Storm Cell Displacement Errors in the Warn-On-Forecast System

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Motivation and Background

- The unspecificity of watches and limited lead time of warnings can impact the preparedness of vulnerable populations, putting them at an increased risk.
- The **Warn-on-Forecast System** (**WoFS**; Heinselman et al. 2023, *WAF*) is a rapidly updating ensemble data assimilation and prediction system providing convective-scale forecast output, which allows for localized severe weather alerts with longer lead times (Stensrud et al. 2009, *BAMS*; Stensrud et al. 2013, *AR*).
- WoFS has notable **storm displacement errors (SDEs**; Britt et al. 2023, *WAF*; Flora et al. 2019, *WAF*; Skinner et al. 2018, *WAF***)** that affect forecast accuracy, potentially leading to suboptimal data assimilation and larger errors in successive forecasts (Stratman et al. 2018, *MWR*; Stratman and Potvin 2022, *MWR*).
- Identify and describe patterns in these SDEs to enhance WoFS accuracy and give forecasters a basis for manual SDE correction or compensation.

Data

- The WoFS employs 36 ensemble members for data assimilation and 18 members for forecasts, generating forecasts with 3-km horizontal grid spacing over a 900 x 900-km square domain (Heinselman et al. 2023, *WAF*).
- The WoFS produces ensemble forecasts every 30 minutes with lead times up to 6 hours and output in 5-minute increments, utilizing ensemble analyses initialized every 15 minutes from the assimilation of various observations, such as radar, satellite, and conventional data.
- To assess SDEs, forecast composite reflectivity (based on the maximum reflectivity in a model column) is used and verified against the composite reflectivity field from the **Multi-Radar Multi-Sensor System** (**MRMS**; Smith et al. 2016, *BAMS*).
- Object-based analysis is utilized to identify storm objects in WoFS and MRMS composite reflectivity fields using criteria such as intensity and area size. WoFS and MRMS storm objects are matched at each forecast output time using Total Interest (TI) scores (Guerra et al. 2022, *WAF*), with SDEs quantified as differences in storm object centroid locations between WoFS/MRMS object pairs (Skinner et al. 2018, *WAF*).

$$\mathrm{TI}_{\mathrm{match}} = 0.5\left[\frac{(D_m - D_{\mathrm{min}})}{D_m} + \frac{(D_m - D_{\mathrm{cnt}})}{D_m}\right]$$

Methods

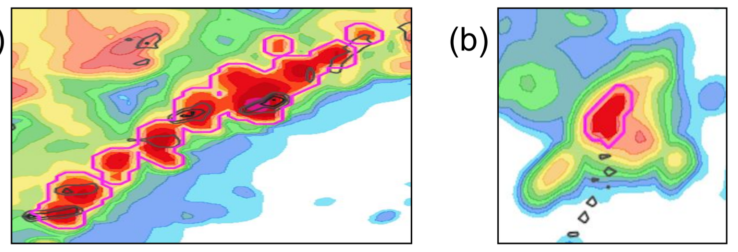

Figure 1. Example of (a) a standard storm cell reflectivity signature and (b) a typical QLCS reflectivity signature. Adapted from Potvin et al. (2022).

- Only discrete storm cells with generally more distinct and consistent SDE patterns will be examined (Fig. 1a). This eliminates potential discrepancies between cellular and quasi-linear convective system/other non-cellular behavior (Fig. 1b).
- This study narrows its focus to storm objects with lead times of less than 3 hours to improve predictability and reduce uncertainty.
- Cell-like objects are isolated using a maximum area threshold of 5000 km^2 and Potvin et al.'s (2022, *JTECH*) cell classification technique, resulting in 2,451,246 matched pairs of cell-like objects for further analysis.
- **Root-mean-square error** (**RMSE**) and **bias** are used to measure SDEs.
- Subjects of interest include yearly variations, differences across forecast ensemble
- members and their PBL schemes, lead time, relative storm age (RSA) and mean intensity.

$$\textit{relative storm age} = \textit{absolute storm age} - \textit{lead time}$$

Results

LEAD TIME AND RELATIVE STORM AGE

- RMSE clearly increases with lead time for a given RSA.
- For lead times of <90 minutes, there is a striking decrease in RMSE with increasing RSA for assimilated storms. The minimum RMSE range occurs between RSAs of 60 and 180 minutes (Fig. 2).
- There is a delayed minimum RMSE range for lead time intervals of [120,180) minutes, occurring between RSAs of 120 and 240 minutes (Fig. 2).
- RMSE increases near-monotonically with RSA beyond RMSE minimums; the oldest storms have higher RMSE values despite having the most time to be well-assimilated. However, for lead time intervals of less than 60 minutes, universal RMSE maximums occur for storms with the smallest RSAs (Fig. 2).
- Absolute RMSE minimums for RSAs between 30 and 210 minutes at lead times less than 15 minutes. Larger biases occur primarily after assimilation, with the largest RMSEs found at the largest RSAs and the longest lead times (Fig. 3).
- Well-assimilated storms see a generally increasing southeasterly to easterly bias with increasing lead time, except for the [0,15)-minute interval, which shows a clear southwesterly bias.

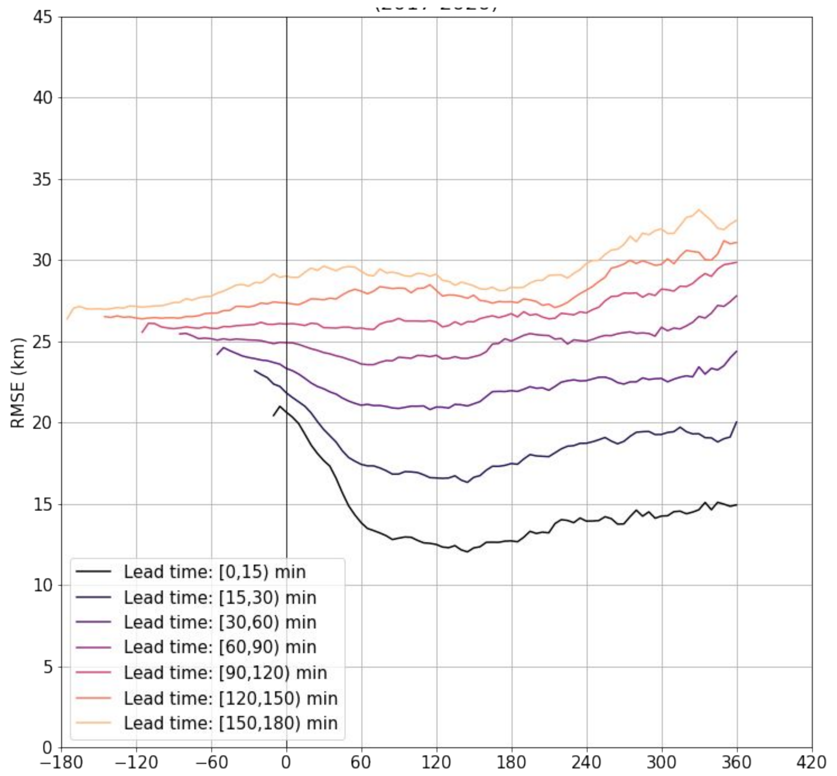

Figure 2. Mean RMSE with respect to RSA and lead time intervals with a rolling mean window of 10 minutes (2017-2020).

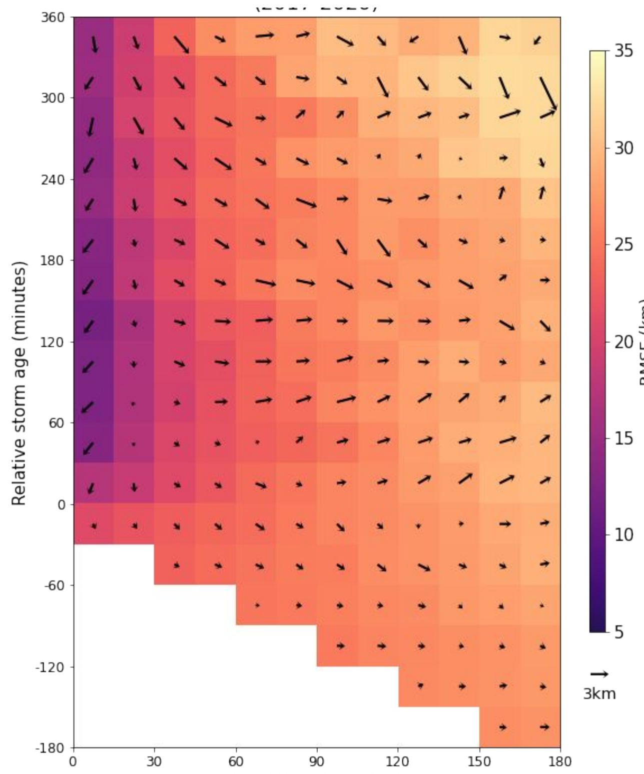

Figure 3. Storm cell displacement errors by RSA and lead time (2017-2020). A color scale represents RMSE while vector direction and magnitude correspond to bias.

LEAD TIME AND OBSERVED MEAN INTENSITY

- Higher mean intensity storms show larger northeasterly biases.
- Storms with both shorter lead times and higher mean intensities have smaller RMSE values, which makes sense in part because a storm is likely to have been well-assimilated by the time it reaches a high intensity.
- There is a clockwise shift from southeasterly to northwesterly biases in the [0,15) minutes lead time interval as mean intensity increases. Larger lead times see a counterclockwise southeasterly to northeasterly shift as mean intensity increases, nearly disappearing for the east-southeast direction.
- Storms with lower mean intensities have notable southeasterly biases, but biases and RMSEs at the smallest mean intensity interval (39-41dBZ) remain disproportionately large, potentially indicating the presence of some MCSs surviving data filtering.
- Similar patterns in bias and RMSE are identified for maximum intensity using a heat and vector map.

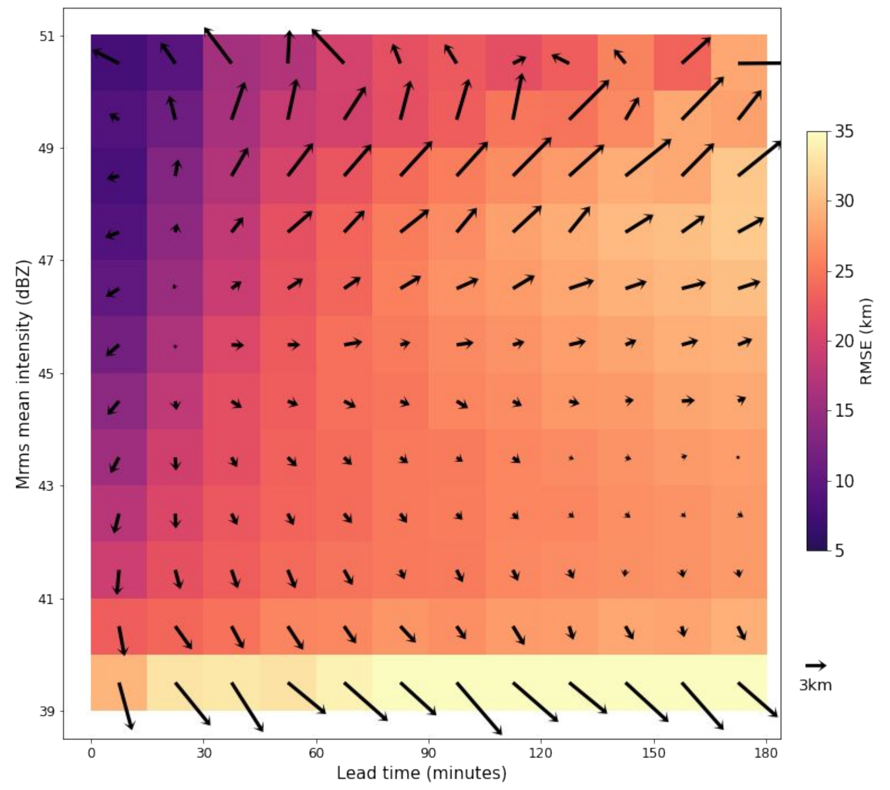

Figure 4. Storm cell displacement errors by MRMS mean intensity and lead time (2017-2020). A color scale represents RMSE while vector direction and magnitude correspond to bias.

Summary and Discussion

- RMSE patterns show clear increases with lead time, with minimum values occurring between 1-3 hours of assimilation (Fig. 2-3).
- Storms of higher mean intensity display a relatively large northeasterly bias (Fig. 4), suggesting that the WoFS may underpredict deviant motion in rotating storms, particularly in cyclonic supercellular storms intensifying and veering to the right (in the Northern Hemisphere) as documented in previous studies (Stratman et al. 2018, *MWR*) and subjective assessments (Skinner et al. 2018, *WAF*).
- Storms with the lowest mean intensities demonstrate southeasterly biases of smaller magnitude (Fig. 4), possibly linked to imperfect cell filtering or the presence of a broader trend inclusive of storm cells.
- Little variance in bias and RMSE were found between the years of study, as well as between ensemble members and planetary boundary layer schemes.
- Methodological improvements are needed, particularly in refining the cell classification approach and considering alternative matching strategies after cell filtering to avoid potential erroneous object matching.
- Future studies could explore SDEs in relation to geographical factors, topography, and terrain, as well as examine directional bias patterns and RMSE values in storms with irregular propagation directions and varying forward speeds.

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