Preprint egusphere-2026-5181

Title: Evaluating a Virtual Tall Tower approach for estimating atmospheric CO2 mixing ratios from near-surface measurements

Authors: Lediane Marcon-Henge, Matthias Peichl, Eric Larmanou, and Alexander Graf

Reply to Referee #1 comments.

We sincerely thank the referee for the careful review of our manuscript and for the constructive comments and suggestions, which have helped us improve its clarity and scientific quality. We have addressed each comment individually, and our detailed responses are provided below in blue.

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).

We thank the referee for this helpful comment. We are preparing an additional figure for the revised manuscript to better illustrate the spatial arrangement of the measurement stations and the surrounding forest, including the measurement heights relative to the ground and forest canopy.

We agree that local characteristics such as canopy structure, vegetation distribution, and topography are relevant for estimating aerodynamic parameters such as the zero-plane displacement height (d). Unfortunately, a vertical leaf area density (LAD) profile is not available for the site.

The Svartberget station is located within the Krycklan Catchment in the Svartberget Experimental Forest, representing a typical boreal forest landscape in northern Sweden. The catchment has gently undulating terrain, with land cover dominated by forests (87% of the total area, mainly Scots pine, Norway spruce, and deciduous species), followed by mires (9%), while lakes and arable or built-up areas account for the remaining fraction (Martínez-García et al., 2022).

According to the ICOS Ecosystem Station Labelling Report (ICOS-RI, 2019), the target area surrounding the EC station is dominated by coniferous forest, with natural variations in tree height, species composition, and tree density. The publicly available ICOS vegetation inventory reports a tree density of approximately 1063 trees ha^{-1} and a basal area of 29.3 m^2 ha^{-1} (2018 inventory). The 2019 inventory reports an upper-canopy height, defined as the arithmetic mean height of the tallest 10% of trees, of 22.4 m in the sparse measurement plots (SP) and 19.9 m in the continuous measurement plots (CP). The value of 22.4 m was adopted as the representative canopy height for the VTT calculations. Given the EC measurement height of 34.5 m, the vertical distance between the EC sensor and this representative upper-canopy height is approximately 12 m. The station target area covers 163.42 ha, with 10.43 ha identified as excluded areas, including nearby roads and mire areas.

The ICOS report also provides a footprint climatology based on approximately five months of measurements during 2018–2019. For that period analyzed, the 80% cumulative footprint isopleth was entirely contained within the defined target area (Figure 1 below). This indicates that the EC measurements were predominantly representative of the designated forest target area during the evaluated period, although local variations in vegetation structure remain.

We will incorporate this information into the revised site description to better illustrate the measurement configuration and surrounding vegetation. The implications of canopy heterogeneity for the prescribed displacement height are also addressed in our response to Comment 2.

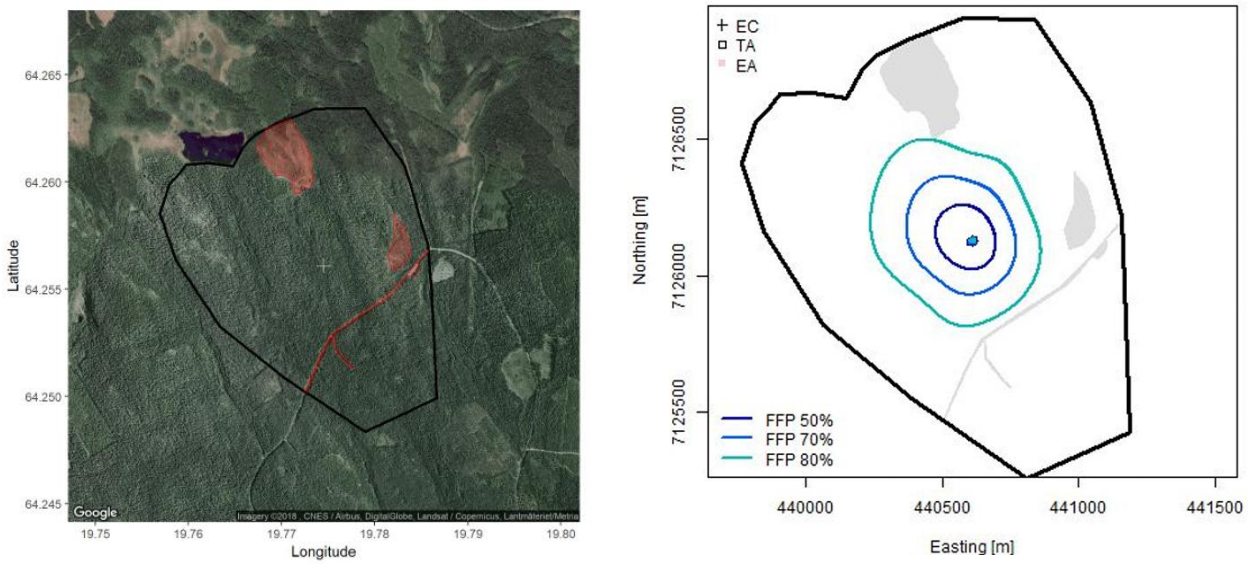

Figure 1: Left-hand side panel : Aerial view of the Svartberget ICOS ecosystem station (SE-Svb), showing the target area (black outline) and excluded areas (shaded polygons). The excluded areas include, among others, nearby road and mire features. The target area covers 163.42 ha and the excluded areas 10.43 ha. Right-hand side panel: Footprint climatology of the EC station in relation to the target area, the EC tower location, and the excluded areas. The 50%, 70%, and 80% cumulative footprint isopleths are shown. For the footprint model quality filtered data from October 2018 to March 2019 was used. Both panels are from the ICOS Ecosystem Station Labelling Report for SE-Svb .

2. Section 3.1.1 (Gradient functions) This section cites both Raupach (1979), in connection with the relation d = 0.75hc, 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 (z0)? 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 dis placement height (d) and roughness length (z0) 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 (z0) 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.

Thank you for this important comment and for drawing our attention to the potential influence of canopy heterogeneity on the displacement height.

In this study, the zero-plane displacement height (d) was prescribed as a fixed fraction of the representative mean canopy height (h_{canopy}), following the relationship $d = 0.76\ h_{canopy}$ proposed by Raupach (1979). It was not independently estimated from wind-speed and EC-derived friction-velocity measurements using the logarithmic wind profile. We will clarify this in Section 3.1.1.

We agree that this parameterization represents a simplification, particularly for heterogeneous forest landscapes. As highlighted by Bohrer et al. (2009) and Salmaso et al. (2026), variations in canopy structure can influence turbulent flow and aerodynamic characteristics. Horizontal and vertical variations in vegetation structure are not explicitly accounted for when prescribing displacement height as a fixed fraction of mean canopy height.

The landscape surrounding the Svartberget station is characterized by a mixture of forest stands, clear-cuts, and mires. Although the ICOS target area is dominated by coniferous forest, variations in tree height, species composition, and tree density occur within this area. As described in our response to Comment 1, the 2019 ICOS vegetation inventory reports an upper-canopy height, defined as the arithmetic mean height of the tallest 10% of trees, of 22.4 m in the sparse measurement plots and 19.9 m in the continuous measurement plots. The value of 22.4 m was adopted as the representative canopy height in our VTT calculations. The available inventory data, including tree density and basal area, provide a general characterization of the canopy, although they do not fully describe its horizontal and vertical heterogeneity.

In the Wang et al. (2007) formulation, displacement height influences the VTT estimates through the effective vertical coordinate $(z-d)/z_i$ used in the gradient functions. Wang et al. (2007) also discuss how canopy characteristics may influence the gradient functions beyond the effects represented through displacement height alone.

In the present study, we evaluated the sensitivity of VTT performance to variations in (d). The investigated ± 90 % range translates to outer d limits of 1.7 and 32.3 m, respectively, and the more realistic uncertainty range according to Table 2 to 6.7 to 17.9 m. Within these ranges, perturbations in (d) produced relatively small changes in VTT performance, with maximum changes of approximately 0.03 µmol mol^{-1} in bias, 0.01 µmol mol^{-1} in RMSE, and negligible changes in (R^2) (manuscript Figure 4).

These results suggest that uncertainty in the prescribed displacement height has a limited influence on the performance of the Wang VTT formulation within the investigated range. Nevertheless, the sensitivity analysis addresses the influence of (d) as an individual model parameter and does not explicitly account for additional effects of canopy heterogeneity on turbulent transport, the gradient functions themselves, or the representativeness of EC measurements.

We will clarify the displacement-height parameterization in Section 3.1.1 and expand the discussion in Section 4.3 to better address the implications and limitations of this simplifying assumption.

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?

We thank the referee for this comment and for highlighting the distinction between the applicability of the VTT formulation and its reliability under shallow boundary-layer conditions.

The criterion requiring the planetary boundary layer height (z_i) to exceed the tall-tower height (z_{TT}) was adopted as a necessary condition for applying the VTT formulation, rather than as an empirically established threshold for reliable performance. The underlying gradient functions describe vertical scalar transport within the convective boundary layer and are expressed in terms of normalized height relative to the boundary-layer depth (Wyngaard and Brost, 1984; Patton et al., 2003; Wang et al., 2007). Therefore, the target estimation height must remain within the domain of applicability of these functions.

We agree that satisfying ($z_i > z_{TT}$) does not necessarily guarantee reliable estimates, particularly under shallow boundary-layer conditions. An important consideration is that PBLH was obtained from ERA5 reanalysis and is therefore subject to uncertainty. When the diagnosed PBLH is only slightly above the tall-tower height, even a relatively small overestimation may mean that the actual boundary-layer top remains below the target height. Consequently, some observations may satisfy the selection criterion while not fulfilling the physical assumptions underlying the VTT formulation.

This provides a possible explanation for the larger errors observed under shallow PBL conditions, although the contribution of PBLH uncertainty cannot be isolated from other

potential error sources in the present analysis. To our knowledge, the literature does not establish a universally applicable minimum PBLH-to-target-height ratio substantially greater than unity that guarantees reliable VTT performance.

We will revise Sections 3.1 and 3.1.2 to clarify the domain of applicability of the gradient functions and the rationale for the selection criterion. And also expand the discussion to better explain the potential influence of ERA5 PBLH uncertainty on VTT estimates under shallow boundary-layer conditions.

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.

We thank the referee for this suggestion. Given the limited number of studies directly addressing the VTT approach, Haszpra et al. (2015) remains a particularly relevant reference. Nevertheless, we will review the citations throughout the manuscript and consider additional references where appropriate.

Technical corrections

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

Thank you for this suggestion. We will adjust the formatting of Table 1 to span the available text width, improving readability and ensuring consistency with Table 2.

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.

Thank you for this helpful suggestion. To make Table 2 self-contained while preserving its readability, we will add definitions of all variables and parameters in a note below the table. This provides the requested information without increasing the number of columns in the already information-dense table.

3. Figure 1 © 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.

We thank the referee for this suggestion. We will adjust the color scheme in the revised figure to improve contrast and readability, while also considering accessibility 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.

We thank the referee for this suggestion. We will review the color scale range and consider adjusting it to improve visual contrast and readability while preserving the representation of the full range of values.

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

We thank the referee for this suggestion. We will add a brief explanation of the Taylor and target diagrams in Section 4.2 to guide readers through Figure 3 and highlight the main differences in performance among the tested scenarios.

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

We thank the referee for this suggestion. The current appendix layout follows the journal's LaTeX template, which requires a \clearpage command between figures and tables, resulting in some blank spaces. We will review the layout and adjust the placement of figures where possible, while maintaining the journal's formatting requirements.

References:

Bohrer, G., Katul, G.G., Walko, R.L. and Avissar, R. Exploring the effects of microscale structural heterogeneity of forest canopies using large-eddy simulations. Boundary-layer meteorology, 132(3), pp.351-382. Doi 10.1007/s10546-009-9404-4, 2009

Graf, A., van de Boer, A., Moene, A., and Vereecken, H.: Intercomparison of Methods for the Simultaneous Estimation of Zero-Plane Displacement and Aerodynamic Roughness Length from Single-Level Eddy-Covariance Data, Boundary-Layer Meteorology, 151, 373–387, https://doi.org/10.1007/s10546-013-9905-z, 2014.

Haszpra, L., Barcza, Z., Haszpra, T., Patkai, Z., and Davis, K. J.: How well do tall-tower measurements characterize the CO2 mole fraction distribution in the planetary boundary layer?, Atmospheric Measurement Techniques, 8, 1657–1671, https://doi.org/10.5194/amt-8-1657-2015, 2015.

ICOS-RI: ICOS Ecosystem Station Labelling Report. Station: SE-Svb (Svartberget), Tech. rep., ICOS Ecosystem Thematic center, 2019.

ICOS-SWEDEN. Svartberget. Online material available at https://www.icos-sweden.se/Svartberget, accessed on November 05th.

Martínez-García, E., Nilsson, M.B., Laudon, H., Lundmark, T., Fransson, J.E., Wallerman, J. and Peichl, M. Overstory dynamics regulate the spatial variability in forest-floor CO2 fluxes across a managed boreal forest landscape. Agricultural and Forest Meteorology, 318, p.108916. https://doi.org/10.1016/j.agrformet.2022.108916, 2022

Patton, E. G., Sullivan, P. P., and Davis, K. J.: The influence of a forest canopy on top-down and bottom-up diffusion in the planetary boundary layer, Quarterly Journal of the Royal Meteorological Society, 129, 1415–1434, https://doi.org/10.1256/qj.01.175, 2003.

Raupach, M. R.: Anomalies in flux-gradient relationships over forest, Boundary-Layer Meteorology, 16, 467–486, https://doi.org/10.1007/BF03163564, 1979.

Salmaso, G., Cal, R. B., and Calaf, M. Vegetated canopy heterogeneity footprints in the roughness sublayer. Journal of Geophysical Research: Atmospheres, 131, e2025JD043959. https://doi.org/10.1029/2025JD043959, 2026

Wang, W., Davis, K. J., Yi, C., Patton, E. G., Butler, M. P., Ricciuto, D. M., and Bakwin, P. S.: A note on the top-down and bottom-up gradient functions over a forested site, Boundary-Layer Meteorology, 124, 305–314, https://doi.org/10.1007/s10546-007-9162-0, 2007.