

Reviewer #2:

The authors presented a very interesting vertical profiling study of meteorological parameters and air pollutants in Germany using an uncrewed aerial system (UAS). Detailed analysis on mixing layer and boundary layer heights were performed using various criteria, and justification given. It also provided interpretations on how the dynamics of planetary boundary layer (PBL) affects vertical distributions of air pollutants, as well as how representative ground-based measurements are to cover the lower part of the PBL. Recommendations are given for accurate identification of the mixing layer and boundary layer heights in both nighttime and daytime scenarios, as well as to reconcile the ground-based and vertical measurements to better represent the relationships between emission and PBL dynamics that shape air pollutant distributions. The study can be published after some minor revisions, and my comments are given as below.

Thank you for your positive review. We incorporated your feedback and/or commented on them in blue.

- Although the authors justified that an extensive comparison is out of the scope of the current study (P13/L357), brief mentioning on recent studies of vertical profiling using UAS in some proper locations in Introduction and Discussion sections might help readers to appreciate the uniqueness of the current study.

Indeed, the integration of our work into previous research was not clear. We added a paragraph in the introduction:

*“Recent studies used multi-platform approaches to improve UAS-based characterization of PBLs. UAS fleets have been applied to monitor atmospheric transport in a horizontal plane (Wetz et al., 2023), or vertical profiles to rule out temporal changes in the probed air masses (Borchers et al., 2025). Ground-based measurement stations have demonstrated to be not always useful as a reference (Barbieri et al., 2019), but also for spatial and temporal correction of UAS-based measurements for in-flight characterization of measurement instruments (Greene and Salesky, 2023; Moormann et al., 2025). For boundary layer studies, such multi-platform studies focused on, e.g., wind dynamics (Greene et al., 2022), altitude- and daytime-dependent aerosol composition within the PBL (Borchers et al., 2025), reconstruction of PBLs after the passage of rain fronts (Moormann et al., 2026), or the air pollutant distribution near civilization (Pohorsky et al., 2025). Furthermore, UAS can detect shallow layers near the ground by variables indicating material, dynamical and thermal mixing layer heights (Greene et al., 2022; Chilinski et al., 2024; Moormann et al., 2026).*

*Two fundamental assumptions for such studies are the representativity of UAS measurements within the PBL in general and the comparability of variables between UAS- and ground-based measurements. Greene et al. (2025) addressed the first assumption along with recommendations for sampling strategies, while this study focuses on the second one, using parallel UAS-based and ground-based in-situ measurements at two similar hilly rural sites in Central and Southern Germany during summer to evaluate [...]”*

And in the summary/discussion section:

*“Night-time vertical profiles of temperature, humidity, wind speed, and trace matter (CO<sub>2</sub>, O<sub>3</sub>, particle concentrations) in the lowermost 120 m were used to detect fine-scale nocturnal*

*stratification as an extended multi-variable approach, in contrast to studies relying on either only a few pollutants (Chilinski et al., 2024; Pohorsky et al., 2025), or solely dynamical tracers (Jozef et al., 2022). To detect shallow mixing layer heights (MLH) on an hourly time scale, we applied the criterion "strong gradient change" to each variable and minimized methodical errors due to temporal air masses changes throughout a flight by a ground-based measurement station as recommended by Greene and Salesky (2023)."*

and

*"Based on gradient-based similarity relationships (Greene et al., 2022; Sorbjan, 2010), we found that solar irradiance should be used as an additional parameter, in addition to PBLH, to describe vertical gradients, [...]"*

- There are a few places that measured data can be provided or referred to, so as to make the points more clearly.

1) P6/L185: I thought latent heat flux was measured in the ground-based MoLa (P4/L103). Please show data to support the statement here in P6/L185.

Thank you for this comment. Highly time-resolved data of temperature and 3D wind have been measured with a flux tower 25 m distant to MoLa (Annex A1). A time series is now included, which shows an increase of the latent heat flux after the fog event in agreement with the statement in the text, while the turbulent kinetic energy remains an order of magnitude lower compared to the campaign's morning mean, reflecting reduced mixing of the lowermost atmosphere. We now have included a comment and reference to the new Fig. S5 in the manuscript:

*"Apparently, the preceding fog event initiated the formation of a cold pool during night (Chachere and Pu, 2016), which converts turbulent energy into an upwards directed latent heat flux and may have formed a shallow inversion layer in  $(45 \pm 5)$  m above the ground (Wilson and Fovell, 2016). Fig. S5 shows that despite irradiance levels during this morning are similar to the campaign's morning mean, turbulent kinetic energy is a magnitude lower than usual at this time of the day, while latent heat flux remains unaffected and still increases until the air is dried to 75% RH."*

Figure S5 is presented here:

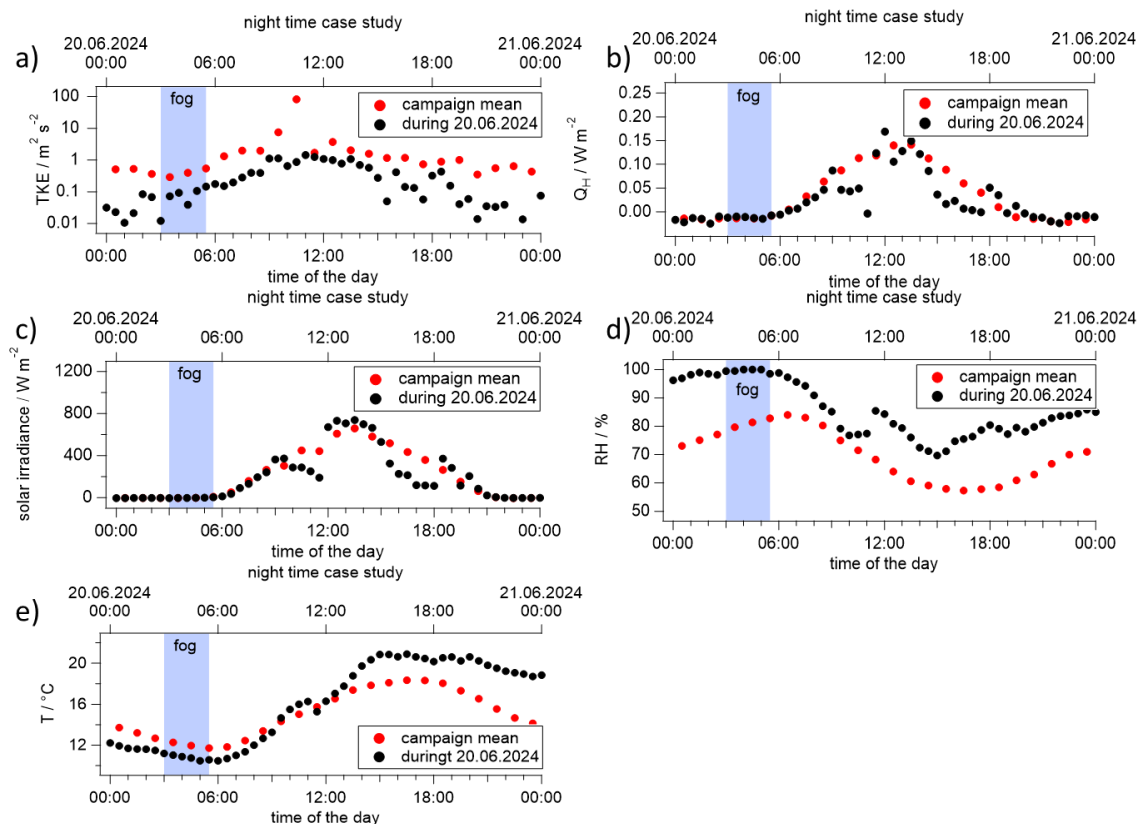


Figure S5: The comparison of the thermodynamical variables turbulent kinetic energy (a), latent heat flux (b), solar irradiance (c), relative humidity (d) and the temperature (e) between the night of the case study and the diurnal mean of the campaign shows similar irradiance and latent heat flux levels, while the turbulent kinetic energy is decreased in the case study night. Available energy is consumed to dry the air rather than to enhance convective mixing, which postpones the expansion of the lowermost atmospheric layer.

2) P9/L280: please show or refer to the data of correlation between PBLH and irradiance.

A reference to Fig. S7 can already be found at the end of the paragraph.

- There are a few places that the authors used O<sub>3</sub> titration by NO to interpret steep slopes of O<sub>3</sub> profiles in early morning and/or foggy conditions. This chemistry is for sure real and may be responsible. But can the author provide a brief comparison of time scales of passive diffusion, active convection, and O<sub>3</sub> + NO reaction to further support that it is the case?

You are correct that there is more than one way to lose O<sub>3</sub>, however chemical loss is the most relevant process:

We included this text in L365:

*“For a general understanding, a rough comparison of the efficiency of physical and chemical loss mechanisms might be useful to demonstrate the relevance of different loss pathways. The chemical loss of O<sub>3</sub> by reaction with NO can be estimated by using the rate constant  $k_{\text{NO}+\text{O}_3} = 1.9 \times 10^{14} \text{ cm}^3 \text{ molecules}^{-1} \text{ s}^{-1}$  and a reasonable NO concentration  $[\text{NO}] \approx 0.1 \text{ ppbv}$  during night and  $[\text{NO}] \approx 0.5$*

– 1.0 ppbv during daytime (Dewald et al., 2022; Iupac, 2025), resulting in lifetimes  $\tau_{chem} = \frac{1}{k_{NO+O_3}[NO]} \approx 30 - 60 \text{ min}$  during daytime and up to 10 h in the night. Physical loss due to diffusion can be estimated by the related lifetime  $\tau_{diff} = \frac{L^2}{K_z}$  with the vertical length  $L$  and the eddy diffusivity  $K_z$ . Assuming  $L=25 \text{ m}$  for the vertical range that is relevant for chemical processes, and  $K_z \leq 0.1 \text{ m}^2 \text{ s}^{-1}$  for moderately stable conditions as in the morning and during night time (diffusion dominated) and  $K_z \approx 1 \text{ m}^2 \text{ s}^{-1}$  for convective conditions as during the day (turbulence dominated) above grassland (Stull, 1988). We can now estimate a diffusion-related lifetime  $\tau_{diff} = 2 \text{ h}$  for stable and a convection-related lifetime  $\tau_{conv} = 10 \text{ min}$  for convective conditions. The lifetimes  $\tau_{chem}$  and  $\tau_{diff}$  are in a similar range, while convective conditions reduce the lifetime. This shows that chemical and physical loss are both relevant depletion pathways and mainly depend on the convective conditions and prevalent NO levels.”

- For PNC, the authors assumed that they are mainly from direct anthropogenic emission and disperse by convection. Was there any new particle formation (NPF) and growth events captured in the campaigns (say in more sophisticated size distribution measurements in MoLa) that might affect this assumption?

Thank you for this comment. On average, the majority of the particles originates from anthropogenic emissions, e.g., air masses from the Frankfurt area (Fig. S2), however NPF took place frequently in the early afternoon as recorded by MoLa (Fig. S9). Therefore, during these times, NPF might be the dominating source over advected anthropogenic air masses. Gradients in the morning are likely due to regional emissions near the ground as the mixing in the morning of the lowermost layers is not sufficiently strong to homogenize the pollutant distribution in the lowest 500 m. We have changed the text in Section 4.2.2 accordingly:

*“PNC<sub>>10 nm</sub> reflects processes in the particle phase and is strongly influenced by anthropogenic emission sources at ground-level, noting that particle formation also happens naturally under radiative influenced conditions also at higher altitudes (see. Fig. S9).”*

to:

*“PNC<sub>>10 nm</sub> reflects processes in the particle phase and can be influenced by anthropogenic emission sources at ground level or by new particle formation (NPF). Figure S2 shows that, although polluted air doubles the particle number concentration, anthropogenic air masses advected from the Frankfurt area are already well-mixed at the measurement site and do not show a gradient in PNC<sub>>10 nm</sub>. Continuous size-resolved particle size distribution measurements (>7 nm) by MoLa at ground level indicate NPF starting around noon on most days, when NPF-precursors are well-mixed in the lowermost layers (Fig. S9). Therefore, NPFs happens along the whole vertical range. Conclusively, the gradient of particles, observed in the morning, is likely due to regional emissions near the ground, when convection has not homogenized the material PBL, yet.”*

- P10/L312: I thought the FLab measurements were up to 500 m only. Where did the data at 1300 m come from? Remote sensing from MoLa? Please clarify.

Indeed, Flab measurements were limited to 500 m above ground level, however, the planetary boundary layer height (PBLH) was estimated by model data, which covers the altitude range from

0 m to several thousand meters above ground level. This was clarified in the sections' first paragraph: *The PBLH was derived from the ICON-D2 model as described in Sect. 2.2.*

- P16/L411: it is not clear whether the 0-25 m results were from ground-based measurement only, or the average of the bins below 25 m from the UAS measurements. Please specify.

In Sect. 4.3.1 we now specify that we have only used UAS measurements for this part of the study:

*“R is the ratio of the mean vertical column value of the lowermost altitude bin (0 - 25 m a.g.l., for 25 m vertical resolution, from drone measurements only) for a certain variable to the respective mean column value over the lowermost 500 m range and [...].”*

- P20/L509: the underestimation of O3 is much larger than 5% shown in Figure 6, and the statement here is inconsistent with the statement in P23/L613. Am I missing anything?

You are right, including the largest uncertainty bar we end up with an  $R = 0.94$ , i.e., an underestimation of 6% (right y-axis in Fig. 6). This was corrected. The statement in P23/L613 refers to the morning and evening hours when several atmospheric layers were present in the lowermost 500 m. However, the values given in P20/L509 refer to stratification-free conditions, as now implemented in the text.

*“Mixing ratios of trace gas variables as CO2 and O3 in the stratification-free lowermost 500 m can be measured at ground with a slight underestimation by 0-2% and 0-6%, respectively.”*

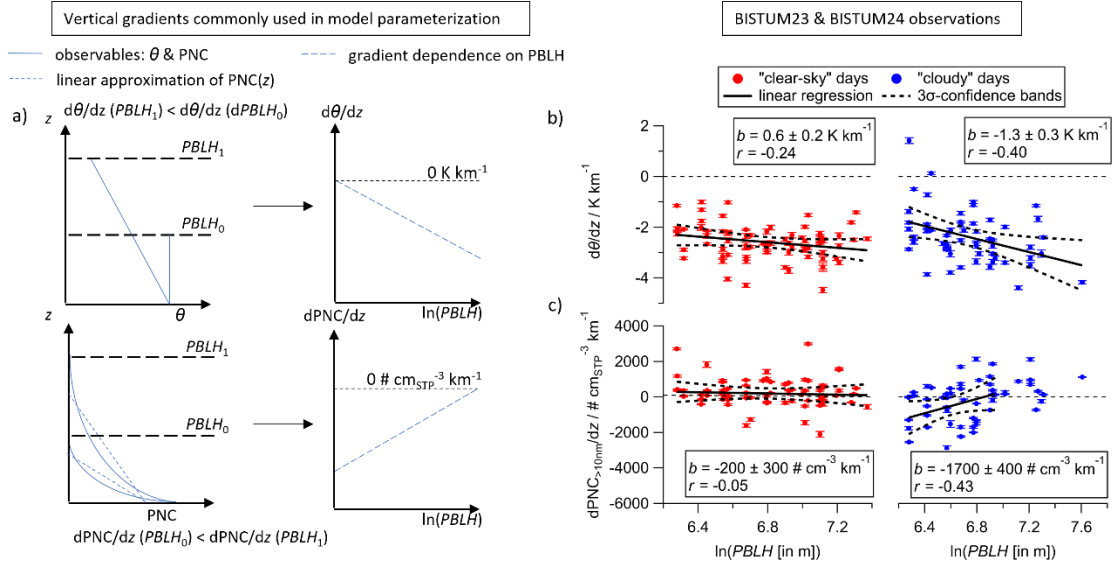
- Section 4.4: the first point of the recommendation is about estimation of PBLH, which makes this section not just about the representativity of ground-based measurements. Better to merge it into Section 5.

Here, we argue from the point that knowing the PBLH helps to estimate the pollutant distribution, see the whole section 4.2.1. With more accurate (more or less frequent) experimental estimations of the PBLH, model estimations are expected to be improved on the long term. In the summary, we refer to this in P25/L630:

*“Further we propose that a vertical characterization should be conducted for every ground-based measurement site to estimate site-specific effects and validate the use of model-derived PBLHs to estimate the range of representative ground-based measurements.”*

- Figure 2: should the schematic sketch of  $dPNC/dz$  vs.  $\ln(z)$  (panel a) have a positive slope as what is shown in cloudy days (blue) data points in panel c?

Thank you for pointing this out. The “ $dPNC/dz$ ” in the right bottom graphic in Fig. 2a) on the y-axis was supposed to show the absolute value of the gradient. For clarity, the blue dotted line was flipped and now shows the value itself, i.e. an increase from a negative value at very small  $\ln(PBLH)$  to larger (negative) values at larger  $\ln(PBLH)$ . Additionally, we added the linear approximation of  $PNC(z)$  in panel a) to clarify that  $dPNC/dz$  was determined from this linear approximation and not from the exponential functions which are theoretically expected. This was added to the legend.  $z_1$  was changed to  $PBLH_1$  as we describe the gradient-dependency with respect to the PBLH and not to an arbitrary altitude. The new Fig. 2 is shown here:



**Figure 2:** (a) Schematic description of the dependency of atmospheric stability (reflected by  $\theta(z)$ , with the altitude  $z$ ) and a pollutant with source at ground level ( $PNC(z)$ ) on altitude for the well-mixed planetary boundary layer with a height  $PBLH_i$  as commonly used in model parameterizations (a, left). Deriving the dependence of  $d\theta/dz$  and  $dPNC/dz$  from PBLH results in a linear-logarithmic dependency of respective gradients on the boundary layer height (a, right). Experimental data of gradients of the potential temperature  $\theta$  (b) and the particle number concentration  $PNC_{>10\text{ nm}}$  (c) in the lowermost 500 m in a mixed PBL from both campaigns are plotted versus associated logarithms of respective planetary boundary layer heights ( $PBLH$ , in m). Linear regression with the slope  $b$  and its 3 $\sigma$ -confidence bands are depicted in solid and dotted lines.

Figures 4 and 5: the legend labeling is a bit misleading. Should it be (closed blue circle): “cloudy” days for 0 – 500 m, (open blue circle): “cloudy” days for 0 m to  $PBLH$ , (closed red circle): “clear-sky” days for 0 – 500 m, and (open red circle): “clear-sky” days for 0 m to  $PBLH$ ?

Thank you for this comment. We changed the legend according to your suggestion to make the graphic easier to read.

- Figure 6: better to rearrange parameters in the x axis according to the discussion, i.e., air pollutants first, and then meteorological parameters, as two clearly separated categories.

We have already tried to separate the parameter type according to the discussion (from left to right: pollutants, meteorological parameters on each x-axis). This was done using two x-axes, so that the representativity  $R$  can be scaled differently to better display the uncertainties from the analysis. The left y-axis scaling covers  $R = 0.5 - 1.8$  and the right y-axis scaling included only  $R = 0.9 - 1.15$ . We prefer not to change the order to keep the scaling easy to read.

- P8/L242: a typo for  $PBLH$ .

This was corrected.

- P13/L352: “permanent” to “static”?

This sentence deals with temporal variability, hence “not permanent” seems to be the better choice to us.

- P14/L384: “stronger” to “more strongly”.

This was changed.

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