AI4NWP Workshop

Short Range Weather Convection Allowing Models (SRW/CAM) Skill Improvements

29 November 2023

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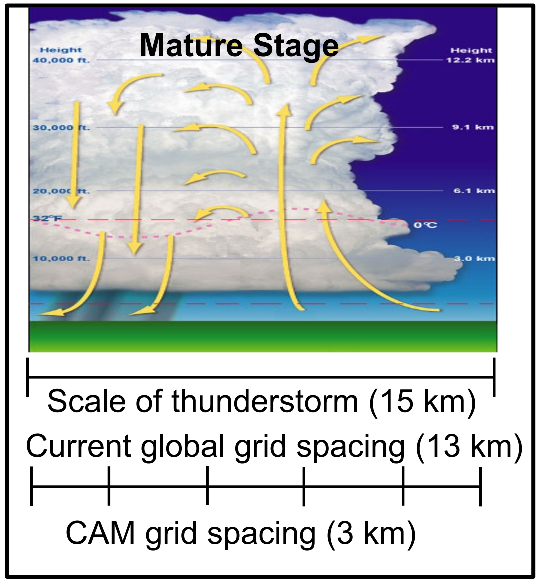
Why CAMs-LAMs?

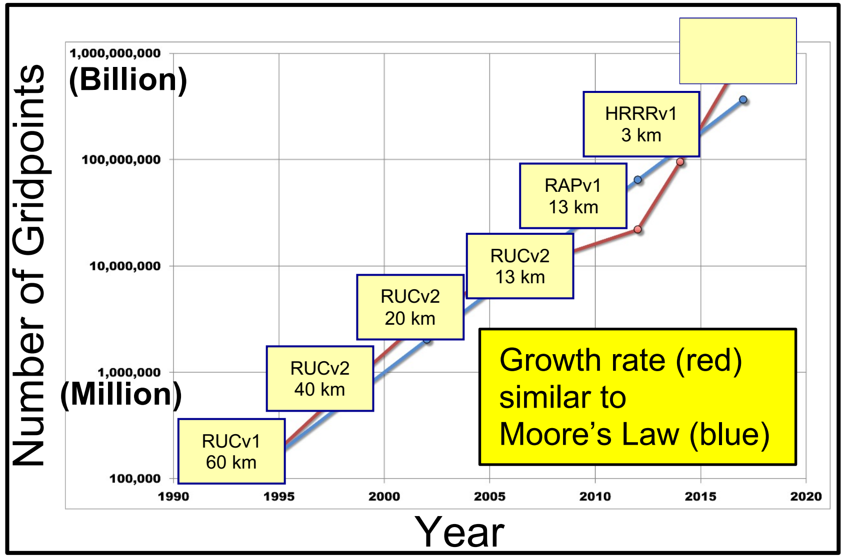
Why Convection Allowing Models (CAMs)?

- Captures bulk properties of many hazardous convective weather systems (i.e. rotating updrafts)
- Permits more accurate forecasts of weather conditions in which such hazardous storms may occur
- Employed most often in regional or limited area modeling framework

Why Limited Area Models (LAMs)?

- Reduces the compute expense and complications associated with a global CAM
- Enables rapid data assimilation/cycling with lower low-latency forecasts than global models
- Emphasizes shorter-range (hours/days) prediction



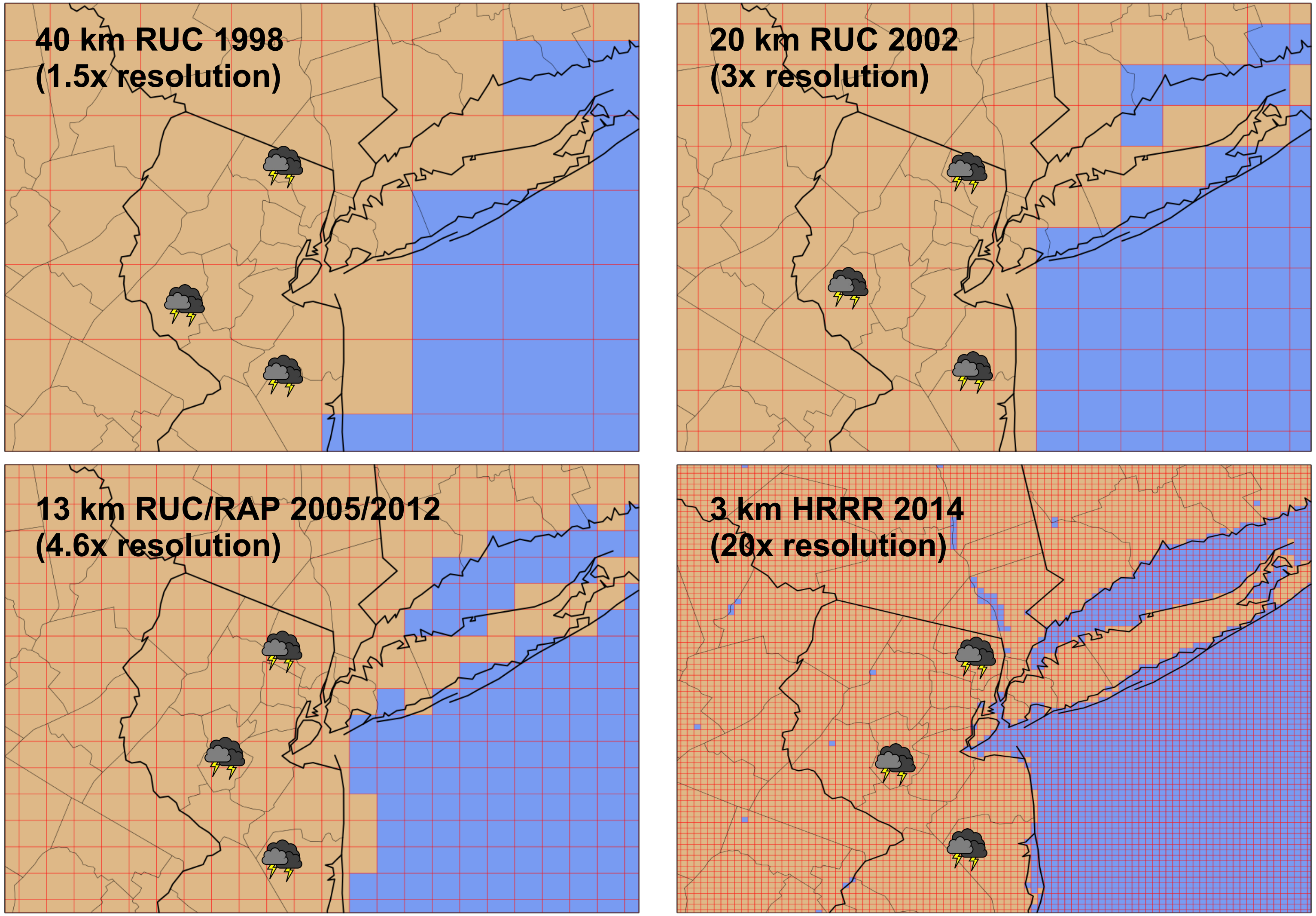


High Resolution Weather Forecasts

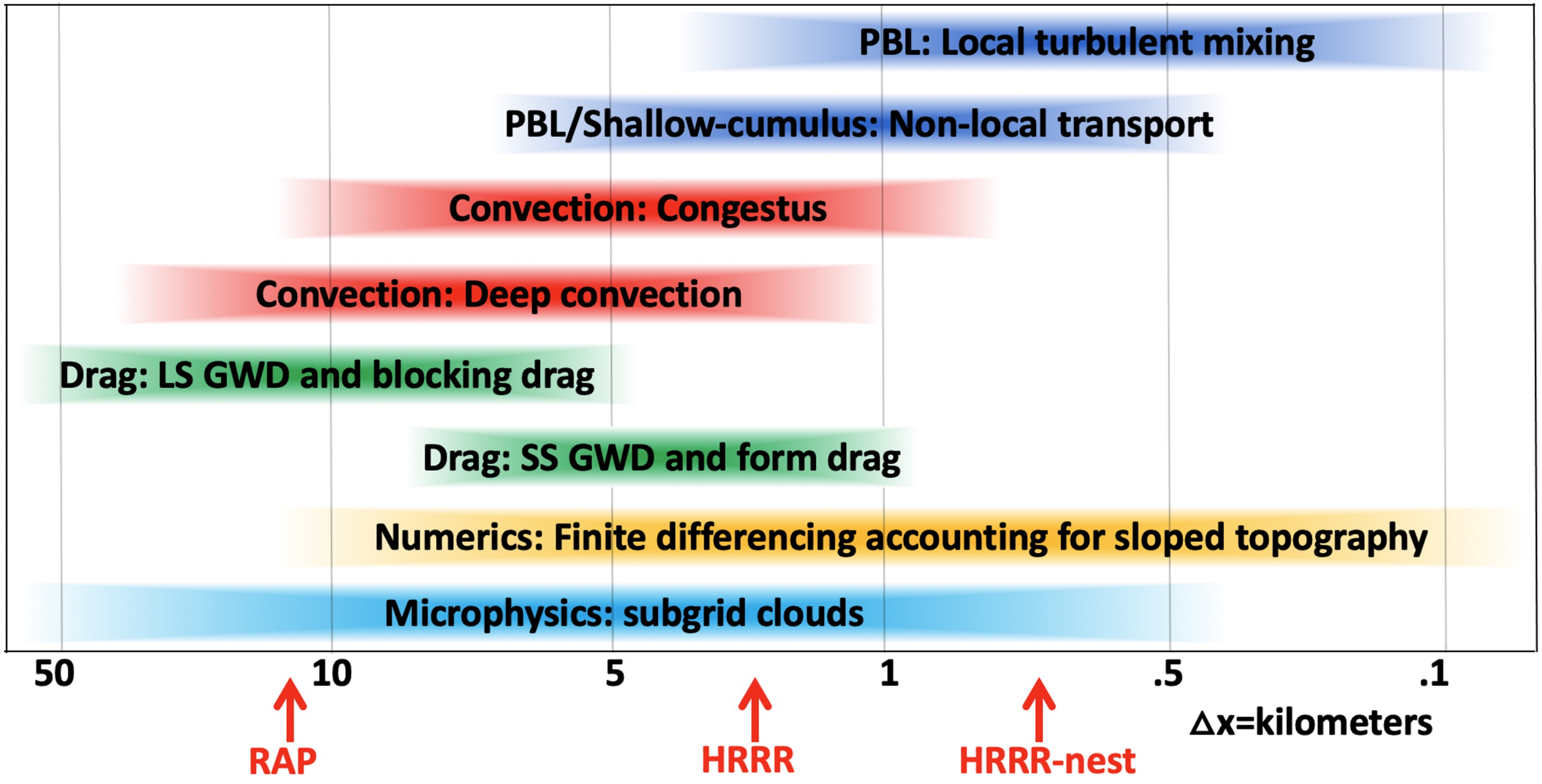
Increasing resolution

More terrain and coastal details

More accurate storm structure



Spatial Scales of Varying Scheme Behavior



Relevance to Communities

Aviation/Transportation Weather Hazards
Tactical and Strategic Planning (0-8 hrs)
FAA, Airlines, Aviators, NCAR, MIT/LL, AWC,

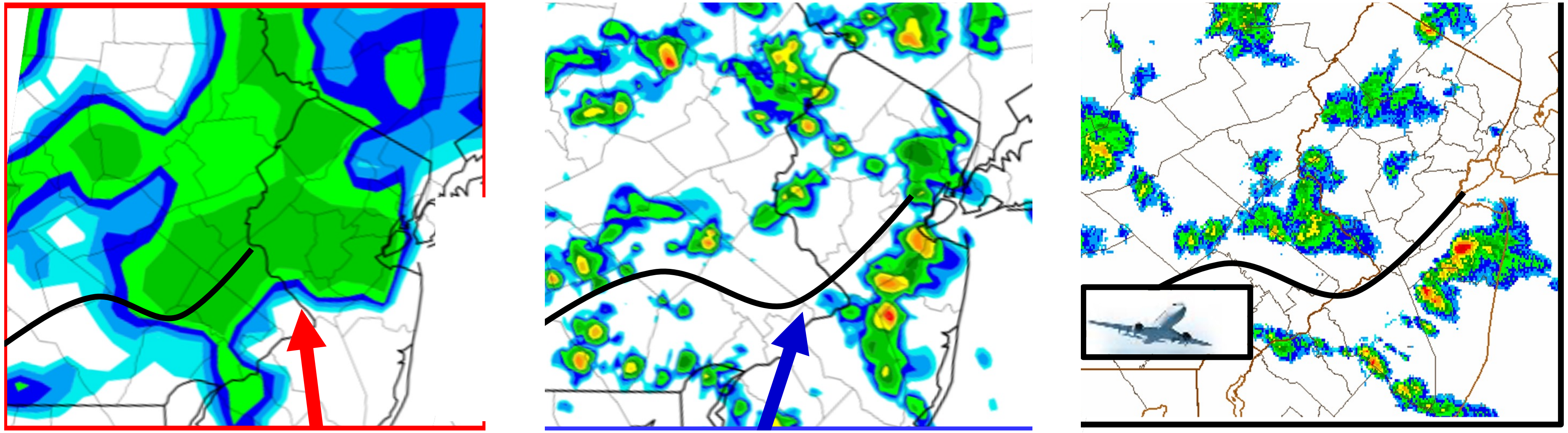
Severe Convective Weather
Warn on Forecast (0-2 hrs)
Severe Weather Watches/Discussions (0-8 hrs)
Severe Convective Outlooks (1-2 days)
SPC, NSSL, NWS

Hydrology and Quantitative Precipitation Forecasts
Flash Flood Watches/Meso Discussions (0-8 hrs)
National Water Model Forcing (0-18 hrs)
Heavy Rain/Snow Outlooks (1-2 days)
WPC, OWP, GLERL, PSL, NWS

Renewable Energy
Wind and Solar Power Generation (0-18 hrs)
Next Day Decision Support (24-48 hrs)
Power Authorities, Energy Companies, ASRE

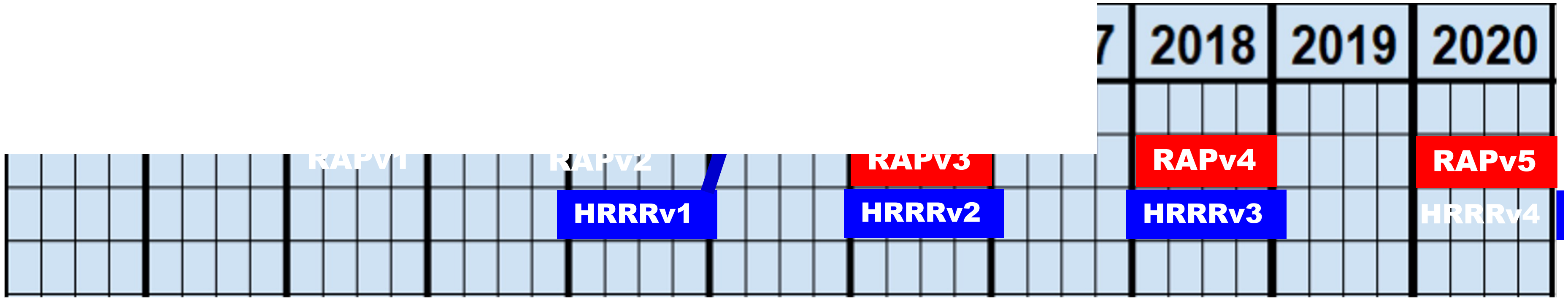
Composition, Air Quality and Health
Wildfire Smoke Concentrations (1-2 days)
IMET, ARL, CSL, NWS

What Improvements to CAM NWP Look Like



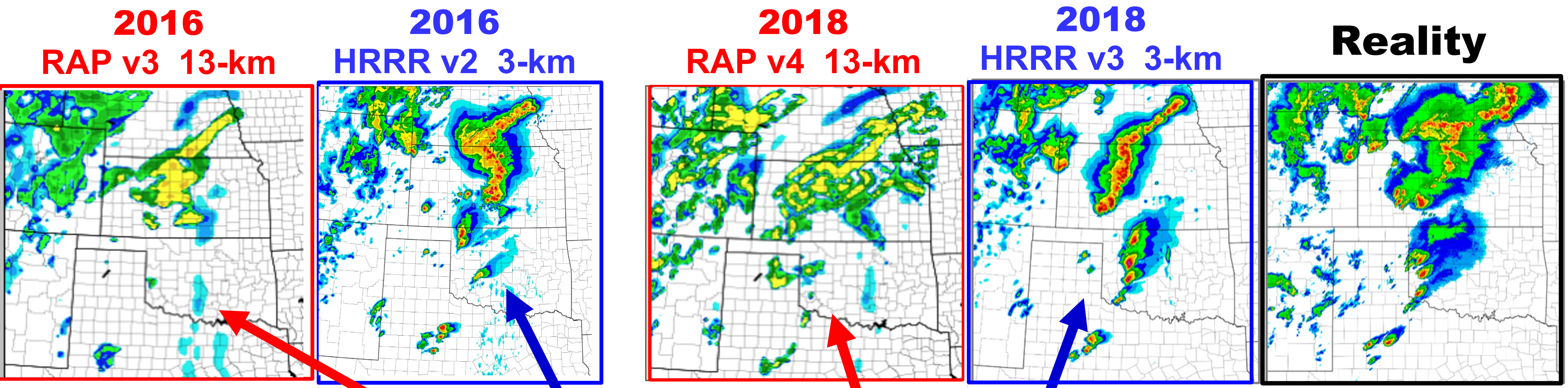
Aviation Application Collaboration: FAA, NCAR, MIT/LL, AWC

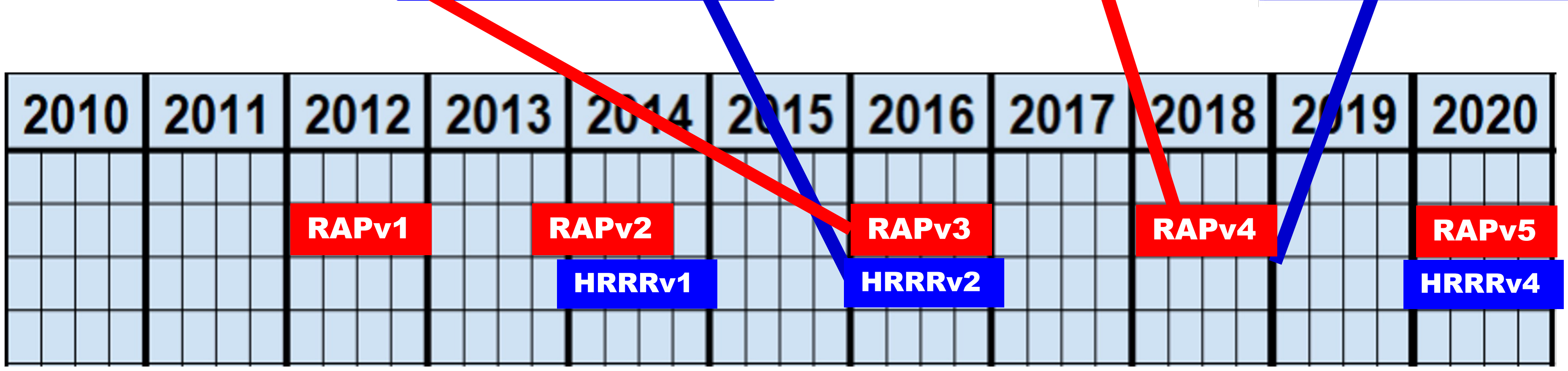
Benefits: less delays, better fuel usage, contributions to safety



Major progress for short-range prediction of convection and other hazardous weather

What Improvements to CAM NWP Look Like



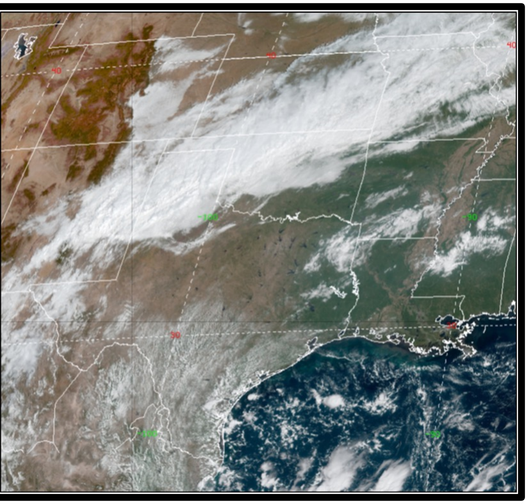


Severe Weather App Collaboration: SPC, NSSL, OU/CAPS, EMC

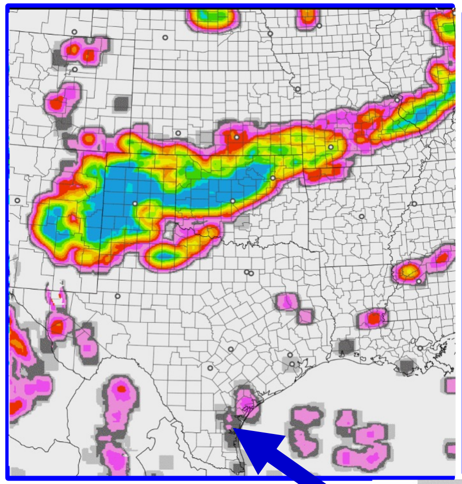
Benefits: improved severe weather guidance, contributes to safety

What Improvements to CAM NWP Look Like

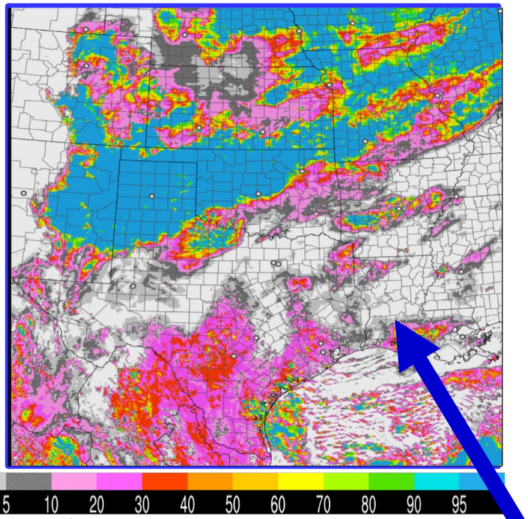
Reality



2018
HRRR v3 3-km



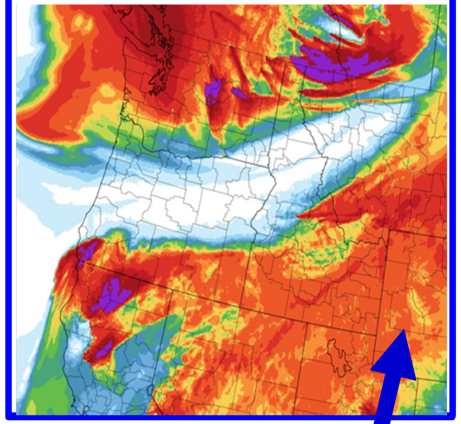
2020
HRRR v4 3-km



4-h forecast cloud fraction

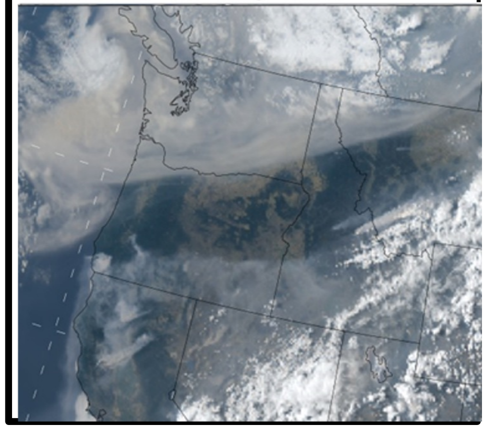
2020
HRRR v4 3-km

Integrated smoke



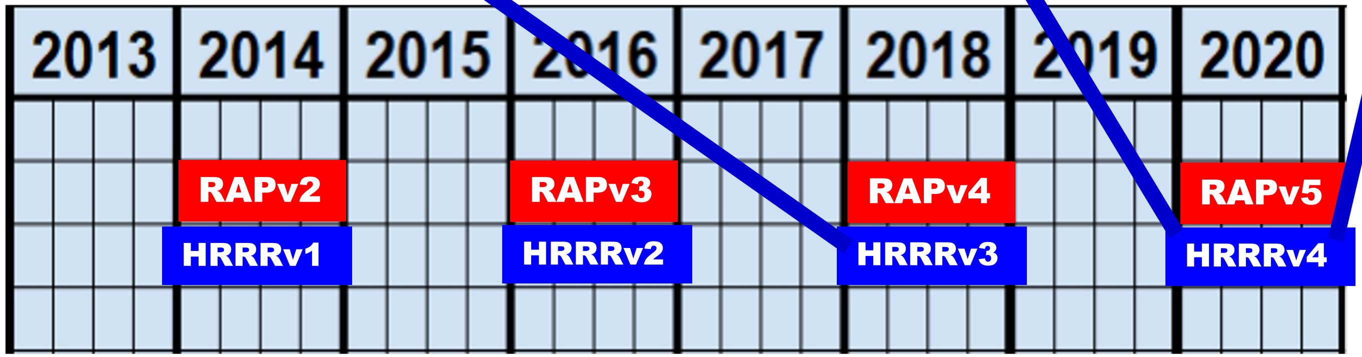
Reality

GOES-16 RGB (ch1, 2, 3) visible image
22:58:46 12 Aug 2018



Improved cloud / ceiling forecast capability

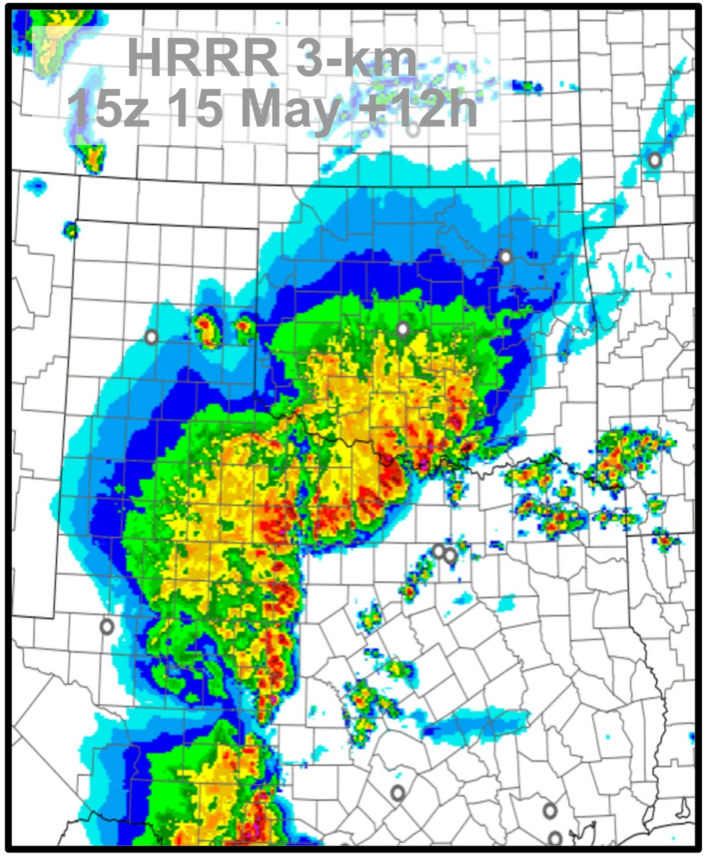
Benefits: Aviation users, NWS and other users

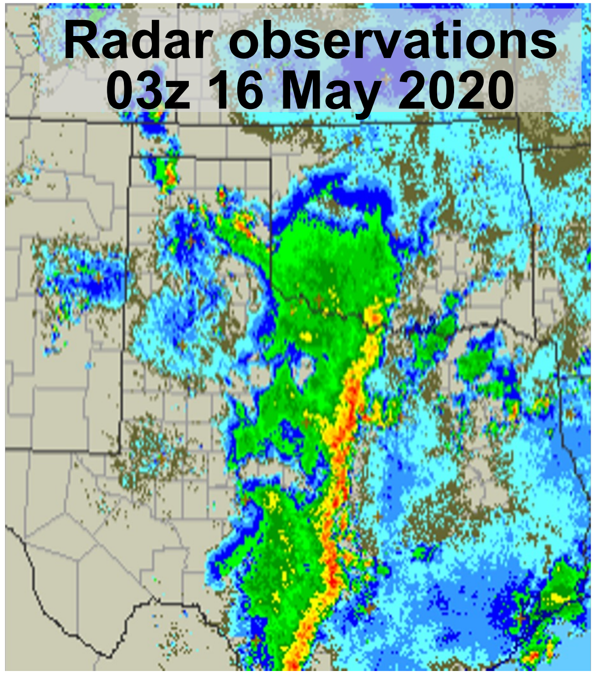


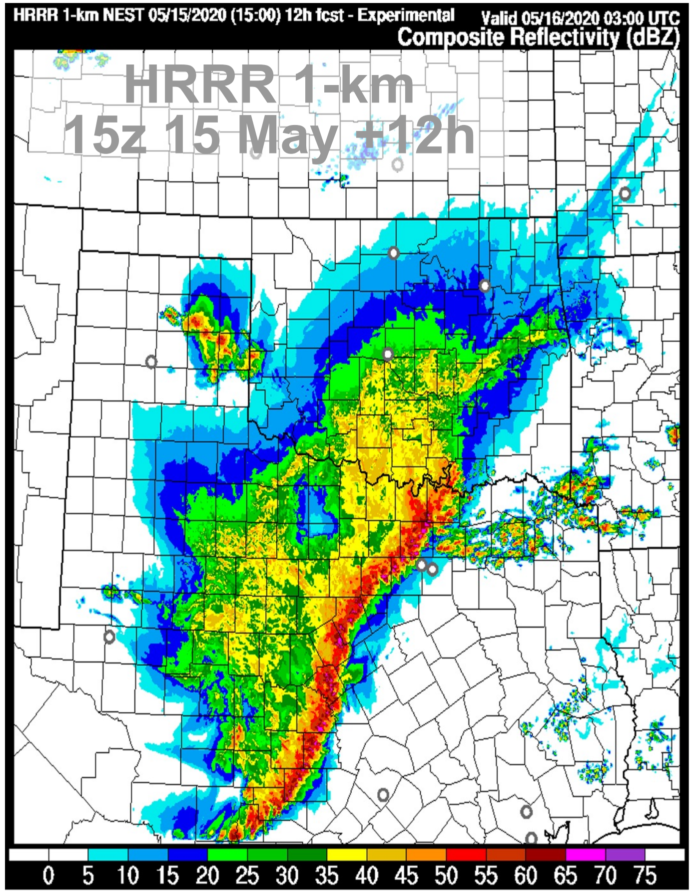
Smoke prediction capability

Benefits: Many users including NWS, state and local entities, etc.

Very High Resolution (≤ 1 km) Nesting Research

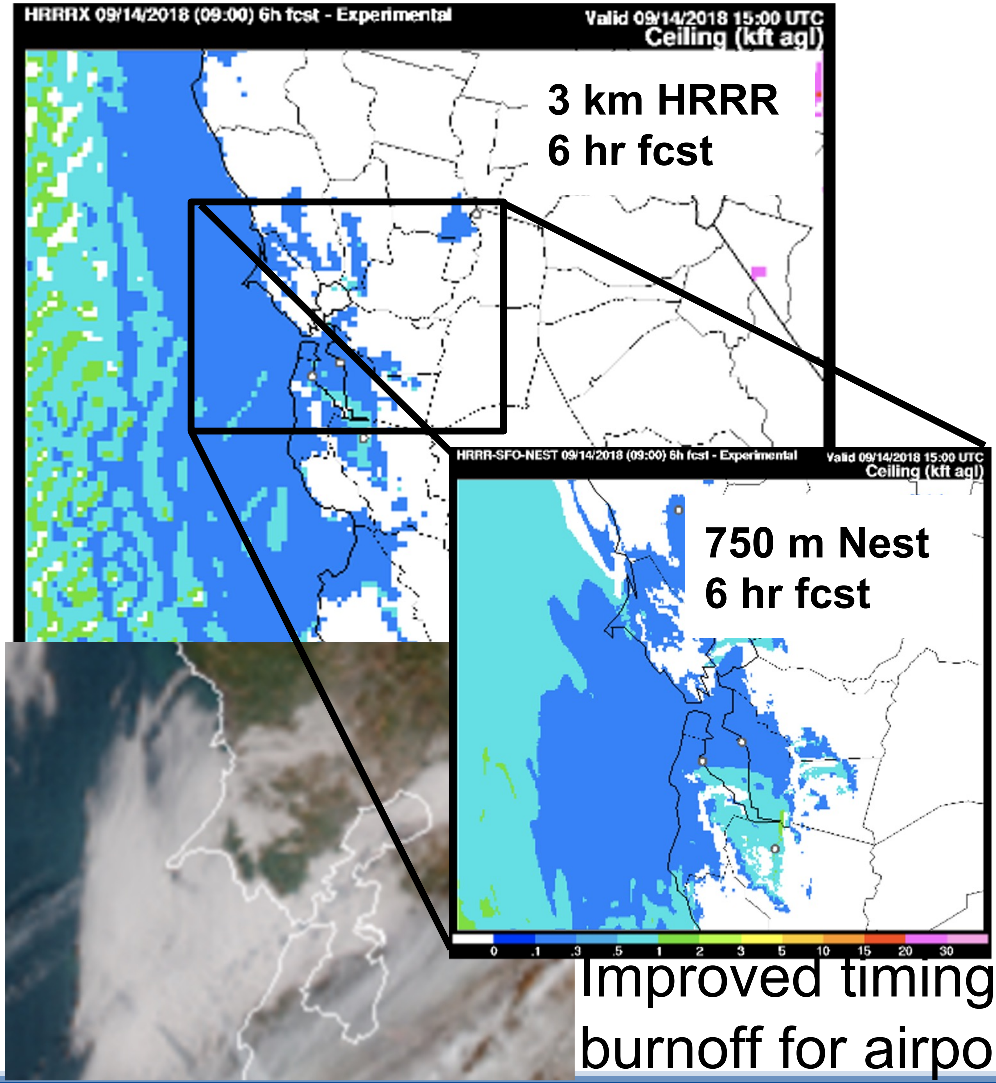




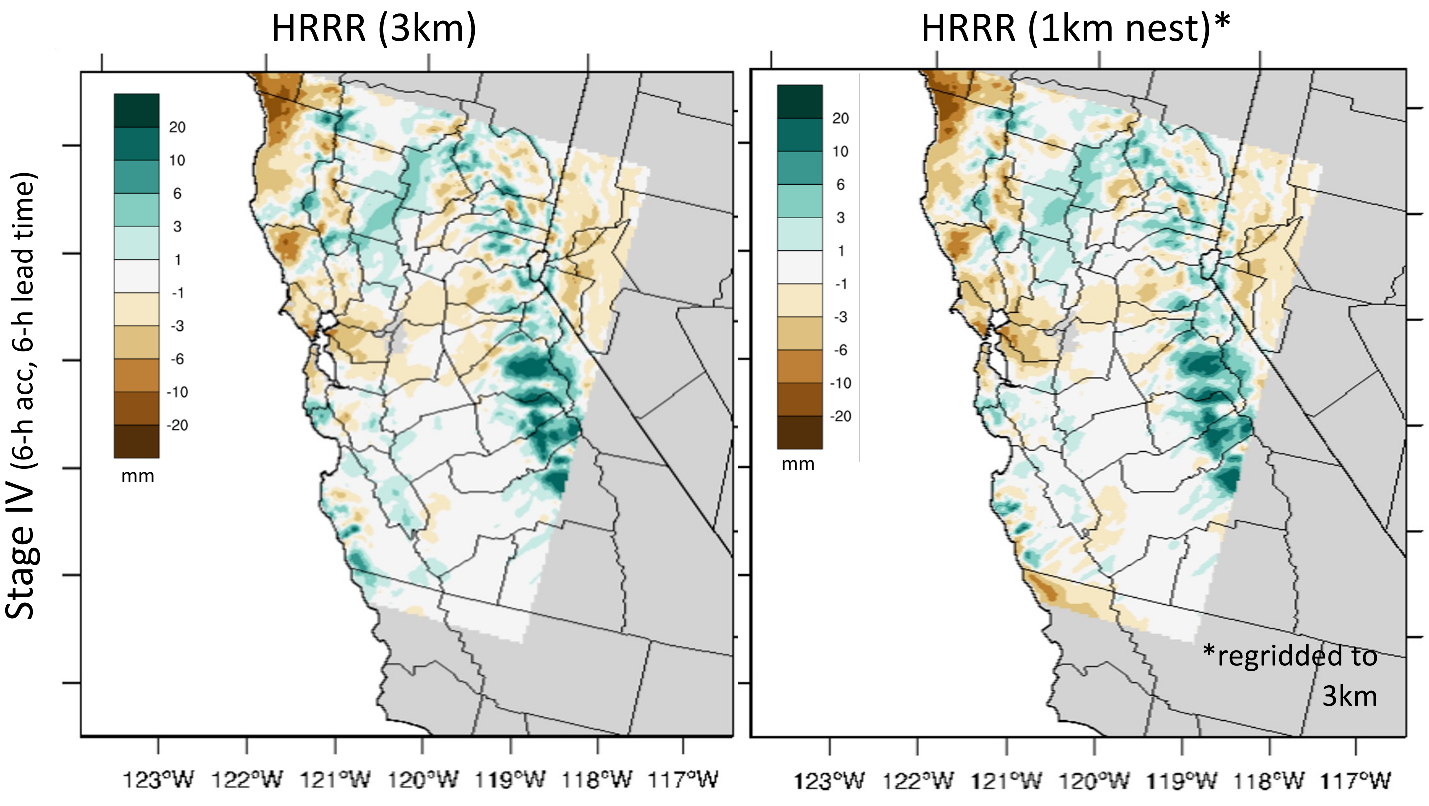


Convection impacts including more accurate initiation and system evolution at 1 km

Very High Resolution (≤ 1 km) Nesting Research

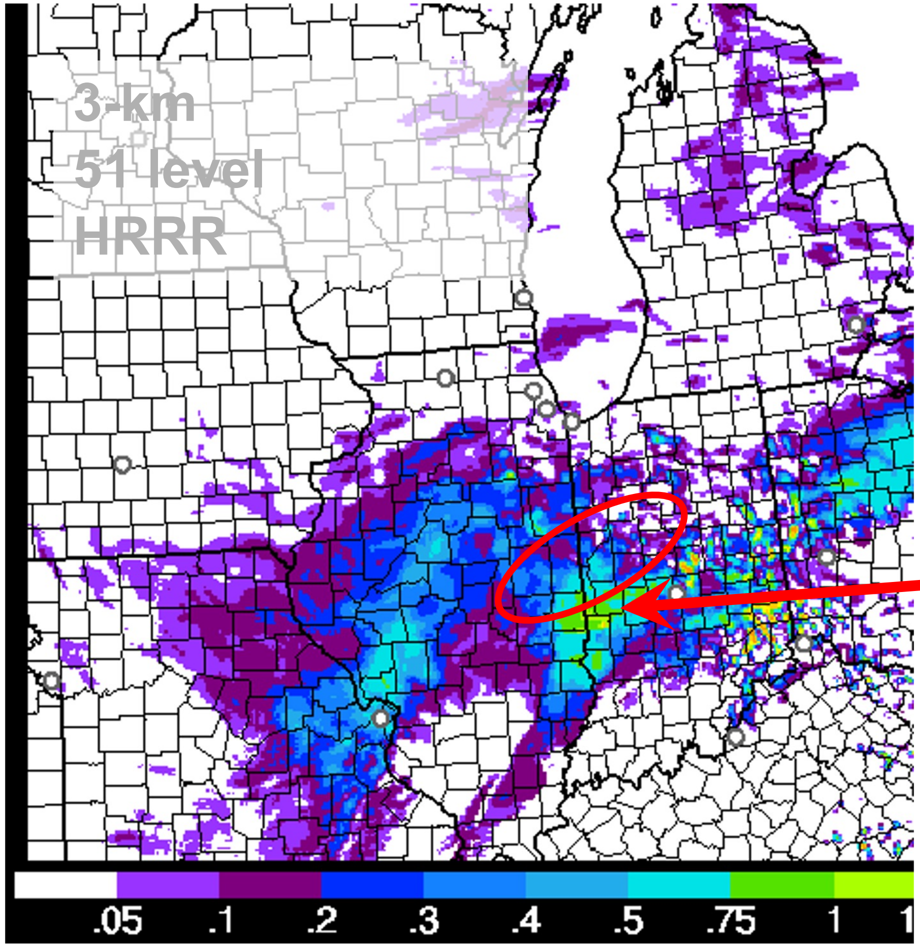


Improved timing of SFO fog burnoff for airport operations

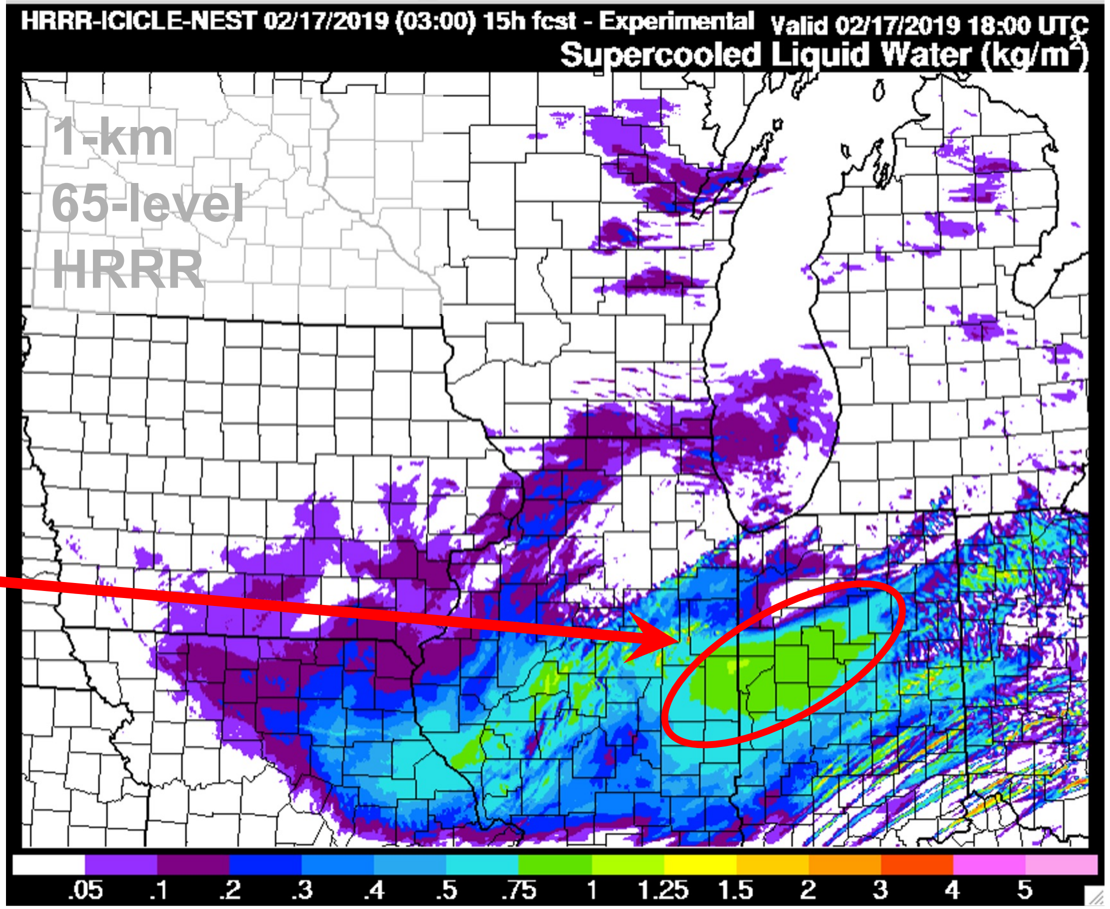


Evaluation of QPF biases with finer orographic detail (English et al. 2021)

Very High Resolution (≤ 1 km) Nesting Research



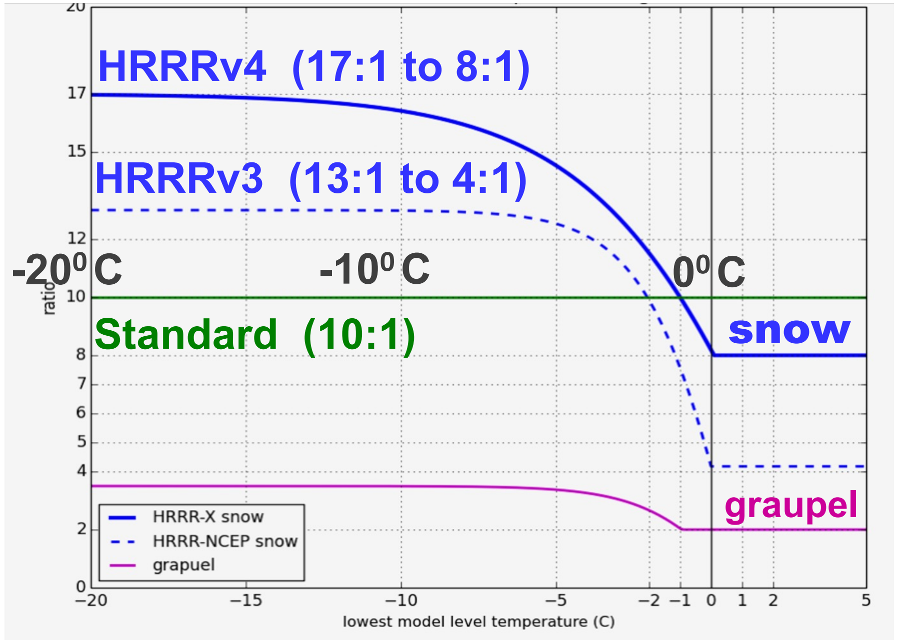
SLW
Improved county-scale location of SLW from 1-km 65-level HRRR run

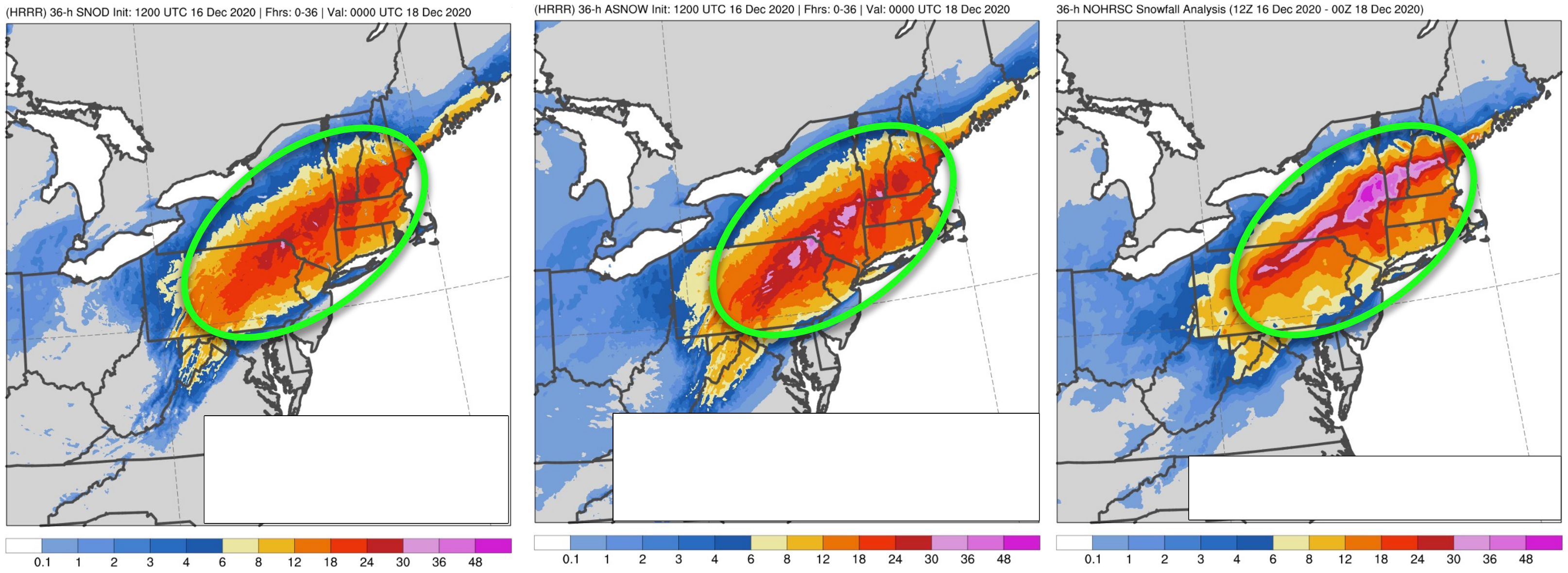


In-flight icing potential from increased supercooled liquid water (SLW)/banding at 1 km

Better Snow Forecasts: Variable Density Snow Accum

Diagnostic formulation for snow-to-liquid ratio





HRRR 36h-h total snow accumulation from 1200 UTC 16 Dec. 2020

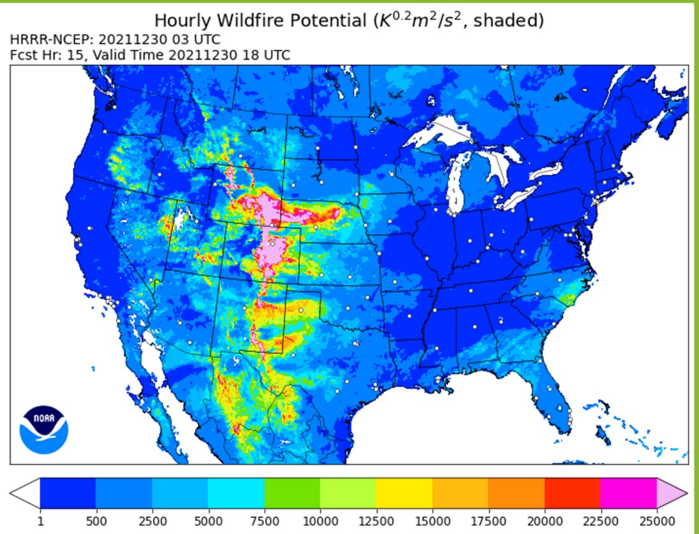
From 7 Jan 2021 EMC Model Evaluation Group Briefing

Shannon Shields, Marcel Caron, Chris McIntosh, Geoff Manikin, Alicia Bentley, Logan Dawson

December 2020 Northeastern US snowstorm

Fire Weather Forecasting Advancements

New Hourly Wildfire Potential (HWP)

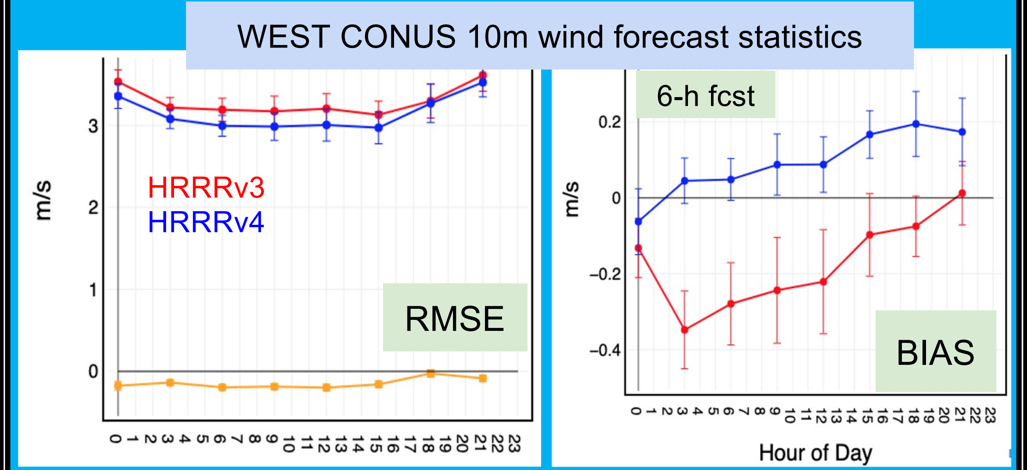


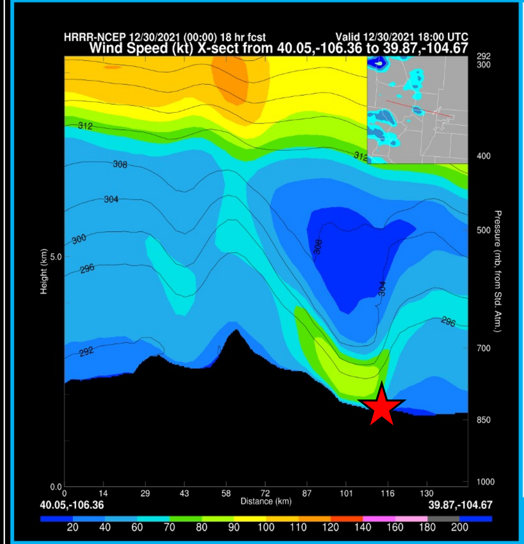
Hourly HRRR weather model forecast inputs:

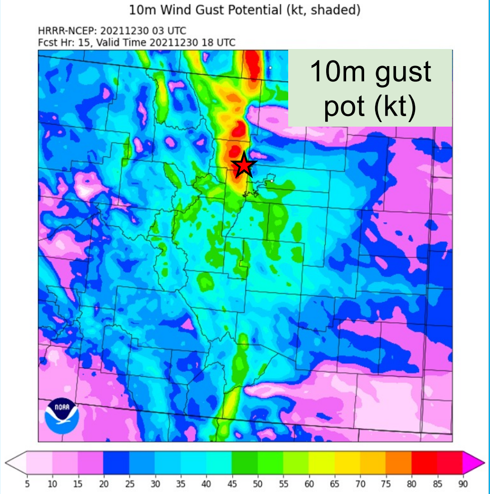
- **Humidity** (2m dewpoint depression)
- **Wind** (10m wind gust potential)
- **Snowpack** (snow water equivalent)
- **Soil state** (soil moisture availability)

Example of 15 hr forecast at start of Marshall Fire (30 Dec 2021)

Improved Operational HRRR Wind Forecasts

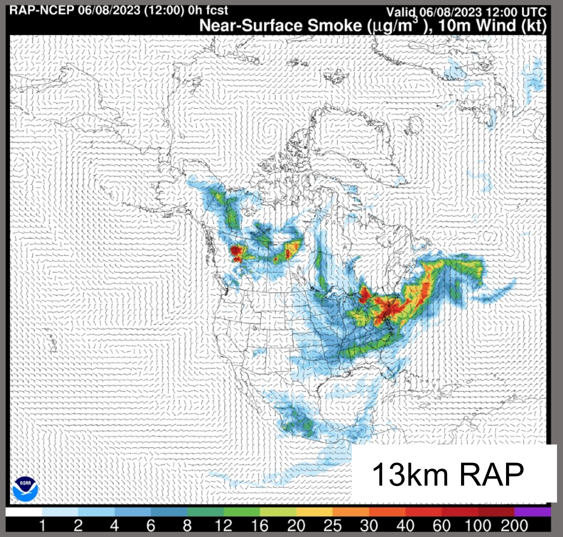


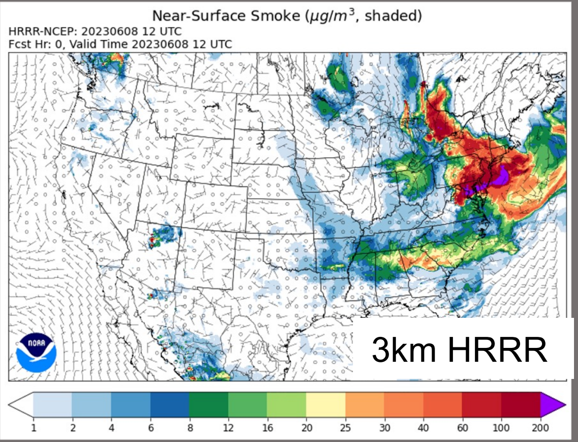




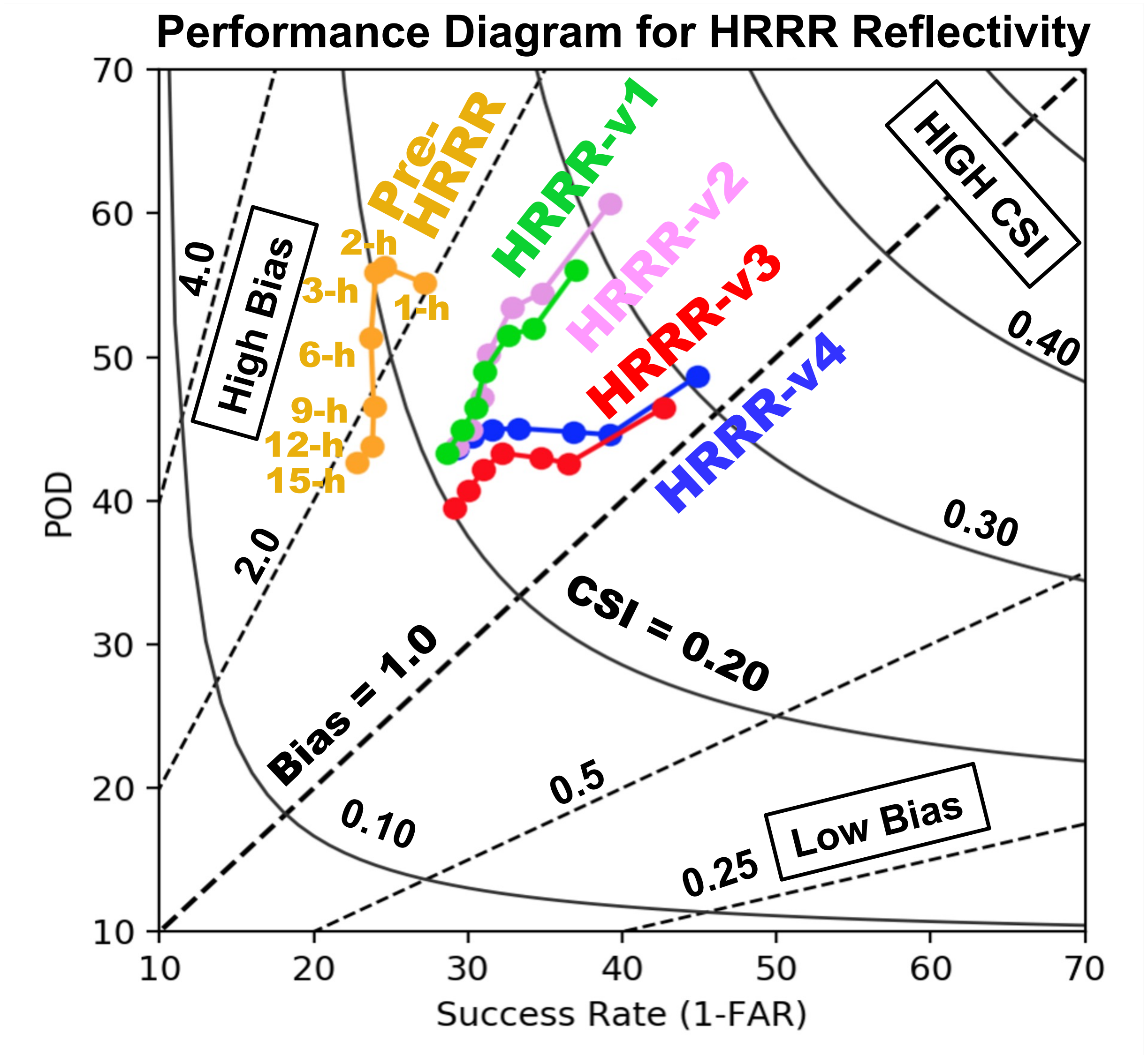
Wind 15 hr forecast at start of Marshall Fire (30 Dec 2021)

Operational Smoke Forecasts



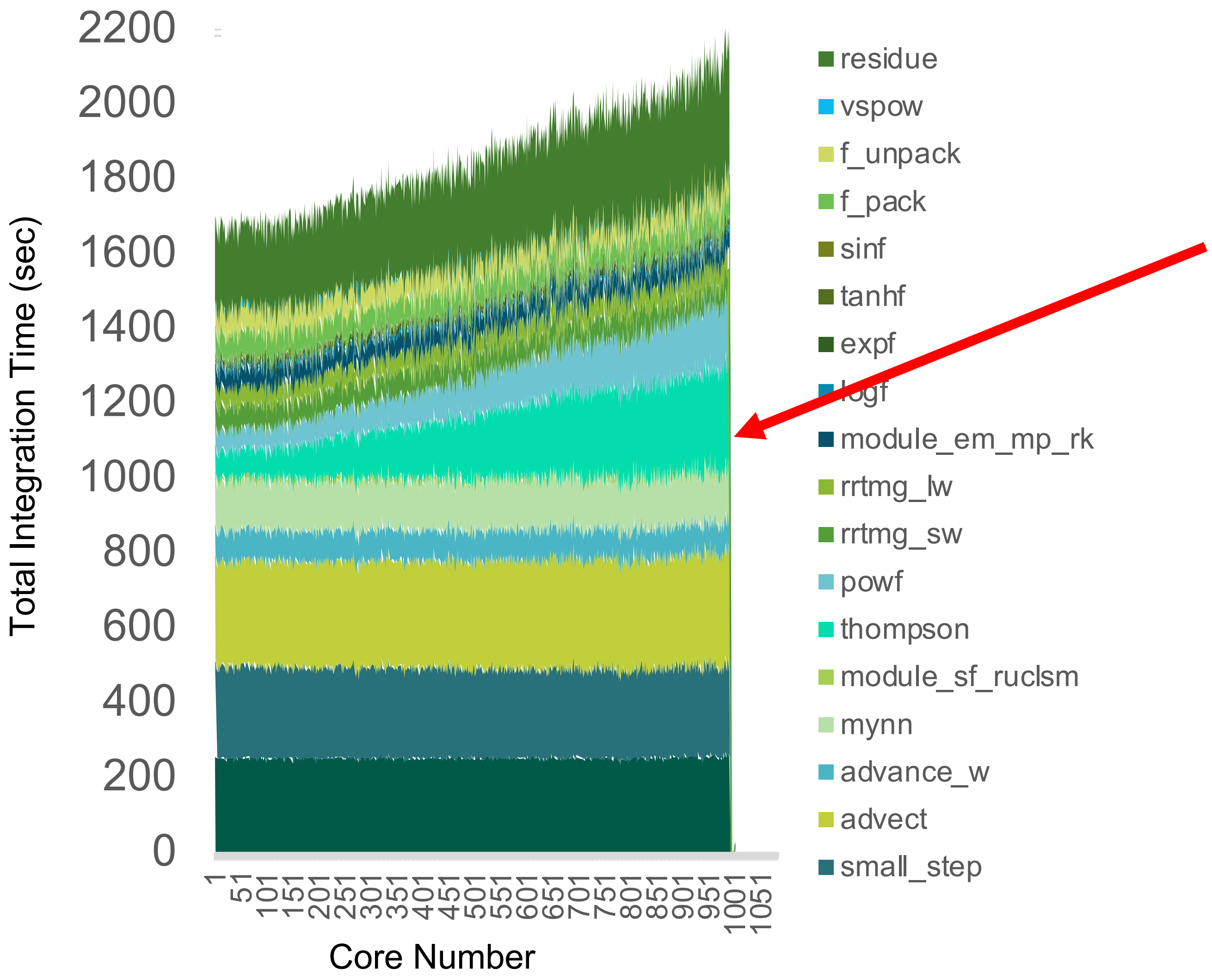


Ongoing Improvements in HRRR Forecasts



- Performance diagram shows CSI / bias
- Illustrates five generations of HRRR skill
- Pre-HRRR: very high bias, low CSI
- HRRRv1: better bias, improved CSI,
- HRRRv2: CSI even better, bias still high
- HRRRv3: bias much better (reduced), some reduction in CSI
- HRRRv4: better CSI, similar bias

HRRR Deconstructed



Original (Starting) Runtime Breakdown:

Thompson **20%**
Microphysics
Not Load Balanced

RRTMG **5%**
Radiation

MYNN 6%
PBL

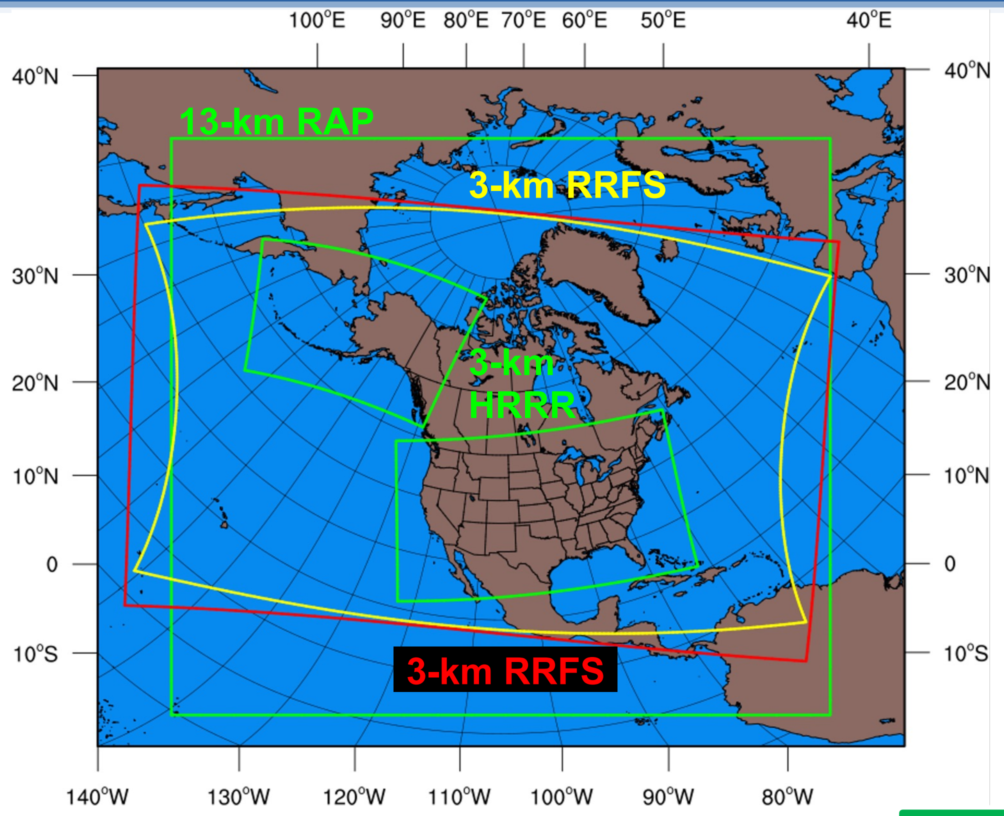
RUC 0.2%
LSM

Dynamics 43%

Other stuff ~25%

Application	Current	Planned upgrades	Target application
Global Weather, Waves & Global Analysis	GFS/GDAS v16.3	GFS v17/ GDAS v17/ GEFS v13/ GODAS v3 — Coupled Reanalysis & Seasonal Reforecast; GFS v18/ GEFS v14/ SFS v1	Medium Range & Subseasonal; Marine & Cryosphere; Seasonal
Global Weather & Wave Ensembles, Aerosols	GEFS v12.3		
Global Ocean Analysis	GODAS v2		
Short-Range Regional Ensembles	SREF v7.1		
Regional Weather (Parent Domain)	NAM v4.2		
Regional Weather (Parent Domain)	RAP v5.1		
Global Ocean & Sea-Ice	RTOFS v2.3		
Seasonal Climate	CDAS2 v1.2 / CFS v2.3		
Regional Hurricane 1	HWRF v13.2	HAFS v1; HAFS v2; HAFS v3; HAFS v4	Hurricane
Regional Hurricane 2	HMON v3.2		
Regional High Resolution CAM 1	HiRes Window v8.1	RRFS v1; RRFS v2/ WoFS v1	Short-Range Regional & Regional Atmospheric Composition
Regional High Resolution CAM 2	NAM nests / Fire Wx v4		
Regional High Resolution CAM 3	HRRR v4.1		
Regional HiRes CAM Ensemble	HREF v3.1		
Regional Air Quality	AQM v6.1	AQM v7	
Regional Surface Weather Analysis	RTMA / URMA v2.10	3DRTMA/URMA v1; 3DRTMA/URMA v2	
Atmospheric Transport & Dispersion	HySPLIT v8.0	HySPLIT v9; HySPLIT v10	Air Dispersion
Coastal & Regional Waves	NWPS v1.4		Coastal
Great Lakes	GLWU v2.0	GLWU v3; GLWU v4	Lakes
Regional Hydrology	NWM v2.1	NWM v3; NWM v4	Hydrology
Space Weather 1 - WAM / IPE	WFS v1.0	WFS v2	Space Weather
Space Weather 2	ENLIL v1		
EMC Verification System	—	EVS v1; EVS v2; EVS v3	Verification

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

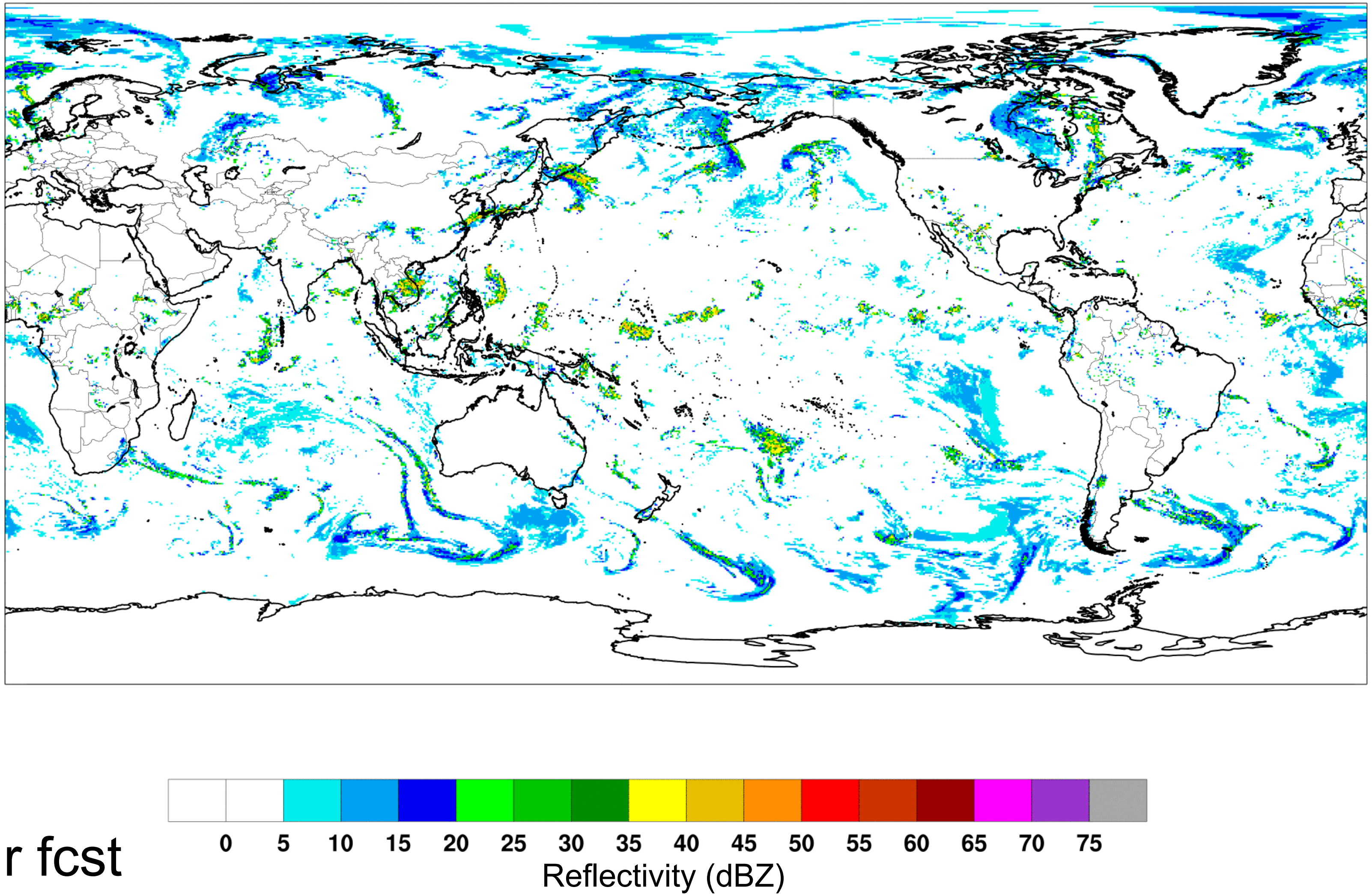
RAP 13-km
953x834x50
(794,802)x50
300MB/3Dnative file
Rotated Lat-Lon

Global Rapidly Updating Storm-Scale Model

Global storm-scale (3 km) forecasts with scale-aware physics suite:

- SW/LW Radiation: RRTMG
- Microphysics: Thompson
- Boundary Layer: MYNN
- Surface Layer: GFS
- Land Surface Model: Noah

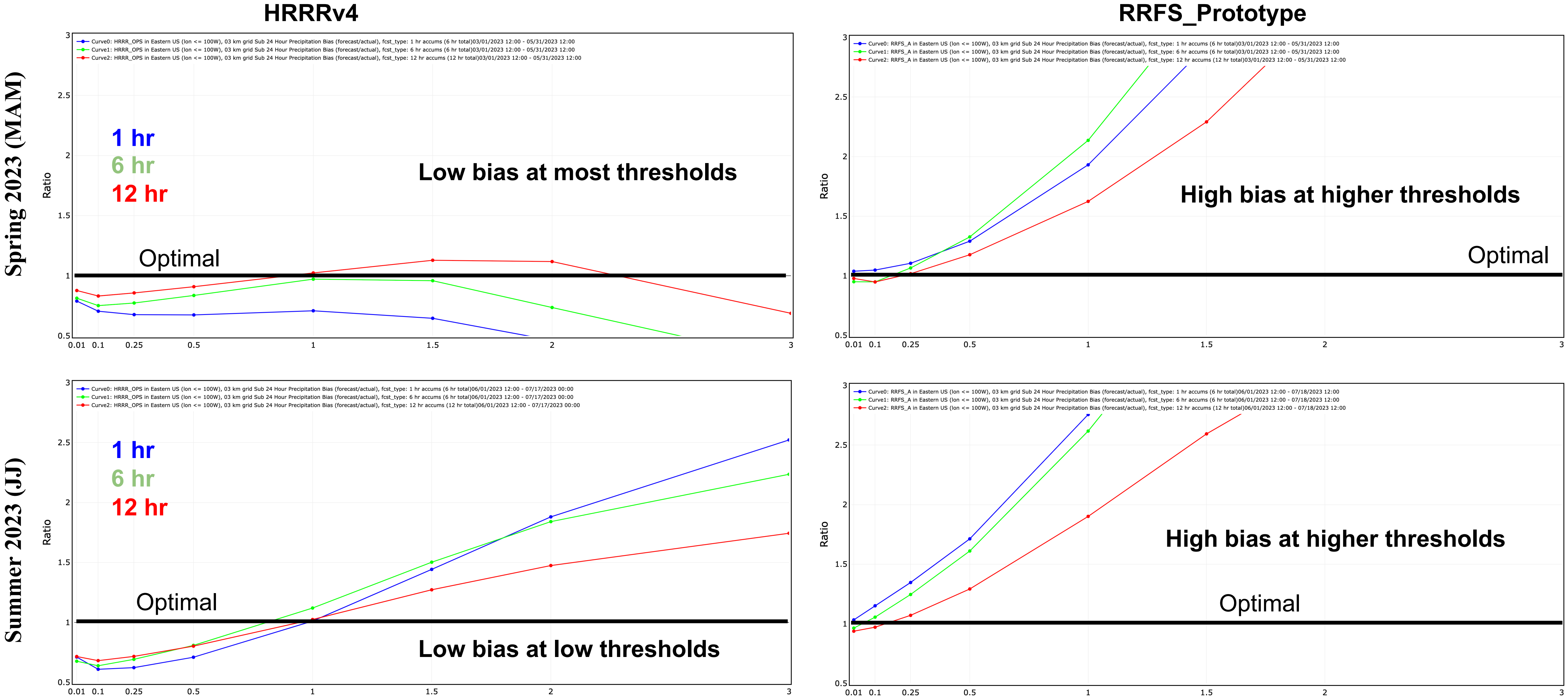
00 UTC 29 Aug 2019 1 km AGL Simulated Radar Reflectivity 0-96 hr 3 km Forecast



96 hr (4 day) global 3 km fcst
13,068 processors (363 nodes)
6 hrs of wall clock time per 24 hr fcst

RRFSv1 Challenges: QPF Warm Season Bias

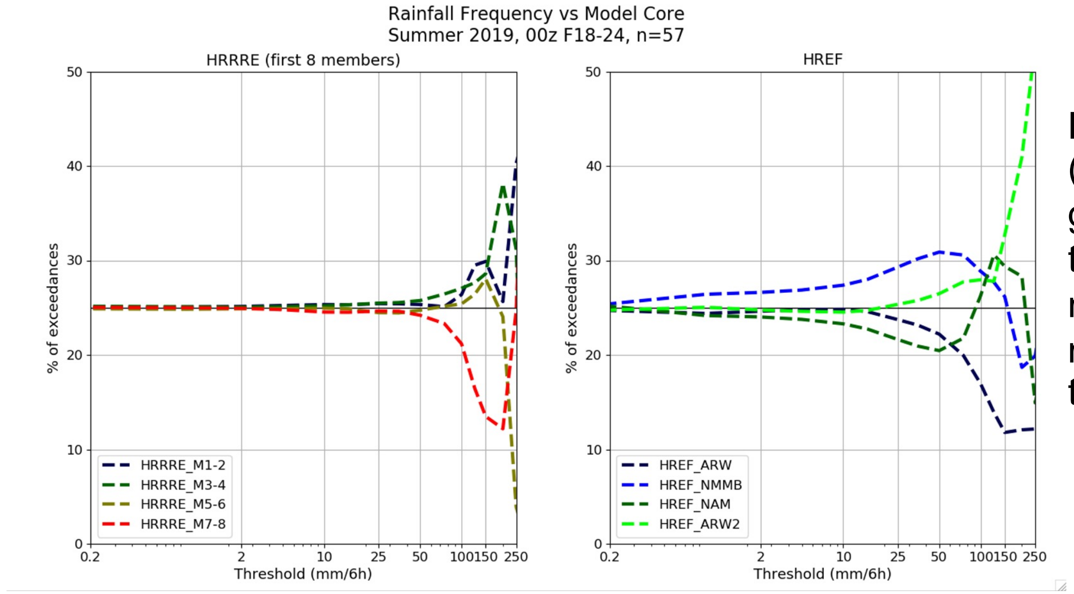
3 km Eastern CONUS QPF Frequency Bias 2023



Forecast Ensemble Characteristics

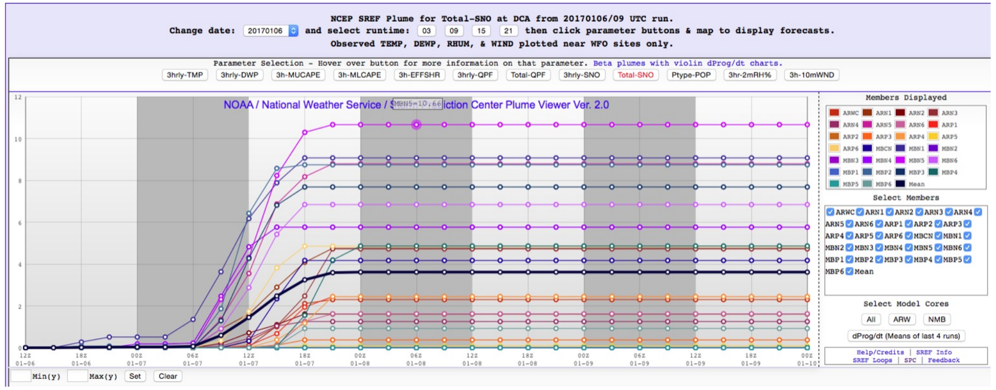
- Deterministic forecasts represent only one possible realization of a forecast outcome "i.e. swing and hit/miss"
- Model forecast ensembles are a common technique to (potentially) capture all possible forecast outcomes (spread)
  - Each ensemble member solution equally likely
  - Diversity of solutions proportional to mean forecast error of day
  - Control (deterministic) member solution should fall within envelope of all member solutions

- **UFS provides common model framework to compose single model ensembles and address challenge of underdispersion**
- Ensemble design is active research:
  - Initial and/or lateral boundary perturbations
  - Time-lagging across multiple initialization cycles
  - Multi- and/or stochastically perturbed physics
  - Multimodel (dynamic core diversity)



CONUS forecasted precipitation biases between members for a single-model ensemble (left) and multi-model HREF ensemble (right)

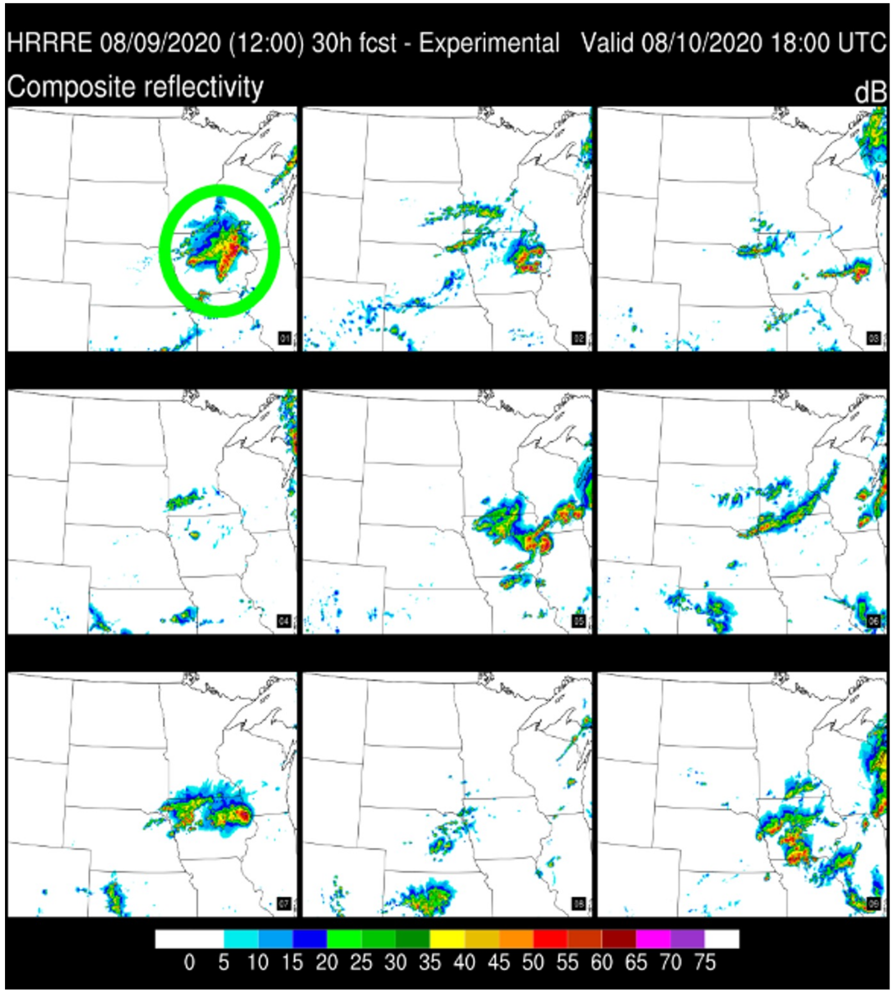
Regional ensembles (SREF and HREF) can generate "artificial" spread through biases resulting in multi-modal distributions or regularly favored members that are not ideal



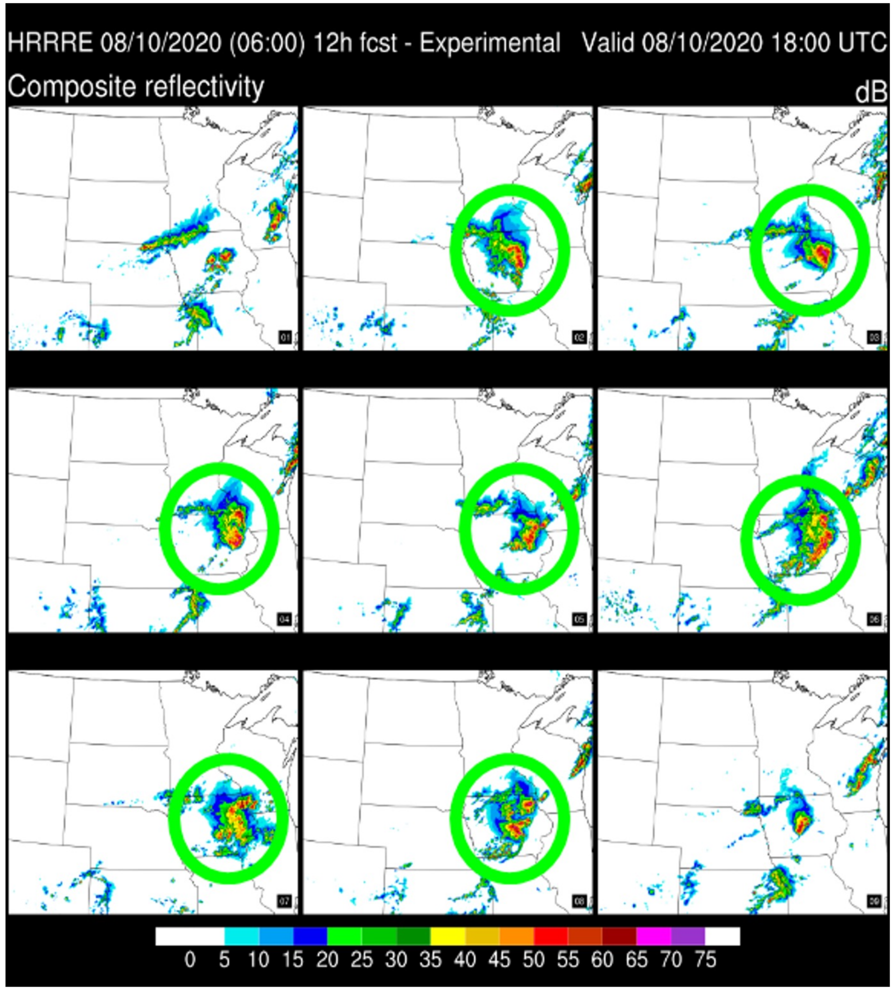
Forecasted snowfall timeseries at DCA across multi-model SREF ensemble with separation by model above/below mean (black)

Ensemble DA & Forecasting ⇒ Better Probabilities

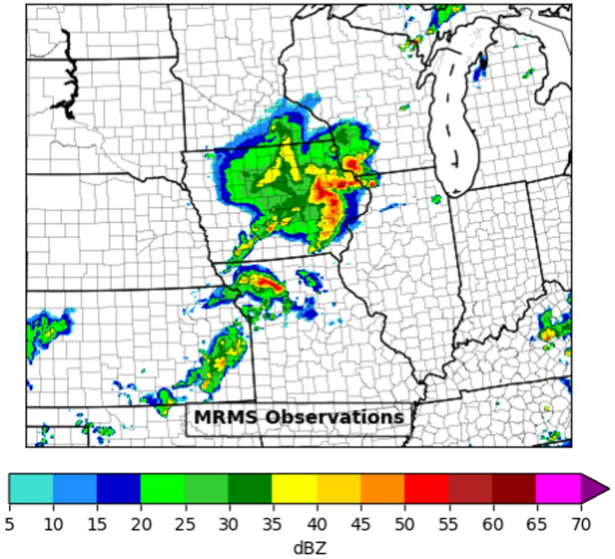
30-h lead-time: get 1 hit



12-h lead-time: 7 of 9 hits

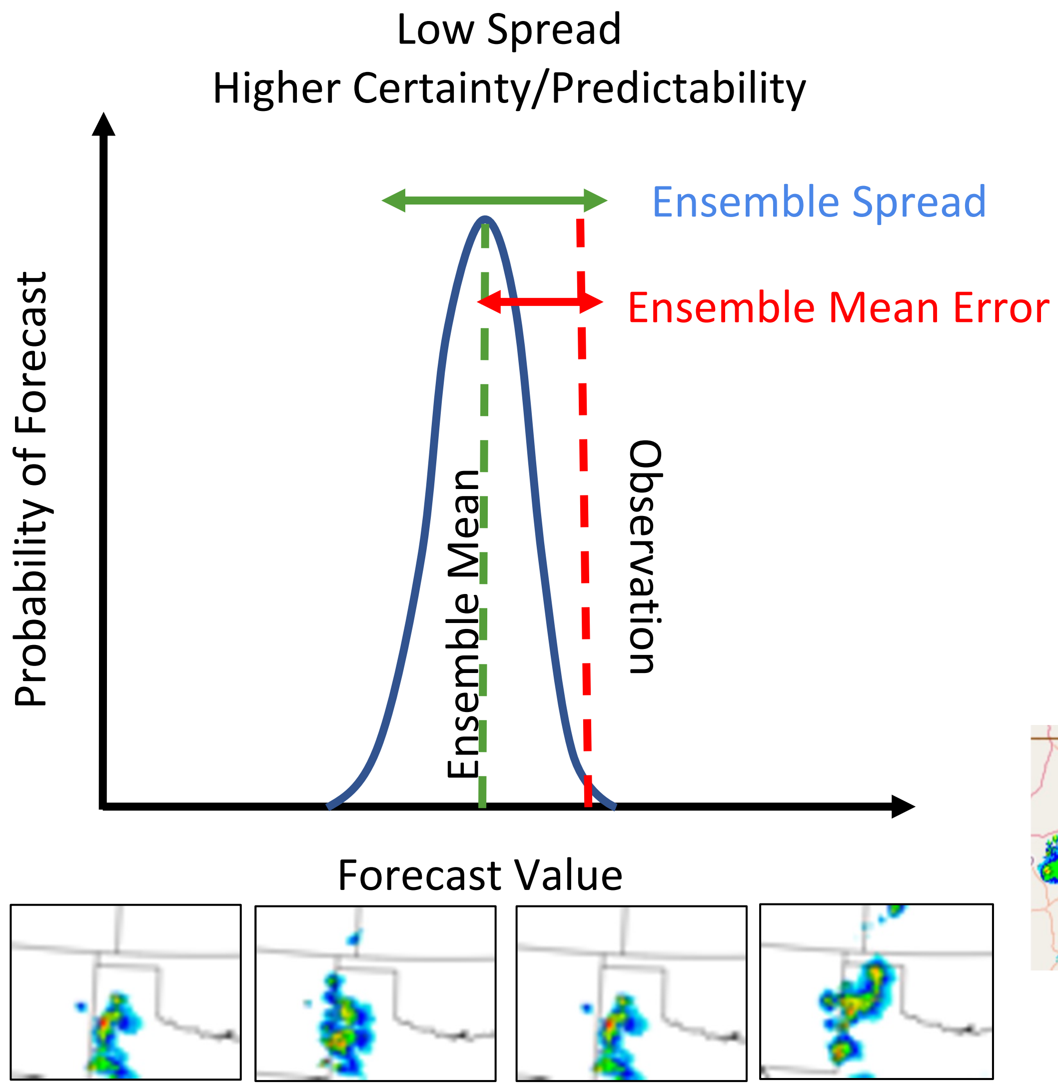


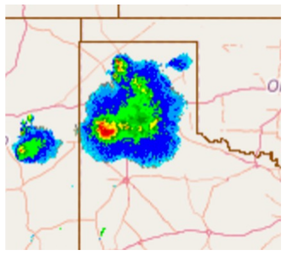
Radar observations

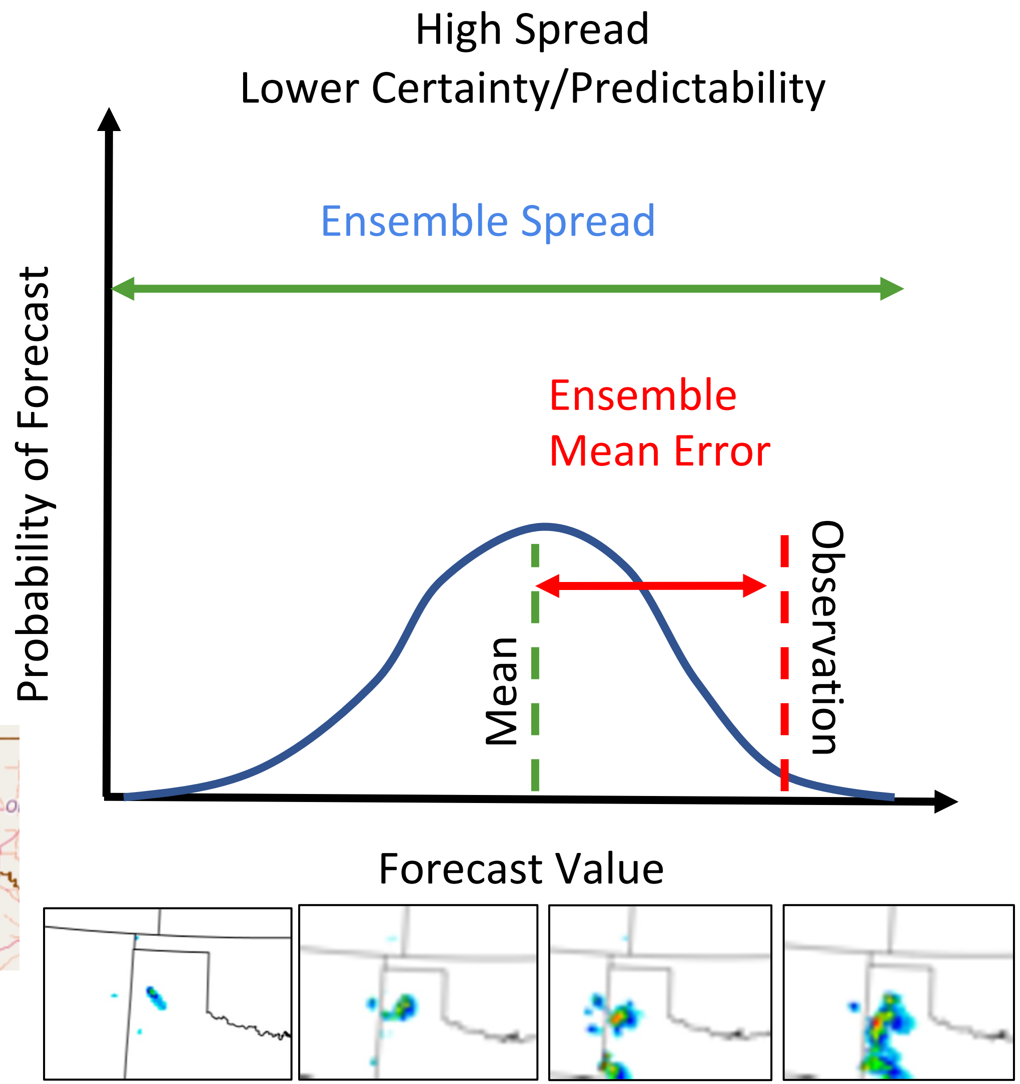


- Longer forecasts show low likelihood for a large impact event
- Shorter forecasts decreased spread, increased confidence
- Stochastic physics to create spread

Ensemble Forecast Challenge: Spread vs Error

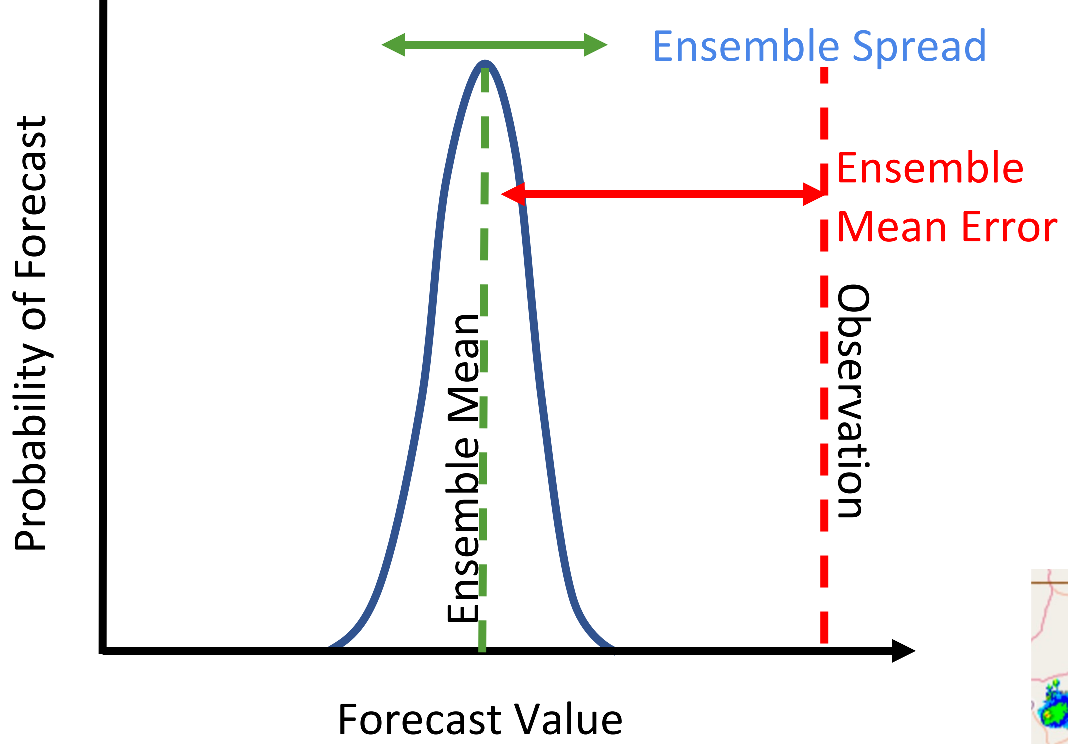


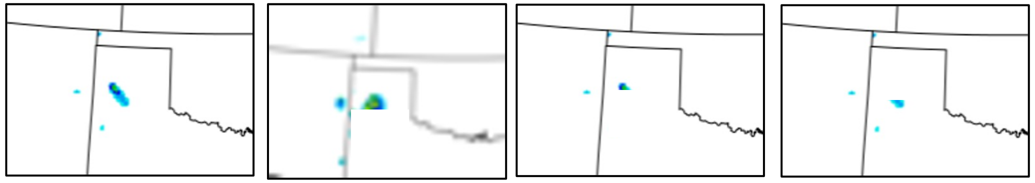


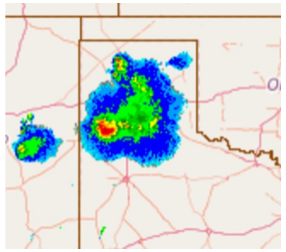


Ensemble Forecast Challenge: Spread vs Error

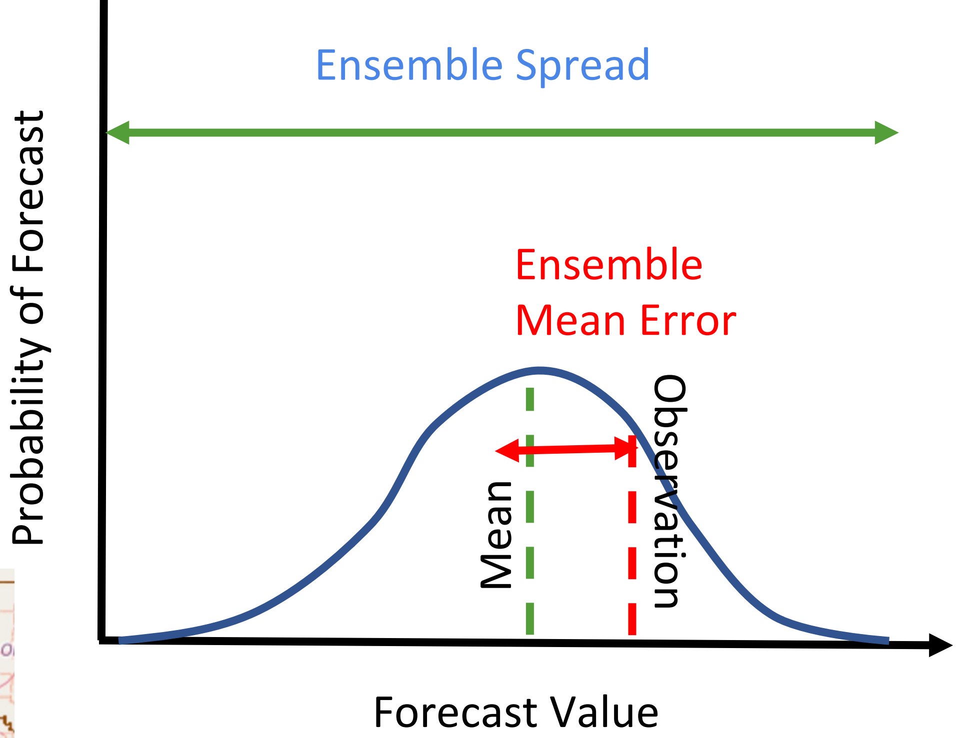
Underdispersive:
Observations frequently fall outside range of ensemble forecasts







Overdispersive:
Ensemble frequently forecasts a very large range of forecasts



SRW/CAM Forecast Verification Metrics

FIELD	LEVEL	DETERMNISTIC METRIC	ENSEMBLE METRIC	PROBABILISTIC METRIC	TEMPORAL ATTRIBUTE	NOTABLE THRESHOLDS	REGION	VERIFICATION APPROACH	VALIDATION SOURCE	CLIMATOLOGY SOURCE
TIER 1										
Heights	Profile	BCRMSE + Bias	RMSE of Ens. Mean + Ensemble Spread	ROC + Reliability + BSS	3-Hourly		Full Domain	Grid-to-obs	Raobs + Aircraft	
Temperature	Profile	BCRMSE + Bias	RMSE of Ens. Mean + Ensemble Spread	ROC + Reliability + BSS	3-Hourly	0ºC for 850 temps, 12ºC for 700 temps	Full Domain	Grid-to-obs	Raobs + Aircraft	
U and V Wind Components	Profile	BCRMSE + Bias	RMSE of Ens. Mean + Ensemble Spread	ROC + Reliability + BSS	3-Hourly	30, 40 kt at 700-hPa 50 kt at 850-hPa	Full Domain	Grid-to-obs	Raobs + Aircraft	
Specific Humidity	Profile	BCRMSE + Bias	RMSE of Ens. Mean + Ensemble Spread	ROC + Reliability + BSS	3-Hourly	15 g/kg at 850 and 925-hPa	Full Domain	Grid-to-obs	Raobs + Aircraft	

https://dtcenter.org/events/2021/2021-dtc-ufs-evaluation-metrics-workshop/final-metrics-lists

SRW/CAM Forecast Verification Metrics

FIELD	LEVEL	DETERMNISTIC METRIC	ENSEMBLE METRIC	PROBABILISTIC METRIC	TEMPORAL ATTRIBUTE	NOTABLE THRESHOLDS	REGION	VERIFICATION APPROACH	VALIDATION SOURCE	CLIMATOLOGY SOURCE
TIER 2										
Precipitation	Surface	Total Interest (MODE), FSS, and Contingency Table Counts	FSS + CTC + Rank Histogram	Reliability Diagram	Hourly to f24 and then 3-hourly, also 24-hourly	3h: 0.25", 0.5", 1" (include 0.1" in winter) and 24h: 1" and 2" (include 0.5" in winter)	CONUS divided into fourths + Alaska	Grid-to-grid, grid-to-obs	CCPA	
Temperature	Sfc/2-m	BCRMSE + Bias	RMSE of Ens. Mean + Ensemble Spread + Ranked Histogram	ROC + Reliability + BSS	Hourly to f24 and then 3-hrly	0ºC, 60ºF (when paired with high Td)?	CONUS divided into fourths + Alaska	Grid-to-obs	METARS + some mesonet + marine obs	
Wind	Sfc/10-m	BCRMSE + Mean Error Bias	RMSE of Ens. Mean + Ensemble Spread + Ranked Histogram	ROC + Reliability + BSS	Hourly to f24 and then 3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	METARS + some mesonet + marine obs	
Dew Point	Sfc/2-m	BCRMSE + Threshold Bias (do not compute stats for low values)	RMSE of Ens. Mean + Ensemble Spread	ROC + Reliability + BSS	Hourly to f24 and then 3-hrly	50, 60, 70ºF (possibly 40 and 50 in the west?); need lower threshold for fire wx	CONUS divided into fourths + Alaska	Grid-to-obs	METARS + some mesonet + marine obs	
Wind Speed	Sfc/10-m	BCRMSE + Bias	RMSE of Ens. Mean + Ensemble Spread + Ranked Histogram	ROC + Reliability + BSS	Hourly to f24 and then 3-hrly	25, 34, 48 kt (marine) 30 kt (blizzard) 20 (fire wx)	CONUS divided into fourths + Alaska	Grid-to-obs	METARS + some mesonet + marine obs	
Simulated Reflectivity	Composite	Fractions Skill Score	FSS (of neighborhood max - 40 km radius)	Fractional Skill Score + Reliability Cuve	Hourly (perhaps sub-hourly for the first few hours?)	30, 40, 50 dbz and 20 for snow	CONUS divided into fourths + Alaska	Grid-to-grid	MRMS Mosaic Composite	
Updraft Helicity	2-5 km	FSS, CTC	RMSE of Ens. Mean + Ensemble Spread	BSS + Reliability + ROC	24-hrly	99th percentile	SPC Convective Outlook areas of "Marginal" or greater	Grid-to-grid	SPC storm reports	Model's Own Climatology
PBL Depth	N/A	BCRMSE + Mean Error Bias	RMSE of Ens. Mean + Ensemble Spread	BSS	Hourly to f24 and then 3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	RAOBs, METAR Ceilometer, ACARS	
Visibility	Sfc	Contigency Table Counts	FSS + CTC + Rank Histogram	Fractional Skill Score + Reliability Cuve	Hourly	flight rules	CONUS divided into fourths + Alaska	Grid-to-obs	METARS	
Latent Heat Flux	Surface	BCRMSE + Bias	RMSE of Ens. Mean + Ensemble Spread	Reliability Diagram	Hourly to f24 and then 3-hrly		North America/CONUS + finer granularity (NCDC)	Grid-to-obs	State Mesonets, SGP ARM, AmeriFlux	

SRW/CAM Forecast Verification Metrics

FIELD	LEVEL	DETERMNISTIC METRIC	ENSEMBLE METRIC	PROBABILISTIC METRIC	TEMPORAL ATTRIBUTE	NOTABLE THRESHOLDS	REGION	VERIFICATION APPROACH	VALIDATION SOURCE	CLIMATOLOGY SOURCE
TIER 3										
Precipitation Type	Sfc	CTC + FSS	FSS (of neighborhood max - 40 km radius) + Rank Histogram	Reliability Diagram	Hourly to f24 and then 3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	METARS + mPING	
Snowfall Accumulation	Sfc	FSS+CTC	FSS + CTC + Rank Histogram	FSS + Reliability Curve	6h, 24h	2-4-8 (6-hrly) 2-5-10 (24-hrly)	CONUS divided into fourths + Alaska	Grid-to-obs	NOHRSC	
Sea Level Pressure	Surface	BCRMSE + Mean Error Bias	RMSE of Ens. Mean + Ensemble Spread + Ranked Histogram	ROC + Reliability + BSS	Hourly to f24 and then 3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	METARS + some mesonets	
Surface-Based CAPE	Surface Parcel	CTC	RMSE of Ens. Mean + Ensemble Spread	Reliability Curve	3-hrly	500, 1000, 2000 (and 250 for low CAPE SVR)	CONUS divided into fourths + Alaska/North America/SPC Convective Outlook Areas	Grid-to-obs	RAOBs + aircraft	
Ceiling	N/A	CTC	Contigency Table Counts	FSS + CTC + Rank Histogram	Hourly to f24 and then 3-hrly	flght rules	CONUS divided into fourths + Alaska	Grid-to-obs	METARS	
Deep Layer Shear	0-6 km	Fraction skill score	Reliability	Reliability Curve	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	RAOB and aircraft data	
Updraft Helicity	0-3 km	FSS, CTC	RMSE of Ens. Mean + Ensemble Spread	BSS + Reliability + ROC	24-hrly	99th percentile	SPC Convective Outlook areas of "Marginal" or greater	Grid-to-grid	SPC storm reports	Model's Own Climatology
Cloud Fraction	Total	CTC + FSS	CTC + FSS + Ensemble Spread	Reliability+ROC	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	Satellite- derived cloud fraction (GOES, VIIRS)	
Soil Moisture	0-10 cm	Bias	RMSE of Ens. Mean + Ensemble Spread	BSS	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	International Soil Moisture Network and Soil Climate Analysis Network	
Soil Temperature	0-10 cm	Bias	RMSE of Ens. Mean + Ensemble Spread	BSS	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	International Soil Moisture Network and Soil Climate Analysis Network	

SRW/CAM Forecast Verification Metrics

FIELD	LEVEL	DETERMNISTIC METRIC	ENSEMBLE METRIC	PROBABILISTIC METRIC	TEMPORAL ATTRIBUTE	NOTABLE THRESHOLDS	REGION	VERIFICATION APPROACH	VALIDATION SOURCE	CLIMATOLOGY SOURCE
TIER 4										
Lapse Rates	0-3 km	RMS Error	RMSE of Ens. Mean + Ensemble Spread	BSS	Hourly		North America/CONUS divided into fourths + Alaska	Grid-to-obs	RAOBs	
Wind Shear	0-2 km	Contingency Table Counts, Equitable Threat Score. Treat as a continuous variable in addition to categorical (FBias, Bias, RMSE)	RMSE of Ens. Mean + Ensemble Spread	CRPSS	Hourly to f24 and then 3-hrly		CONUS divided into fourths + Alaska	Grid-to-grid and grid-to-obs	SPC mesoanalysis/3DRTMA, RAOBs, VAD winds	
Time-Derived Height (Falls/Rises)	500-hPa	RMSE + Mean Error Bias	RMSE of Ens. Mean + Ensemble Spread	BSS	3-hrly		CONUS divided into fourths + Alaska + Some sort of HI/PR region	Grid-to-grid and grid-to-obs	ECMWF Analysis / RAOB data	
Cloud Fraction	Low	CTC + FSS	CTC +FSS + Ensemble Spread	Reliability + ROC	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	Satellite-derived cloud fraction (GOES, VIIRS)	
Cloud Fraction	Middle	CTC + FSS	CTC +FSS + Ensemble Spread	Reliability + ROC	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	Satellite-derived cloud fraction (GOES, VIIRS)	
Cloud Fraction	High	CTC + FSS	CTC +FSS + Ensemble Spread	Reliability + ROC	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	Satellite-derived cloud fraction (GOES, VIIRS)	
Sensible Heat Flux	Surface	BCRMSE Error, Bias	RMSE of Ens. Mean + Ensemble Spread	BSS	Hourly to f24 and then 3-hrly		North America/CONUS + finer granularity (NCDC)	Grid-to-obs	State Mesonets, SGP ARM, AmeriFlux	
Soil Moisture	10-40 cm	Bias	RMSE of Ens. Mean + Ensemble Spread	BSS	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	International Soil Moisture Network and Soil Climate Analysis Network	
Soil Temperature	10-40 cm	Bias	RMSE of Ens. Mean + Ensemble Spread	BSS	3-hrly		CONUS divided into fourths + Alaska	Grid-to-obs	International Soil Moisture Network and Soil Climate Analysis Network	
Relative Humidity	Sfc/2-m	BCRMSE + Threshold Bias	RMSE of Ens. Mean + Ensemble Spread	ROC + Reliability + BSS	Hourly to f24 and then 3-hrly	25,50,75	CONUS divided into fourths + Alaska	Grid-to-obs	METARS + some mesonet + marine obs	

SRW/CAM Summary

- CAMs provide precision and details for a variety of high-impact weather hazards
- CAM precision does come with some accuracy challenges – time-space displacements, precip biases
  - → AI pattern recognition/bias correction
- CAM expense significant (compared to coarser regional/global) in compute, storage and dissemination
  - → AI component replacement
- Established community metrics for evaluating CAM performance
  - → AI performance for discrete/categorical measures
- Desire for more efficiency in running CAMs (GPUs, AI, etc…)
  - → AI component replacement
- Need for more DA/forecast ensemble members and improved ensemble design
  - → AI hybrid/augmentation
- Desire for storm-scale CONUS analysis (~1 km, 3D, 15 min?) reanalysis dataset
- Questions about CAM dataset fragility given frequent changes to model physics/DA and dycore?
  - → AI training needs/robustness