The Role of Convective-Scale Static Background Error Covariance in RRFS Hybrid EnVar for Direct Radar Reflectivity Data Assimilation over the CONUS

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Hybrid background error covariance

- Previous studies using simple models hypothesized that the **hybridization** of a static covariance matrix with a flow-dependent ensemble-based covariance matrix can leverage the advantages of both (e.g., Hamill and Snyder 2000; Wang et al. 2007, 2009).

- Many studies have confirmed the benefits of hybrid error covariance matrices for ***large-scale*** data assimilation (DA) and numerical weather prediction (NWP) (e.g., Buehner 2005; Wang et al. 2008, 2013; Kuhl et al. 2013; Clayton et al. 2013; Penny et al. 2015; Bowler et al. 2017).

Convective-scale static covariance

- While static covariance for large-scale DA has been established for a long while, additional considerations are needed to develop static covariance for ***convective-scale*** DA and NWP.
- Wang and Wang (2021) developed a **convective-scale static covariance matrix** for direct radar reflectivity assimilation.
- Wang and Wang (2021) has shown with the WRF-ARW model that the utilization of a convective-scale static covariance matrix in the hybrid EnVar can improve the convective-scale analysis and prediction compared to using the ensemble covariance alone.
- In this study, the convective-scale static covariance for **FV3-LAM** is further developed and examined in the **RRFS** context.

Objectives

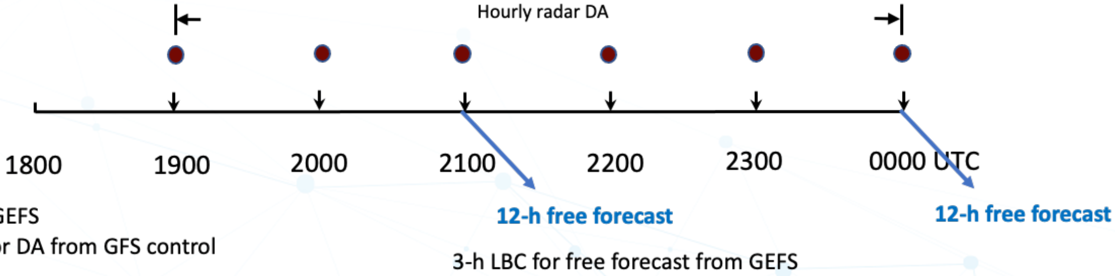
❑ The new **convective-scale static B** developed for **FV3-LAM** is employed to directly assimilate radar reflectivity using **RRFS** 3DVar and hybrid EnVar frameworks. The following questions are addressed:

- Can we reduce the cost of **convective-scale static B** without degrading much of its performance?
- What is the impact of using various **hybridization/weighting** between the ensemble-based and static covariances?
- How is the hybrid EnVar compared to the 3DVar and pure EnVar?

Experiment design

- Schematics of DA and forecast experiments

37 members
= 1 (control member from GFS) +
30 (analyses valid at 1800 UTC) +
6 (6-h forecasts from analysis valid at 1200 UTC)



Hourly radar DA

1800 1900 2000 2100 2200 2300 0000 UTC

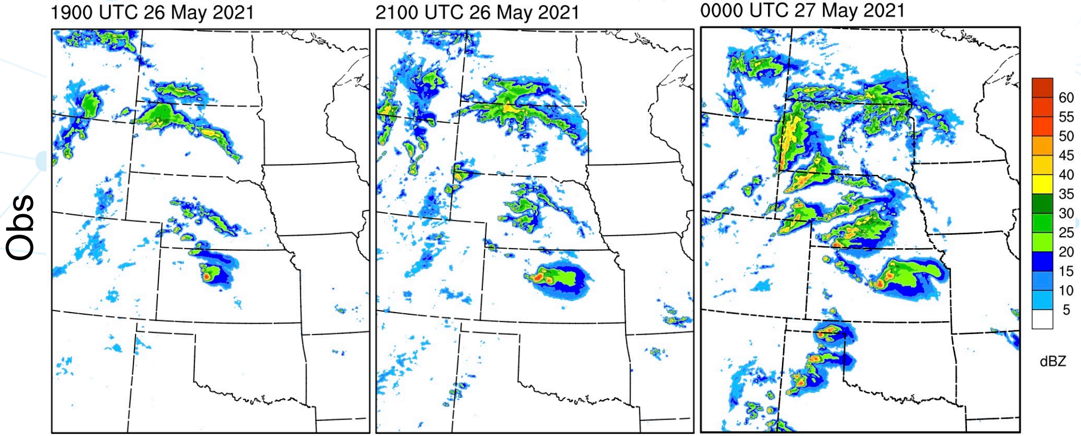
ICs from GEFS
1-h LBC for DA from GFS control

12-h free forecast

12-h free forecast

3-h LBC for free forecast from GEFS

- Case overview of 26–27 May 2021



1900 UTC 26 May 2021

2100 UTC 26 May 2021

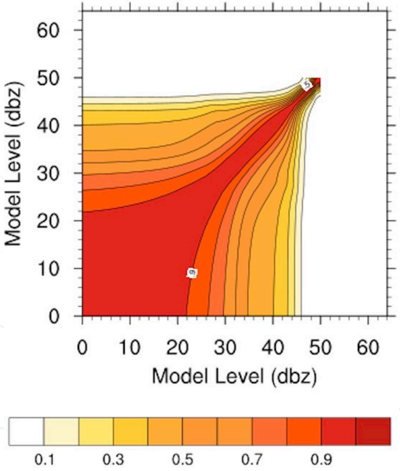
0000 UTC 27 May 2021

Part I: Cost reduction for convective-scale static B

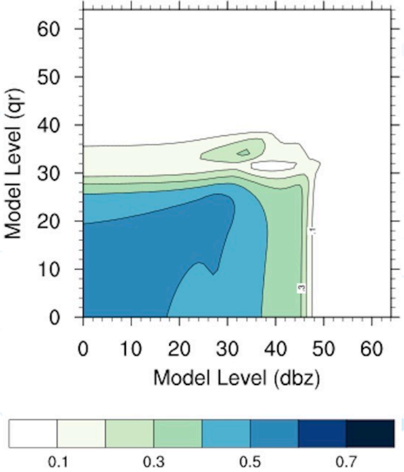
a. Calculation of static B for FV3-LAM

- Correlations in static **B** make physical sense

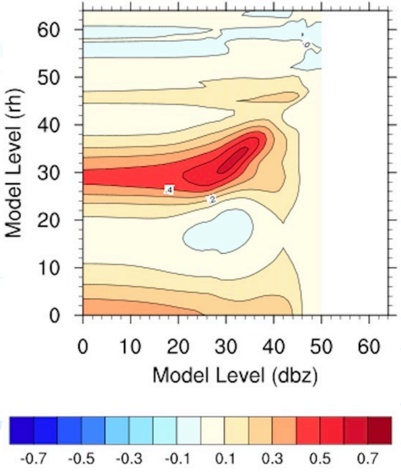
Cor(dBZ, dBZ)



Cor(qr, dBZ)

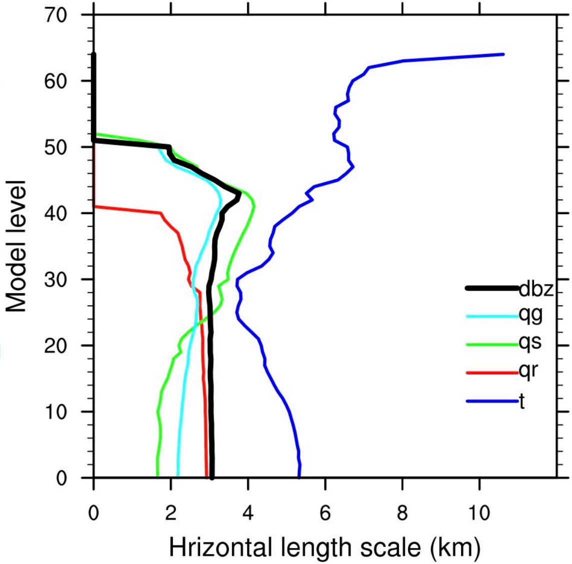


Cor(rh, dBZ)



- Consequence of rain falling freely under the 20th level.
- The variations of reflectivity at low levels are mostly affected by rainwater.
- The source (lifting condensation level) and sink (cold pool) of precipitation.

- Horizontal length scales
  - The horizontal length scales for hydrometeors are physically reasonable.



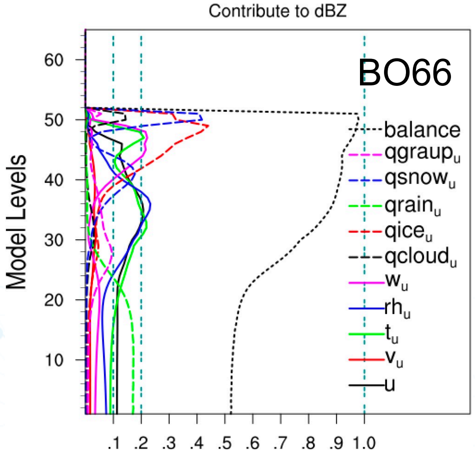
Part I: Cost reduction for convective-scale static B
b. Physical transform coefficient selection

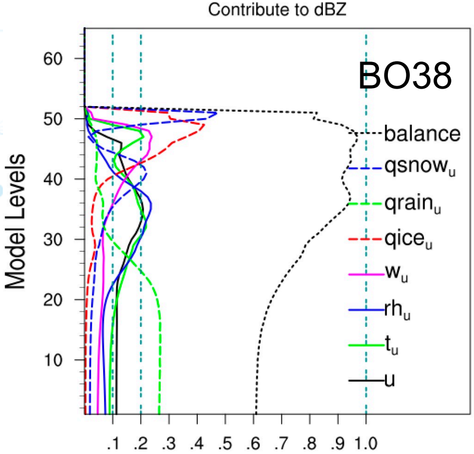
- Physical transform coefficients (Wang and Wang 2021)

$$\begin{pmatrix} u \\ v \\ t \\ \mathrm{ps} \\ \mathrm{rh} \\ w \\ \mathrm{ql} \\ \mathrm{qr} \\ \mathrm{qs} \\ \mathrm{qi} \\ \mathrm{qg} \\ \mathrm{dbz} \end{pmatrix} = \begin{pmatrix} \mathbf{I} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{r}_{11} & \mathbf{I} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{r}_{21} & \mathbf{r}_{22} & \mathbf{I} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{r}_{31} & \mathbf{r}_{32} & \mathbf{r}_{33} & \mathbf{I} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{r}_{41} & \mathbf{r}_{42} & \mathbf{r}_{43} & \mathbf{r}_{44} & \mathbf{I} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{r}_{51} & \mathbf{r}_{52} & \mathbf{r}_{53} & \mathbf{r}_{54} & \mathbf{r}_{55} & \mathbf{I} & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{r}_{61} & \mathbf{r}_{62} & \mathbf{r}_{63} & \mathbf{r}_{64} & \mathbf{r}_{65} & \mathbf{r}_{66} & \mathbf{I} & 0 & 0 & 0 & 0 & 0 \\ \mathbf{r}_{71} & \mathbf{r}_{72} & \mathbf{r}_{73} & \mathbf{r}_{74} & \mathbf{r}_{75} & \mathbf{r}_{76} & \mathbf{r}_{77} & \mathbf{I} & 0 & 0 & 0 & 0 \\ \mathbf{r}_{81} & \mathbf{r}_{82} & \mathbf{r}_{83} & \mathbf{r}_{84} & \mathbf{r}_{85} & \mathbf{r}_{86} & \mathbf{r}_{87} & \mathbf{r}_{88} & \mathbf{I} & 0 & 0 & 0 \\ \mathbf{r}_{91} & \mathbf{r}_{92} & \mathbf{r}_{93} & \mathbf{r}_{94} & \mathbf{r}_{95} & \mathbf{r}_{96} & \mathbf{r}_{97} & \mathbf{r}_{98} & \mathbf{r}_{99} & \mathbf{I} & 0 & 0 \\ \mathbf{r}_{101} & \mathbf{r}_{102} & \mathbf{r}_{103} & \mathbf{r}_{104} & \mathbf{r}_{105} & \mathbf{r}_{106} & \mathbf{r}_{107} & \mathbf{r}_{108} & \mathbf{r}_{109} & \mathbf{r}_{1010} & \mathbf{I} & 0 \\ \mathbf{r}_{111} & \mathbf{r}_{112} & \mathbf{r}_{113} & \mathbf{r}_{114} & \mathbf{r}_{115} & \mathbf{r}_{116} & \mathbf{r}_{117} & \mathbf{r}_{118} & \mathbf{r}_{119} & \mathbf{r}_{1110} & \mathbf{r}_{1111} & \mathbf{I} \end{pmatrix} \begin{pmatrix} u \\ v_u \\ t_u \\ \mathrm{ps}_u \\ \mathrm{rh}_u \\ w_u \\ \mathrm{ql}_u \\ \mathrm{qr}_u \\ \mathrm{qs}_u \\ \mathrm{qi}_u \\ \mathrm{qg}_u \\ \mathrm{dbz}_u \end{pmatrix}$$

augmented CVs

  - Total number of physical transform coefficients = 66 (**BO66**)



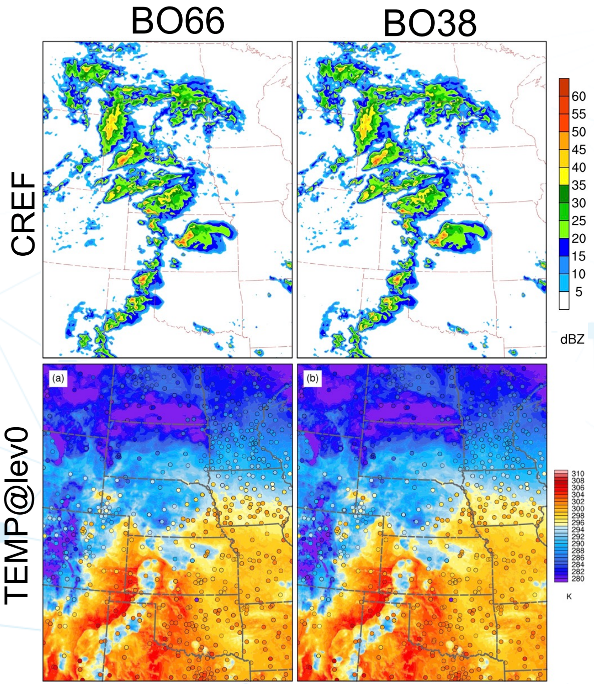


- Benefits from physical transform coefficient selection
  - Ratio of explained-variance to the total variance (≥ **10%**)

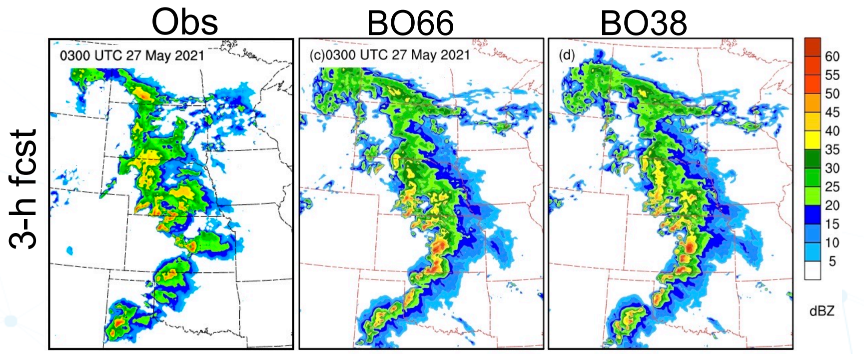
    => 38 physical transform elements are selected (**BO38**)
  - Decrease minimization cost (~25%)

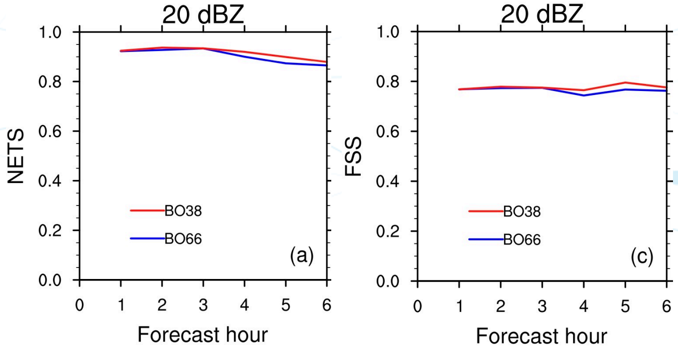
Part I: Cost reduction for convective-scale static B
b. Physical transform coefficient selection

- ➢ Single-cycle analysis at 0000 UTC



- ➢ Subsequent forecasts of CREF

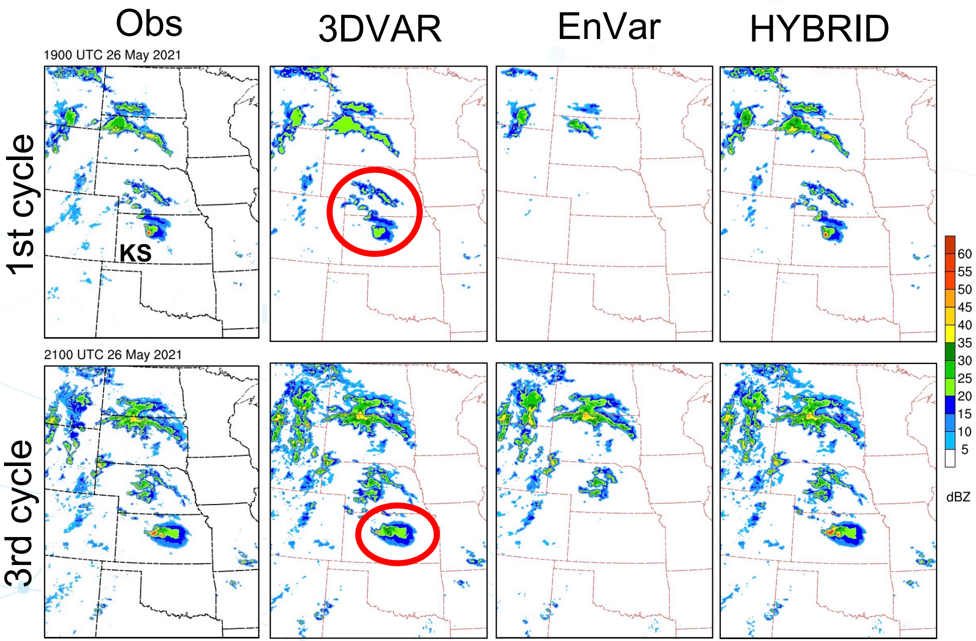




- Selecting and maintaining the critical physical transform coefficients have slight influence on the analysis and short-term forecasts.

Part II: Impact of hybridization
a. Hybridization: analysis

- ➢ Analysis until 2100 UTC



❑ 3DVAR vs EnVar

- Although 3DVAR is much cheaper than EnVar, it outperforms EnVar in adding the missed storm in KS.

❑ HYBRID

- In HYBRID, the static/ensemble covariance weight is set to 30%/70%.
- HYBRID fits closer to observations than 3DVAR.
- Compared to EnVar, HYBRID performs better in adding the storm in KS.

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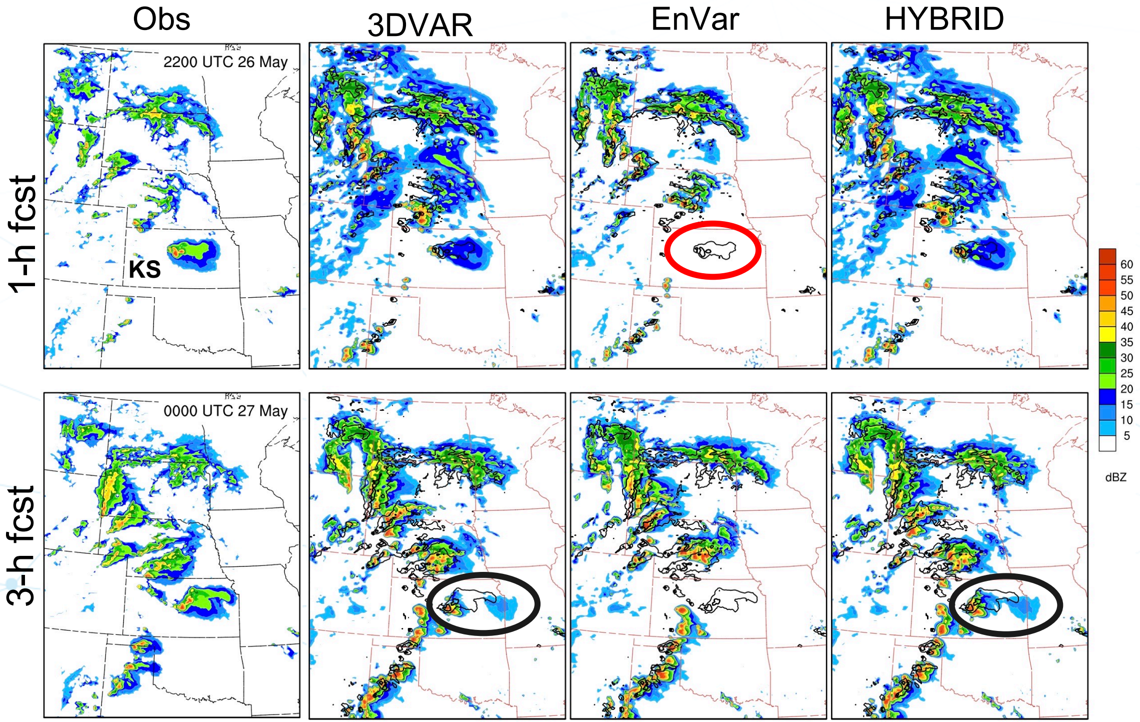
Part II: Impact of hybridization
a. Hybridization: forecasts

- Forecasts from 2100 UTC



☐ 3DVAR vs EnVar vs HYBRID

- Both 3DVAR and HYBRID can capture the storm in KS, but EnVar fails.
- Compared to 3DVAR, HYBRID better maintains the storm in KS.

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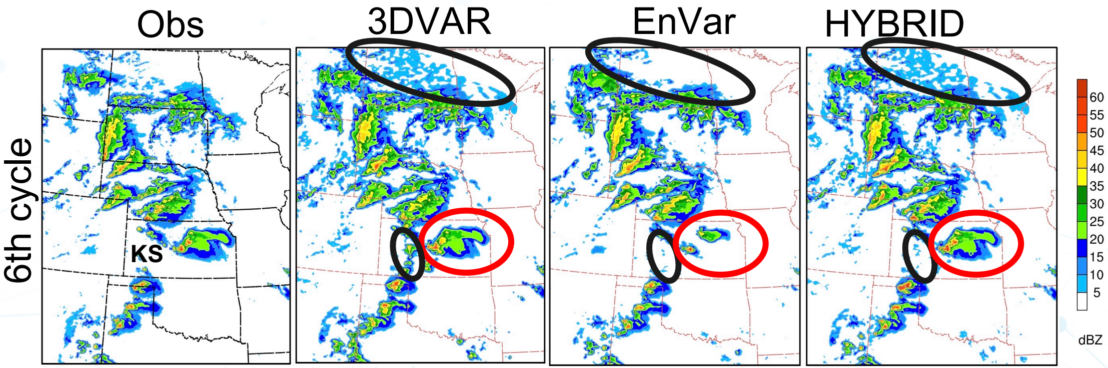
Part II: Impact of hybridization
a. Hybridization: analysis

- Analysis at 0000 UTC



❑ 3DVAR vs EnVar

- 3DVAR outperforms EnVar in adding the storm in KS.
- EnVar produces less spurious weak reflectivity over the Northern Plains than 3DVAR.

❑ HYBRID

- HYBRID partially suppresses the spurious reflectivity compared to 3DVAR.
- The observed storm in KS is better added in HYBRID than in EnVar. Compared to EnVar, however, more spurious weak reflectivity exists in HYBRID.

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Part II: Impact of hybridization
b. Adaptive hybridization

❑ HYBRID_CR

- **Consistency ratio** (CR) is used as an indicator of ensemble quality to define the regions where the combination of static and ensemble covariances is required (Wang and Wang 2021).

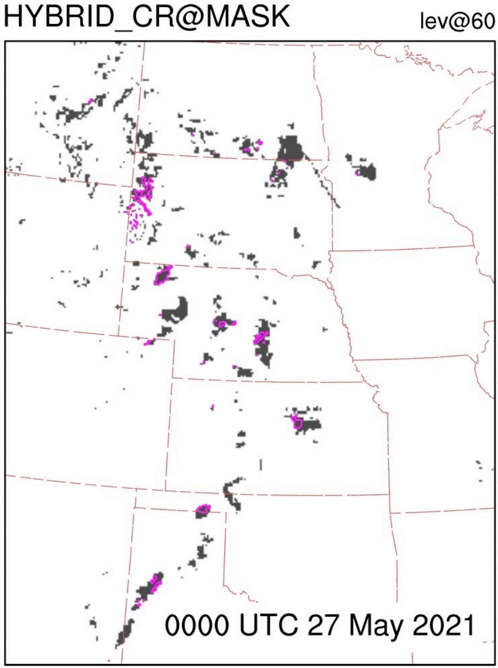
- The way to assign weighting

  CR < 1.0, => the weight of static **B** = 30%
  CR >= 1.0, => the weight of static **B** = 0.0

- Specifically, for each level,

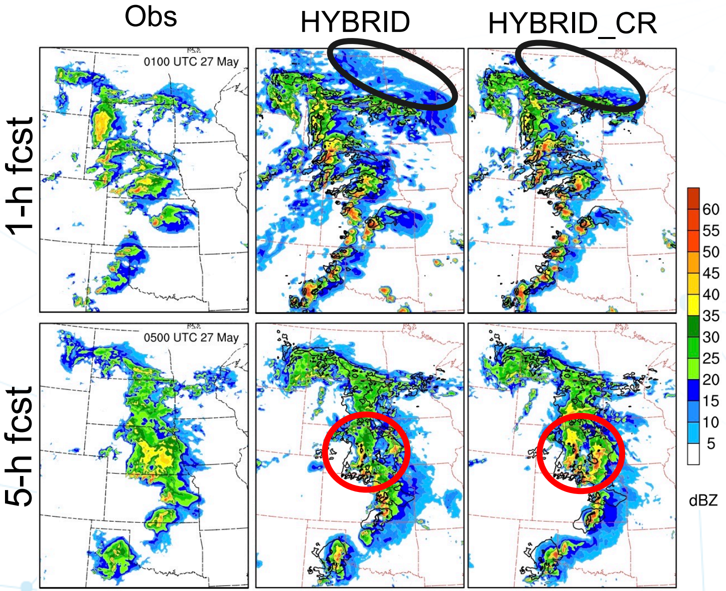
  gray shadings outside magenta contours => add static **B** from the bin of 'weak'
  gray shadings inside magenta contours => add static **B** from the bin of 'strong'

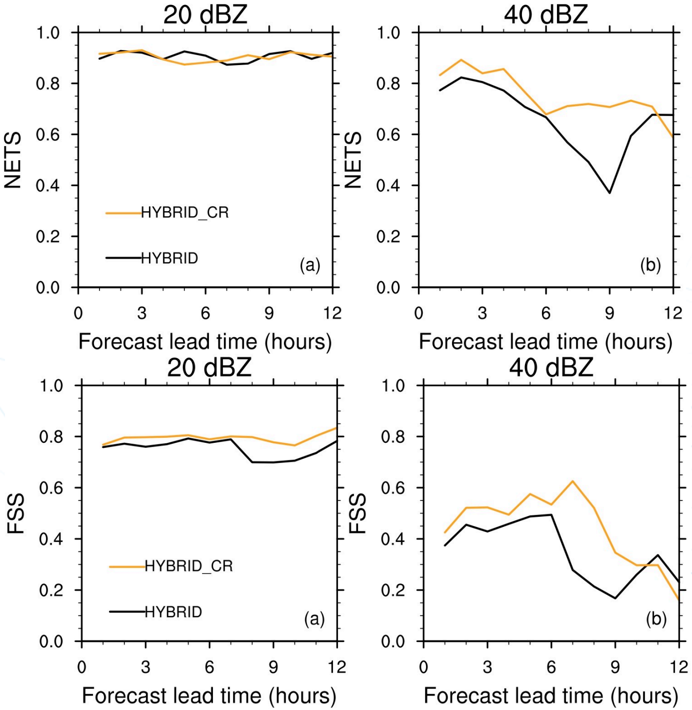
3D mask



Part II: Impact of hybridization
b. Adaptive hybridization: forecasts

- Forecasts from 0000 UTC





- HYBRID_CR produces less spurious weak reflectivity than HYBRID.
- HYBRID_CR better captures the reflectivity cores than HYBRID.
- The improved forecast skills in HYBRID_CR are well maintained.

Summary

- The **convective-scale static B** is further developed for **FV3-LAM** to directly assimilate reflectivity within the **RRFS** hybrid EnVar system.

- To reduce the cost, an approach to select and maintain the most critical cross-variable correlations is implemented to calculate convective-scale static **B**.

- Results on the impact of hybridization show that
  1) 3DVar with the new static **B** outperforms pure EnVar in adding observed reflectivity;
  2) Hybrid EnVar can get the advantages from both 3DVar and pure EnVar;
  3) CR-based adaptive hybridization further increases forecast skills.

- Ongoing and future work
  Conduct further R&D on adaptive weighting for convective-scale DA.