Implementation, Testing, and Evaluation of Radar Data Assimilation Capabilities within the JEDI Hybrid EnVar/EnKF System for the Rapid Refresh Forecast System

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Technical Background

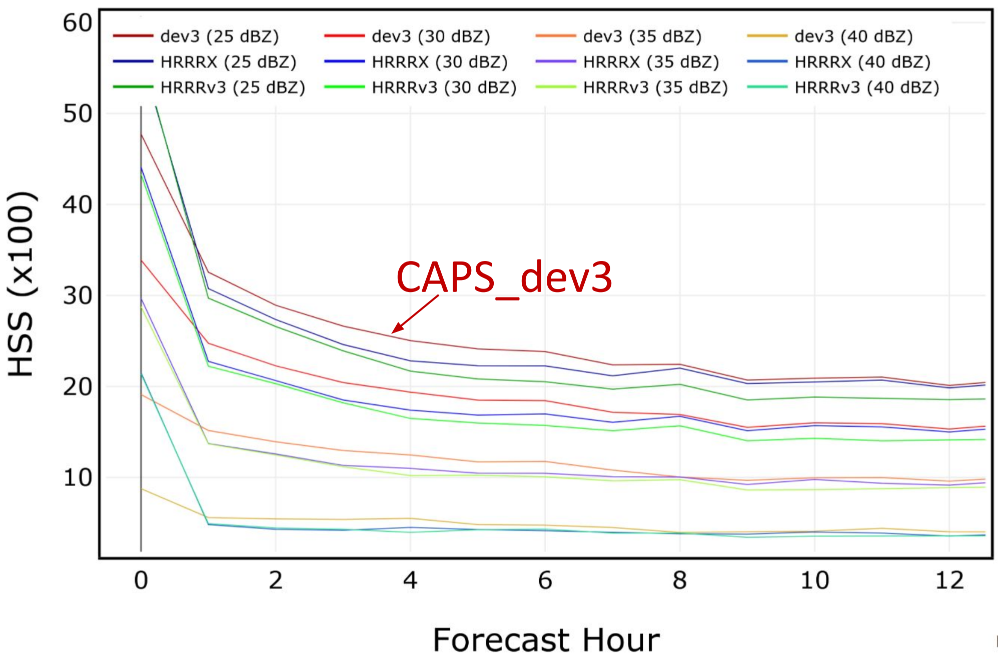
- Under the support of NOAA JTTI and WoF program grants, several techniques and treatments for radar DA were recently developed at CAPS and implemented within the GSI hybrid EnVar. They include:

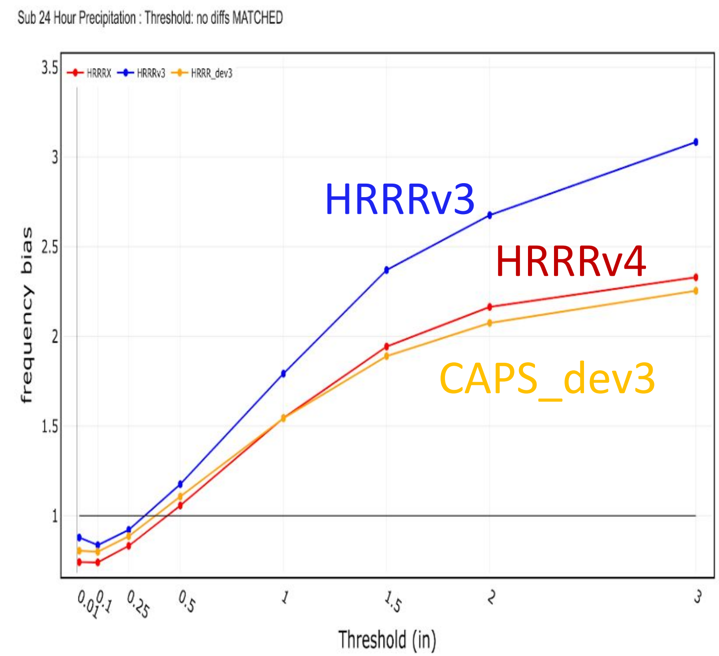
1) the proper specification of static background errors of hydrometeors (Liu et al. 2019),
2) additional treatments needed to avoid spurious increments near zero-Z or zero-background mixing ratios (Liu et al. 2020),
3) the use of a Z operator and its adjoint consistent with the Thompson microphysics scheme used in the prediction model (Liu et al. 2022),
4) the use of power-transformed hydrometeor mixing ratios and number concentrations as control variables to accelerate minimization convergence and effectively assimilate radial velocity and other observations simultaneously with Z data (Chen et al. 2021; Li et al. 2022),
5) direct radar DA capabilities within GSI framework were demonstrated via extensive parallel testing superior performance to HRRRv4 (Duda and Ladwig, 2022)

Scores for Extended Runs at GSL
Hourly reflectivity Heidke Skill Scores and 6 h Precip Biases

Dev3 = CAPS(same as HRRRV4 except for direct radar DA replacing cloud analysis)

HRRRX=HRRRv4, HRRRv3





Bias for 6 h precip

approximately 140 forecasts were run in real time from
late July through 02 September 2020

From Duda and Ladwig (2022)

Motivations

- The Rapid Refresh Forecast System (RRFS) based on Joint-Effort for DA Integration (JEDI) DA framework and the limited area FV3 (FV3-LAM) will be the NOAA next-generation DA and forecast system aiming at convection-allowing weather forecasting, replacing several current regional operational systems.

- implement direct radar DA capabilities within the JEDI-based hybrid EnVar/EnKF DA system, and test and evaluate the system for the target RRFS model.

Outline

1. Migrate radar DA capabilities from GSI into JEDI-FV3
    - Add the I/O interface of MRMS reflectivity and the NEXRAD Level-2 radial velocity data to JEDI IODA module
    - Add the control variables of hydrometeor mixing ratios and total number concentrations to the JEDI-FV3-LAM interface and apply control variable transform for the hydrometeors
    - Fully port radar Z operators and their adjoint codes from GSI into JEDI

2. Preliminarily test radar DA using JEDI coupled with FV3-LAM
    - Test the **radar-enhanced JEDI LETKF/LGETKF** with FV3-LAM and compare with results of radar-enhanced GSI EnSRF
    - Compare radar DA using JEDI LETKF coupled with FV3-LAM with **Thompson and NSSL MP and Z operators**
    - Test the **radar-enhanced JEDI En3DVar** with FV3-LAM and compare with results of radar-enhanced GSI En3DVar

3. Implement **IAU initialization** technique within FV3-LAM and evaluate its impact on high-frequency radar DA cycle

4. Current **issues** for JEDI-based radar DA in 3-km CONUS domain

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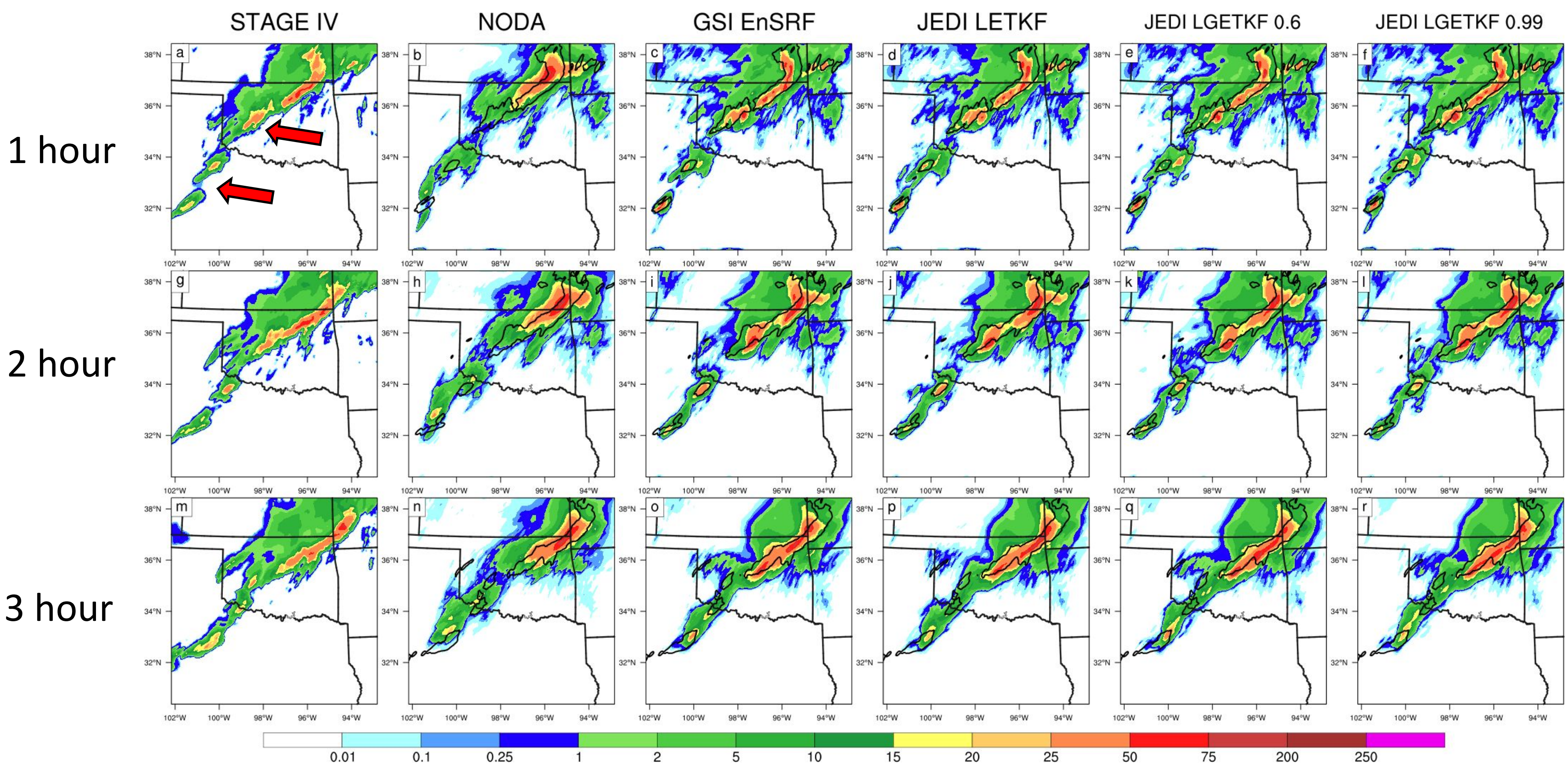
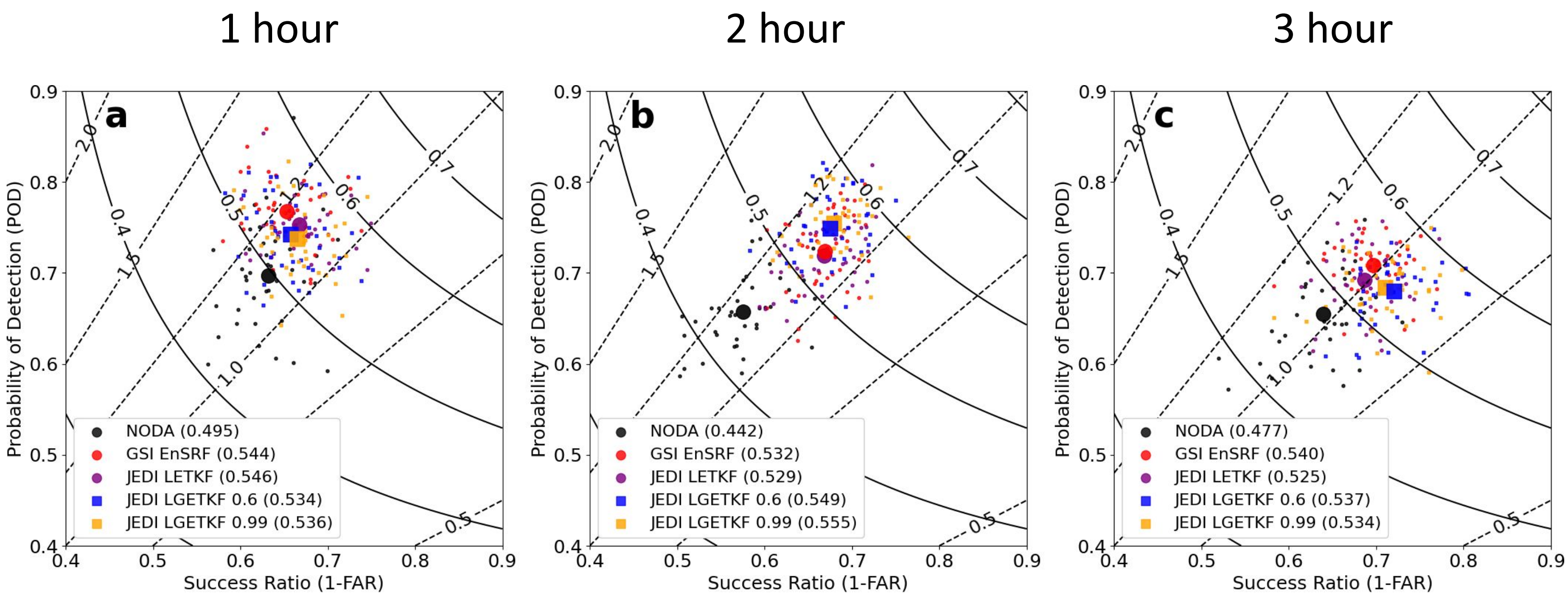
Hourly precipitation probability-matched mean

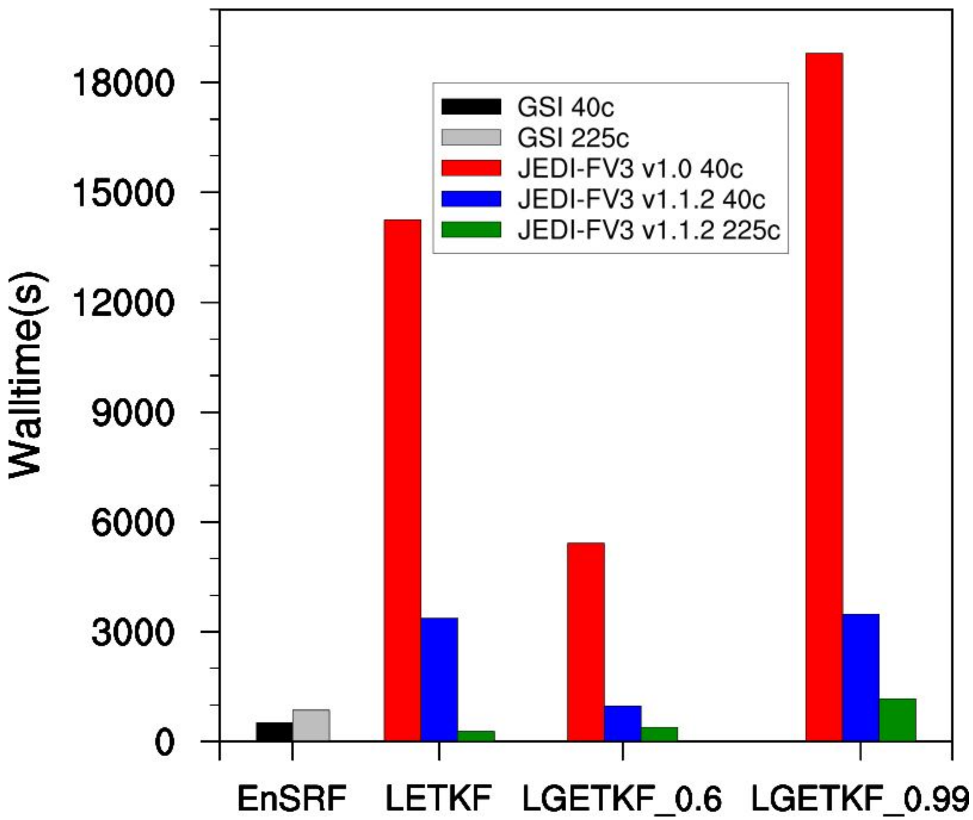


Observed precipitation exceeding 10 mm is contoured in black in the results from forecast experiments

Performance diagrams of composite reflectivity hourly forecast for 45 dBZ thresholds



Total elapsed time for single EnKF analyses



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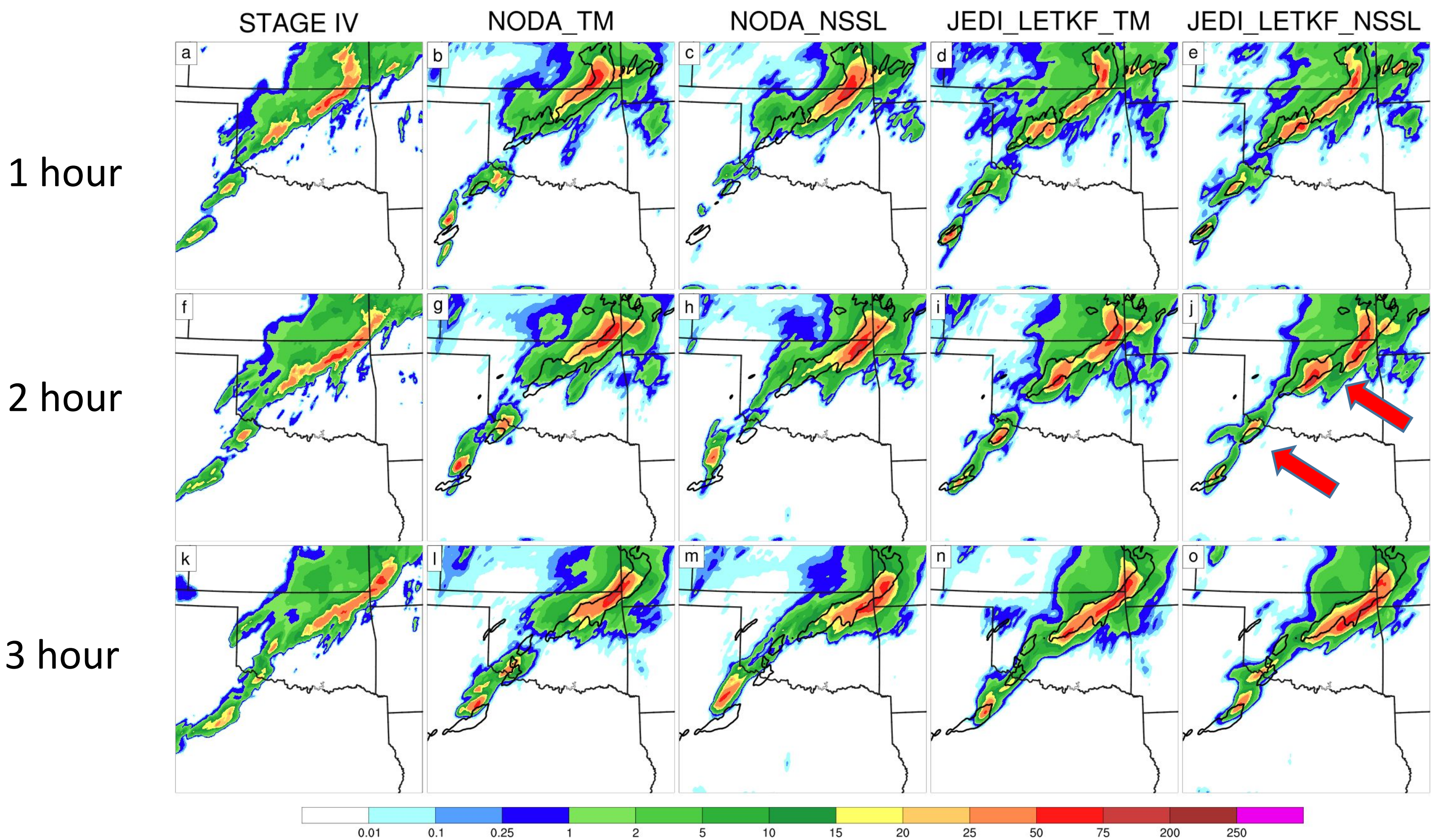

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A new *Z* Operator based on Thompson MP for Variational DA

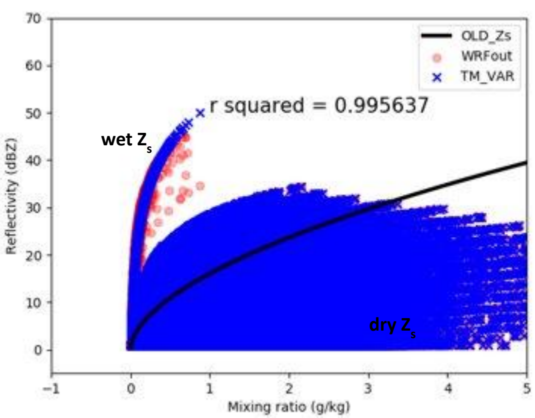
- Compared to *Z* operator based on Thompson MP in Liu et al. (2022), we added temperature-dependent properties to make it more consistent with TM MP

- Z_s: 1) The formula of TM microphysics code was employed for dry snow

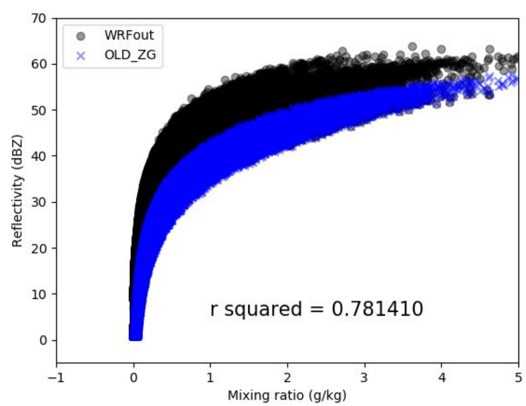
2) Fitting function was tuned for wet snow

- Z_g: We employed two fitting functions for dry/wet graupel, respectively

Z_s

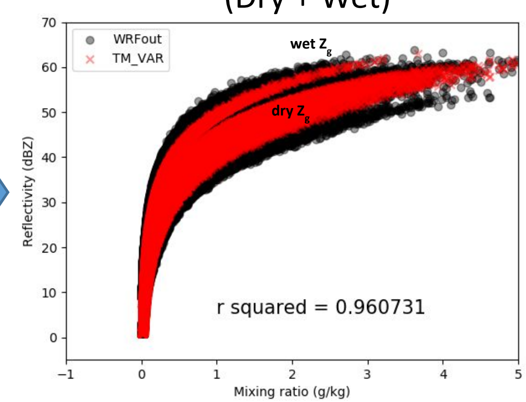


Old Z_g

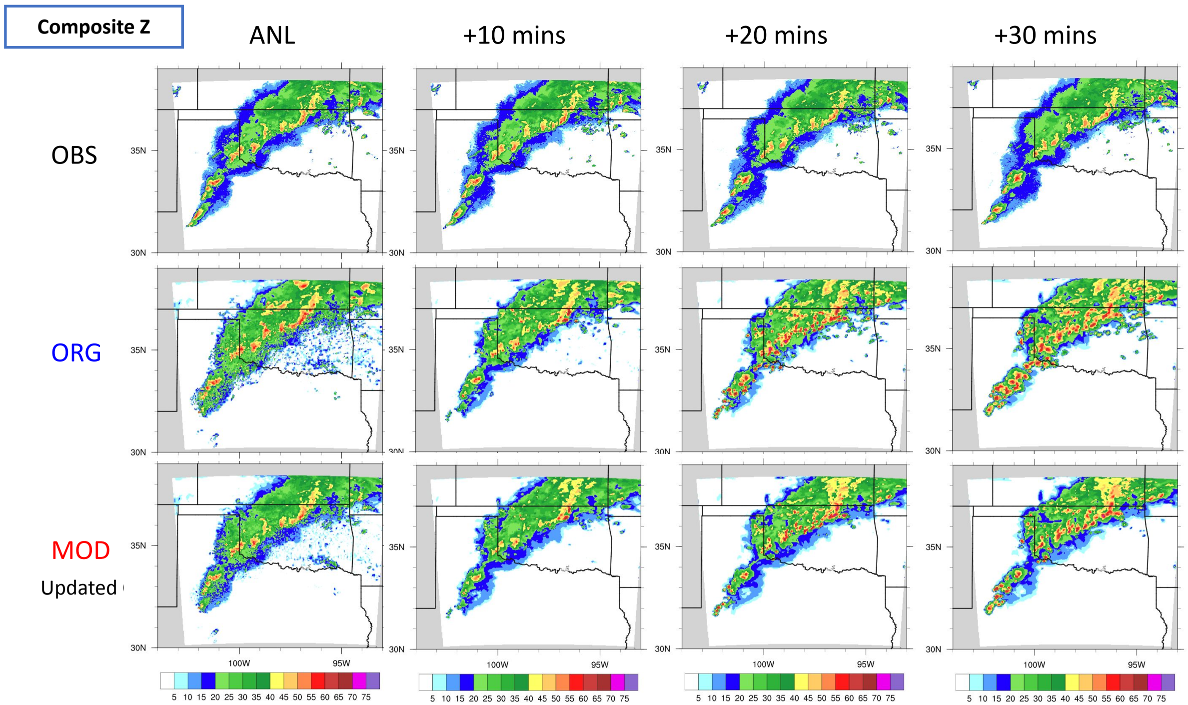


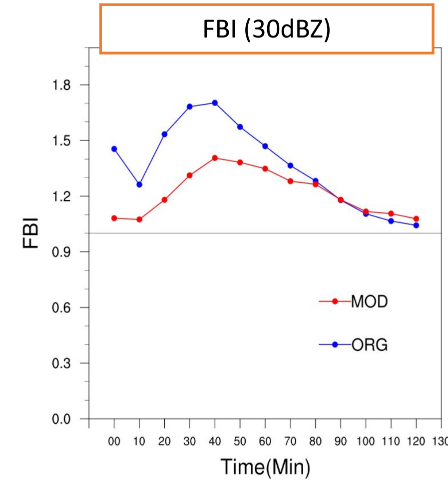
New Z_g

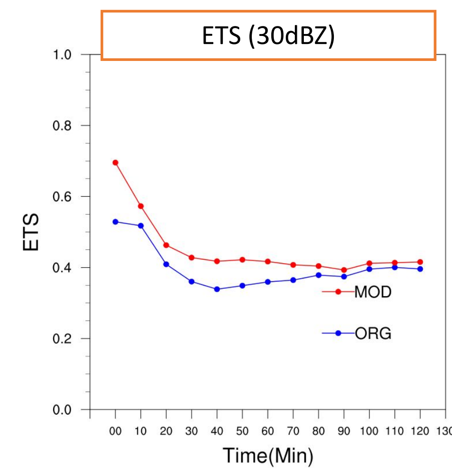
(Dry + Wet)



Comparison of 1-Time EnVAR DA Results on WRF after Update



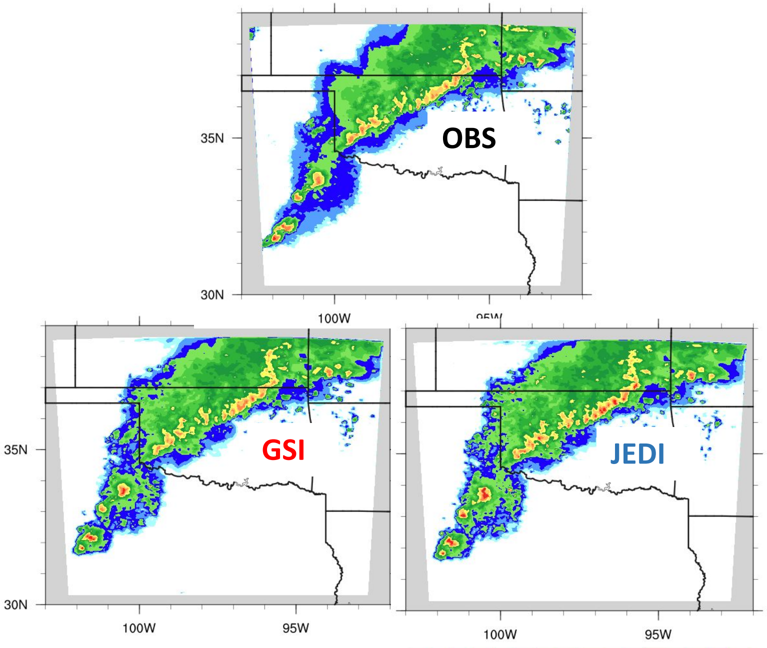




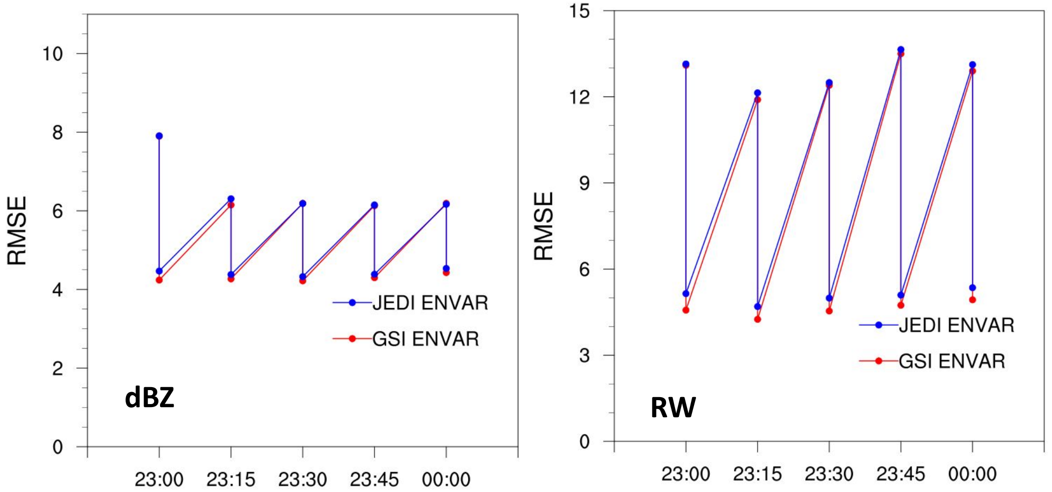
- dBZ from forecasts of the WRF model (WRFv3.8_WOFS_2019)
- Weak spurious echoes at analysis were reduced in **MOD**.
- **MOD** shows better fits to **OBS** for both analyses and forecasts.
- **ORG** generally has more spurious echoes w.c.t **MOD** at the early hour.
- **MOD** also has better statistics in both FBI and ETS up to 2-hour.

Comparison of JEDI En3DVar and GSI En3DVar

Composite Z at the final cycle

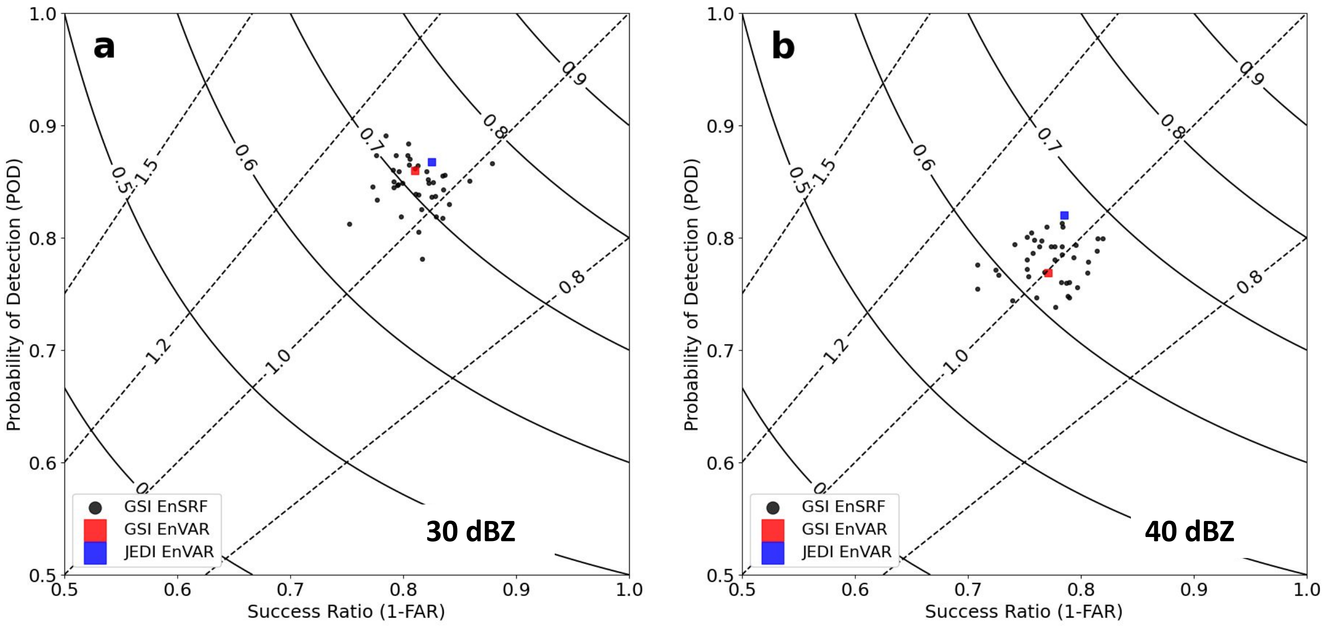


RMSE



- JEDI En3DVar produces a analysis comparable to that of GSI EnVar even though using different localization procedures (NICAS for JEDI and RF for GSI)

Performance diagrams of composite reflectivity 3-hour forecast



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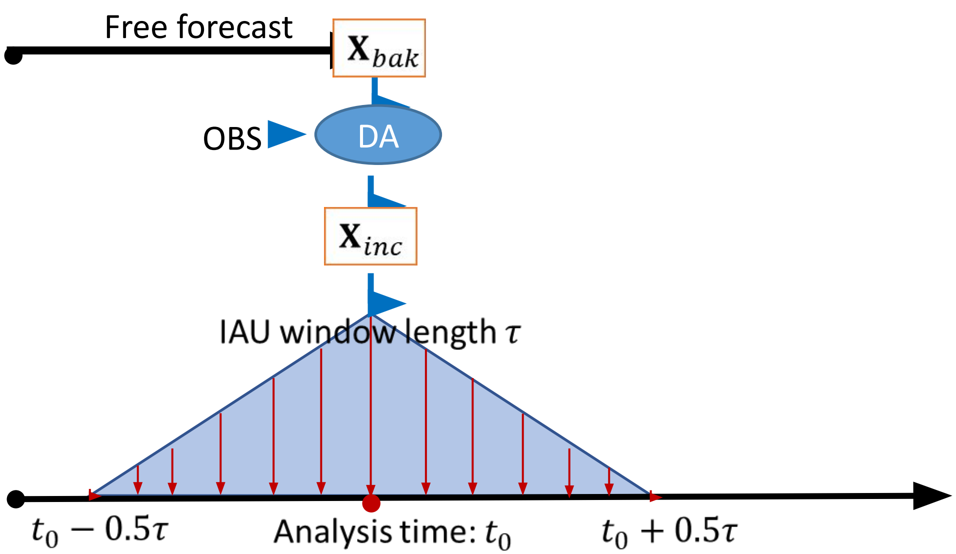
The incremental analysis update approach

IAU (Incremental analysis update) is an approach that uses the analysis increment as a continuous forcing for the model prognostic variables (Bloom et al. 1996) to combat the imbalance that was introduced from data assimilation.



Schematic flow-chart of the IAU approach

Model forcing

IAU forcing

$$\mathbf{X}_t = \mathbf{X}_{t-1} + \left(\frac{\partial \mathbf{X}}{\partial t}\Big|_t + W(t)\delta\mathbf{X}\right)\Delta t$$

$$\boldsymbol{\delta}\mathbf{X} = \mathbf{X}_{inc} \Big/ \int_{t_0-0.5\tau}^{t_0+0.5\tau} W(t)dt$$

$W(t)$ is the weight of IAU forcing term at time t;

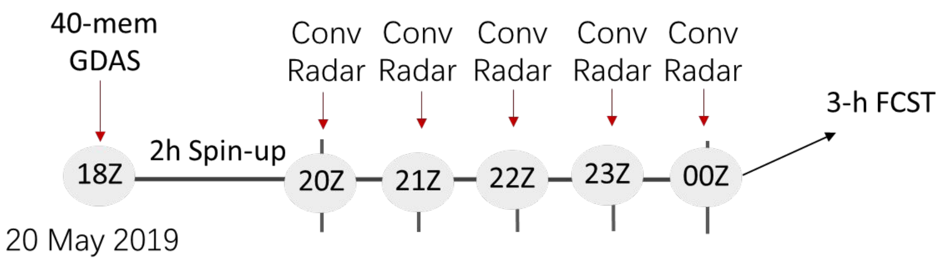
τ is the IAU window length;

Δt is the time step length.

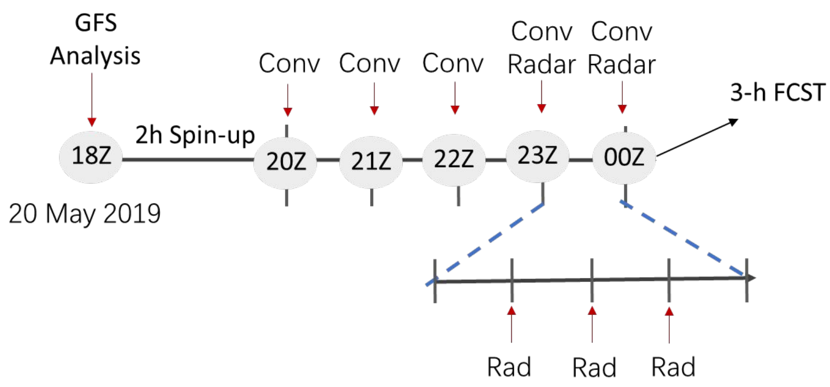
Experimental configurations for a squall-line case study

A squall-line case that occurred on 20 May 2019 is selected as the case of interest. The UFS/FV3 model is used as the NWP model, and the JEDI LETKF is employed as the data assimilation system.

IAU experiment with hourly cycling configuration (Exp-DA-1h, Exp-IAU-1h):

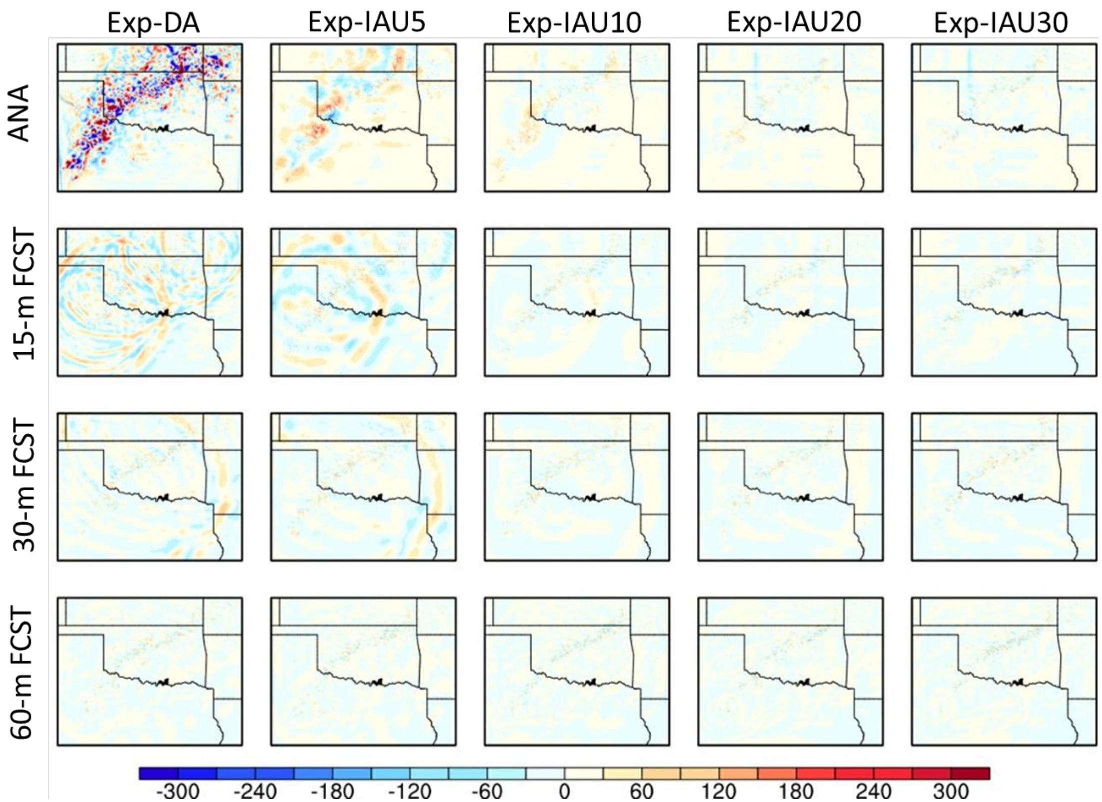


IAU experiment with 15-min cycling configuration (Exp-DA-15m, Exp-IAU-15m):



- All experiments were initialized from 40- mem GEFS 3-h forecasts. After 2-h spin-up, data assimilations were carried out from 2000 UTC 20 to 0000 UTC 21. Then, 3-h forecasts were launched;
- The JEDI LETKF is employed as the DA system. The localization scale is 300 km for conventional DA and 18 km for radar DA;
- All IAU experiments were configured with a 5-min IAU window. The weight of IAU forcing is a triangle with the largest weight at the analysis time and zero weight at the begin and end of the IAU window.

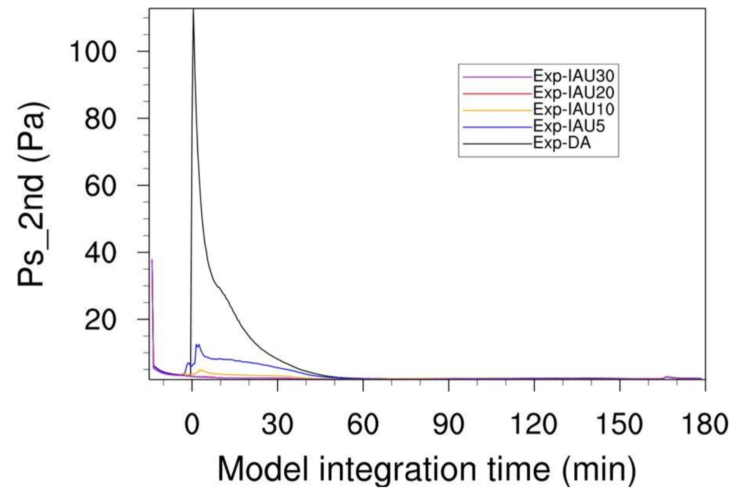
Impacts of different IAU length on imbalance



Surface pressure difference (Pa) during model integration

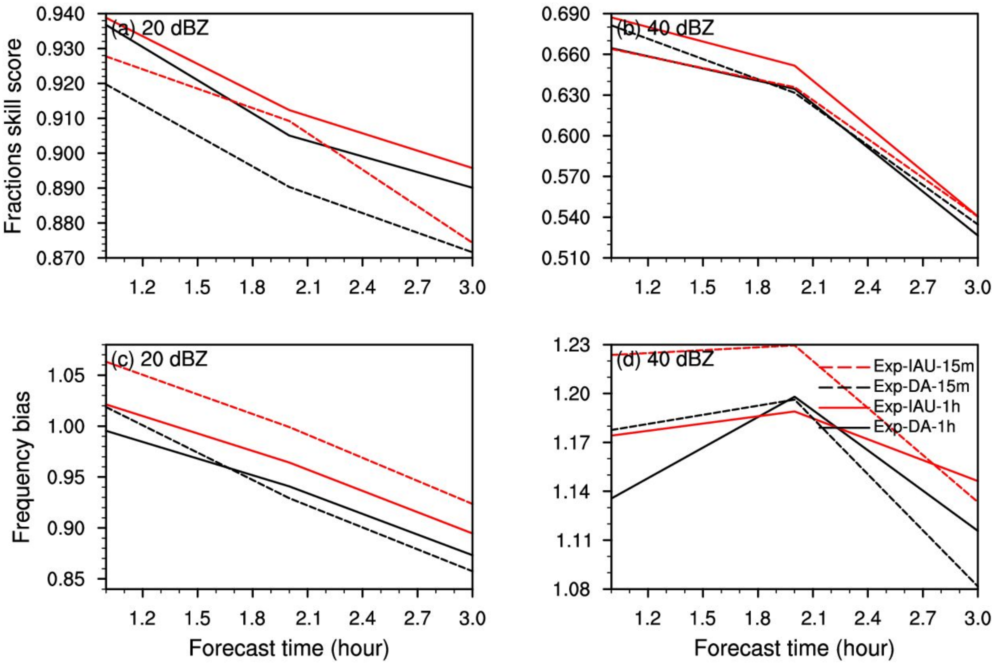
Mean absolute second derivative of surface pressure (Houtekamer and Mitcheel 2005) :

$$Ps\_2nd = \frac{1}{N_x \cdot N_y} \sum_{1}^{N_y} \sum_{1}^{N_x} \left| p_s(t+\Delta t) - 2p_s(t) + p_s(t-\Delta t) \right|$$

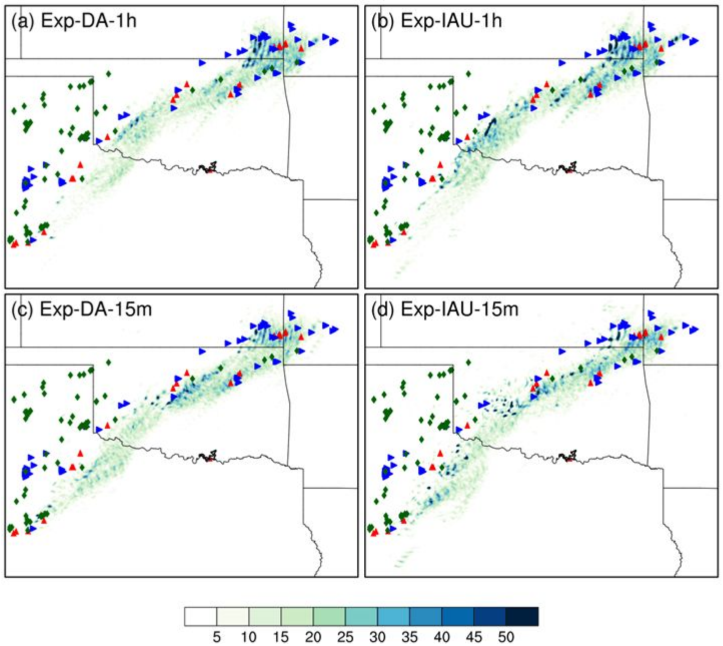


- The IAU approach greatly reduces the imbalance caused by data assimilation.

Impacts of IAU on reflectivity forecast



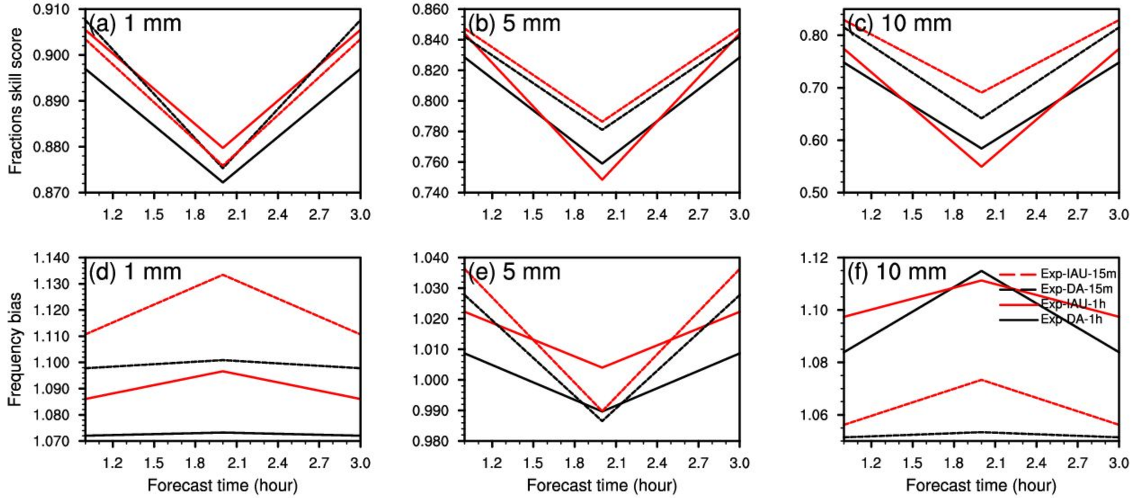
FSS (radii = 30 km) and BIAS of composite reflectivity forecast



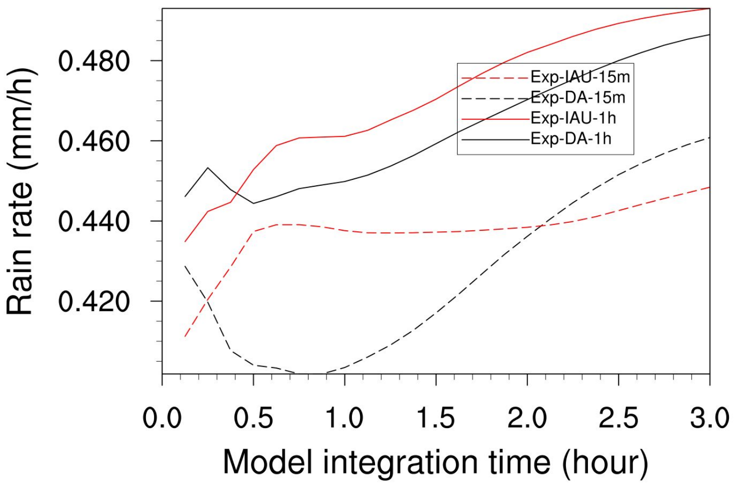
1-3-h 2-5 km UH swaths (Green: damaging winds; Blue: hails; Red: tornados)

IAU experiments have higher forecast skills than DA experiments with relatively higher FSSs but slightly larger BIAS.
IAU experiments tend to predict larger UH swaths around the areas where severe weather occurred.

Impacts of IAU on precipitation forecast



FSS (radii = 30 km) and BIAS of hourly accumulated precipitation forecast



Time evolution of domain-averaged rainfall rate (mm/h)

- IAU outperformed DA experiments for the hourly accumulated precipitation forecast with relatively higher FSS skills.
- Compared to DA experiment, IAU experiments have relatively stable rainfall rate during the 3-h forecast. DA experiments experienced a reduction of rainfall rate during the first 30 to 45 minutes, which may be because of the reduction of hydrometeors.

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Issues for JEDI-based radar DA

- **EnKF DA**

 - **Distributing observations under 'halo' needs to be improved.** To be specific, Frontera administrators blocked our queue accesses by stating that the JEDI EnKF application over CONUS was beating one OST heavily instead of spreading the load onto multiple OSTs on '/scratch' disk. They recommend users to fix IO.

 - **I/O needs to be improved (e.g., parallel I/O, precision).** For example, it takes about 30% of walltime to dump out analysis ensembles in case of large-domain simulations.

- **Variational DA**

 - It takes quite some time to create BUMP files for variational DA applications required for JEDI-based radar DA. This is because horizontal subsampling should be done by using many grid-points to estimate a smaller localization lengthscale for radar DA. It takes about 2 hours to create BUMP localization matrix file (resol=6, rh=15 km) for 310X310 domain for lastest “develop” branch while over 48 hours for JEDI-FV3 v 1.1.2.

 - **Memory usage steadily increases during the inner loop in JEDI variational DA applications.** Conducting EnVAR experiments on large domains (e.g., CONUS) is currently taking too much cost. 5.1 TB memory for only 9 ensemble members.

 - **There are very few documents available on BUMP**

Summary

- Capabilities to directly assimilate radar Z and Vr data have been developed within GSI framework, which were systematically compared with HRRRV3 and HRRRV4. The direct radar DA method somewhat outperformed both.
- Those capabilities are being moved into JEDI EnKF/EnVar, and beg to be used in future RRFS-V2.
- The performance of Radar DA with JEDI is comparable to that with GSI while the latest version (v1.1.2) JEDI has more computational efficiency than GSI.
- IAU initialization technique is implemented within FV3-LAM. The unphysical oscillation of surface pressure in the early forecast hour is effectively suppressed by IAU. In addition, the 1–3-hour reflectivity forecasts are somewhat improved by IAU procedure in terms of performance diagrams

Future work

- Test the NICAS in JEDI BUMP package or a multigrid beta filter to produce model static background error covariance BEC and localize ensemble BEC of hydrometeors for radar DA

- Evaluate the JEDI system with radar DA in a quasi-operational setting at GSL using target RRFS configurations over an extended period

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