Cloud Assimilation & Representation in RRFS & 3DRTMA

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GSL Development Team

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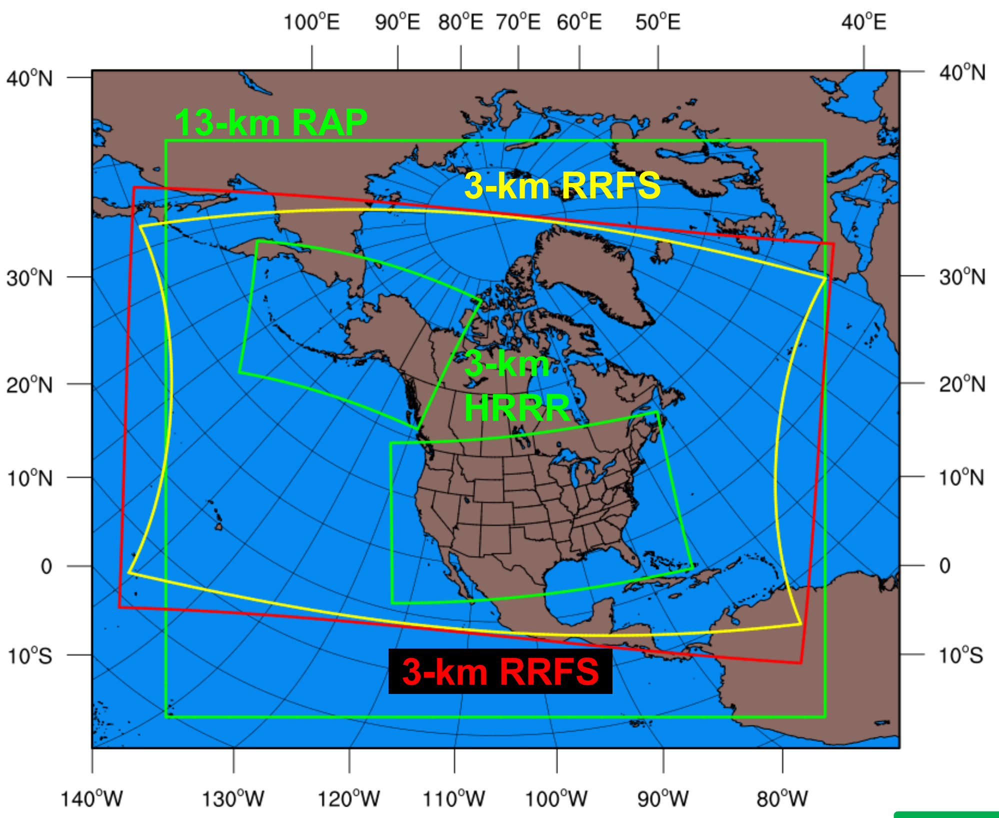
NOAA Model Operational Implementation Timeline

UFS-R2O Approved Implementation Schedule FY23-26

NPS Modeling System	Current Version	Q4 FY 21	Q4FY21-Q3FY22 Moratorium	Q4 FY 22	Q1 FY 23	Q2 FY 23	Q3 FY 23	Q4 FY 23	Q1 FY 24	Q2 FY 24	Q3 FY 24	Q4 FY 24	Q1 FY 25	Q2 FY25	Q3 FY25	Q4 FY 25	Q1 FY 26	Q2 FY26	Q3 FY26	UFS Application
Global Weather, Waves & Global Analysis	GFS/ GDASv16.2																			UFS Medium Range & Sub-Seasonal
Global Weather and Wave Ensembles, Aerosols	GEFSv12			Coupled Reanalysis and SubX Reforecast Production							GFSv17/ GEFSv13	Seasonal Reforecast Production							GFSv18/ GEFSv14/ SFSv1	
Short-Range Regional Ensembles	SREFv7																			
Global Ocean & Sea-Ice	RTOFSv2						RTOFSv3													UFS Marine & Cryosphere
Global Ocean Analysis	GODASv2						GODASv3													
Seasonal Climate	CDAS/ CFSv2																			UFS Seasonal
Regional Hurricane 1	HWRFv13						HAFSv1				HAFSv2				HAFSv3				HAFSv4	UFS Hurricane
Regional Hurricane 2	HMONv3																			
Regional High Resolution CAM 1	HiRes Window v8									RRFSv1										UFS Short-Range Regional HiRes CAM & Regional Air Quality
Regional High Resolution CAM 2	NAM nests/ Fire Wxv4																			
Regional High Resolution CAM 3	RAPv5/ HRRRv4														RRFSv2				RRFSv3/ WoFSv1	
Regional HiRes CAM Ensemble	HREFv3																			
Regional Mesoscale Weather	NAMv4																			
Regional Air Quality	AQMV6	AQMv6																		
Regional Surface Weather Analysis	RTMA/ URMA v2.8									3DRTMA/ URMAv3					3DRTMA/ URMA v4				3DRTMA/ URMA v5	

RRFSv1 Grids



RRFS 3-km
7912x5412x65
(42,819,744)x65
Extended Schmitt Gnomonic (ESG)

→ Model Interp →

RRFS 3-km Output
4881x2961x65
(14,452,641)x65
Rotated Lat-Lon

→ UPP Diagnostics Algorithms →

GRIB2 3-km
4881x2961x65
Nat, Prs, Sfc
10GB/ 3Dnative file

→ wgrib2 Interp →

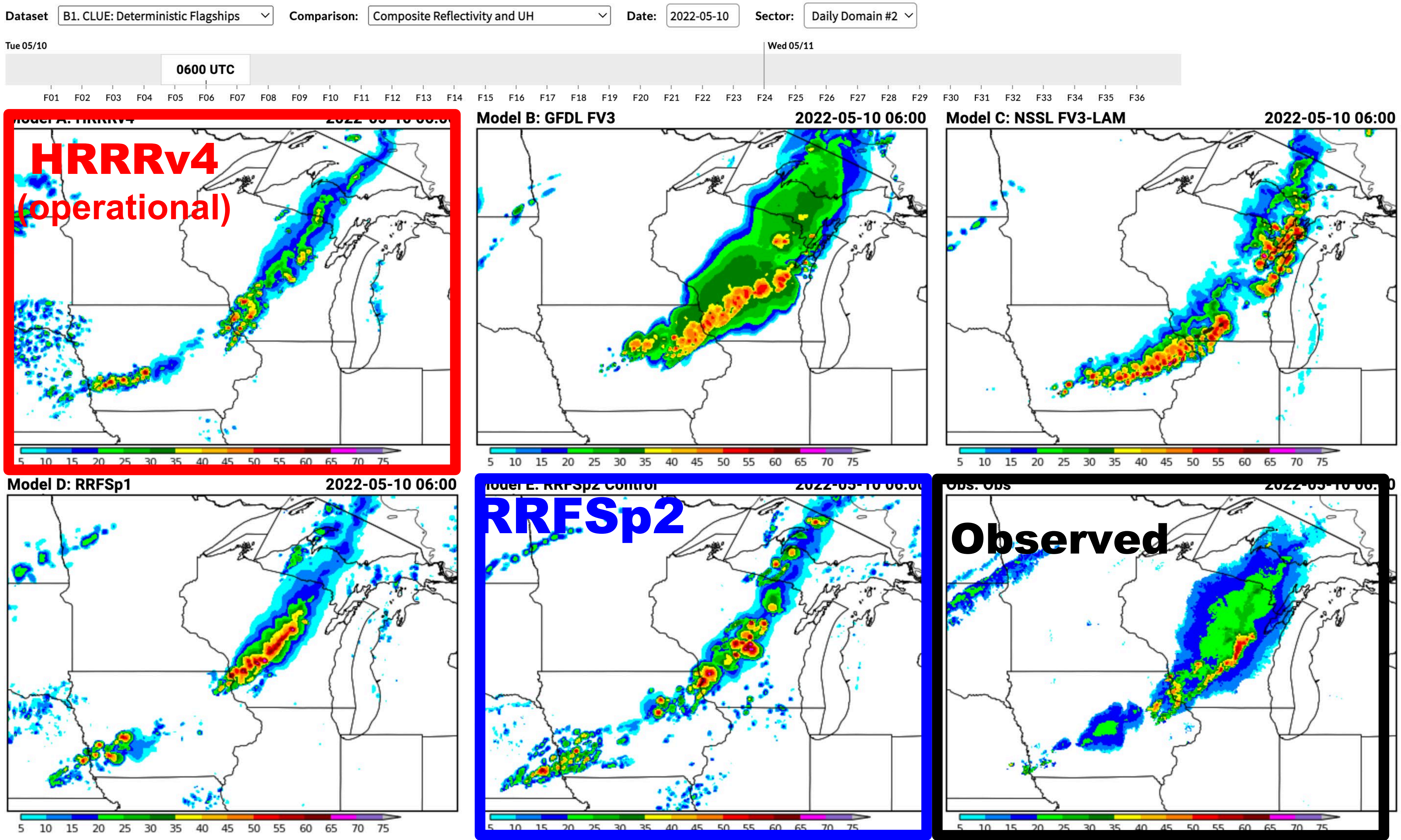
GRIB2 Cutouts:
HRRR-CONUS (3 km)
NAM-AK (3 km)
NAM-HI (2.5 km)
NAM-PR (2.5 km)
RAP-like (13 km)
130-like (13 km)

HRRR-CONUS 3-km
1799x1059x50
(1,905,141)x50
800MB/3Dnative file
Lambert Conformal

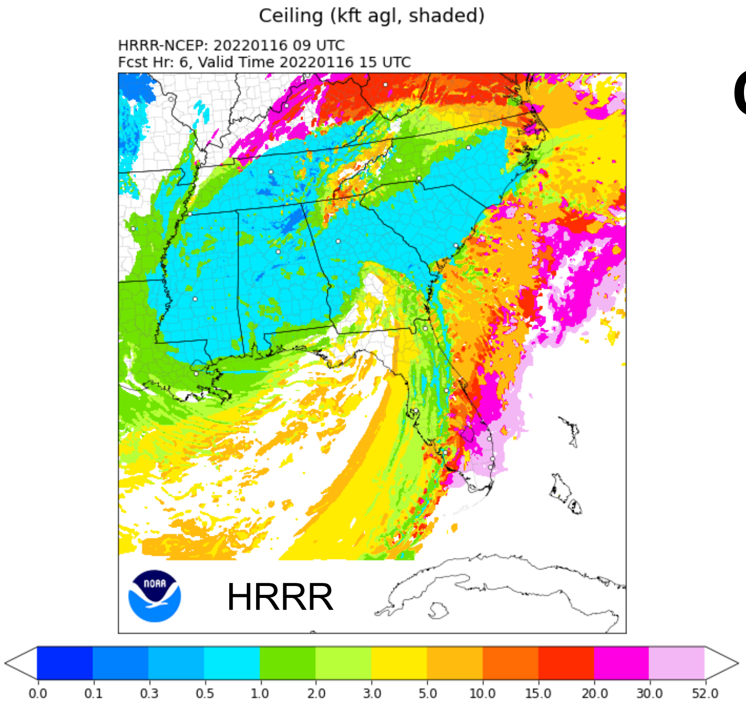
HRRR-AK 3-km
1299x919x50
(1,193,781)x50
500MB/3Dnative file
Polar Stereographic

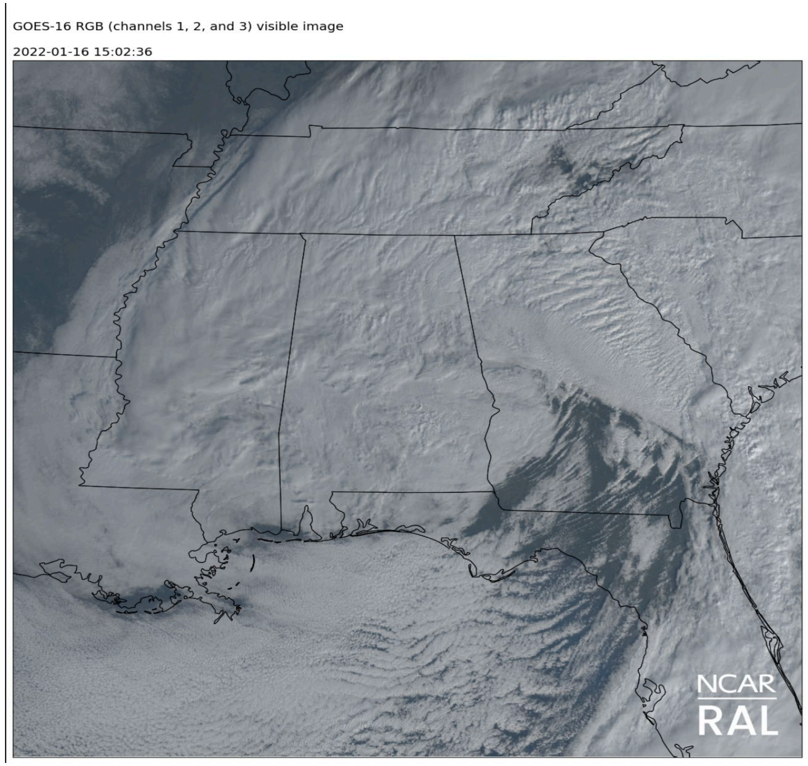
RAP 13-km
953x834x50
(794,802)x50
300MB/3Dnative file
Rotated Lat-Lon

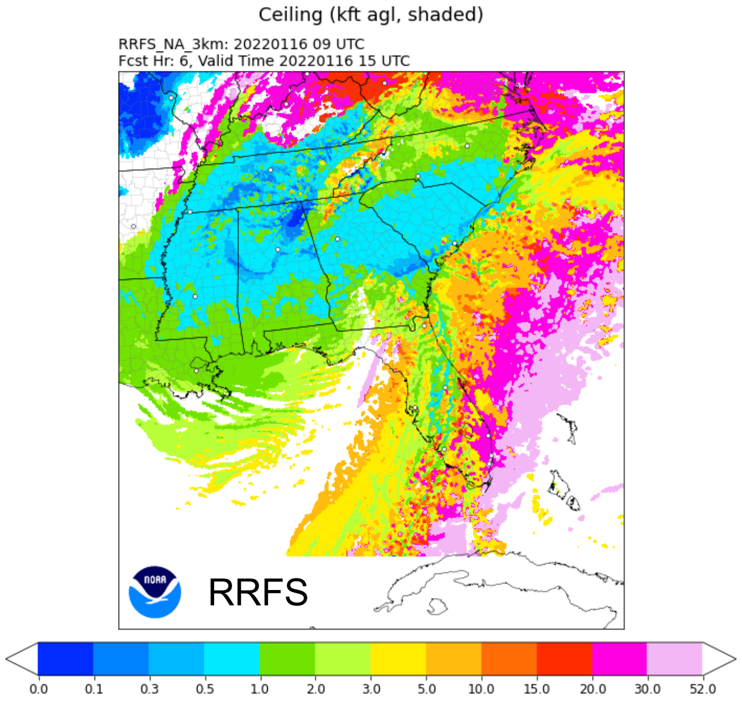
Sample RRFS forecast from HWT

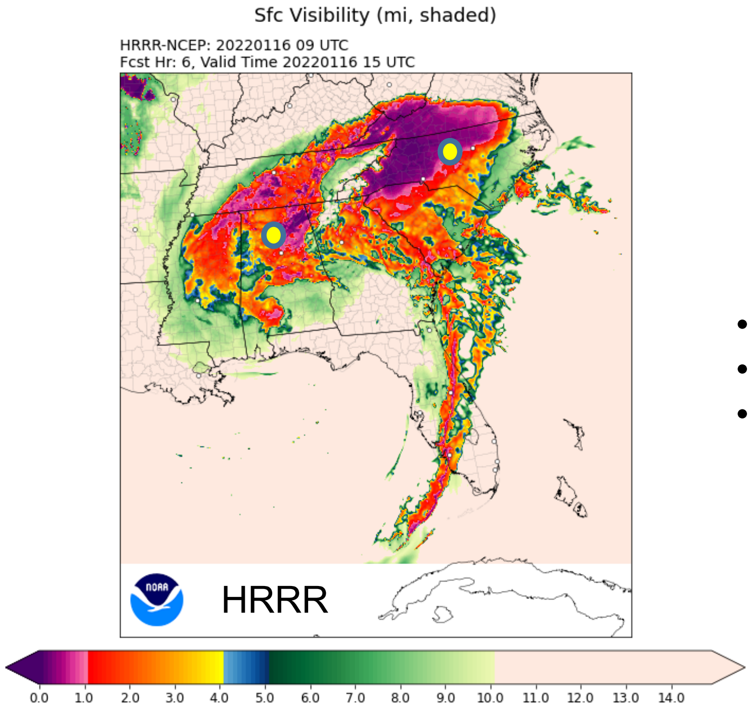


Ceiling/vis - valid 16 Jan 2022 15Z (6-hr forecast)



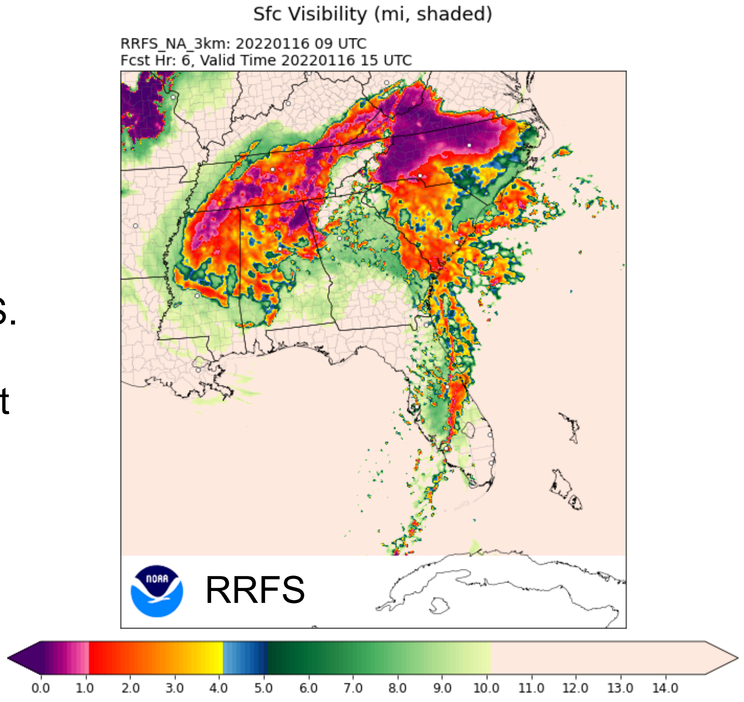




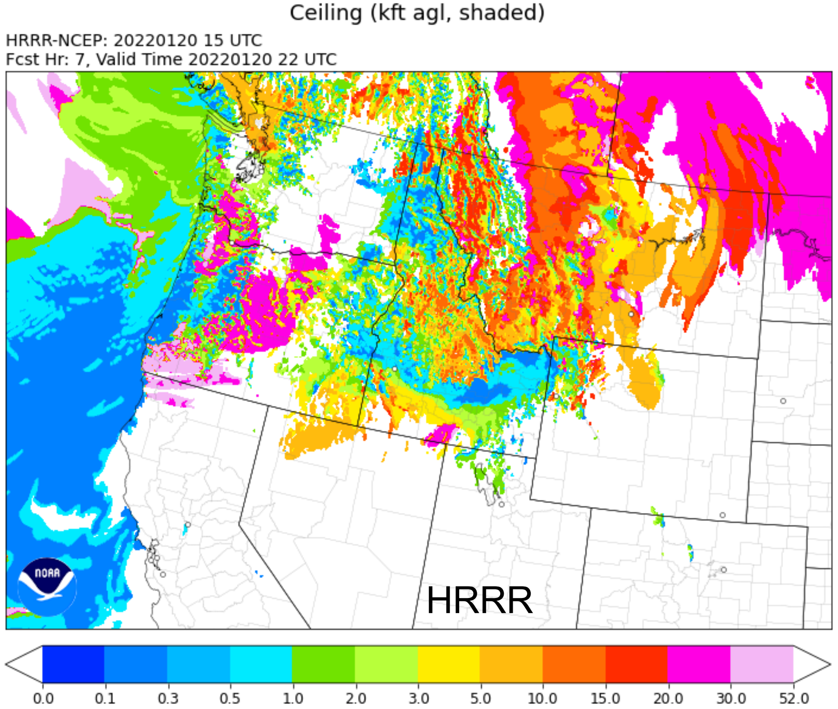


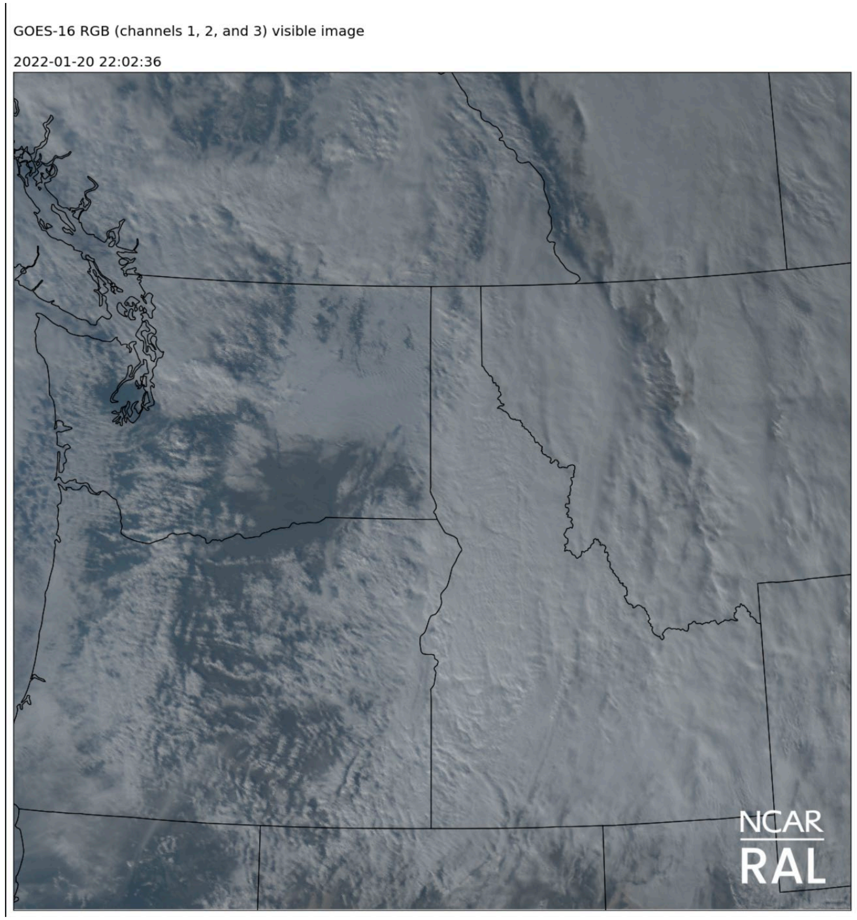
- HRRR captures the clearing in southern GA better than RRFS.
- RRFS shows lower ceilings in core of storm over TN Valley.
- RRFS ceiling has “speckled” features similar to reflectivity, but captures cloud waves in Gulf.

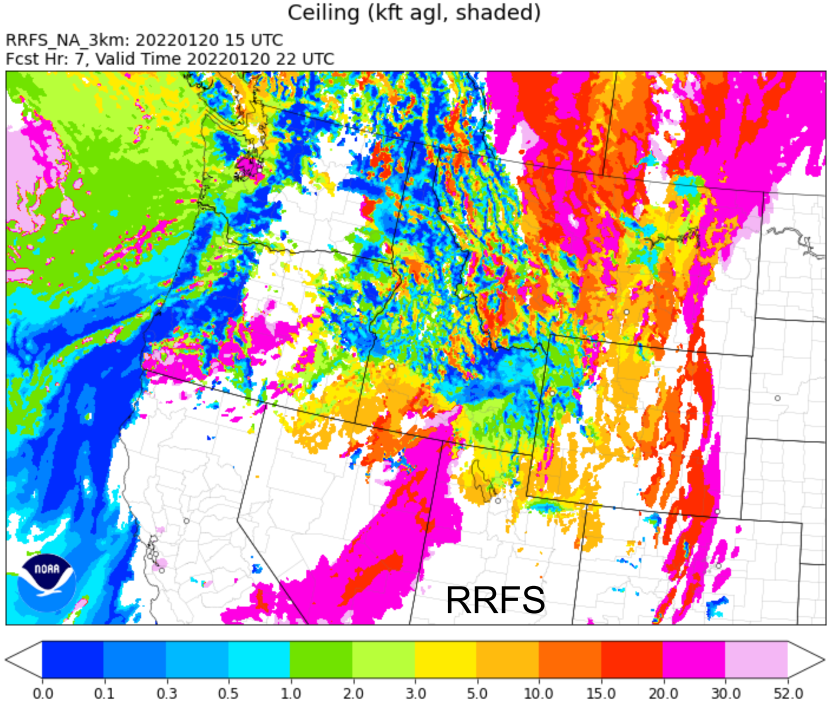
- HRRR and RRFS visibility are very similar, less influenced by moisture bias.
- RRFS visibility is lower than HRRR in the NW quadrant but higher in the northern GA sector.

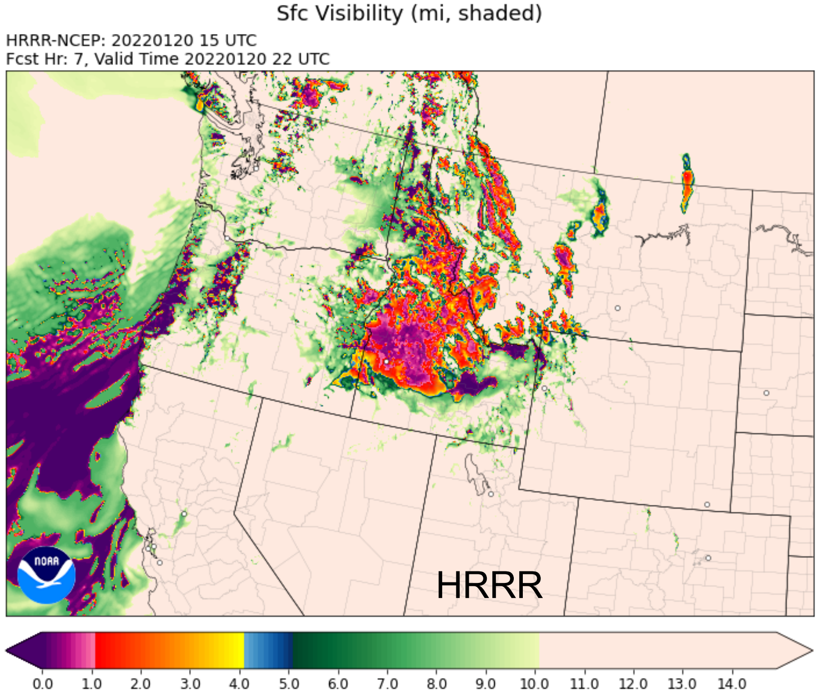


Ceiling/Vis - valid 20 Jan 2022 15Z (7-hr forecast)

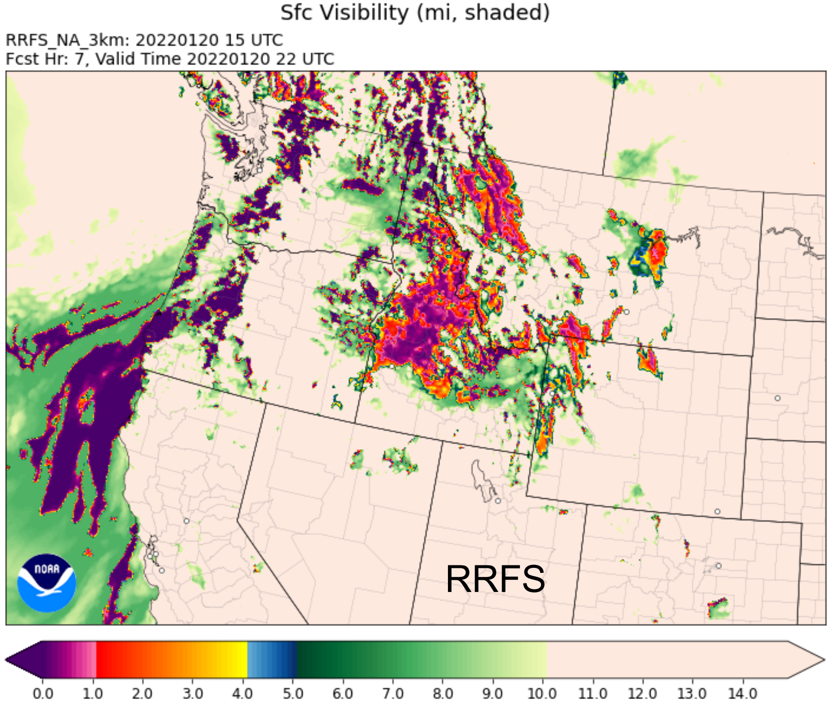








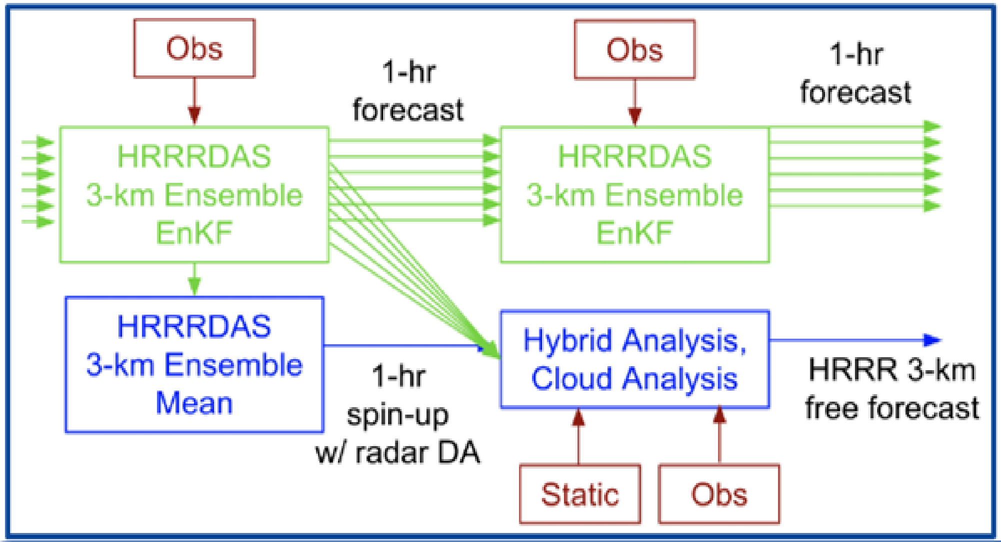
- RRFS ceilings and visibilities are both lower than HRRR along coast.



Research and Development Areas

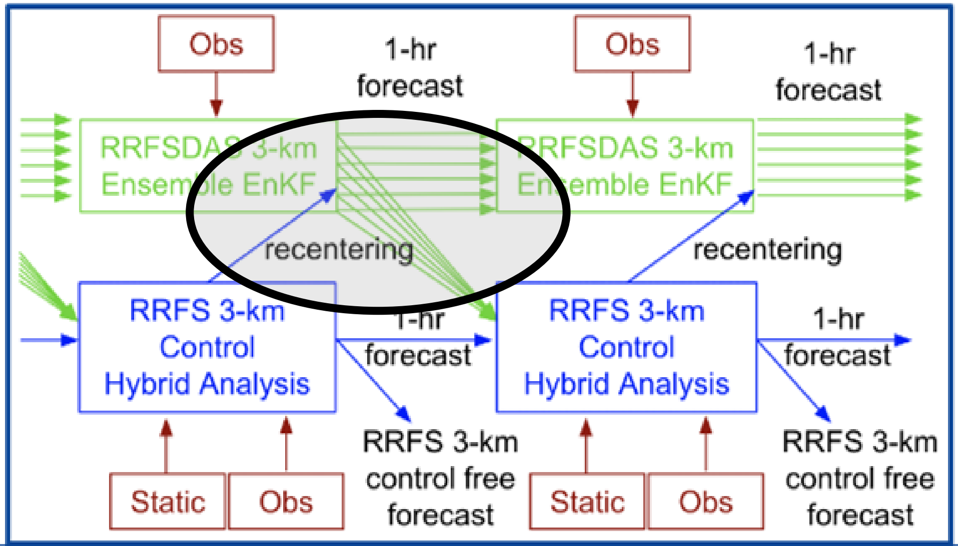
1. Data Assimilation
   - Observations type and use — Use cloud base & cloud top data; partial cloud obs
   - Algorithm/process for minimization — Cloud Analysis and/or variational, ensemble, hybrid
   - Background error covariance — How to relate observed cloud base to model state
2. Diagnostics
3. Model Representation
   - Physics
   - Dynamics
4. Verification

RRFSv1 Data Assimilation System



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

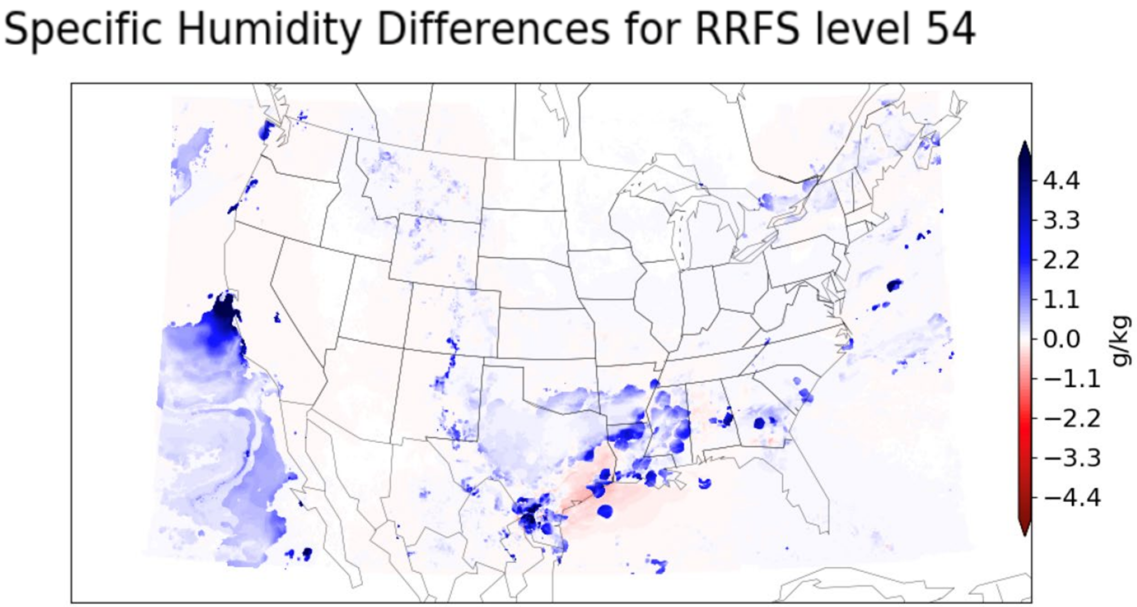


RRFSv1 HiRes Ensemble DA

- 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

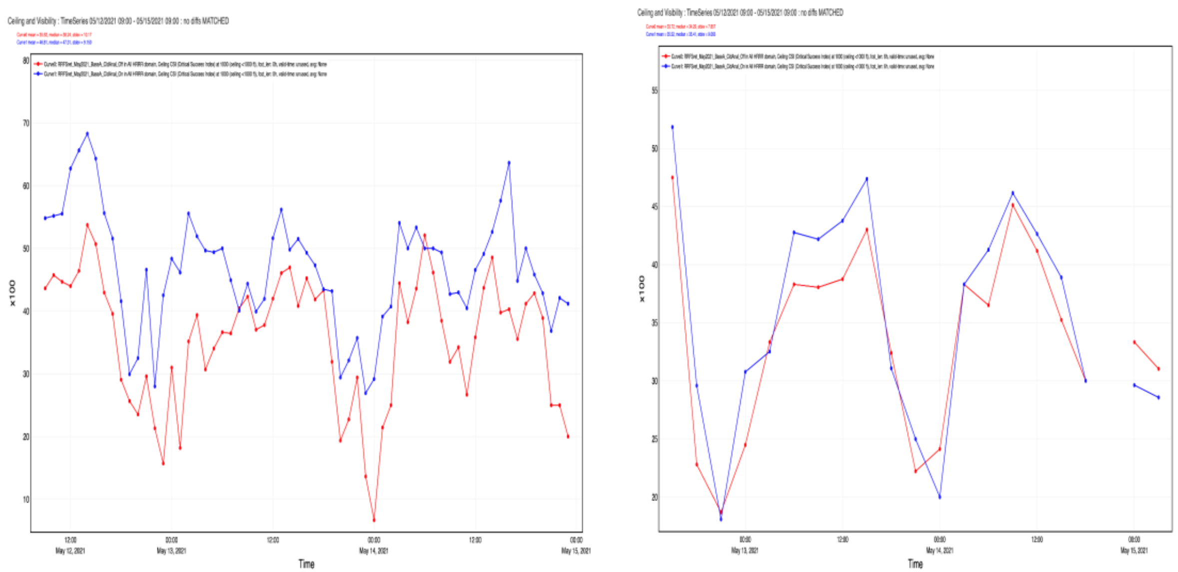
Real-time RRFS Cloud Assimilation

- Case study and retrospective experiments completed to test the non-variational hydrometeor analysis for RRFS.
- It is now in the real-time CONUS RRFS runs.
- Still a few technical issues for the large North American domain.



Difference field for specific humidity showing change that occurs to the analysis when the hydrometeor analysis is turned on relative to being turned off.

Cloud analysis adds and removes moisture, achieves a more skillful & realistic representation of ceilings; impact on thermodynamic environment is positive or neutral.



Critical Success Index (CSI) scores for RRFS forecasts of ceiling below 1000 feet AGL. Left: 00h analysis. Right: 06h forecasts. Blue: hydrometeor analysis on. Red: hydrometeor analysis off.

Cloud Analysis Publication

Stratiform Cloud-Hydrometeor Assimilation for HRRR and RAP Model Short-Range Weather Prediction

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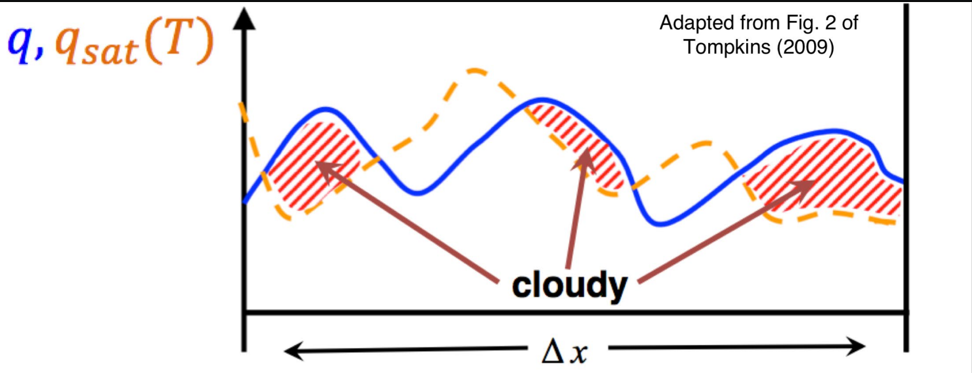
MWR-D-20-0319.1

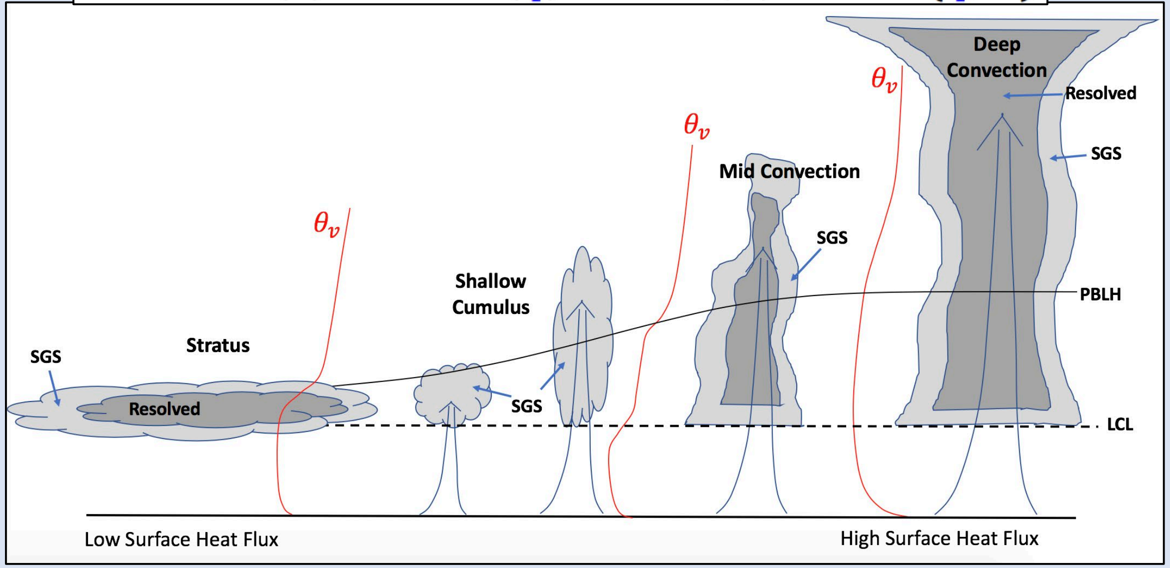
Improved Subgrid-Scale Cloud Representation

Subgrid-Scale (SGS) Clouds

- **Key Idea**: thermodynamic variability within a grid volume may produce small areas of saturation (*clouds*)
- Variability is subgrid (unresolved): *must be parameterized*



$$Var(s) \propto Var(q) + Var(T) - Cov(q, T)$$



Key Changes for RAPv5 / HRRRv4:

- Mixing ratio (q_{cldwat} and q_{cldice}) of SGS clouds:
  - Removed constraints on q_x for stratiform SGS
  - Increased coverage of convective SGS via MYNN mass-flux approach
- Cloud fraction:
  - Stratiform: slightly reduced, except in high grid-scale RH
  - Use a modified Chaboreau and Bechtold (2002, 2005) scheme exclusively; discontinue use of Xu and Randall (1996)
- Effective radii (r_e) of SGS clouds:
  - Water: use Turner et al. (2007)
  - Ice: use Mishra et al. (2014)

Olson et. al 2019 technical memorandum on the MYNN-EDMF scheme for more info (https://repository.library.noaa.gov/view/noaa/19837)

Use of Model Subgrid Cloud Fraction for DA

- Subgrid cloud fraction background is used to determine if the hydrometeor analysis should modify the model state to build clouds.

- Specifically, if there is a broken or overcast cloud observation, **and** the subgrid cloud fraction is greater than 0.45, then the model state is not modified to build clouds.

- The rationale for this limitation is that the model already has some cloud representation via the cloud fraction, so the explicit cloud specification is not needed.

- If the model background cloud fraction is below 0.45, then the cloud building specification does occur.

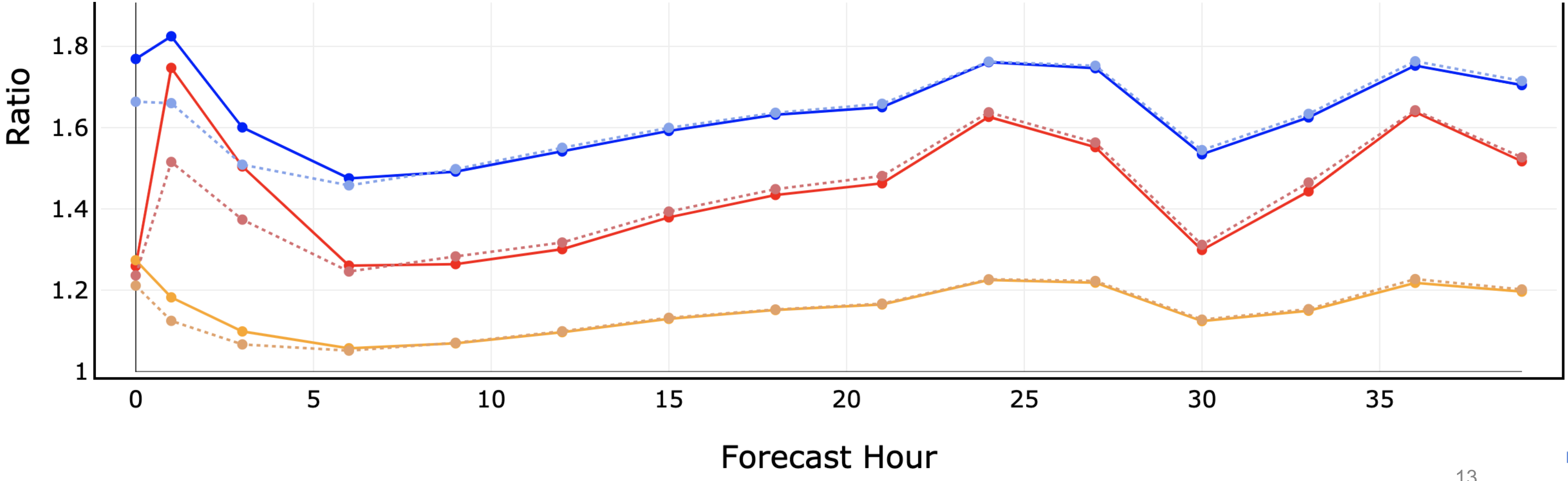
- The 0.45 cloud fraction threshold was selected to be slightly bigger than the experimental ceiling diagnostic threshold of 0.4.

Cloud Fraction Limited Building Ceiling Bias

Winter RAP Retro
~15 days of data (2/1/2019 to 2/15/2019)

- Reduction in high bias for all ceiling thresholds when cloud fraction is used to limit cloud building

RAP < 500ft — Cloud Fraction Limited Building < 500ft
RAP < 1,000ft — Cloud Fraction Limited Building < 1,000ft
RAP < 3,000ft — Cloud Fraction Limited Building < 3,000ft
(dashed)



Background Error Covariance (BEC) for Clouds

- The use of observational data in challenging geographic situations (e.g. narrow valleys, coastlines) may benefit from advanced background error covariance modeling that accounts for standing features.
- Long time series that represent climatological features can be used to augment daily ensemble data.

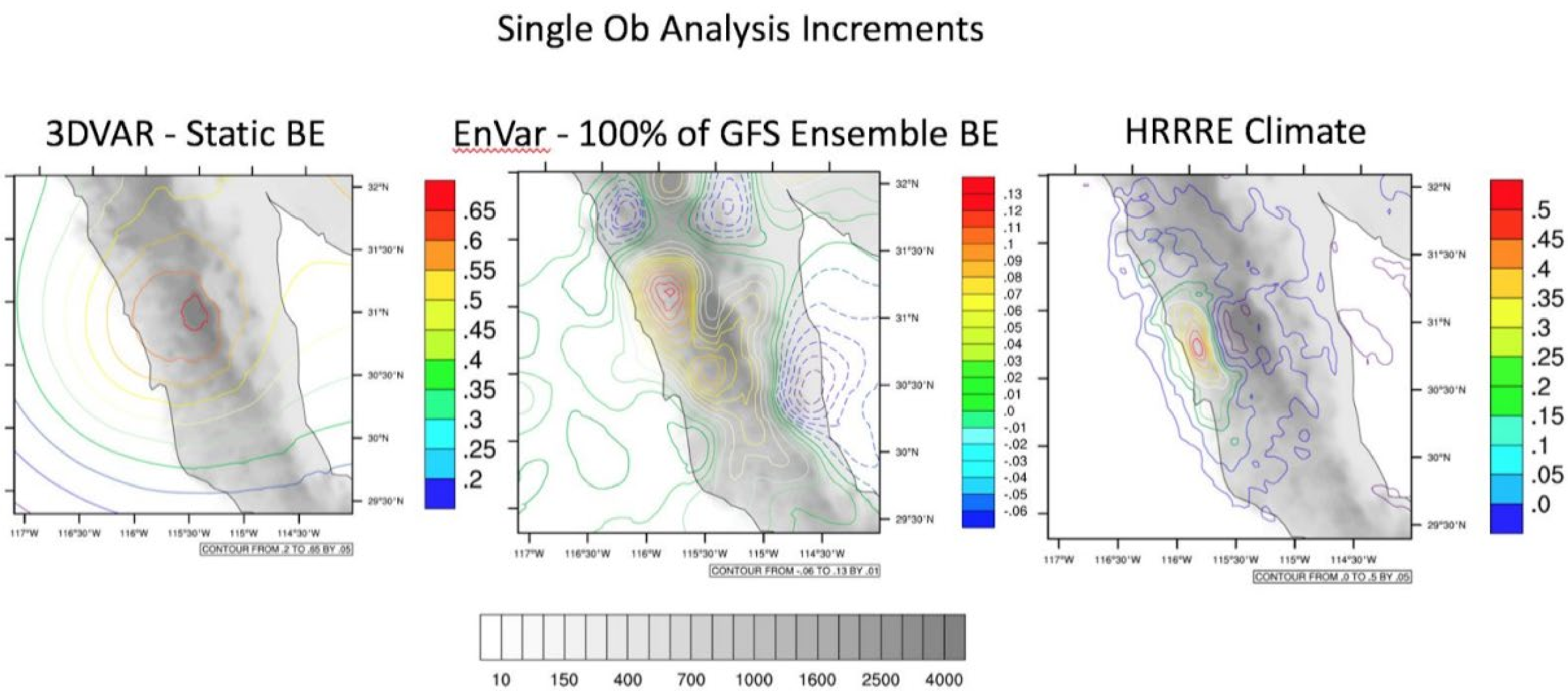
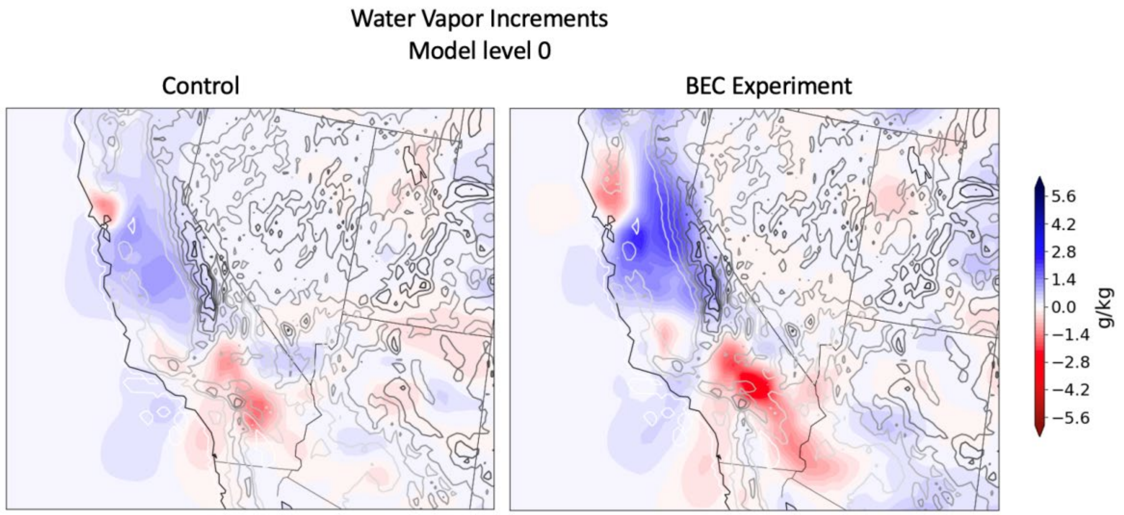


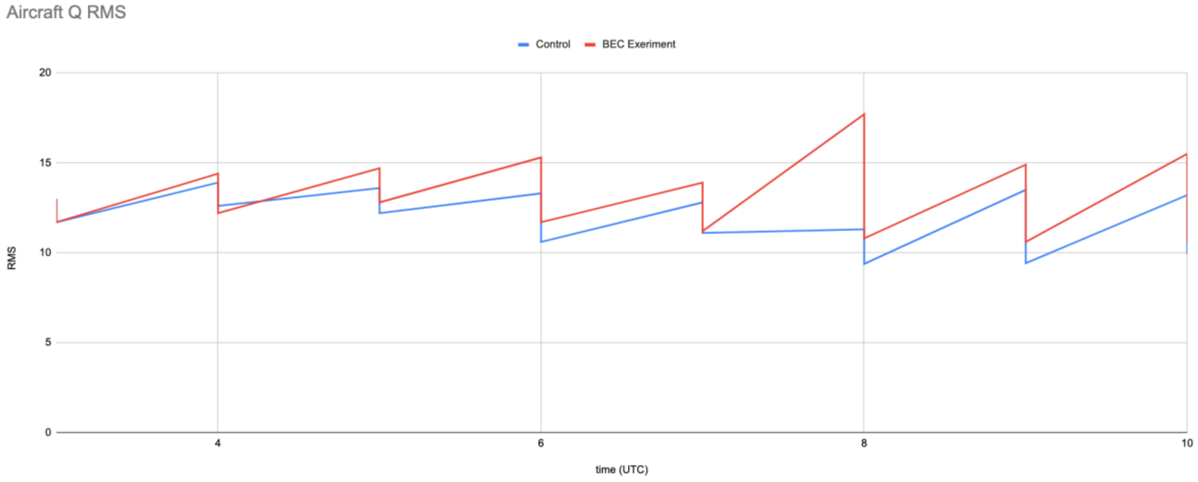
Figure 3. Terrain height (gray shaded in meters) and temperature analysis increment (colored contours) from a single temperature observation at the center of the domain.

Representing standing features in BEC

- Retrospective experiments using climatological BEC data show promising increment distributions.
- However the increased fit to the obs creates noise and leads to model drift.
- This BEC data may benefit RTMA.



Zoomed view of RAP water vapor increments at the lowest model level. Model terrain is also plotted in the grayscale contours.



Root mean square difference between the Aircraft moisture observations and the background and the analysis for 8 hours of cycling with the control (blue) and BEC experiment (red).

Research and Development Areas

1. Data Assimilation
   - Observations type and use
   - Algorithm/process for minimization
   - Background error covariance
2. Diagnostics   Generate C&V from model state
3. Model Representation
   - Physics
   - Dynamics
4. Verification

Ceiling Diagnostics

- Ceiling skill depends not only on an accurate model forecast/analysis, but also on the diagnostic algorithm that computes ceiling
- Now that the model represents subgrid clouds, that information can be used in diagnostics

Legacy Ceiling Diagnostic

For each grid column, ceiling is diagnosed where:

- grid-scale $q_c + q_i > 10^{-6}$ g g^{-1}, or
- grid-scale RH at PBL top > 95%

Experimental Ceiling Diagnostic #2

Combination of explicit and subgrid clouds applying the summation principle*, ceiling is diagnosed where:

- Summation of explicit cloud and/or subgrid cloud fraction > 0.4
- If an adjoining grid box has a lower ceiling, that lower value is assigned.

*Sky cover at any level is equal to the summation of the sky cover in the lowest layer, plus the additional sky cover in all successively higher layers up to and including the layer in question.

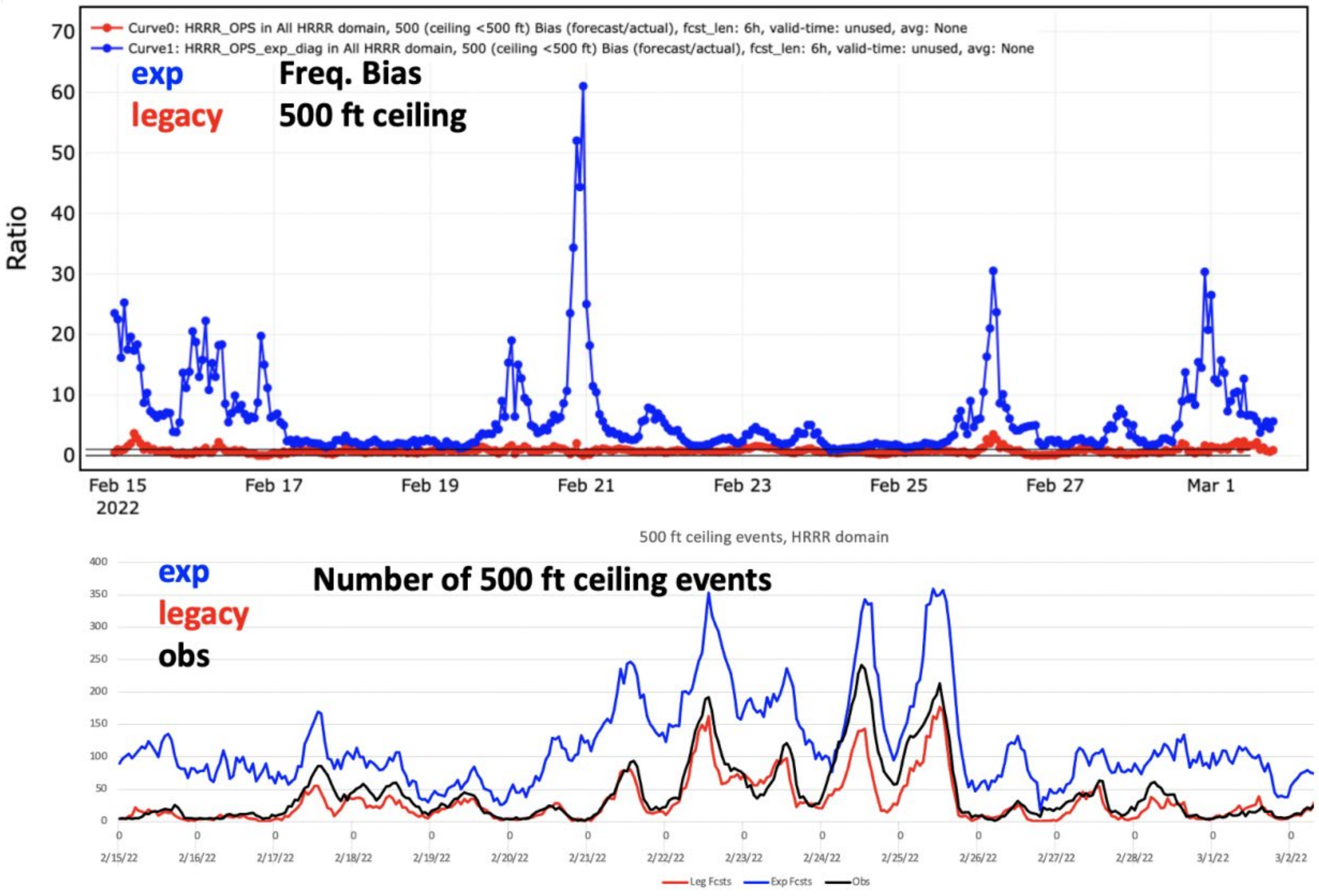
Each diagnostic includes:

- Thin, surface-based cloud layers (< ~80 m deep) are disregarded
- If grid-scale snow is present, the diagnosed ceiling is lowered
- Legacy and EXP2 available in HRRRv4 output

https://rapidrefresh.noaa.gov/Diag-vars-NOAA-TechMemo.pdf

Diagnostics

- Legacy ceiling diagnostic outperforms the experimental in cool season due to higher bias in low clouds.
- Spikes in bias occur when fewer than 10 stations CONUS wide have ceiling below 500ft.
- Experimental is able to capture some low ceiling events that the legacy misses and it has more potential because it is based on subgrid clouds.



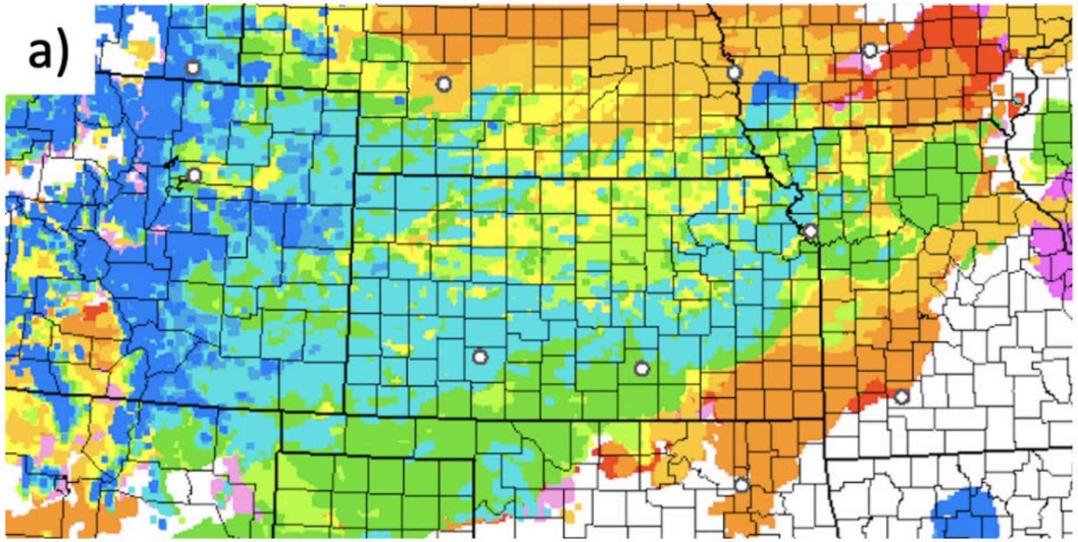
(top) 500 ft ceiling frequency bias for 6h forecasts, from HRRR legacy (red) and experimental (blue) diagnostics, and (bottom) number of forecasted events over the same time period, compared with the number of observed events (black).

Experimental Ceiling Diagnostic

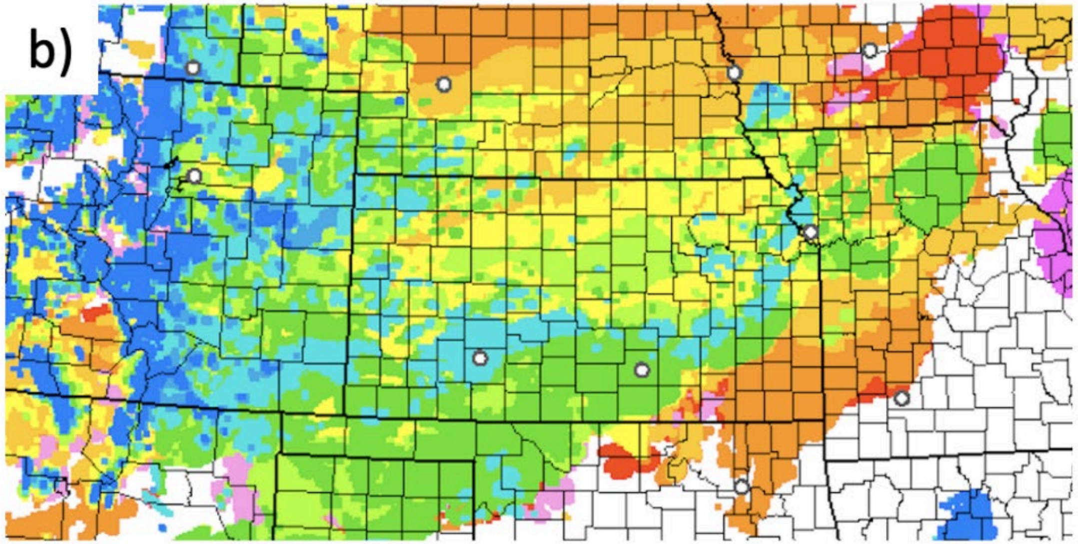
- Experimental is sensitive to cloud fraction threshold.

1h HRRR forecasts of cloud ceiling height
using the exp2 diagnostic
valid at 11 UTC 10 Mar 2022.

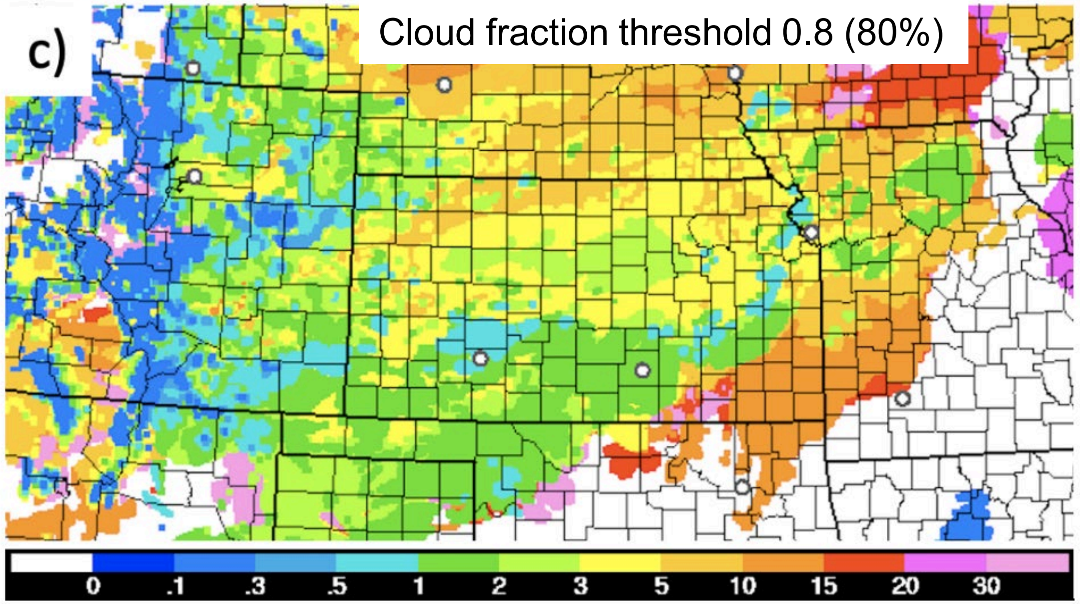
operational setting
minimum cloud fraction to represent a ceiling set to 0.4 (40%)



Cloud fraction threshold 0.6 (60%)



Cloud fraction threshold 0.8 (80%)



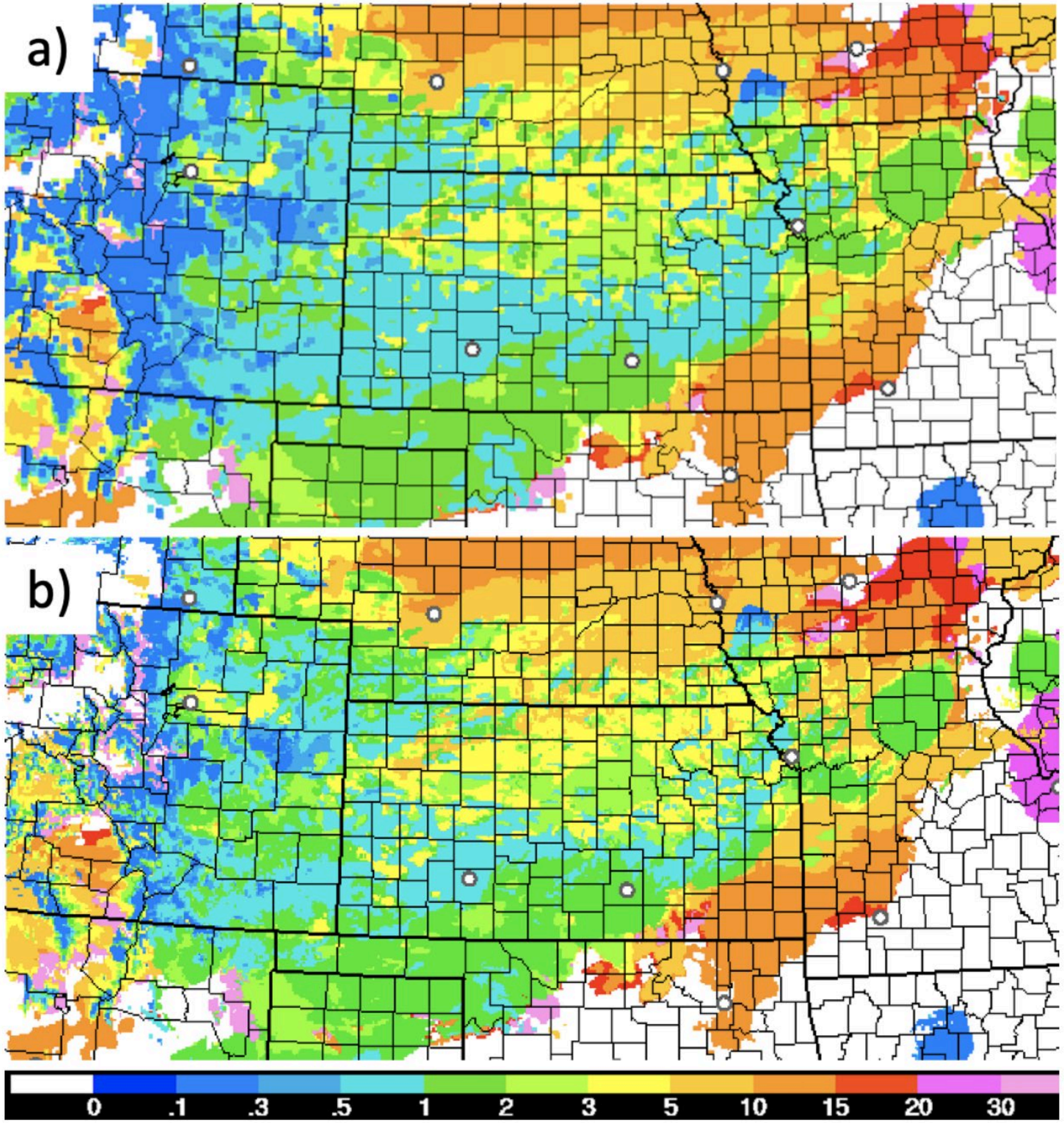
Experimental Ceiling Diagnostic

- Experimental is sensitive to horizontal search radius.

1h HRRR forecasts of cloud ceiling height using the exp2 diagnostic valid at 11 UTC 10 Mar 2022.

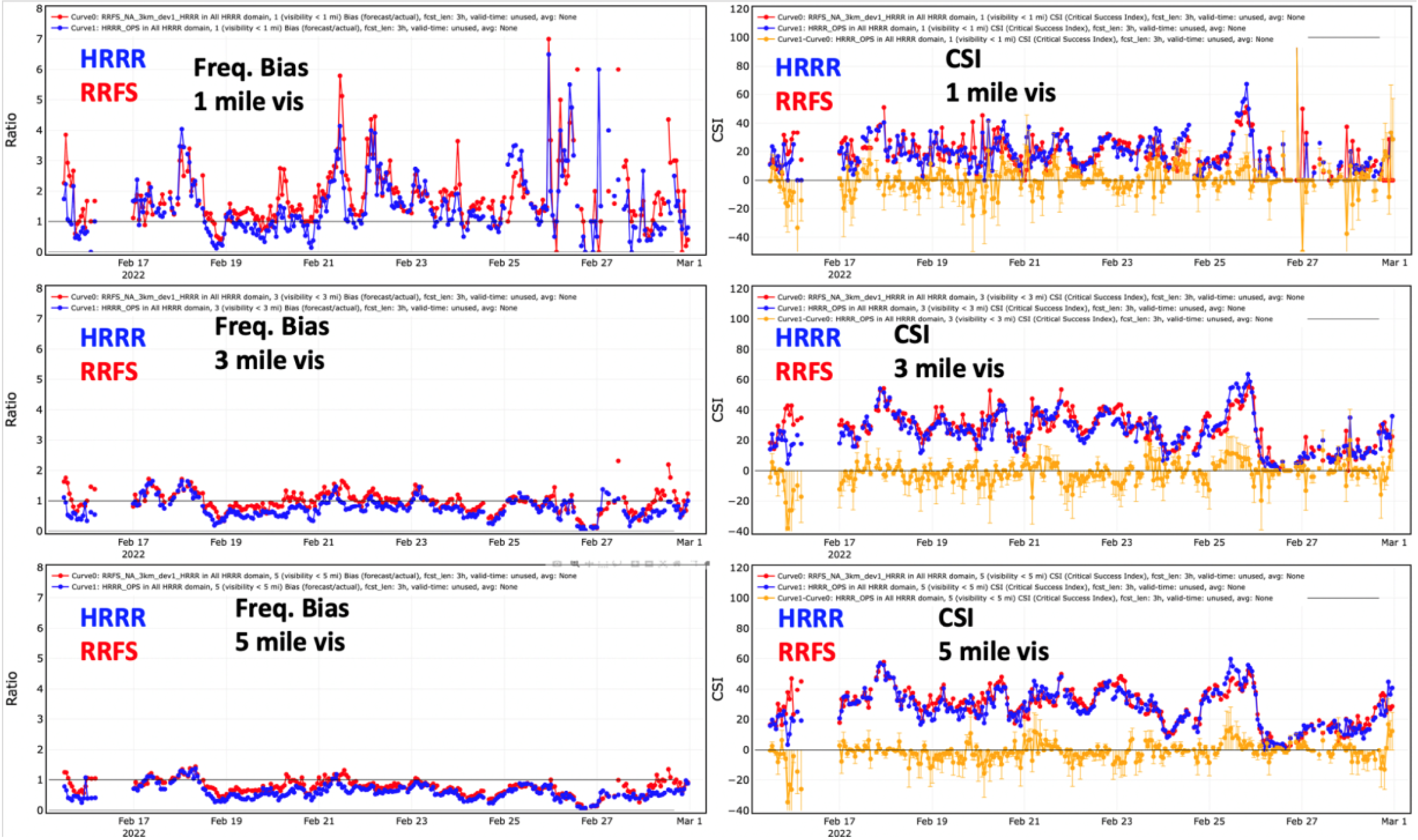
operational setting, using a neighborhood search radius of one 3km gridpoint (a)

neighborhood search removed



Diagnostics

- Visibility diagnostic in RRFS output is comparable in skill to HRRR output.
- Little impact from additional vertical levels in RRFS.



HRRR (blue) and RRFS (red) visibility forecasts for 3h forecasts over the CONUS domain during 14 Feb - 1 Mar 2022. Frequency bias (left) and (right) critical success index (right), for occurrence of visibilities less than 1 (top), 3 (middle), and 5 miles (bottom). Note that the CSI panels also show the hourly difference between HRRR and RRFS (HRRR minus RRFS, with positive values indicating superior performance by HRRR, in orange).

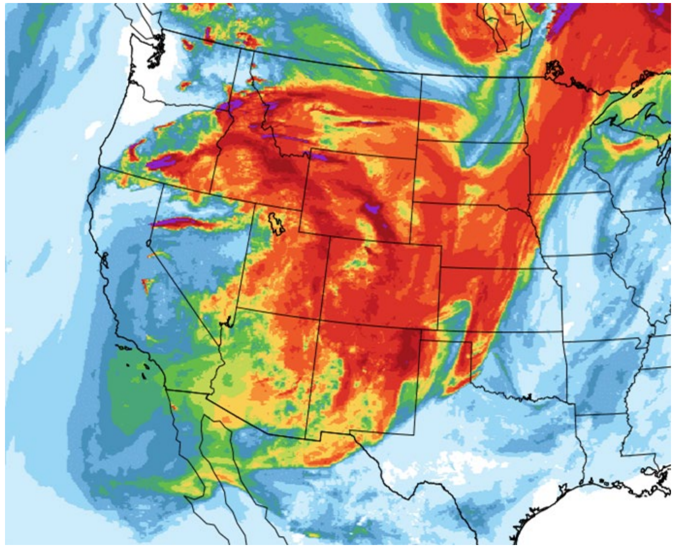
Research and Development Areas

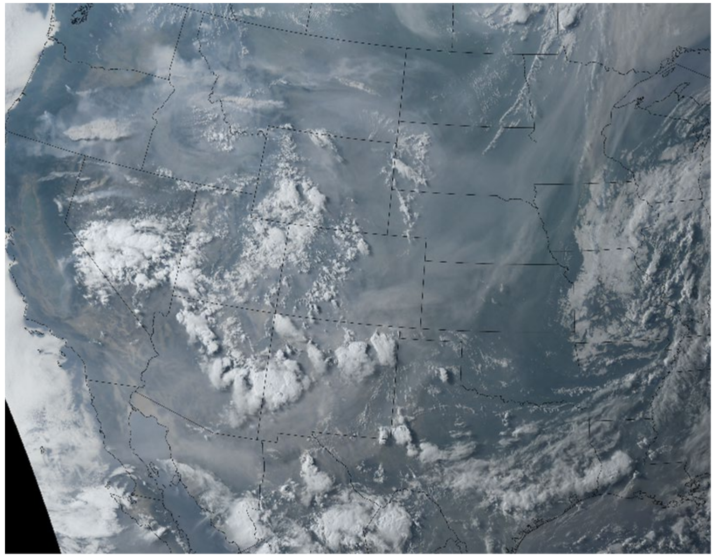
1. Data Assimilation
   - Observations type and use
   - Algorithm/process for minimization
   - Background error covariance
2. Diagnostics
3. Model Representation
   - Physics
   - Dynamics   Represent explicit & subgrid clouds; thermodynamic environment; PBL
4. Verification

Physics Development

Recent Accomplishments

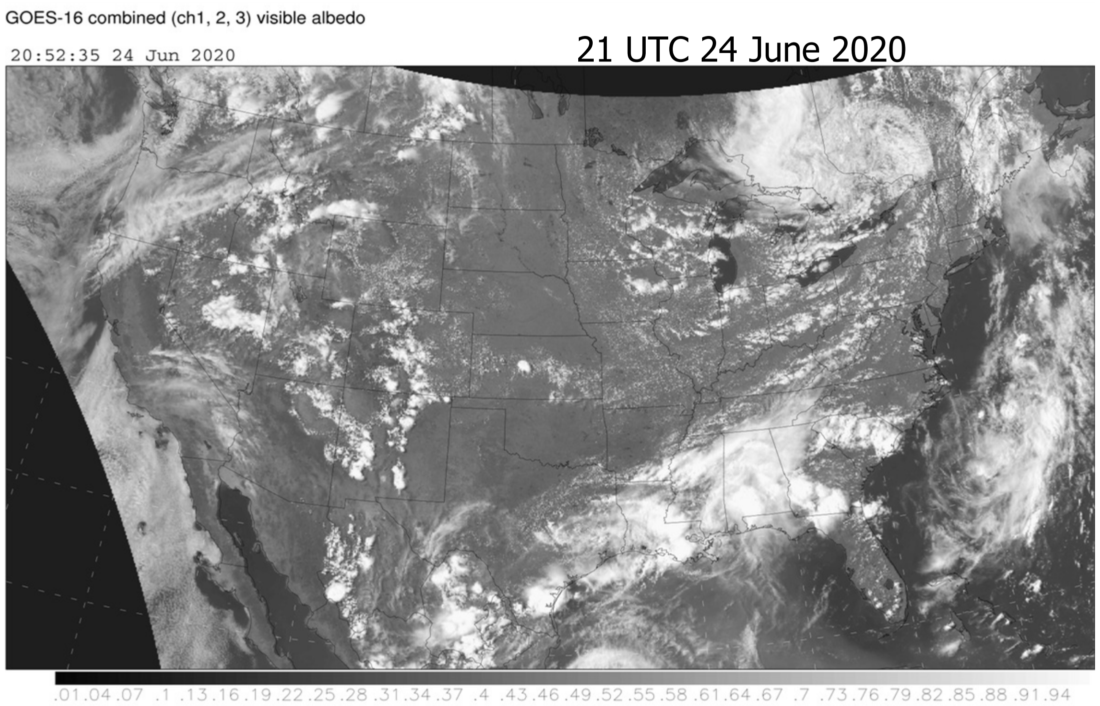
- Physically-based enhancements result in improvements in practically all forecast variables
- Eliminated much of the gap between RRFS and HRRR performance
- Refined treatment of clouds / ceiling from partial cloudiness
- Improved conservation of heat and moisture
- SPP stochastic physics implemented in RRFS (FV3) for ensembles
- Highly improved surface aerosol emissions for Thompson-Eidhammer microphysics (with NCAR)
- Testing of inclusion of mixed physics in storm-scale ensemble forecasts
- Recent work to add CLM small lake model and FVCOM large lake model



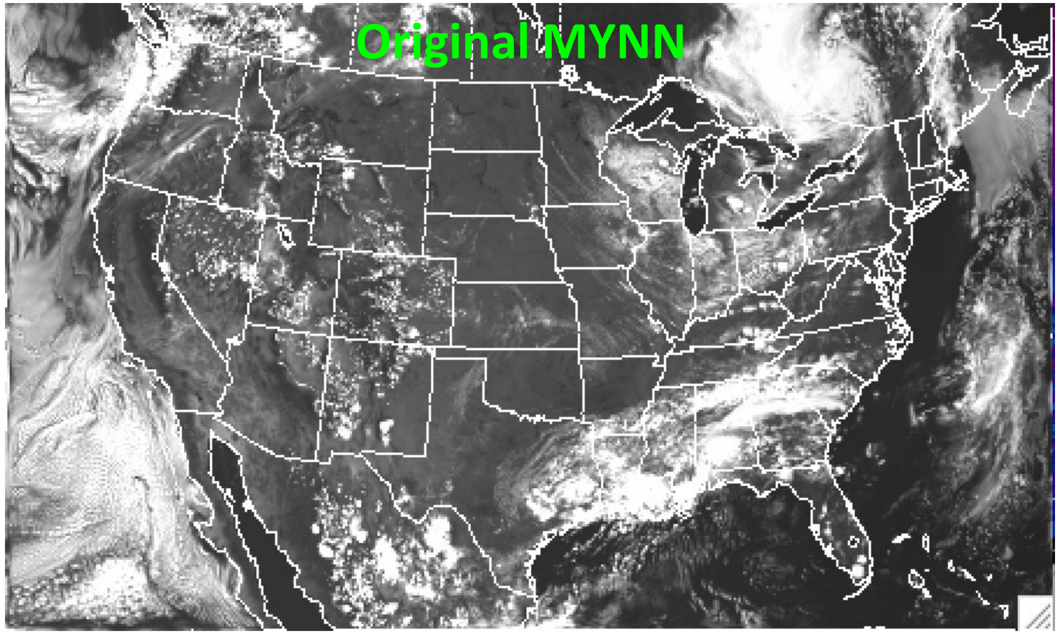


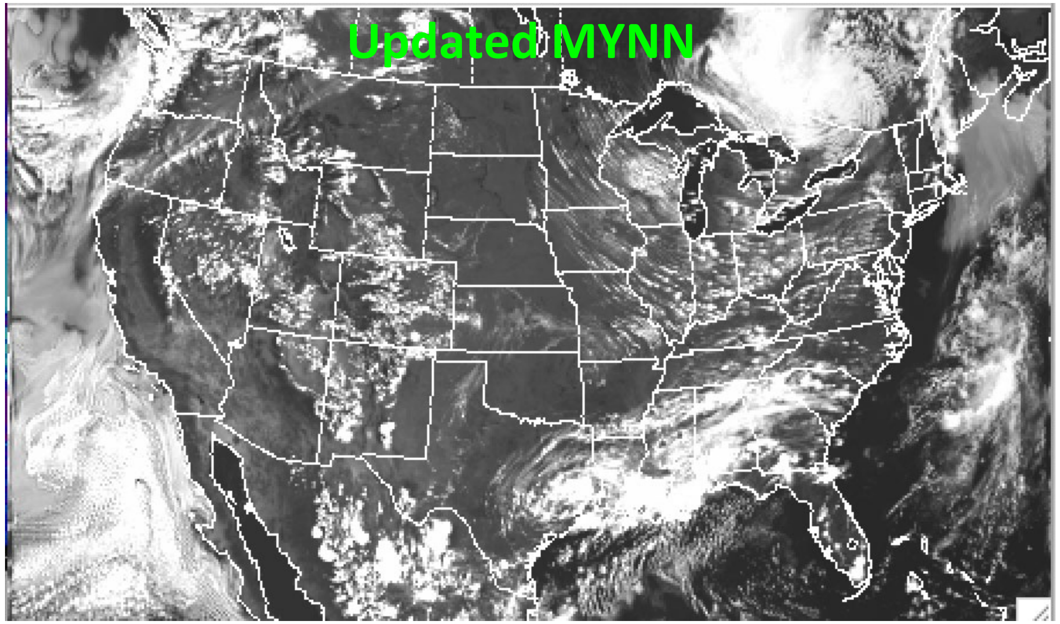
12Z 12 July 2021 + 12h HRRR fcst vertically integrated smoke and 00z visible satellite image

Improved Cloud Morphology



Model runs initialized at 09 UTC 24 June 2020 12-hr forecast valid at 21 UTC:

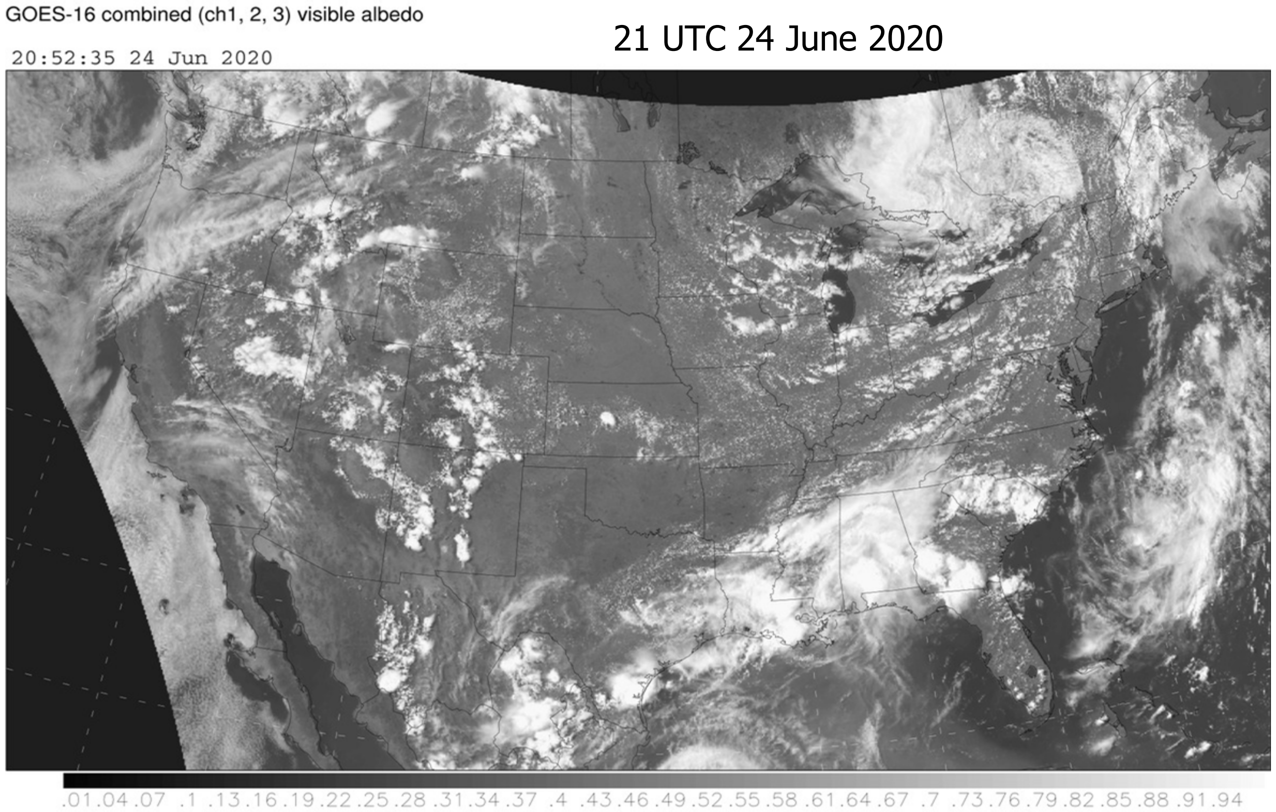


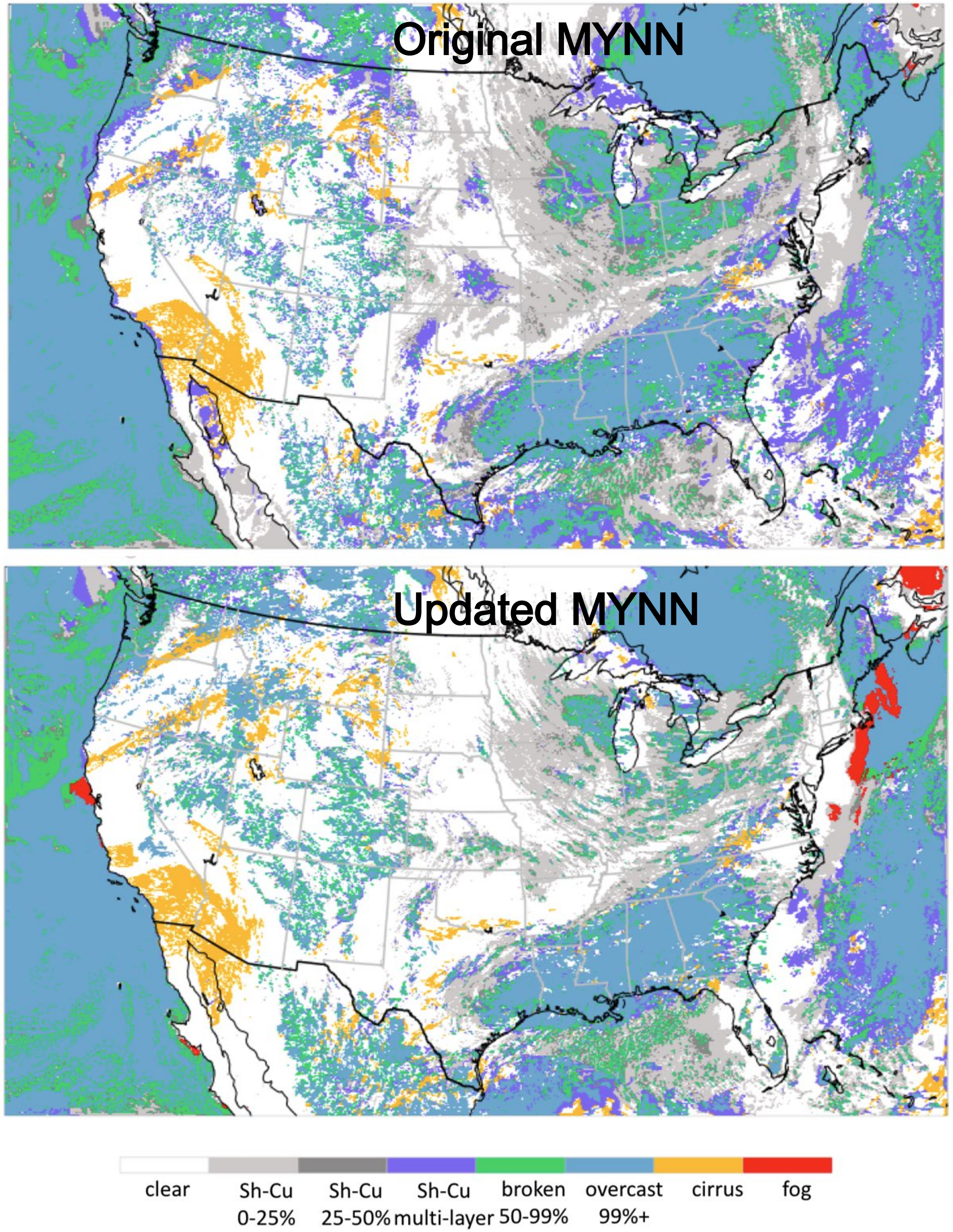


An example of improvements to the subgrid-scale clouds for a variety of cloud types:

- Shallow-cumulus fields have improved coverage
- Convective clouds over over West are more robust
- Atlantic marine clouds better match satellite imagery
- Cirrus over NW US is improved but still under-represented

Cloud Regime Diagnostic





- Meant to help categorize model biases by cloud regime to better uncover the sources of model errors

Thank you!

This research is in response to requirements and funding by the Federal Aviation Administration (FAA). The views expressed are those of the authors and do not necessarily represent the official policy or position of the FAA.