Response to Reviewer Comment #1

We thank this reviewer for their valuable suggestions that have helped to improve this manuscript. Taking into account the comments from all reviewers below, we reorganized several sections of our manuscript. The following document contains our detailed responses to your comments, with our responses in plain text given underneath your original comments in bold type.

Synopsis:
This paper attempts to highlight the capability of the ARM network to gather and used the wealth of data to attempt to address issues with current radar methodology. Data collected during MC3E is analyzed to show how well the ARM network captured three events. Dual-Doppler 3DVAR technique is used show that the results when compared to vertical profiler data located in the vicinity are similar in magnitude, but for one case discussed upward iterative techniques do not perform as well.

Thank you for your appreciation of our manuscript. Taking into account your suggestions and other reviewer comments, we extended our retrieval analysis to include five events. Those events are listed in Table 1, and new analyses are provided throughout the reorganized sections of our manuscript. Additional details on this change are also shown in responses to reviewer comments below.

General Comments:

Overall, the work done in this paper is good, but more discussion and expansions of results is needed to make this paper more robust to justify the conclusions that are trying to be made. Especially in the comparison between traditional dual-Doppler methods and 3DVAR methods. I would like to see more details on the quality control methods used rather than just stating 'standard methods' were used.

Need some expansion on the analysis of results and methodology to help readability. The author used capital lambda in the document but in the figures lower case lambda was used. Please fix as it was confusing. Chapters 5 and 6 need to be expanded on in areas detailed below and reworked to address readability and clarity.

Agree. We extended the comparison (analysis dataset) to the five MC3E cases wherein our datasets were appropriate (e.g., solid collection during deeper convective events).

- The RMSE of radial velocity and the normalized mass continuity residual (NMCR) estimated from the 3DVAR and the iterative upward integration method are now listed in our revised manuscript Table 4.
- A new Figure 6 shows an example of the comparison of retrieved vertical velocity and horizontal divergence, and vertical profiles of RMSE and NMCR for the May 20, 2011 case. The results of our analyses are described in our revised section 5. This portion of our study has been moved from section 6 in the previous manuscript.

We also extended our comparisons of the radar reflectivity and vertical air velocity retrievals between the 3DVAR method and the radar wind profiler retrievals to include all five MC3E cases.

- The MBD, MAD, RMSD, Spearman's rank correlation (ρ), and the Pearson product-moment correlation (r) are listed in revised Tables 5 and 6.
- Figures 7, 9, and 10 show examples of direct comparisons of the time series of reflectivity and vertical velocity retrieved from the wind profiler retrievals and the 3DVAR retrievals for the April 25 and May 20 cases. The comparisons are discussed in section 6 in the revised manuscript.

We also have added improved descriptions about radar data correction / quality control and other factors (in response to other reviewer comments as well) to our revised section 2.

- Radar reflectivity observed by CSAPR-I7 was corrected for attenuation in rain using the CSAPR-I7 specific differential phase (Kdp) measurements as from open-source ARM coding options (e.g., Bringi and Chandrasekar, 2001; Giangrande et al., 2013b, 2014).
- Because XSAPR reflectivities were significantly attenuated in rain and occasionally extinguished to within/behind heavier rain regions, only mean Doppler velocity measurements (not impacted by partial attenuation) were used (as available) in our velocity retrievals. Aliased radial velocity measurements from all radars were corrected / dealiased using the four-dimensional technique described in James and Houze (2001). Each radar volume was manually inspected to check for conspicuous errors and artifacts.

In the manuscript, capital lambda ($\mathbf{\Lambda}$) represents a $n \times n$ matrix of constraint weights where n is identical to the number of analysis points, while lower case lambda represents diagonal element of the matrix $\mathbf{\Lambda}$, which is treated as adjustable parameters. Although the matrix $\mathbf{\Lambda}$ has a number of elements, this study uses constant values of λ for $\mathbf{\Lambda}_c$, $\mathbf{\Lambda}_p$, $\mathbf{\Lambda}_b$, and $\mathbf{\Lambda}_s$. For $\mathbf{\Lambda}_o$, λ_o weights are calculated from the nearest neighbor weight and observational data quality based on normalized coherent power for each radar. We specified this in section 3 and revised text, tables, and figures appropriately.

Major:

1) 2.2: When using KVNX did you change the objective analysis parameters to deal with the coarser resolution and change in spatial coverage of the data from KVNX. It does not appear you did but I would suggest that maybe it is investigated to not introduce artifacts into the Barnes interpolation.

We agree with the reviewer's question. Interpolation methods could produce artifacts such as ring-like structure as pointed out by Collis at al. (2010). The objective parameters should be appropriately set to reduce such artifacts. Collis at al. (2010) in particular presented ring-like artifacts due to data sparsity that appeared above 11 km in altitude. For the present study, we used a constant value for the smoothing parameter $\kappa = 2$ km^2 in Eq. (1) for all radars. This value is enough large to collect data in sparse data regions below 10 km altitude (maximum height of the analysis domain in this study) and reduces the ring-like artifact. In the dense data regions, we limited the maximum number of samples for interpolation to nearest 200 to avoid over smoothing. This number 200 could be too large, but we found it reasonable to allow for a similar behavior over the entire domain. We believe that a more detailed analysis on the effect of changing these smoothing parameters (relative to each radar) on the retrieval results (e.g., an additional sensitivity analysis set) would be better suited as topics for another manuscript.

Moreover, in the 3DVAR algorithm, observation constraint weights are calculated from the nearest neighbor weight and observational data quality based on normalized coherent power for each radar. The nearest neighbor weight at each grid point is calculated by Eq. (1) for the nearest radar data point to the grid point. This can reduce impacts of errors attributable to low radar data sampling rate on the retrieval. We added figures of the nearest neighbor distances and nearest neighbor weights in Figure 3.

2) Advection correction is ignored for paper, why? Especially with 20 May where KVNX is used. Advection correction has been shown to help improve dual Doppler retrievals. It should be discussed and determined how dealing with advection changes the results between the two retrieval techniques discussed in this paper.

This is an important question, since we understand that advection could impact our retrieval results and interpretation as compared with other methodologies. We also recognize that it is challenging, but important to correct for advection effects in the multi-Doppler wind retrieval and similarly demonstrate this correction as also meaningful/important as compared to other observational references. While we have attempted to improve our discussion on these ideas, we believe a more complete analysis of these ideas is something suited for a follow-up manuscript. As such, we have decided to present our results and associated discussions of these multi-Doppler radar wind retrievals without including advection correction in this paper (noting that our responses to follow should accompany this manuscript online).

Moreover, since we do not want to pass the buck on this responsibility for this response to reviewers, we have attempted a simple advection correction procedure in which the radar reflectivity and radial velocity were horizontally shifted according to PPI scan time and horizontal winds as observed by the radiosonde. The figure we provide below (Figure R1) shows vertical profiles of NMCR and radial velocity RMSE for the 4 radars we were using for the intense convection case at 1037 UTC on May 20, 2011.

As from the image, the retrieval with advection correction improves the mass continuity residual. However, the advection corrected retrieval produced larger radial velocity RMSE values, and these converged on a larger cost function value (not shown). We suggest this highlights that an advanced topic that cannot be simply addressed as an add-on to the current manuscript. In that sense, our future plans include investigating how the PPI volume scan can reconstruct 3D structure of clouds, taking account of advection and time evolution of clouds using radar forward simulator and high-resolution (0.5 km) and high-frequent (every 20 seconds) model output.

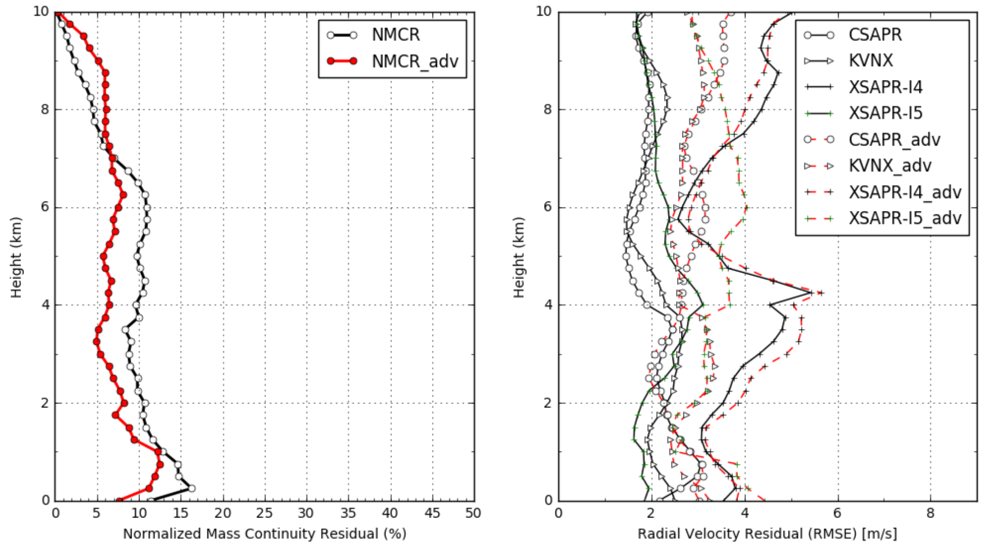

Figure R1: Vertical profiles of NMCR (left) and radial velocity RMSE (right) from the 3DVAR retrievals without advection correction (black lines) and with a simple advection correction (red lines) for 1037 UTC on May 20, 2011.

3) Page 7 line 8: What is the spatial/temporal distance from the radiosonde profiles to the analysis grid. Does using the radiosondes as the background create issues or biases in the background due to time and distance from the grid as well as the evolution of the environment over time. Why not use a derived sounding from model analysis (e.g. RAP) as the background?

We thank the reviewer for drawing our attention to this aspect of our manuscript that was not clear. For this effort, we used the ARM-provided Merged Sounding value-added product. This provides a time series of atmospheric moisture, temperature, pressure, and horizontal wind profiles at the SGP CF at 1-minute intervals 266 altitude levels; This product is obtained by using a combination of observations from radiosonde soundings at SGP CF (available every 3 hours during MC3E), microwave radiometers, surface meteorological instruments, and European Centre for Medium Range Weather Forecasts (ECMWF) model output. The product employs a double-sigmoid function for blending weights when deciding between radiosonde and ECMWF profiles (e.g., originated as a way to use the ECMWF to 'gap fill' for times and locations when timely radiosondes were unavailable). The retrieval in this study used a profile nearest the analysis time from the product. We described this in better detail in revised section 2.

4) The results and analysis of the three cases are not identically carried out but they should be. Why is the upward iterative technique only compared to one case and not all three? I think comparisons between all cases should be carried out in a similar manner. As well as, similar panel plots for 20 May that is included with the other two cases discussed. There are no reflectivity plots for 20 May that is similar to the other two cases and there should be. Expansion and reworking of 5.2 and 6 will help

improve the strength of the paper.

As mentioned in our response to the reviewer's general comment, we agree and have extended the comparison analysis between 3DVAR and upward integration techniques to the five MC3E cases. The RMSD of radial velocity and the normalized mass continuity residual (NMCR) estimated from the 3DVAR and an iterative upward integration method are now provided. Figure 6 shows an example of comparison of retrieved vertical velocity and horizontal divergence, and vertical profiles of RMSE and NMCR for the May 20 case. The result of analysis is described in section 5, which has been moved from section 6 in the previous manuscript.

5) I would suggest doing analysis of the differences between the iterative and 3DVAR techniques over all three cases to show differences between the two techniques over three different regimes (QLCS, elevated front, and supercell environments). This would help show the importance of using the 3DVAR technique.

Thank you for the suggestion. As shown in Table 4, the 3DVAR technique provides lower NMCR and radial velocity RMSE values than the upward integration technique for the five cases – but, we would confirm that the NMCR values from the April 25 and May 11 cases are very low, and we find similar retrievals (behaviors) between the two compared retrieval techniques. Note that these two cases are classified as nocturnal elevated convection (April 25) and widespread stratiform precipitation with embedded convection (May 11), respectively. In other words, both cases included arguably weaker convective cell regions, and the propagation speeds for these events were generally also much slower. The remaining cases are of the more typical severe convective and MCS type events, e.g., those having larger areas of stronger, faster moving convective cells. The result may suggest that the iteration upward integration technique is still highly usable and comparable to the 3DVAR approach for the two weaker convective, slowing moving events where the mass continuity equation is a dominant parameter; For the severe convection and MCS cases, the 3DVAR technique is arguably more viable. We have added an improved discussion on these ideas to section 5.

Minor:

Page 2 line 8: Please expand on reasoning why profiling radars provide high detail in time and height and how without the reader knowing which band the radar is operating in how it can sample the most intense convective cores. Feels like there should be a few citations proving this.

In section 2.4, we have cited Tridon et al. (2013) and Giangrande et al. (2013a), who provided the necessary details on wind profiler operations, configurations and retrieval examples for typical measurements in deep convective cells passing over the SGP Central Facility and extended profiler sites during MC3E. The radar is operating at UHF frequency ranges, which would collect relatively unattenuated (in rain) measurements in deeper convective cells that propagate overhead. Table 2 provides the wind profiler settings for its ‘precipitation’ radar operation modes, which are significantly different than what is typically assumed as boundary layer wind profile modes of operation.

In figure 2: Why are there lines of constant height moving radially away from the WSR-88D nearest neighbor distance plot. It looks different than the other radars. I am not sure why similar heights can occur radially outward.

The figure shows a distance between the grid point and the nearest radar data point at each grid point. In regions where the radar data points are sparse, a radar data point is shared by some grid points in the vicinity of the radar data point. The radial shape in C- and X-SAPR plots is not as obvious because radar data points (VCP coverage in elevation angle space) are enough to avoid these behaviors. Because the density of radar data points decreases with distance from the radar for the NEXRAD radar (KVNX), which is also the furthest radar from the analysis domain, the radial shape problem becomes most evident in attempts to locate co-gridded regions for these datasets.

Page 6 line 22: What is the time difference from the air density calculation and the analysis? For example, the air density within the squall line should be very different from the environment ahead of it. When are those values updated and the sensitivity to those changes applied.

We agree with the reviewer that the air density can vary within MCSs and this is a potential source of uncertainty. As also mentioned in response to the reviewer’s major comment #3, this study used air density profiles as from the ARM-provided Merged Sounding value-added product available at 1-minute intervals 266 altitude levels. The retrieval in this study used a profile nearest the analysis time from the product as the background. This assumption has been commonly used for multi-Doppler radar retrievals. As with other responses, we believed this analysis for the impact of air density was beyond the scope of this manuscript.

However, since the role of air density may not be obvious, again for the benefit of this response to our reviewers, we have attempted a simple sensitivity test to better demonstrate the potential impact of air density (profile variability) on 3DVAR wind retrievals. Three different air density profiles as shown in a figure below (Figure R2) were used for an interesting convective time around 1037 UTC on May 20, 2011: the control profile (black) and ± 2 kg m^{-3} of the control (blue and red) have been tested. The figure also shows 50, 75, 90, and 95 percentiles of retrieved updraft and downdraft values as one reference for potential impacts on key storm metrics. In the case of these larger profile shifts in air density, the differences between the three sets of retrievals are relatively small. In that sense, we believe that the impact of air density variability (e.g., perhaps to include spatial variability) was generally not significant for influencing wind field retrievals to the same level as other considerations we highlighted in this manuscript.

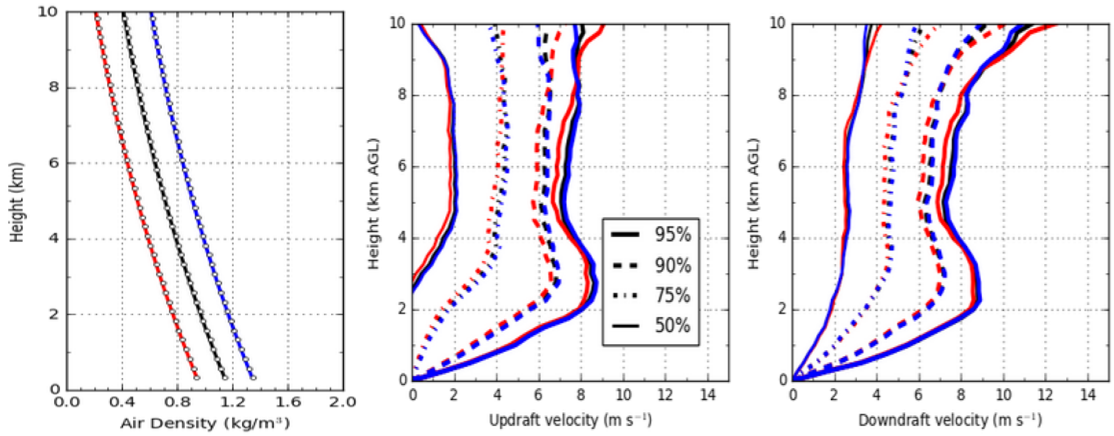

Figure R2: Vertical profiles of air density used for a sensitivity analysis (left) and probability density percentiles of updraft (middle) and downdraft(right).

Page 8 line 18: Is there a citation or study that shows the velocity measurement error can be 0.5 m s^{-1}. Need to justify using 0.5 m s^{-1} as the top of the error.

Agree. The standard deviation of radial velocity (V_{SD}) depends on several factors including the sampling of the radars, SNR, and spectrum width, as discussed in several texts (e.g., Doviak and Zrnić 1993; Bring and Chandrasekar, 2001). We believe the 0.5 m s^{-1} value that we employed is a useful value for sensitivity testing – one that may be consistent with a modest SNR value for severe weather event echoes (e.g., 20 dB), having an average of median spectrum width, 2.4 m s^{-1} (Fang et al, 2004). The V_{SD} could be larger than 0.5 m/s in these convective situations, e.g., reach ~1.0 m s^{-1} at larger spectrum width values. Again, this V_{SD} will also depend on sampling / scan speed (Bharadwaj, 2014, personal communication). V_{SD} values are around 0.5 m s^{-1} with echo SNR ~ 40 dB for an average scan speed used during MC3E (e.g., 18-20 degrees/sec). We have revised statements on these items in the updated manuscript.

Page 9 Line 6: I would switch this paragraph with the one after it to help readability.

We reorganized sections and figures. The paragraph and figure you pointed out were moved in section 5.

Page 9 Line 28: Move the last sentence to the beginning of the sensitivity analysis to give the reader the ability to know where to reference as you describe.

Done.

Page 10 Line 18: How the new R_s was determined to be 750 m?

We empirically determined this value for Rs. We believe that this appears reasonable as it represents approximately the horizontal distance of beam width (8 degrees ~ 1.5 km) of the RWPs, e.g. at around 10 km altitude.

Page 11 Line 20-23: These two sentences seem out of order.

We modified those sentences to read "The most prominent features in both retrievals are a deep updraft region above 3 km altitude and strong updraft values greater than 8 m s^{-1}."

Page 11 Line 25: Move the detail about the time axis for the plots higher up to where the plot is initially discussed near line 20 so the change from the expected axis is noted earlier.

Done.

Page 12 Line 19: How do we know that this upwards motion is associated with the squall line convergence zone when there is not plot to give context that relate the two together.

Some strong convergence and updraft were shown in Fig. 6. However, we decided to remove this sentence from the text.

Chapter 6: How many times was the iterative upward technique iterated over the entire column? What was the method used to determine if/when the iterative technique converged on a solution? You mention number of iterations for the 3DVAR technique but none for the upward iterative technique.

We iterated the solution of the iterative upward technique until the gradient of cost function falls 0.01. Generally, the iterative upward technique converged with about 220 iterations.

Page 14 Line 8-9: This sentence should be removed or changed to not be as strongly worded as there has been other studies where multiband radars have been used together for analysis. See papers resulting from the VORTEX2 field project.

We rewrote section 7 and decided to leave out the sentence from the text.

Page 14 Line 27: It is hard for me to accept that the iterative wind retrieval is inferior to the 3DVAR technique from only 1 example and one that did not use advection correction.

We modified this sentence to be more specific as "Overall, the 3DVAR technique can produce smaller errors in updraft retrievals than the iterative upward integration technique particularly for severe convection events including large areas of strong convection." We extended the comparison analysis between the 3DVAR and the iterative upward integration technique to the five cases and discussed the advection effect in section 7.