Direct Assimilation of GOES-R Geostationary Lightning Mapper (GLM) Data within JEDI LETKF, LGETKF, and Hybrid System for UFS Convection-Allowing Predictions

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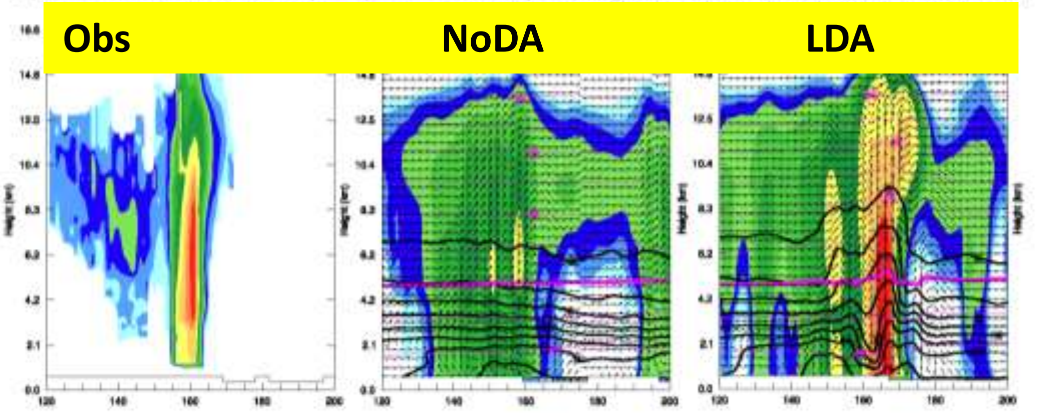
Our Past Research: Direct Assimilation of GLM FED Data Using GSI System

In our past studies, direct assimilation capabilities of real GLM FED were developed within the GSI EnKF and variational DA framework for convection-allowing NWP, which, in case studies, noticeably improved the initial representation and prediction of convective storms for up to several hours.

Vertical cross sections of reflectivity, temperature, water vapor mixing ratio, and wind vector fields after 1-h FED DA



1. Kong, R., et al., 2020: Assimilation of GOES-R Geostationary Lightning Mapper Flash Extent Density Data in GSI EnKF for the Analysis and Short-Term Forecast of a Mesoscale Convective System. *Mon. Wea. Rev*., 148, 2111-2133.

2. Kong, R., et al., 2024: Assimilation of GOES-R geostationary lightning mapper flash extent density data in GSI 3DVar, EnKF and hybrid En3DVar for the analysis and short term forecast of a supercell storm case. *Adv. Atmos. Sci*. In press.

3. Kong, R., et al., 2022: Development of New Observation Operators for Assimilating GOES-R Geostationary Lightning Mapper Flash Extent Density Data Using GSI EnKF: Tests with Two Convective Events over the United States. *Mon. Wea. Rev*., 148, 2111-2133.

Current Research: Advancing GLM FED Assimilation within JEDI DA Framework

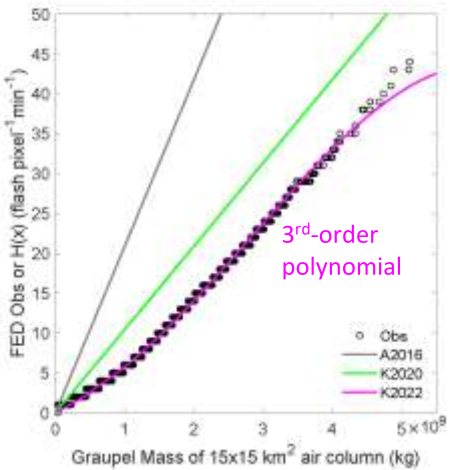
- Our current research has further advanced the direct assimilation capabilities for real GLM DED data within the JEDI EnKF and variational DA framework.
- The Rapid Refresh Forecast System (RRFS), exploring the FV3 dynamical core, will become the United States' next-generation convection-allowing weather forecasting system (RRFS-v1).
- The RRFS system is expected to use the new Joint Effort for DA Integration (JEDI) framework in the near future.
- Effective assimilation of GLM data into the operational RRFS using JEDI is anticipated to be highly beneficial.

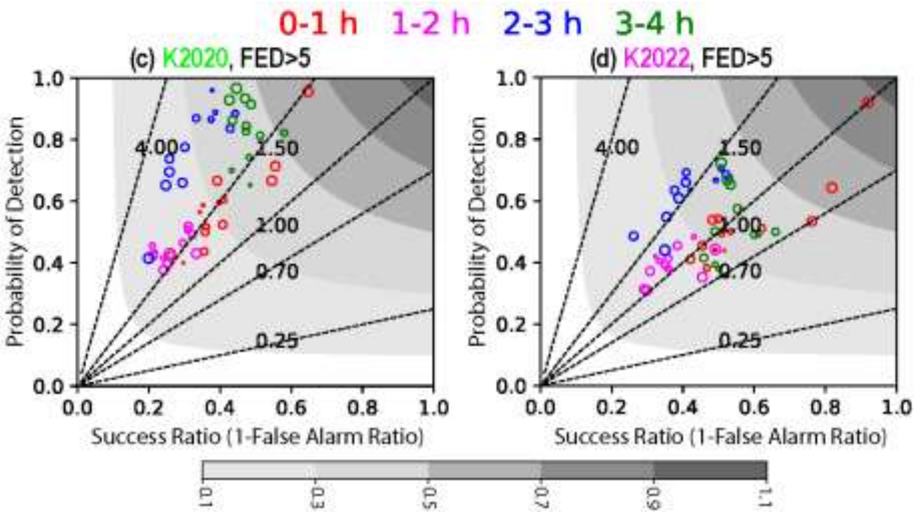
Outline of Current Study

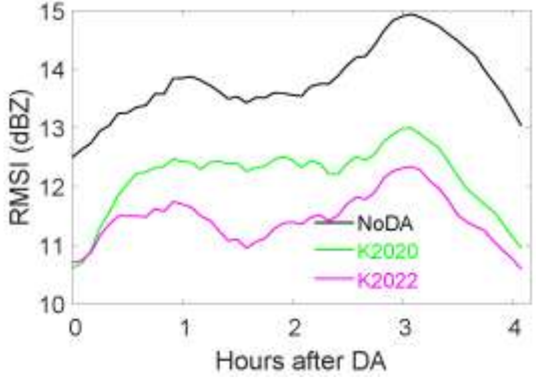
1. **The Nonlinear FED Observation Operator.**
2. **Testing Different DA Algorithms and Vertical Localization Radii in FED DA within the JEDI Framework:**
   a) **Single-Point DA Experiment**: To validate the accuracy of the implementation and evaluate their performance with varying vertical localization radii.
   b) **Cycled Data Assimilation Experiments**: To determine the optimal localization radius for the following experiments.
   c) **Compare Analysis of LDA with Different Algorithms**: Not to establish superiority among algorithms, but to provide a fundamental overview of each algorithm's performance.
3. **Exploring Additional Impacts of FED DA Beyond Conventional DA and Comparing Performance with Radar DA.**

Develop nonlinear FED observation operator

- **The FED observation operator** relates FED observation with model simulation of the graupel mass field.
- Developed new nonlinear observation Operators by fitting the FED observations directly to model simulations of graupel mass field (using WRF Thompson MP scheme; Kong et al. 2022).
- The newly fitted operator reduced the bias of the 0-4 h FED forecasts after DA as well as the RMSIs of the 0-4 h composite reflectivity forecasts after FED DA relative to the former operator used by Kong et al. (2020).

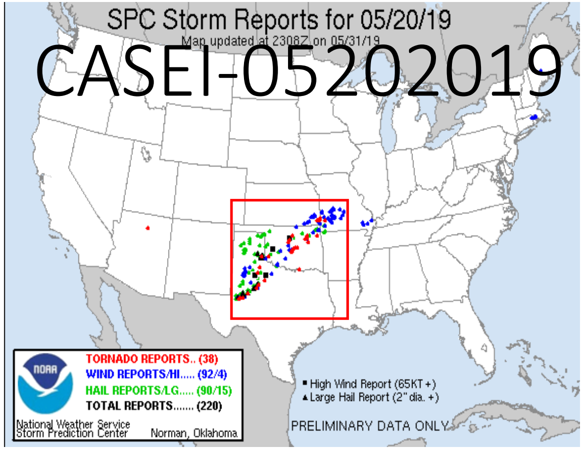


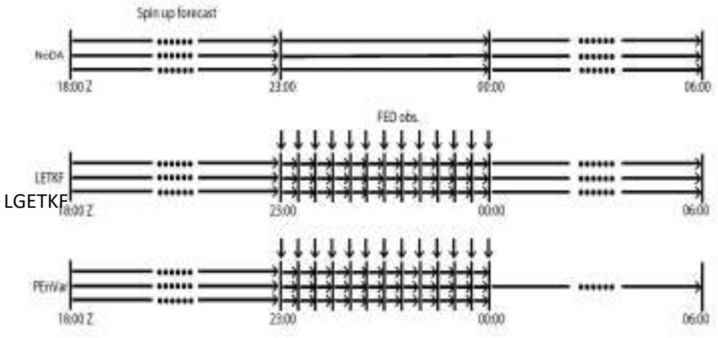




Reproduced from Figs. 4, 13, 15 in Kong et al. 2022

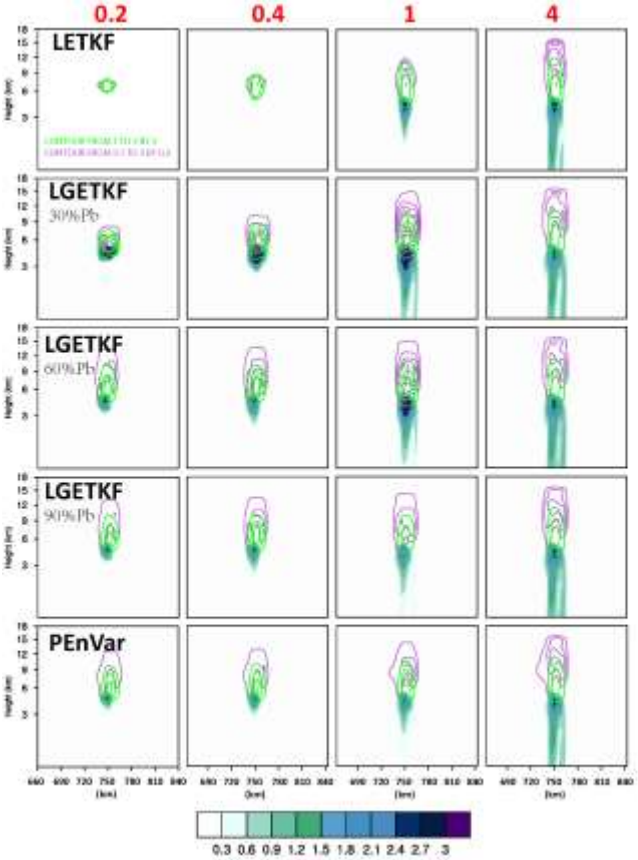
Testing Different DA Algorithms and Vertical Localization Radii in FED DA within the JEDI Framework





Experiment	DA Methods	Vertical Localization Radius in log(P)
NoDA	Does not assimilate any data.	NA
LETKF	LETKF	0.2, 0.4, 1, 4
LGETKF30%Pb	LGETKF (30% retained Pb)	0.2, 0.4, 1, 4
LGETKF60%Pb	LGETKF (90% retained Pb)	0.2, 0.4, 1, 4
LGETKF90%Pb	LGETKF (90% retained Pb)	0.2, 0.4, 1, 4
PEn3DVar	PEn3DVar (0% static background, 100% ensemble covariance)	0.2, 0.4, 1, 4

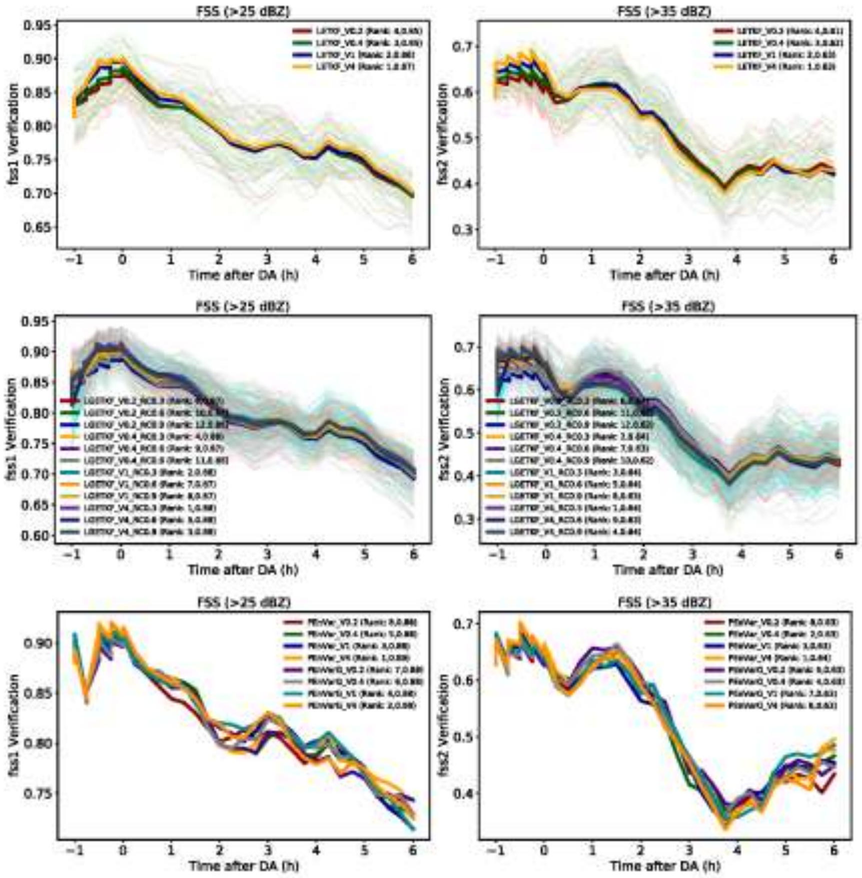
Single point experiments on vertical localization radius with JEDI LETKF, LGETKF, and pure En3DVar



- To validate the accuracy of the implementation.
- To evaluate their performance with varying vertical localization radii.
    - When vertical localization radii are small, LGETKF and PEn3DVar exhibit greater vertical extensions of the analysis increments compared to LETKF.
    - LGETKF and PEnVar produce similar increments when a higher percentage of retained Pb (90%) is used.
    - When vertical localization is set to a large value (i.e., 4), all data assimilation experiments yield similar increments.

Vertical cross sections of mixing ratio increments (g kg^{-1}) of rain (shading), snow (purple contours), and graupel (green contours) after the first DA with the same horizontal localization of 15 km and different vertical localizations of 0.2, 0.4, 1, and 4 in log(P) space, using LETKF, LGETKF with 30%, 60%, and 90% retained covariance, and pure En3DVar algorithms, respectively.

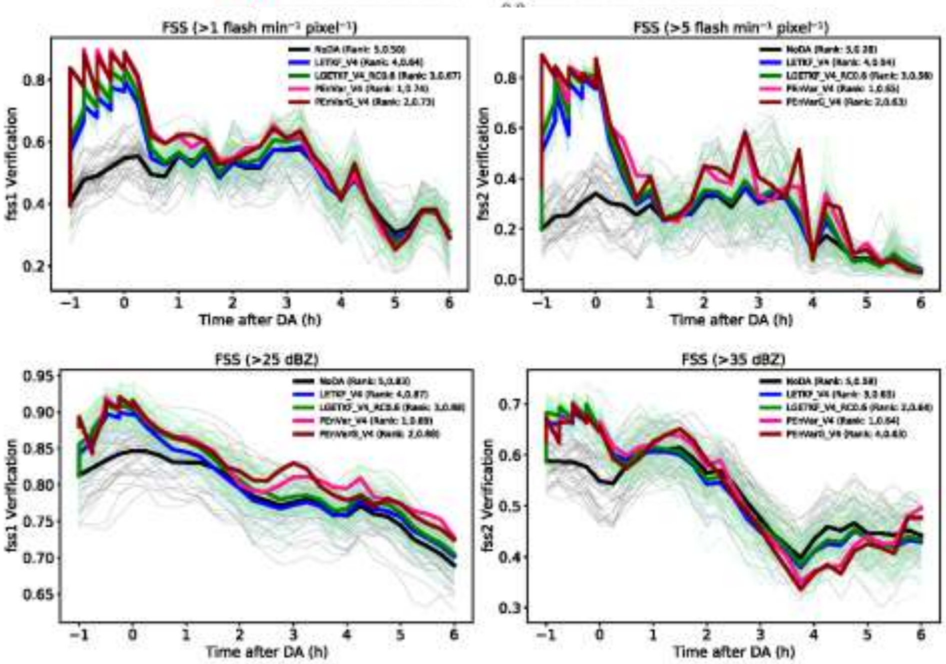
Cycled DA experiments on Vertical Localization Radius with JEDI LETKF, LGETKF, and Pure En3DVar



- Conducting Sensitivity Experiments on Vertical Localization Radius (0.2, 0.4, 1, and 4 in log(P) space), for LGETKF, the retained Pb is also tested.
- The sensitivity experiments reveal that the optimal radius of 4 (the largest) consistently yields the best results across all data assimilation experiments, including LETKF, LGETKF, and PEn3DVar. As a result, a radius of 4 is chosen for subsequent experiments.
- The percentage of retained background error covariance (Pb) in LGETKF does not exhibit significant variations when using a larger vertical localization radius. Therefore, a value of 0.6 is selected for future experiments.

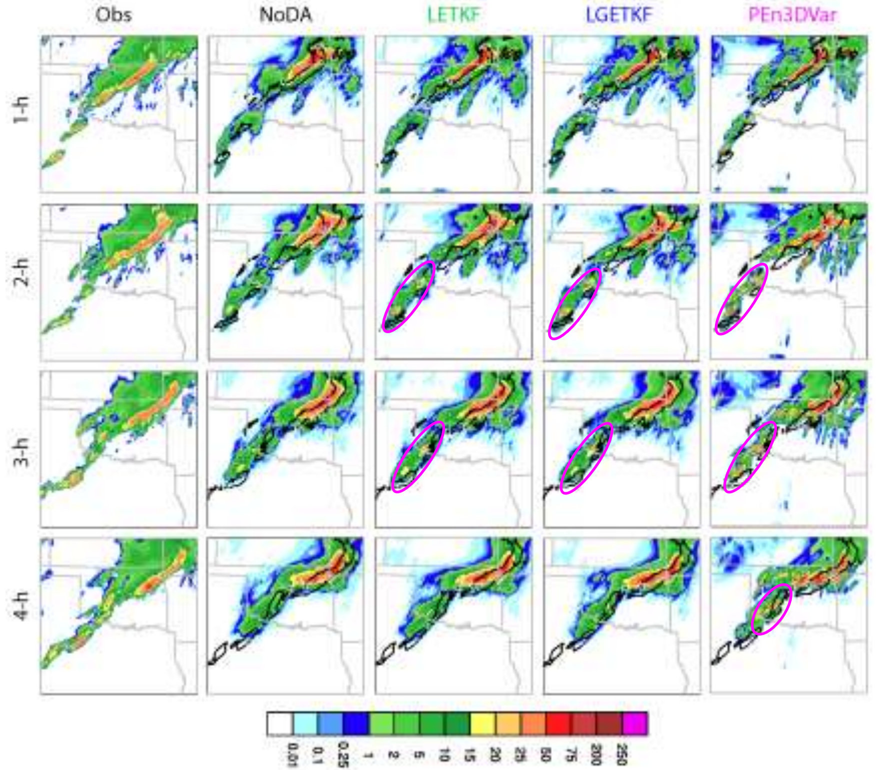
Compare Analysis of LDA with Different Algorithms

(Not to establish superiority among algorithms, but to provide a brief overview of each algorithm's performance)



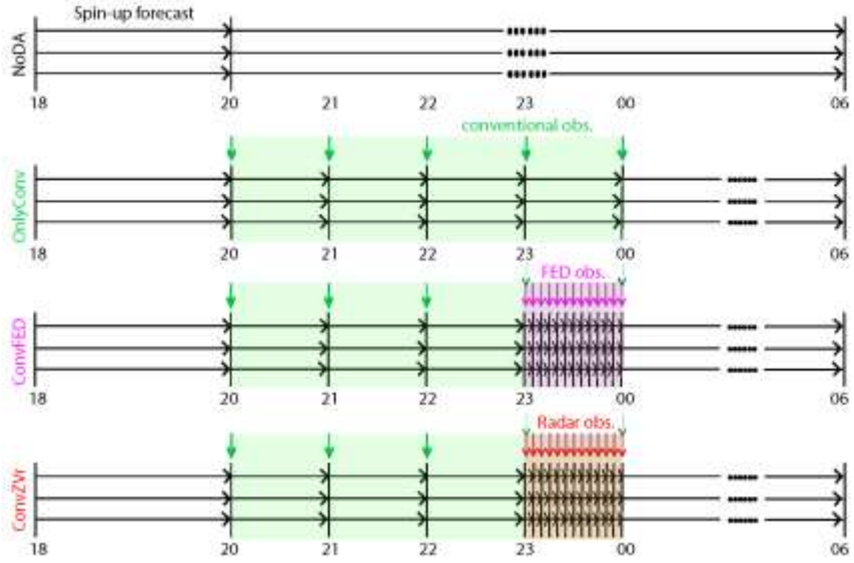
JEDI PEnVar outperforms JEDI LETKF, LGETKF in terms of FSS in FED and composite reflectivity analyses/forecasts and more accurate precipitation forecasts after DA for this case.

The algorithm differences in LGETKF/LETKF and PEn3DVar are believed to be one reason. Unlike EnKF, which has ensemble analyses, PEn3DVar starts with the mean field, which may also cause differences.



1-4h hourly precipitation forecasts from observations, probability matched mean of NoDA and LETKF, LGETKG, and PEnVar, respectively. Using the largest vertical localization radii in previous slide.

Examine the impacts of FED DA in addition to conventional DA, and compare the results with radar DA

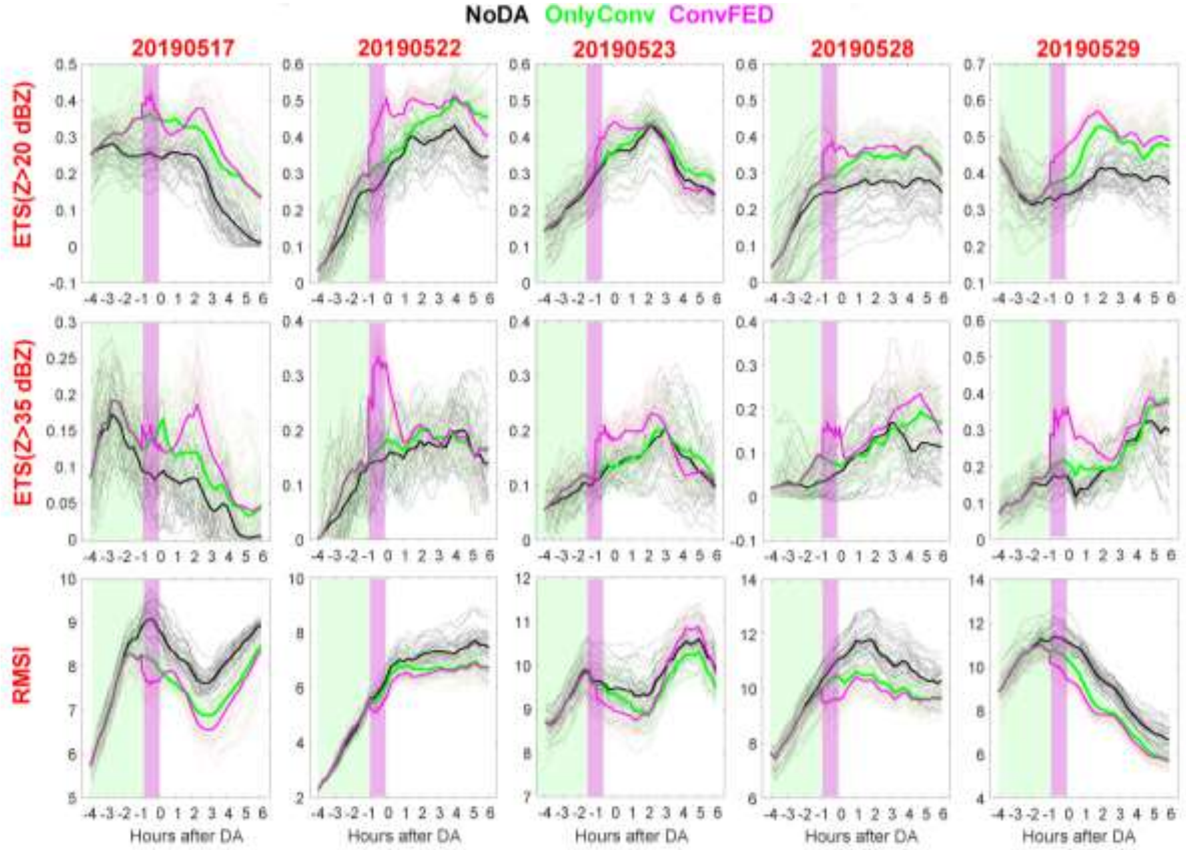


Flow chart of the DA experiments

Name	Description
NoDA	No DA (reference)
OnlyConv	Assimilate conventional observations hourly using JEDI LETKF.
ConvFED	Assimilate both conventional observations hourly and FED observations every 5-min for the last 1-h DA window using JEDI LETKF.
ConvZVr	Assimilate both conventional observations hourly and radar reflectivity and radial velocity observations every 5-min for the last 1-h DA window using JEDI LETKF.

Experimental design

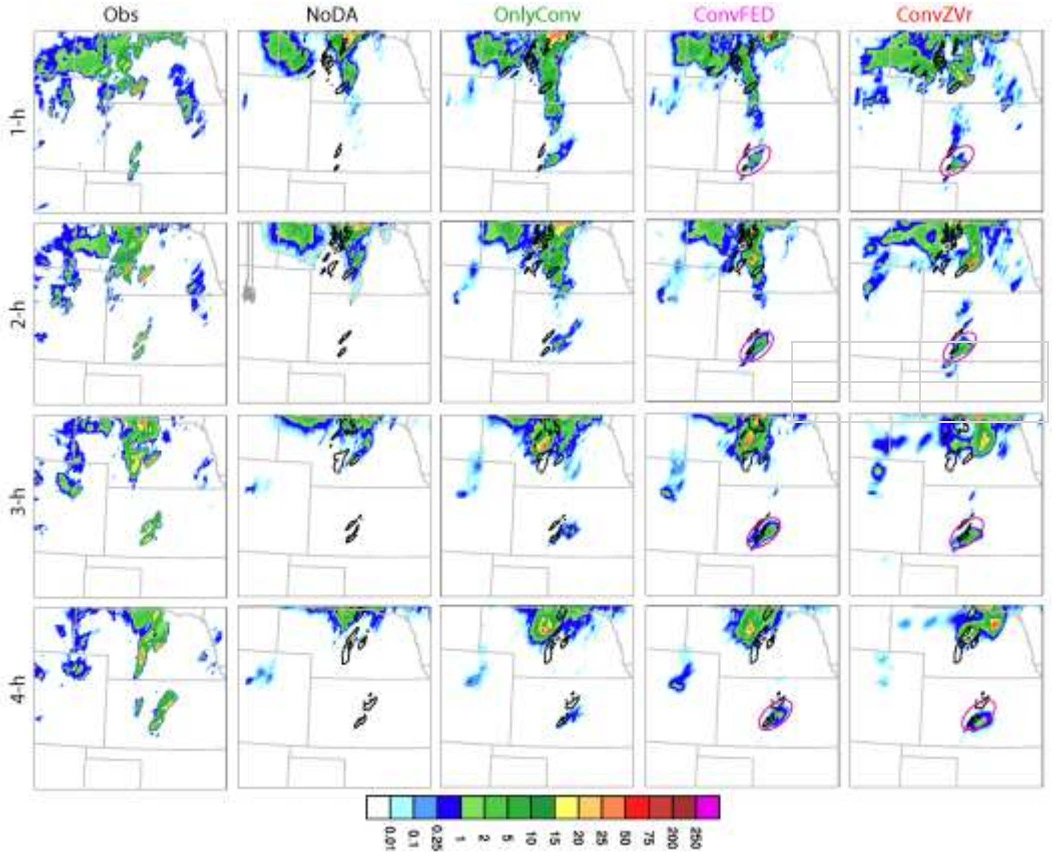
Exploring Additional Impacts of FED DA Beyond Conventional DA for Five Convective Storm Cases



Verification against MRMS composite reflectivity field (10-h in total)

- Assimilating conventional data can enhance storm forecasts compared to NoDA.
- Incorporating FED data along with conventional data can further improve storm forecasts.
- Suggest positive impacts of FED DA on storm forecasts.

Examine the impacts of FED DA in addition to conventional DA, and compared the results with radar DA (CASE-II 05/17/2019).



1-4 h rainfall forecasts against MRMS

Overlaid with observed precipitation higher than 10 mm/h (black contours)

- 1-4 h hourly precipitation forecasts from observations, probability matched mean of NoDA, OnlyConv, ConvFED, and ConvZVr for storm case on May 17, 2019, respectively.
- ConvFED and ConvZVr perform similarly and both better capture southern precipitation area relative to OnlyConv, and they all outperform NoDA.
- FED DA produces comparable storm forecasts as that of radar DA.

Conclusions

- **Successful Implementation**: We have integrated GOES-R GLM lightning data assimilation into the JEDI DA frameworks for convective storm numerical weather prediction.
- **Method Validation**: Through a single-case study, we have validated our implementation, utilizing LETKF, LGETKF, and PEn3DVar. This validation process has affirmed the accuracy of our methods and established that assimilating lightning data consistently yields reliable results.
- **Enhanced Predictions**: When incorporating lightning data, as evidenced in multi-case experiments employing LETKF, we consistently observed significant improvements in storm analysis and forecasts relative to the baseline experiments that assimilate conventional data alone.
- **Comparable to Radar**: Our experiments have also revealed that the assimilation of lightning data, when combined with conventional data, produces results that are comparable with those achieved by simultaneously assimilating radar and conventional data.