Comparison of Volume Velocity Processing (VVP) and 3DVAR+DIV Retrieval Algorithms of 3D Wind Fields in the Mesosphere and Lower Thermosphere with Meteor Radar Observations.

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OESCHGER CENTRE CLIMATE CHANGE RESEARCH

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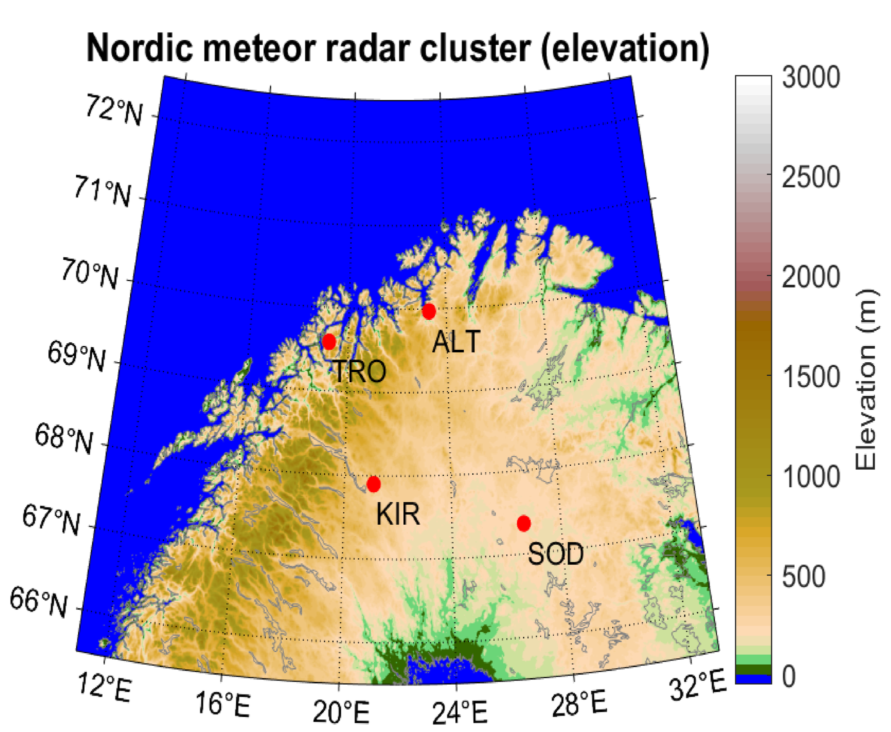
Motivation

Estimation of 3D wind fields in the Mesosphere and Lower Thermosphere (MLT) is essential for understanding the dynamics of the atmosphere. A key challenge is retrieving vertical wind profiles due to biases in meteor radar observations. This study compares two advanced wind retrieval methods: Volume Velocity Processing (VVP) and 3DVAR+DIV, using data from the Nordic Meteor Radar Cluster (NORDIC).



Here, the Nordic Meteor Radar Cluster (NORDIC), consisting of five monostatic systems, is presented. These include;

- Tromsø (69.59^o N, 19.2^o E)
- Alta (70.0^o N, 23.3^o E; ALT)
- Kiruna (67.9^o N, 21.1^o E; KIR)
- Sodankylä (67.4^o N, 26.6^o E; SOD)

The 3DVAR+DIV (Three-Dimensional Variational Analysis with Divergence Constraint) and VVP (Velocity Volume Processing) models are used for wind retrievals using the observation data collected from these stations. Preliminary results highlight differences between VVP and 3DVAR+DIV methods, indicating the importance of the choice of method when studying atmospheric wave activity, turbulence, and atmospheric dynamics.

Method

The dataset used in this study spans September 2024, capturing meteor radar observations for wind retrieval analysis.
The radial wind equation is mathematically expressed as;

$$V_r = usin(\theta)cos(\phi) + vsin(\theta)sin(\phi) + wcos(\theta)$$

The horizontal wind components (u,v) are modeled in the Volume Velocity Method (VVP) as;

$$u(x,y) = u_0 + \frac{\delta u}{\delta x}\Delta x + \frac{\delta u}{\delta y}\Delta y$$

$$v(x,y) = v_0 + \frac{\delta v}{\delta x}\Delta x + \frac{\delta v}{\delta y}\Delta y$$

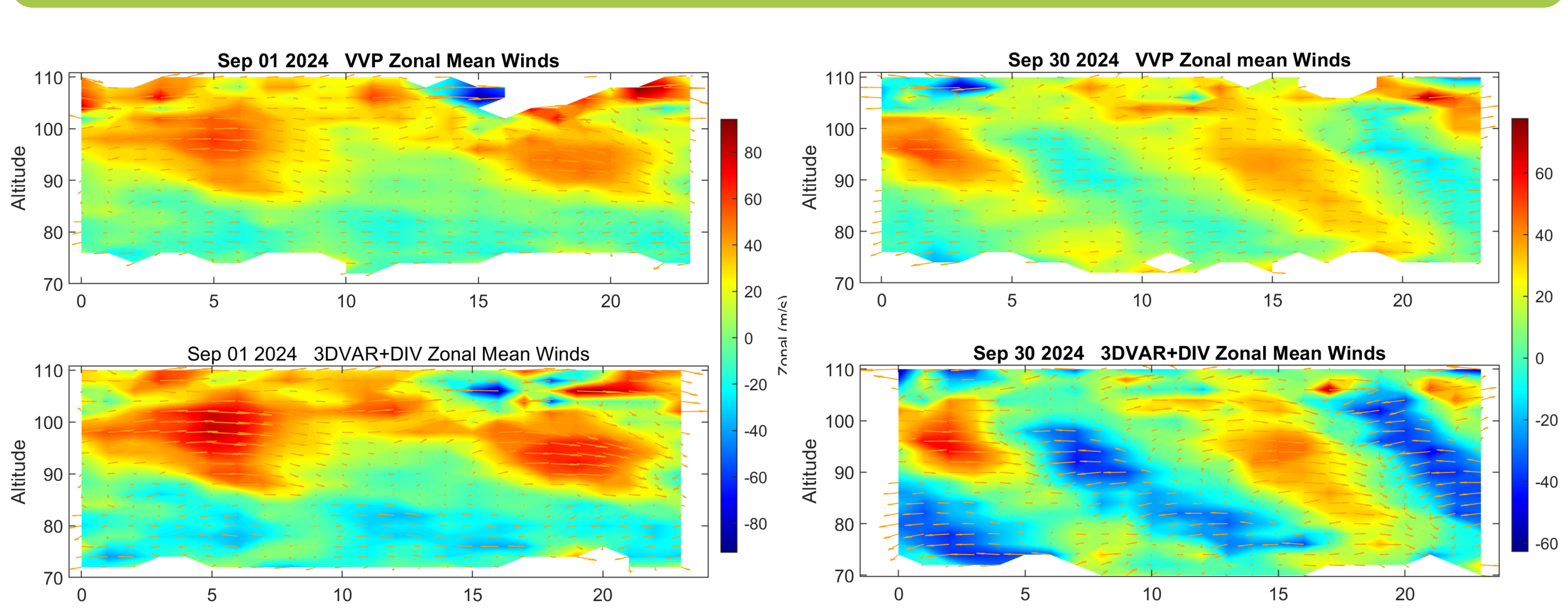
The vertical wind component (w) is computed by considering the physical constraints that adhere to the mass continuity equation, ensuring conservation of mass;

$$\frac{\delta(\rho)}{\delta t} + \Delta \cdot (\rho u) = 0$$

$$\Delta \cdot (u) = \frac{\delta u}{\delta x} + \frac{\delta u}{\delta x} + \frac{\delta u}{\delta x} = \Delta_H \cdot u + \frac{\delta w}{\delta z} = 0$$

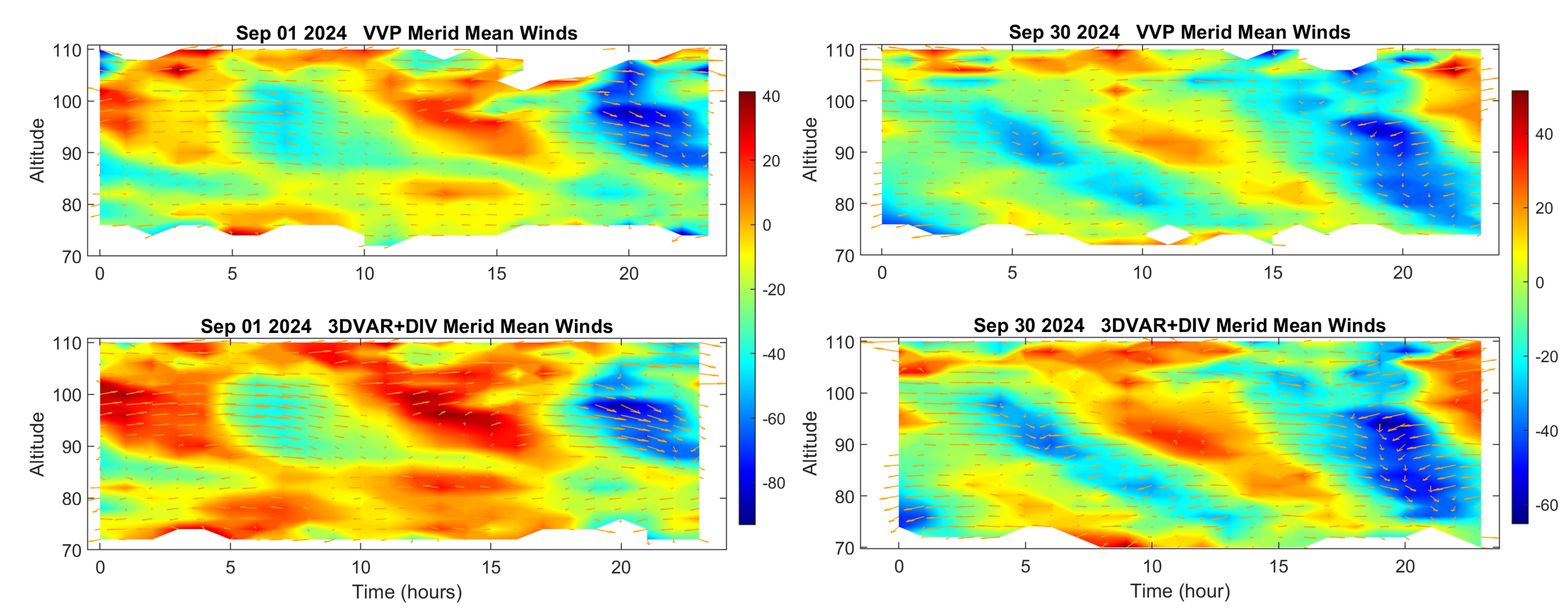
$$\Delta w = -\int_{z_1}^{z_2} \Delta_H \cdot udz$$

Zonal Wind Patterns on September 1st and 30th, 2024



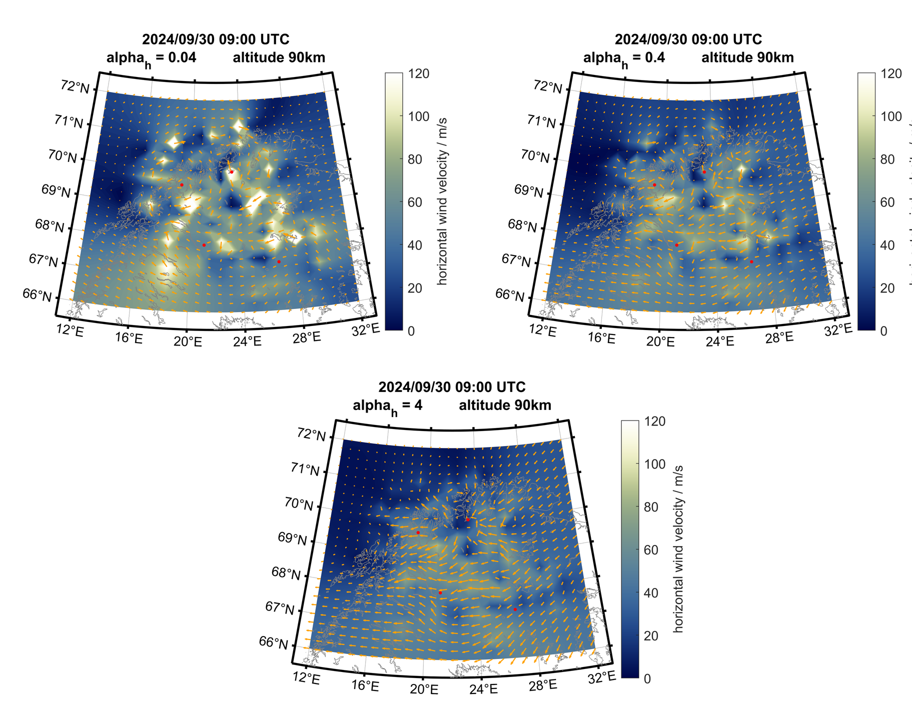
- Red represents eastward (positive) winds, blue indicates westward (negative) winds, and green/yellow signifies near-zero zonal wind speeds.
  - → 1st September, 2024:
    - ⋆ Strong eastward winds (red regions) are observed at higher altitudes (above 90km), while westward winds (blue regions) are more prominent at lower altitudes (70–80 km).
  - → 30th September 2024:
    - ⋆ Strong zonal wind fluctuations with more pronounced westward winds, especially at lower and mid-altitude regions, are observed, suggesting increased turbulence.

Meridional Wind Patterns on September 1st and 30th, 2024



- Red represents northward winds, blue indicates southward winds, and green/yellow signifies near-zero meridional wind speeds.
  - → 1st September, 2024:
    - ⋆ Strong northward winds (red regions) dominate most of the day, whereas, strong southward winds (blue region) appear in the late hours (around 20:00).
  - → 30th September, 2024:
    - ⋆ More pronounced fluctuations with alternating regions of northward (red) and southward (blue) winds are observed. Increased variability in the meridional wind components indicates greater dynamism in wind patterns.

Impact of Alpha Regularization on 3DVAR+DIV



Proper tuning of alpha regularization is critical for ensuring model robustness.

- Lower alpha (0.04): Introduces more noise, and high-frequency variations are observed.
- alpha (0.4): Produces a good balance between smoothness and detail preservation.
- Higher alpha (4): Produces smoother results but loses fine details. Potentially masking important dynamic features.

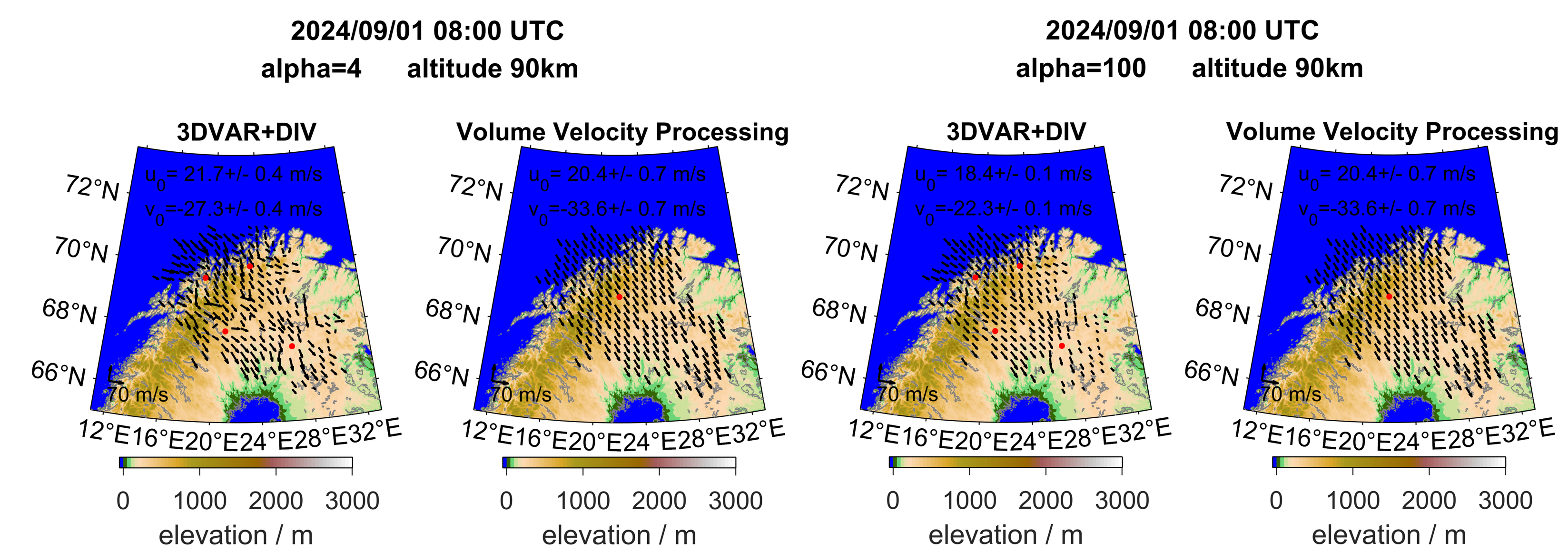
Conclusions

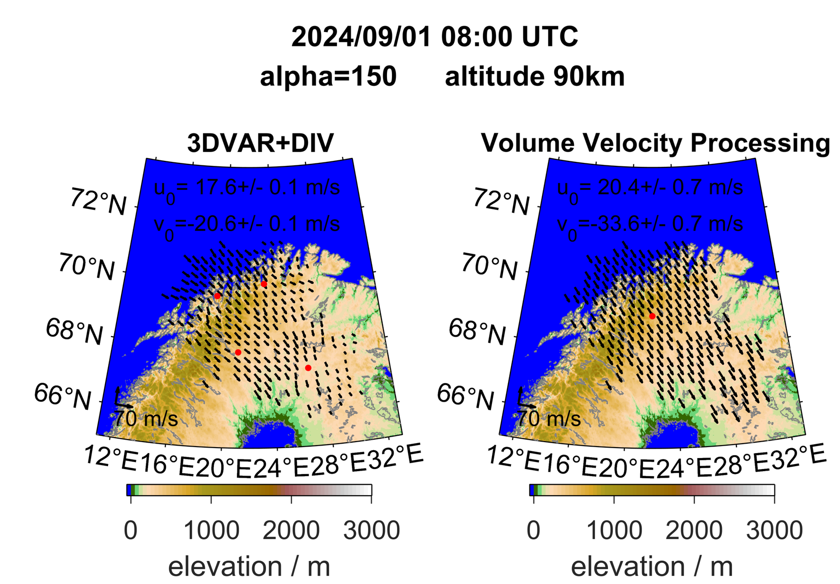
- 3DVAR+DIV and VVP are capable methods for retrieving wind fields.
- The VVP method captures the broad wind structure and smoothens out wind fluctuations, potentially missing some small-scale variations and localized dynamics.
- 3DVAR+DIV captures small-scale wind variations, providing a more detailed representation of atmospheric dynamics crucial for studying atmospheric wave dynamics, rapid wind changes, turbulence, and disturbances.
- Regularization is crucial in balancing smoothness and detail in model predictions. Too much alpha regularization leads to over-smoothing and loss of details, while too little can lead to noisy predictions and potential overfitting. The middle ground (normal alpha) provides a balanced trade-off between capturing details and maintaining robustness.

Future Works

- Further analysis can help determine which method better captures real atmospheric conditions and how these differences impact global atmospheric circulation models.
- Plan to explore optimal alpha regularization values for different atmospheric balance smoothness and detail more effectively to improve model performance in varying conditions.
- Extend the analysis over longer periods to assess how the 3DVAR+DIV and VVP methods perform across seasonal variations, different atmospheric events the evolution of wind patterns.

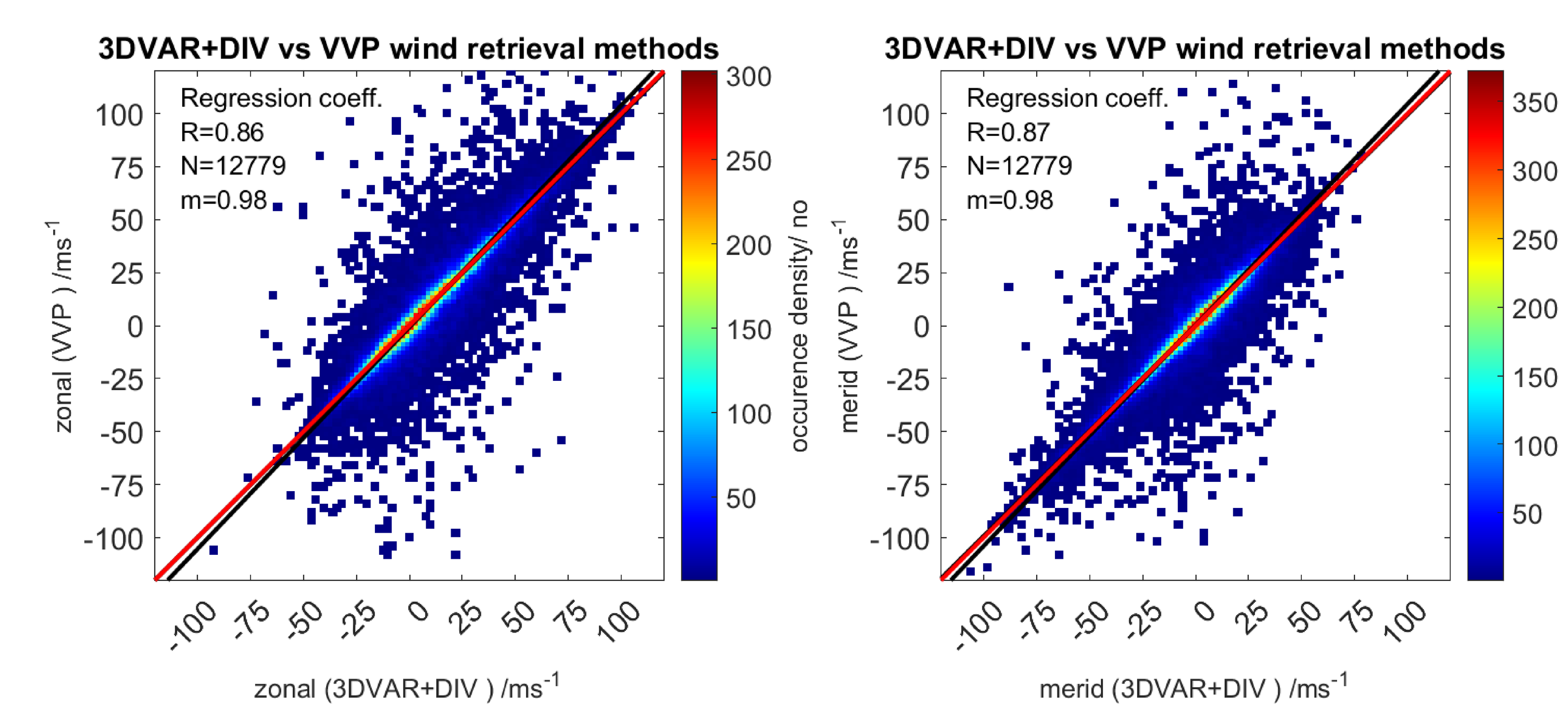
Wind fields comparison between VVP and 3DVAR+DIV Methods





- VVP provides a smoother wind field by averaging over volumes, effectively filtering out small-scale variability.
- 3DVAR+DIV resolves finer-scale turbulence, divergence, and localized variations.
- A higher alpha in 3DVAR+DIV results in wind fields that resemble the VVP result due to stronger smoothing. However, excessive smoothing (high alpha) leads to a loss of small-scale information.

Correlation Analysis



- Strong agreement between methods; with high correlation (R ≈ 0.8) and nearly identical and equal wind estimates ((m ≈ 0.98).
- Increased scatter highlights the divergence between methods, primarily due to;
  - → VVP's linear extrapolation towards domain edges, introduces inaccuracies.
  - → 3DVAR+DIV ability to resolve small-scale structures, capturing more wind field variations compared to VVP.
- This reveals both methods effectively retrieve wind fields, but VVP is less accurate in extreme wind conditions and boundary regions, whereas 3DVAR+DIV is preferable for detailed wind field analysis.

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