



Comparison of tomographic wind retrievals with different geometric implementations for multistatic meteor radar networks

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Abstract. A growing number of multistatic meteor radar networks are being established worldwide. The multistatic geometry with overlapping observation volumes of several meteor radars or passive receivers permits the inference of higher-order kinematic properties of the wind field or even the retrieval of arbitrary wind fields using tomographic algorithms. Furthermore, there is the long-standing question of the reliability of the vertical wind. In this study, we present a novel Volume Velocity

- 5 Processing in spherical coordinates and perform an initial cross-comparison to previous implementations of the Volume Velocity Processing and the advanced 3DVAR+DIV retrieval. We performed a detailed climatological and multiyear comparison of mean winds, horizontal divergence, relative vorticity, stretching, and shearing deformation using observations of the Nordic Meteor Radar Cluster consisting of the meteor radars at Tromsø, Alta, Kiruna, and Sodankylä. Our results underscore that the spherical implementation of Volume Velocity Processing reduces/minimizes altitude-dependent biases caused by projection
- 10 errors resulting from an incomplete representation of the observation geometry in the mean horizontal and vertical winds. All algorithms exhibit a very high correlation for the mean horizontal winds, but we found substantial differences in the vertical wind velocity and for the higher-order kinematic properties between the novel algorithm and previous versions of the Volume



Velocity Processing. Furthermore, the novel algorithm reproduces a consistent seasonal pattern of the vertical velocity with upwelling during the hemispheric summer at the altitude of the zonal wind reversal and a corresponding but weaker downwelling during the winter months. The magnitudes of the vertical wind appear to be physically consistent with theoretically expected upward and downward motions and are in the order of a few cm/s. We also identified a scaling effect of the vertical wind in dependence on the temporal resolution and spatial averaging represented by a circle of influence in the new retrieval, which was confirmed by the measurement response of the 3DVAR+DIV retrieval. The most reliable vertical winds were obtained for a temporal resolution of 15-30 minutes and a spatial domain of about 200-250 km centered between all meteor radars of the Nordic Meteor Radar Cluster.

1 Introduction

The mesosphere and lower thermosphere (MLT) covers altitudes of approximately 70 to 120 km and serves as a key transitional region between the upper and middle atmosphere, which is influenced by forces from above, such as high-energy inputs from solar radiation, and from below through atmospheric waves (Liu, 2016; Plane et al., 2023). This region exhibits complex spatiotemporal dynamics primarily driven by atmospheric waves with different spatiotemporal scales, including gravity waves, tides, planetary waves, quasi-biennial oscillations, and interyear differences, that contribute to variability in the lower region of the upper atmosphere. These phenomena are crucial for understanding the general circulation of the atmosphere, as the propagation and dissipation of these waves transport energy and momentum horizontally and vertically (Lindzen, 1981). The vertical coupling between the lower, middle, and upper atmosphere is strongly influenced by the prevailing wind fields, underscoring the importance of understanding the wind fields in the middle atmosphere (Fritts et al., 2002; Andrews et al., 1987). A comprehensive understanding of the MLT is essential to elucidate the wave-driven forcing of the upper atmosphere and the corresponding energy exchange between the upper and middle atmospheres. This wave-driven vertical coupling results in the cold summer mesopause temperatures, which can drop below 140 K at high latitudes, making the summer MLT the coldest place on Earth. The summer MLT deviates up to 100 K from the radiatively determined equilibrium temperature (Becker, 2012; Smith, 2012).

Meteoroids are extraterrestrial particles of cometary, asteroidal, or metallic composition that occasionally enter planetary atmospheres (Vondrak et al., 2008; Janches et al., 2009; Dawkins et al., 2023a). Upon entry, they are referred to as meteors. As they penetrate the atmosphere, they produce an ionized trail due to frictional heating, a phenomenon known as meteor ablation in the MLT. The capability of meteor radars to detect specular or transverse scatter reflections from meteor trails enables continuous monitoring of the MLT, allowing for measurement of various atmospheric and meteor-related parameters, including mean winds and wind fluctuations (momentum flux), neutral air density variability, temperature, and pressure, as well as all parameters associated with meteoroid origin such as the velocity, mass and source radiant (see e.g., Manning et al. (2006),



Hook (1970), Holdsworth et al. (2004), Fritts et al. (2010), Hocking et al. (2001), de Wit et al. (2014), Yi et al. (2019); Hall
45 and Tsutsumi (2020), Wilhelm et al. (2019), Kozlovsky et al. (2025), Hindley et al. (2022), Reid (2024), Stober et al. (2012b),
Dawkins et al. (2023b), He et al. (2024), Dawkins et al. (2023a) among others).

During the past decades, Meteor radars have evolved into reliable and robust instruments for atmospheric measurements at the
MLT, capable of continuous, automated, and remote operations, functioning uninterrupted as long as a power supply is avail-
able, regardless of weather conditions. A typical monostatic meteor radar measures horizontal winds with a temporal resolution
50 of about 1 hour, based on a limited number of meteor detections. However, increasing the number of meteors detected within
a given spatial volume and time interval improves both accuracy and resolution of the wind measurement, as achieved with
multi-static meteor radar networks. Such multistatic meteor radar networks can achieve temporal resolutions of a few minutes
(Stober et al., 2023; Qiao et al., 2025).

Over the past five years, several multistatic meteor radar networks have become operational, offering an unprecedented oppor-
55 tunity for observing atmospheric dynamics in three dimensions. These multistatic systems enable the observation of a standard
atmospheric volume, which is ideal for inferring the spatial variability of three-dimensional (3D) winds by utilizing advanced
statistical inversion methods and tomographic approaches, such as algebraic least squares fits based on the Volume Velocity
Processing (VVP) introduced by Waldteufel and Corbin (1979), which was later applied in various studies (e.g., Stober and
Chau (2015), Chau et al. (2017); Conte et al. (2025) and Zeng et al. (2024).) and more sophisticated Bayesian approaches
60 such as the 3DVAR+DIV retrieval algorithms (Stober et al., 2021a, 2022; Qiao et al., 2025) or other Bayesian implementations
(Volz et al., 2021).

The Volume Velocity Processing (VVP) retrieval method is an advancement of the earlier so-called Velocity Azimuth Display
(VAD) method (Browning and Wexler, 1968). Both approaches apply an appropriate fitting procedure to infer mean winds
and to obtain a first-order approximation of the spatial variability of the flow field, under the assumption that these inhom-
65 geneities can be linearly approximated (Browning and Wexler, 1968; Waldteufel and Corbin, 1979; Stober and Chau, 2015;
Zeng et al., 2024). However, when the MLT winds are assumed to be arbitrary, this method encounters a limitation that can be
overcome using the three-dimensional variational (3DVAR) algorithm implemented as part of the Agile Software for Gravity
wave Regional Dynamics (ASGARD) framework, demonstrating that non-linear error propagation, Gaussian weighting, and
smoothness regularization can be applied to derive horizontal wind components (Stober et al., 2021a). The 3DVAR resolves 3D
70 wind fields across all grid cells, incorporating variable geographic and Cartesian coordinate grids. The 3DVAR+DIV method
is an advancement of the 3DVAR algorithm (Stober et al., 2022, 2023; Qiao et al., 2025), combining the radial velocity obser-
vations with the continuity equation. This method represents a transition from purely observation-driven parameter estimation
to more physics and model-based data analysis.

In this study, we present statistics from the Nordic Meteor Radar Cluster (NORDIC) observations covering the period from
75 January 2021 to June 2025, along with a Spherical Velocity Volume Processing (SVVP) method based on spherical geometry
and a first-order approximation of the ellipsoidal shape of our Earth. We developed this novel algorithm to reduce biases in the
estimated vertical winds, which are crucial for inferring reliable momentum fluxes and assessing the mean vertical motion due
to the residual circulation. We compare the newly developed SVVP with a previous VVP routine to highlight the importance



of spherical geometry on derived parameters, including mean 3D winds, horizontal divergence, relative vorticity, stretching, and shearing deformation. We also perform a comparison to the Bayesian 3DVAR+DIV retrieval algorithm to investigate the temporal and spatial variability of the three-dimensional wind field in the MLT. The comparison focuses on statistical analyses, including an initial assessment of vertical winds, which are constrained by the continuity equation and horizontal divergence. This paper is structured as follows. In Section 2, we present the data description and statistical overview. Section 3 introduces the Volume velocity Processing on a sphere. Section 4 presents the results of wind climatology and statistical analysis. Section 5 provides the discussion. Finally, Section 6 summarizes our conclusions. We also provide supplementary material containing additional results for all radii and temporal scales of the VVP analysis.

2 Nordic Meteor Radar Cluster

In this study, we utilize observations from the Nordic Meteor Radar Cluster (NORDIC). A multi-static radar network of meteor radars located across Northern Scandinavia that consists of five mono-static meteor radars namely, Tromsø (69.59° N, 19.2° E; TRO), Alta (70.0° N, 23.3° E; ALT), Sodankylä (67.4° N, 26.6° E; SOD), Kiruna (67.9° N, 21.1° E; KIR), Svalbard (78.2° N, 16.0° E; SVA). However, for this study, we only use the mainland systems, and the Svalbard meteor radar was omitted. The period that is analyzed spans from January 2021 to June 2025. Figure 1 and Table 1 illustrate the geographical locations of the four meteor radar stations and the technical parameters of the NORDIC Meteor Radar Cluster.

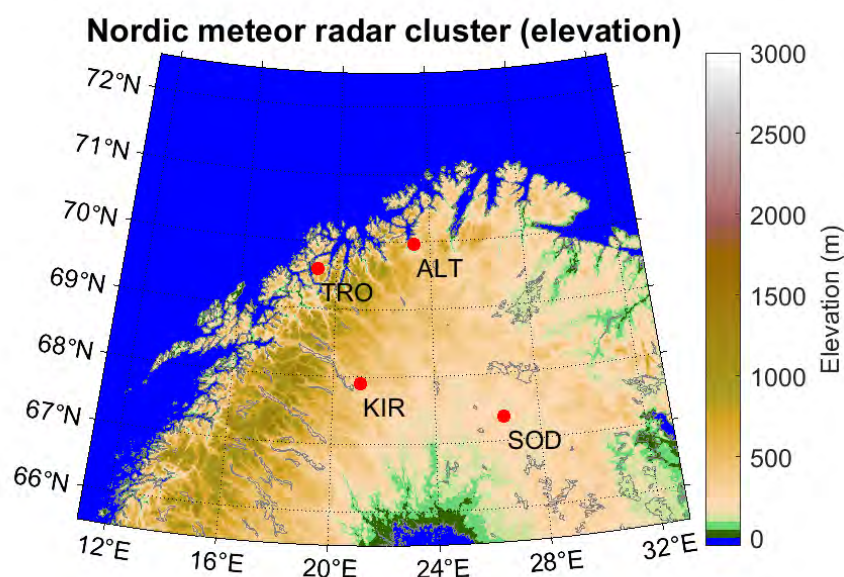


Figure 1. Nordic Meteor Radar Cluster locations at TRO, ALT, KIR, and SOD (red dots). The plot is generated with etopo1 using the m_map package (Amante and Eakins, 2009).



	Frequency (MHz)	Peak Power (kW)	PRF (Hz)	Coherent Integrations	Pulse Form/Code	Sampling (km)
TRO	30.25	7.1	400	4	4-bit complementary	1.5
ALT	31.00	10.1	440	4	4-bit complementary	1.8
KIR	32.55	6/15	2144/625	4	mono/7-bit Barker	2/1.5
SOD	36.90	7.5/15	2144	4	mono	2

Table 1. Operational Parameters of the NORDIC Meteor Radar Cluster network. PRF describes the Pulse Repetition Frequency. The MR located at Kiruna was updated on 18th March 2024 and has been operating with new experiment parameters since then. In September 2009, the Sodankylä MR was upgraded to a 15 kW transmitter.

Figure 2 presents the two-dimensional (2D) horizontal distribution of meteors detected by the radar stations (indicated by color-coded dots) recorded over three days (1-3 April 2021), along with the altitude distribution for the entire study period.

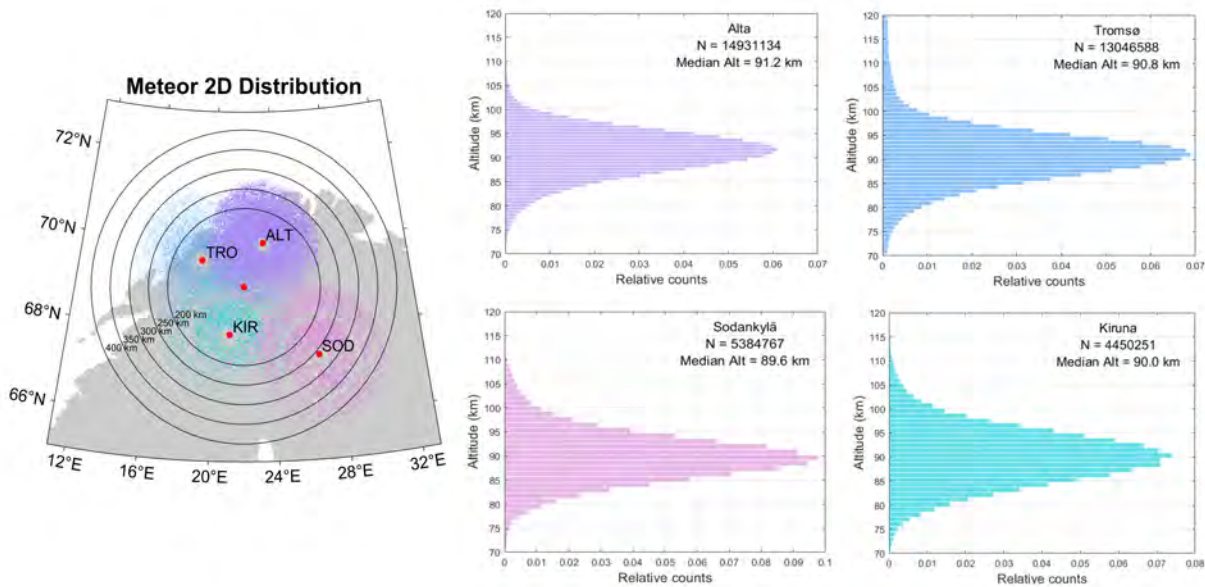


Figure 2. The 2D Horizontal distribution of meteor positions detected by the meteor radar stations (indicated with color-coded dots) from 1 - 3 April 2021, with each point representing a detected meteor. Red dots indicate station locations, with their labels identifying each station; the unlabeled dot marks the central reference point used for the SVVP retrievals. The concentric rings represent distance in km from this central reference point. The altitude distribution of meteors detected at each station is also shown, indicating the total number of meteors observed during the study period (January 2021 - June 2025) and the corresponding median altitude for each station. The colors blue, Cyan, purple, and magenta correspond to meteors detected at TRO, ALT, KIR, and SOD stations, respectively.

The scatter plot on the map illustrates the spatial distribution of meteor echoes, with colors representing the meteor echoes for each station: blue for Tromsø, purple for Alta, cyan for Kiruna, and magenta for Sodankylä. The stations exhibit overlapping



coverage regions, with TRO, ALT, and KIR showing substantial overlap with each other compared to SOD, although SOD partially overlaps with KIR. The altitude distributions approximately shows a Gaussian profile within the altitude range of 70–120 km, peaking around 90 km for all stations, with median altitudes of 90.8 km for TRO, 91.2 km for ALT, 90.0 km for KIR, and 89.6 km for SOD. Among all the stations, it is observed that the Alta radar station detected the highest meteor count, followed by Tromsø, Sodankylä, and Kiruna.

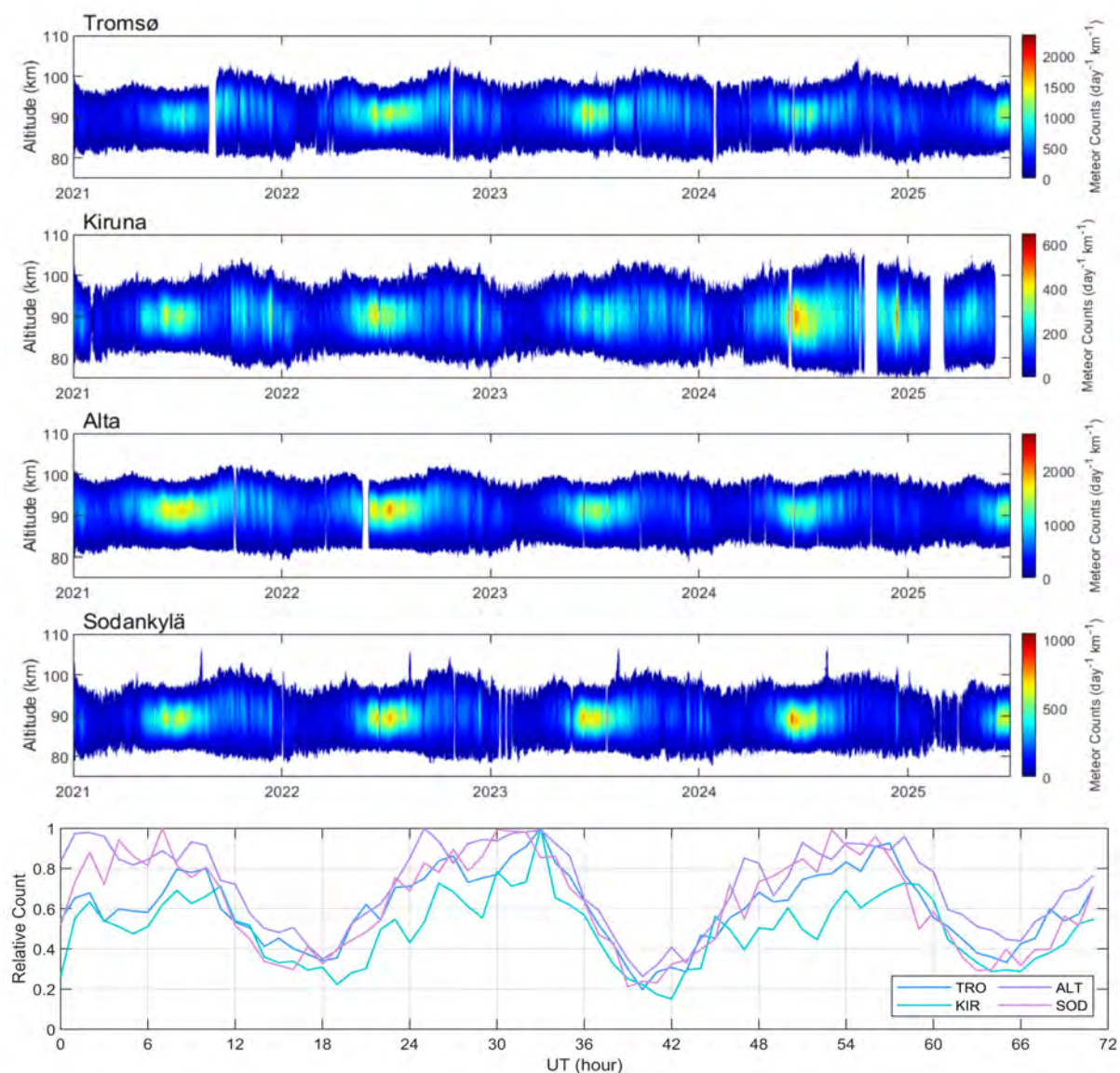


Figure 3. Altitudinal profile of daily meteor echoes detected by all four meteor radars. The lower stair-step diagram illustrates the hourly temporal distribution of meteors from April 1-3, 2021. The four colors have the same meaning as in the previous figure.



The altitudinal profile of the long-term changes in the detected meteor echo rates for all stations during the study period, along
105 with the hourly distribution of meteors for 3 days (1-3 April), is illustrated in Figure 3. A distinct inter-annual variation pattern
is revealed, with a pronounced change in the number of meteor echoes with altitude and season. Meteor echoes are detected
between the altitudes of 82 km 95 km and during the summer months for all the radar stations. The white lines represent gaps
in the measurements of a system. In particular, the update in Kiruna in 2024 resulted in a gap, and a second gap occurred
in 2025. The temporal distributions of selected days exhibit a similar trend, showing a diurnal variation, reaching maximum
110 values in the morning (8–10 UTC) and minimum values in the evening (17–19 UTC).

The wind components in the MLT region are obtained using the 3DVAR+DIV algorithm with geographic grid coordinates
(Stober et al., 2022) and the novel spherical VVP algorithm described in the next section. The retrievals have temporal resolu-
tions of 15min, 30min, and 1h, covering altitudes from 70 to 110 km with a vertical resolution of 2 km. The horizontal domain
(radius) implemented in the new spherical VVP algorithm was varied from 200 to 400 km in steps of 50 km. Unless otherwise
115 specified, the reference results presented in this study correspond to the 250 km horizontal domain for the VVP method and
a 30-minute temporal resolution for both algorithms. For the 3DVAR+DIV retrievals, the Tikhonov regularization parameter
(α) of 0.4 and 150 was used to assess their impact on the derived wind fields. The complete set of results is presented as
Supplementary material.

3 Derivation of Volume Velocity Processing on a Sphere

120 Over the past decade, Volume Velocity Processing (VVP) has become a more commonly used approach to assess spatial wind
variability in multistatic meteor radar observations (Stober et al., 2013; Stober and Chau, 2015; Chau et al., 2017; Zeng et al.,
2024). Additionally, the basic idea of the VVP remains consistent with the original publications from Browning and Wexler
(1968); Waldteufel and Corbin (1979). However, the implementation of the algorithm can become more complicated when
describing larger domain areas (Stober et al., 2021a; Qiao et al., 2025; Zeng et al., 2024), which can extend horizontally to sev-
125 eral hundred kilometers. Here, we will outline the most recent version of our VVP implementation. The revised version builds
on previous developments presented in Zeng et al. (2024), but is now generalized to spherical coordinates and incorporates
higher-order corrections to account for the ellipsoidal shape of the Earth, and not only considers the WGS84 model for each
measurement, but also the spherical geometry for the observation volume.

Recalling the original form of the VVP for plane geometry presented in Waldteufel and Corbin (1979), we can express the wind
130 field by a Taylor expansion consisting of mean zonal, meridional, and vertical wind components and first-order deviations given
by linear spatial derivatives;

$$\begin{aligned} u(x, y) &= u_0(x_0, y_0) + \frac{\partial u}{\partial x} \cdot \Delta x + \frac{\partial u}{\partial y} \cdot \Delta y \\ v(x, y) &= v_0(x_0, y_0) + \frac{\partial v}{\partial x} \cdot \Delta x + \frac{\partial v}{\partial y} \cdot \Delta y \\ w(x, y) &= w_0(x_0, y_0) . \end{aligned} \tag{1}$$



135 Here u , v , and w correspond to the zonal, meridional, and vertical wind components, respectively. The subscript 0 indicates the domain reference coordinate (x_0, y_0) , which is a free parameter that can be arbitrarily selected. However, it turns out that the domain center appears to be a good choice. Thus, $\Delta x = x - x_0$ and $\Delta y = y - y_0$ measure the distance to any coordinate (x, y) . After a mathematical expansion and rearranging the horizontal derivatives, the first-order kinematic inhomogeneities of any linear or non-linear wind field can be approximated by the horizontal divergence, the relative vorticity, and the stretching and shearing deformation;

$$\begin{aligned}
 u &= u_0 + \underbrace{\frac{1}{2} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \cdot \Delta x}_{\text{hor. divergence}} - \underbrace{\frac{1}{2} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \cdot \Delta y}_{\text{rel. vorticity}} + \underbrace{\frac{1}{2} \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right) \cdot \Delta x}_{\text{stretching def.}} + \underbrace{\frac{1}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \cdot \Delta y}_{\text{shearing def.}} \\
 v &= v_0 + \underbrace{\frac{1}{2} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \cdot \Delta y}_{\text{hor. divergence}} + \underbrace{\frac{1}{2} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \cdot \Delta x}_{\text{rel. vorticity}} - \underbrace{\frac{1}{2} \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right) \cdot \Delta y}_{\text{stretching def.}} + \underbrace{\frac{1}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \cdot \Delta x}_{\text{shearing def.}} .
 \end{aligned} \tag{2}$$

The advantage of these higher-order kinematic terms is that they can be linked to other dynamic parameters, which are more intuitive for dynamic flow fields than the spatial derivatives alone. Furthermore, horizontal divergence is related to the vertical velocity, which is often more difficult to measure. Assuming incompressibility of the atmosphere permits reducing the continuity equation to the following expression (Stober et al., 2022);

$$\text{div}(\mathbf{u}) = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 . \tag{3}$$

The change of the vertical velocity Δw between two layers can then be derived by vertical integration of the horizontal divergence;

$$\Delta w = \int_{z_1}^{z_2} \text{div} \cdot v_h \, dz . \tag{4}$$

This vertical velocity profile depends on the boundary condition of the integral, which has to be determined separately. However, the method was often implemented for the data analysis of meteorological wind profilers in the troposphere. In these cases, the initial surface boundary condition for the vertical wind is zero. Furthermore, the Cartesian coordinates and plane geometry are sufficiently accurate for the small measurement domains typically covered by wind profilers, allowing for the reliable measurement of horizontal divergence and, thus, the inference of vertical winds.

However, multistatic meteor radar networks cover much larger domain areas extending over hundreds of kilometers, and, therefore, it is crucial to consider and represent the Earth's ellipsoidal geometry in the retrievals (Stober et al., 2018, 2021a). In particular, vertical winds are very sensitive to projection errors. Tomographic retrievals, such as the 3DVAR and 3DVAR+DIV algorithms, approximate the Earth's ellipsoid shape by the World Geodetic System 84 (WGS84) reference ellipsoid (National Imagery and Mapping Agency, 2000). The horizontal divergence is inferred by calculating the distance between grid cells in zonal and meridional directions to estimate the spatial derivatives, accounting for the change in the Earth's radius with latitude. A similar method was implemented in a revised VVP algorithm dedicated to larger domain meteor radar networks presented



in Zeng et al. (2024). Including the WGS84 geometry seems to be reliable up to scales of a few tens of kilometers. However,
 165 for much larger domains, the horizontal divergence and, thus, the vertical velocity, tend to produce more spurious results.
 Here, we introduce a new VVP based on local spherical coordinates to account for the latitude-dependent change of the Earth's
 radius. In contrast to previous routines, we outline in detail the basic steps and derive the key transformations that facilitate
 a comparison with the kinematic terms expressed in Cartesian coordinates, as shown in Eq. 3. Coordinates on a sphere are
 defined by a radius r , an azimuth ϕ , and a colatitude from the North Pole $\theta = 90^\circ - \Phi$ for a given latitude Φ . For all further
 170 derivations, we will keep the mathematical convention. Furthermore, we define the zonal and meridional wind components as
 $\dot{\phi}$ and $\dot{\theta}$, respectively. The vertical velocity is given by $\dot{r}$. The conversion to the well-known Cartesian vector winds in the ENU
 (East-North-Up) frame of reference is given by;

$$\begin{aligned} u &= r \sin \theta \dot{\phi} \\ v &= -r \dot{\theta} \\ 175 \quad w &= \dot{r} \end{aligned} \quad (5)$$

Furthermore, we need to transform the spatial derivatives into spherical coordinates. It is worth noting that the derivative also
 acts on the basis vectors. Recalling that a geometric object (vector) is independent of the coordinate system, leading to the
 identity for any given wind vector in the form;

$$u \cdot e_x + v \cdot e_y + w \cdot e_z = \mathbf{u} = \dot{r} \cdot e_r - r \dot{\theta} \cdot e_\theta + \sin \theta r \dot{\phi} \cdot e_\phi. \quad (6)$$

180

Here, (e_x, e_y, e_z) is the basis vector in Cartesian coordinates and (e_r, e_θ, e_ϕ) denotes the basis vector in spherical coordinates.
 Considering the additional contributions of the derivatives due to the basis vectors, we can write the spatial derivative terms of
 our wind vector in spherical coordinates as;

$$\frac{\partial u}{\partial x} \cdot e_x = \frac{\partial \dot{\phi}}{\partial \phi} \cdot e_\phi \quad (7)$$

$$185 \quad \frac{\partial u}{\partial y} \cdot e_y = \left(2\dot{\phi} \cdot \cos \theta + \sin \theta \cdot \frac{\partial \dot{\phi}}{\partial \theta} \right) \cdot e_\theta \quad (8)$$

$$\frac{\partial v}{\partial x} \cdot e_x = -\frac{1}{\sin \theta} \frac{\partial \dot{\theta}}{\partial \phi} \cdot e_\phi \quad (9)$$

$$\frac{\partial v}{\partial y} \cdot e_y = \left(-\frac{\partial \dot{\theta}}{\partial \theta} - \dot{\theta} \cdot \cot \theta \right) \cdot e_\theta \quad (10)$$

Furthermore, the Δx and Δy terms have to be expressed in spherical geometry as well. We calculate the distance of the
 190 arc-segment between two geographic points using the WGS84 reference ellipsoid as implemented in Zeng et al. (2024);

$$\begin{aligned} \Delta x &= r_m \cdot \sin \theta_m \Delta \phi = r_m \sin \theta_m (\phi - \phi_0) \\ \Delta y &= r_m \Delta \theta = r_m (\theta - \theta_0) \end{aligned} \quad (11)$$



Here r_m and θ_m denote the mean Earth radius and mean zenith distance considering the reference geographic location in spherical coordinates (ϕ_0, θ_0) and any other geographic position expressed in zenith distance/co-latitude (ϕ, θ) (mathematical convention). These coordinates are related to the well-known geographic latitude by $\Phi = 90 - \theta$ and ϕ corresponds to the longitude λ . We can now rewrite eq. 1 in spherical coordinates and approximate the ENU vector wind (u, v, w) at geographic coordinates (long, lat) by the following set of equations;

$$\begin{aligned} u(\lambda, \Phi) &= u_0(\lambda_0, \Phi_0) + \frac{\partial \dot{\phi}}{\partial \phi} r_m \sin \theta_m \Delta \phi - \sin \theta_0 \cdot \frac{\partial \dot{\phi}}{\partial \theta} r_m \Delta \theta + 2u_0 \cdot \frac{\cos \theta_0}{r_0 \sin \theta_0} r_m \Delta \theta \\ v(\lambda, \Phi) &= v_0(\lambda_0, \Phi_0) - \frac{1}{\sin \theta_0} \frac{\partial \dot{\theta}}{\partial \phi} r_m \sin \theta_m \Delta \phi + \frac{\partial \dot{\theta}}{\partial \theta} r_m \Delta \theta + v_0 \cdot \frac{\cot \theta_0}{r_0} r_m \Delta \theta \\ w(\lambda, \Phi) &= w(\lambda_0, \Phi_0) . \end{aligned} \quad (12)$$

Here, we have already introduced some additional sign conventions. The colatitude is defined with opposite sign compared to the meridional wind, and we replaced the angular velocity with the 3D Cartesian local vector winds in the ENU frame of reference. This step is not trivial, and we cross-checked all terms by comparing them to the standard VVP and by performing the derivation in latitudinal spherical coordinates. Transforming the VVP from Cartesian into spherical coordinates, which are more appropriate for the larger domain size typically covered by multistatic meteor radar networks, results in additional terms. The mean winds have an additional contribution due to the latitudinal extent of the observational domain. The resulting set of equations using latitude as a reference is given in Appendix A. The meridional spatial derivatives for the zonal and meridional gradients depend on the mean zonal and meridional wind as well. The above-presented solutions apply to meteor radar networks at high, mid-, and low latitudes in the Northern Hemisphere. However, there is a singular term in the meridional wind equation that results in two singularities, one at each pole. From eq. A6, we can also calculate the corresponding expression of the horizontal divergence $(\nabla_h \mathbf{u})$, and relative vorticity $(\nabla \times \mathbf{u})_r$ in spherical coordinates;

$$\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = \nabla_h \cdot \mathbf{u} = \left(\frac{\partial \dot{\phi}}{\partial \phi} + \frac{\partial \dot{\theta}}{\partial \theta} - v_0 \cdot \frac{\cot \theta}{r_0} \right) \quad (13)$$

$$\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) = (\nabla \times \mathbf{u})_r = \left(\frac{1}{\sin \theta} \frac{\partial \dot{\theta}}{\partial \phi} - \sin \theta \cdot \frac{\partial \dot{\phi}}{\partial \theta} + 2u_0 \cdot \frac{\cos \theta}{r_0 \sin \theta} \right) , \quad (14)$$

and the stretching and shearing deformation;

$$\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right) = \left(\frac{\partial \dot{\phi}}{\partial \phi} - \frac{\partial \dot{\theta}}{\partial \theta} + v_0 \cdot \frac{\cot \theta}{r_0} \right) \quad (15)$$

$$\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) = \left(\frac{1}{\sin \theta} \frac{\partial \dot{\theta}}{\partial \phi} + \sin \theta \cdot \frac{\partial \dot{\phi}}{\partial \theta} - 2u_0 \cdot \frac{\cos \theta}{r_0 \sin \theta} \right) . \quad (16)$$

Considering that line-of-sight velocities or radial velocities are always measured in the ENU frame of reference for each MR, we implemented a fitting scheme around the variables $u_0, v_0, w_0, \frac{\partial \dot{\phi}}{\partial \phi}, \frac{\partial \dot{\phi}}{\partial \theta}, \frac{\partial \dot{\theta}}{\partial \phi}$, and $\frac{\partial \dot{\theta}}{\partial \theta}$ and calculated the higher-order kinematic terms from the obtained coefficients. A crucial aspect of the solver is the dependency of the gradient terms on the mean winds, or that the mean wind also contributes to the gradient. Our choice of the fitting coefficients in spherical coordinates avoids solving a nonlinear problem.



Besides formulating the mathematical equations in spherical coordinates, we keep the nonlinear error propagation for all coefficients and also the generalized Tikhonov regularization, which was used in previous implementations (Stober et al., 2022; Zeng et al., 2024; Lieberman et al., 2025). The nonlinear error propagation includes the line-of-sight velocity uncertainty from the recorded data, an angular uncertainty of 2° for the zenith and azimuth angle, and the temporal and spatial shear terms as introduced in Stober et al. (2018); Gudadze et al. (2019); Hindley et al. (2022). The nonlinear error propagation is solved iteratively, as the mean wind directly scales the angular uncertainties. More details are provided in Appendix B.

The Tikhonov regularization remains valid also for the spherical coordinate implementation to obtain reliable vertical velocities.

We calculate a predictor from the grid cells above and below a reference coordinate in altitude as well as in time, using a time step before and after. This regularization approach helps to cure ill-conditioned spatial sampling. However, the vertical wind shows a much better agreement between the direct Doppler-derived vertical velocity and the horizontal divergence-inferred vertical wind, providing confidence in the overall reliability of the implementation. The climatologies and long-term measurements presented in the results section are based on the Doppler-derived measurements, as a detailed analysis of the divergence-estimated vertical winds is beyond the scope of this paper. The divergence estimated vertical winds require a lower or upper integration boundary, which is not straightforward to implement.

We also determine a mean seasonal or long-term vertical wind bias based on the considerations presented in Rodgers (2000). The underlying assumption is that multi-year or long-term vertical winds should have a vanishing mean. Considering that even a mean deviation in the vertical wind of 1 mm/s over one year would result in enormous vertical motions of 31 km/year. Such large vertical motions of air packages are not observed nor predicted by GCMs. In this study, we estimated the bias from even longer time series. Typical bias values range from 1 to 4 cm/s and are subtracted to obtain the vertical wind speeds shown in the climatology and multi-year data.

4 Results

In this section, we first present the seasonal and monthly mean wind variations and higher-order kinematic fields in the MLT region, based on the VVP plane geometry, spherical geometry (SVVP), their corresponding differences, and the 3DVAR+DIV method. We established a common data analysis pipeline to harmonize and reduce the data, removing the geophysical variability with periods shorter than a month. We compute 31-day average zonal, meridional, and vertical daily mean winds with a boxcar for each altitude. All algorithms leverage identical nonlinear error propagation and data curation to avoid impacts on the results due to data gaps or other data filtering. The comparisons solely show the impact of the different geometries and spatiotemporal filters. The seasonal comparisons are based on a 31-day window with periodic boundary conditions. A similar procedure was applied in a previous study (Stober et al., 2021b). The median is computed when 40% of all possible measurements for a time-altitude bin are available, but a reliable monthly mean is only obtained with a data coverage of 80% or not more than 11 missing days per month. This threshold is considered the minimum required by the World Meteorological Organisation (WMO) for climatologies. All comparisons are conducted based on a 30-minute temporal resolution, with a radius of 250 km for the SVVP, as a baseline. The radius of 250 km for the SVVP appeared to provide the best overlap between all



four MR without including large blank spaces in the domain (see Figure 2).

4.1 Climatologies of Mean Winds Derived from SVVP Retrieval

First, we compare the climatological mean state of the zonal, meridional, and vertical wind components based on the newly
260 implemented SVVP algorithm (spherical geometry) with the previous VVP method (plane geometry). Figure 4 and 5 show
the seasonal wind climatology of all three wind components in the MLT in both spherical (left column) and plane geometry
(center column) with their corresponding differences (right column). The zonal (east-west) and meridional (north-south) wind
components capture the horizontal circulation pattern.

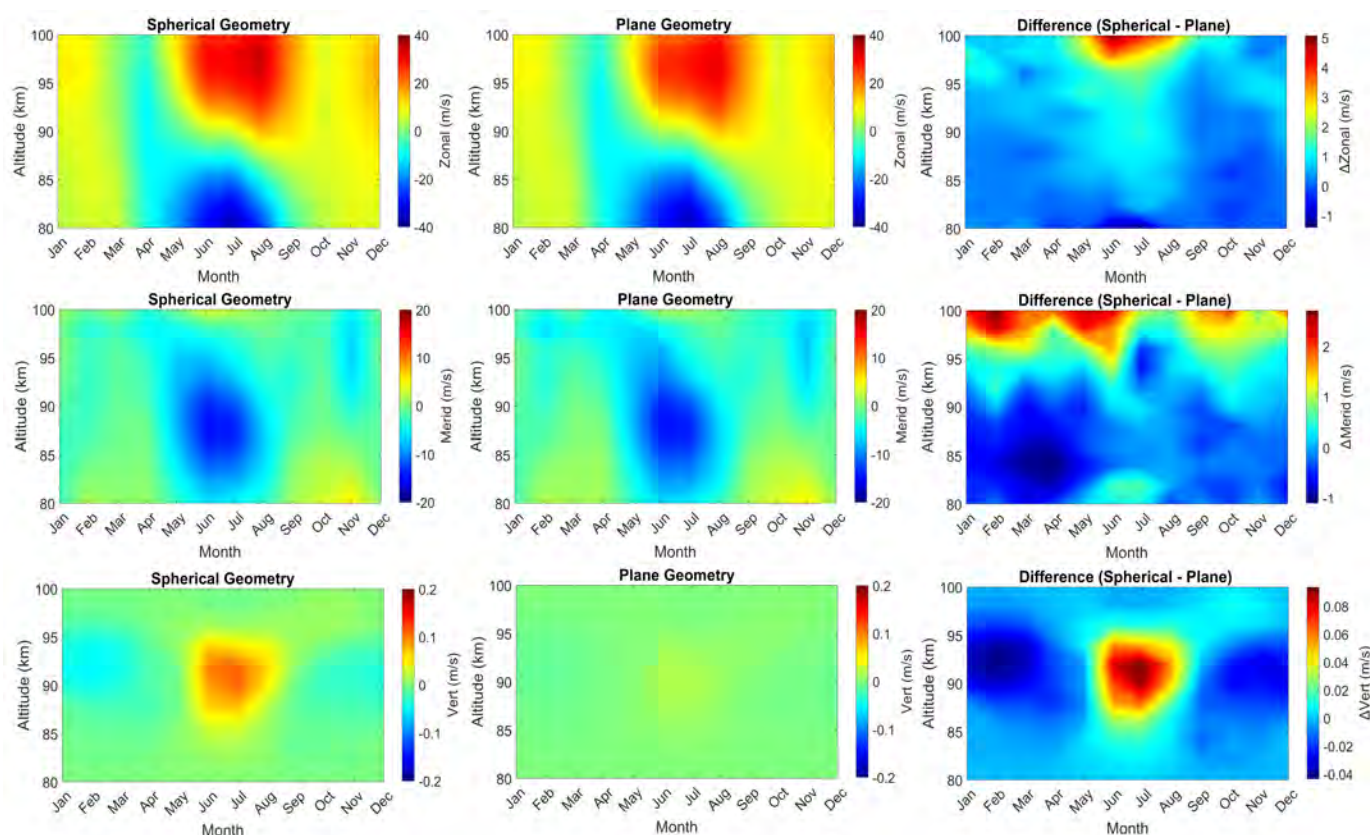


Figure 4. Monthly mean Zonal, meridional, and vertical wind components retrieved using the Volume Velocity Processing (VVP), showing the spherical geometry, plane geometry, and their corresponding differences.

Zonal winds reflect the expected seasonal behaviour with eastward winds during hemispheric winter and the characteristic
265 summer wind reversal from westward to eastward winds around 90 km. Furthermore, the zonal wind climatology captures the
spring transition (March-April) at all altitudes into westward winds during the summertime, indicating a seasonal reversal of



circulation. The opposite pattern is observed during the summer months; then, at the end of summer (late September–October), the wind shear weakens, leading to eastward winds at all altitudes. The difference plot indicates a systematic underestimate of the mean winds with altitude when using the plane geometry analysis. The eastward summer jet is underestimated by up to 5 m/s at 100 km altitude. The smallest differences between the two algorithms are found below 85 km altitude. Meridional winds also show the expected seasonal pattern with weak northward winds during winter and southward winds during the hemispheric summer. The largest differences between spherical and plane geometry are again observed at the upper altitudes of the meteor layer above 95 km, reaching almost 3 m/s. The vertical component exhibits a characteristic seasonal structure with upward and downward motions associated with large-scale atmospheric dynamics. The differences between spherical and plane geometry are in the order of 10 cm/s. Although the absolute difference appears to be small, it is considerable. Implementing the spherical geometry results in vertical wind magnitudes of about 10–12 cm/s at around 90 km altitude, corresponding to the height of the zonal wind reversal and the maximum of the meridional wind.

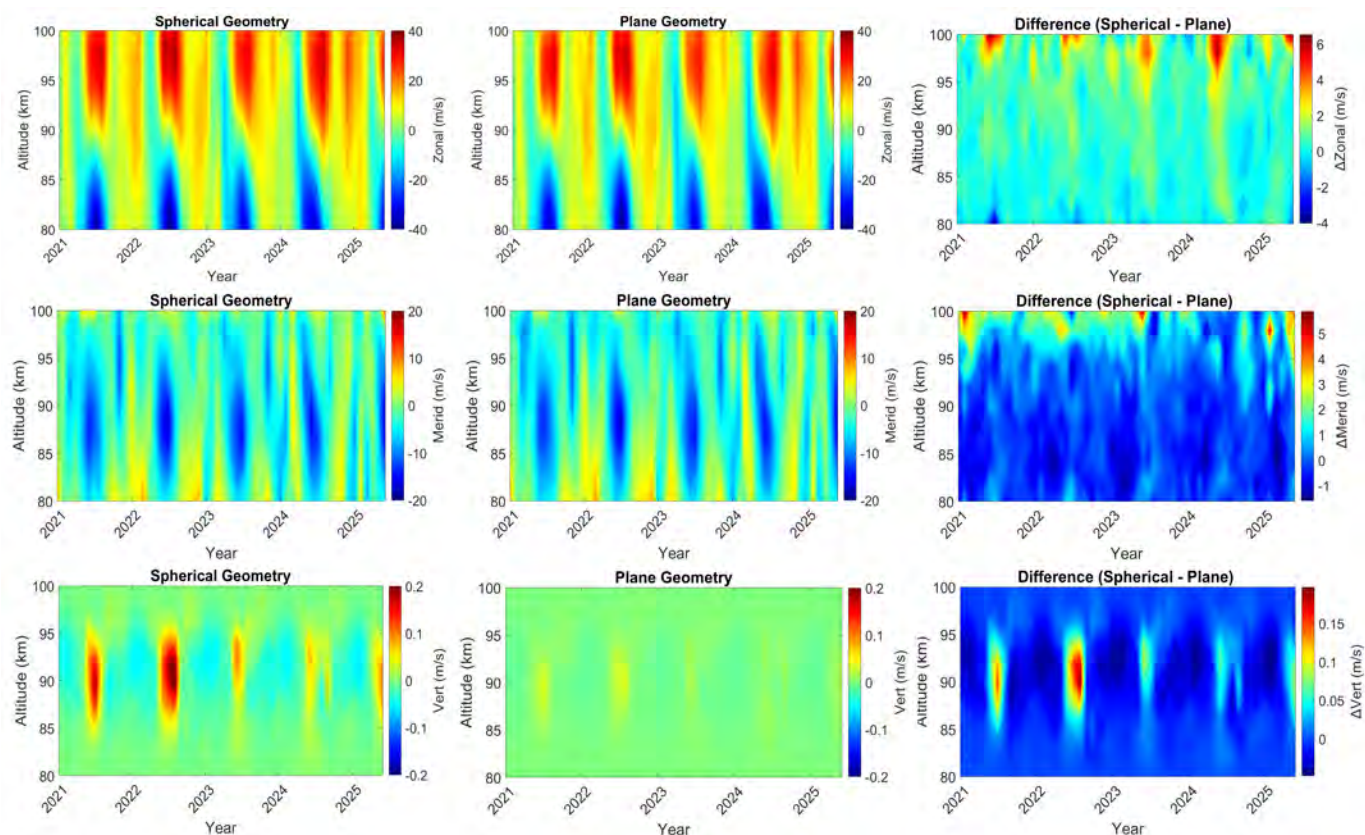


Figure 5. Seasonal mean zonal, meridional, and vertical wind components retrieved using the Volume Velocity Processing (VVP), showing the spherical geometry, plane geometry, and their corresponding differences.



We also analyzed the time series using the 31-day boxcar average for all data available from 2021 to summer 2025. The zonal, meridional, and vertical wind components exhibit the typical climatological behaviour and reveal some interannual variability. All differences between the two algorithms are also reproduced with similar magnitude over the entire time series. Most remarkable are the changes in the vertical wind magnitudes during hemispheric summer. Apparently, for the years 2021 and 2022, both algorithms obtained 30% larger wind upwelling during summer than for the other years. This increased upwelling is accompanied by stronger eastward zonal winds during the summer, whereas the years with weaker vertical winds also indicate a slightly different transition from the winter circulation to the hemispheric summer wind pattern.

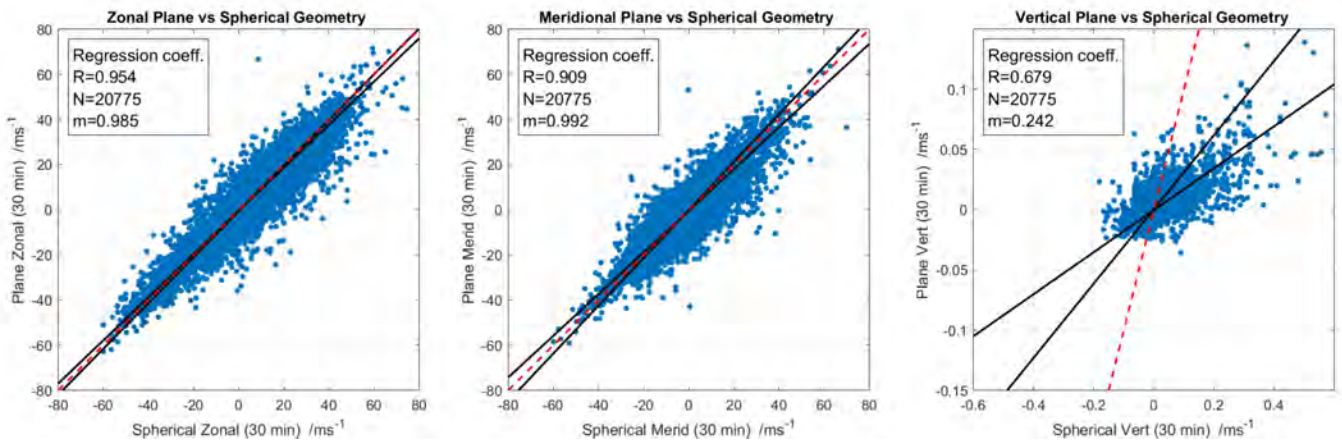


Figure 6. Correlation between the spherical geometry and plane geometry retrieved zonal, meridional, and vertical wind components using Volume Velocity Processing (VVP), based on the dataset used for figure 4 and 5. Each panel presents daily mean scatter points, robust regression fits, 1:1 reference lines, and annotated statistics (correlation coefficient (R), sample size (N), and the slope (m)).

The comparison between the spherical and plane geometries in Volume Velocity Processing (VVP) retrievals shows a strong agreement for the horizontal wind components. However, the agreement is less good for the vertical wind component. Both zonal and meridional winds exhibit a high correlation coefficient of $R = 0.954$ and $R = 0.909$, respectively, with robust regression slopes exceeding 0.98 to 0.99, which indicates that there is no substantial bias between both algorithms for these wind components. This indicates that the geometry has only a minimal but still some impact on the large-scale flow estimates. In contrast, the vertical wind component shows a moderate correlation with a correlation coefficient of $R = 0.679$ and a robust regression slope of 0.242, which reflects its great sensitivity to the geometrical assumptions and measurement uncertainties.

Figure 7 and 8 show the higher-order kinematic variables which are the horizontal divergence ($\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$), shearing deformation ($\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$), stretching deformation ($\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$), and the relative vorticity ($\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$), all within the magnitude of ± 0.1 m/s/km in both spherical and plane geometries along with their corresponding differences. These variables characterize different types of atmospheric horizontal motions, capturing divergence, eastward/westward (zonal) stretching, southwest/northeast stretching, and counter-clockwise rotation, represented as the positive values in the panels. The seasonal and annual variations are exhibited in both geometric panels, but are more pronounced in the spherical geometry than in the planar geometry, as highlighted

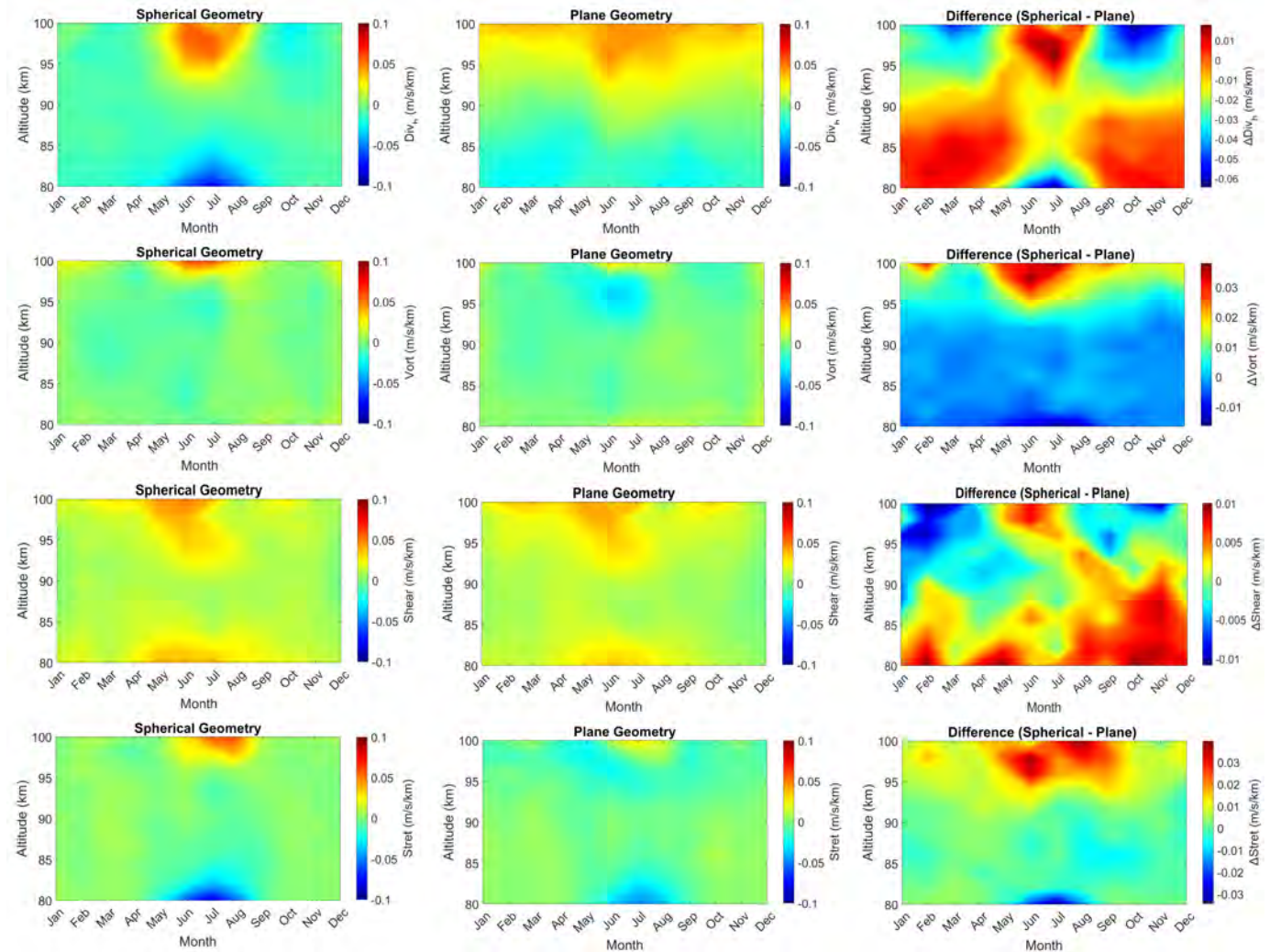


Figure 7. Monthly composites of horizontal divergence, shearing deformation, stretching deformation, and relative vorticity computed using Volume Velocity Processing (VVP), showing the spherical geometry, plane geometry with corresponding difference.

by the difference plots. Horizontal divergence is positive throughout the year at altitudes above 90 km during the mid-year (summer), pronouncedly seen in the spherical geometry, and the difference panel shows a big difference in higher altitudes above 96 km. There are high positive differences at lower altitudes during winter and negative differences during summer, just up to 94 km. Stretching deformation exhibits similar characteristics to divergence, with higher values during summer. Spherical geometric approximation shows high impact on the shearing deformation and relative vorticity variables, revealing strong biases at higher altitudes with differences exceeding $\pm 0.02 m/s/km$ during summer months. The plane geometry approximation is seen to reproduce the large-scale characteristics of the atmospheric horizontal motions, and the spherical geometry approximation introduces significant changes and corrections, indicating the impact of Earth's curvature effects in the amplification of

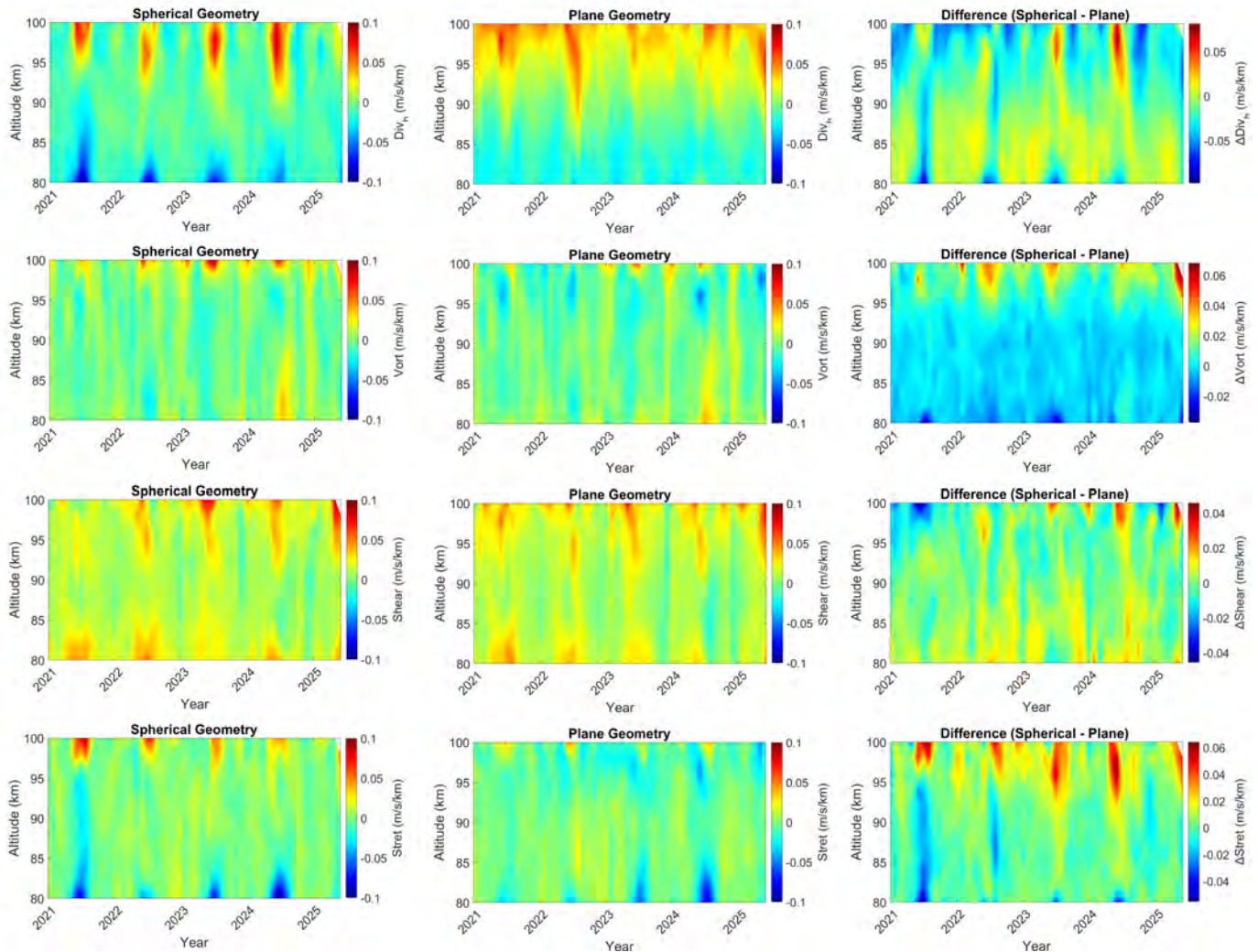


Figure 8. Seasonal composites of horizontal divergence, shearing deformation, stretching deformation, and relative vorticity using Volume Velocity Processing (VVP), showing the spherical geometry, plane geometry with corresponding difference.

seasonal and altitudinal variability.

Figure 9 presents an intercomparison correlation of daily mean zonal, meridional, and vertical wind components computed using three temporal resolutions (15, 30, and 60 minutes) under spherical geometry. The objective of this analysis is to evaluate the consistency of the simulated winds across varying temporal resolutions. Corresponding analyses for the plane geometry
310 are provided in the supplementary material. The zonal winds (left panels) exhibit a nearly perfect linear relationship across all temporal correlation comparisons, with correlation coefficients exceeding 0.96 and regression slopes almost unity ($m = 0.99$ and 1.027 for 15-30 mins and 60-30 mins, respectively). The meridional wind component (middle panels) also shows a strong correlation, though slightly weaker than the zonal wind, with a correlation coefficient close to 0.91 and regression

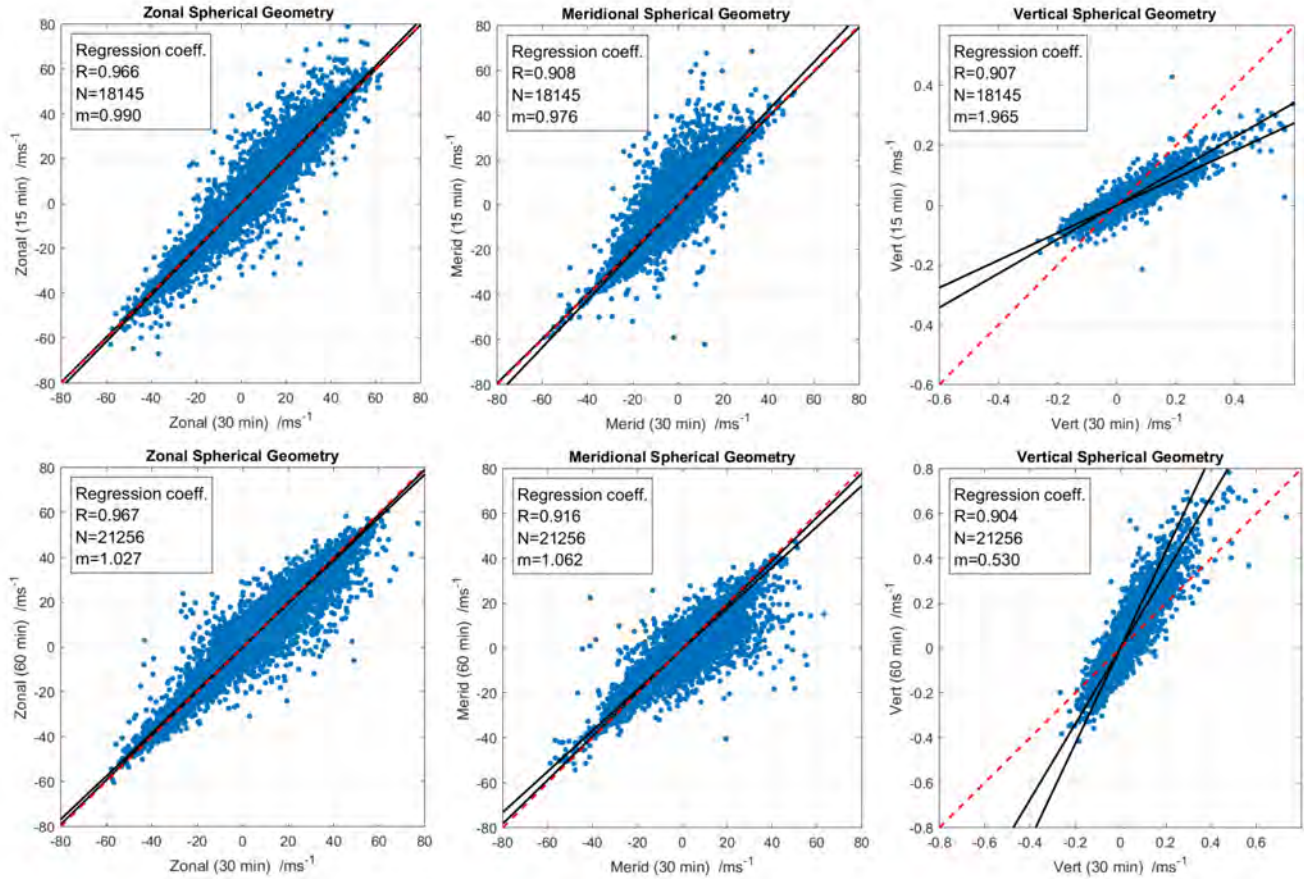


Figure 9. Correlation comparing daily mean wind velocity components (zonal, meridional, and vertical) calculated for different temporal resolutions under spherical geometry. The top row compares 15-minute and 30-minute temporal resolutions, while the bottom row compares 60-minute and 30-minute temporal resolutions. Each panel shows the daily mean scatter point, robust regression fit (black solid line), 1:1 reference line (red dashed), and statistics indicating correlation coefficient (R), number of samples (N), and regression slope (m).

slopes remaining close to 1 ($m = 0.976$ and 1.062 for 15-30 mins and 60-30 mins, respectively), indicating only minor differences between the different temporal resolution datasets. These results suggest that the zonal wind flow is well resolved, and the moderate decrease in correlation in the meridional component reflects greater small-scale variability, typically in the geophysical flows due to mesoscale and synoptic-scale fluctuations. In contrast, the vertical wind component (right panels) shows lower correlation coefficients ($R \approx 0.90$), with regression slopes markedly deviating from unity, $m = 1.965$ and 0.530 for 15-30 mins and 60-30 mins, respectively. This pronounced sensitivity to temporal resolution reflects the inherent transient nature of vertical velocities, which have very small magnitudes on seasonal scales. Vertical winds appear to be strongly influenced by small-scale gravity waves and their wave-mean flow interactions, driven by wave breaking. It is observed that shorter temporal resolutions preserve more high-frequency variability and, thus, capture more of the high-frequency gravity wave spectrum,



minimizing effects due to incomplete sampling of spatiotemporal gravity wave variability. This comparison demonstrates that while horizontal wind components (zonal and meridional) are highly consistent across temporal resolutions, the vertical wind
325 exhibits a strong dependence on geometry and temporal scale.

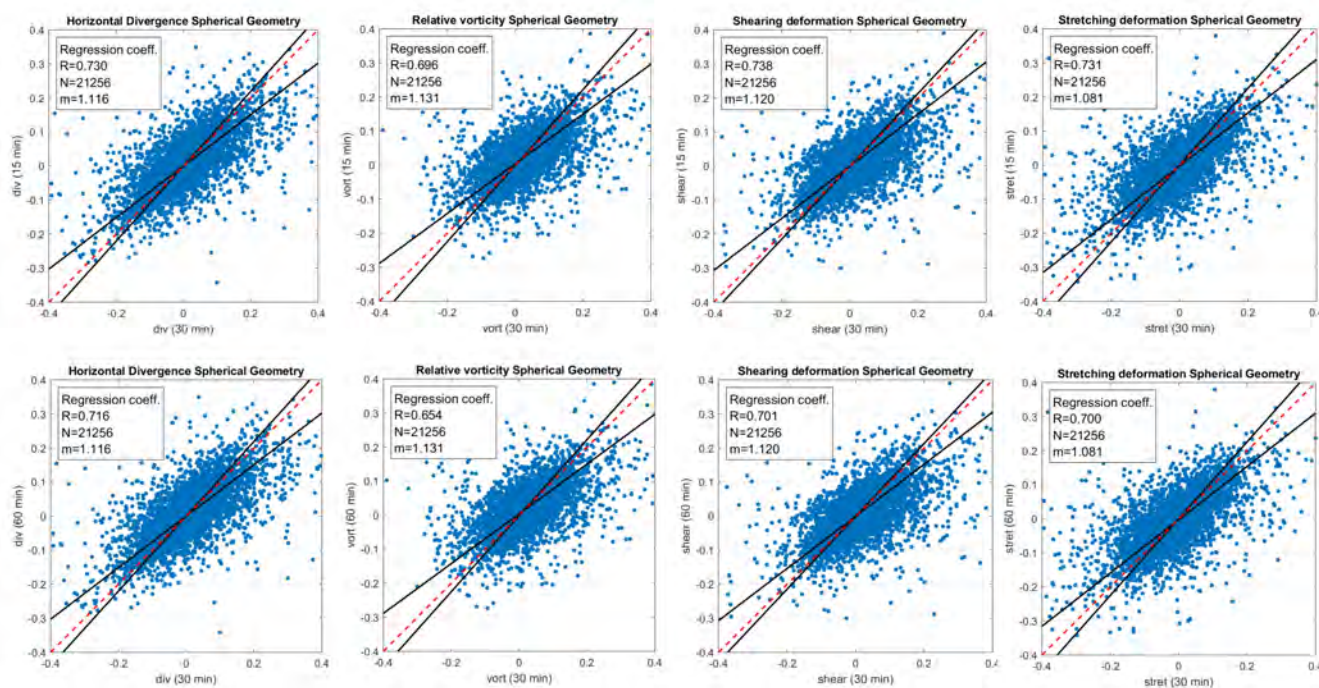


Figure 10. Comparison correlation of high-order kinematic variables; horizontal divergence, shearing deformation, stretching deformation, and relative vorticity computed for different temporal resolutions under spherical geometry. The top row compares 15-minute and 30-minute temporal resolutions, while the bottom row compares 60-minute and 30-minute temporal resolutions. Each panel shows the daily mean scatter point, robust regression fit (black solid line), 1:1 reference line (red dashed), and statistics indicating correlation coefficient (R), number of samples (N), and regression slope (m).

Figure 10 presents an intercomparison of the higher-order kinematic variables, including horizontal divergence, shearing deformation, stretching deformation, and relative vorticity components derived under spherical geometry for three temporal resolutions (15, 30, and 60 minutes). As in the previous analysis of the wind components, the 30-minute temporal resolution is
330 used as the reference to evaluate the influence of temporal scale on these kinematic variables. Corresponding analyses for the plane geometry are provided in the Supplementary material.

The correlation between the datasets is moderate, with a correlation coefficient ranging from approximately 0.68 to 0.78. Shearing deformation shows the highest correlation with a correlation coefficient of $R \approx 0.76$ for 15 - 30 minute and $R \approx 0.71$ for 60 - 30 minutes comparison, while relative vorticity exhibits a slightly lower correlation coefficient of $R \approx 0.75$ for 15 - 30 minute
335 and $R \approx 0.68$ for 60 - 30 minutes comparison. Robust regression slopes for all variables remain close to unity ($m \approx 1.08 - 1.11$),



reflecting general linear agreement but with noticeable scatter. Although the derived kinematic variables maintain reasonable consistency across all temporal resolutions, they exhibit more variability than the wind components (see Figure 7 and 8). This highlights that temporal resolution significantly influences diagnostics of the kinematic variables, particularly, of the horizontal divergence and relative vorticity, which are indicators for wave breaking and flow stability (Vadas et al., 2003; Vadas, 2013).

340

4.2 Climatologies of Mean Winds from 3DVAR+DIV Retrievals

The seasonal wind climatology of all three wind components derived with the 3DVAR+DIV retrieval is illustrated in Figure 11. The horizontal winds show a consistent climatological pattern and interannual variability, but not for the vertical winds, because

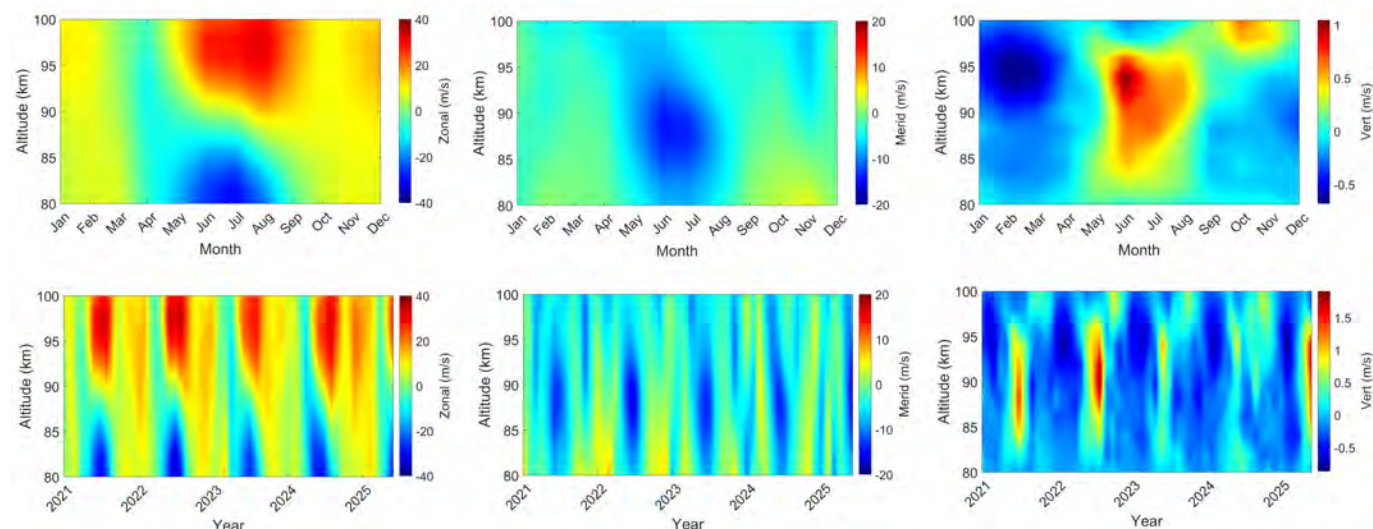


Figure 11. Monthly and seasonal composites of zonal, meridional, and vertical wind components utilizing 3DVAR+DIV.

spatial derivatives and wind fitting are not yet implemented in spherical geometry in the 3DVAR+DIV retrieval framework.

345 The vertical component exhibits enhanced upwelling between approximately 84 km and 96 km during summer, and above 97 km from September to mid-November. The magnitude of the upwelling between 84 km and 96 km during summer is more pronounced in 2021 and 2022 than in the rest of the years. The vertical wind magnitudes (domain mean) derived from the 3DVAR+DIV retrievals are larger than the values obtained with the SVVP method by almost a factor of 10. This systematic deviation of the mean vertical wind is partially explained by the lower statistics of meteor measurements in each grid cell, resulting in an inflation of uncertainties that affect the Tikhonov regularization constraint for the vertical wind component in the 3DVAR+DIV version. This effect is not visible for the horizontal winds. The higher-order kinematic variables derived from the 3DVAR+DIV retrieval are horizontal divergence and relative vorticity, presented in figure 12. Both variables exhibit climatological variability consistent with the SVVP, indicating good agreement in the representation of mesoscale dynamical features. The horizontal divergence displays enhanced values above 90 km from mid-February to December, similar to what

350

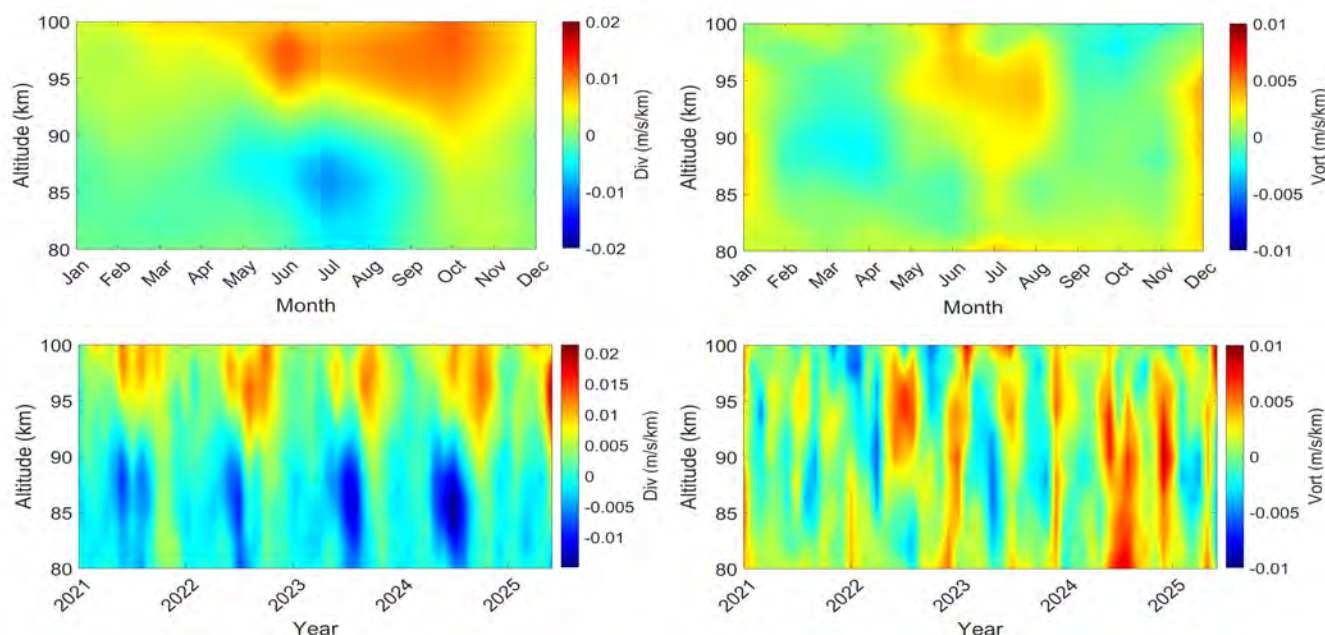


Figure 12. Monthly and seasonal composites of horizontal divergence and relative vorticity computed using 3DVAR+DIV.

was found in the VVP (plane geometry), while reduced divergence is observed between 80 km and approximately 89 km. Its seasonal pattern is consistent throughout the examined years. The relative vorticity exhibits high magnitudes above 90 km during the summer months, reflecting rotational motion associated with seasonal changes in the mean circulation.

4.3 Sensitivity 3DVAR+DIV Wind Retrievals to Tikhonov regularization

Figure 13 illustrates the sensitivity of 3DVAR+DIV wind retrievals to the Tikhonov regularization parameter controlling the mathematical coupling between grid cells describing the smoothness of the retrieved wind field α ($\alpha = 0.4$ and $\alpha = 150$), compared with the SVVP retrieval method. A small Tikhonov parameter provides more freedom to the solver to obtain small-scale variability, whereas an increased Tikhonov parameter enforces smoothness, removing small-scale features. All retrievals show a dominant large-scale southwesterly wind flow pattern, consistent with the prevailing synoptic forcing during the analyzed period. However, noticeable deviations in the wind magnitude and spatial smoothness are evident among the retrievals.

The 3DVAR+DIV retrieval method with small Tikhonov regularisation constraint ($\alpha = 0.4$; left panel) weakens the background smoothness constraint, allowing the solution to capture finer-scale flow features, likely related to small-scale gravity waves forced by tropospheric weather patterns, orography or secondary wave generation at the stratosphere due to the breaking of primary GW (Vadas et al., 2024; Becker et al., 2022; Becker and Vadas, 2020). This approach enhances the depiction of local circulation but also introduces small-scale noise and spatial inconsistencies, reflecting the stronger influence of the divergence constraint and reduced smoothing. In contrast, increasing the Tikhonov parameter to $\alpha = 150$ (middle panel) strengthens the

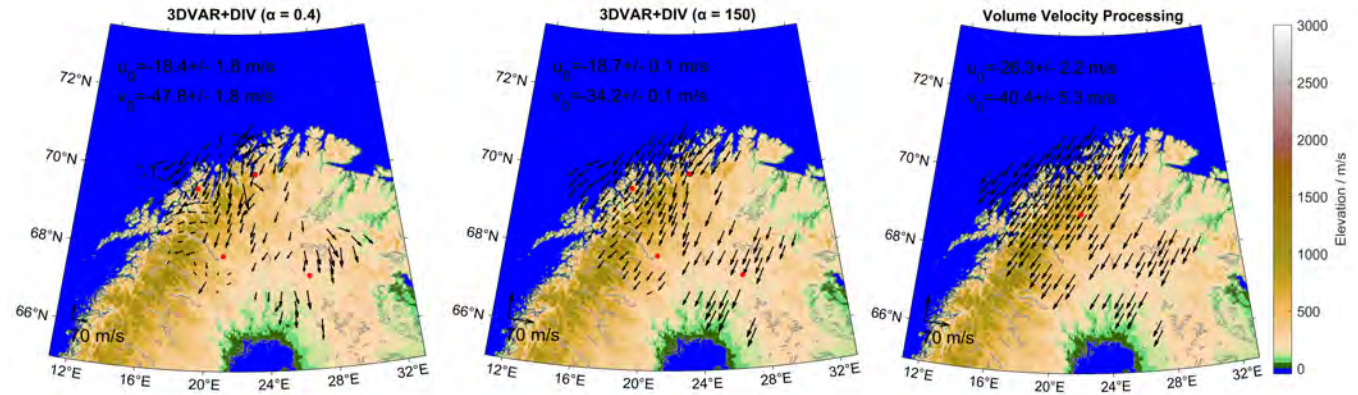


Figure 13. Horizontal wind fields over the NORDIC Meteor Radar Cluster for 00:00 UTC on 1 January 2021. The wind field derived using 3DVAR+DIV with Tikhonov regularization parameter of 0.4 (left panel), 150 (middle panel), and SVVP (right panel). The background shows the topography (m a.s.l.), while black arrows represent horizontal wind vectors. Red dots are the station locations for 3DVAR+DIV and the reference location for SVVP. The colorbar shows elevation in meters above sea level.

constraint, suppressing local fluctuations and producing a more coherent flow field with smoother gradients at the expense of hampering the retrieval of smaller-scale fluctuations in the wind field. The SVVP retrieval (right panel) yields the smoothest and most conservative wind field among the three approaches, with minimal spatial variability due to its approximation of only first-order inhomogeneities within the radar sampling volume. Quantitatively, the mean horizontal wind components reveal variations among the methods. The zonal and meridional wind components for 3DVAR+DIV with $\alpha = 0.4$ are approximately $-18.4 \pm 1.8 \text{ ms}^{-1}$ and $-47.8 \pm 1.8 \text{ ms}^{-1}$ respectively, while increasing α to 150, yields smoother, more stable wind slow of $-18.7 \pm 0.1 \text{ ms}^{-1}$ and $-34.2 \pm 0.1 \text{ ms}^{-1}$ with significantly reduced uncertainties and due to the stronger regularization stabilizing inversion showing smoother spatial gradients. The low α case exhibits greater deviations in regions with sparse radar coverage, leading to localized wind direction and magnitude biases. The SVVP method produces horizontal mean winds of roughly $-26.3 \pm 2.2 \text{ ms}^{-1}$ and $-40.4 \pm 5.3 \text{ ms}^{-1}$, characterized by relatively larger uncertainties and weaker wind magnitudes due to its limited ability to resolve horizontal gradients and its susceptibility to the propagation of measurement noise through the least-squares fitting. These findings underscore a fundamental trade-off between spatial resolution and retrieval stability. Reduced regularization strength enhances the variability of the resultant retrieved wind field, permitting the investigation of the gravity wave forcing of the MLT due to orography, weather pattern, or polar vortex induced primary or secondary gravity waves (Vadas et al., 2024), critical for understanding wind flow dynamics in the MLT, but increases susceptibility to noise due to the sparsity of data. Conversely, higher regularization yields smoother, dynamically consistent solutions suitable for data assimilation and climatological applications describing a large-scale mean flow. The 3DVAR+DIV effectively resolves spatial heterogeneity while maintaining physical coherence when the regularization parameter is carefully optimized, a capability not obtained with the SVVP approach. Currently, the 3DVAR+DIV performs best with regularizations strengths between $\alpha = 0.4 - 5$.



Figure 14 presents the correlation between the VVP/SVVP (in both spherical and plane geometry) and the 3DVAR+DIV for the wind components, which further quantifies the relationship between the two retrieval methods. In the comparison between VVP in spherical geometry and 3DVAR+DIV, the zonal and meridional wind components are highly correlated, with correlation coefficients of $R = 0.974$ and $R = 0.951$, respectively. The corresponding robust regression slopes slightly exceed 1, indicating both algorithms exhibit no substantial bias in representing horizontal winds. The vertical wind component shows a moderate correlation ($R = 0.768$) with a robust regression slope of 0.105, validating and consistent with the climatology results and highlighting its sensitivity to geometric assumptions. Considering that the 3DVAR+DIV estimates the gradient terms using the VVP (plane) approximation along the meridian or at constant latitude to derive the wind velocity derivatives. The

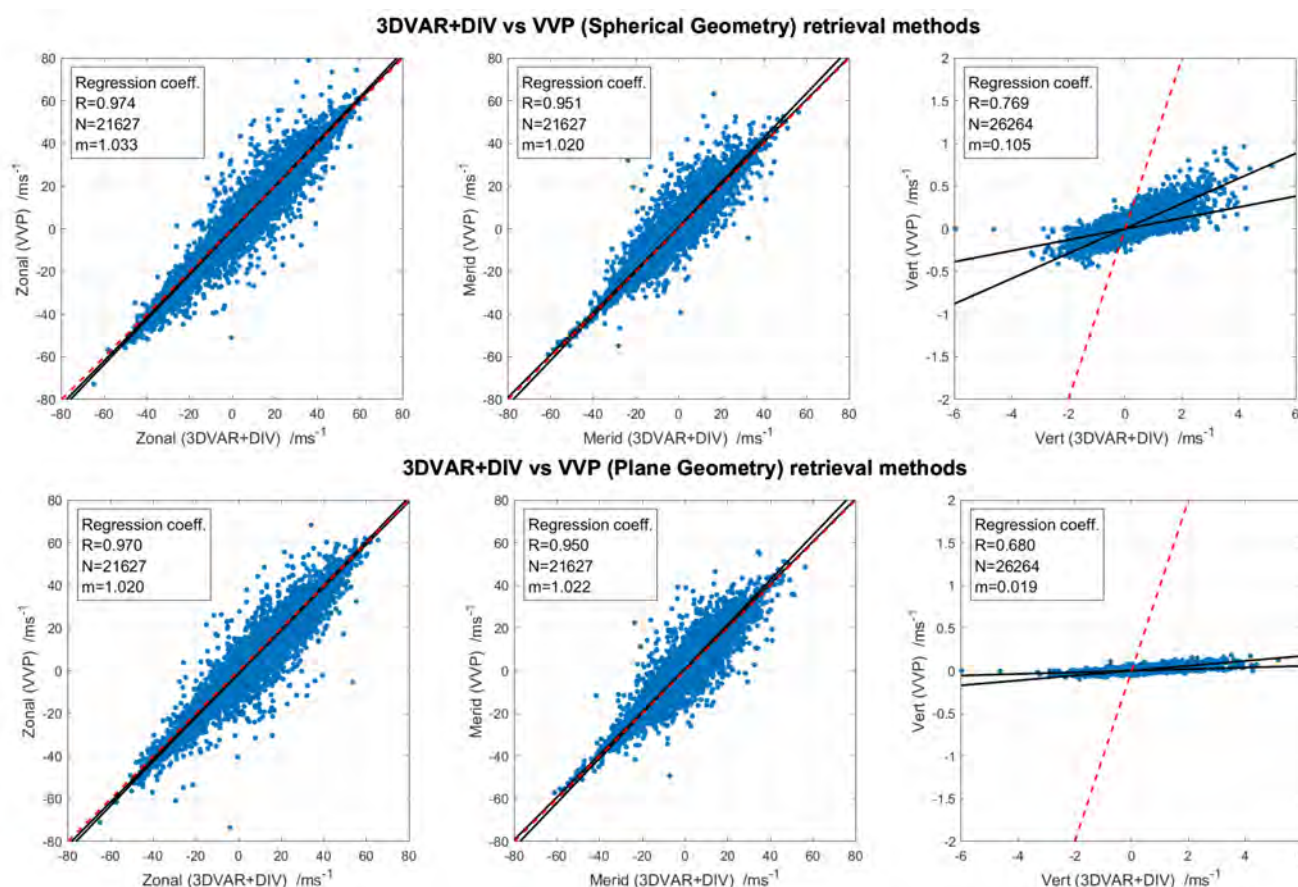


Figure 14. Correlation between Volume Velocity Processing (VVP) and 3DVAR+DIV retrieved zonal, meridional, and vertical wind components. Each panel includes daily mean scatter points, robust regression fits, 1:1 reference lines, and annotated statistics (correlation coefficient (R), sample size (N), and the slope (m)).

comparison between VVP in the plane geometry and the 3DVAR+DIV shows a slight but noticeable lower correlation. The horizontal wind component depicts correlation coefficients of $R = 0.97$ and $R = 0.95$ for zonal and meridional, respectively,



with robust regression slopes slightly exceeding unity. The vertical wind component exhibits a further reduction in correlation ($R = 0.68$) and a robust regression of 0.019, reflecting the limitation introduced by planar geometric simplification in vertical wind estimation. The horizontal wind correlations remain high and largely invariant to the choice of geometric assumption; they are marginally reduced in the plane approximation. The vertical wind retrieval, however, is notably more sensitive to the underlying geometry implemented in the retrieval, underscoring the importance of representing wind speeds and spatial derivatives in spherical coordinates to mitigate projection effects resulting in severe biases of the vertical wind. Considering that the 3DVAR+DIV uses the divergence-derived vertical wind as regularisation outlines the potential of how the vertical wind can be improved when transitioning to spherical geometry for the divergence and vorticity embedded in the retrieval.

410 5 Discussion

Increasingly, multistatic meteor radar networks are being established worldwide. These networks also cover much larger domain areas and have rather different layouts, considering the combination of passive and active radars. The Nordic Meteor Radar Cluster is unique in that it only includes monostatic radars with good overlap in the network (Stober et al., 2021a, 2022), although passive receiver stations can be added in the future. Multistatic networks also offer the possibility to implement different mathematical approaches to infer 3D winds, such as the Bayesian 3DAVR+DIV retrieval (Stober et al., 2022; Qiao et al., 2025) or algebraic least square fits based on different implementations of the VVP (Waldteufel and Corbin, 1979; Stober and Chau, 2015; Chau et al., 2017; Zeng et al., 2024).

The 3DVAR+DIV retrieval solves the ill-posed and ill-conditioned tomographic problem for a pre-defined geographic domain. Considering the entropy definition introduced by Shannon (1948) and Shannon and Weaver (1949), we calculate the Shannon measurement response, an additional diagnostic to estimate the mixing of a priori information and contributions from the measurements on the final solution of the state vector. This diagnostic also reveals correlations inside the domain volume due to the implemented mathematical smoothness constraint. These correlations are estimated by averaging kernels, a standard diagnostic in many remote sensing applications (Sica and Haeferle, 2015; Hagen et al., 2018; Krochin et al., 2022, 2024). The VVP and SVVP are based on a least square fit and approximate the spatial variability by expanding the wind field into a Taylor series. The coefficients are solved by an algebraic solution to a linear set of equations. The advantage of the VVP/SVVP is the reduced computational resources compared to a 3DVAR+DIV retrieval.

In this study, we present a novel implementation of the VVP in spherical coordinates (SVVP) and approximate the ellipsoidal shape of the Earth for iso-surfaces based on WGS84 coordinates (Zeng et al., 2024). There have been previous implementation attempts of the VVP in spherical coordinates by mixing Cartesian and spherical coordinates (Chau et al., 2017). However, our resulting equations are substantially different concerning the gradient terms. A comparison of the VVP in plane geometry and the newly developed SVVP shows remarkable differences in the higher-order kinematic terms, such as horizontal divergence, relative vorticity, and stretching and shearing deformation. The horizontal wind components exhibit smaller but still noticeable deviations. In particular, the horizontal divergence shows a characteristic altitude variation in plane geometry with positive



values above 90 km during the entire year. Such a vertical structure also leads to biases in vertical winds derived from the
435 horizontal divergence, resulting in climatological vertical wind speeds of several m/s, which seems to be physically unrealistic
for a seasonal value (Chau et al., 2017). The implemented SVVP shows a clear seasonal pattern and no systematic altitude
structure for the horizontal divergence, which also results in much more realistic seasonal vertical winds in the order of several
cm/s.

The vertical winds calculated in this study were debiased following information theory (Rodgers, 2000). The most robust esti-
440 mate of the vertical motion over longer periods is provided by the meteor ablation altitude and reaches values of a few hundred
meteors per decade (Stober et al., 2012a, 2014; Dawkins et al., 2023b). Therefore, it is reasonable to subtract this mean vertical
wind from the climatology and the long-time series to remove potential offsets in the network due to the alignment of the
antennas or possible phase offsets in the interferometry. These bias corrections are almost constant with altitude and in the
order of 1-3 cm/s for diameters of 200 and 250 km in the SVVP analysis. Larger domains tend to produce also larger and
445 altitude-dependent bias corrections.

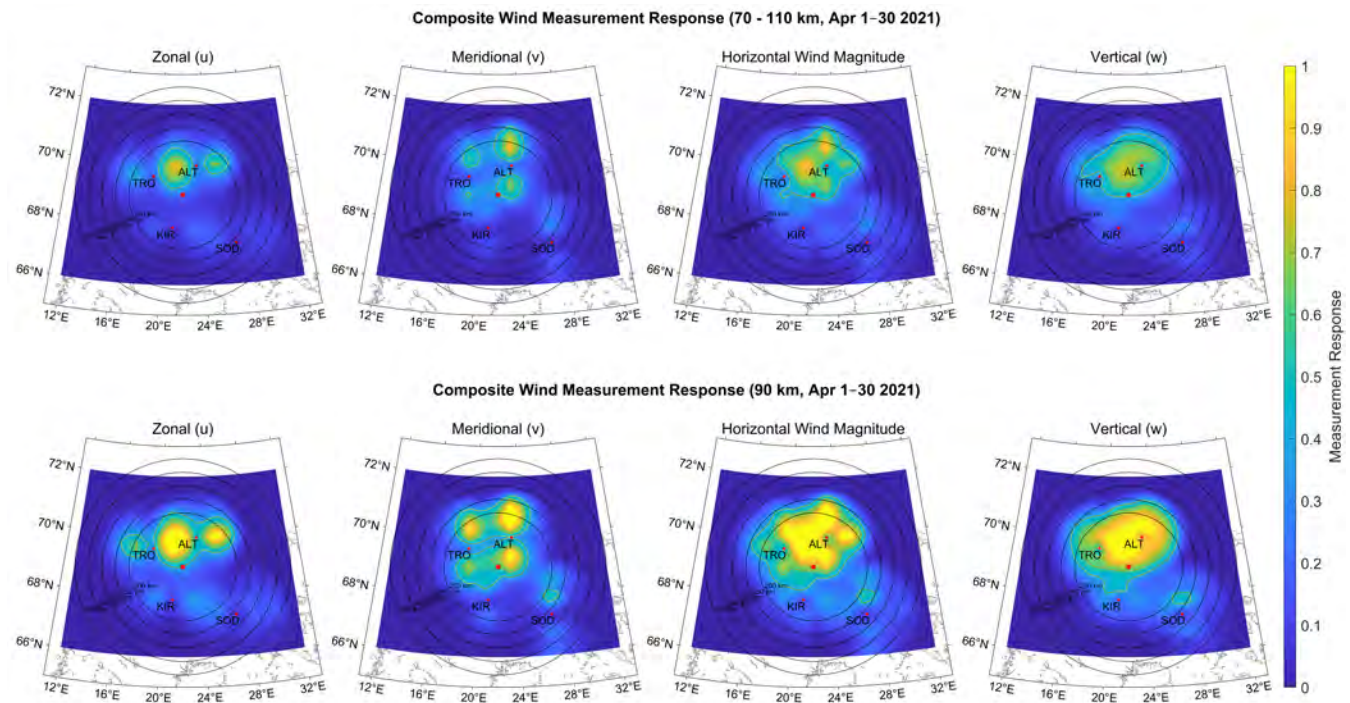


Figure 15. Composite wind measurement response for the zonal, meridional, horizontal wind magnitude (vector sum of zonal and meridional), and vertical wind components from 1 - 3 April 2021 at 90 km altitude, retrieved using 3DVAR+DIV method. Red dots indicate station locations, with their labels identifying each station; the unlabeled dot marks the central reference point used for the SVVP retrievals. The concentric rings represent distance in km from this central reference point.



We also performed a sensitivity study, defining circles of influence around the selected reference coordinates of 200 to 400 km in radius with a step size of 50 km. Furthermore, we analyzed all the measurements collected by the Nordic Meteor Radar Cluster from 2019 to 2024 using temporal resolutions of 15, 30, and 60 minutes to determine the impact of temporal averaging. For the comparison, we selected a temporal resolution of 30 minutes as a reference. The temporal resolution had almost
450 no influence on the derived horizontal wind components and resulted in a correlation of 0.96 for the zonal and 0.91 for the meridional wind. However, the vertical wind indicated a clear scaling behavior with larger vertical winds for the lower temporal resolution and smaller values for the 15-minute analysis. The 15-minute temporal analysis resolves more of the gravity wave spectrum and, thus, suffers less from incomplete sampling and averaging of gravity waves inside the domain. Comparing different circles of influence for the Nordic Meteor Radar Cluster reveals the best consistency for radii of 200 and 250 km,
455 with a tendency towards systematic deviations at increasing radii. In particular, the horizontal divergence, and consequently the vertical wind, appears to be inflated for larger circles of influence compared to the smaller domains with 200-250 km radius. Only the 200-250 km circle is truly multistatic, when we increase the volume even more, not all wind components are equally well determined in all parts of the domain. This becomes clearer when looking at the measurement response from the 3DVAR+DIV shown in Figure 15. Only the 200 and 250 km circle of influence exhibits an almost homogenous spatial
460 distribution in the measurement response, whereas the 400 km circle indicates areas with dark blue color or lies even outside the pre-defined 3DVAR+DIV domain. Furthermore, when the domain size is increased too much, additional projection errors due to the elliptical shape of the Earth become significant, which are not yet accounted for in the derived equations but are crucial for determining reliable vertical winds. Vertical winds are also more sensitive to the overall statistics inside the domain; therefore, the upper and lower edges of the meteor layer are problematic due to the lower number of meteor detections, and,
465 thus, the vertical winds are only trustworthy between 85-95 km altitude.

6 Conclusions

Accurate estimation of three-dimensional wind fields in the mesosphere and lower thermosphere (MLT) is crucial for advancing our understanding of atmospheric dynamics and variability. However, it has posed a longstanding significant challenge in atmospheric science, particularly regarding the reliable retrieval of vertical wind. The MLT region is influenced by radiative
470 forcing from both above (space) and wave-driven dynamics from the middle atmosphere, posing challenges to GCMs to reproduce a realistic mean state of the dynamics (Stober et al., 2021b; Hindley et al., 2022). Neutral winds in the MLT play a vital role in mediating the transport of energy and momentum, thereby coupling the upper and lower atmosphere and shaping the global circulation patterns.

In this paper, we present 3D spatially resolved wind fields in the MLT using advanced retrieval techniques. Specifically, we
475 introduce a novel SVVP method in spherical coordinates to improve the physical consistency of wind retrievals, and we compared its performance against the conventional VVP method in plane geometry and the 3DVAR+DIV method. Utilizing meteor radar observations spanning from 2021 to summer 2025 from the Nordic Meteor Radar Cluster, we analysed data statistics, seasonal mean wind characteristics, and inter-method correlations. Wind retrievals were performed with temporal resolutions



of 15, 30, and 60 minutes and radii ranging from 200 km to 400 km in steps of 50 km. The 30-minute temporal resolution was used as the reference to evaluate the impact of temporal averaging. All retrieval methods reproduced the expected climatological pattern of mean winds; however, correlation analyses revealed some discrepancies among methods. The 3DVAR+DIV approach better captures small-scale variability, whereas the VVP/SVVP methods produced a smoother wind field. Notable differences emerged in the wind components and the higher-order kinematic variables between the plane and the spherical implementations of the VVP. The horizontal wind components showed smaller but still systematic deviations. In particular, the horizontal divergence in the plane geometry indicated a characteristic altitude variation with positive bias throughout the year, pointing to systematic issues. The SVVP exhibited a clearer seasonal pattern and no systematic altitude structure, which also resulted in more realistic seasonal variations in vertical winds in the order of several cm s^{-1} consistent with theoretical expectations. Our findings highlight the importance of a correct geometric representation of the implemented retrieval and temporal averaging to ensure sufficient statistics to obtain reliable MLT winds. The newly improved SVVP method demonstrates enhanced physical consistency. It provides a robust framework for future investigations of MLT dynamics, including wave-mean flow interactions and momentum coupling processes in the middle/upper atmosphere for longer time series. In contrast, the 3DVAR+DIV retrieval is beneficial for high-resolution case studies.

Appendix A: Latitude implementation Spherical coordinates

We also calculated the SVVP equations using latitude θ , instead of a colatitude. Please note that θ here denotes the latitude. We used both sets of equations to remove ambiguities in the signs for each term.

$$\begin{aligned} u &= r \cos \Phi \dot{\phi} \\ v &= r \dot{\theta} \\ w &= \dot{r} \end{aligned} \tag{A1}$$

The gradient terms take the form;

$$\frac{\partial u}{\partial x} \cdot e_x = \frac{\partial \dot{\phi}}{\partial \phi} \cdot e_{\phi} \tag{A2}$$

$$\frac{\partial u}{\partial y} \cdot e_y = \left(-2\dot{\phi} \cdot \sin \theta + \cos \theta \cdot \frac{\partial \dot{\phi}}{\partial \theta} \right) \cdot e_{\theta} \tag{A3}$$

$$\frac{\partial v}{\partial x} \cdot e_x = \frac{1}{\cos \theta} \frac{\partial \dot{\theta}}{\partial \phi} \cdot e_{\phi} \tag{A4}$$

$$\frac{\partial v}{\partial y} \cdot e_y = \left(\frac{\partial \dot{\theta}}{\partial \theta} - \dot{\theta} \cdot \tan \theta \right) \cdot e_{\theta} \tag{A5}$$



The reconstructed wind field components are taking the form;

$$\begin{aligned}
 505 \quad u(\lambda, \Phi) &= u_0(\lambda_0, \Phi_0) + \frac{\partial \dot{\phi}}{\partial \phi} r_m \cos \theta_m \Delta \phi + \cos \theta_0 \cdot \frac{\partial \dot{\phi}}{\partial \theta} r_m \Delta \theta - 2u_0 \cdot \frac{\sin \theta_0}{r_0 \cos \theta_0} r_m \Delta \theta \\
 v(\lambda, \Phi) &= v_0(\lambda_0, \Phi_0) + \frac{1}{\cos \theta_0} \frac{\partial \dot{\theta}}{\partial \phi} r_m \cos \theta_m \Delta \phi + \frac{\partial \dot{\theta}}{\partial \theta} r_m \Delta \theta - v_0 \cdot \frac{\tan \theta_0}{r_0} r_m \Delta \theta \\
 w(\lambda, \Phi) &= w_0(\lambda_0, \Phi_0) .
 \end{aligned} \tag{A6}$$

Appendix B: Non-linear error propagation

All retrievals use a nonlinear error propagation as weighting of the least-squares solver, which is implemented as the singular-
 510 value decomposition (SVD). The line of sight velocity uncertainty is provided in the mpd- or met-file data from the commercial software package of each radar. The angular uncertainty of 2° for each angle is included by performing a Gaussian error propagation. We calculate all statistical uncertainties based on the radial velocity equation;

$$v_r(\phi_{err}) = \left| \frac{dv_r}{d\phi} \right| \cdot \Delta \phi = | -u \cdot \sin \phi \sin \theta + v \cdot \cos \phi \sin \theta | \cdot \Delta \phi \tag{B1}$$

$$v_r(\theta_{err}) = \left| \frac{dv_r}{d\theta} \right| \cdot \Delta \theta = | u \cdot \cos \phi \cos \theta + v \cdot \sin \phi \cos \theta - w \cdot \sin \theta | \cdot \Delta \theta . \tag{B2}$$

515 There is also a contribution of the mean winds in the error propagation, which is estimated from the radial wind equation as follows;

$$v_r(u_{err}) = \left| \frac{dv_r}{du} \right| \cdot \Delta u = | \cos \phi \sin \theta | \cdot \Delta u \tag{B3}$$

$$v_r(v_{err}) = \left| \frac{dv_r}{dv} \right| \cdot \Delta v = | \sin \phi \sin \theta | \cdot \Delta v \tag{B4}$$

$$v_r(w_{err}) = \left| \frac{dv_r}{dw} \right| \cdot \Delta w = | \cos \theta | \cdot \Delta w \tag{B5}$$

520 The uncertainties in the winds are solved iteratively. The initial weight is zero during the first iteration. All successive iterations are performed by propagating the SVD fitting uncertainties.

Furthermore, we include a sampling error. We define an arbitrary reference time and altitude using a boxcar in altitude and time with a height of 3 km and a time of 2 hour. All meteors that are detected within this boxcar are weighted by a Gaussian weight depending on how far the meteor in altitude and time occurred relative to the reference of the grid cell center. The magnitude
 525 of this weighting function is calculated from the spatio-temporal Laplace filter, which estimates a predictor using the altitudes above and below, as well as the time steps before and after a reference altitude-time bin. A more detailed description can be found in Stober et al. (2018); Gudadze et al. (2019); Hindley et al. (2022).

Author contributions. LPP conducted the data analysis and prepared the manuscript. GS and WK conceptualized and designed the newly developed VVP method and contributed to the interpretation and discussion of the results. AK, MT, NG, SN, ML, JK, and NM maintained
 530 the operations of the Nordic Meteor Radar Cluster and provided the observational data utilized in this study. All authors contributed to the discussion of the scientific findings and provided valuable feedback and revisions that improved the manuscript.



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540 References

- Amante, C. and Eakins, B. W.: ETOPO1 arc-minute global relief model: procedures, data sources and analysis, 2009.
- Andrews, D., Holton, J., and Leovy, C.: Middle Atmosphere Dynamics, International Geophysics, Elsevier Science, ISBN 9780120585762, <https://books.google.de/books?id=N1oNurYZefAC>, 1987.
- Becker, E.: Dynamical Control of the Middle Atmosphere, *Space Science Reviews*, 168, 283–314, [https://doi.org/10.1007/s11214-011-9841-](https://doi.org/10.1007/s11214-011-9841-5)
545 5, 2012.
- Becker, E. and Vadas, S. L.: Explicit Global Simulation of Gravity Waves in the Thermosphere, *Journal of Geophysical Research: Space Physics*, 125, e2020JA028034, <https://doi.org/10.1029/2020JA028034>, e2020JA028034 10.1029/2020JA028034, 2020.
- Becker, E., Vadas, S. L., Bossert, K., Harvey, V. L., Zülicke, C., and Hoffmann, L.: A High-Resolution Whole-Atmosphere Model With Resolved Gravity Waves and Specified Large-Scale Dynamics in the Troposphere and Stratosphere, *Journal of Geophysical Research: Atmospheres*, 127, e2021JD035018, <https://doi.org/10.1029/2021JD035018>, 2022.
550
- Browning, K. and Wexler, R.: The Determination of Kinematic Properties of a Wind field Using Doppler Radar, *J. App. Meteorol.*, 7, 105–113, 1968.
- Chau, J. L., Stober, G., Hall, C. M., Tsutsumi, M., Laskar, F. I., and Hoffmann, P.: Polar mesospheric horizontal divergence and relative vorticity measurements using multiple specular meteor radars, *Radio Science*, pp. n/a–n/a, <https://doi.org/10.1002/2016RS006225>,
555 2016RS006225, 2017.
- Conte, J. F., Chau, J. L., Renkwitz, T., Latteck, R., Tsutsumi, M., Jacobi, C., Gulbrandsen, N., and Nozawa, S.: Observing mesoscale dynamics with multistatic specular meteor radars: first climatology of momentum flux, horizontal divergence and relative vorticity over northern central Europe, *Annales Geophysicae*, 43, 603–619, <https://doi.org/10.5194/angeo-43-603-2025>, 2025.
- Dawkins, E. C., Stober, G., Carrillo-Sánchez, J. D., Janches, D., Weryk, R., Hormaechea, J. L., Bruzzone, J. S., and Plane, J. M.: A
560 novel methodology to estimate pre-atmospheric dynamical conditions of small meteoroids, *Planetary and Space Science*, 238, 105 796, <https://doi.org/https://doi.org/10.1016/j.pss.2023.105796>, 2023a.
- 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, e2022GL101953, <https://doi.org/https://doi.org/10.1029/2022GL101953>, e2022GL101953 2022GL101953,
565 2023b.
- de Wit, R. J., Hibbins, R. E., Espy, P. J., Orsolini, Y. J., Limpasuvan, V., and Kinnison, D. E.: Observations of gravity wave forcing of the mesopause region during the January 2013 major Sudden Stratospheric Warming, *Geophysical Research Letters*, 41, 4745–4752, <https://doi.org/10.1002/2014GL060501>, 2014.
- 570 Fritts, D. C., Vadas, S. L., and Yamada, Y.: An estimate of strong local body forcing and gravity wave radiation based on OH airglow and meteor radar observations, *Geophysical Research Letters*, 29, 71–1–71–4, <https://doi.org/10.1029/2001GL013753>, 2002.
- Fritts, D. C., Janches, D., Iimura, H., Hocking, W. K., Mitchell, N. J., Stockwell, R. G., Fuller, B., Vandepeer, B., Hormaechea, J., Brunini, C., and Levato, H.: Southern Argentina Agile Meteor Radar: System design and initial measurements of large-scale winds and tides, *Journal of Geophysical Research: Atmospheres*, 115, <https://doi.org/10.1029/2010JD013850>, 2010.
- 575 Gudadze, N., Stober, G., and Chau, J. L.: Can VHF radars at polar latitudes measure mean vertical winds in the presence of PMSE?, *Atmospheric Chemistry and Physics*, 19, 4485–4497, <https://doi.org/10.5194/acp-19-4485-2019>, 2019.



- Hagen, J., Murk, A., Rüfenacht, R., Khaykin, S., Hauchecorne, A., and Kämpfer, N.: WIRA-C: a compact 142-GHz-radiometer for continuous middle-atmospheric wind measurements, *Atmospheric Measurement Techniques*, 11, 5007–5024, <https://doi.org/10.5194/amt-11-5007-2018>, 2018.
- 580 Hall, C. and Tsutsumi, M.: Neutral temperatures at 90 km altitude over Svalbard (78°N 16°E), 2002–2019, derived from meteor radar observations, *Polar Science*, 24, 100 530, <https://doi.org/10.1016/j.polar.2020.100530>, 2020.
- He, M., Forbes, J. M., Jacobi, C., Li, G., Liu, L., Stober, G., and Wang, C.: Observational Verification of High-Order Solar Tidal Harmonics in the Earth's Atmosphere, *Geophysical Research Letters*, 51, e2024GL108 439, <https://doi.org/https://doi.org/10.1029/2024GL108439>, e2024GL108439 2024GL108439, 2024.
- 585 Hindley, N. P., Mitchell, N. J., Cobbett, N., Smith, A. K., Fritts, D. C., Janches, D., Wright, C. J., and Moffat-Griffin, T.: Radar observations of winds, waves and tides in the mesosphere and lower thermosphere over South Georgia island (54° S, 36° W) and comparison with WACCM simulations, *Atmospheric Chemistry and Physics*, 22, 9435–9459, <https://doi.org/10.5194/acp-22-9435-2022>, 2022.
- Hocking, W., Fuller, B., and Vandepeer, B.: Real-time determination of meteor-related parameters utilizing modern digital technology, *Journal of Atmospheric and Solar-Terrestrial Physics*, 63, 155 – 169, [https://doi.org/http://dx.doi.org/10.1016/S1364-6826\(00\)00138-3](https://doi.org/http://dx.doi.org/10.1016/S1364-6826(00)00138-3),
590 radar applications for atmosphere and ionosphere research - PIERS 1999, 2001.
- Holdsworth, D. A., Reid, I. M., and Cervera, M. A.: Buckland Park all-sky interferometric meteor radar, *Radio Science*, 39, n/a–n/a, <https://doi.org/10.1029/2003RS003014>, rS5009, 2004.
- Hook, J.: Winds at the 75–110 km level at College, Alaska, *Planetary and Space Science*, 18, 1623–1638, 1970.
- Janches, D., Dyrud, L. P., Broadley, S. L., and Plane, J. M. C.: First observation of micrometeoroid differential ablation in the atmosphere,
595 *Geophysical Research Letters*, 36, <https://doi.org/https://doi.org/10.1029/2009GL037389>, 2009.
- Kozlovsky, A., Stober, G., Sherstyukov, R., Lester, M., Belova, E., Kero, J., Tsutsumi, M., Gulbrandsen, N., and Nozawa, S.: Atmospheric Gravity Waves and Medium Scale Traveling Ionospheric Disturbances at Auroral Latitudes, *Surveys in Geophysics*, <https://doi.org/10.1007/s10712-025-09880-0>, 2025.
- Krochin, W., Navas-Guzmán, F., Kuhl, D., Murk, A., and Stober, G.: Continuous temperature soundings at the stratosphere and lower
600 mesosphere with a ground-based radiometer considering the Zeeman effect, *Atmospheric Measurement Techniques*, 15, 2231–2249, <https://doi.org/10.5194/amt-15-2231-2022>, 2022.
- Krochin, W., Murk, A., and Stober, G.: Thermal tides in the middle atmosphere at mid-latitudes measured with a ground-based microwave radiometer, *Atmospheric Measurement Techniques*, 17, 5015–5028, <https://doi.org/10.5194/amt-17-5015-2024>, 2024.
- Lieberman, R. S., Stober, G., Becker, E., Janches, D., Ma, J., and Liu, A.: Two-Day Wave Modulation of Gravity Wave
605 Momentum Fluxes Observed Over South America, *Journal of Geophysical Research: Atmospheres*, 130, e2024JD042 788, <https://doi.org/https://doi.org/10.1029/2024JD042788>, e2024JD042788 2024JD042788, 2025.
- Lindzen, R. S.: Turbulence and stress owing to gravity wave and tidal breakdown, *Journal of Geophysical Research: Oceans*, 86, 9707–9714, <https://doi.org/10.1029/JC086iC10p09707>, 1981.
- Liu, H.-L.: Variability and predictability of the space environment as related to lower atmosphere forcing, *Space Weather*, 14, 634–658,
610 <https://doi.org/10.1002/2016SW001450>, 2016.
- Manning, L., Villard, O., and Peterson, A.: Meteoric echo study of upper atmosphere winds, *Proceedings of the IRE*, 38, 877–883, 2006.
- National Imagery and Mapping Agency: Department of Defense World Geodetic System 1984: its definition and relationships with local geodetic systems, Tech. Rep. TR8350.2, National Imagery and Mapping Agency, St. Louis, MO, USA, http://earth-info.nga.mil/GandG/publications/tr8350.2/tr8350_2.html, 2000.



- 615 Plane, J., Gumbel, J., Kalogerakis, K. S., Marsh, D. R., and von Savigny, C.: Opinion: Recent developments and future directions in studying the mesosphere and lower thermosphere, *Atmospheric Chemistry and Physics*, 23, 13 255–13 282, 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.
- 620 Reid, I. M.: Meteor Radar for Investigation of the MLT Region: A Review, *Atmosphere*, 15, <https://doi.org/10.3390/atmos15040505>, 2024.
- Rodgers, C. D.: *Inverse Methods for Atmospheric Sounding: Theory and Practice*, Singapore: World Scientific, 2000.
- Shannon, C. E.: A Mathematical Theory of Communication, *Bell System Technical Journal*, 27, 379–423, <https://doi.org/https://doi.org/10.1002/j.1538-7305.1948.tb01338.x>, 1948.
- Shannon, C. E. and Weaver, W.: *The Mathematical Theory of Communication*, University of Illinois Press, Urbana, IL, ISBN 978-0-252-72548-7, 1949.
- 625 Sica, R. J. and Haefele, A.: Retrieval of temperature from a multiple-channel Rayleigh-scatter lidar using an optimal estimation method, *Appl. Opt.*, 54, 1872–1889, <https://doi.org/10.1364/AO.54.001872>, 2015.
- Smith, A. K.: Global Dynamics of the MLT, *Surveys in Geophysics*, 33, 1177–1230, <https://doi.org/10.1007/s10712-012-9196-9>, 2012.
- Stober, G. and Chau, J. L.: A multistatic and multifrequency novel approach for specular meteor radars to improve wind measurements in the MLT region, *Radio Science*, 50, 431–442, <https://doi.org/10.1002/2014RS005591>, 2014RS005591, 2015.
- 630 Stober, G., Jacobi, C., Matthias, V., Hoffmann, P., and Gerding, M.: Neutral air density variations during strong planetary wave activity in the mesopause region derived from meteor radar observations, *Journal of Atmospheric and Solar-Terrestrial Physics*, 74, 55–63, <https://doi.org/https://doi.org/10.1016/j.jastp.2011.10.007>, 2012a.
- Stober, G., Jacobi, C., Matthias, V., Hoffmann, P., and Gerding, M.: Neutral air density variations during strong planetary wave activity in the mesopause region derived from meteor radar observations, *Journal of Atmospheric and Solar-Terrestrial Physics*, 74, 55 – 63, <https://doi.org/10.1016/j.jastp.2011.10.007>, 2012b.
- 635 Stober, G., Sommer, S., Rapp, M., and Latteck, R.: Investigation of gravity waves using horizontally resolved radial velocity measurements, *Atmospheric Measurement Techniques*, 6, 2893 – 2905, <https://doi.org/10.5194/amt-6-2893-2013>, 2013.
- 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.
- 640 Stober, G., Chau, J. L., Vierinen, J., Jacobi, C., and Wilhelm, S.: Retrieving horizontally resolved wind fields using multi-static meteor radar observations, *Atmospheric Measurement Techniques*, 11, 4891–4907, <https://doi.org/10.5194/amt-11-4891-2018>, 2018.
- Stober, G., Kozlovsky, A., Liu, A., Qiao, Z., Tsutsumi, M., Hall, C., Nozawa, S., Lester, M., Belova, E., Kero, J., Espy, P. J., Hibbins, R. E., and Mitchell, N.: Atmospheric tomography using the Nordic Meteor Radar Cluster and Chilean Observation Network De Meteor Radars: network details and 3D-Var retrieval, *Atmospheric Measurement Techniques*, 14, 6509–6532, <https://doi.org/10.5194/amt-14-6509-2021>, 2021a.
- 645 Stober, G., Kuchar, A., Pokhotelov, D., Liu, H., Liu, H.-L., Schmidt, H., Jacobi, C., Baumgarten, K., Brown, P., Janches, D., Murphy, D., Kozlovsky, A., Lester, M., Belova, E., Kero, J., and Mitchell, N.: Interhemispheric differences of mesosphere–lower thermosphere winds and tides investigated from three whole-atmosphere models and meteor radar observations, *Atmospheric Chemistry and Physics*, 21, 13 855–13 902, <https://doi.org/10.5194/acp-21-13855-2021>, 2021b.
- 650 Stober, G., Liu, A., Kozlovsky, A., Qiao, Z., Kuchar, A., Jacobi, C., Meek, C., Janches, D., Liu, G., Tsutsumi, M., Gulbrandsen, N., Nozawa, S., Lester, M., Belova, E., Kero, J., and Mitchell, N.: Meteor radar vertical wind observation biases and mathematical debiasing strate-



- gies including the 3DVAR+DIV algorithm, *Atmospheric Measurement Techniques*, 15, 5769–5792, [https://doi.org/10.5194/amt-15-5769-](https://doi.org/10.5194/amt-15-5769-2022)
2022, 2022.
- 655 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.
- Vadas, S. L.: Compressible f-plane solutions to body forces, heatings, and coolings, and application to the primary and secondary gravity waves generated by a deep convective plume, *Journal of Geophysical Research: Space Physics*, 118, 2377–2397, <https://doi.org/10.1002/jgra.50163>, 2013.
- 660 Vadas, S. L., Fritts, D. C., and Alexander, M. J.: Mechanism for the Generation of Secondary Waves in Wave Breaking Regions, *Journal of the Atmospheric Sciences*, 60, 194 – 214, [https://doi.org/10.1175/1520-0469\(2003\)060<0194:MFTGOS>2.0.CO;2](https://doi.org/10.1175/1520-0469(2003)060<0194:MFTGOS>2.0.CO;2), 2003.
- Vadas, S. L., Becker, E., Bossert, K., Hozumi, Y., Stober, G., Harvey, V. L., Baumgarten, G., and Hoffmann, L.: The Role of the Polar Vortex Jet for Secondary and Higher-Order Gravity Waves in the Northern Mesosphere and Thermosphere During 11–14 January 2016, *Journal of Geophysical Research: Space Physics*, 129, e2024JA032521, <https://doi.org/https://doi.org/10.1029/2024JA032521>, e2024JA032521 2024JA032521, 2024.
- 665 Jet for Secondary and Higher-Order Gravity Waves in the Northern Mesosphere and Thermosphere During 11–14 January 2016, *Journal of Geophysical Research: Space Physics*, 129, e2024JA032521, <https://doi.org/https://doi.org/10.1029/2024JA032521>, e2024JA032521 2024JA032521, 2024.
- Volz, R., Chau, J. L., Erickson, P. J., Vierinen, J. P., Urco, J. M., and Clahsen, M.: Four-dimensional mesospheric and lower thermospheric wind fields using Gaussian process regression on multistatic specular meteor radar observations, *Atmospheric Measurement Techniques*, 14, 7199–7219, <https://doi.org/10.5194/amt-14-7199-2021>, 2021.
- 670 Vondrak, T., Plane, J. M. C., Broadley, S., and Janches, D.: A chemical model of meteoric ablation, *Atmospheric Chemistry and Physics*, 8, 7015–7031, <https://doi.org/10.5194/acp-8-7015-2008>, 2008.
- Waldteufel, P. and Corbin, H.: On the Analysis of Single-Doppler Radar Data, *Journal of Applied Meteorology and Climatology*, 18, 532 – 542, [https://doi.org/10.1175/1520-0450\(1979\)018<0532:OTAOSD>2.0.CO;2](https://doi.org/10.1175/1520-0450(1979)018<0532:OTAOSD>2.0.CO;2), 1979.
- 675 Wilhelm, S., Stober, G., and Brown, P.: Climatologies and long-term changes in mesospheric wind and wave measurements based on radar observations at high and mid latitudes, *Annales Geophysicae*, 37, 851–875, <https://doi.org/10.5194/angeo-37-851-2019>, 2019.
- Yi, W., Xue, X., Reid, I. M., Murphy, D. J., Hall, C. M., Tsutsumi, M., Ning, B., Li, G., Vincent, R. A., Chen, J., et al.: Climatology of the mesopause relative density using a global distribution of meteor radars, *Atmospheric Chemistry and Physics*, 19, 7567–7581, 2019.
- Zeng, J., Stober, G., Yi, W., Xue, X., Zhong, W., Reid, I., Adami, C., Ning, B., Li, G., and Dou, X.: Mesosphere/Lower Thermosphere 3-Dimensional Spatially Resolved Winds Observed by Chinese Multistatic Meteor Radar Network Using the Newly Developed VVP Method, *Journal of Geophysical Research: Atmospheres*, 129, e2023JD040642, <https://doi.org/https://doi.org/10.1029/2023JD040642>, e2023JD040642 2023JD040642, 2024.
- 680 3-Dimensional Spatially Resolved Winds Observed by Chinese Multistatic Meteor Radar Network Using the Newly Developed VVP Method, *Journal of Geophysical Research: Atmospheres*, 129, e2023JD040642, <https://doi.org/https://doi.org/10.1029/2023JD040642>, e2023JD040642 2023JD040642, 2024.