Response Peter A. Taylor: egusphere-2026-684

We thank the two referees, as well as Dr. Bruce Hicks and Dr. Peter A. Taylor, for their valuable comments and constructive suggestions. We greatly appreciate their feedback and have carefully addressed their comments in both our responses and the revised manuscript. Before addressing the individual comments, we would like to clarify the general aim and scope of our study.

The main aim of this study is to investigate whether the prototypical nocturnal boundary layer (NBL) above tropical rainforests, as commonly represented in weather and climate models, adequately captures the observed dynamics of this layer. By a prototypical or canonical NBL, we refer to the boundary layer developing above a bulk (zero-order) representation of the canopy and governed primarily by the interplay between turbulence generated by wind shear and stable thermal stratification associated with longwave radiative cooling.

Our aim is therefore to bridge the complexity of the observed nocturnal canopy–atmosphere system, influenced by thermal stratification, turbulence, and interactions across the canopy–atmosphere interface, with the necessarily simplified and relatively coarse representations commonly used in weather and climate models. We do not attempt to characterize all processes occurring within the canopy or all sources of variability in the observed NBL. Rather, we use the observations to assess to what extent the canonical representation captures the main characteristics and governing processes of the NBL above the rainforest, and to identify where this simplified representation may become insufficient.

To address this question, we make use of a comprehensive observational dataset to characterize the main features and governing processes of this canonical NBL above the rainforest. Specifically, we analyse: (i) the evolution of the NBL height using different criteria that reflect the different mechanisms controlling its development (Fig. 2); (ii) the characteristic vertical profiles of turbulence and state variables (Figs. 3 and 5); (iii) the stability within and above the canopy (Fig. 4), which provides an important lower boundary condition and may introduce variability at the canopy–atmosphere interface; and (iv) the individual terms in the budgets of turbulent kinetic energy, heat, and carbon dioxide above the canopy (Figs. 6, 7, and 8). These budgets enable us to quantify, among other processes, the role of stable thermal stratification associated with longwave radiative cooling near the canopy top and the mechanical production of turbulence by wind shear.

Together, these four elements provide an observational characterization of the prototypical NBL above the rainforest and establish a framework that can be used in future work to systematically evaluate model representations of turbulent kinetic energy, potential temperature, and carbon dioxide under nocturnal boundary-layer conditions.

In the revised version of the manuscript, we have further strengthened and clarified this central objective throughout the paper. Below we have responded to the comments raised one by one. If adjustments of the manuscript are indicated below the response, the newly added text is indicated in blue.

Responses

1. *In the cited paper by Andreae et al (2015) there are several comments about terrain inhomogeneity. These include, in Section 2.1, "From the perspective of micro-meteorological flux measurements, this is not an ideal type of terrain because it induces significant up-slope and down-slope circulations. The effects of local topography on the local flux measurements from the small towers are the subject of ongoing investigations." Figure 1b of the Andreae paper shows the topography in the region around*

the ATTO site. There appears to be considerable topographic variability within a 5 km circle around the 325m ATTO tower. Andreae state "The tower site is located approximately 12 km NE of the Uatumã River (Fig. 1b). As is typical for this region in the central Amazon Basin, there is little large-scale relief, but at smaller scales a dense drainage network has produced a pattern of plateaus and valleys with a maximum relief height of about 100m …."

My main concern would be the assumptions made in Section 2.5 concerning horizontal homogeneity. "To evaluate the governing equation with our observations, we made the following two assumptions: 1) The atmosphere is horizontally homogeneous (∂ψ ∂x = ∂ψ ∂y =0) and 2) subsidence is negligible (w = 0) are done." These lead to Equations 3,4,5. Remainder terms are included and will include advection associated with horizontal inhomogeneity. "The R_θ encompasses the molecular diffusion term, the latent heat term and the advection of heat (Stull, 1988)."

The problem is that these remainder terms are generally as large as the other terms, at least in the weakly stable case (Figures 6, 7, 8).

> **Response:** We agree with Dr. Taylor on the concern about horizontal homogeneity. In both the results and discussion, we stress that the contribution of (horizontal and vertical) advection of heat and CO_2 could play an important role in the governing equations of heat and CO_2. However, we have decided to make this assumption to be able to solve the governing equations with the available observations which are clearly limited on space. Since our observations are tower measurements (at one location), we cannot calculate the advection terms. In the revised manuscript we have already stressed more clearly that the assumptions are dictated by the availability of the ATTO observations.
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> (L 144-145 in manuscript): To calculate the budgets using only our observations, we had to make the following two assumptions: (1) The atmosphere is horizontally homogeneous ($\frac{\partial\bar{\psi}}{\partial x} = \frac{\partial\bar{\psi}}{\partial y} = 0$) and (2) subsidence (vertically advective term) is negligible (w = 0).

2. *We are told (line 375) that "To the east (main wind direction) of the ATTO, a swampy area is located …", but there is little mention of wind direction data elsewhere, although we are told "we found that NLLJ formation (associated with low turbulence) occurred under Northeast winds, in line with the lower roughness area to the Northeast." Key questions are whether wind direction was measured, and did it have any impact on boundary-layer depths and other boundary layer parameters. Maybe wind direction could be added to profile plots like Figure 5.*

> **Response:** To elaborate on the wind observations in relation to the observed NBL features. The wind direction has been measured all night. Information on the wind direction is added in Table 1. The dominant wind direction during the campaign was from the South-East (SE). In the levels above 100 m, the wind is from a SE direction during almost all nights, only for two nights (11-12 and 12-13 August) a South-western (SW) wind direction was observed. In the levels between 35 and 100 m (above the canopy) the observed wind direction was more variable. During five of the nights the wind direction was from a SE direction. Within the same five nights the highest wind speeds at 298 m were observed. In two nights (11-12 and 15-16 August) the wind direction was SW, this corresponds in general to medium wind speeds at the top of the tower. In the nights where North (N) / North-East (NE) wind direction in the layer between 35 and 100 m prevailed, in low windspeeds are observed. Except for one night with NE (13-14 August) wind, where in contrast the windspeed was not low.

In the same nights where the low-level (between 35 and 100 m) wind direction was N / NE and low in magnitude, we observed a nocturnal low-level jet (NLLJ). In the nights where an NLLJ was observed the estimated h_{NBL} was significantly lower compared to the other nights.

The information on wind direction and speed has been added to the results discussion in Section 3.1.

Table 1. Dominant observed wind directions above and below 100 m, wind speed at the top of the tower (298 m), and mean h_{NBL} with standard deviations for the nights of the CloudRoots campaign. The two nights where a NLLJ was observed are highlighted in yellow.

Night	Wind direction (> 100 m)	Wind direction (35- 100 m)	U_298m (m s^{-1})	h_{NBL} (m)
8-9 August	SE	SE	8.0 ± 1.4	169 ± 25
9-10 August	SE	SE	6.5 ± 0.9	153 ± 20
10-11 August	SE	SE	4.9 ± 0.9	160 ± 24
11-12 August	S / SW	S / SW	5.4 ± 1.6	171 ± 34
12-13 August	SW / SE	N / NE	1.5 ± 0.9	132 ± 24
13-14 August	SE	NE	6.9 ± 0.7	171 ± 14
14-15 August	SE	N / NE	5.1 ± 0.9	176 ± 23
15-16 August	SE	SW	5.2 ± 1.0	180 ± 35
16-17 August	SE	SE	5.3 ± 1.3	167 ± 25
17-18 August	SE	N / NE	3.0 ± 0.9	135 ± 21
18-19 August	SE	SE	8.6 ± 1.5	165 ± 16

3. *In discussing boundary-layer depths and Fig 1. Line 102 states "To not limit ourselves to h_{NBL} at measuring heights, we fitted a 2nd-order logarithmic function to vertical profiles of θ, CO_2 and U (Stull, 1988)." Checking though Stull I could not find this but envisage a form, for θ, like*

$(\theta - \theta_0) / \Delta\theta = A\,(\ln (z\text{-}zc) - \ln z_{0\theta}) + B\,(\ln (z\text{-}zc))^2$ where zc is canopy height and $z_{0\theta}$ is a temperature roughness length. Or the 2^{nd} order could be ln(ln (z-zc)?

We should be given details of the "2nd-order logarithmic function" used and confirmation that a displacement height was used. Values determined of A, B and $z_{0\theta}$ might also be interesting. These should include U and CO_2 profile fits.

Response: The logarithmic profiles (θ, CO_2, U) have been fitted using Equation 1. In Equation 1, z represents the height (from the canopy top). Note here that we did only fit the profile above the canopy. The coefficients a, b and c have been fitted using a least-squares polynomial fit (numpy.polyfit) (Eq. 1), for the specified time of the profile. Because we fitted the coefficient per profile, they are very variable and show no clear trend. In the revised manuscript we have added more detailed information in the following way.

$$y = a\ln(z)^2 + b\ln(z) + c \quad (1)$$

(L 101-102 in manuscript): Before estimating h_NBL we fitted a 2nd-order logarithmic function to the observed vertical profiles of θ, CO_2, U from the canopy top up to the highest measuring level. The 2nd-order logarithmic function was fitted using a least-squares polynomial. The logarithmic functions allow us to estimate h_NBL not only at the present measuring heights, but also in between the measuring levels.

4. *As I see it the best h_{NBL} estimate should be the simple TKE < 0.2 TKE_0 criterion. In Fig 2 this and the estimate based on U criterion seem to have the most variability. This variability may be real and averages over 12 different days at selected hours seems a questionable way to present these data. Each day may have totally different external parameters, like wind speed and direction?*

Response: 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 must be limiting under strongly stable thermodynamically conditions, where turbulence is almost absent. These strongly stable conditions were often TKE and u^* approach zero have been observed in at least one hour every night during the two-week measuring period. Additionally, in the strongly stable periods, the vertical profiles TKE, Ri and u^*, show very often random patterns. For example, the observations reveal profiles characterized by a stable boundary layer beneath a region of enhanced turbulent activity aloft. This could complicate and mislead the h_{NBL} calculations using turbulent based variable criteria. Here, we think the gradient method is a more trustworthy method to determine h_{NBL}. We have strengthened the formulation of this finding in the final manuscript.

Additionally, our criteria to calculate the boundary layer height (as measured from the displacement height) are based on the book Stull (1988). To our knowledge this comprehensive range of estimation criteria based on diverse NBL physical criteria is seldom applied to observational date set, and it can be useful in the comparison with weather and climate model results. As such, the goal of comparing multiple criteria is to determine which method yields most reliable estimates the NBL height. More important, and due to the different opposite drivers controlling the NBL dynamic, 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 sites only with a single flux measurement. As one of the main results of this research, we do acknowledge the variability within and between the nights and therefore one of the main conclusions is to use several criteria in calculating and evaluation the nocturnal boundary layer height. Following this comment, we have stressed this in the conclusion.

References

Mendonca, A. C. S., Dias-Junior, C. Q., Acevedo, O. C., Marra, D. M., Cely-Toro, I. M., Fisch, G., Brondani, D. V., Manzi, A. O., Portela, B. T. T., Quesada, C. A., and Mortarini, L.: Estimation of the nocturnal boundary layer height over the Central Amazon forest using turbulence measurements, Agricultural and Forest Meteorology, 367, 110 469, https://doi.org/https://doi.org/10.1016/j.agrformet.2025.110469, 2025a.

Stull, R. B. (1988). *An introduction to boundary layer meteorology*. Kluwer Academic Publishers.