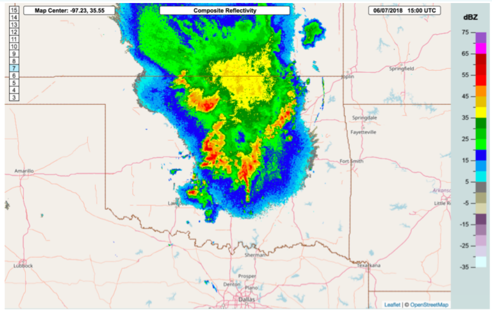


MRMS 6hr QPE
18 UTC 07 June

HRRRE Init 12 UTC 07 June 2018: 03 hr forecasts



HRRRE Nine Members
3 hr forecasts
Valid 15 UTC 07 June 2018



MRMS CREF
15 UTC 07 June

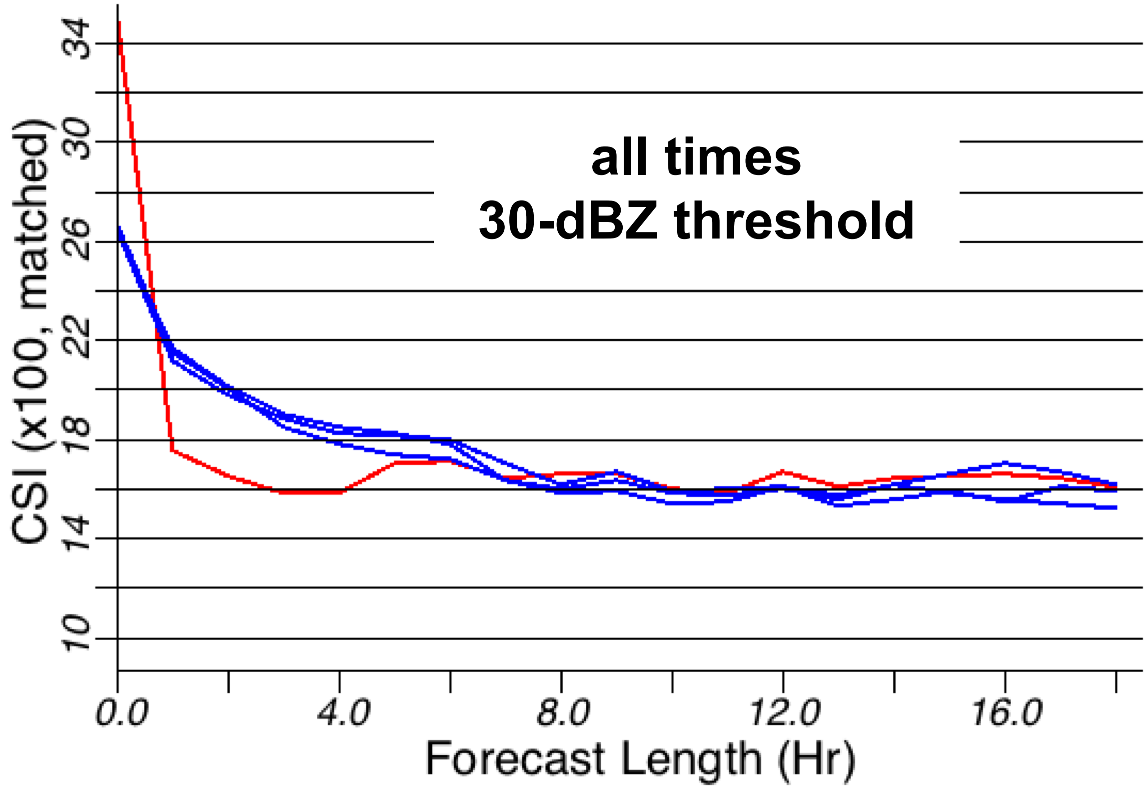
All members depicted a scenario with sustained convection in OK

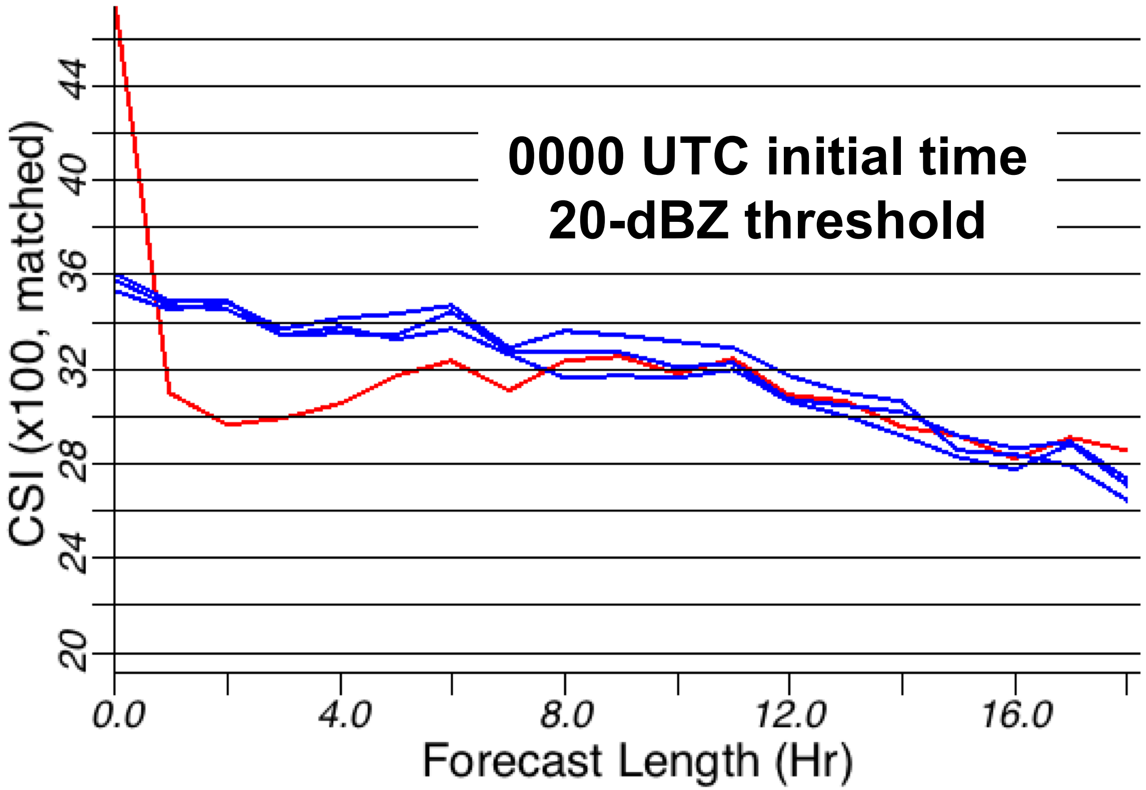
HRRR and HRRRE Reflectivity Forecast Skill

CSI (20 km)
Eastern US
15 Mar – 5 May 2018

HRRR
- **reflectivity-based T tend. during 1-h model spinup**
- **hydrometeor specification**

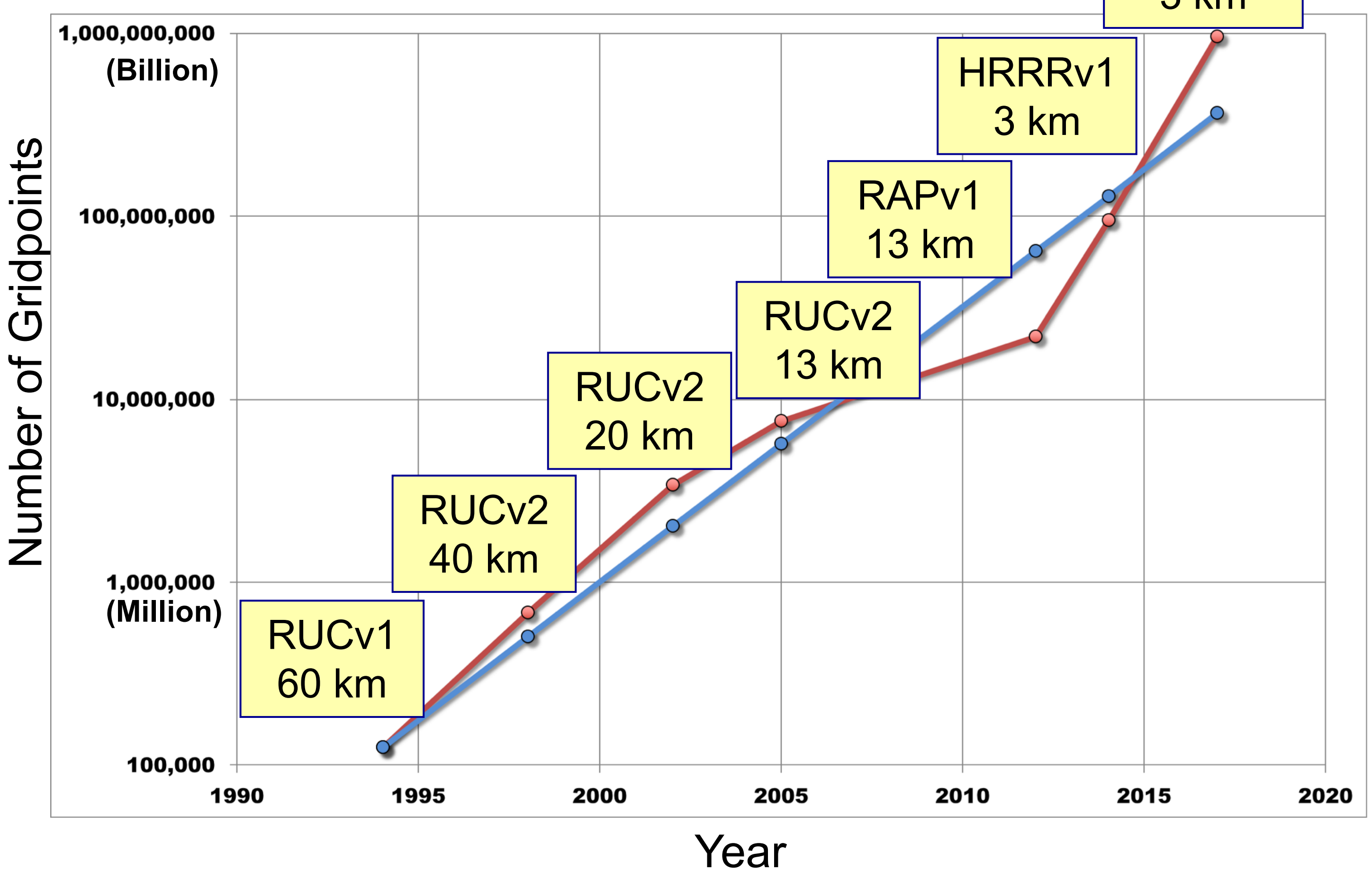
HRRRE members 1, 2, 3
- **EnKF reflectivity assimilation**

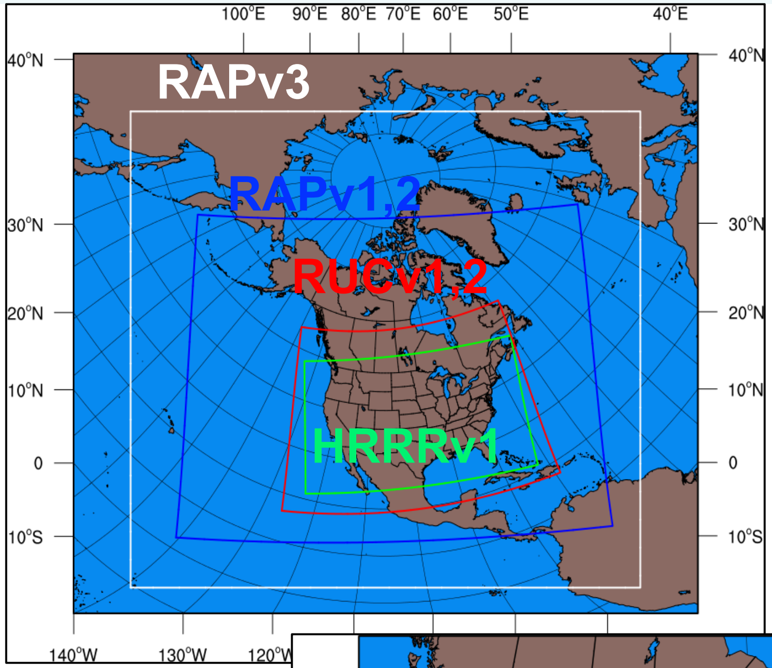




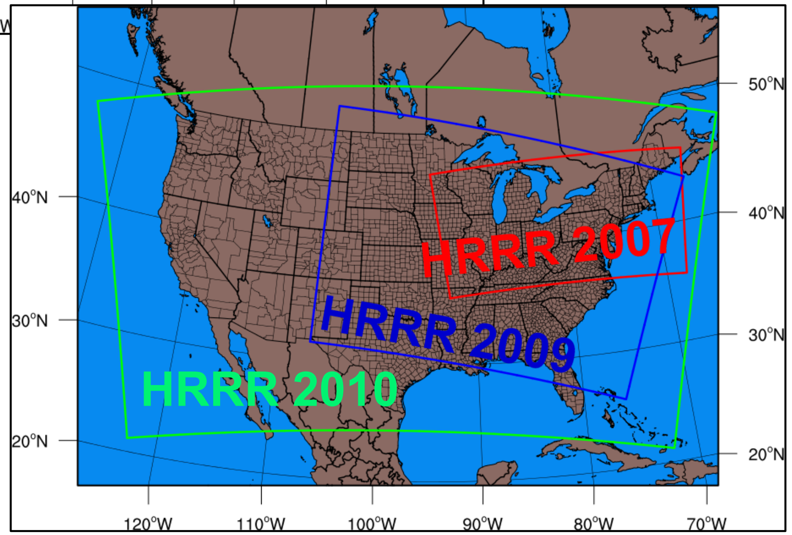
High Impact Weather Prediction Needs: HPC

Growth rate Similar To Moore's Law

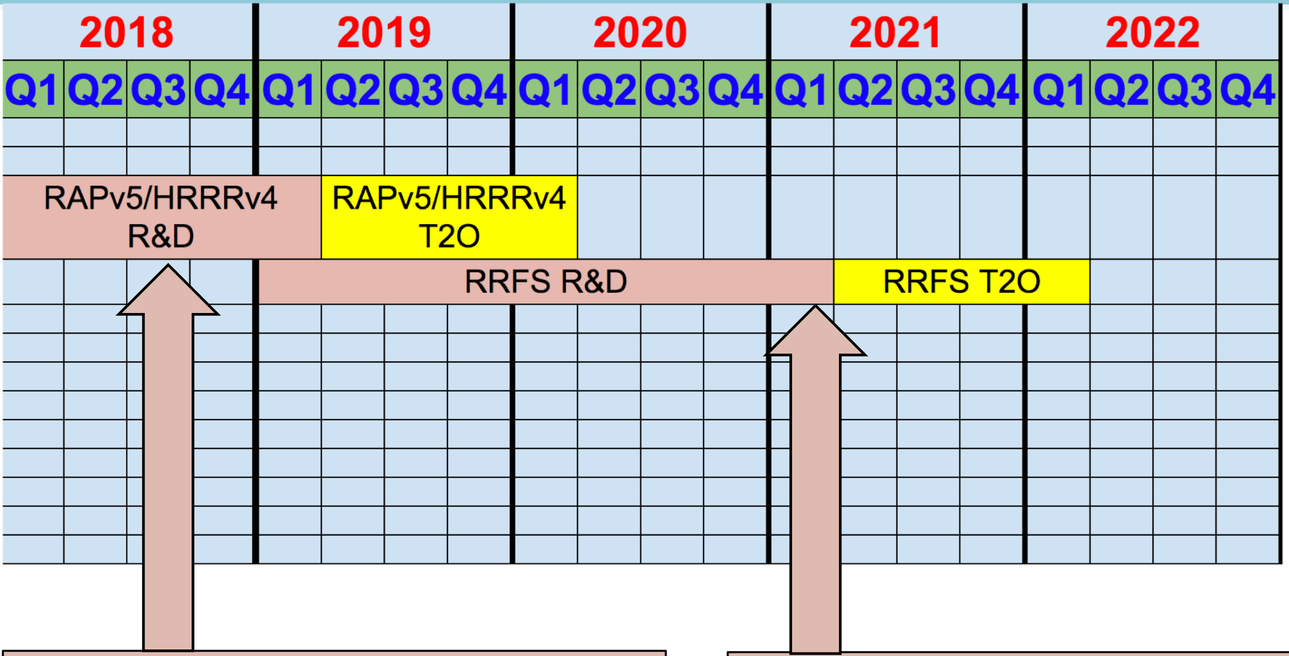




Larger Forecast Domains



ESRL/GSD Regional Model Projects



Final WRF-ARW (v4.0)
HRRRE analysis (DA)
RAP/HRRR-smoke
More vertical levels?

First Regional FV3
"Rapid Refresh Forecast System"
Transition all existing RAPv5/HRRRv4 design/capabilities to FV3 core
Single model storm-scale ensemble forecasts?

Path to FV3

2018
- HRRREv1 real-time evaluations
- More HRRREv1 retro testing and development

2019
- HRRREv1 configuration frozen
- Code delivery to EMC as part of HRRRv4

2020
- HRRRv4/HRRREv1 operational
- Switch to FV3 dycore

2021
- FV-HRRR development
- Merger of CAMs begins

2022
- FV-HRRR becomes RRFS in operations

GSD-EMC Plan for CAM Unification

FY	ARW-Framework	FV3-Framework
2018	- RAPv4/HRRRv3 Operational - RAPv5/HRRRv4 Experimental Dev: • Storm-Scale Ensemble DA • Larger CONUS Domain • Improved Physics • Testbed and objective verification	- Real-time 15-km Global + 3 km FV3 Nest - Regional Stand-Alone FV3 + DA developed, tested - Multiple physics options tested on CAM scales, including RAP/HRRR Physics Suite - Comparisons between global nests and stand-alone regional to ensure consistent behavior - Testbed and objective verification
2019	- RAPv5/HRRRv4 Experimental Testing • Storm-Scale Ensemble DA - JEDI Observation Operators - HRRRv3 included in HREFv3 - Testbed and objective verification	- Optimization of CAM-scale DA and physics - Hourly-Updating CAM Ensemble DA - JEDI Observation Operators - FV3 CAM included in HREFv3 - Testbed and objective verification
2020	- RAPv5/HRRRv4 Implementation - ARW Development Frozen	- FV3-Rapid-Refresh Optimization • Complete JEDI Integration • In-Core DA
2021		Real-Time Experimental Rapid Refresh Forecast System (RRFS) • FV3-HRRR Ready • Merge NPS CAM Products
2022		RRFS Operational • Unified 3-km CAM Ensemble Physics/DA for Days 1-3