

Response Reviewer 1: egosphere-2026-684

We thank the referee for the valuable comments and constructive suggestions. These comments are appreciated and will be carefully addressed in both the response and the revised manuscript.

The main aim of this study is to investigate whether the prototypical nocturnal boundary layer above tropical rainforests, as commonly represented in weather and climate models, adequately captures the actual dynamics of this layer. To this end, we make use of a comprehensive observational dataset that enables us to analyse, the nocturnal boundary layer height evolution (Fig. 2 in the manuscript), characteristic vertical profiles of turbulence and state variables (Fig. 3 and 5 in the manuscript), the stability within and above the canopy (Fig. 4), as well as an estimation of the mechanisms that drive the above canopy evolution of state variables. The latter mechanisms include buoyancy consumption, shear production, longwave cooling rate, among others (Fig. 6, 7, and 8)

A main focus has been to characterize the dynamics of the stable boundary layer overlying the forest, with the available observations of the CloudRoots-Amazon22 measuring campaign. There, we analysed its extent, its degree of stability and the drivers of its diurnal evolution. However, references to within-canopy processes are necessary to properly interpret the coupled system. We analysed within-canopy properties (Fig. 3 and 5 in the manuscript) and stability (Fig. 4), although our within canopy analysis was limited by observations, which lacked important information such as within-canopy longwave radiative transfer, leaf and branch temperatures.

In the revised version of the manuscript, we will further strengthen and clarify this central objective throughout the paper. Below we will respond to the comments raised one by one. If changes are indicated in the manuscript, the adjusted text is coloured in blue.

Major comments

Comment 1: *There are two radiative coolings at night: longwave radiative cooling from the surface and the canopy layer, and the cooling associated with vertical radiative divergence within the air layer, either above or within the canopy. For the development of the NBL, radiative cooling below the NBL is generally much more important than vertical radiative divergence, based on previous field observations as far as I understand. It is therefore important to distinguish the two especially when discussing radiative cooling from the soil surface and the canopy surface. I was often confused about which process was discussed in the manuscript.*

Response 1: We acknowledge the difference between the longwave radiative cooling from the surface and the cooling by atmospheric vertical radiative divergence. In the revised manuscript we will be clearer on which definition we use. Longwave radiative cooling of the canopy can be defined as the heat lost by the surface (including canopy and soil) during the night. Longwave radiative vertical divergence is the rate at which the atmosphere itself gains or loses heat due to the net radiation difference between atmospheric layers. In this study, we focus on the cooling of the atmosphere above the canopy associated with the vertical divergence of radiative fluxes. This is the term that appears in the governing heat equation (Eq. 4 in the Manuscript). In the revised manuscript for clarification, we will rename radiative cooling with atmospheric longwave cooling rate when we refer to this vertical radiative divergence. To prevent further confusion, as shown below, we will clearly state in Section 2.5.2 with the introduction of Eq. 4, that we refer to the vertical radiative divergence term as atmospheric longwave cooling rate from that moment onward.

(L 164 – 166 in manuscript): In Eq. 4 the net tendency of θ ($\partial\theta/\partial t$), is controlled by three terms, from left to right: the turbulent transport of heat (term 1), the **vertical longwave radiative divergence (atmospheric longwave cooling rate from here onward)** (term 2), defined such that the radiation is positive towards the (canopy) surface and R_θ (term 3).

Additionally, for the interpretation of the results (Fig. 7 in manuscript), it is important to stress that we only study the layer on top of the canopy. Because there are no multiple level radiation measurements

available (only at 75 m), we estimated the longwave radiative profiles using the RTE+RRTMGP with input from ERA5 (Appendix A in manuscript). The input data of ERA5 does not describe a detailed canopy layer and can therefore not be used to estimate the within canopy radiative divergence.

As can be seen in Fig. 7 and Fig. A1 from the manuscript, the largest longwave radiative divergence occurs at the canopy-atmosphere interface (Fig. A1), here the atmospheric longwave cooling rate is at its maximum (Fig. 7). We expect this strong longwave radiative divergence to be driven by the strong radiative cooling that takes place near the canopy top, where the net loss of longwave radiation is maximized. This radiative cooling gives rise to two distinct dynamical effects. First, it promotes the formation of the nocturnal boundary layer (NBL) above the canopy, which is the primary focus of this study. Second, it contributes to the gradual development of a relatively well-mixed layer within the canopy itself. The coexistence of these two responses highlights the key role of canopy-top radiative cooling in shaping the nocturnal structure of the forest-atmosphere system.

Finally, we want to clarify the text in line 245 where we stated: “We hypothesise that the mixing within the canopy layer originates from the cold layer forming on top of the canopy following the strong longwave radiative cooling.”

(L 245 -247 in manuscript): We hypothesise that the mixing within the canopy layer originates from the cold layer forming in the dense canopy crowns, where the biomass of the vegetation radiatively cools, creating a locally cold layer, promoting sinking motions due to density changes and enhancing convective turbulence, in the canopy layer.

Comment 2: *With the above considerations in mind, my major confusion is why the authors used six criteria to classify the observation based on previous investigations. Although the fundamental physics governing the atmospheric boundary layer is the same, the observation heights and canopy structure in this study differ from all the studies listed in Table 1. Why can the authors not analyse their own observations directly and then highlight the unique characteristics of different stability regimes based on what they observe? After reading the abstract, I expected a comparison between the air layers above and within the canopy and kept looking for distinct stability regimes in each layer. Only after reading the manuscript several times, I realized that all six criteria are based on observations above the canopy layer. Thus, the distinction between strongly and weakly stable regimes applies only to the air layer above the canopy.*

Response 2: We understand the confusion of the referee and acknowledge that our description should be clarified. Our criteria are indeed applied to the atmosphere aloft of the canopy, although we also explore how these regimes are related to the stability within canopy in Fig. 4. As mentioned before, our main interest is the stable atmosphere above the canopy, however we make references to the in-canopy atmosphere to understand the results. We justify the use of the six criteria based on the prototypical NBL profiles described by Stull (1988), which are currently used in weather and climate models to describe the NBL. These criteria are among others, used in the ECMWF-IFS model, because its resolution is too large to resolve the stable boundary layer (Edwards et al., 2020). Given that these prototypical NBL profiles are used in weather and climate models to simulate the NBL, it is important to understand the physical behaviour of these prototypes. At the same time, it is important to acknowledge that these prototypes are only observed in less than 6% of the time (as indicated by the reviewer), causing a mismatch between reality and models. The comparison of the six criteria is also valuable because of the diversity of processes governing the nocturnal boundary layer. These include temperature stratification, wind shear, and turbulence, each of which influences the structure and evolution of the NBL in different ways. Evaluating multiple criteria therefore provides a more comprehensive assessment of NBL formation and development than any single metric alone.

In the revised manuscript we will clarify the description for the criteria for strongly and weakly stable profiles in Section 2.2 as follows:

(L 90 – 97 in manuscript):

2.2 Criteria for assessing strongly and weakly stable regimes

To distinguish between the strongly and weakly stable regimes, we employed six criteria (θ , CO₂, U, Ri, TKE, u^*) that describe prototypical NBL profiles based on previous characterisation studies, adjusted to the CloudRoots observations (Table 1). More specifically, the criteria are based on gradients between 50 and 25 m for θ and 79 and 39 m for CO₂. We determined thresholds on the degree of stratification (Stull, 1988) (Table 1), which are consistent with the strongly and weakly stable characterisation reported by Culf et al. (1999). The other four criteria are based on thresholds found in the studies indicated in Table 1.

These prototypical NBL profiles are important for the parameterization of the NBL in numerical weather models (Edwards et al., 2020). Therefore, it is crucial to understand how well these prototypical profiles represent the nocturnal observations in the Amazon rainforest. It is well known, that NBL parameterizations are often based on grassland observations, hereby not considering the canopy-atmosphere interactions. Since NBL parameterization normally coarsely reproduced canopy layer, the vertical profiles can only be related to the above canopy atmosphere, where the stable stratification forms. Because of this we apply our six criteria, to the atmospheric layer above the canopy.

Comment 3. *Since the study deals with turbulent transfer across the two layers, a brief description of turbulence measurements such as sensor types and data processing methods would help readers understand the data used in the study even if detailed information is available elsewhere.*

Because the study concerns the CO₂ and heat exchange between the two layers, it is also important to know the canopy density, tree types, and whether low vegetation is present near the soil surface.

In addition, because the analysis is based on measurements from two towers, the manuscript should specify how far apart the two towers are and whether they are within the same forest stand.

Response 3: Thank you for pointing out the difficulties in understanding the data used. Even though all the information is available in the literature mentioned in the manuscript, we will add the important information to the data description (Section 2.1). We will clarify your questions on data one by one below (all this information will be added to section 2.1):

- The turbulent measurements were done with 3D ultrasonic anemometers and processes with Eddy Pro; raw data has been processed over 30-minute periods using Reynolds averaging. A more elaborate description including other measurement devices used will be added to the data description in the revised manuscript.
- The vegetation at the ATTO site can be characterized as a dense tropical forest with a LAI of approximately 5.3 m²m⁻² (Gomes Alves et al. (2023)). The leaf area density profile is bimodal, indicating the presence of an understory vegetation layer at approximately 4 m (see Fig. 2b of Gomes Alves et al. (2023))
- The 325 m ATTO tall tower (-2.1448° N, -59.0008° E) and the shorter 81 m Instant tower (-2.1468° N, -59.0068° E) are 670 m apart. The Instant tower is densely surrounded by vegetation while the ATTO tower is located in more disturbed and open forest. Here it is important to know that the within canopy measurements were done on the INSTANT tower, therefore the within canopy measurements are representative for dense forest canopy.

Comment 4: *I am particularly puzzled by evaluation of the boundary layer height. From what I understand, the measurement extends only to 298 m, assuming above the ground. With an average tree height of about 20 m, the maximum depth of the air layer above the canopy layer is therefore about 278 m. Considering the development of the stable air layer above a cooling surface, the NBL impacted by the surface can be quite shallow. Therefore, the NBL height, h_{NBL} , might be directly inferred from vertical profiles of turbulent variables measured from the two towers. Furthermore, any coupling between the two layers should be readily observable from the vertical variation of turbulent variables across the two layers under different conditions.*

Response 4: To clarify the confusion, our criteria to calculate the boundary layer height (as measured from the soil surface) are again based on the book Stull (1988). To our knowledge this comprehensive range of estimation criteria based on NBL physics has never been applied to the data set. The goal of comparing multiple criteria is to determine which method yields most reliable estimates the NBL height. Additionally, the study shows that the gradient method is a trustworthy alternative for turbulence-based estimates, if vertical flux profiles are not available (which is the case for a lot of atmospheric vertical towers).

Even though a recent study by Mendonca et al. (2025) shows that turbulent fluxes can estimate the h_{NBL} . We find that only using the turbulence measures is not sufficient in strongly stable conditions, where turbulence is almost absent. These strongly stable conditions are often observed in the two-week measuring period, occurring in the Amazonian dry season. In the strongly stable periods, as can be observed from Fig. 2 (TKE, Ri and u^*), very often random patterns are observed in the turbulent vertical profiles, which makes the h_{NBL} calculations with turbulent based variables complicated. Here the potential temperature gradient ($\partial\theta/\partial t$) criteria is a more trustworthy method to determine h_{NBL} .

We agree with the referee that the coupling can be determined based on the turbulent flux between the two layers. As can be observed in Appendix B, if the two layers are coupled in the weakly stable regime there is a negative heat flux ($w' > 0, \theta' < 0$ or $w' < 0, \theta' > 0$) observed above the canopy. However, the goal of Section 2.3 is to estimate the h_{NBL} , in the results Sections 3.2 and 3.3 we investigate the coupling between the two layers in more detail. In the revised manuscript we will highlight the relation between the coupling of the two layers and fluxes in more detail in Sections 3.2 and 3.3. Below some examples are given.

(L 279 – 281 in manuscript): In the weakly stable night, Ri_{can} decreased between 22:00-02:00 LT, indicating a coupling between the stable and canopy layer where mixing between the two layers is possible, this is in accordance with the observations in Santos et al. (2016).

(L 305-306 in manuscript): We observe that in the weakly stable regime, the increased U results in $0.2 \text{ m}^2 \text{ s}^{-2} > \text{TKE} > 0.4 \text{ m}^2 \text{ s}^{-2}$, $Ri < Ri_c$ and $0.2 \text{ m s}^{-1} > u^* > 0.3 \text{ m s}^{-1}$ at 50 m (Fig. 5def). Additionally, in profiles of TKE and u^* (Fig. 5df) there is mixing observed between the within canopy and atmosphere aloft, indicating that the two layers are coupled in this regime.

(L 358 – 359 in manuscript): The difference can be explained by enhanced shear in the weakly stable regime, which increased transport of cold air from within the canopy to aloft, the transport of cold air around the canopy top can be observed in Appendix B, Fig. B1.

Comment 5: *The description of the data used in this study is confusing. See my detailed comments below.*

Response 5: Thank you for pointing out the points that are not clear below, before we tackle those comments, we want to give some general response, resolving hopefully already part of the confusion. In the results, for Sections 3.1 and 3.2 the complete data range of the campaign between 8 and 19 August 2022 has been used. Note here that officially the campaign lasted until 21st of August, but we decided to use the data up to the 19th due to data limitations (We will clearly state this in the revised manuscript). Only in Section 3.3 does the analysis make use of the selected hours indicated in Table 2, which represent the prototypical NBL profiles. To avoid future confusion, in the revised manuscript, we will explicitly mention this in the introduction of both the methods and results sections. Additionally, as you suggested we plan to state the used data range in all the Figure captions.

Detailed comments

Figure 1: Is this figure intended as a schematic illustrating the five criteria? Also are NLLJs frequently observed under the strongly stable conditions?

Response: Indeed, the figure is intended as the schematic illustration of the five criteria. The NLLJ has been observed during two nights in the period between 8 and 19 August 2022. As mentioned in the results

L 212 on the night between 12-13 August and 17-18 August. However, to guide the reader we will add this information to the methods:

(L 116 – 117 Manuscript): The U criterion was subdivided into two parts, based on whether a nocturnal low-level jet (NLLJ) Blackadar (1957) is observed above the NBL or not. In the measuring period of the CloudRoots campaign a weak NLLJ was observed in two nights (12-13 August and 17-18 August).

L.112: What is h_{θ} ?

Response: h_{θ} is the estimated h_{NBL} found by using the criteria based on θ . The description can be found in L 103.

L 119: How do the authors justify the assumption of $U=U_g$? It seems to me that this is an unnecessary assumption, especially if the goal is simply to classify the strongly and weakly stable regimes.

Response: Thank you for pointing this out, we did some further investigation and discovered that it is indeed not valid to use the windspeed measured at 298 m, to estimate U_g . During the measuring campaign radio soundings were released during two hours in two nights (00:00 and 03:00 LT on the 12th and 13th of August) (Fig. 1). In Fig. 1 we observe that U_g is reached around 2000 m height. Between 2000 m and 5000 m we find a four-hour average value of U_g of 10 m s⁻¹. At 298 m we find a four-hour average windspeed of 4.3 m s⁻¹. From this we can conclude that we indeed cannot estimate U_g with the windspeed measured at 298 m.

However, we want to be able to estimate our h_{NBL} directly from our observed vertical wind profile. We therefore plan to instead calculate the h_{NBL} with an alternative method based on the vertical wind speed profile. We propose to use the vertical gradient ($\partial U/\partial z$) and estimate h_U with a similar method as for θ and CO₂. We believe this to work based on the logarithmic wind speed profiles observed in Fig. 2 (3rd row).

The method can be explained based on the NBL physics. On top of the boundary layer where friction is very low, the wind speed becomes constant with height, based on this principle we can find h_U once $\partial U/\partial z \sim 0$ ms⁻¹. In Fig. 2 (3rd row), we show the results for one night (11-12 August), the remaining nights show similar results. In this night we find values for h_U , between 100 m and 200 m, which is in accordance with our results based on the other four methods. In Fig. 3, we show the updated version of Fig. 2 from the manuscript. In Fig 3. we can observe that h_U estimated with the new method closely approaches the five methods mean. Nevertheless, we must stress one limitation, no value for h_U can be found with linear vertical wind profiles, (05:00 and 06:00 UTC in Fig. 2), as the gradient does not reach 0 m s⁻¹.

In the Manuscript, we will update Section 2.3 and 3.1 and Figures 1 and 2, according to explanation above.

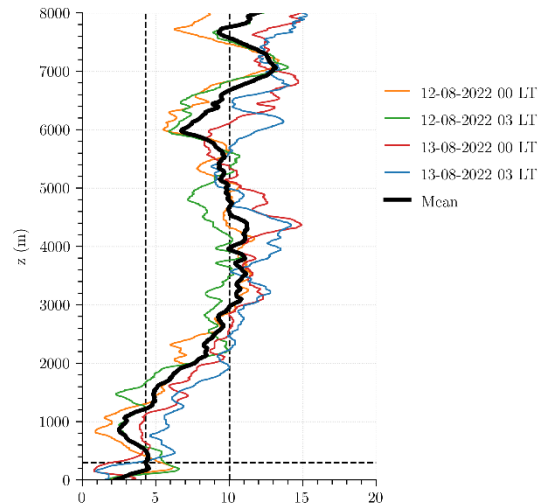


Figure 1. Radiosonde profiles of windspeed, during four periods in two nights. Here the thick black line indicates the mean of the two profiles, the horizontal dotted line the highest tower measurement at 298 m, and the vertical dotted lines the average windspeed at 298 m and the average Geostrophic windspeed between 2000 and 5000 m.

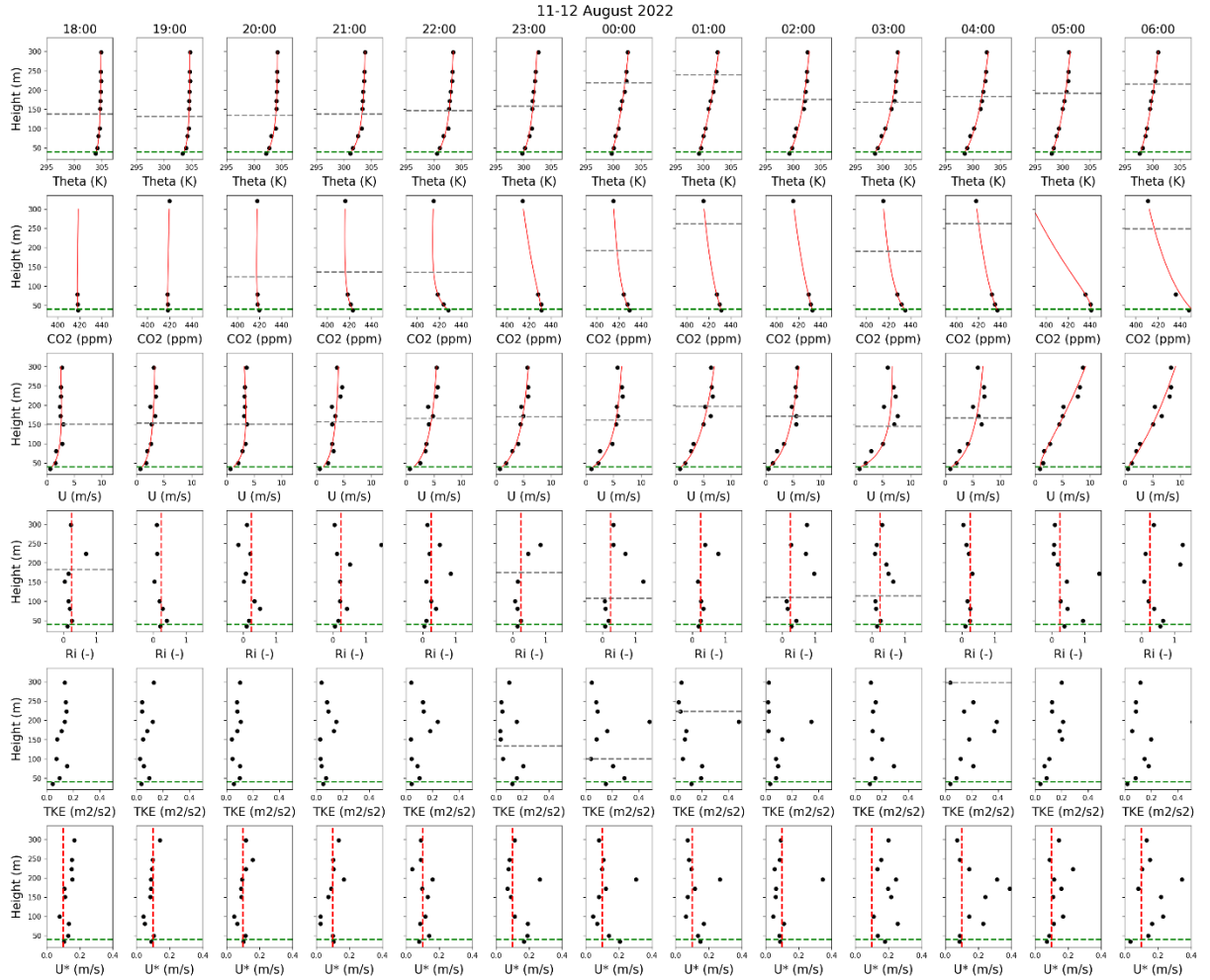


Figure 2. Vertical profiles from top to bottom: θ , CO_2 , U , Ri , TKE and u^* . The black dots represent the tower observations, the red lines the fitted logarithmic profiles, the horizontal green line the canopy top, the horizontal grey line the estimated h_{NBL} , the vertical red line for Ri the critical Richardson number (0.25) and for U^* the threshold value of 0.1 m/s.

L 123: If “sufficient turbulence above the canopy is required for the application of the criteria”, why is it necessary to separate the strongly and the weakly stable stratification?

Response: To clarify, only for the estimation criteria based on Ri (Fig 1d) and TKE (Fig 1e), sufficient turbulence is needed, so according to Table 1 (in the manuscript) below 0.25 for Ri and above $0.1 \text{ m}^2 \text{ s}^{-2}$ for TKE . The separation is needed because if there is limited turbulence h_{NBL} will always be found at the canopy top for strongly stable periods, because the conditions to define h_{NBL} will be already met here. We plan to clarify in the following way.

(L 123-124 in manuscript): The final two methods, based on Ri (calculated as the gradient Richardson number) and TKE , are only applied in the weakly stable regime, as sufficient turbulence (below (above) Ri_c (TKE) thresholds mentioned in Table 1) above the canopy is required for the application of the criteria. The above distinction is needed for Ri because if $Ri > Ri_c$ at the canopy top the h_{Ri} will always be found at the canopy top based on our method. For TKE we need the distinction because if $TKE < 0.1 \text{ m}^2 \text{ s}^{-2}$ at the canopy top, TKE_0 already approaches zero and does not decrease by 80% in the vertical profile.

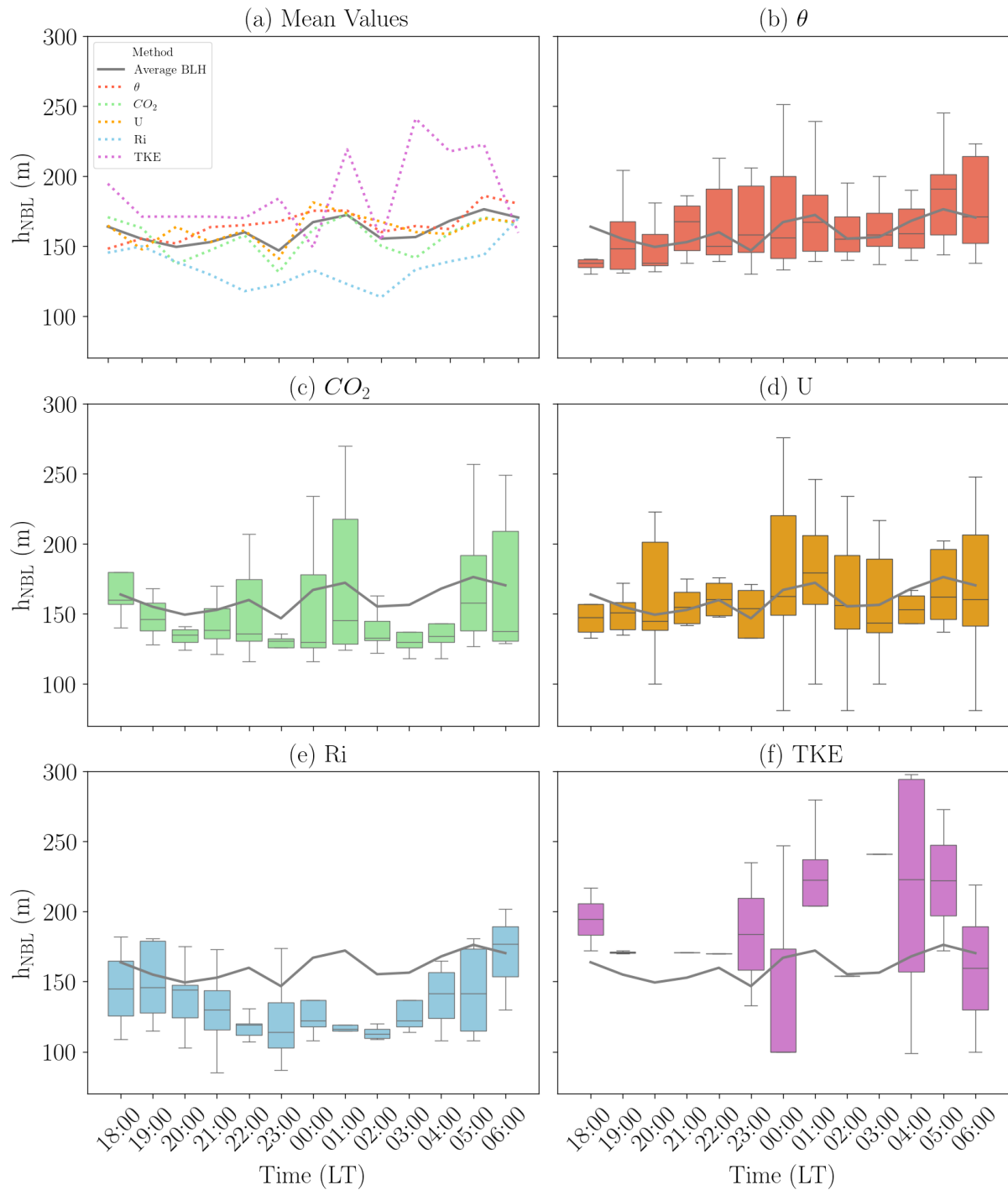


Figure 3. New version of Figure 2 in the manuscript. Hourly nocturnal boundary layer height in LT (UTC-4), estimated for the period between 8 and 19 August 2022. Panel (a) gives the mean boundary layer height for each of the five criteria (θ , CO_2 , U , Ri & TKE) and the average of those five criteria (grey line). The remaining five graphs give the variation between the nights for every hour, for (b) potential temperature (θ), (c) CO_2 , (d) windspeed (U), (e) Richardson number (Ri) and (f) turbulent kinetic energy (TKE). Here, the grey line represents the five-criterion mean boundary layer height.

L 126: At which measurement level is TKE assumed to be 0.2 TKE₀?

Response: To clarify, there is no constant level where TKE is assumed to be 0.2 TKE₀. It should be interpreted as a threshold to find h_{NBL} with the TKE criteria. We will clarify this in the manuscript as follows.

(L 125 – 126 in manuscript): h_TKE is determined where TKE has been largely reduced compared to its value at the canopy top. We find the values of h_TKE at the first height where $TKE = 0.2TKE_0$, where TKE_0 is the observed TKE value at the canopy top. We chose to use a threshold of 20% of the TKE values relative to the canopy top (instead of 5%), due to predominantly stable conditions during the observation period (Fig. 1e).

Eq. (2). Ri_can is not actually an in-canopy layer Richardson number as stated in L. 133. Instead, it represents a Ri across the canopy top.

Response: We agree with the referee that Ri_can represents the stability of the canopy layer including the canopy interface and the first meters of the roughness layer. Therefore, it indeed accounts for the stability across the canopy top. We will stress this in the revised manuscript:

(L 131 in manuscript): we introduce Ri for the stable layer above the canopy and within canopy atmosphere which includes the canopy roughness layer reaching until 35 m height.

L. 157: Do the authors mean horizontal advection of TKE?

Response: No, we understand the confusion, but with advection of TKE we mean both the horizontal and vertical advection of TKE. We will change ‘advection’ to ‘horizontal and vertical advection in the manuscript for clarification.

L. 158: is θ_v derived from sonic anemometer temperature measurements?

Response: θ_v is calculated from air temperature and relative humidity measurements, measured by a thermohygrometer (IAKM, Galtec Germany) with a measuring frequency of 1 min. However, the turbulent flux was indeed measured by a sonic anemometer (CSAT-3b). Related to main comment 2, we will add a table in the data description section describing the measuring devices.

L. 168: Assuming latent heat release to be zero at night is questionable. Even under very stable conditions with weak turbulent mixing, evaporation generally continues throughout the night.

Response: We understand the confusion, during the night the trees may continue transpiring and the soil evaporating, and dew can be formed. However, given that we solve the governing equation in Section 2.5 above the canopy top, we assume it is valid to assume that the evapotranspiration of soil and vegetation is stored in the canopy layer. That this assumption is indeed valid, can be observed in the paper of Gonzales-Armas et al., (2025) where the evapotranspiration flux approaches $0 \text{ W m}^{-2} \text{ s}^{-1}$ at the beginning and end of the day (Fig. 8b in Gonzales-Armas et al., (2025)). Additionally, they observe a peak in the water storage flux at 50 m in the early morning, suggesting a storage of moisture in the NBL canopy (Fig. C14b in Gonzales-Armas et al., (2025)).

L. 180: What do the authors mean by “sufficient to get a realistic estimate of radiative cooling”? See Hoch et al. (2007 JAMC, 46, 1469).

Response: We acknowledge that the approximation of the radiative divergence term is not the perfect solution where a lot of assumptions are involved. However, as there are no multiple level radiation measurements present (only at 75 m), using the RTE+RRTMGP with input from ERA5 was the best current estimate we can give. In Appendix A, we show the observed differences between the ERA5 vertical profiles and tower observations.

In the paper of Hoch et al. (2007 JAMC, 46, 1469), they point out that the temperature tendency and radiative divergence term are out of phase. While this is a very interesting finding, we believe this not to be directly applicable to our data. To take this finding into account we would have to study the time series of the complete night, and not a subset of a few hours. Additionally, due to the above-mentioned measuring limitation, we had to use ERA5 data which does not have a high enough temporal and spatial resolution to reproduce the differences found in the study with enough accuracy.

L. 187: *There is no molecular viscosity in the CO2 balance.*

Response: Indeed, thank you for pointing this error out. To be correct there is no molecular viscosity in the CO2 balance, we wanted to mention the molecular diffusivity. We will correct this in the revised manuscript.

L. 196: *With such a valuable two-weeks observational dataset, only eight hours of the data are used for the study? That corresponds to less than 6% of the nighttime observations. What characterizes the excluded hours? Where they associated with Intermittent turbulent mixing? Since clouds are mentioned here, where the selected hours limited to cloud-free conditions? By the end of the manuscript, it appears that Scv clouds were frequently present even during the dry season. Is there a way to identify impacts of cloud cover on surface radiative cooling and the subsequent development of the NBL? How representative are the selected data for this study overall? How many nights were ultimately included in the analysis?*

Response: Related to comment 5 above, we want to clarify that we use the eight selected hours only in section 3.3. During this period solve the governing equation for the two NBL prototypes (strongly and weakly stable). However, we agree that it is informative to stress that the NBL prototypes are only observed in less than 6% of the hours, and what characterized the remaining hours. We will add a small discussion in the final manuscript, covering information about the limited selected hours (<6 % of data range), which we chose to use to represent the prototypical NBL that is used to represent the NBL in numerical weather models. We will especially highlight that these idealized model conditions therefore only represent this very small range of observed profiles and are therefore likely to generate a mismatch between model and reality.

To answer your question about the characterization of the remaining hours, they could indeed be characterized by moments of intermittent turbulence, or elevated layers of increased turbulence, complicating the calculations beyond the scope of this paper, as holds as well for the effect of clouds. However, in future research the complete data series could be used, including a more thorough investigation into the effect of clouds on the NBL (see Section 4.2 in the Manuscript)

L. 200: *Should this refer to Fig. 2 instead of Fig.5?*

Response: Indeed, thank you for pointing this out, we correct this in the revised manuscript.

L. 238: *Only 8 hrs data were used for the study. How many independent data points can be obtained from a two-hour average?*

Fig. 3: *Are these profiles derived from the 8-hours observations mentioned earlier?*

L.243: *“..., a shallow stable daytime layer within the canopy was present”. Based on Fig.3, both the entire NBL and the within-canopy layer appear stable. Is Fig. 3 constructed from the three nights listed in Table 2? If ambient wind and temperature vary from night to night, then Fig. 3 does not represent the temporal variation of theta and CO2 during any individual night. What exactly does the figure represent then?*

Response (three comments above): With the response to comment 5 in mind, I will clarify the three comments above at once. In Figure 3 the results shown are based on the period between 8 and 19 August 2022. The 2-hour average therefore consists of 4 datapoint per night (30 min temporal resolution) over 11 nights, total 44 individual points for every 2-hour period. Because Figure 3 is constructed from the complete data range and not the subset of 8 hours, it therefore does represent the average temporal evolution of the NBL throughout the night. As pointed out in comment 5, we will more clearly stress the used data range, in the section introductions and figure captions.

L. 250: *S2, ...S4 and W3 are not introduced here without prior explanation. I eventually found them in Table 2, and they are only discussed later in L 294. Does this mean that all analyses are based on the three nights listed in Table 2? On 13 August, the NBL apparently transitioned from weakly stable to strongly stable conditions. It would be interesting to see how this transition occurred.*

Response: We acknowledge the confusion, S2, S3, S4 and W4 are introduced in Table 2, this should be stated more clearly. However again with the response to comment 5 in mind, the results of Fig. 3 are based on the period from 8 to 19th of August. Here we only highlighted S2, S3, S4 and W4 as an example to clearly indicate the difference between the behaviour of the two regimes (Figure B1). We will emphasize this in the results section for clarification and indicate table 2 to guide the reader as follows:

(L249 -251 in manuscript) In addition, [when we inspect the selected hours used in Section 3.3 \(Table 2\) as an example](#), we observed a positive heat flux ($w'\theta'$) during S2, S3, S4 and W3 within the canopy layer, which potentially is related to the downward movement of cold air ($w' < 0$ & $\theta' < 0$) (Appendix B).

L. 253: *A case study illustrating the evening transition would be particularly informative.*

Response: We agree with the referee that this would be particularly informative, however this is beyond the scope of this study, which focusses on the nighttime processes. However, we agree that research focus on transient states is very relevant for subsequent research.

L. 255: *“Black error bars”? All the horizontal bars in the figure appear red. How were the error bars calculated? Do they represent variations between nights?*

Response: To clarify, in the figure there are two types of error bars. Indeed, the red ones represent total variation both within the two-hour period and between night. However, within the red error bars there are smaller black error bars (this is best visible at 4m in the CO₂ profiles), which represent the variation within the two-hour average period. The black error bars are calculated as the means of the within two-hour variation from the 11 nights. They therefore represent the average standard deviation of the within hour variation. In the revised manuscript we will make the lines of the error bars thicker, so the difference between the two error bars will become better visible.

L. 257: *The two proposed mechanisms sound good. Which one is more important for the present study?*

Response: Even though we agree this would be interesting to know, it remains hard to determine what causes the large variation in CO₂ molar fractions at 4m between nights. As the daily variation in the stable canopy layer can be influenced by multiple processes acting non-homogeneous over time. For example, if there has been precipitation on one day this will influence the soil temperature and moisture, thereby influencing the respiration rate and CO₂ molar fractions. Additionally, it has been observed by Moonen et al., (2025) that there are ejections of CO₂ from the stable canopy layer into the atmosphere during the day, how often and how deep these ejections reach in the canopy, strongly influences the CO₂ molar fraction at 4m. Additionally, a third reason should be added, because the indicated preference of CO₂ to build up in topographical points of lower elevation, low-level horizontal advection of areas with high CO₂ concentration over the forest floor can cause large difference in CO₂ molar fraction in stable conditions (de Araújo et al., 2010). We will add the third reason to the revised manuscript and indicate that the processes are acting on different timescales, which makes the dominant process dependent on the daily conditions.

L. 273: *“from 11 nights”? I am totally lost here. The “eight hours” mentioned at the beginning of section 3 gave the impression that the entire section was based on that limited dataset. Does the observational dataset vary between subsections of section 3? As Table 2 does not cover the full period from 18:00 to 06:00, please specify the data used for each figure and analysis.*

Response: With the response to comment 5 in mind, only section 3.3 is based on the eight selected hours in table 1. In the revised manuscript we will mention the data range we used for each subsection, in the Section introduction and in the Figure captions.

Figure 5. *I find this figure is the most informative although I still don't know which nights are represented.*

Response: With the response to comment 5 in mind, from this section onward we make the data selection. Therefore, Fig. 5 represents the average prototypical strongly stable profiles (average of S1-S2-S3-S4)

and the average prototypical weakly stable profiles (average of W1-W2-W3-W4), as mentioned in table 2.

L. 313: “the four selected periods”, where were they described?

Response: Thank you for pointing out the confusion. The periods are described in Table 2, so the four strongly selected periods refer to S1, S2, S3, S4 and the four weakly stable periods refer to W1, W2, W3, W4. In the revised manuscript we clarify it as follows:

(L312 – 313 in manuscript): In Fig. 6, the average logarithmic fitted profiles are plotted for the four strongly (S1, S2, S3, S4) and four weakly stable (W1, W2, W3, W4) profiles indicated in Table 2. The shaded area indicates the standard deviation between these four selected hours for both the strongly and weakly stable regimes.

Figures 6, 7, 8: What do the shaded areas represent?

Response: To clarify, the shaded areas represent the standard deviation between the strongly stable points (S1, S2, S3, S4) and weakly stable points (W1, W2, W3, W4). We will clarify this in the figure headings as follows:

(Figure caption 6, 7, 8 in manuscript): ... according to Eq. 3/4/5, based on the selected profiles described in Table 2. Here the red line represents the average of the four strongly stable profiles (S1, S2, S3, S4) and the shaded area, the standard deviation. Blue is the same, but for the four weakly stable profiles (W1, W2, W3, W4). ...

L. 448: Clouds. Yes, it would be interesting to see their impact on NBL development.

Response: We agree with the referee that it would be valuable to study the impact of clouds on the NBL; however, this is beyond the scope of this paper. As highlighted in the discussion (Section 4.2) we do expect clouds to have an influence on formation of the NBL. In terms of NBL formation we expect this effect to mainly influence the radiation balance of the NBL. It is well known that the presence of clouds reduces the nighttime cooling, likely, preventing a strongly stable atmosphere from forming. Additionally, as daytime clouds were found to be important for the ventilating of CO₂ from the boundary layer (de Feiter et al., 2025), it would be valuable to study the effects of nighttime clouds on the CO₂ transport in the NBL.

L. 486: The study focuses on nighttime conditions during which stable layers are present throughout. Is the discussion here referring to longwave radiation emitted from the canopy top or to radiative divergence cooling within the atmosphere?

Response: See response to comment 1, in the manuscript we refer to the vertical longwave radiative divergence which cools the atmosphere. But likely the strong vertical longwave radiative divergence is caused by the net longwave emission of the canopy top, which cools the biomass and gets transferred to the air.

Fig. B1: Interesting! Whenever winds are strong over the canopy layer (W1-W4), turbulent mixing in the air layer above the canopy can penetrate into the canopy layer resulting in enhanced heat transfer. When winds above the canopy layer are weak (S1-S4), the positive heat flux below the canopy crown (presumably) in the nearly neutral canopy layer (Fig. 5a) may develop because shear-generated turbulent mixing transports warm air downward from above the canopy while turbulent development near the soil surface remains constrained.

Response: Thank you for the useful input. This nice example shows the advantage of using the prototype for the strongly and weakly stable regime. The separation of the two regimes allowed us to point out the different dynamics governing the two regimes, which would not be possible in by using average over the complete CloudRoots period. To stress the interesting results, we will in the revised manuscript, connect this finding to section 3.2.1. In Fig. 4 (in the manuscript) you can observed in the mostly weakly stable night, that $Ri < Ri_c$ above the canopy and during part of the night at the interface between canopy and

atmosphere, this will increase the heat flux (as observed in Fig B1). While for the strongly stable period Ri decreases in in the last hours of the night, indicating enhanced mixing through, movements of warm air upward ($w' > 0$ & $\theta' > 0$) or cold air downward ($w' < 0$ & $\theta' < 0$). However, the movement of warm air downward as you suggested is not possible because of the sign convention.

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