Responses to comments from Referee #3

Thank you very much for your comments and suggestions. Providing this valuable feedback has helped to improve the current manuscript. We have modified the manuscript, taking into account all referee's suggestions. The following contains our detailed responses to your comments, with our responses in plain type given underneath your original comments in bold type.

Overarching Comments

This paper describes a rigorous evaluation of the North et al. (2017) 3DVAR multi-Doppler air motion retrieval using a high resolution cloud resolving model and a radar-model simulator and carefully examining selected common sources of uncertainty: characteristics of the scanning strategy, time updates of the scanning strategy, and advection corrections to the data. The novel aspect of the paper is that the experiments can control for many aspects of the sources of uncertainty given the high temporal resolution of the model output which can be subsampled nearly arbitrarily for comparison with the retrievals. The paper makes the case that for some characteristics of estimating vertical velocity in triple-Doppler networks, that having a Doppler radar capable of scanning a PPI in less than 2 minutes is desirable, particularly for accurately estimating the characteristics of weak updrafts.

Thank you for the appreciation for this study.

One major comment I have is that while the paper's methodology is thorough and the figures are clear and illustrative, the presentation of the results is done in an illogical fashion and does not allow for an easy read. The text refers to many multi-panel figures in a repeated fashion that lead the reviewer to do a lot of page flipping. I suggest breaking up the Figures 5, 6, 7, and 8 into different figures that follow the logical flow of Section 3 without having to refer back to the figure subpanels over and over again. Alternatively, discussion of the variables in Figs. 5-8 could be done sequentially by retrieved variable rather than by observing strategy. I believe that the former strategy would be easier for the authors to do.
I believe the paper is acceptable for publication with these minor revisions in mind.

Thank you for the suggestion. We broke Figures 6, 7, and 8 up into three figures:
Figure 6: UF, MF, w profiles for WRF outputs and 3FullGrid.
Figure 7: UF, MF, w profiles for 3XR and 3LR simulations and those for the limited area.
Figure 8: UF, MF, w profiles for 4SR simulations and 3XR simulations coupled with the advection correction.

Specific Comments

1. Should the title be revised to include 3DVAR retrievals? The paper does not include other traditional dual-Doppler retrievals such as in CEDRIC (which have different assumptions about integrating the continuity equation than 3DVAR), or more advanced analyses such as in SAMURAI (Bell et al.). Different techniques could fare better or worse than the 3DVAR technique.

Thank you for the suggestion. We changed the title to “Investigation of observational error sources in multi Doppler radar three-dimensional variational vertical air motion retrievals.” Moreover, we referred to those papers (Miller and Fredrick, 1998 and Bell et al., 2012) in Introduction.

2. It should be stated in the methodology that this analysis is based on a single case, and performance assessment could vary for different storm characteristics and propagation speeds. For example, a slow moving tropical squall line in low vertical wind shear could present less of a challenge for multi-Doppler retrievals than the highly-sheared May 20 MC3E squall line.

Thank you for the valuable comment. We added a following sentence in Section 4: “The assessment of the multi-Doppler radar retrieval presented in this study could vary for different storm characteristics (e.g., isolated storm and less wind shear).”

3. P5, L3, and elsewhere: the apostrophe is unnecessary.

Done.

4. P5, L25: suggest removing the word ‘at’.

Done.

5. P6, L15-16: the CRSIM simulates the phase shift and the differential phase shift, not the phase and specific differential phase, correct?

The CR-SIM can simulate the specific differential phase (K_{DP}) at each gridbox, but not the differential phase shift (ϕ_{DP}).

6. P7, L8: An analysis domain top of 10 km does not top the storm, correct? This would not allow for correct estimation of the storm-top divergence properly in the interpolated simulated radar data. Does this lead to some of the uncertainty unnecessarily?

Correct; the top of the analysis domain (10 km) was not the storm top. Above 10 km altitude, the radar data density more decreases, and an uncertainty in the retrieved vertical velocity can increase with height, because these heights are poorly constrained by radial velocity observation. Collis et al. (2010) showed that radar mapping artifact where radar coverage is poor can lead to minimum vertical velocity errors of the order of 2 m/s at these heights. In our 3DVAR technique, the mass continuity constraint was applied at each grid box, and the calculation was performed until the cost function was minimized without such heights including poor radial velocity constraint. We tested a 3XRSnap simulation including higher altitudes upto 15 km. Figure below shows a comparison of the updraft fraction (UF) profiles with the WRF simulation (black lines) and the original 3XRSnap simulation (red lines). In the present case, updraft fractions for updrafts > 5 m/s and > 10 m/s above 10 km were smaller than 0.04 and 0.005, respectively. The updraft fractions for updrafts > 5 m/s from the new simulation (blue lines) converged on the small updraft fractions above 10 km, unlike the profile from the original 3XRSnap simulation, However, at other altitudes, errors became larger compared to the original 3XRSnap simulation (e.g., 5-9 km and below 4 km for updrafts > 5 m/s, and 4-8 km for updrafts > 10 m/s). We will need more analysis to address this impact in a separate paper. Thank you for the insight.

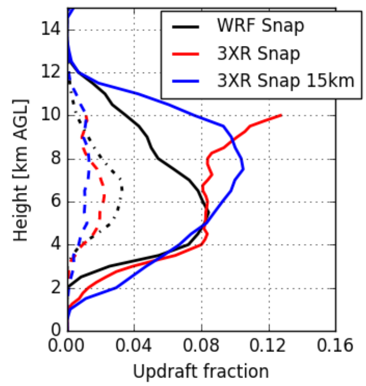

Fig. R2. Vertical profiles of updraft fractions with different thresholds of 5 m s^{-1} (solid lines) and 10 m s^{-1} (dashed lines). Black lines represent the WRF snapshot at 12:18:00 UTC, red lines represent the original 3FullGrid simulation presented in the manuscript, and blue lines represents the 3FullGrid simulation that the vertical domain was extended to 15 km AGL.

7. P8, L20: "not unfolded correctly observed Doppler velocity" needs rewording.

We revised the phrase to read "unfolding of observed Doppler velocity."

8. P9, L14: "at" should be in.

Done.

9. P13, L2: The tilt would depend on the propagation speed and the vertical wind shear, which in some regimes (especially in the tropics) could be smaller than in this case.

The referee is correct. We revised this sentence to read "horizontal advection and wind shear are expected to tilt the cloud and dynamical structures in vertical." Thank you for pointing this out.

10. P13, L11: The smoothness function is a Cressman or Barnes filter? If not, what equation did you use?

The advection correction procedure seeks to minimize a cost function that contains the frozen-turbulence constraint and so-called "penalty" terms that confer spatial smoothness on the pattern-translation components. The advection correction procedure is designed to produce smooth pattern-translation components U and V, but does not specifically attempt to smooth the scalar field being advected (i.e., reflectivity in the present study). The smoothness on the U and V components is obtained through the smoothness terms in the cost function, which are proportional to the squares of the horizontal gradients of U and V. As shown in Shapiro et al. (2010), the Euler-Lagrange equations arising from minimization of this cost function contain terms (arising from the smoothness terms) that involve the Laplacians of U and V. Such terms act to "diffuse" the U and V fields, resulting in smooth U and V solutions. Theoretically, the procedure would preserve spatial discontinuities in the advected scalar field, if discontinuities were present in the input PPI data and if the scalar field satisfied the frozen-turbulence constraint.

For the referee's reference, we would like to show the cost function (Shapiro et al. 2010):

$$J \equiv \iiint \left[\alpha \left(\frac{\partial R}{\partial t} + U \frac{\partial R}{\partial x} + V \frac{\partial R}{\partial y} \right)^2 + \beta \left| \nabla_h U \right|^2 + \beta \left| \nabla_h V \right|^2 \right] dx\, dy\, dt$$

where U and V represent pattern-translation components, and R represents the advected scalar fields, which is the simulated radar reflectivity in the present study. The second and third terms are smoothness terms, and a coefficient β is the smoothness weighting coefficient.

In the revised manuscript, we added a following phrase to the first paragraph of section 2.4.4:

"The advection correction procedure seeks to minimize a cost function that contains the frozen turbulence constraint and terms that confer spatial smoothness on the pattern-translation components."

and revised the sentence to read:

"A weighting coefficient of the spatial smoothness terms in the cost function coefficient depends on the analysis grid spacing and the structure of the field being advected. An appropriate value of the coefficient can be determined by running some sensitivity tests. Based on preliminary tests (not shown), we deemed a coefficient of 300 dBZ^2 to be acceptable."

11. P14, L1: Suggest inserting "potentially" before "large".

We rephrased this as "large potential uncertainties." In the revised manuscript.

12. P14, L25-26: "...but it tends to have higher uncertainty in the areas around the location of strong convection..." - this seems highly subjective. Can you make a quantitative statement related to this topic?

The updraft fraction for 1-5 m/s from the 3XRSnap simulation was overestimated by 0.1 – 0.17 above 2 km AGL, which accounts for 40-88% of that from the WRF output. The height of the error peak was around 5-6 km, which corresponds to the peak of UF_5 and UF_{10}. We added this description after this sentence.

Discussion paper

13. P15, L7: Regarding an updraft core defined as being larger than 0.5 km2: Is

this at a single level? This is one single pixel, correct? Since the retrieval has a resolution that is effectively 4-6 times the grid spacing, would one expect it to retrieve such small updraft features? Perhaps it is not surprising then that the retrievals have such issues resolving updrafts (particularly weak ones) that are single pixels in the grid? Perhaps increasing this threshold to have larger-sized updrafts (say larger than 2-3 km3) would reveal different uncertainties.

This threshold corresponds to 8 pixels for the wind retrieval data and 2 pixels for the WRF data at a single level. The referee's comment is right; in the retrieval, a single data point could affect surrounding several grid points. Therefore we carefully decided this threshold to remove such noise in the retrieval results.

14. P15, L16: Suggest inserting an "A" before "Noticable".

Done.

15. P16, L8-10: This sentence is awkward.

We rephrased this sentence as "In subsequent sections, a more detail analysis of the impact of the different options in the observational setup on the UF, MF and $\overline{w}$ profiles are discussed."

16. P20, L12-13: "cloud evolution cannot maintain the instantaneous cloud structures": Can you be more specific what you mean by this?

We rephrased this sentence as "cloud evolution alters vertical and horizontal distributions of hydrometeors and vertical velocity, resulting in observing different cloud life stages by different PPI scans."

17. P22, L6: "As previous literature has pointed out..."

Done.

18. P22, L8: 4.5 km is mid-levels, no?

We changed it to "> 4.5 km."

19. P22, L16: Need comma after "i.e."

Done.

20. P22, L18: "inferior" should be "lower"?

The word "inferior" means "lower in quality" in this sentence. We would like to use this word here.

21. P22, L28: Suggest replacing “hard” with “challenging”.

Done.

22. P23, L10: Scott G.’s last name is misspelled.

We are sorry about this. We corrected it in the revised manuscript.

23. P23, L20: “DOW’s” should be “Doppler on Wheels mobile radars”

Done.