Responses to comments from Referee #4

Thank you very much for your comments and suggestions. 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.

This paper investigates the impact of some sources of uncertainty on multiple-Doppler analysis of ground based radar data, with emphasis on vertical velocity. It is well written, clear and easily understandable. In fact, I don't have much to say about the points raised by the authors. The analysis process is good and the scientific argumentation is excellent.
Having said that, however, I am a little sceptical about the overall impact of this work and its general interest for the radar user community. Without being rude, it seems quite obvious that improving the VCP, the number of radars, or the time sampling resolution will have a positive impact on retrieved wind fields and, in particular, vertical velocity.
Discussion paper
This has been shown previously by many authors in many different radar network configurations. While I agree that findings and recommendations resulting from this study would be useful for ARM RGP laboratory users, they would be difficult to apply to other networks. Furthermore using numerical model outputs and radar simulators to build a reference wind field is quite common nowadays and cannot be considered as a new concept.
Actually reading section 2.3 of the paper should generate quite some frustration among any scientist interested in radar wind retrieval. Indeed, questions regarding the impact of prescribed hydrometeor fall speed, potential masks, attenuation by rainfall (especially at X-band), or velocity folding count among the main sources of questioning for users and developers of multiple-Doppler analysis methods. To the best of my knowledge, these issues have never really been addressed to date and I was hoping that this study would help to clarify them, which would have contributed to make this paper a truly original contribution to the field. To be consistent with my remark, however, I must mention that the study on the impact of advection is original and does answer important questions.

To sum up, the work presented by the authors is of good quality, but its contribution to the field with respect to previous studies seems quite poor to me and results are barely applicable to networks other than ARM RGP laboratory. From there I see two options: 1/ Improving the paper by investigating additional sources of uncertainty such as Vt, velocity folding, attenuation... among others, or 2/ Clearly state that this study aims to optimize the performance of the ARM RGP network, without seeking to generalize its findings. Option 1 would require substantial additional work, but would undoubtedly represent an important contribution to the field. Option 2 would mostly imply cosmetic work (title, introduction, conclusions), but the impact of this paper would be limited.

Thank you for the referee's appreciation for the study and pertinent comments. As the referee pointed it out, the analysis in this manuscript is limited to a 3DVAR multi Doppler radar technique and impacts of radar sampling limitation. First, we changed the title to "Investigation of observational error sources in multi Doppler radar three-dimensional variational vertical air motion retrievals."

We totally agree with the referee that the hydrometeor velocity estimates and the signal attenuation are major sources of errors in the wind retrieval. We have tested an impact of hydrometeor velocity estimate using reflectivity-based mass-fall velocity relationships proposed by Caya (2001) on the retrieved vertical velocity. Please see a response to the referee #2's second comment. The retrieved vertical velocities from the simulation using the relationships were underestimated. However, it is hard to say whether the fall velocity estimate from these relationships or the hydrometeor fall velocity predicted by model simulation is more reliable. The present study focused on the uncertainties attributed to radar observation sampling, and we decided not to include the sensitivity test of the hydrometeor fall velocity estimate.

The (along-track) attenuation of hydrometeors can significantly impact the radar reflectivity measurements, but we confirmed that the reflectivity attenuation did not mask the Doppler velocity fields significantly in the analysis area. A figure attached below shows the simulated attenuated and non-attenuated radar reflectivity fields and associated Doppler velocities for the X-SAPR I4 radar at an elevation angle of 4.5 degrees. In all simulations in the present study, we used the Doppler velocity associated with the attenuated reflectivity. On the other hand, the attenuation in the reflectivity field can induce underestimations in the reflectivity-based hydrometeor fall velocity estimates. The underestimated hydrometeor fall velocity estimates could induce underestimation of the vertical velocity as shown in the response to the referee #2's second comment.

Our radar simulator does not include an option of simulating radial velocity folding, and we have not investigated an impact of the folded radial velocity on the vertical velocity retrieval. Recent velocity unfolding techniques can produce unfolded Doppler velocity fields with high accuracy (e.g., James and Houze, 2001). We expect that the folded Doppler velocity issue can be resolved in recent and future studies.

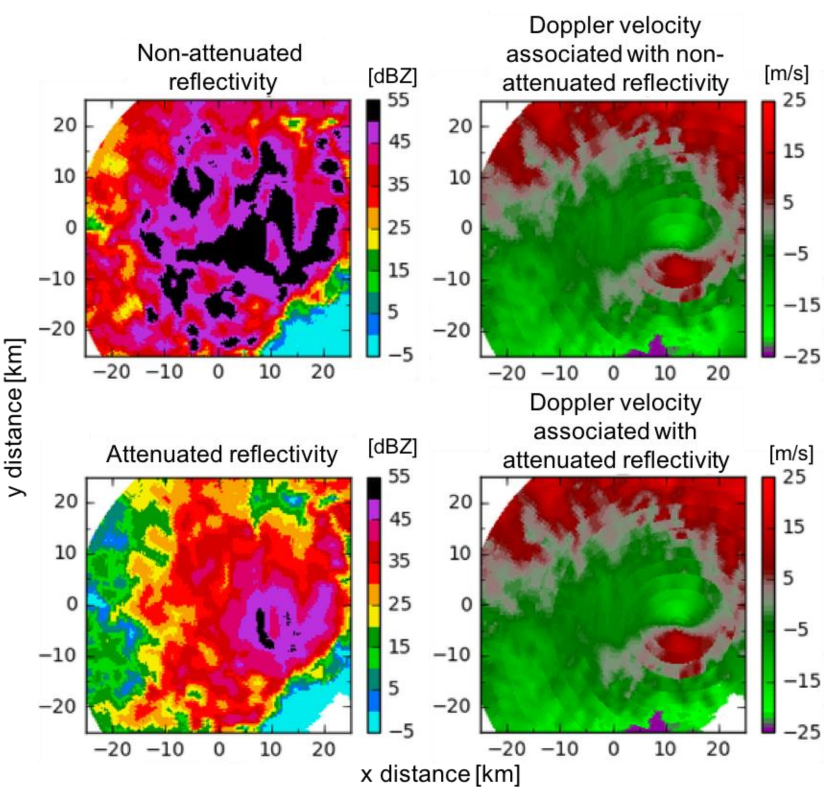

Fig. R3. PPI images of simulated reflectivity without attenuation (top left), Doppler velocity without reflectivity attenuation (top right), reflectivity with along-path two-way attenuation (bottom left), and Doppler velocity associated with the attenuated reflectivity (bottom left) for the X-SAPR I4 radar at an elevation angle of 4.5 degrees at 12:18:00 UTC.

As the referee pointed it out, the results of application of the advection correction to the wind retrieval are consistent with the previous studies; the advection correction is effective for shorter time period VCPs (< 2min). The present study also took into account the volume sampling and compared their impacts. The magnitude of improvement by the increase of elevation angles is larger than that by advection correction, even though the VCP needs 2 minutes. We modified the abstract and conclusion to more simplify them in response to other referee's comments and highlighted the result.

We also agree with the referee that the analysis in this manuscript is limited to the ARM radar network at the Southern Great Plains. Although the manuscript simulated the ARM precipitation radars, the similar radar network has been installed in many regions such as France (e.g., Bousquet et al. 2007), Germany (Helmert et al. 2014), and Japan (Maesaka, et al. 2011), and is expected to be extended to more countries. Moreover, future field campaigns targeting deep convection would be strongly motivated to install multiple Doppler radars to observe vertical air motions in convective clouds (e.g., https://www.arm.gov/news/features/post/52835). The present analysis can give valuable information to improve the observation strategies and decide optimized scan strategies for the networks. In the revised manuscript, we added a following sentence to the last paragraph: "Although the present study focused on the ARM X-band radar network, the similar dense radar network has been installed in several regions (e.g., Bousquet et al., 2007; Maesaka, et al. 2011; Helmert et al., 2014) and field campaigns targeting deep convection (past, on-going and future) would be strongly motivated to install multiple Doppler radars to observe vertical air motions in convective clouds. The present analysis can give valuable information to improve the observation strategies and decide optimized scan strategies for the networks."

From a cloud resolving model (CRM) perspective, the present study would notify the CRM communities of large uncertainties in the multi-Doppler radar-retrieved vertical air motion in upper parts of convective clouds, although some of the CRM simulation studies concluded that the CRMs significantly overestimated updrafts compared to multi-Doppler radar vertical velocity retrievals.

We have extended this OSSE study to a tropical convection case from Tropical Warm Pool – International Cloud Experiment and isolated storms over a Houston area. Those OSSEs commonly showed that limited radar sampling would cause underestimation of strong updraft areas. We are preparing separate papers for detailed analyses using the experiments.

References:

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James, C.N. and Houze, R.A.: A Real-Time Four-Dimensional Doppler Dealiasing Scheme. J. Atmos. Oceanic Technol., 18, 1674–1683, https://doi.org/10.1175/1520-0426(2001)018<1674:ARTFDD>2.0.CO;2, 2001.

Helmert, K., and Coauthors: DWDs new radar network and post-processing algorithm chain. *Proc. Eighth European Conf. on Radar in Meteorology and Hydrology (ERAD 2014)*, Garmisch-Partenkirchen, Germany, DWD and DLR, 4.4, 2014. [Available online at http://www.pa.op.dlr.de/erad2014/programme/ExtendedAbstracts/237_Helmert.pdf]

Maesaka, T., Maki, M., Iwanami, K., Tsuchiya, S., Kieda, K., and Hoshi, A.: Operational rainfall estimation by X-band MP radar network in MLIT, Japan. Proc. 35th Int. Conf. on Radar Meteorology, Pittsburgh, PA, Amer. Meteor. Soc., 142. 2011. [Available online at https://ams.confex.com/ams/35Radar/webprogram/Paper191685.html.]

Other remarks:
1/ Results are based on a single case. Authors should keep that in mind in their conclusions. The effectiveness of vertical wind retrieval depends on many factors, including wind shear for example.

Thank you for the important suggestion. Taking into account the referee #3's suggestion, we added a following sentence to the conclusion: "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)."

2/ More details are needed regarding the wind retrieval method used in this paper. What about data interpolation and air-mass continuity equation (e.g., boundary conditions)?

We used the 3DVAR multi-Doppler radar wind retrieval technique shown in North et al. (2017). This technique first needs to interpolate the radar data into the Cartesian coordinate. We used a Barnes distance-dependent weight (Eq. 1 in the revised manuscript) for the interpolation. The equation was applied in both horizontal and vertical interpolations. At each grid box, radar moments are estimated using the nearest 200 radar data gates with weights (Eq. 1) using a smoothing parameter $\kappa = 0.13\ km^2$ for interpolation. The cutoff distance is determined as the distance where the weight is less than 0.01 ($d \approx 0.8$ km). These parameters are chosen so that the statistical error in retrieved vertical velocity is minimal for the present case. These settings for gridding are fixed for all radar simulations. We slightly modified Section 2.3 to briefly describe this gridding method.

As referee #1 pointed out, the gridding process can also be an error source in the vertical velocity retrieval. This error can be included and seen when we compare the 3FullGrid simulation with the other simulations using radar VCPs. We added this discussion to the second paragraph of Section 3.1 in the revised manuscript.

We used the 3DVAR wind retrieval technique described in North et al. (2017). The optimal wind field solution in the technique is obtained at the minimum of a cost function which contains the radial velocity observation constraint, anelastic mass continuity constraint, surface impermeability constraint, background wind field constraint, and spatial smoothness constraint. The mass continuity equation is an element of the cost function, and technique, the constraint was applied at each grid box. We used the surface impermeability constraint to dictate that vertical velocity vanishes at the ground with a relatively large weight. We modified Section 2.3 to read:
"The wind retrieval algorithm inputs the Cartesian coordinate Z and V_r fields from each radar and uses 3DVAR technique continuity constraint proposed by Potvin et al. (2012a). In the technique, the optimal wind field solution in the technique is obtained at the minimum of a cost function which consists of the physical constraints of radar radial velocity observations, anelastic mass continuity, surface impermeability, background wind field, and spatial smoothness. The surface impermeability constraint was used to dictate that vertical velocity vanishes at the ground with a relatively large weight."

3/ More details are needed about the investigated weather system. Authors should include additional material to better describes the overall structure of the storm (e.g. vertical cross-section of model/radar reflectivity/wind fields).

We added short descriptions about the observed MCS and WRF-simulated MCS to the first paragraph of Section 2 and Section 2.1, respectively.

For the observed MCS, we added: “This squall-line MCS was oriented in northeast-southwest direction extending for approximately 1000 km (Fan et al., 2017). The convective region had approximately 50 km width and trailed a distinct stratiform precipitation area when it passed through the ARM SGP site from 09:20 UTC to 11:40 UTC.”

For the WRF-simulated MCS, we added: “The simulated MCS comprised a convective precipitation region at the leading edge of the system and a stratiform precipitation trailed by the convective region, as similar as the observation. The MCS passed through the ARM SGP radar observation site approximately one hour later than the observation (at around 12:18 UTC), and a stronger convective precipitation region formed slightly (~20 km) to the north of the ARM SGP site.”

Moreover, we referred previous studies by Liu et al. (2015), Wu and McFarquhar (2016), and Fan et al. (2017), where dynamical and microphysical structures were analyzed.