Authors Response

Review: Review Report

This manuscript presents an innovative extension of the traditional VVP technique by explicitly accounting for spherical geometry and Earth curvature effects. This is an important and often overlooked issue in large-scale radar wind retrievals. The mathematical derivation is rigorous, and the analysis is comprehensive. The study represents a valuable methodological contribution to MLT wind retrievals.

However, I have several concerns that should be addressed before publication.

General Reply: *We thank the reviewer for the thorough assessment of our manuscript and appreciate the constructive feedback. In response, we have revised and clarified all concerns. We have submitted a companion paper that addresses the validation of the novel method, SVVP, and de-biasing methods. However, we note that the sensitivity experiment is computationally intensive and may not yield robust results. The Tromsø and Alta stations provide the most recorded data, and removing them would compromise the reliability of the estimation. We have included Figure 14 to illustrate optimal coverage for the selected reference point. Detailed responses to each comment are provided in the attached PDF. The revised manuscript will be prepared with Latexdiff tracked changes.*

1. *Expanded the method section to address bias correction*
2. *Added an Appendix on wind time series*
3. *Moved Figures 5 and 8 to the new appendix*
4. *Added Figure 14 to illustrate the influence of the circle radius*
5. *Added tables 2 and 3 to summarize correlation results*

Comments:

Review: Major Comments

Reviewer Comment: The primary conclusion of the manuscript is that SVVP provides more physically realistic vertical winds than the conventional VVP approach. However, the current analysis only demonstrates differences between retrieval methods and does not establish which solution is closer to the true atmospheric state. Therefore, the current results demonstrate that SVVP produces different retrievals from VVP, but do not yet conclusively demonstrate that SVVP is more accurate. If possible, comparisons with independent observations (e.g., nearby Na lidar) would substantially strengthen the manuscript. At a minimum, the authors should discuss the current limitations and opportunities for validating MLT vertical wind retrievals.

Response: *We submitted a companion paper addressing the above-mentioned concerns. Figure 1 presents a comparison between our retrievals and the Japanese Meteorological reanalysis (JAWARA) and a free run of SE-WACCM-X. In the revision, we will include a table showing the sensitivity of the vertical winds on the heating/cooling rates to clarify which numbers are more physically realistic.* There are already two publications with a comparison of the VVP method and lidar wind measurements

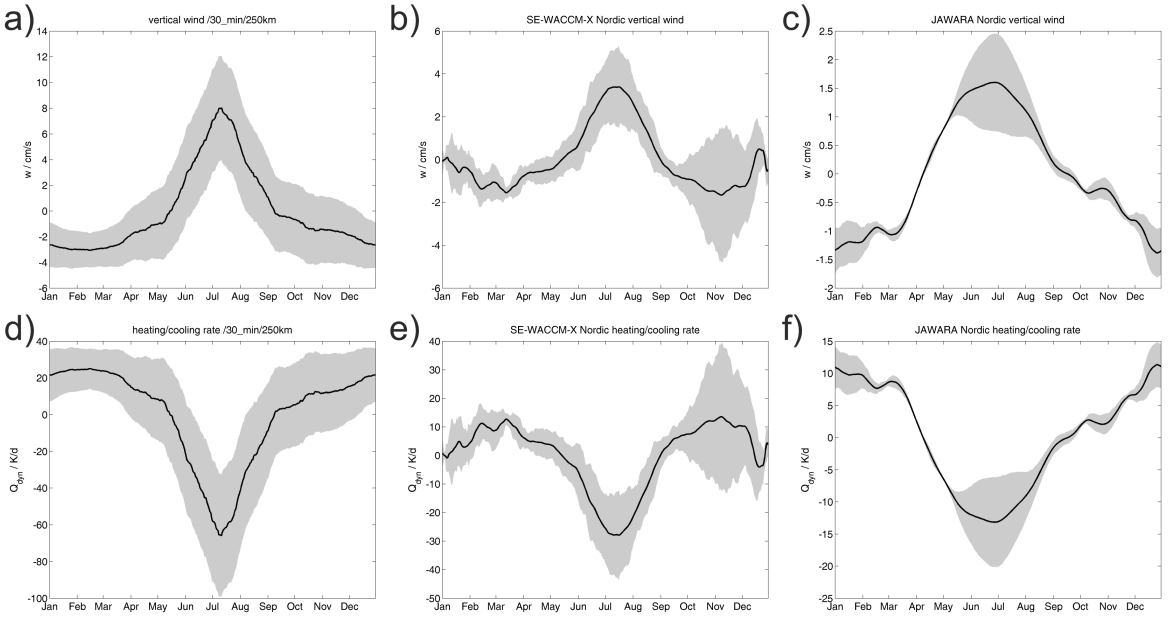

Figure 1. Vertical winds (top row) and heating/cooling rate(bottom row) for Nordic Meteor Radar Cluster with a 250 km diameter domain (left column), the free-running SE-WACCM-X (middle column), and the JAWARA reanalysis (right column).

(Qiao et al., 2025; Ban et al., 2026).

Reviewer Comment: I strongly encourage the authors to perform a leave-one-radar-out sensitivity experiment by excluding each radar in turn and repeating the retrieval. Such an analysis would provide a quantitative assessment of the robustness of the derived vertical winds and help determine whether the results are strongly dependent on the network geometry.

Response: *Such an experiment would require substantial additional CPU time on our HPC Ubelix. The best and most robust results are obtained using all 4 systems. As soon as Tromso or Alta are removed, the number of meteor detections drops significantly, and a robust estimate is no longer feasible. Sodankyla or Kiruna MRs are less critical, and the loss of one system is still visible, but will not lead to a major degradation of the results. On the other hand, Alta and Tromso show the largest phase disagreement and, thus, the largest position errors for the localization of individual meteors. However, this position uncertainty is still a factor of 2 lower than assumed in the non-linear error propagation. We added some sentences discussing this point.*

Reviewer Comment: The vertical wind bias correction plays a central role in the final results. However, the manuscript does not sufficiently discuss the assumptions behind this procedure. It is unclear whether the correction is derived from the entire multi-year dataset or shorter temporal intervals. Different choices may influence the resulting climatology and long-term variability, and it remains unclear to what extent the apparent improvement in vertical winds originates from the SVVP formulation itself versus the adopted bias-correction procedure. A sensitivity analysis of the retrieved vertical winds to the adopted bias-correction strategy would strengthen confidence in the conclusions.

Response: *This issue is discussed in a companion paper. The bias correction is performed using the entire data set. As the reviewer noted, shorter periods would affect the results. We will expand this section to clarify our procedure. The underlying reason for the de-biasing goes back to the textbook of Rodgers (2000). The most precise and accurate information on the long-term vertical wind is obtained by tracking the mean altitude of the detected meteors over decades (Stober et al., 2014; Dawkins et al., 2023, 2024). We found a long-term change of a maximum of 850 m over one decade. This translates into a vertical velocity of* $2.6 \cdot 10^{-6} m/s$*, which is essentially zero for one year. Thus, the mean Doppler and divergence-derived vertical wind should reflect this value at all altitudes of the meteor layer. We added a paragraph discussing this aspect in the revised manuscript.*

Reviewer Comment: As a broader perspective, the authors may consider discussing whether the method could be adapted to weather radar networks and tropospheric wind retrievals, where more independent observations are available for validation.

Response: *The SVVP and 3DVAR+DIV algorithms are applicable to all multistatic network data that provides range, time, angle of arrival, and line-of-sight velocity. Weather radar networks often perform VAD scans with overlapping volumes, which is suitable for applying both algorithms. However, very often the Doppler velocity is aliased due to the fast scanning mode. Meteorological wind lidar networks for the boundary layer could also be analyzed, although the full earth geometry might be less relevant at such low altitudes close to the surface.*

Reviewer Comment: The manuscript concludes that radii between 200 and 250 km provide the best performance. Is there a quantitative criterion that favors one radius over the other, or are both considered equivalent within uncertainty?

Response: *This conclusion is based on Figure 2 and Figure 14. We calculated heat maps, meteor detection density plots, and individual meteor detection plots. Both radii show the best coverage for the selected reference point. Larger radii often are biased due to asymmetric sampling (almost monostatic geometry or only certain sectors are covered). Smaller radii would result in much lower detection rates and, thus, the data sparsity would cause other issues. However, both radii result in equivalent results within the error budget.*

Review: Minor Comments

Reviewer Comment: Figures 7–10 contain a substantial amount of overlapping information. The authors may consider combining these figures into one or two multi-panel figures to facilitate direct comparison between VVP, SVVP, and 3DVAR+DIV. In addition, some of the quantitative comparisons could be more effectively summarized in tables.

Response: *We will revise the Figure content and move some of the panels to the appendix to avoid redundant information. We also summarize the correlation results for mean winds and some of the higher-order parameters in a Table.*

Reviewer Comment: The manuscript would benefit from a summary table quantifying the differences among VVP, SVVP, and 3DVAR+DIV retrievals (e.g., bias, RMSD, correlation coefficients), rather than relying primarily on visual inspection of multiple figures.

Response: *We will add a table summarizing correlation results.*

Reviewer Comment: The statement that the SVVP method produces "more realistic" vertical winds may be somewhat strong given the lack of independent validation. Consider using more cautious wording such as "more physically consistent" or "more self-consistent".

Response: *Agreed. This will be changed.*

References

Ban, C., Fang, X., Yi, W., Zeng, J., Stober, G., Pan, W., Li, T., and Xue, X.: A comparative study of mesospheric zonal wind observations from Na lidar and multistatic meteor radars above Hefei, China, Atmospheric Measurement Techniques, 19, 1697–1709, https://doi.org/10.5194/amt-19-1697-2026, 2026.

Dawkins, E. C. M., Stober, G., Janches, D., Carrillo-Sánchez, J. D., Lieberman, R. S., Jacobi, C., Moffat-Griffin, T., Mitchell, N. J., Cobbett, N., Batista, P. P., Andrioli, V. F., Buriti, R. A., Murphy, D. J., Kero, J., Gulbrandsen, N., Tsutsumi, M., Kozlovsky, A., Kim, J. H., Lee, C., and Lester, M.: Solar Cycle and Long-Term Trends in the Observed Peak of the Meteor Altitude Distributions by Meteor Radars, Geophysical Research Letters, 50, e2022GL101 953, https://doi.org/https://doi.org/10.1029/2022GL101953, e2022GL101953 2022GL101953, 2023.

Dawkins, E. C. M., Janches, D., Stober, G., Carrillo-Sánchez, J. D., Lieberman, R. S., Jacobi, C., Moffat-Griffin, T., Mitchell, N. J., Cobbett, N., Batista, P. P., Andrioli, V. F., Buriti, R. A., Murphy, D. J., Kero, J., Gulbrandsen, N., Tsutsumi, M., Kozlovsky, A., Lester, M., Kim, J.-H., Lee, C., Liu, A., Fuller, B., O'Connor, D., Palo, S. E., Taylor, M. J., Marino, J., and Rainville, N.: Seasonal and Local Time Variation in the Observed Peak of the Meteor Altitude Distributions by Meteor Radars, Journal of Geophysical Research: Atmospheres, 129, e2024JD040 978, https://doi.org/https://doi.org/10.1029/2024JD040978, e2024JD040978 2024JD040978, 2024.

Qiao, Z., Liu, A. Z., Stober, G., Fuentes, J., Vargas, F., Adami, C. L., and Reid, I. M.: Chilean Observation Network De Meteor Radars (CONDOR): multi-static system configuration and wind comparison with co-located lidar, Atmospheric Measurement Techniques, 18, 1091–1104, https://doi.org/10.5194/amt-18-1091-2025, 2025.

Rodgers, C. D.: Inverse Methods for Atmospheric Sounding: Theory and Practice, Singapore: World Scientific, 2000.

Stober, G., Matthias, V., Brown, P., and Chau, J. L.: Neutral density variation from specular meteor echo observations spanning one solar cycle, Geophysical Research Letters, 41, 6919–6925, https://doi.org/https://doi.org/10.1002/2014GL061273, 2014.