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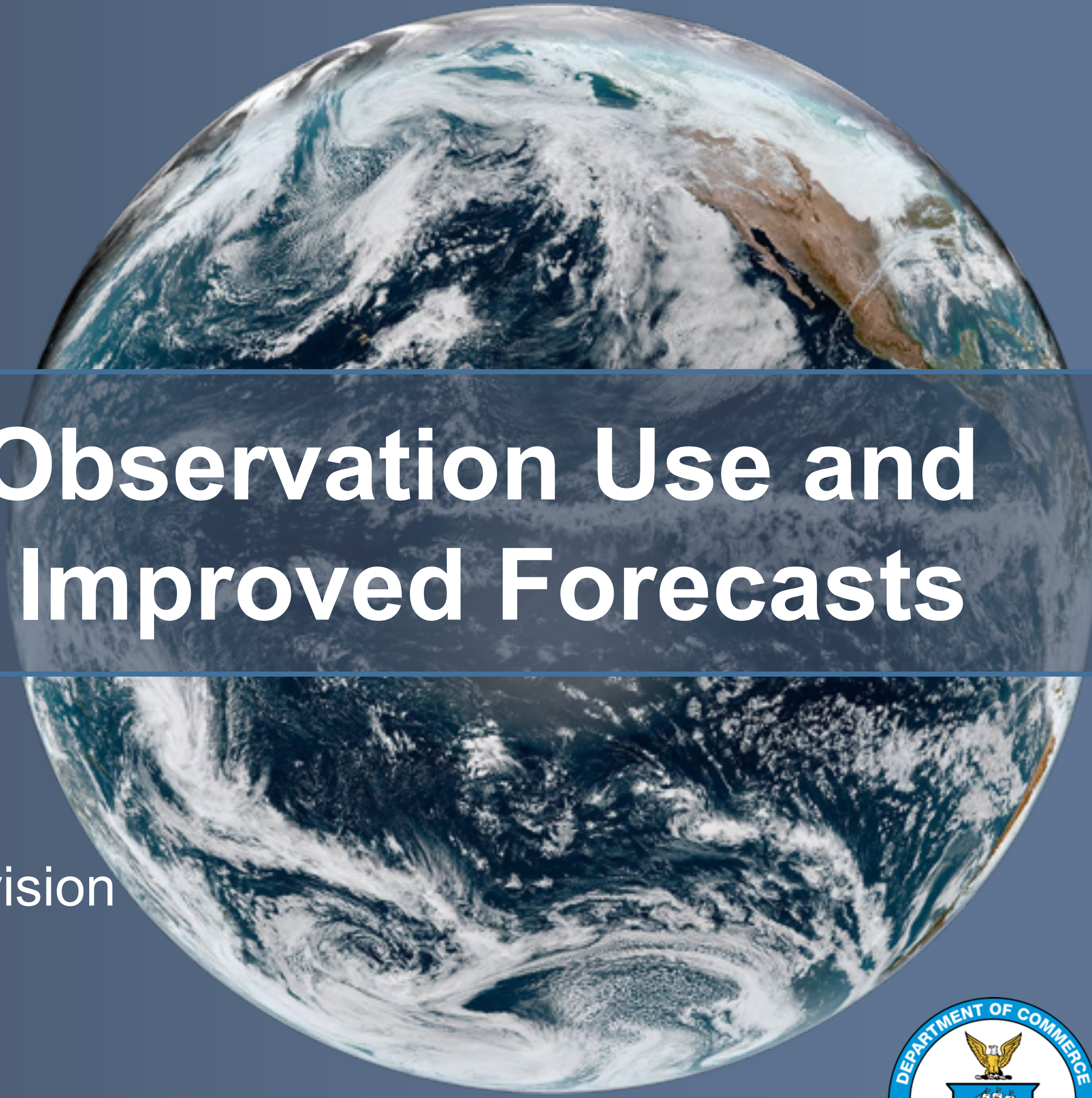


Earth System Prediction: Observation Use and Analysis Development for Improved Forecasts

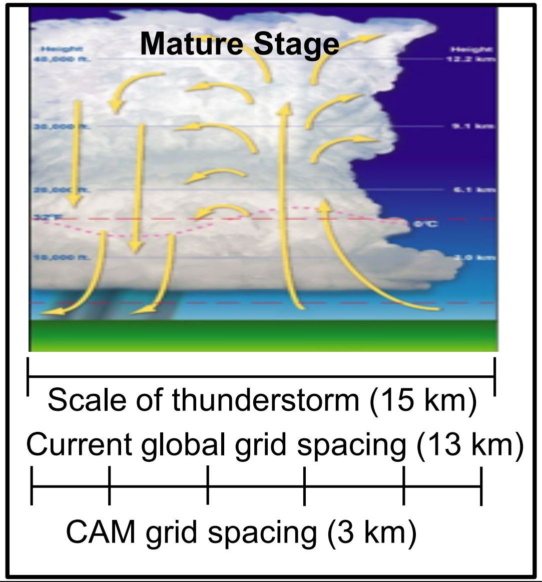
Curtis Alexander
Chief, Assimilation and Verification Innovation Division

Global Systems Laboratory

Regional Data Assimilation and NWP

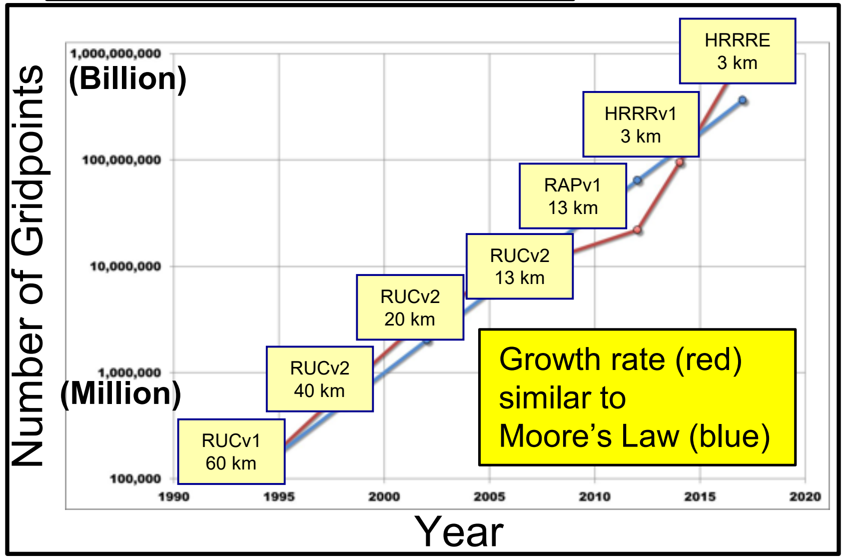
Why Convection Allowing Models (CAMs)?

- 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



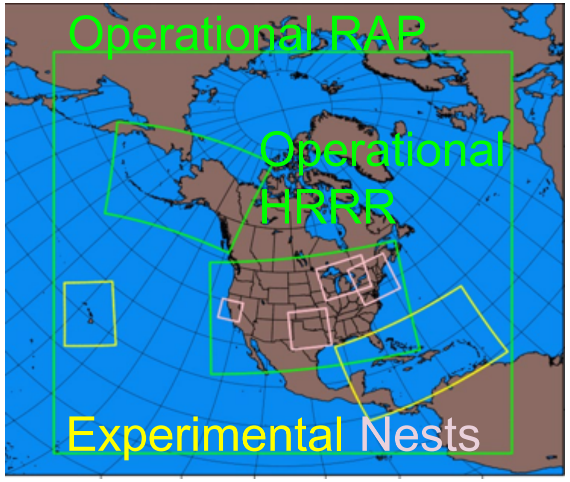
Why Limited Area Models (LAMs)?

- 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



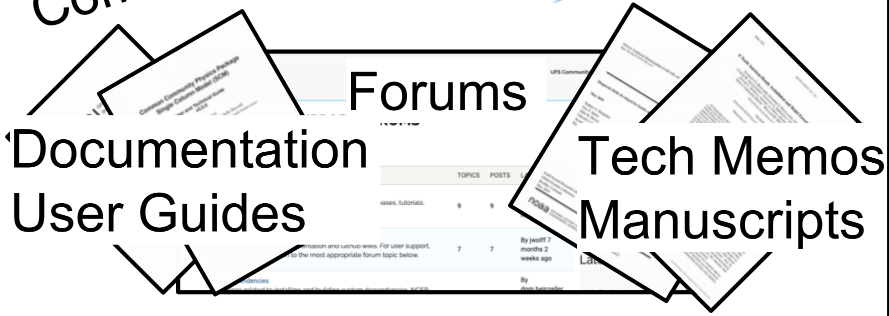
Regional Modeling Excellence in GSL

Quality of Research



Community Software Contributions

WRF GSI JEDI CCPP



Forums

Documentation
User Guides

Tech Memos
Manuscripts

Relevance to Communities

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

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

Hydrology and Quantitative
Flash Flood Watches/Meso
National Water Model Forci
Heavy Rain/Snow Outlooks
WPC, OWP, GLERL, PSL,

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

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

Organizational Performance

From 2012-2020:
Five RAP operational transitions
Four HRRR operational transitions

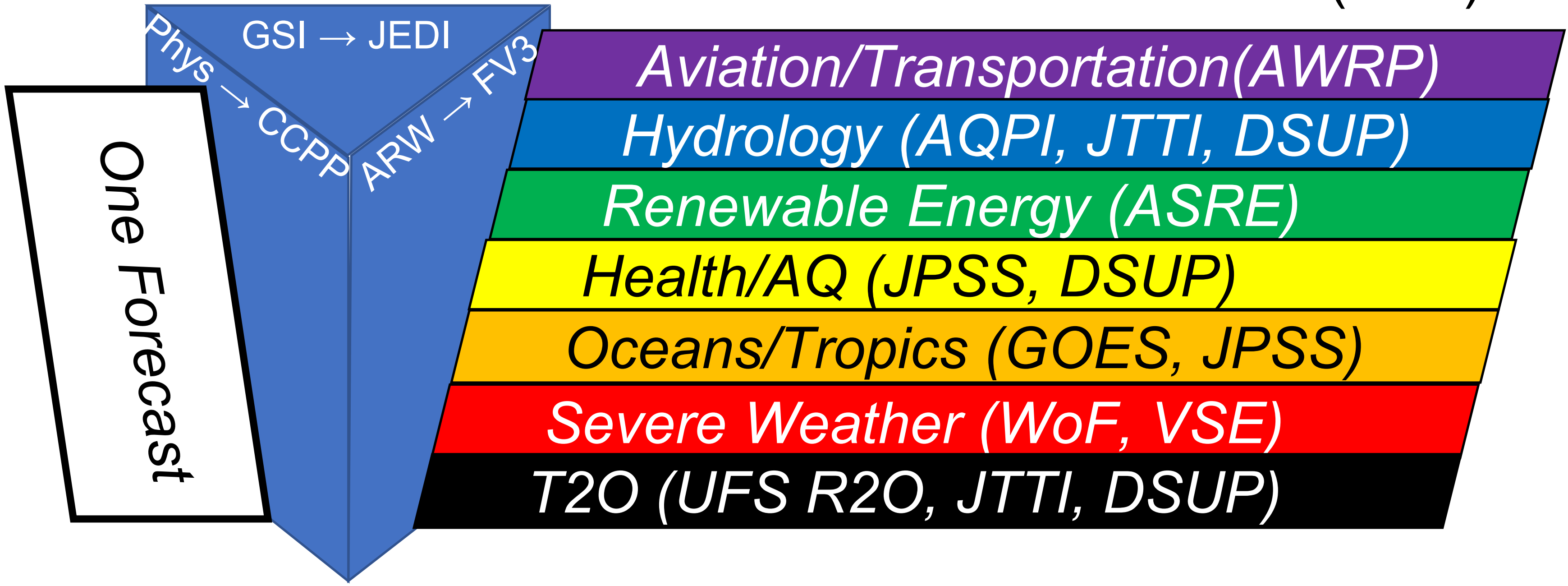
With each transition:
Added DA/model sophistication
+
Increasing R2O efficiency
=
Doubling of R2O capacity every two years "GSL's Law"

Data Assimilation: GSL Making Forecasts Better

Seamless collaboration across divisions within GSL, CIs, OAR labs, NWS and external organizations

Doubling of DA staff to ~15 in last five years

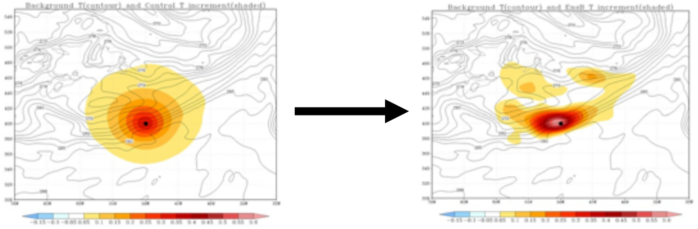
World-Class RAP/HRRR → Next Generation RRFS (UFS)



Observations and Impacts (Eric James)

\+

Analysis Development (Terra Ladwig)



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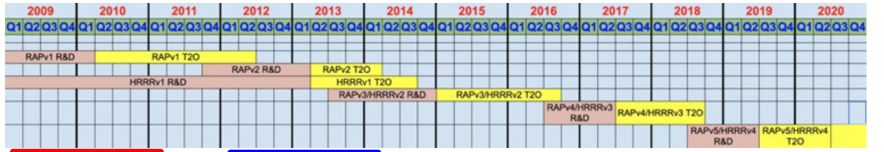
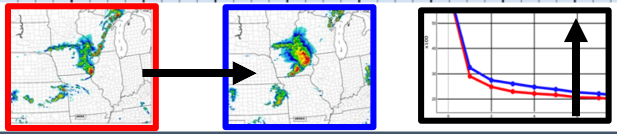
Improved Weather Prediction (Steve Weygandt)





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Observations & Their Impacts

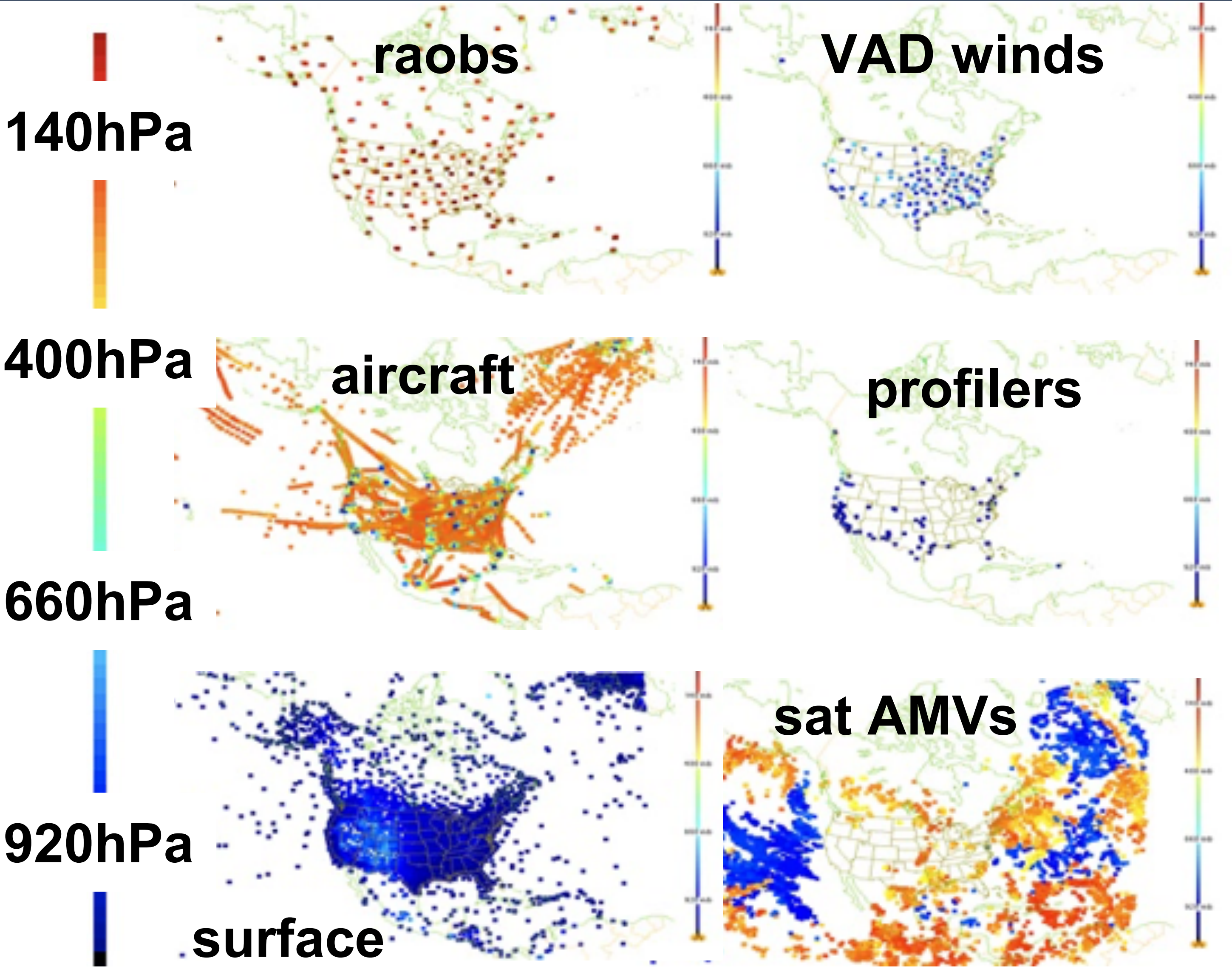
Eric James
Senior Research Associate, Assimilation and Verification Innovation Division

Global Systems Laboratory

Weather Observations for Analysis/Fcst Systems

- Effective rapidly-updating analysis/forecast systems ***depend critically*** upon optimal use of observations:
  - **Verification**
  - **Data Assimilation**

- Quantifying obs impacts ensures an **effective data assimilation system,** and **identifies opportunities for expansion.**

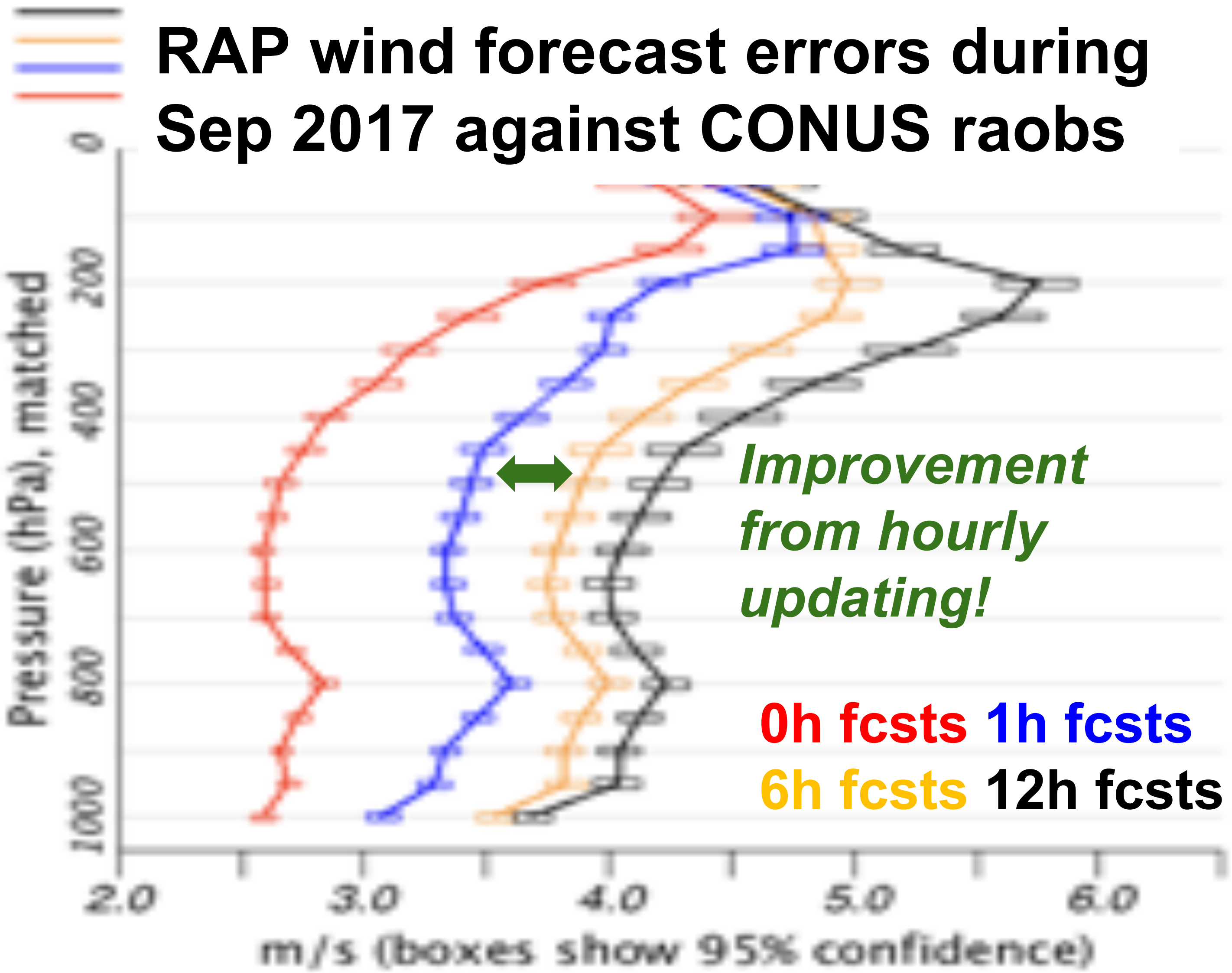


Why run rapidly updating NWP models?

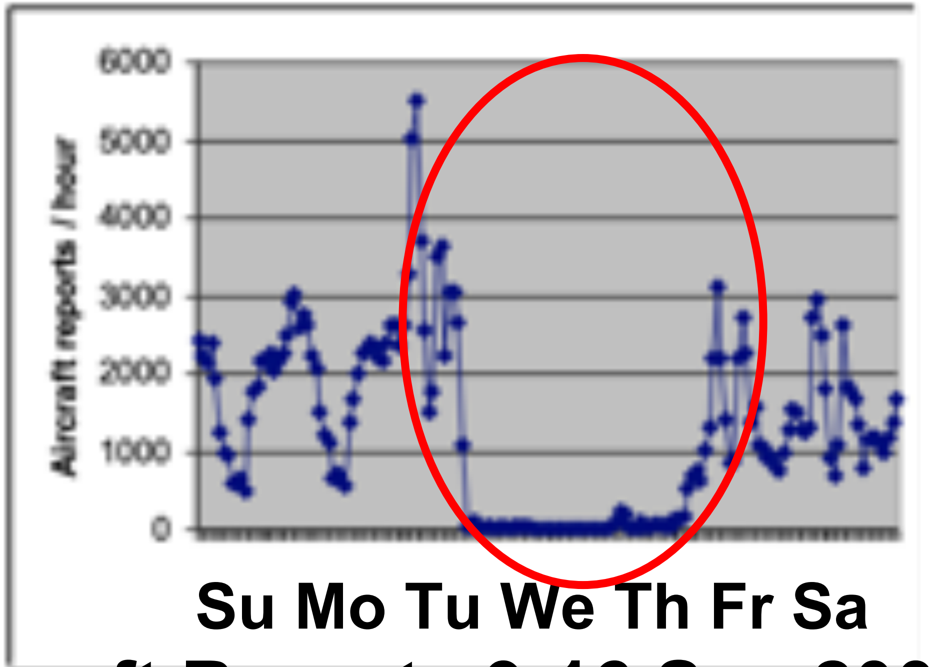
Frequent updates allow:

- Use of the **most recent weather observations** for improved forecasts.
- **Updated information** for decision makers.

RAP wind forecast errors during Sep 2017 against CONUS raobs

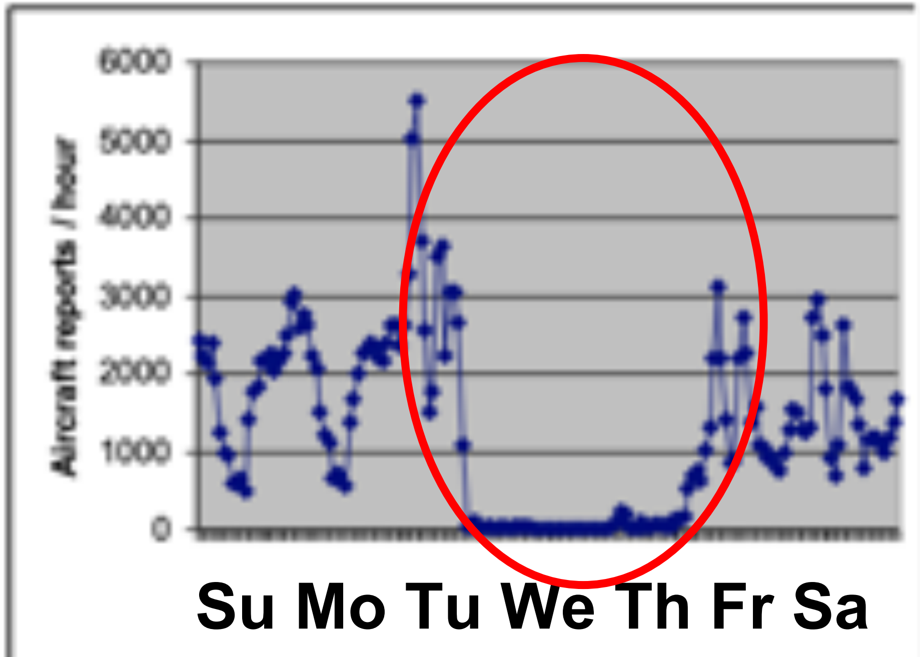


Why run rapidly updating NWP models?



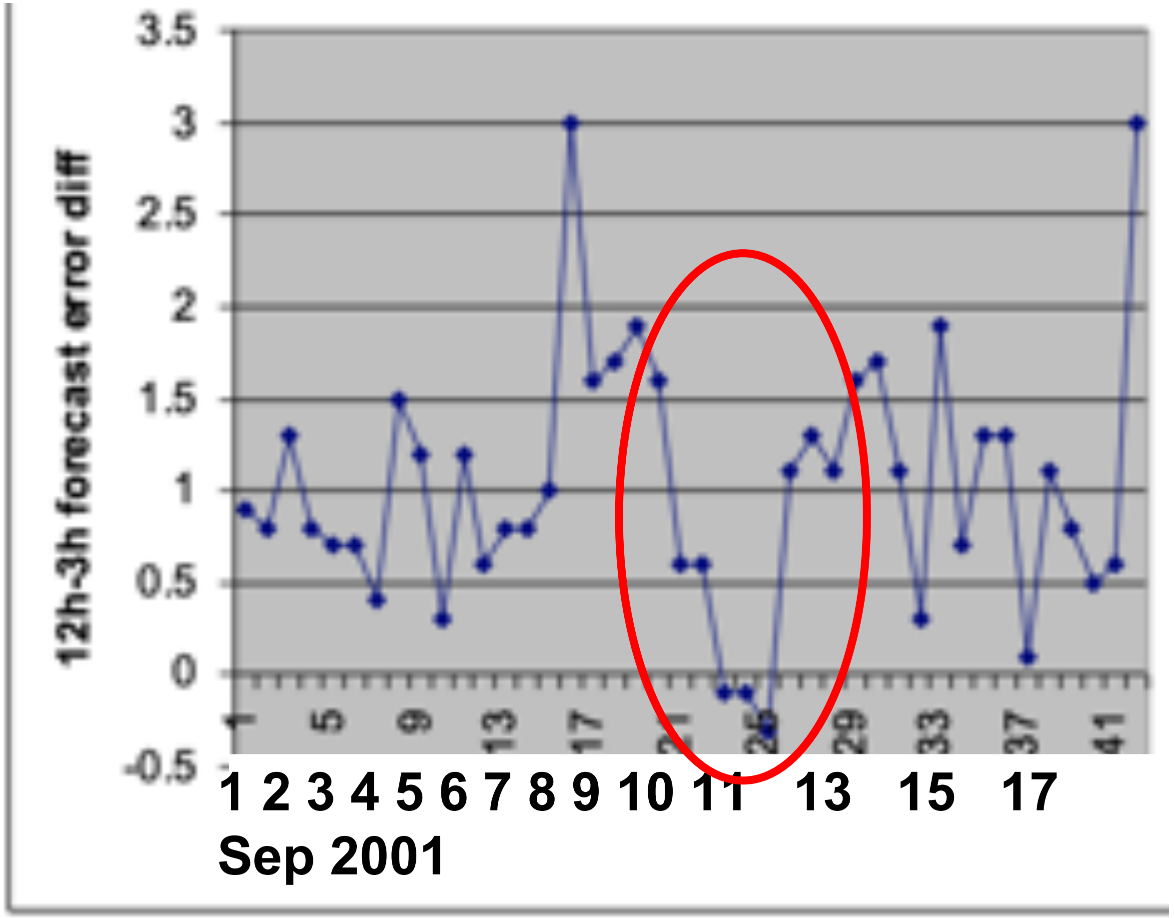
Aircraft Reports 9-16 Sep 2001

Why run rapidly updating NWP models?



Aircraft Reports 9-16 Sep 2001

250hPa wind forecasts: difference in error: 12h fcst err - 3h fcst err



Without any aircraft reports, ***3h forecast errors are just as large as 12h forecast errors!***

Monitoring and Quality Control of Observations

Observation quality monitoring carried out via realtime **O minus B** statistics (**O**bservation minus **B**ackground)

Differences over time are used to construct dynamic lists for use or rejection of observations, for surface mesonet and aircraft observations.

Example: temperature bias (bs_T) exceeding 2.0 K warrants rejection:

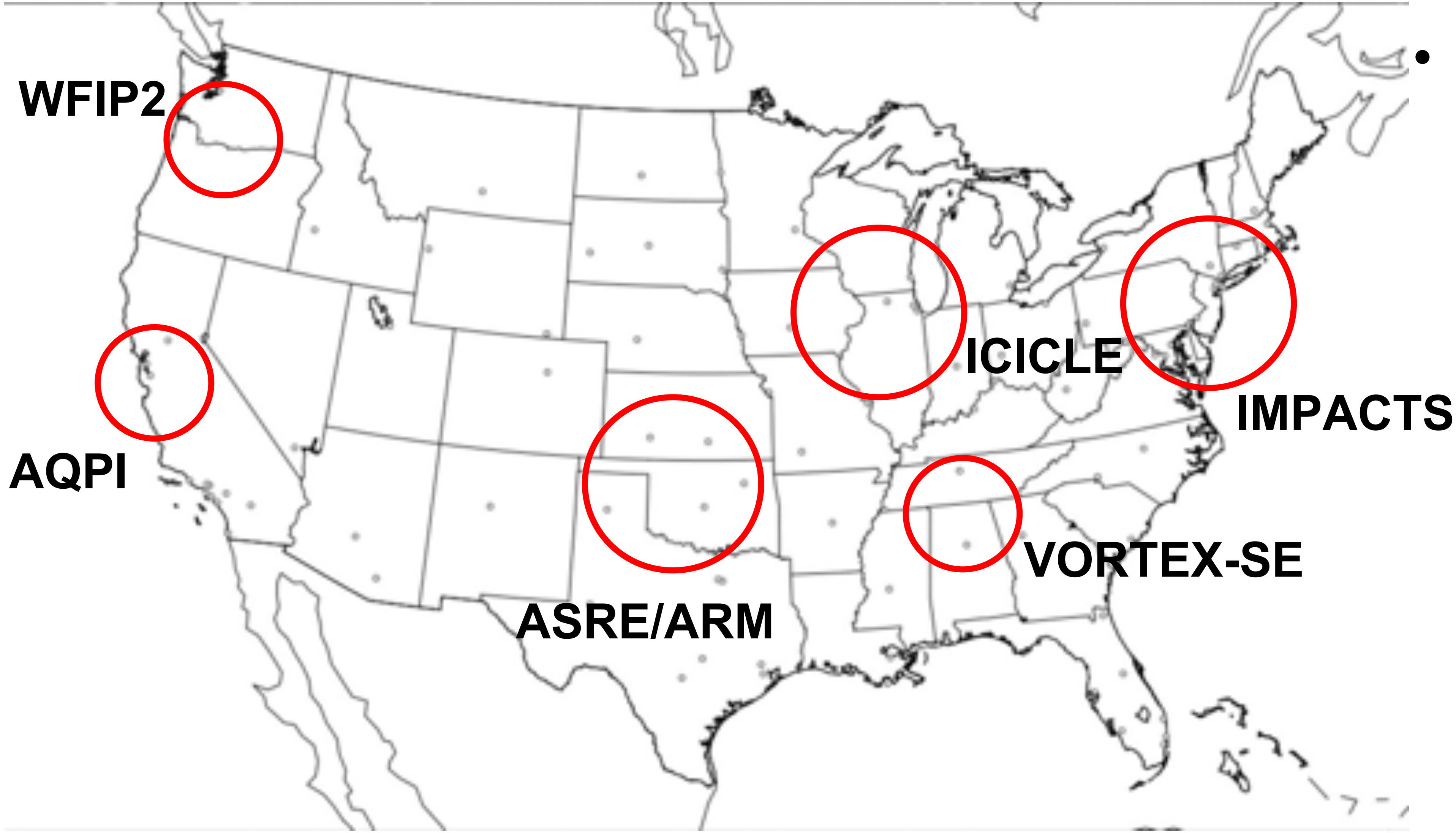
aircraft tail Number

temp bias

temperature bias > threshold: reject obs from this aircraft.

;tail	errors	FSL	MDCRS	N	bs_T	Std_T	bs_S	std_S	bs_D	std_D	std_W	rms_W	bs_RH
0000250	T - -	7103	---------	1032	0.8	0.[illegible]	0.2	2.8	1	9	2.0	4.0	0.0
00000251	T - -	6752	---------	211	0.6	[illegible].4	2.0	4.5	-5	9	3.2	5.6	0.0
CNJCA117	T W -	7124	---------	245	$\boxed{8.0}$	14.4	-0.6	11.9	4	27	16.1	17.7	0.0

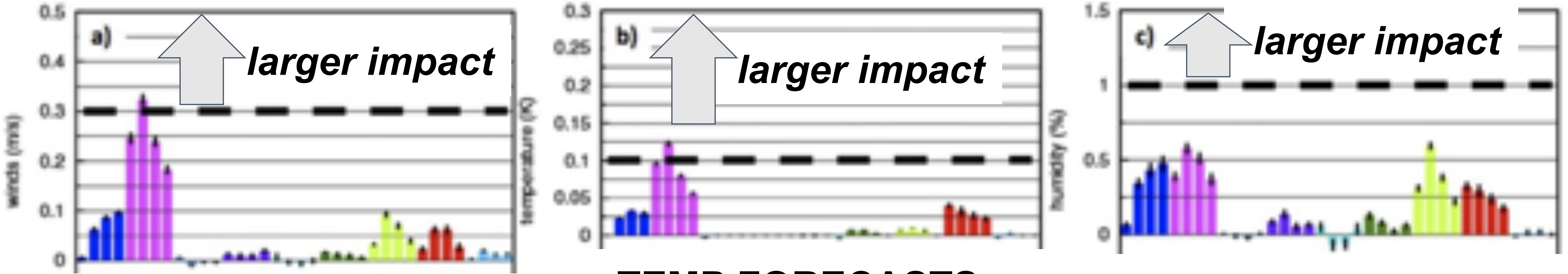
Collaborating for Targeted Observations



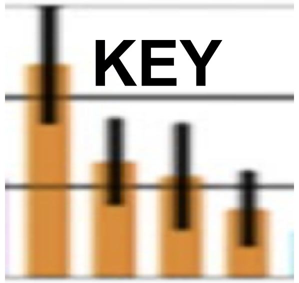
- Field campaigns since 2015 have focused on:
  - Wind Energy
  - Landfalling Pacific storms
  - Aviation hazards (convection / icing)
  - Severe storms

Observing System Experiments (OSEs)

- **RAPv3** data denial experiments carried out for three multi-season 10-day periods. Verification against North American raobs.



WIND FORECASTS **TEMP FORECASTS** **RH FORECASTS**



3 6 9 12h forecasts

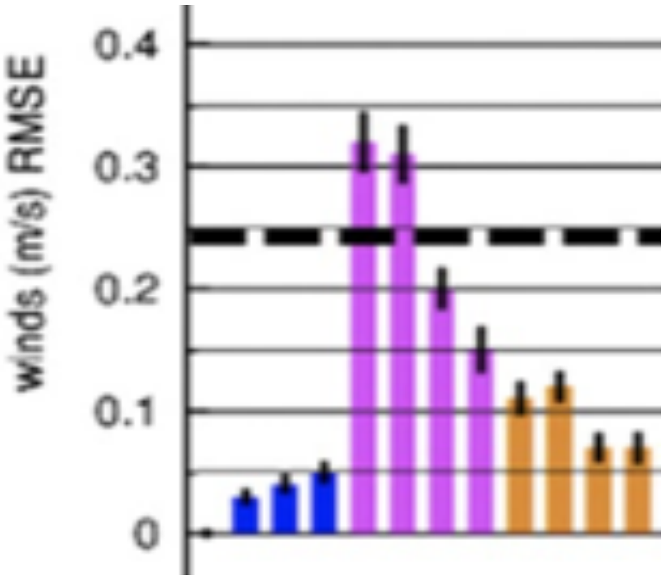
raobs
aircraft
profilers
radar reflect
VAD winds
GPS-Met PW
GOES satellite
surface
satellite AMVs

Dashed lines: 25% error reduction
Significance: 1 standard error (67% significance)

James and Benjamin **2017**

What was the impact of the COVID-19 decrease in aircraft observations?

- We designed a set of partial data denial experiments which exclude ~80% of aircraft observations, similar to what happened at the peak of COVID-19 lockdowns.



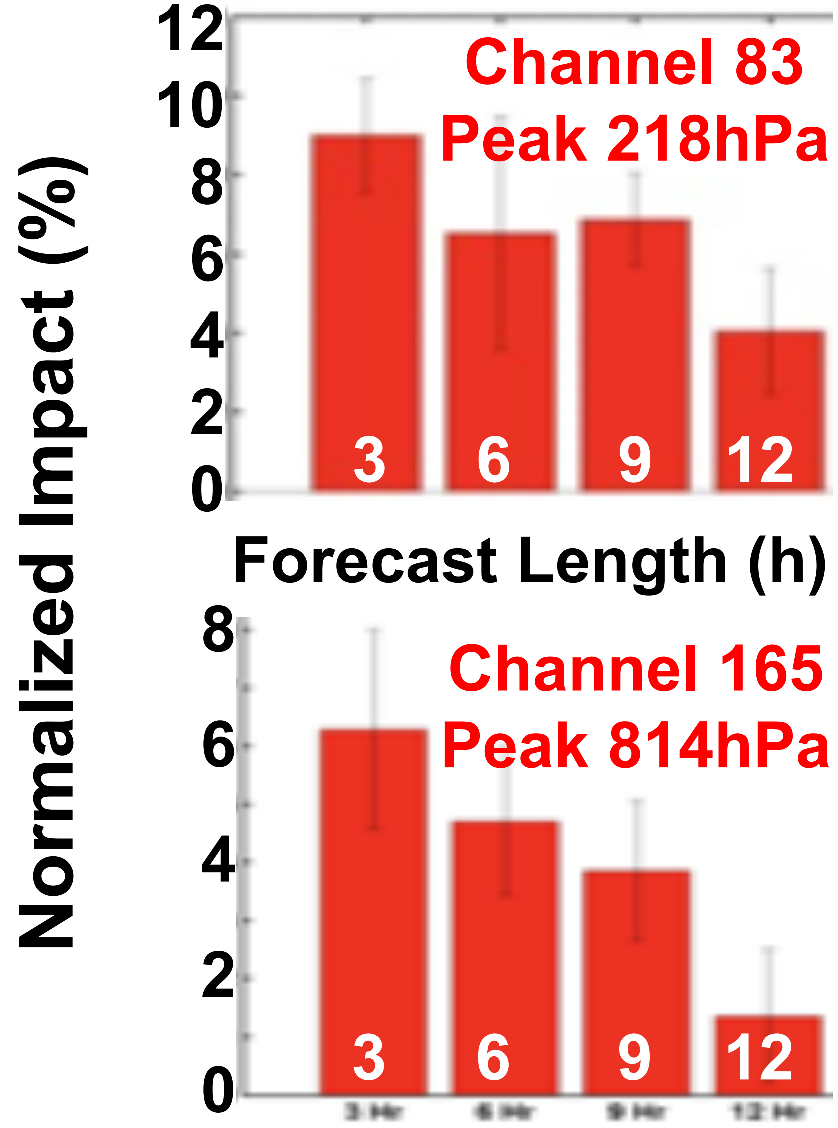
- Wind forecast impacts for winter (Feb 2019)

raobs
all aircraft
80% of aircraft obs

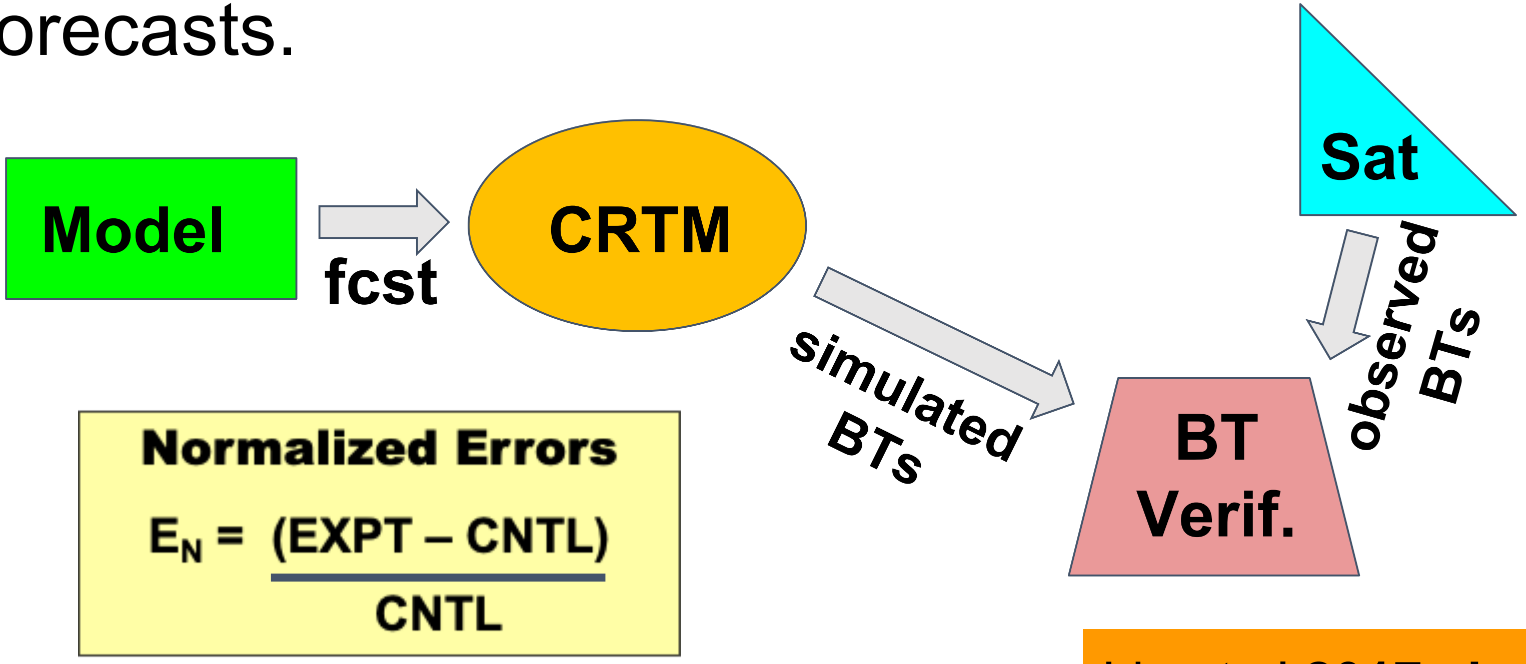
- Across seasons / variables, we find ***30% higher errors*** without any aircraft obs and ***12% higher errors*** without 80% of aircraft obs

James et al **2020**

Satellite Radiance Direct Broadcast Impacts in RAP



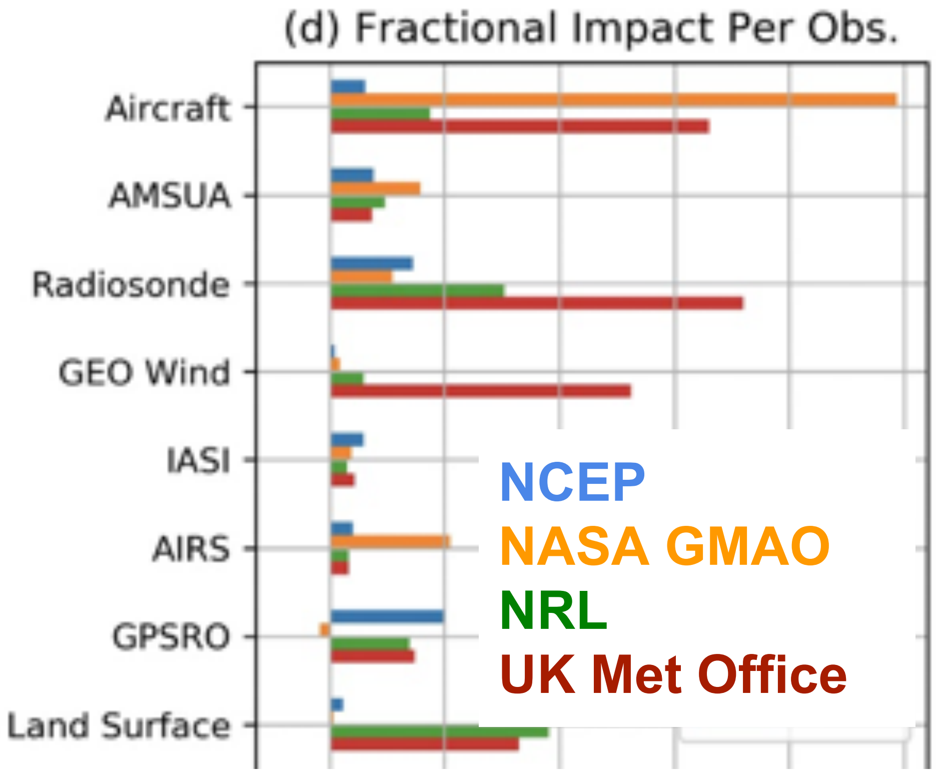
- 4-week retro test 1-28 Sep 2017.
- Hourly verification of brightness temp forecasts against ***CrIS*** observations reveals significant radiance impacts in RAP for short range forecasts.



Lin et al **2017a,b**

Ensemble Forecast Sensitivity to Obs Impacts

- ***OSEs (data denial experiments)*** quantify impact of one selected change upon forecast skill; ***FSOI/EFSOI*** quantifies impact of all assimilated obs.
- GSL was involved with EFSOI installation in GFSv16, implemented on 22 Mar 2021 (collaboration with ***NCEP/EMC***)



- Other ongoing collaborations:
  - GSL represents a unique perspective with rapidly-updating regional obs impacts at ***WMO Impacts Workshop*** every 4 years.
  - Preliminary coordination meetings with other NOAA labs within the ***NOAA QOSAP program*** (recommendation C4.6).

NOAA Global Systems Laboratory

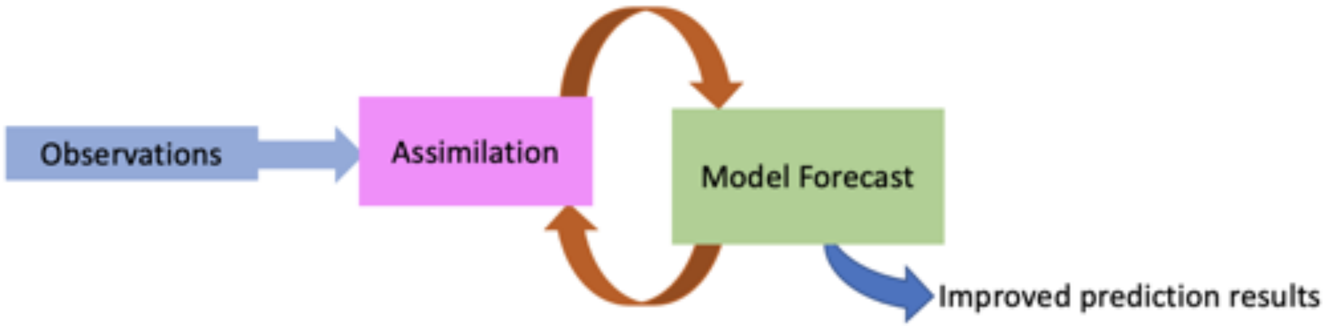
Development of Analysis Systems

Terra Ladwig,
Chief, Data Assimilation Branch & Research Scientist
Assimilation and Verification Innovation Division

Global Systems Laboratory

GSL is a World Leader in Rapidly Updating DA

- Short-term hazardous weather forecasts rely heavily on the quality of the initial conditions.
- In order to capture high temporal observations rapid assimilation is required, as demonstrated in the previous sub-section.
- GSL has developed and deployed two types of data assimilation techniques.
  a. Advanced data assimilation, specifically 3DEnVAR and EnSRF
  b. Non-conventional state or tendency specification



Recommendation C4.1

3D Ensemble-Variational Data Assimilation

- 3DEnVar uses both static and ensemble background error covariances.

Analysis increments for a single observation near a frontal boundary highlight how ensemble flow dependent background error covariances can improve the distribution of observational information.

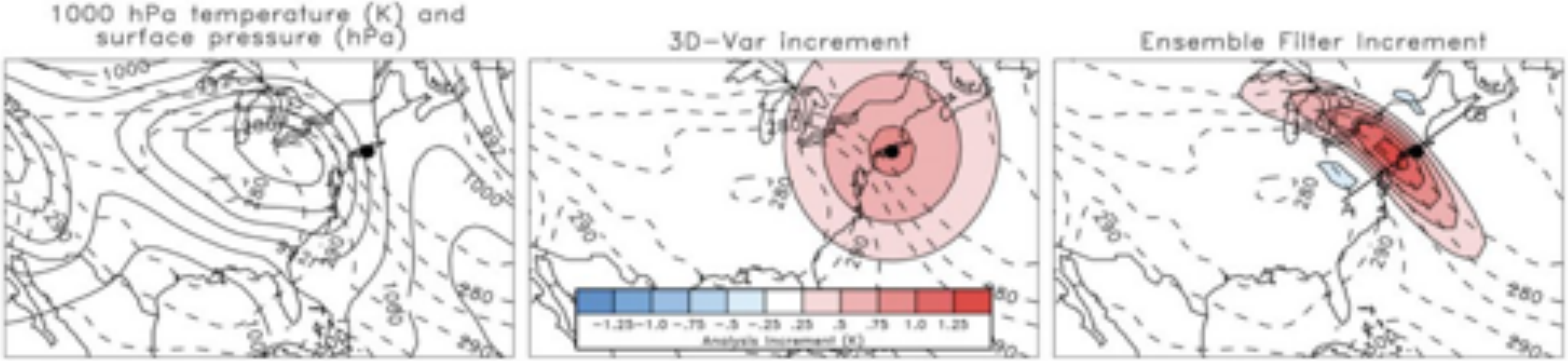
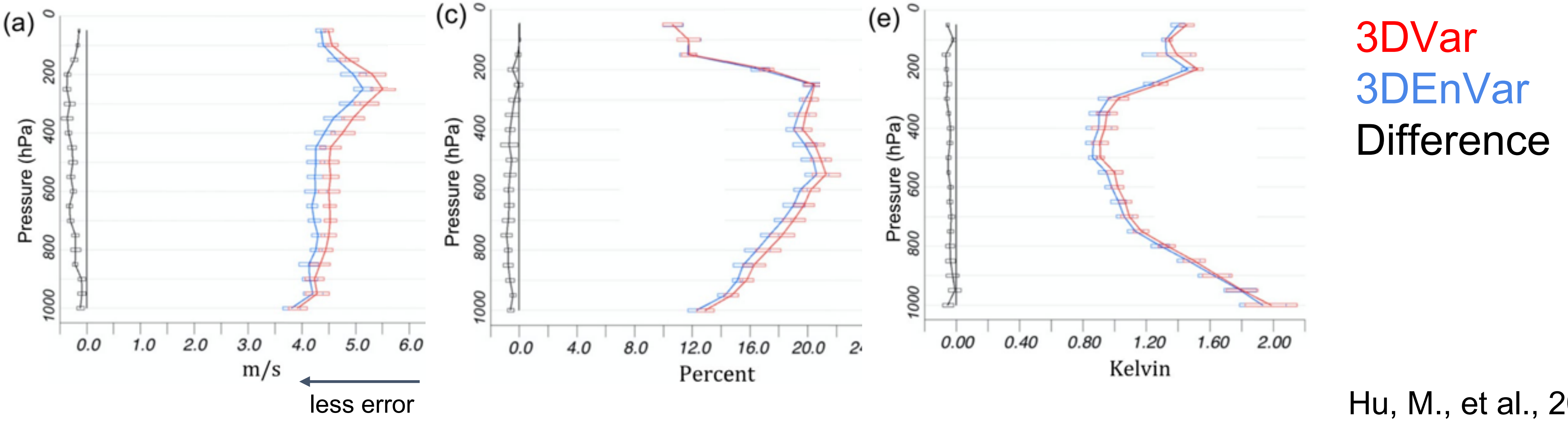


Figure from Tom Hamil

3D Ensemble-Variational Data Assimilation

- 3DEnVar is very successful for regional hourly data assimilation in RAP/HRRR and has superior skill over purely a 3D-variational analysis (shown below).
- Ensemble background error covariance data from the global system, GDAS, is effectively used with static errors in the RAP 3DEnVar.

6-hour Forecast RMS Wind, Relative Humidity, Temperature



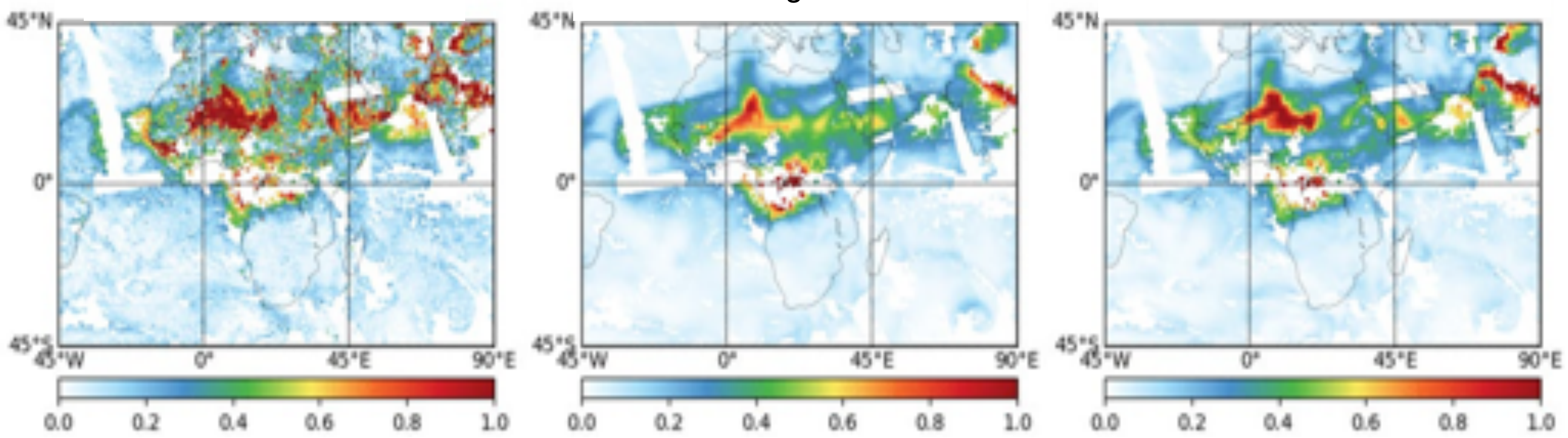
Hu, M., et al., 2017.

Assimilation System for Aerosol Analysis and Forecasting

- Satellite based observations of Aerosol Optical Depth (AOD) at 550 nm are assimilated with JEDI software and enable aerosol prediction.
- High AOD indicates large aerosol concentrations that can impact radiation, cloud and rain formation, and air pollution.

Assimilating VIIRS AOD Retrievals in Action:
Dust Storm over North Africa June 15-25, 2016

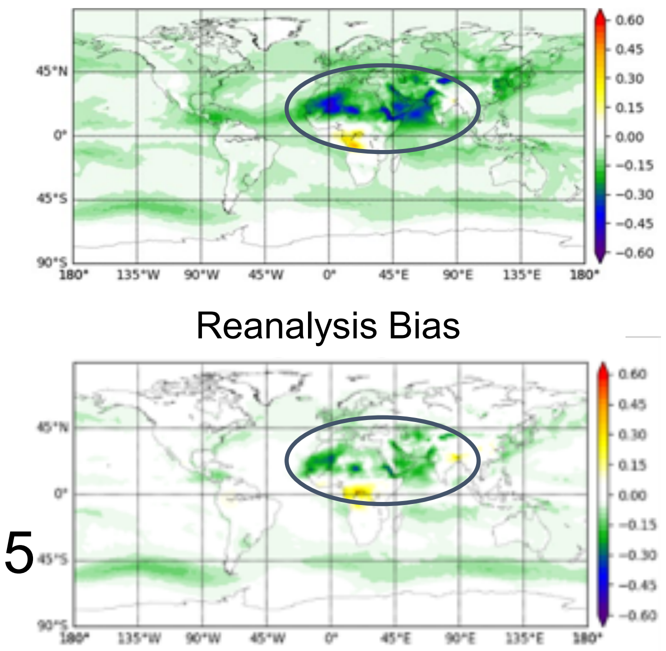
Observations Background Analysis



Evaluation Statistics
June 2016

Free Forecast Bias

Reanalysis Bias



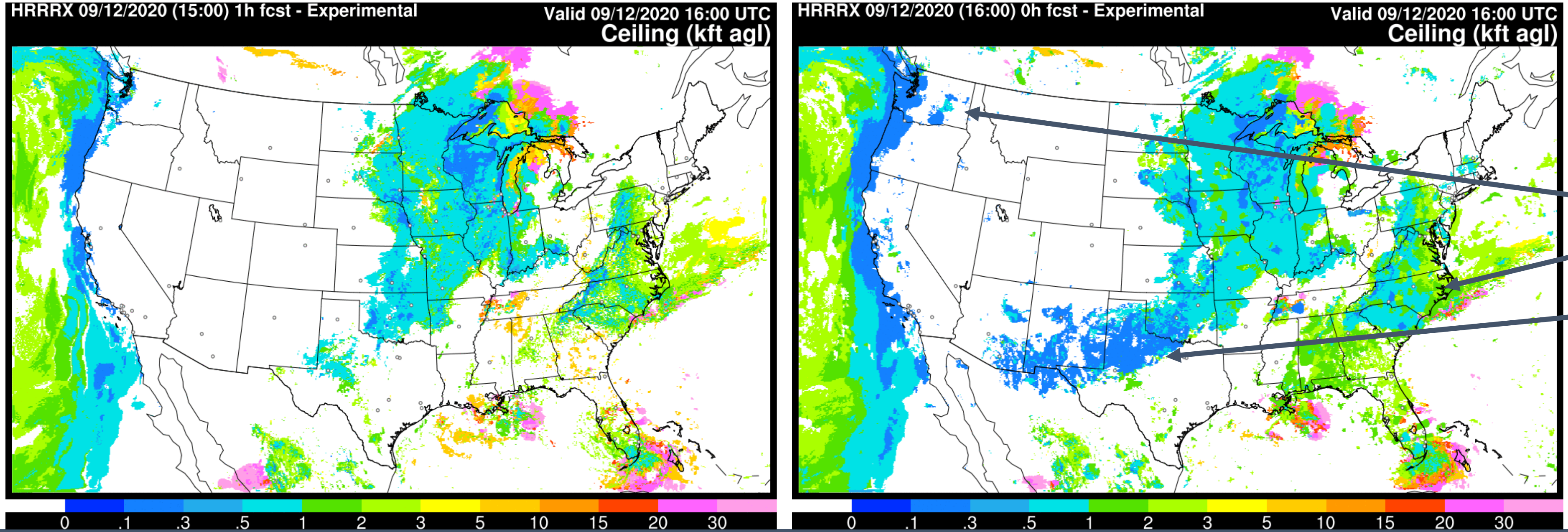
- Regional variational assimilation (GSI based) of hourly in-situ PM2.5 measurements and AOD for RRFS-CMAQ is under development.

Stratiform Cloud-Hydrometeor Assimilation

- Accurate cloud and precipitation initialization is fundamental to short-range prediction systems such as RAP & HRRR.
- The stratiform cloud-hydrometeor assimilation improves retention of observed cloudy and clear 3D volumes in subsequent model forecasts.
- Cloud ceiling and visibility forecasts have more skill due to the cloud assimilation.

1-Hour Forecast (Background) Ceiling

Analysis Ceiling



Analysis captures low ceilings in several locations.

Benjamin et al. 2021.

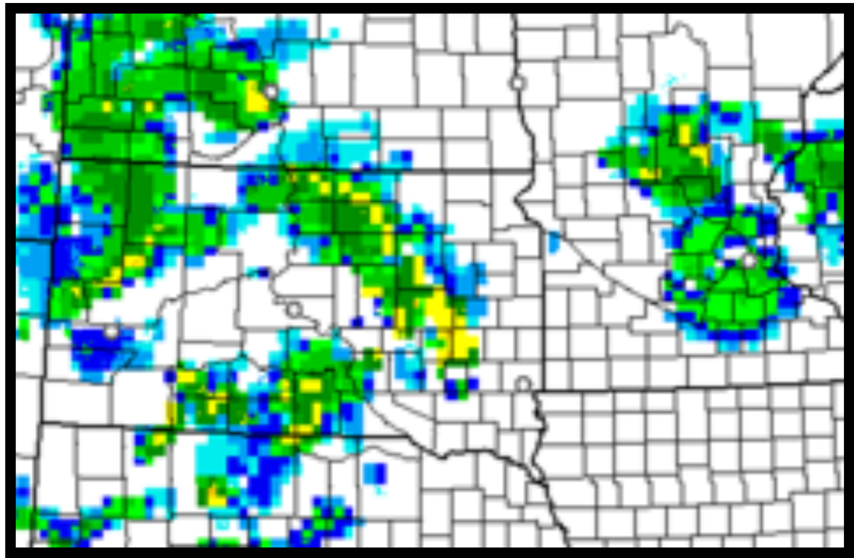
Latent-Heating Based Precipitation Assimilation

- Assimilation of precipitation related observations, especially for convection is essential to the success of HRRR/RAP short-term forecasts.
- Radar reflectivity observations, as well as lightning (flash centroid density), are mapped to latent heating temperature tendencies that are applied to the model physics to force convection and lack of convection.

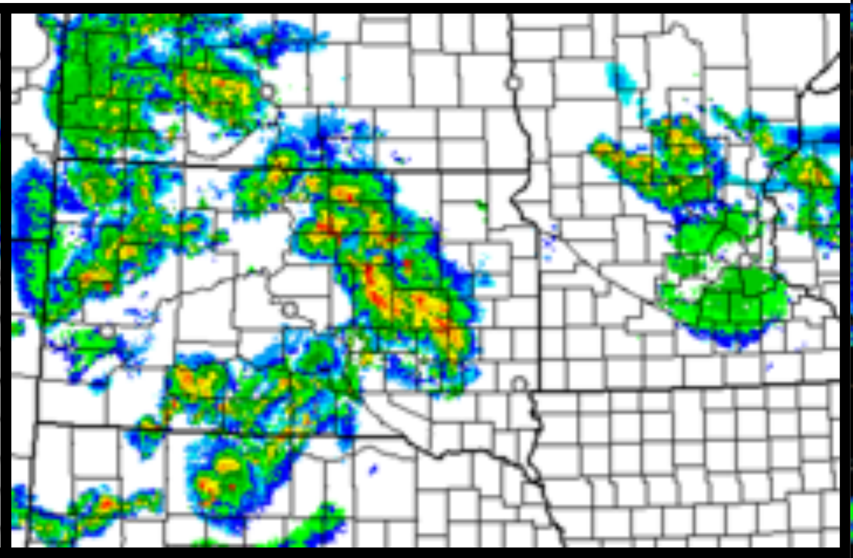
Weygandt et al.
Expected in 2022

Reflectivity Analysis

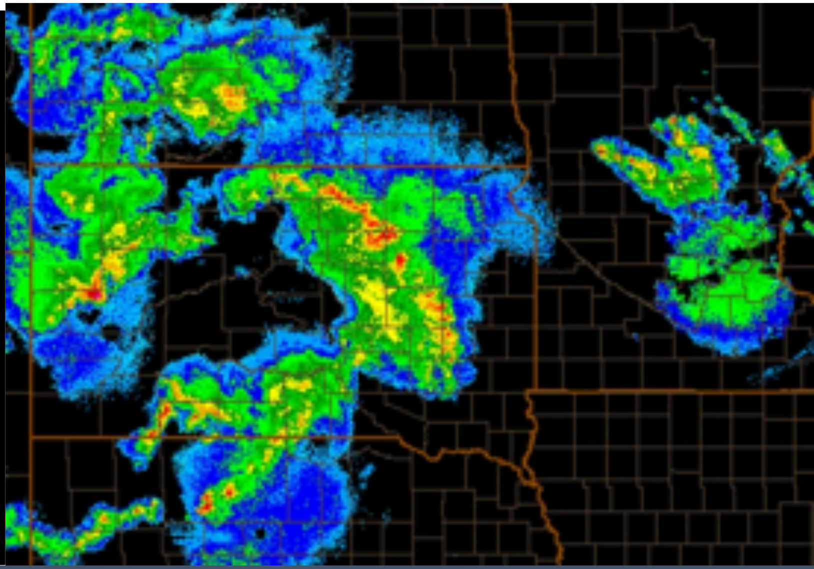
Without Latent-Heating



With Latent Heating



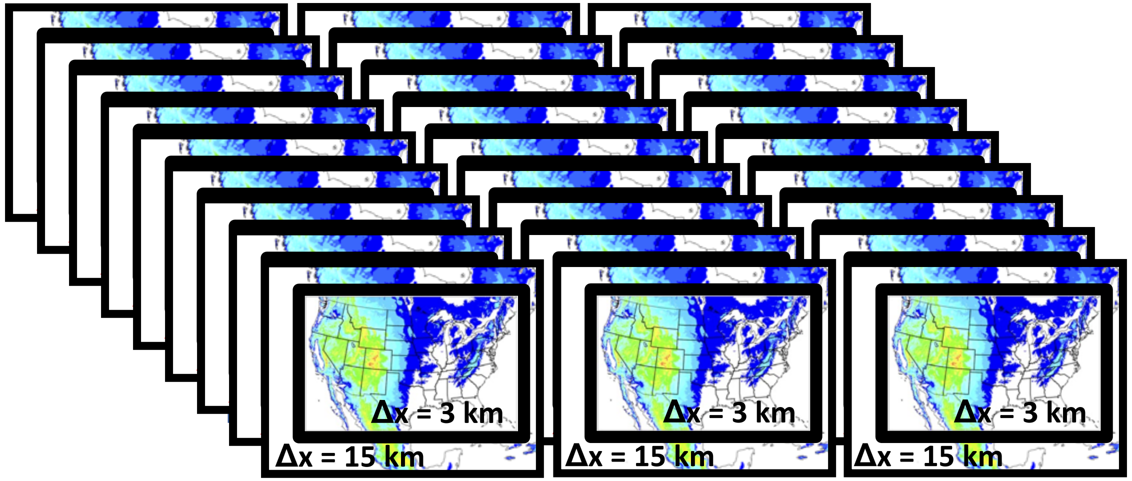
Observations



Convective-Scale Ensemble Based Assimilation

- Ensemble covariances provide temporal and flow dependent information, which is especially important near small scale nonlinear phenomena.
- Convective-scale ensemble assimilation has improved initial conditions for the HRRR and is a foundation for future implementations.

HRRR-Data Assimilation System (HRRRDAS)



operational

Deterministic HRRRv4
- Initial conditions
- Background Error Covariances

research

HRRR-Ensemble (HRRRE)
- Storm-Scale Ensemble Forecasts

Three-Dimensional Real-Time Mesoscale Analysis (RTMA-3D)
- Background Error Covariances
- Storm-Scale Analysis Uncertainty

Warn-On-Forecast (WoF) System
- Initial Conditions
- Boundary Conditions

Recommendation C4.2

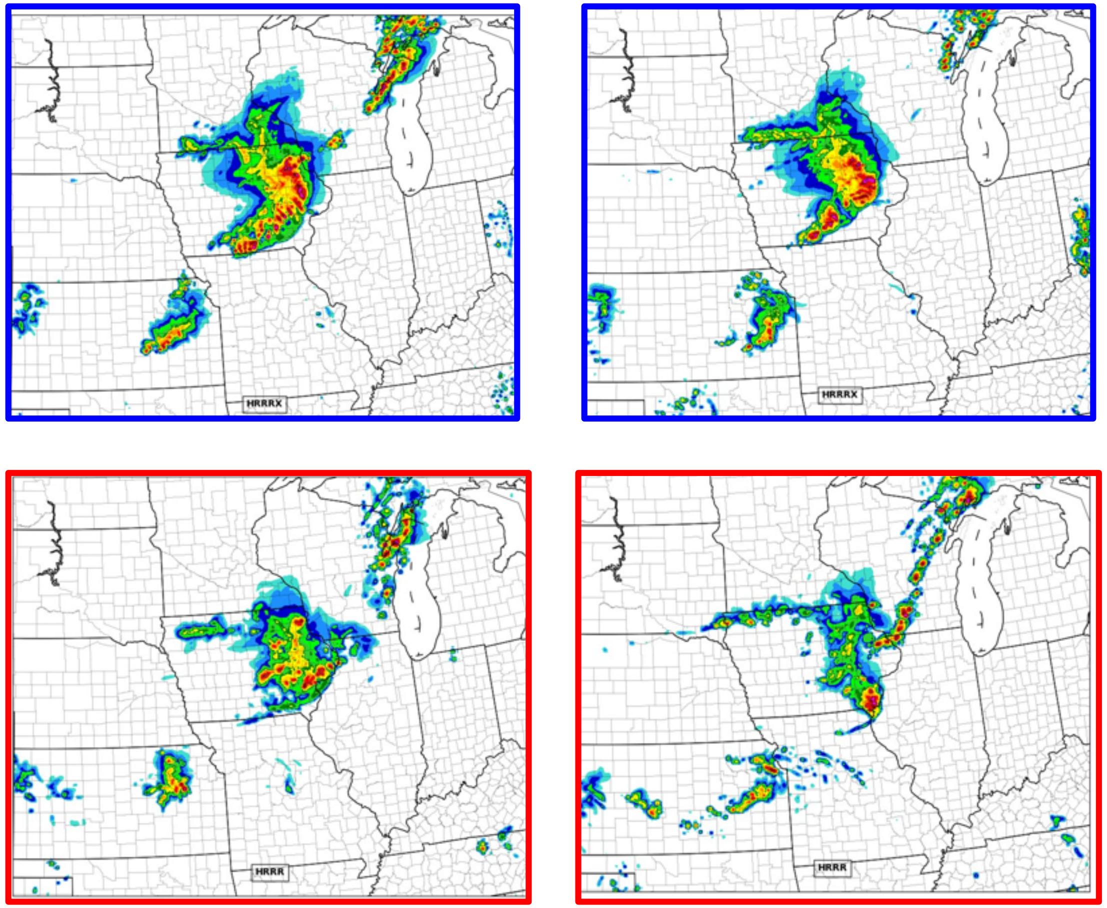
HRRRDAS Initial Conditions Improves HRRRv4

Case Study 18 UTC 10 August 2020

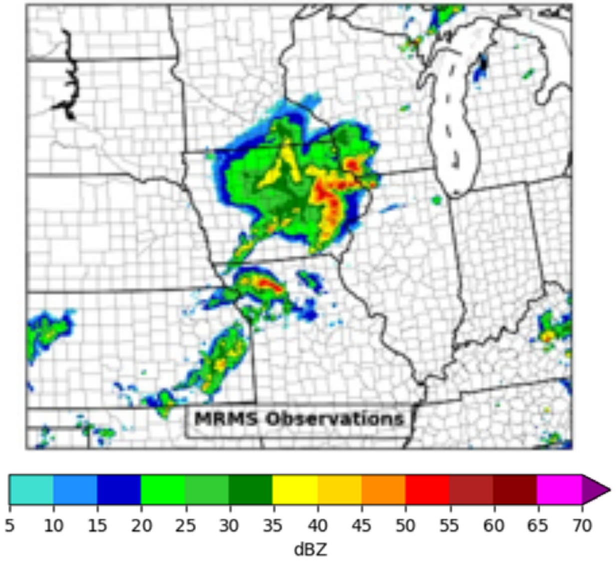
15 hour forecast | 13 hour forecast

HRRRv4 w/HRRRDAS

HRRRv3



Radar observations



- Challenging forecast of very damaging derecho
- HRRRv4 consistently shows a more organized and accurate convective system due to improved initial conditions from HRRRDAS.
- HRRRDAS uses hourly assimilation cycles to incorporate both conventional and radar observations and the ensemble mean provides convective scale motions and thermodynamics to HRRRv4.

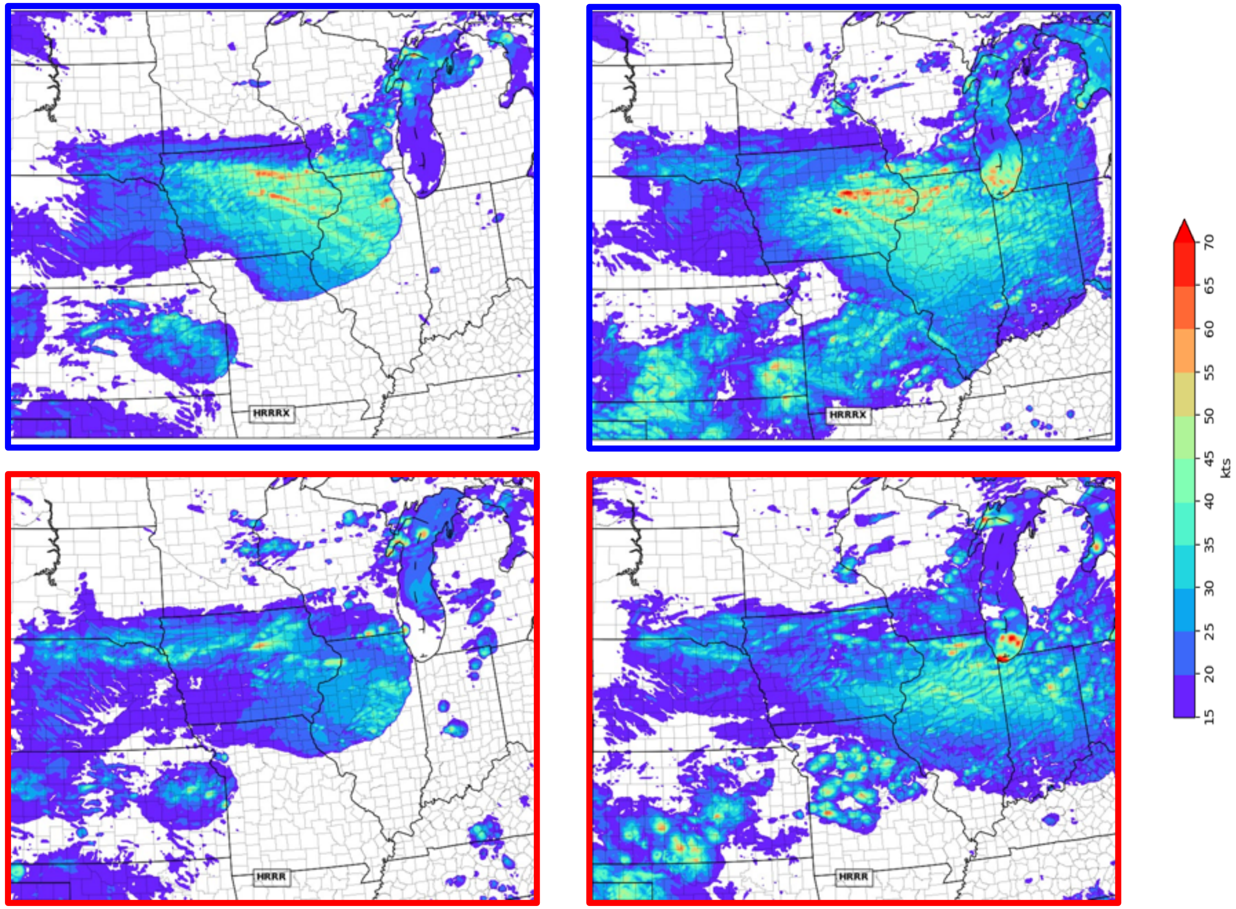
HRRRDAS Initial Conditions Improves HRRRv4

10m Max Wind Speed 10-11 August 2020

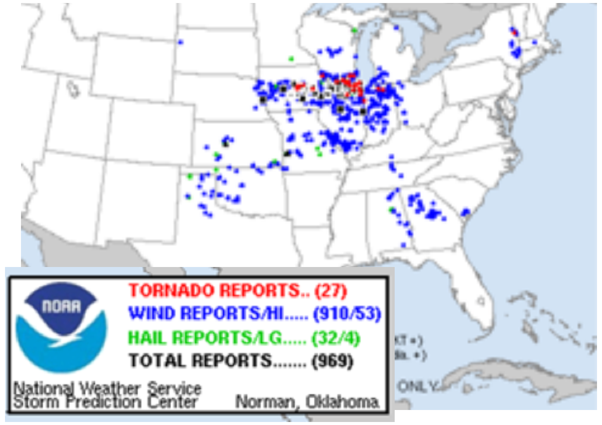
18 hour Forecasts Valid at 21 UTC | 18 hour Forecasts Valid at 3 UTC

HRRRv4 w/HRRRDAS

HRRRv3



SPC Storm Reports

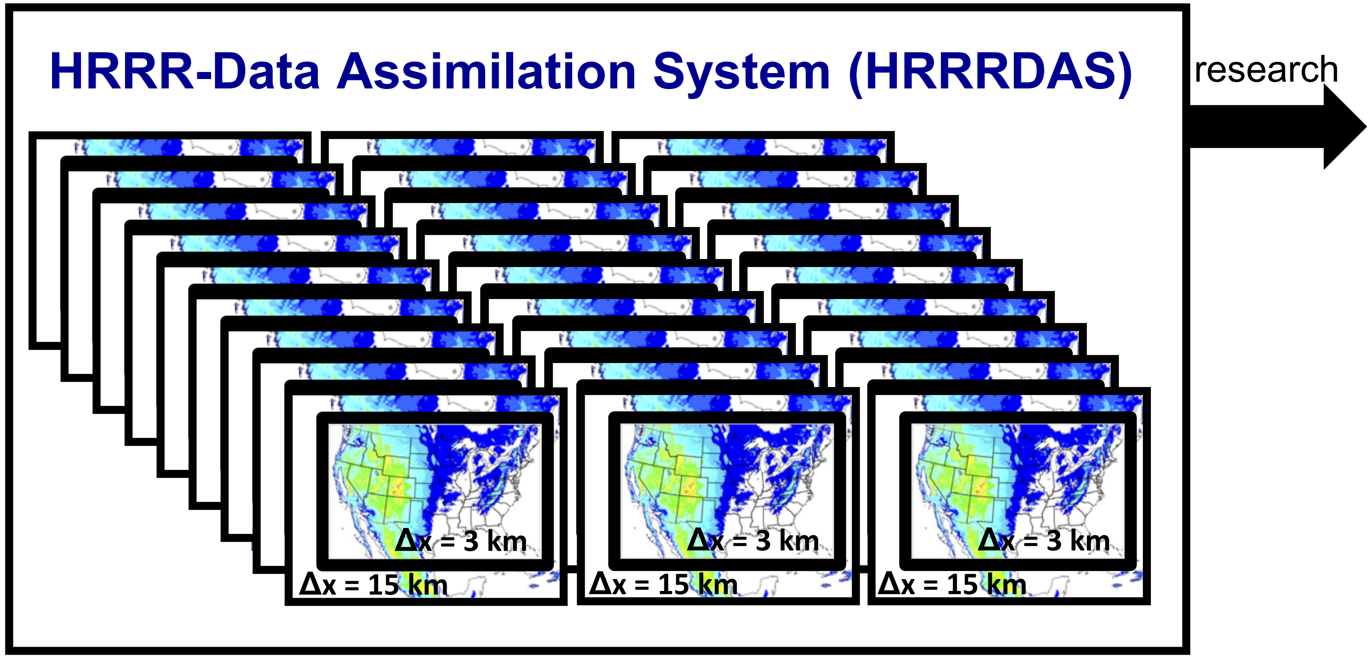


The HRRRv4 wind solutions correctly have:

- stronger overall winds and more coverage further east
- stronger winds starting earlier in the system’s life over central Iowa
- narrow corridors of very intense winds over eastern Iowa

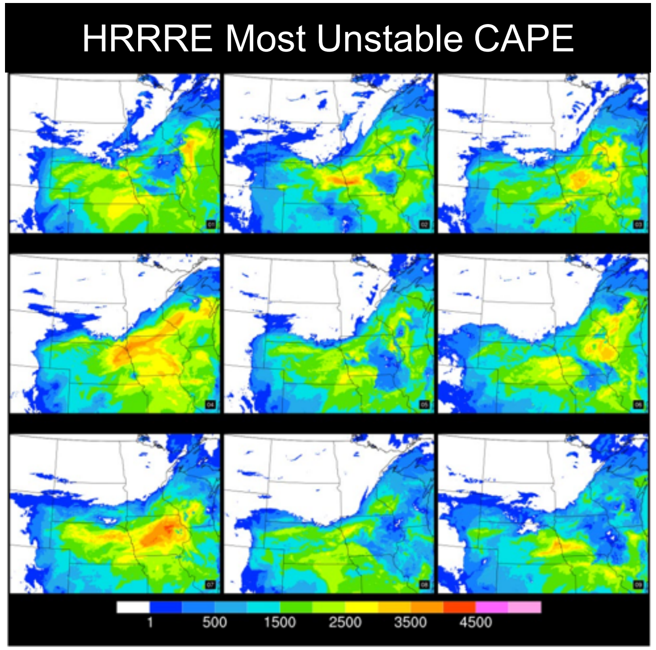
Ensemble Forecast Challenge: Spread vs Error

Ensemble forecasts can provide the range of possibilities that might occur and a measure of uncertainty in a forecast.



HRRR-Ensemble (HRRRE)

- Storm-Scale Ensemble Forecasts

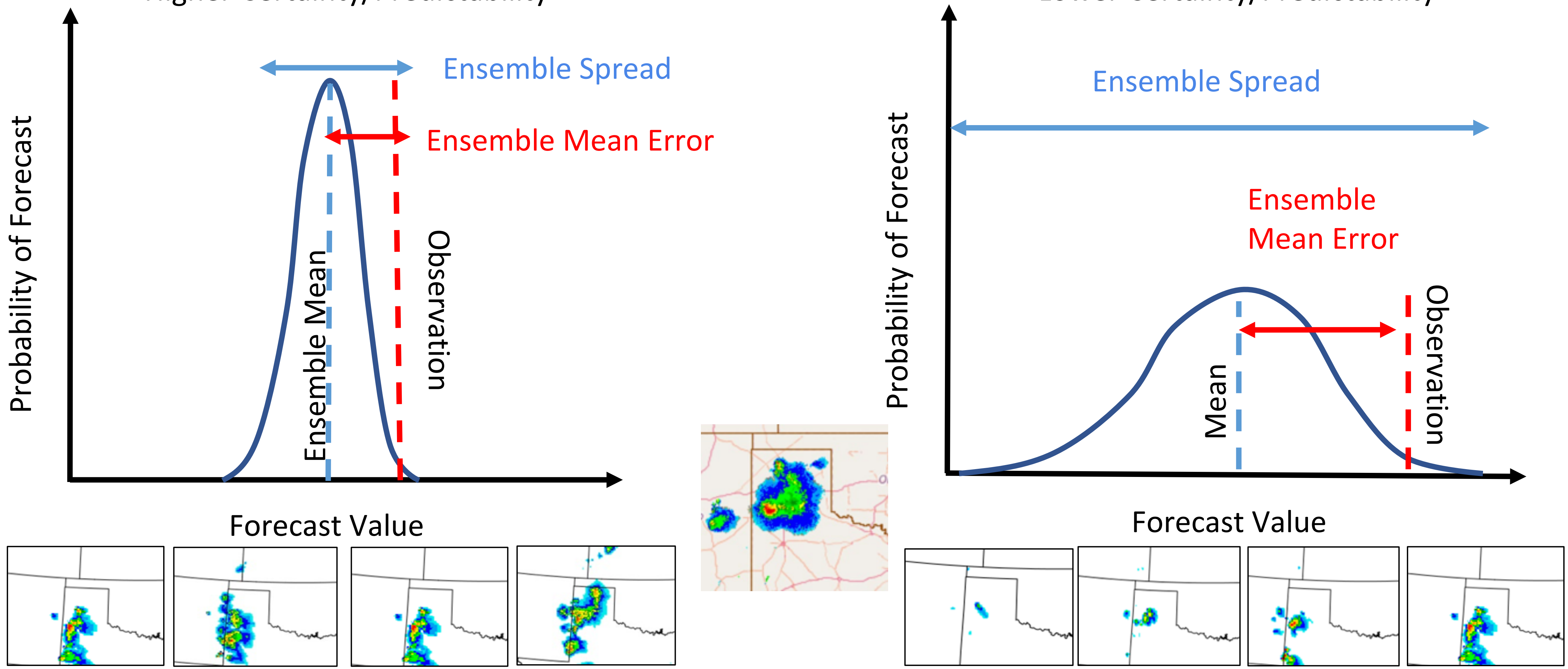


Recommendation C4.2

Ensemble Forecast Challenge: Spread vs Error

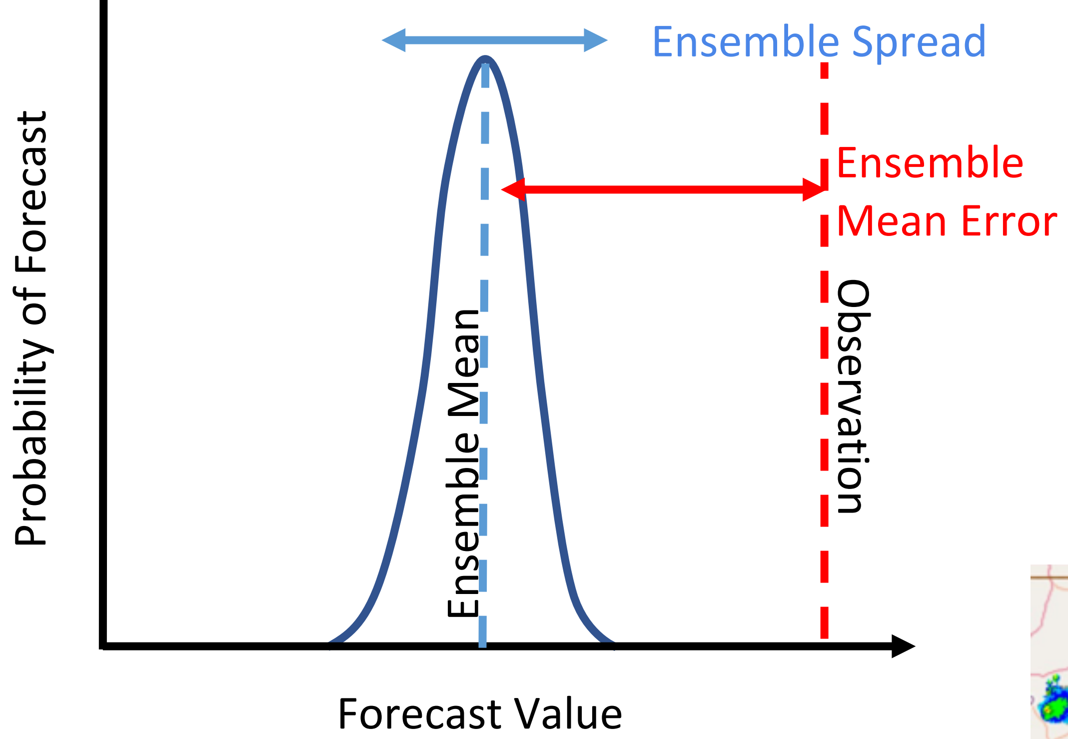
Low Spread
Higher Certainty/Predictability

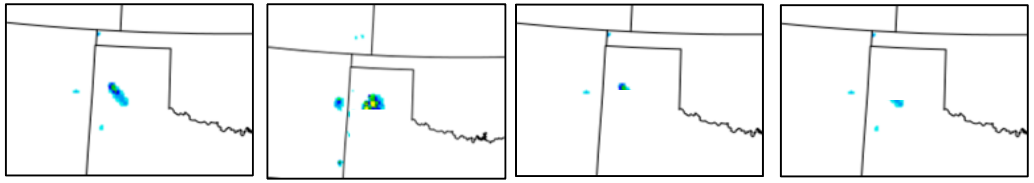
High Spread
Lower Certainty/Predictability

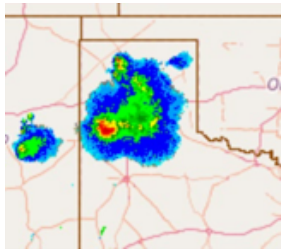


Ensemble Forecast Challenge: Spread vs Error

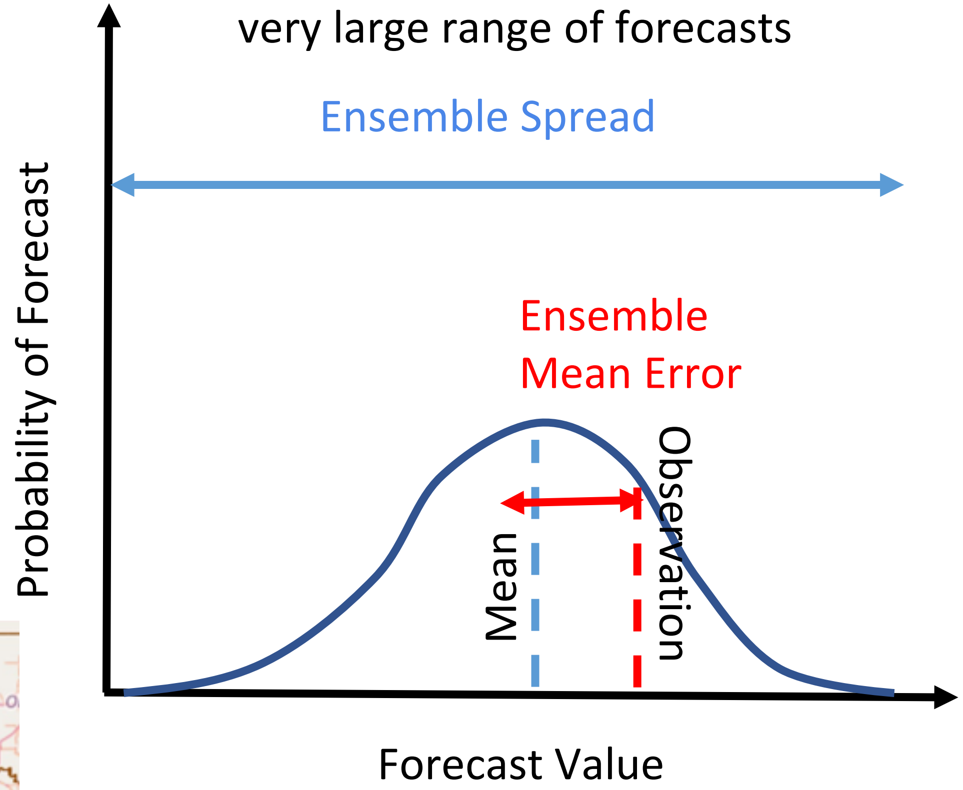
Underdispersive:
Observations frequently fall outside range of ensemble forecasts

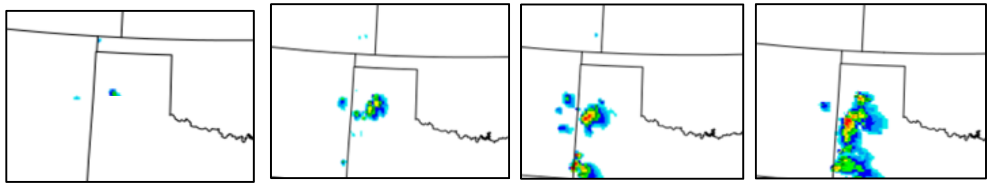






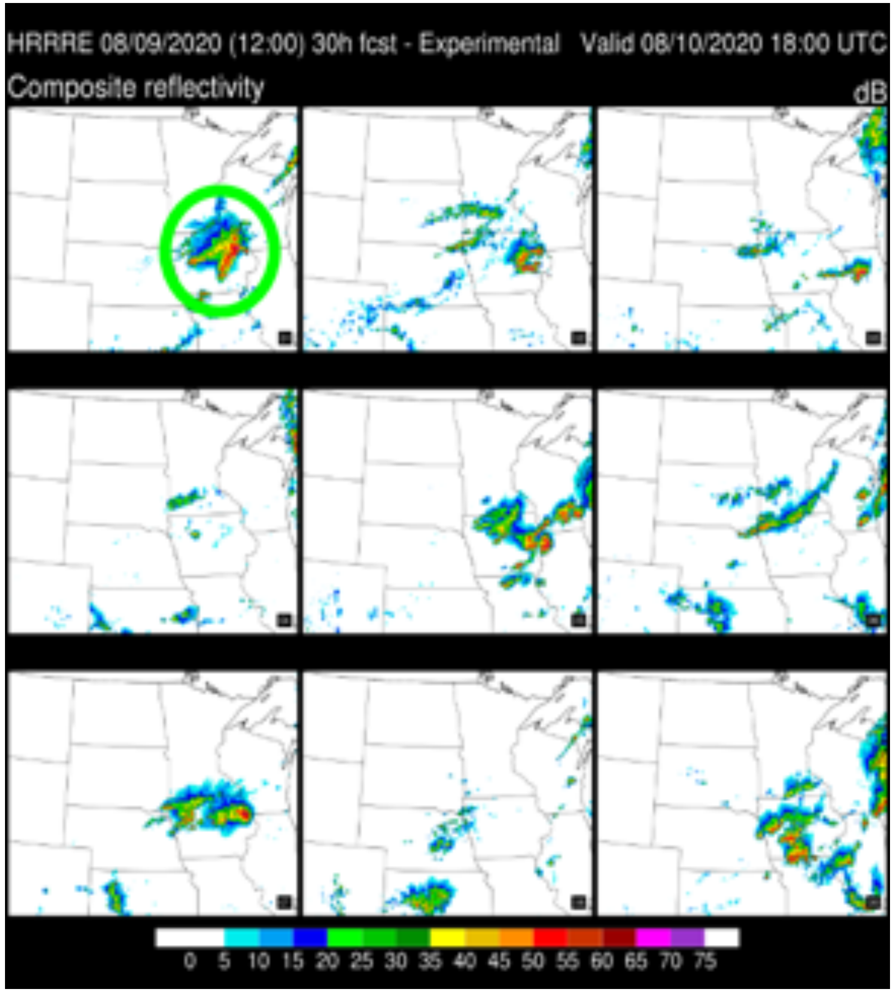
Overdispersive:
Ensemble frequently forecasts a very large range of forecasts



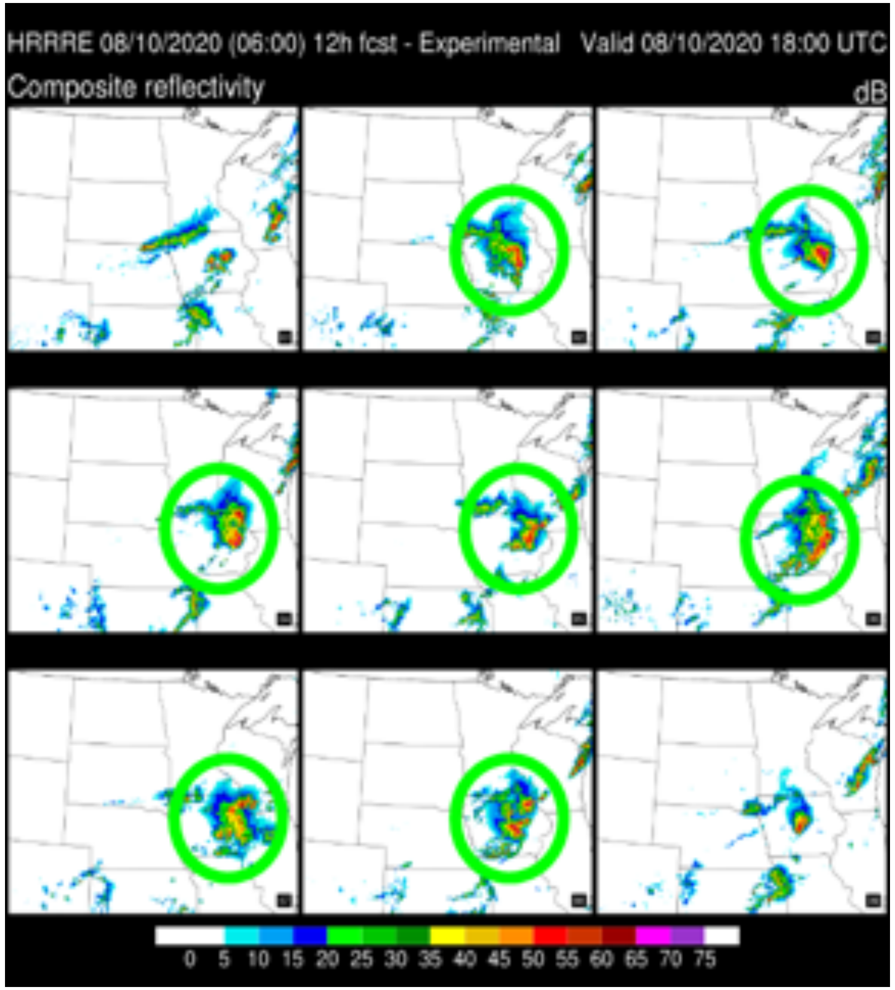


Ensemble DA & Forecasting ⇒ Better Probabilities

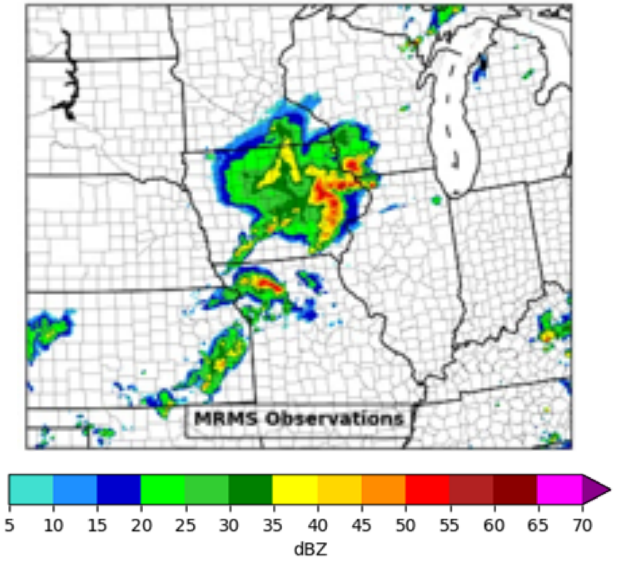
30-h lead-time: get 1 hit



12-h lead-time: 7 of 9 hits



Radar observations



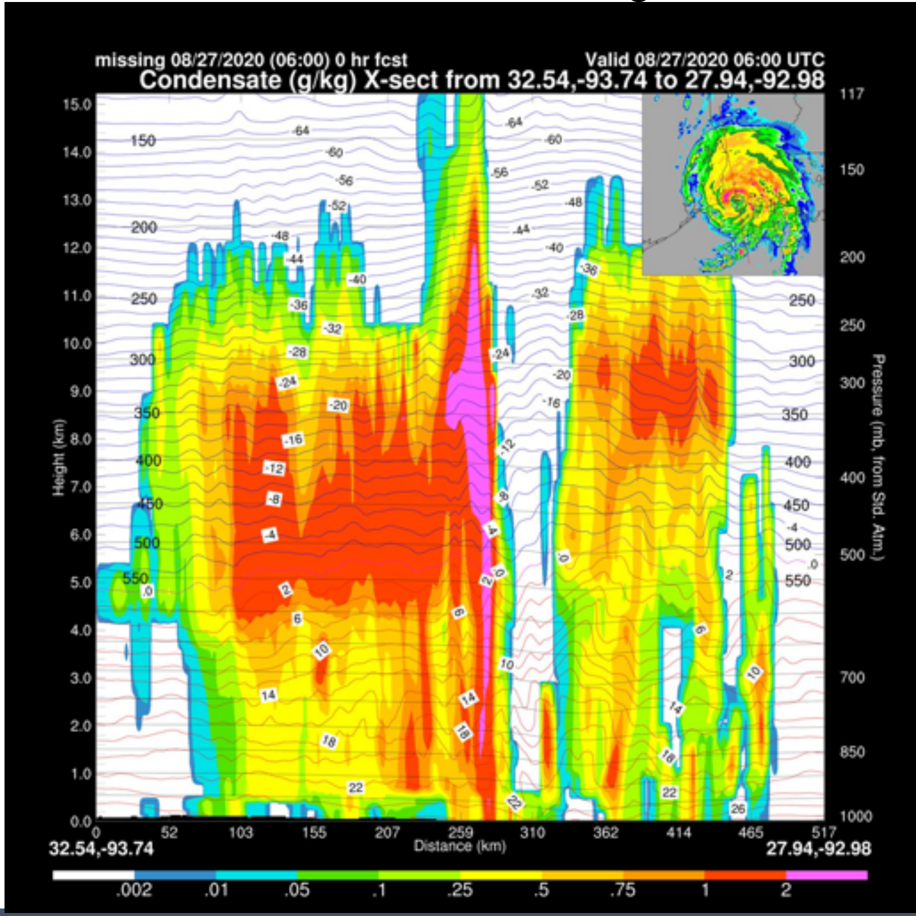
- Longer forecasts show low likelihood for a large impact event
- Shorter forecasts decreased spread, increased confidence
- HRRRE includes stochastic physics to create spread

NOAA Unified Analysis: RTMA-3D Nowcast/Analysis of Record

GOAL: Record the best estimate of the convective-scale Earth system state.

- Collaborative development with EMC (JTTI & UFS R2O)
- RTMA-3D is not constrained by the need to initialize a forecast (close fit to obs; model behavior not considered)
- RTMA-3D provides 15 min gridded analysis of 3D atmospheric fields with application in multiple areas:
  - General analysis and reanalysis applications
  - Severe weather; targeting replacement of Mesoanalysis System (SPC)
  - Aviation parameters; targeting 3D cloud coverage/ceiling grids (AWC)
  - Hydrodynamical modeling input and water in all forms - snow cover, soil moisture, lake forecasts, heavy rainfall
  - Model verification 'truth' dataset
- Operational implementation planned for 2024

Experimental RTMA-3D during Hurricane Laura 27 Aug 2020

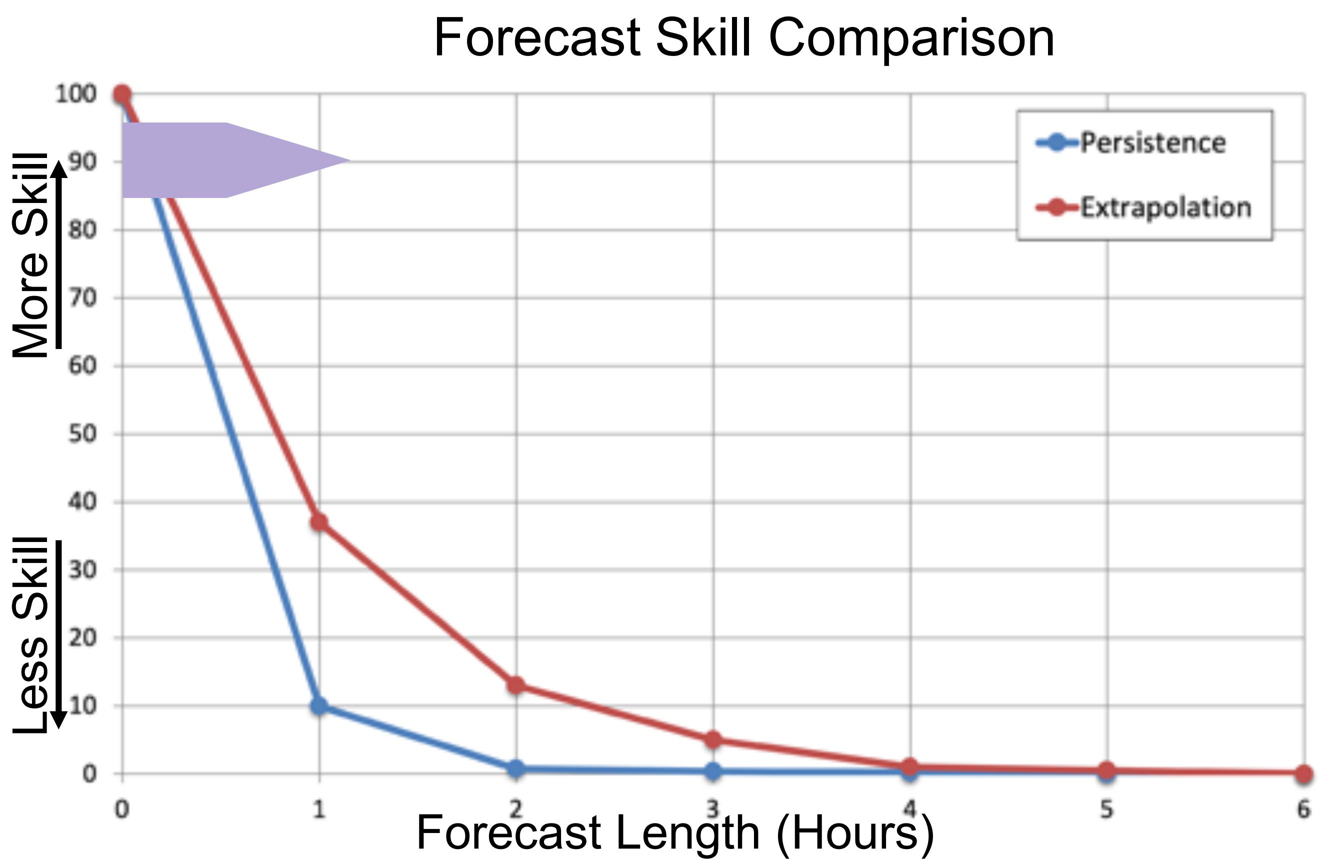


Recommendation C4.7

Summary of Assimilation Systems Impacts

GSL is a World Leader in Rapidly Updating DA

- The RTMA-3D analysis system fits obs very closely and is valuable for nowcasting.



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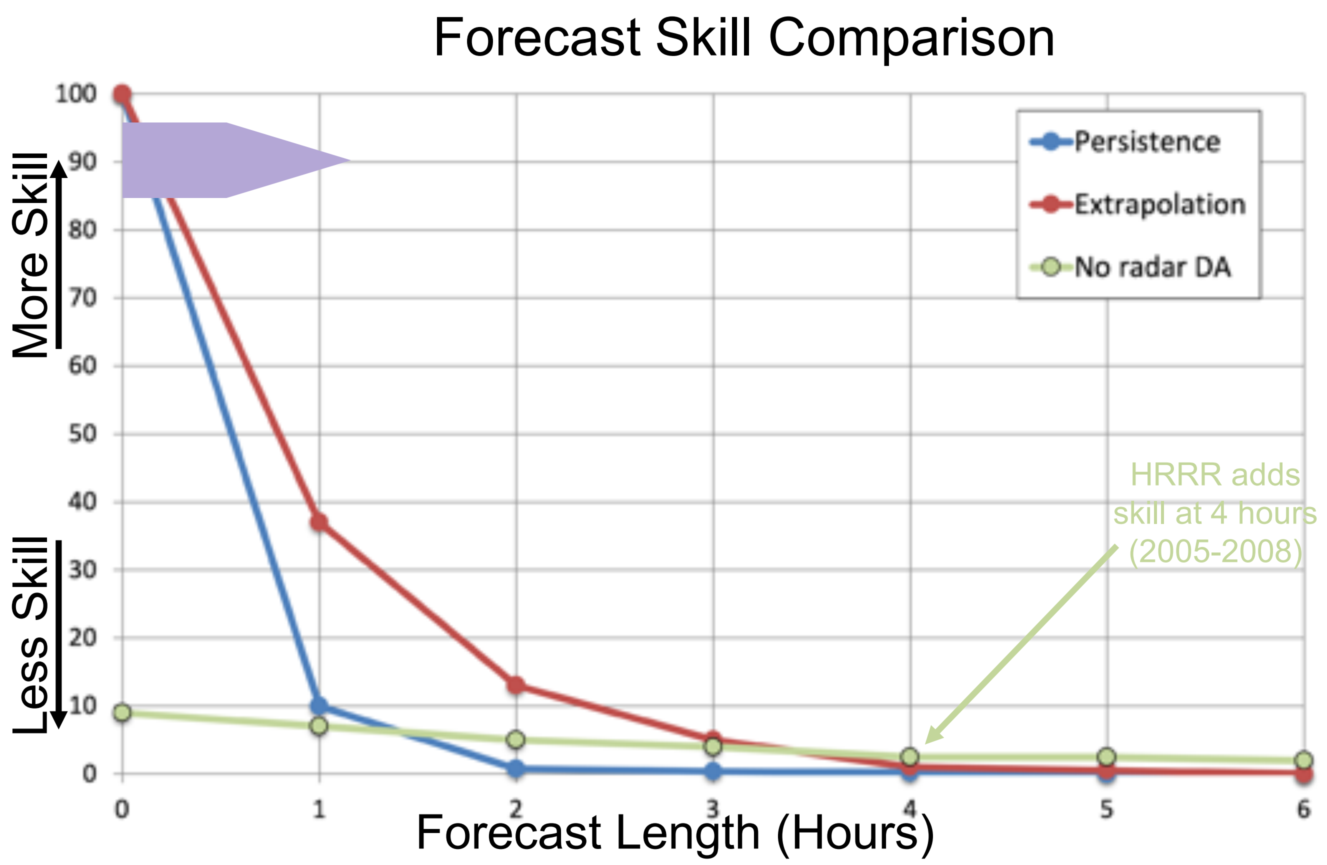

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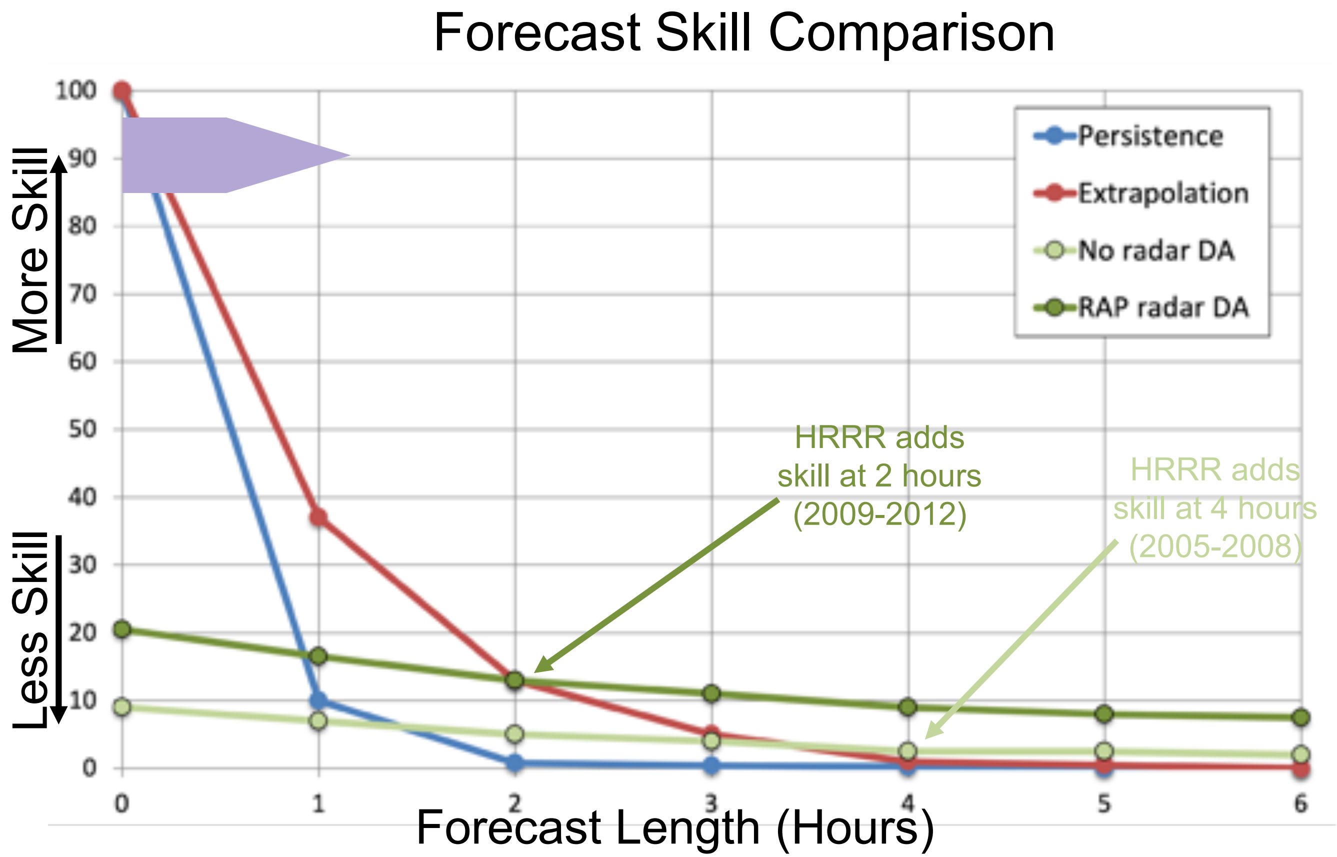

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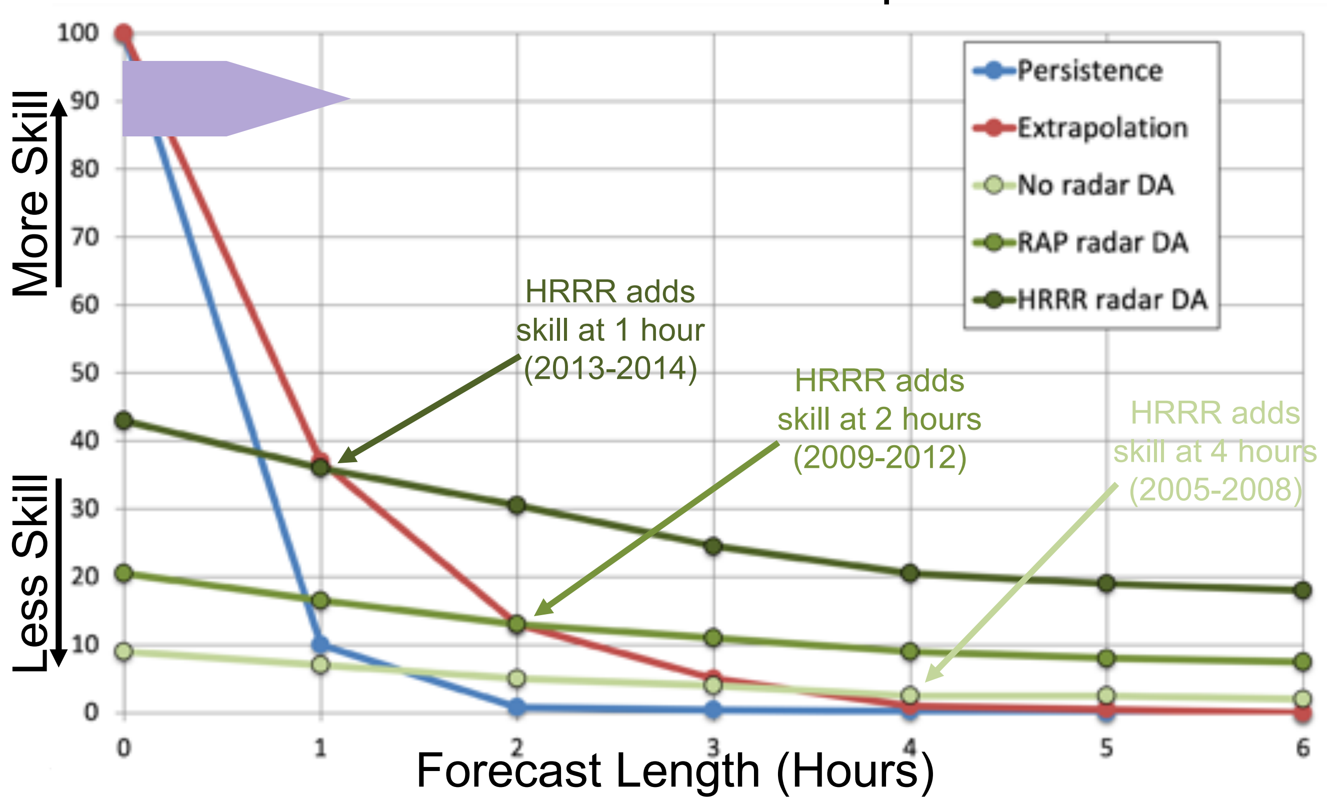
Forecast Skill Comparison



Summary of Assimilation Systems Impacts

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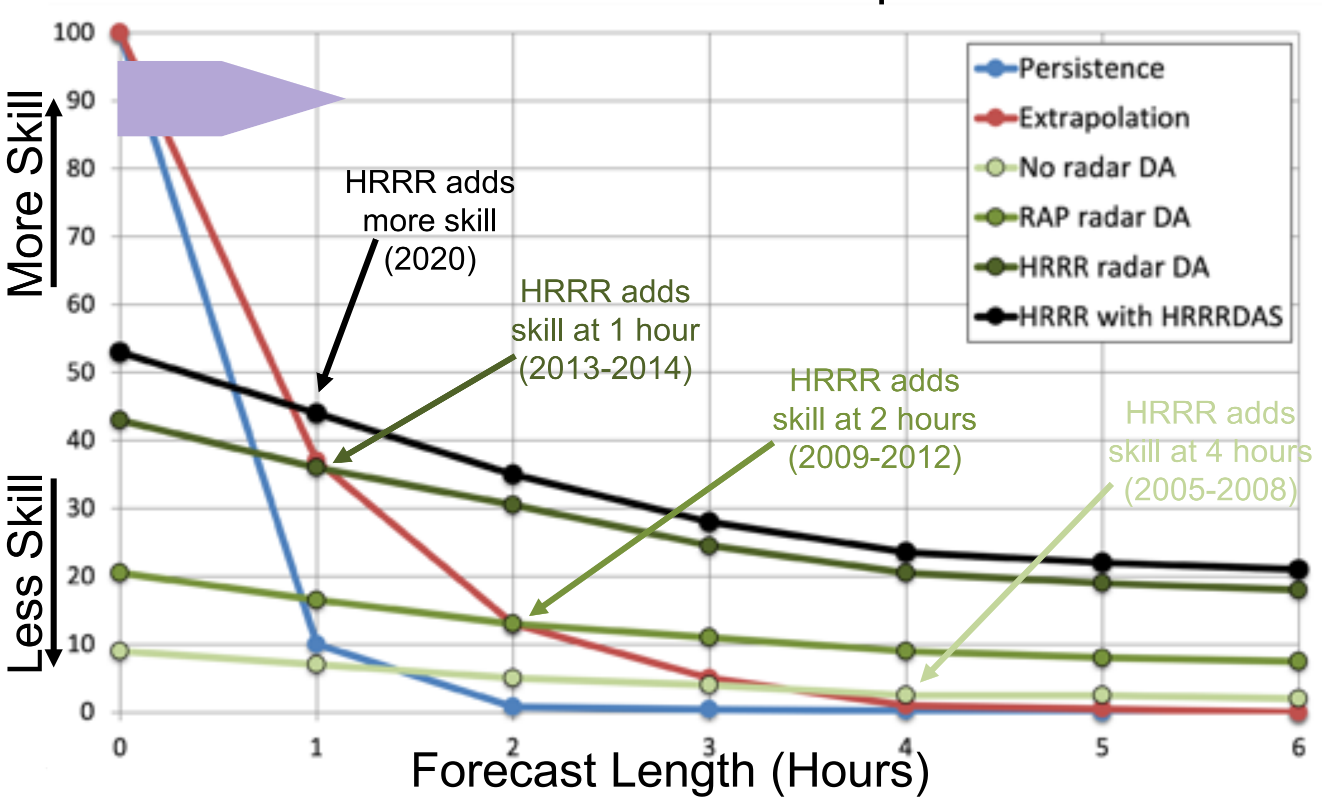
- The RTMA-3D analysis system fits obs very closely and is valuable for nowcasting.
- Convective-scale forecasts lead to useful predictions.
- Improved mesoscale initial conditions push forecast value to shorter time scales.
- Latent-heating radar assimilation push forecast value to nowcasting time scales.
- Convective-scale ensemble with direct reflectivity assimilation provides initial conditions that increase forecast skill across lead-times.

Forecast Skill Comparison



NOAA Global Systems Laboratory

Earth System Prediction: Summary of Observation Use and Analysis Development for Improved Forecasts

Global Systems Laboratory

Making Forecasts Better with Data Assimilation Advances

- **Development of analysis systems has advanced forecast skill**
  - Built on the success of hybrid variational/ensemble approaches and specification techniques
  - Transitioning towards use of only advanced techniques for increased observation information retention
  - Expanding ensemble assimilation and forecast development for future success
- **Extensive experience with conventional, targeted and novel observations**
  - Applying observations to model data assimilation and verification applications
  - Documenting relative impacts on predictive skill
  - Using various sensitivity techniques (OSEs, FSOI)
- **World Leader in R&D of high-resolution rapidly updating models**
  - Working with many collaborators to improve skill, accumulating innovations for many stakeholders, and finishing with operational transitions

Thank you!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