Authors Response

Review: Review Report

This manuscript presents a significant methodological advancement for multistatic meteor radar wind retrievals by formulating the Volume Velocity Processing (VVP) in a rigorous spherical coordinate system (SVVP). The authors demonstrate the impact of this new implementation using four years of observations from the Nordic Meteor Radar Cluster and provide a thorough intercomparison with both the traditional plane-geometry VVP and the more sophisticated 3DVAR+DIV tomographic retrieval. The topic is timely, the analysis is comprehensive, and the results convincingly show that accounting for Earth's curvature is essential—particularly for vertical wind estimates and higher-order kinematic quantities. The manuscript is generally well structured, and the figures effectively support the narrative.

Nevertheless, several aspects require improvement before the paper can be recommended for publication in Atmospheric Measurement Techniques. These concern the presentation and discussion of the validation/uncertainty aspects, the quality of the language, and the completeness of the figure captions and citations. Below, I list specific comments and suggestions, separated into major and minor issues.

General Reply: *We thank the reviewer for the thorough assessment of the submitted manuscript and appreciate the constructive feedback. In response, we have revised and clarified several aspects, including the discussion, language quality, figure captions, and citations. In particular, we have addressed most of the specific concerns in a companion paper and have further expanded the section on the derivation of Volume Velocity Processing on a Sphere, now including details on vertical wind bias correction. For the analysis of radius performance, we have added Figure 14, which shows 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 Seasonal Climatology*
3. *Moved Figures 5 and 8 to the new appendix*
4. *Added Figure 14 to illustrate the influence of the circle radius*

Comments:

Review: Major Comments

Reviewer Comment: Treatment of vertical wind bias and uncertainty. The manuscript mentions that a bias correction of 1-4 cms^{-1} is subtracted from the vertical winds (lines 225–227, 417–423) based on the assumption that the long-term mean vertical wind should be zero.

This correction is critical because the absolute values of the vertical wind are central to the conclusions. The authors should provide more details: how exactly is the bias estimated? Is it a single constant per station, per altitude, or per domain size?

The statistical significance of the debiased vertical wind patterns (e.g., upwelling of 10 cms^{-1} in summer) should be evaluated, perhaps with confidence intervals or by showing that the bias-subtracted values indeed vary seasonally and not merely as residual noise.

Moreover, the 3DVAR+DIV vertical winds are an order of magnitude larger (lines 328–330). The authors attribute this to lower meteor counts per grid cell and the Tikhonov regularization. A more quantitative explanation (e.g., typical measurement response, averaging kernels) would strengthen the discussion.

Response: *The bias is estimated from the calculated climatology and the five-year-long time series consisting of all measurements. The climatological bias is almost identical to the resolved long-term record. The bias is estimated for each altitude separately. The most precise measurement of the vertical motion is provided by the meteor ablation altitude, which has been determined for almost 2 decades and shows a long-term trend and solar cycle effects Stober et al. (2014); Dawkins et al. (2023). Transferring these long-term trends into a vertical velocity corresponds to* $2.7 \cdot 10^{-6}$*m/s, which is essentially negligible. Therefore, the Doppler and divergence-derived vertical winds should result in a seasonal mean vertical velocity that is zero for all altitudes. Considering that 1 mm/s vertical velocity would result in an upwelling of 31.536 km. This is not observed from trace gases or other indirect measurements on seasonal time scales (Yue and Wang, 2025). A more detailed discussion is provided in a companion paper. Figure 1 shows a comparison of the derived bias correction and the corresponding measurement statistics.*

We also performed a comparison to existing meteorological analysis and the free-running SE-WACCM-X model computing. The grey shaded areas indicate the 1-σ *interval of our statistical uncertainties, which also includes geophysical variability. Figure 2 shows the resulting vertical winds integrated as a seasonal mean profile average between 84-94 km. The model data was prepared with a similar data pipeline. The observations are convolved with the model grid and averaged.*

The 3DVAR+DIV winds are much more sensitive to projection errors, causing a substantial increase in the vertical winds. Typically, only 1-3 meteors enter the solution of a grid cell, which appears to be sufficient for horizontal winds, but results in large uncertainties for the vertical winds. Typical uncertainties are in the order of 1-3 m/s, and thus, the seasonal pattern can not be reproduced and is dominated by individual measurements and the much larger uncertainties. The comparison here is

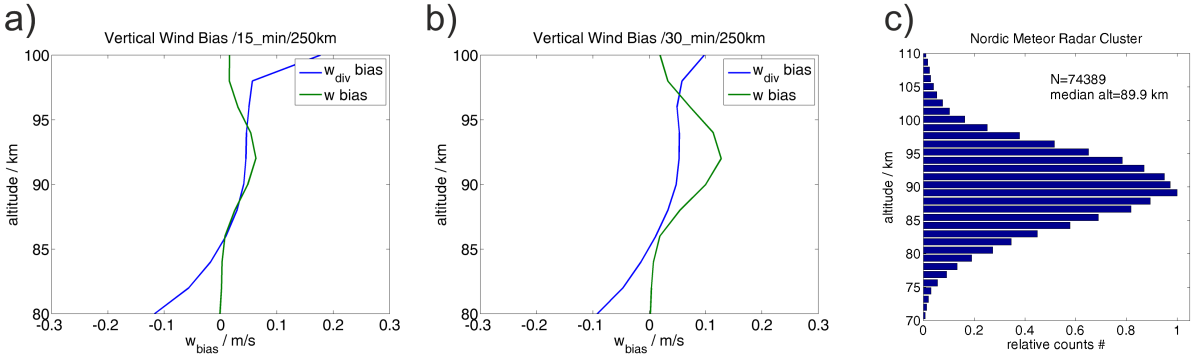

Figure 1. Vertical wind seasonal bias for 15 and 30 minute temporal resolution is shown in panels a) and b), respectively. A normalized altitude distribution is visualized in panel c) as a proxy for the measurement statistics.

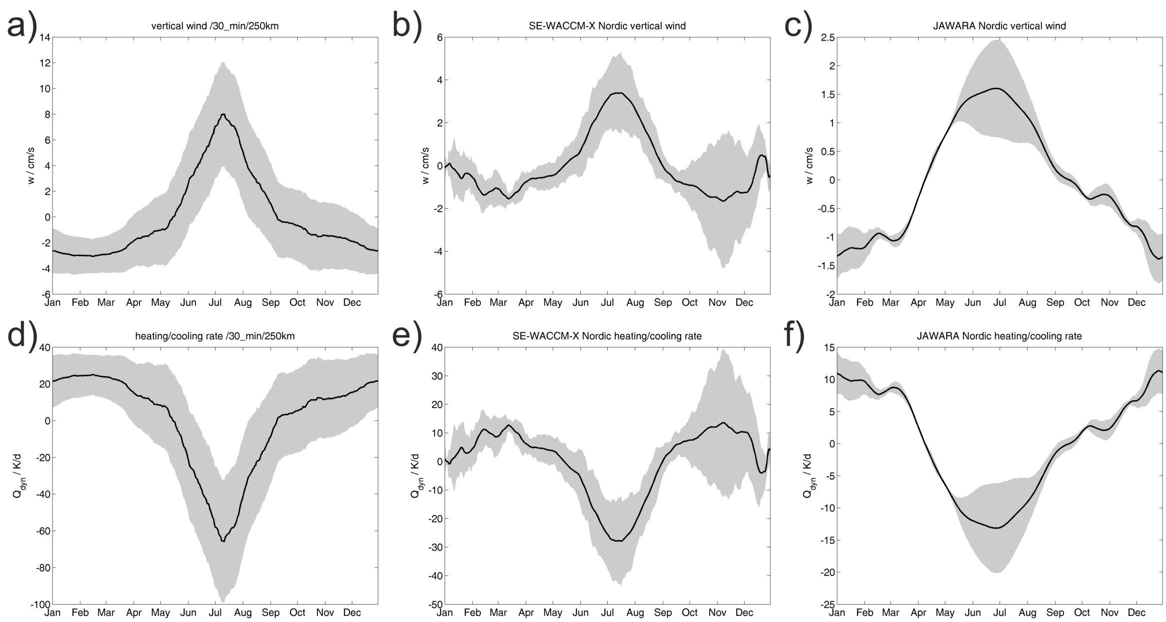

Figure 2. Vertical winds (top row) and heating/cooling rate(bottom row) for Nordic Meteor Radar Cluster with a 250 km diameter domain (left column), the free-running SE-WACCM-X (middle column), and the JAWARA reanalysis (right column).

only included to demonstrate that for the seasonal vertical winds, the 3DVAR+DIV algorithm needs to be further improved. The measurement response shown in Figure 15 underscores our conclusion that a 200-250 km radius is the optimal sampling volume. The averaging kernels are not stored due to the enormous size of these data.

Reviewer Comment: Intercomparison with 3DVAR+DIV and sensitivity to Tikhonov parameter. Section 4.3 presents a single snapshot (1 January 2021) to illustrate the effect of the regularization parameter.

The representativeness of this single case should be commented on. Are the differences shown robust across many days/seasons?

The text states that "the 3DVAR+DIV performs best with regularization strengths between $\alpha = 0.4$ 5. How was this range determined? A brief description of the metric used (e.g., cross-validation, spectral analysis) would be helpful.

The comparison between VVP and 3DVAR+DIV vertical winds (Fig. 14) shows a regression slope of only 0.105 (spherical) and 0.019 (plane). The discussion merely notes that this "validates and [is] consistent with the climatology results". Given the huge difference in magnitude, a deeper analysis of why the two methods disagree so strongly is warranted. The role of the divergence-derived vertical wind in 3DVAR+DIV versus the Doppler-derived vertical wind in SVVP should be explicitly addressed.

Response: *The Tikhonov parameter was optimized using several criteria: the mean wind should not have a bias compared to the monotonic mean wind analysis, the spectral analysis shows planetary waves, tides, and gravity waves (coherent wave structure) (Qiao et al., 2025) and a spectral slope of -5/3 (horizontal wavelength spectra). Furthermore, we used the Hunga Tonga eruption to test whether the gravity wave was captured (Stober et al., 2023, 2024). We expand this discussion in the revision to clarify our choice, but also to make clear that the numbers are based on rather soft criteria. However, the shown examples (we added one more) are representative of typical wave fields at 90 km altitude.*

The difference in the magnitude of the vertical winds obtained from the 3DVAR+DIV and the SVVP has several reasons. The 3DVAR+DIV implicitly enforces the continuity equation, which depends on the integration boundary. During the retrieval, we enforce a zero vertical mean when integrated above the entire meteor layer for each grid cell. This introduces rather large uncertainties for the climatological mean values, which cannot be reproduced with this approach. Furthermore, the assumption of an incompressible flow does not hold for the small scales. Mach numbers above M>0.5 are frequently observed (see Qiao et al. (2025).

Reviewer Comment: Temporal and spatial resolution sensitivity. The analysis of temporal resolution (15, 30, 60min) and domain radius (200–400km) is well motivated.

In Fig.9, the vertical wind regression slopes deviate markedly from unity (1.965 for 15 vs 30min, 0.530 for 60 vs 30min). The authors suggest this reflects the gravity-wave spectrum, but they do not investigate whether this scaling is linear or whether a "true" reference exists. A more systematic treatment—e.g., power spectral density comparisons or an estimate of the gravity-wave contribution—would elevate the discussion.

The optimal radius (200–250km) is justified by the 3DVAR+DIV measurement response (Fig.15). However, the measurement response shown is for the 3DVAR+DIV retrieval, not for SVVP. It would be more direct to show, for the SVVP, how the number of meteors and the condition number of the least-squares matrix vary with radius. The current argument is indirect and should be clarified.

Response: *We will add more information on the scaling behaviour. So far, it shows a linear scaling dependency. An absolute 'true' reference is not available. A detailed analysis of the Stokes drift can only be obtained from the 3DVAR+DIV by analyzing spatial gravity wave spectra. Averaging 60-minutes leads to a smearing of fast (ducted) gravity waves, which induces larger deviations. The 15-minute retrieval suffers from data sparsity and likely does not capture all the small-scale features with their maximal amplitude. The 30-minute appears to be somewhere in between. Figure 3 shows the frequency spectra for all three temporal resolutions. From Lidar observations, it is known that the smallest scales are related to the largest vertical velocities (Chu, Xinzhao et al., 2026).*

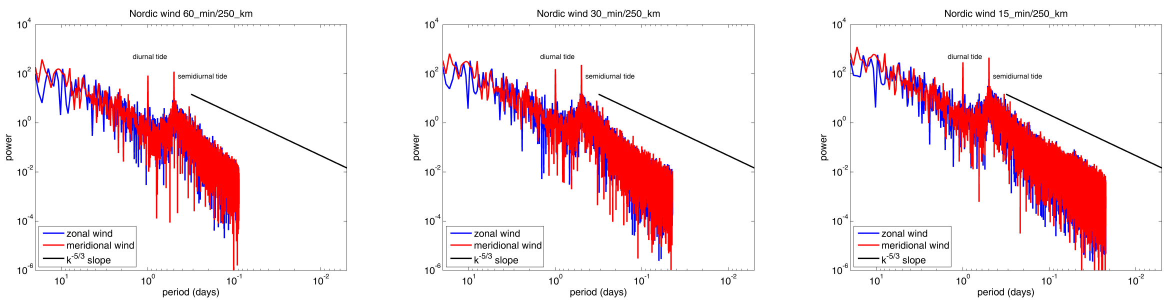

Figure 3. Atmospheric Wave spectra for the horizontal wind components for 15, 30, and 60 minutes.

Review: Minor Comments

Reviewer Comment: Figures 4 and 5 (monthly and seasonal composites) are redundant; consider merging them or moving one to supplementary material.

Response: *We move long-term composites to the Appendix material.*

Reviewer Comment: In Fig.6 (correlation plots), the robust regression method should be named (e.g., Theil-Sen, iteratively reweighted least squares).

Response: *We used iteratively reweighted least squares (IRLS) with a bisquare (Tukey) weight function. The figure caption has been updated accordingly.*

Reviewer Comment: The comparison of information content / Shannon entropy is only briefly mentioned and not shown. Either remove this remark or add a figure/table that supports it.

Response: *We use the measurement response in Figure 14 to justify the circle of influence. We will link this paragraph to this Figure to support its relevance.*

Reviewer Comment: The paragraph about the influence of the circle of influence on vertical wind is very insightful. It would be even stronger if the authors could show a simple plot of the retrieved vertical wind (or its bias) as a function of radius for a fixed time/altitude.

Response: *We already added Figure 1 in a previous reply. A detailed discussion is available in a companion paper. We revised and expanded the information in the revised version.*

Reviewer Comment: The conclusion that SVVP is “more physically consistent” is well supported, but the limitations of the method (e.g., inability to capture non-linear gradients, reliance on a single reference point) should be acknowledged more explicitly.

Response: *We will point out the limitations of the method concerning the underlying assumptions.*

References

Chu, Xinzhao, Li, Xianxin, Jandreau, Jackson, and Chen, Yingfei: Vertical Wind Measurements with High-Resolution Lidars & Impacts on Antarctica Upper Atmosphere Studies, EPJ Web Conf., 362, 01 035, https://doi.org/10.1051/epjconf/202636201035, 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.

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.

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.

Stober, G., Liu, A., Kozlovsky, A., Qiao, Z., Krochin, W., Shi, G., Kero, J., Tsutsumi, M., Gulbrandsen, N., Nozawa, S., Lester, M., Baumgarten, K., Belova, E., and Mitchell, N.: Identifying gravity waves launched by the Hunga Tonga–Hunga Ha'apai volcanic eruption in mesosphere/lower-thermosphere winds derived from CONDOR and the Nordic Meteor Radar Cluster, Annales Geophysicae, 41, 197–208, https://doi.org/10.5194/angeo-41-197-2023, 2023.

Stober, G., Vadas, S. L., Becker, E., Liu, A., Kozlovsky, A., Janches, D., Qiao, Z., Krochin, W., Shi, G., Yi, W., Zeng, J., Brown, P., Vida, D., Hindley, N., Jacobi, C., Murphy, D., Buriti, R., Andrioli, V., Batista, P., Marino, J., Palo, S., Thorsen, D., Tsutsumi, M., Gulbrandsen, N., Nozawa, S., Lester, M., Baumgarten, K., Kero, J., Belova, E., Mitchell, N., Moffat-Griffin, T., and Li, N.: Gravity waves generated by the Hunga Tonga–Hunga Ha'apai volcanic eruption and their global propagation in the mesosphere/lower thermosphere observed by meteor radars and modeled with the High-Altitude general Mechanistic Circulation Model, Atmospheric Chemistry and Physics, 24, 4851–4873, https://doi.org/10.5194/acp-24-4851-2024, 2024.

Yue, J. and Wang, N.: Estimation of adiabatic cooling and warming in the mesosphere and lower thermosphere, Journal of Atmospheric and Solar-Terrestrial Physics, 269, 106 492, https://doi.org/https://doi.org/10.1016/j.jastp.2025.106492, 2025.