Referee comments on egusphere-2026-5181

Evaluating a Virtual Tall Tower approach for estimating atmospheric CO_2 mixing ratios from near-surface measurements

The manuscript evaluates the performance of an existing Virtual Tall Tower (VTT) method for estimating CO_2 mixing ratios at 150 m above ground from eddy-covariance (EC) measurements at 35 m, using tall-tower (TT) observations at Svartberget, a boreal forest site in northern Sweden, as a reference. The dataset spans five years and includes EC flux measurements, TT observations of CO_2 mixing ratios, and planetary boundary-layer heights (PBLH) from the ERA5 reanalysis. The authors highlight a trade-off between measurement quality and spatial coverage: TT observations provide high-quality measurements but are available at relatively few sites, whereas EC systems offer faster-response measurements and broader spatial coverage, albeit with lower precision. They explore the potential of the VTT method to bridge this gap, assessing its strengths and limitations. This study provides a good starting point for further applications of the VTT method. However, additional work is needed to account for different site types, surface heterogeneity, broader atmospheric conditions, topography, and accurately calibrated EC measurements. Overall, the manuscript is well written and easy to follow. The methods and analyses appear robust, and I have no major concerns. Nevertheless, I offer several comments below that I believe would strengthen the manuscript.

Specific comments

1. **Section 2.1 (Site description)**

   Please consider including a figure with two panels: an aerial view showing the surrounding forest and the locations of the tall tower (TT) and the eddy-covariance (EC) station, and a schematic side view indicating the measurement heights relative to the ground and forest canopy. I consulted external sources to better understand the site layout; such a figure would help readers visualise both the horizontal and vertical arrangement of the measurements.

   Please also provide the vertical leaf area density (LAD) profile, if available, and describe the site with attention to the following features: vertical and horizontal canopy heterogeneity, including any gaps, clearings, or variations, vegetation density, as well as topography. These characteristics are relevant to assessing the assumptions used later to estimate parameters such as the zero-plane displacement height (d).

2. **Section 3.1.1 (Gradient functions)**

   This section cites both Raupach (1979), in connection with the relation $d = 0.75\,h_c$, and Wang et al. (2007). Could you clarify how the displacement height was determined in this study? Was it prescribed as a fixed fraction of canopy height, or estimated from wind-speed and EC-derived friction-velocity (u_*) measurements using the logarithmic wind profile and an assumed roughness length (z_0)?

   I raise this question because relations such as Raupach's, traditionally applied to homogeneous canopies over flat terrain, may not hold for heterogeneous forests with gaps or large clearings, or for sparse canopies with low vegetation density and uneven horizontal and vertical distributions. Studies discussing how such heterogeneity can affect the displacement height (d) and roughness length (z_0) include Bohrer et al. (2009) and Salmaso et al. (2026). Studies discussing the effects of canopy heterogeneity on aerodynamic parameters include Bohrer et al. (2009) and Salmaso et al. (2026). Although the latter is limited to neutral conditions and does not explicitly report the displacement height (d),

it shows that canopy heterogeneity substantially reduces the equivalent roughness length (z_0) and momentum absorption within the canopy. These findings suggest that d may also be affected, although this effect is not directly quantified. Please clarify whether canopy heterogeneity and the vertical distribution of vegetation were accounted for, and if not, discuss potential implications and limitiation for the VTT estimates.

3. **Section 3.1.2 (PBLH)**

   In line 160, you state that the planetary boundary layer height (PBLH) must exceed the tall-tower (TT) height, i.e., PBLH/h > 1. In line 250, you note that the largest errors occur under the shallowest PBLH conditions. Could you provide references supporting this assumption and clarify whether the literature recommends a minimum PBLH/h ratio greater than—or substantially greater than—unity for the method to perform reliably?

4. **Haszpra et al. (2015)** Thi article is cited frequently throughout the manuscript. This is appropriate given its relevance, but where possible, please support your statements with additional references.

Technical corrections

1. **Table 1** Please consider expanding the table to the full page width for consistency with Table 2 and improved readability.

2. **Table 2** Although the variables are defined in the text, please consider adding a column with their definitions to make the table self-contained and improve readability.

3. **Figure 1 (c)** The color chosen for the TT observations is too similar to the orange used for the full TT. Please consider replacing it with a more distinguishable color, such as light gray, while ensuring sufficient contrast for readers with color vision deficiencies.

4. **Figure 2** Please consider narrowing the color scale range, perhaps to $[-2, 2]$, to improve visual contrast. With the current range, the darkest blue and red shades are difficult to discern.

5. **Figure 3** Please consider adding one or two sentences in the text to guide readers through this figure and highlight its main findings.

6. **Appendix** Please consider placing each figure closer to the text that describes it and adjusting the layout to reduce the large areas of blank space.

References

Gil Bohrer, Gabriel G Katul, Robert L Walko, and Roni Avissar. Exploring the effects of microscale structural heterogeneity of forest canopies using large-eddy simulations. *Boundary-layer meteorology*, 132:351–382, 2009. doi: https://doi.org/10.1007/s10546-009-9404-4.

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M. R. Raupach. Anomalies in flux-gradient relationships over forest. *Boundary-Layer Meteorology*, 16(3):467–486, 1979. doi: 10.1007/BF03335385.

Giulia Salmaso, Raúl B Cal, and Marc Calaf. Vegetated canopy heterogeneity footprints in the roughness sublayer. *Journal of Geophysical Research: Atmospheres*, 131(10):e2025JD043959, 2026.

Weiguo Wang, Kenneth J. Davis, Chuixiang Yi, Edward G. Patton, Martha P. Butler, Daniel M. Ricciuto, and Peter S. Bakwin. A note on the top-down and bottom-up gradient functions over a forested site. *Boundary-Layer Meteorology*, 124:305–314, 2007. doi: 10.1007/s10546-007-9162-0.