

Reviewer #1:

This study (egusphere-2026-2494) investigates how irradiance and mixing layer height (MLH) affect the vertical distribution of trace substances in rural areas of Germany, using data from two summer drone measurement campaigns conducted up to 500 m above ground, along with data from ground-based stations. The findings suggest that irradiance is the primary factor influencing diurnal mixing mechanisms. Furthermore, the research highlights that ground-based measurements do not always accurately represent the conditions throughout the entire mixed layer. However, several concerns need to be addressed.

Dear reviewer #1,

Thank you for your detailed feedback on our manuscript. We have to admit that we missed the publication of Tan et al. (2025), which provides valuable input to our analysis and, in addition, helps to understand our observations. We included the categorization of different types of PBLs introduced by Tan et al. (2025) in the introduction/motivation, analysis and discussion sections. Individual comments to your feedback are given after the respective bullet points.

1. In this study, the sample size for nighttime analysis is quite small, relying on data from only one night (June 20–21, 2024). Although the data is of high resolution, its statistical representativeness is limited, so caution should be taken when drawing conclusions. It is advisable to include additional nighttime profiles or to clearly define the study as a case study.

You are completely right that the statistical representativity of this study is limited. However, this section does not aim on providing the general fine-structure for a specific location, but aims on showing the sensitivity and necessity of measuring a variety of variables in highly resolved vertical profiles. To make this clearer, we now have inserted “case study” into the sections title (Sect. 3) to highlight the limited statistical significance due to the limited sample size:

“Case study: Height criteria and fine-scale structure of the nocturnal boundary layer”

We also specified this in the last section of the introduction by adding the information that the insights result from a single nighttime event:

“a [...] using gradient-based methods (up to 120 m altitude with 2 m vertical resolution) during a single nighttime event, featuring a fog event and a low-level jet”

2. In section 3, the authors conduct a multi-variable analysis of MLH using various meteorological variables, including potential temperature, temperature, humidity, wind speed, and the bulk Richardson number, as well as profiles of trace substances such as O₃, CO₂, and particle number and mass concentrations. While this comparative approach offers potential value, the manuscript currently treats the resulting height estimates primarily as alternative indicators of a single “MLH.” Conceptually, boundary-layer height can be classified into three distinct physical categories (e.g., Tan et al. (2025)):

Thermal PBL height defined by static stability, e.g., potential-temperature or virtual-potential-temperature gradients/parcel method.

Dynamic PBL height defined by dynamic stability, e.g., bulk Richardson number or wind-shear criteria

Material PBL height, defined by the vertical distribution of atmospheric constituents, e.g., aerosol or trace gas gradients.

The three heights mentioned are not interchangeable; they correspond to distinct physical processes and often differ, particularly when there is weak dynamical forcing or when residual-layer chemistry and surface sources or sinks are present. The current manuscript fails to adequately recognize or discuss this important distinction. The authors should explicitly define and consistently distinguish thermal, dynamic, and material boundary-layer heights throughout the text, figures, and captions. The authors should also clarify why differences among the three methods are inevitable, focusing on the physical mechanisms involved instead of suggesting that one of the measured MLH values is a more accurate or comprehensive representation of MLH.

We totally agree on the fundamental issue that the distribution of different atmospheric variables is caused by various different atmospheric processes, and hence result in the detection of different mixing layer heights in the atmosphere. Therefore, the differentiation between thermal, dynamical and material PBL is useful.

Firstly, we explain explicitly why we use the term “mixing layer” in the introduction instead the term “PBL”, because the mixing layer is not always identical to the PBL:

“The mixing layer height (MLH) describes the upper boundary of a well-mixed lowermost layer, where chemically or dynamically different air masses adjoin. Reliably distinguishing the mixing layer from the adjacent layers is essential for the interpretation of microphysical and dynamical processes. The most-studied stratification in the lowermost troposphere is the PBL and free troposphere, at which boundary chemical, and thermodynamical different layers interface. We use the term “mixing layer” explicitly to describe a distinct atmospheric layer, independent on its location and time, i.e., a mixing layer can be the PBL or any shallow layer near ground.”

Secondly, we want to make use of your feedback and refer to dynamical, thermal and material MLHs, which itself can easily be assigned by our set of measured variables. We introduced the classification of Tan et al. (2025) in our introduction in L49 and in the first paragraph in Section 3/L140:

“Tan et al. (2025) characterized different PBLHs simultaneously and distinguished between a thermal, dynamical and material PBLH and attributed them to different atmospheric processes, which explains why different PBLHs coexist.”

“Remote sensing of various variables, revealed the simultaneous existence of different types of MLHs based on the variables referring to statical or dynamical stability and the vertical distribution of atmospheric constituents that identified stratification in a complex terrain with mountainous, urban and waterbody influences. Respective variables led to the definition of a thermal, dynamical and material boundary layer, respectively (Tan et al., 2025). This differentiation between those categories helps to explain atmospheric processes.”

The core logic in section 3 is flawed. The author tries to pinpoint a so-called "ground truth" that would perfectly represent the average state of the mixing layer. However, as previously mentioned, the three types of PBLH have different implications. The thermal, dynamic, and material boundary

layer heights each reflect distinct physical properties, and the differences among them highlight the complexity of atmospheric processes rather than being attributed to measurement errors.

We understand your concern and fully agree that different boundary layer heights can be deduced from different atmospheric processes. In section 3, we want to highlight the advantage of using a multi-variable in-situ measurement approach to identify the fine-structure of the lowermost atmosphere during night. We made this clearer now by the following statement:

“Deriving the fine-structure of the NBL from different types of MLHs allows explaining atmospheric processes that cannot be identified otherwise.”

In the whole text of section 3, we now explicitly name the kind of boundary layer based on the variables they were observed by. Now, we also added a discussion about the coupling of thermal and dynamical boundary layer heights to the material boundary layer height during night:

“These analyses of the NBL fine-structure using hourly vertical profiles of multiple variables show that there is a strong difference between the power and potential of different variables to detect details in atmospheric stratification. We could show that in the early night, a dynamical MLH goes along with a material MLH, due to long-range transport. In contrast a developing fog event was identified using a thermal MLH even before it was observable using a material MLH, while a dynamical MLH was absent in a similar altitude range. A material MLH still indicated the slow recovering of the fog’s aftermaths. The absence of a dynamical and thermal MLH at this time in this altitude range highlights the low dynamics due to a lack of energy, which could be converted by latent heat that hinders convective mixing.”

and the daytime (see response in next comment).

3. In section 4, the discussion focuses on the representativeness of near-surface measurements for column-averaged concentrations of CO₂, O₃, and particle number density within the lowest 500 m. This topic is closely related to the material boundary layer, particularly concerning the actual vertical distribution and mixing of atmospheric constituents. However, the entire analysis framework in Section 4 relies exclusively on planetary boundary layer heights derived from the ICON-D2 model, which is defined only by thermal PBL height. Consequently, the manuscript equates the thermal mixed-layer height with the height that governs the vertical distribution of the very tracers being assessed for representativeness. This substitution lacks justification. The authors' own nocturnal results in Section 3 have already demonstrated that thermal and material layer heights often differ. This discrepancy also applies to the daytime conditions discussed in Section 4. Relying solely on thermal PBL height as a reference for a material boundary layer issue introduces a conceptual inconsistency. Such flawed reasoning undermines the physical interpretation of the reported gradients and the R metric. The authors should either (i) derive and use material layer heights based on their own in-situ tracer profiles for the daytime analysis, or (ii) provide a rigorous justification, supported by direct comparisons, for why the ICON-D2 thermal PBL height can be deemed a reliable proxy for the material mixed layer in this context.

Thank you for pointing out that the combination of the ICON-D2 obtained PBL height and the UAS measurements might result in inconsistencies and that a more detailed explanation and justification

of this combination is missing. From our point of view, this combination is reasonable due to following aspects that were integrated into the manuscript, if not already included:

- a) The ICON PBLH is estimated on “ [...] Brunt–Väisälä frequency $> 5 \times 10^{-5} \text{ s}^{-1}$, vertical gradient of potential virtual temperature $> 0.3 \text{ K km}^{-1}$, and vertical gradient of absolute humidity must be curved” (Section 2.3). While the Brunt-Väisälä frequency and the potential virtual temperature are variables defining the thermal PBLH, the criterion of using the gradient of the absolute humidity refers to the material PBLH as defined by Tan et al. (2025).
- b) Xin et al. (2026) shows that in summer time under convective conditions different types of PBLH (categorized in Tan et al., 2025) are “tightly coupled”. This implies that markers which indicate the dynamical/thermal PBLH can also be used for a rough estimation of the material PBLH. This is probably even more the case for our rural remote measurement site, compared to a measurement in a megacity as in Xin et al. (2026), where an inhomogeneous system of convective and pollution sources complicates the analysis of PBLHs even more. Furthermore, a differentiation between nighttime and daytime BL regimes is recommended in Xin et al. (2026), when a tight coupling is not necessarily given. This is considered in our study by using solely daytime periods in section 4. The modeled PBLH was not used in section 3.
- c) The analysis of representativity and gradients in section 4 is solely applied for periods when the PBLH exceeded the probed vertical range, i.e., 500 m. Assuming a scenario, in which the thermal, dynamical and material PBLH differ by 10% would flatten the gradients in Figs. 2 and 4, accordingly. However, the interpretation would not change, since the relative uncertainty is larger anyway. Surface chemistry or diffusional losses would be affected negligibly; hence R values are even more robust.

To address your concerns and a) and b) of our response, we added the following statement at the end of section 2.3:

“The obtained model-based PBLH qualifies for comparison with trace substance and meteorological variables, as a) dynamical, thermal and material PBLHs show a tight coupling in summer daytime under strongly convective conditions (Xin et al., 2026) and b) thermal and material criteria were used in the model for the estimation of a single combined PBLH.”

and this statement in the beginning of section 4:

“Recent studies differentiate between a thermal, material and dynamical PBLH that can originate from different atmospheric processes as already shown in section 3 (Tan et al., 2025). In summer time, especially during daytime, these PBLHs are tightly coupled, hence a further differentiation is not required here (Xin et al., 2026).”

and c) in the discussion of the gradients and the representativity R in section 4.3.3:

“As the PBLH varies depending on its definition, for example, whether it is identified as thermal, dynamical or material PBLH, a 10% variability between different PBLHs in summer would result in a 10% change in the gradients of the variables in Fig. 4. However, the interpretation would not substantially change under such conditions since the relative uncertainty is larger anyway. R values

are even more robust since surface chemistry and diffusional losses occur in the lowest layer and would be negligibly affected by a slightly different PBLH. ”

References

- Tan, Y., Xin, J., Qin, X., Ma, Y., Xu, J., Du, Y., Shang, C., Zhao, L., Tian, Y., Fan, Q., Zhou, X., Ren, Y., Wang, P., Hao, F., Yin, N., Ren, X., Peng, K., Jia, D., Pan, X., Li, J., Wang, Z., and Butt, A. Q.: Differences Among Thermal, Dynamic, and Material Boundary Layers Over Complex Terrain, *Journal of Geophysical Research: Atmospheres*, 130, <https://doi.org/10.1029/2024jd043043>, 2025.
- Xin, J., Ahmed, M., Tan, Y., Tang, G., Ren, X., Zhao, D., Yang, L., Qiu, N., Cao, J., Lei, Z., and Ma, Y.: Seasonal Evolution of Thermal, Dynamic, and Material Boundary Layers and their impacts on air pollution in the Megacity Beijing, <https://doi.org/10.5194/egusphere-2026-4121>, 2026.