Authors Response

Review: Review Report

This manuscript presents a spherical formulation of the Volume Velocity Processing (VVP) technique and applies it to four years of observations from the Nordic Meteor Radar Cluster. The topic is relevant, and the mathematical formulation is carefully developed. However, the manuscript does not provide sufficient evidence to support its central claim that the spherical formulation produces more accurate or physically realistic wind retrievals, particularly for the vertical wind component. The analysis demonstrates differences between retrieval methods, but does not establish improved retrieval accuracy.

Demonstrating differences between retrieval methods is not equivalent to demonstrating improved accuracy. Consequently, several fundamental issues are insufficiently addressed and require substantial additional work before the scientific conclusions can be considered adequately supported.

General Reply: *We thank the reviewer for the assessment of the publication and his comments. The manuscript includes a supplement with 49 Figures to outline the sensitivity of the retrieval to different radii and temporal resolutions. We added the leave-one-station-out experiment with a reduced analysis to the reply. To avoid redundancy in the supplement, we will not show the data in the manuscript, but add it as Figure 51 to the supplement. The main narrative of the paper is the differences between planar geometry and the spherical implementation of the higher-order kinematic terms. As the data curation and all retrieval steps are identical between both implementations and only the fitting function was adapted, our results sufficiently demonstrate the impact of the geometry on the quantities. Furthermore, we included full non-linear error propagation and also performed various analysis experiments with synthetic data (Stober et al., 2021a, 2022). Our conclusion related to the vertical wind is based on the results from SABER trace gas observations presented in Yue and Wang (2025). We will weaken otherwise the conclusions to avoid overly strict claims on the reliability. However, the basic question related to spherical or WGS84 approximation was already discussed in Stober et al. (2021b, 2018) and is widely accepted. Here, it is just implemented for volume quantities. The manuscript is revised according to all reviewers' suggestions. Please find point-by-point replies to the raised concerns in the attached PDF. The revised manuscript is prepared with latexdiff.*

Comments:

Review: Major Comments

Reviewer Comment: 1. Lack of rigorous validation

The primary weakness of the manuscript is the absence of a validation framework capable of assessing retrieval accuracy. The manuscript repeatedly concludes that the spherical formulation yields more realistic vertical winds and reduces biases present in conventional VVP. However, these conclusions are based on comparisons between retrieval methods rather than comparisons against a known reference. Agreement or disagreement with VVP or 3DVAR+DIV does not establish which solution is closer to the true atmospheric state.

Response: *The main narrative of the publication is to highlight the importance of spherical geometry compared to planar geometry for the volume quantities of horizontal divergence, relative vorticity, stretching, and shearing deformation. Considering that Earth is often represented as a sphere in GCMs, it is natural that this should be considered in observations and inferred quantities. We present a detailed comparison of the horizontal winds, which agree with previous studies and reflect the currently accepted climatological behaviour. Our conclusion is based on the more realistic physical representation of the geometry compared to the previous version. In particular, the horizontal divergence results in a much more realistic seasonal pattern. We clarified in the revision to point out that VVP and SVVP are calculated on identical data curation pipelines, which also means that synthetic data will not change the results regarding these differences. Concerning the vertical winds, we explicitly state in the revision that the SVVP vertical wind velocities show a better agreement with trace gas measurements from SABER (Yue and Wang, 2025) to underline the improvement.*

Reviewer Comment: If independent observations are unavailable (e.g., rockets, MST radars, and/or from satellites), the authors should perform validation using realistic synthetic atmospheric fields generated from direct numerical simulations or global circulation models. Such approaches are standard in the atmospheric remote sensing community and allow retrieval biases, uncertainties, and resolution limits to be quantified under controlled conditions. Examples include the Observing System Simulation Experiments (OSSE) framework described by Cucurull et al. (2024), which provides a systematic methodology for retrieval validation, and its application to MLT wind retrievals by Urco et al. (2024).

Response: *Zonal and meridional winds have been evaluated within the OSSE framework very recently (Hsu et al., 2026). MR winds are indeed improving the model skill when assimilated. The higher-order kinematic terms derived in this study are more of a diagnostic quantity and hold only as long as the linear approximation is valid (this is explicitly stated in the revision). Urco et al. (2024) present an Informed Machine learning approach. The resulting cost function is very similar to the 3DVAR+DIV with the generalized Tikhonov regularization. Just the way the regularization terms are derived differs. However, the paper also outlines the limitations when synthetic data is used for the performance evaluation of retrievals. The manuscript presents a single case study of 24 hours, and equations (16) to (21) refer to Cartesian coordinates; it remains unclear in which geometry* *the cost function is actually implemented and whether spherical geometry was used for the volume quantities used in the neuronal network.*

Figure 14/15 (Hunga-Tonga case) shows entirely different structures compared to the DNS simulations and the synthetic meteor radar data. It's also unexpected that the vertical wavelength is rather short in the vertical cross-section (other observations indicated a very long vertical wavelength of the HTHH GW), but very consistent in the latitudinal section. There is also a clear offset in the daily mean vertical winds of 1-2 m/s, which translates to a mean upwelling of 129.6 km in 24 hours. This outlines that synthetic data mainly helps to verify the mathematical implementation of an algorithm, but still generates open questions when applied to real data. Furthermore, there are low-latitude observations in which the HTHH wave was clearly in the transonic flow regime, and compressibility effects played a major role (Qiao et al., 2025). It appears to be an unexpected choice to select such a case as a reference to test an incompressible model.

Otherwise, the method is rather similar to the 3DVAR+DIV approach (non-stationary compressible solution). On the other hand, the incompressible Boussinesq approximation has additional assumptions that are not constrained by the data. A rigorous validation would imply that all variables are cross-compared. However, the paper confirms previous results related to the 3DVAR, 3DVAR+DIV, and SVVP.

Reviewer Comment: Such experiments would allow the authors to quantify retrieval bias, random error, uncertainty propagation, and the effective spatial and temporal resolution of the proposed method.

Response: *Such experiments have been conducted before (Stober et al., 2021a) to validate the Reynolds-stresses. This was further verified in Lieberman et al. (2025) for a Quasi-two-day wave study. Later, we used synthetic data to derive Tikhonov regularizations (similar to Urco et al. (2024), but with a different approach) to get more realistic wind fields, including vertical winds. We also compared the vertical winds for seasonal data between the retrieval and ICON-UA (Stober et al., 2022). This regularization also includes corrections for the scattering geometry, which are not mentioned or included in other simulation studies. However, this results in a major issue when applying the retrieval to synthetic data. Equation (1) in Urco et al., 2024 assumes isotropic point scattering, as the Bragg vector k denotes the movement of the scattering center (specular point), which is not identical to the line-of-sight velocity for (transverse scatter meteor radars). In the past, this was addressed by implicitly neglecting the vertical velocity in the cost function, corresponding to a Tikhonov regularization with $||\infty||$ for the vertical component. Such a difference leads to very good agreement when synthetic data is used, but causes deviations when applied to real observations. We decided to investigate the geometric effect by using real data and only replacing the fitting function. The key Figures of the paper would remain unaffected by using synthetic data, but one could introduce arbitrary climatologies. Simulating compressibility effects and dissipation is beyond current availability. We have a simulation of the scattering effect (digital twin), but it requires more work to be applicable for such studies.*

Reviewer Comment: More fundamentally, the manuscript does not define an objective performance metric by which the proposed method can be judged superior to conventional VVP. Without a quantitative success criterion, the interpretation of "improvement" remains subjective.

Validation deferred to a companion paper or future publication cannot be used to support conclusions made in the present manuscript. The proposed method requires validation within the manuscript itself.

Response: *This study is designed to demonstrate the impact of the geometric implementation between the two Volume Velocity Processing algorithms. The focus of the VVP vs. SVVP comparison is designed to only outline the impact of the geometry. All other aspects of both algorithms are identical. We also show examples of residuals in the revised manuscript. The vertical winds are qualitative compared to the SABER CO2 trace gas measurements published in Yue and Wang (2025). We did not claim a superiority of one algorithm over another. We conclude that there are differences, and qualitative comparisons indicate better agreement for the SVVP relative to the VVP implementation.*

Reviewer Comment: 2. Failure to demonstrate that spherical geometry is a dominant source of error

The central premise of the manuscript is that Earth curvature introduces significant biases in VVP retrievals and that these biases are mitigated by the spherical formulation. However, the manuscript does not quantify the relative importance of geometric effects compared to other error sources.

Potential contributors include measurement uncertainty, meteor sampling variability, network geometry, temporal averaging, regularization choices, vertical-wind bias correction, and inversion assumptions. The current analysis, therefore, demonstrates that SVVP produces different retrievals than conventional VVP, but does not demonstrate that these differences arise primarily from the spherical representation.

The manuscript currently assumes that curvature effects are responsible for the observed differences, but this assumption is never tested quantitatively.

A quantitative error budget is needed to establish whether curvature effects are indeed a dominant source of retrieval error. Without such analysis, the attribution of the observed differences to spherical geometry remains largely qualitative.

Response: *We disagree with the reviewer. The comparison between both geometries is designed only to be affected by the spherical geometry for the volume quantities (horizontal divergence, relative vorticity, stretching, and shearing deformation). Both analyses leverage identical data curation pipelines, which include all filters, geometric WGS84 corrections for each meteor, the non-linear error propagation, the number of iterations, and all other aspects, such as the SVD solver or circle of influence. Only the fitting function is changed between the two versions. We are not aware that we can more clearly demonstrate the effect of the geometry on the volume quantities. The geometric comparison will not be different when applied to synthetic data. The main reason for considering SVVP to be more reliable is the vertical profiles of the horizontal divergence. The VVP results in an all-year convergence above 95 km. This appears to be unlikely.*

Reviewer Comment: 3. Insufficient sensitivity and robustness analysis

The robustness of the proposed retrieval method is insufficiently characterized. Several sensitivity analyses are required. In particular, a leave-one-radar-out experiment would provide valuable information regarding the dependence of the retrieved winds on network geometry and station availability. The argument that removing major stations degrades the retrieval is not a justification for omitting the experiment. On the contrary, quantifying the degradation is precisely the purpose of such a sensitivity study.

Similarly, robustness could be assessed through leave-random-measurements-out experiments, where a fraction of the meteor detections (e.g., 10–50%) is removed and the retrieval repeated. Such analyses would help quantify the stability of the inferred winds and their sensitivity to sampling density.

Response: *The supplementary material includes 49 Figures, presenting all correlations for all time resolutions and radii of influence. These Figures present a very detailed sensitivity study for all retrievals used in the manuscript. Furthermore, Figure 3 in the paper shows the diurnal cycle, which is identical to the leave out 50% of the data from the retrieval as part of the diurnal cycle. We show the different resolutions to exactly address this issue. The 15-minute temporal resolution uses only 25% of the data compared to the 60-minute retrieval. However, for the sake of completeness, we have performed a leave-one-station-out experiment for the VVP and SVVP. The comparison is found below in the Figure 1 and as Figure S51 in the supplementary material.*

Reviewer Comment: The vertical-wind bias correction also plays a central role in the manuscript's conclusions. However, no systematic sensitivity analysis is presented to determine how strongly the results depend on the adopted bias-correction strategy. It remains unclear how much of the apparent improvement originates from the SVVP formulation itself and how much originates from the subsequent correction procedure.

Furthermore, the need for an externally imposed bias correction raises additional questions regarding the robustness of the vertical wind retrieval itself. If the proposed formulation substantially reduces geometric biases, the manuscript should clarify why a subsequent empirical correction remains necessary and quantify its impact on the reported results.

Response: *The most accurate and precise measurement of the vertical wind with meteor radars is obtained by tracking the peak altitude of the meteor detections. This peak altitude follows a constant density surface, and the width of the meteor layer indicates the stratification. Previous studies have monitored the long-term changes of the meteor layer (Stober et al., 2014; Dawkins et al., 2023, 2024). Based on these studies, the maximum change in altitude of the meteor layer was 850 m per decade. This translates into a vertical wind of approx.* $2.6 \cdot 1'^{-6} m/s$*, which is essentially negligible. A perfect system should observe this mean velocity in the Doppler or divergence-derived vertical velocity. Thus, we calculated over 5 years a mean bias value for each altitude, which is subsequently subtracted from the data. The nature of the bias is likely related to tiny pointing offsets of the system. These radars were installed almost two decades ago, and at this time, no one ever thought about absolute pointing accuracy. Such bias corrections are common in remote sensing and often are instrument-related. We expanded this section and added these details to the revised manuscript. We also compared the bias correction for the climatology and obtained the same numbers as for the 5-year data. The magnitude of the vertical winds as well as the seasonal behaviour is discussed in the context of trace gas measurements presented in Yue and Wang (2025).*

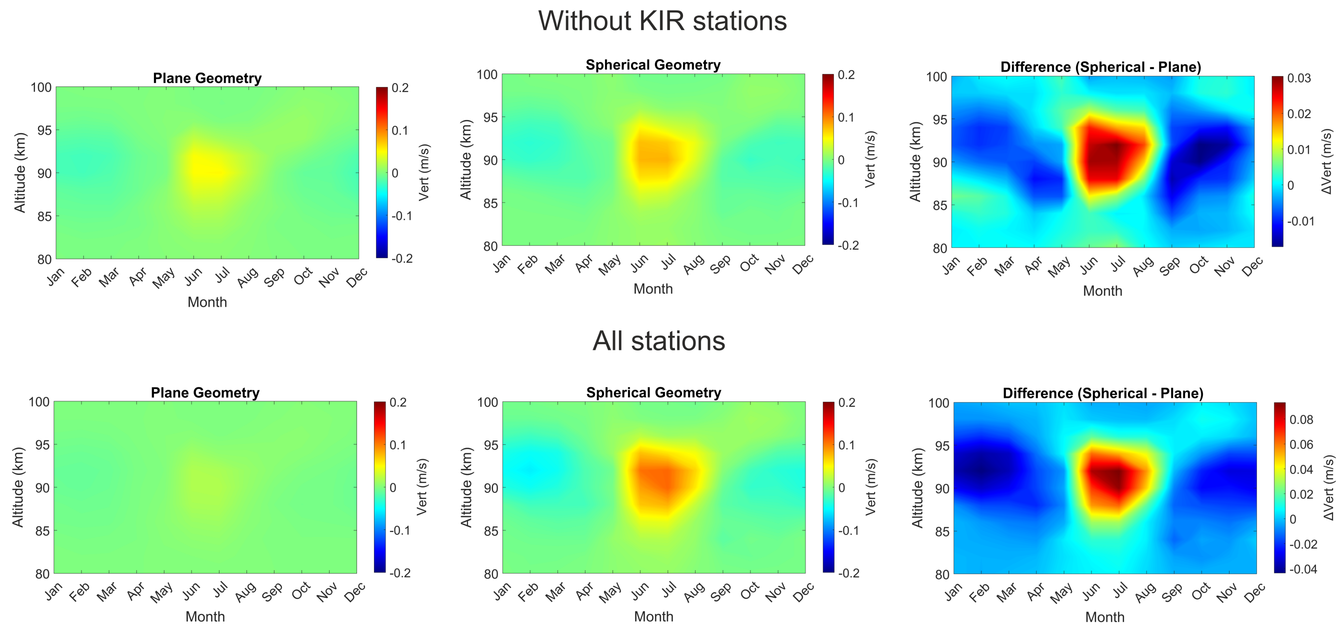

Figure 1. Monthly mean vertical wind components retrieved using the Volume Velocity Processing (VVP), showing the spherical geometry, plane geometry, and their corresponding differences for the experiment with all stations (bottom row) and without the KIR station (top row).

Reviewer Comment: 4. Lack of uncertainty characterization and scale-dependent analysis

The manuscript does not adequately characterize retrieval uncertainty, effective resolution, or recoverable scales.

Many conclusions are based on differences in vertical wind magnitude, smoothness, divergence, and temporal variability. However, the manuscript does not establish which spatial and temporal scales can be reliably reconstructed by either method. Consequently, it is difficult to determine whether the reported differences reflect improved physical reconstruction, changes in effective filtering, or different regularization behavior.

In particular, the manuscript does not establish the smallest recoverable scales, the scales dominated by regularization, or the scales for which the retrieval becomes unreliable.

Several issues raised by the analysis—including the interpretation of vertical-wind amplitudes, the dependence on temporal averaging, the selection of the optimal domain radius, and the comparison with 3DVAR+DIV—ultimately require a quantitative assessment of retrieval uncertainty and resolution. Without such information, the physical interpretation of the results remains ambiguous.

Response: *The manuscript presents long-term observations (5-years) and climatologies of mean winds and higher-order kinematic terms. The SVVP algorithm is meant to provide a much less computationally costly approach to derive mean flow properties. The main goals are to infer seasonal patterns and the climatological behaviour. Vertical winds are not the main narrative, but have been mentioned to discuss previous results. All small scales, including atmospheric tides and gravity waves, are filtered through the ASF2D (Baumgarten and Stober, 2019; Stober et al., 2020). Furthermore, only daily mean values are* *used to calculate the climatologies and long-term time series. This bandpass filter essentially removes all small scales and keeps only the mean flow and planetary waves. The manuscript does not make any claims about small scales or resolvable waves. Small-scale features will remain the key aspect for the more advanced retrievals, such as 3DVAR, 3DVAR+DIV, or sub-versions of these approaches, including machine learning techniques. The seasonal patterns are reproduced for all resolutions within the error margins. The error scales with* $1/\sqrt(n)$*. Where* n *is the number of independent measurements. In this paper, we have no intention to investigate small-scale gravity waves or tides. The 3DVAR+DIV algorithm and also the standard retrievals have proven to reproduce the Hunga Tonga gravity wave and its global propagation (Stober et al., 2023, 2024; Vadas et al., 2023b, a). However, this is not a topic here and beyond the scope of the paper. We further illustrate in the revised manuscript the error propagation by showing examples of residual fits with error bars for each meteor within one time-altitude bin for planar and spherical geometry.*

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