

1 **Effects of vegetation and topography on the boundary layer structure above**
2 **the Amazon forest**

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ABSTRACT

27 Observational data from two field campaigns in the Amazon forest were
28 used to study the vertical structure of turbulence above the forest. The anal-
29 ysis was performed using the reduced turbulent kinetic energy (TKE) budget
30 and its associated two-dimensional phase space. Results revealed the exis-
31 tence of two regions within the roughness sublayer in which the TKE budget
32 cannot be explained by the canonical flat terrain TKE budgets in the canopy
33 roughness layer or in the lower portion of the convective ABL. Data analysis
34 also suggested that deviations from horizontal homogeneity have a large con-
35 tribution to the TKE budget. Results from LES of a model canopy over ideal-
36 ized topography presented similar features, leading to the conclusion that flow
37 distortions caused by topography are responsible for the observed features in
38 the TKE budget. These results support the conclusion that the boundary layer
39 above the Amazon forest is strongly impacted by the gentle topography un-
40 derneath.

41 **1. Introduction**

42 The importance of tower observations in our understanding of turbulence in the lower portion
43 of the atmospheric boundary layer (ABL) can hardly be exaggerated. In addition to advancing our
44 ability to understand turbulence, the deployment of eddy-covariance systems on towers has be-
45 come the standard method to quantify surface-atmosphere exchanges of momentum, energy, and
46 mass. In particular, the FLUXNET network (Baldocchi et al. 2001; Baldocchi 2008) with over 500
47 sites is considered the ground truth to assess models and calibrate remote sensing techniques used
48 to infer spatial and temporal patterns of evapotranspiration and carbon fluxes. One particularly dif-
49 ficult problem of great importance is the interpretation of measurements above forests in complex
50 terrain (Lee 1998; Baldocchi et al. 2000). A few field campaigns have been designed with the spe-
51 cific goal of studying forests over complex terrain (Marcolla et al. 2003; Feigenwinter et al. 2010;
52 Arnqvist et al. 2015; Grant et al. 2015; Fernando et al. 2019), and despite significant progress in
53 the development of theory (Finnigan and Belcher 2004; Ross and Vosper 2005; Poggi et al. 2008;
54 Belcher et al. 2012) and the increasing number of studies based on numerical simulations (Ruck
55 and Adams 1991; Ross 2008; Dupont et al. 2008; Patton and Katul 2009; Ross 2011; Chen et al.
56 2019, 2020), a framework to interpret tower observations over forests in complex topography is
57 still not available.

58 The focus here is on the central portion of Amazonia, a region of gentle topography covered by
59 a tall and dense forest. Given the fairly small differences in topographic elevation in this region,
60 most of the previous studies interpreted observations in the Amazon based on results and theory
61 for flow over flat topography (Kruijt et al. 2000; Chor et al. 2017; Ghannam et al. 2018; Dias-
62 Júnior et al. 2019), the main exception being the work on day- and night-time drainage slope
63 flows by Tóta et al. (2012a,b). However, the presence of dense vegetation enhances the effect

64 of topography on the flow, such that effects of gentle topography should not be dismissed. In
65 particular, flow separation occurs at much smaller slopes over forested hills than over rough hills
66 (Finnigan and Belcher 2004; Ross and Vosper 2005). Recent large-eddy simulations with real
67 topography for a small region of the Amazon clearly shows the occurrence of flow separation in
68 the lee of fairly small hills (Chen et al. 2020).

69 In this paper we focus on the budget of turbulent kinetic energy (TKE) as a means to understand
70 observations from two field campaigns in different sites in central Amazonia. In particular, we
71 use the reduced TKE budget and its associated phase space introduced by Chamecki et al. (2018)
72 to analyze the two data sets. Chamecki et al. (2018) showed that data above the Amazon forest
73 displayed much larger spread in the reduced TKE phase space than data from the inertial sublayer
74 (ISL) where Monin-Obukhov Similarity Theory (MOST) is applicable. This spread implies a
75 much larger number of possible states regarding the terms in the TKE budget. However, the
76 authors did not explain the cause for such behavior. In a study using data from a different site in
77 Amazonia, Dias-Júnior et al. (2019) found no evidence of the existence of the inertial sublayer over
78 the Amazon forest. They hypothesized that the canopy roughness sublayer merged directly into
79 the mixed layer, as previously suggested by a schematic figure presented by Malhi et al. (2004).
80 Here we revisit the datasets used by Chamecki et al. (2018) and Dias-Júnior et al. (2019), and use
81 the TKE phase space together with LES data to interpret the observations.

2. Theory

a. The reduced TKE budget

We start from the most general form of the TKE budget written as

$$\underbrace{-\overline{u'_i u'_j} \frac{\partial \bar{u}_i}{\partial x_j}}_P + \underbrace{\beta \overline{u'_i \theta'_v} \delta_{i3}}_B - \varepsilon = \underbrace{\frac{\partial \bar{e}}{\partial t}}_{-A_e} + \underbrace{\bar{u}_i \frac{\partial \bar{e}}{\partial x_i}}_{-T_e} + \underbrace{\frac{\partial \overline{u'_i e}}{\partial x_i}}_{-T_e} + \underbrace{\frac{1}{\rho} \frac{\partial \overline{u'_i p'}}{\partial x_i}}_{-\Pi_e} = R. \quad (1)$$

In Eq. (1), repeated indices indicate an implicit summation, $e = (1/2)u'_i u'_i$ so that \bar{e} is the TKE, θ_v is virtual temperature, $\beta = g/\bar{\theta}_v$ is the buoyancy parameter, and δ_{ij} is the Kronecker delta. The terms on the left-hand side of the equation represent local shear production (P), buoyancy production/destruction (B), and the TKE dissipation rate (ε). The storage term ($\partial \bar{e}/\partial t$) and all the transport terms that could produce a local imbalance between production and dissipation appear on the right-hand side, and are lumped together into the residual term (R). For convenience, we define the transport terms such that positive values correspond to a local source of TKE. For some terms, this sign convention differs from the usual definition (Stull 1988). The transport terms are the turbulent transport (T_e), the mean advection (A_e), and the pressure transport (Π_e). Hereafter we assume that the storage term is negligible and that local imbalance is caused only by transport of TKE.

Following Chamecki et al. (2018), we normalize this “reduced TKE budget” (in which all imbalance terms are lumped together) by the local TKE dissipation rate and write

$$(P/\varepsilon) + (B/\varepsilon) - 1 = (R/\varepsilon). \quad (2)$$

We use R/ε to diagnose the local TKE budget, noting that $R/\varepsilon = 0$ represents a state of local balance between production and dissipation of TKE. Positive (negative) values of R/ε are associated with regions in which production is larger (smaller) than dissipation, and we refer to R as the *local imbalance term*.

102 To facilitate interpretation of tower observations, it is useful to split R into a vertical component
 103 that is consistent with the hypothesis of horizontal homogeneity (R^v) and a horizontal compo-
 104 nent caused by deviations from that state (R^h). Under stationary and horizontally homogeneous
 105 conditions, the second equation in (1) reduces to

$$R^v = -T_e^v - \Pi_e^v = \frac{d\overline{w'e}}{dz} + \frac{1}{\rho} \frac{d\overline{w'p'}}{dz}. \quad (3)$$

106 Thus, we can write

$$R^h = R - R^v = R + T_e^v + \Pi_e^v, \quad (4)$$

107 and utilize R^h/ε as a measure of the importance of horizontal heterogeneity on the TKE bud-
 108 get. The pressure transport term is always a difficult issue in the analysis of the TKE budget,
 109 as it is usually not directly measured (Wyngaard 2010). For horizontally homogeneous flows in
 110 the convective boundary layer, the pressure transport term is typically smaller than the dominant
 111 terms in the budget (Lenschow et al. 1980). For flow above canopies, LES results suggest that
 112 the pressure transport term has the same sign as the turbulence transport but with much smaller
 113 magnitude (Dwyer et al. 1997). Given the lack of reliable measurements and the likely smaller
 114 role of pressure transport in horizontally homogeneous conditions, hereafter we exclude it from
 115 our discussions, effectively assuming $T_e^v \gg \Pi_e^v$ and thus $R^h \approx R + T_e^v$.

116 *b. Structure of daytime ABL over forests*

117 The classic structure of the convective boundary layer (CBL) over horizontally homogeneous
 118 rough surfaces comprises 3 main layers (see Fig. 1a): the surface layer ($z/z_i \leq 0.1$), the mixed
 119 layer ($0.1 \leq z/z_i \leq 0.8$), and the entrainment layer ($0.8 \leq z/z_i \leq 1.2$), where z_i is the CBL height.
 120 Numbers in parenthesis are just a rough estimate of the region occupied by each layer. In terms of
 121 the TKE budget, we expect a state of approximate local balance between production and dissipa-

tion within the surface layer (i.e., $R \approx 0$). As shown by Chamecki et al. (2018), MOST functions imply production slightly smaller than dissipation across the range of stability. Note that MOST is only applicable in a portion of the surface layer, in which the details of the surface roughness are no longer relevant (i.e., $z \gg z_0$, where z_0 is the surface roughness length) and the friction velocity is the appropriate velocity scale. The latter is usually considered to be true as long as $z/|L_o| \leq 2$, where L_o is the Obukhov length. Under more convective conditions (i.e., when $z/L_o < -2$), in the matching layer, the local free-convection velocity becomes the appropriate velocity scale (Kaimal and Finnigan 1994). To facilitate things, we refer to the entire layer $z/z_i \leq 0.1$ as the surface layer, and reserve the term inertial sublayer (ISL) to the portion where the log-law is applicable in neutral conditions and MOST is expected to hold in non-neutral cases (below the blue dashed line in Fig. 1a).

Above the surface layer, production is larger than dissipation in the lower part of the mixed layer ($R > 0$) and production is smaller than dissipation in the upper portion ($R < 0$). This separation is indicated by the red dashed line in Fig. 1a. Thus, in idealized homogeneous conditions, the excess of TKE produced in the lower half of the CBL is exported (mostly) by turbulent transport to the upper half of the CBL, where it is dissipated. Aircraft measurements by Lenschow et al. (1980) show that indeed $\overline{w'e} > 0$ within the ABL (i.e., the flux of TKE is directed upwards) and suggest that the change in the sign of the turbulent transport (T_e^v) occurs at $z/z_i \approx 0.4$.

In the presence of a vegetation canopy such as a forest, the TKE budget in the surface layer is significantly modified by the vegetation, giving rise to the roughness sublayer (RSL). In the region inside and just above the canopy, the canopy height h_c is adopted as the appropriate length scale. As sketched in Fig. 1b, in the neutrally stratified ($B = 0$) RSL, production is larger than dissipation above the canopy (and in the uppermost region inside the canopy) and the imbalance term is positive. The excess of energy is transported by turbulence into the (lower) canopy, where

146 local production is smaller than dissipation (Brunet et al. 1994), implying a negative imbalance
 147 ($R < 0$). Thus, turbulent transport is negative above the canopy and positive within the canopy,
 148 with a downward flux of TKE (Fig. 1b). These modifications of the TKE budget extend up to
 149 $z/h_c \approx 2$, where the local equilibrium between production and dissipation is reestablished and the
 150 RSL blends into a classical inertial sublayer in which the log-law is valid (Kaimal and Finnigan
 151 1994; Pan and Chamecki 2016). This limit for the top of the RSL is consistent with the usual range
 152 adopted in the literature between $z/h_c = 2$ and $z/h_c = 3$ (Harman and Finnigan 2007), and it is also
 153 consistent with the empirical value $z/h_c \approx 2.2$ based on the enhancement of eddy diffusivities for
 154 heat and water vapor (Cellier and Brunet 1992). If we extend this picture to unstable conditions,
 155 MOST would be valid above $z/h_c \approx 2$ as well (Cellier and Brunet 1992).

156 Thus, for convective conditions above a forest, the existence of an ISL where MOST is appli-
 157 cable is bounded below by the RSL, and above by the mixed layer or the matching layer. In the
 158 application of MOST above a canopy, the vertical origin is placed at a distance d_0 from the ground,
 159 which is defined as the mean level of momentum absorption by the canopy (Jackson 1981) and is
 160 termed the displacement height. Thus, a point in the ISL must satisfy simultaneously 3 criteria:
 161 (i) $(z - d_0)/z_i \leq 0.1$, (ii) $(z - d_0)/|L_o| \leq 2$, and (iii) $z \geq 2h_c$. In free-convection with a regime
 162 dominated by convective cells, $z_i/|L_o| > 20$ (Salesky et al. 2017), condition (ii) is more restrictive
 163 than (i). Conversely, in forced convection with a regime dominated by rolls, condition (i) is more
 164 restrictive. As first hypothesized by Malhi et al. (2004) and later discussed by Dias-Júnior et al.
 165 (2019), it is possible that the ISL does not exist above tall forests. Here we can quantify this asser-
 166 tion by assessing if there exists a height z such that all 3 conditions are simultaneously satisfied.
 167 Combining the 3 criteria above, the existence of an inertial layer in which MOST is valid is only

possible if the following two derived conditions are simultaneously satisfied:

$$h_c/|L_o| \ll 2/(2 - \alpha) \quad (5)$$

$$h_c/z_i \ll 0.1/(2 - \alpha) \quad (6)$$

where $\alpha = d_0/h_c$. Thus, for fixed atmospheric conditions (given by L_o and z_i), there is a maximum canopy height which allows an ISL to exist. Usual values of α are in the range $(2/3) \leq \alpha \leq (3/4)$, and for $\alpha = 0.7$ the two criteria for the existence of an ISL become $h_c \ll \min\{1.5|L_o|, 0.08z_i\}$.

3. Methods

a. Observational data

The main focus of this study is the analysis of data from two field campaigns designed to measure turbulence above the Amazon forest: the GoAmazon campaign, which took place from March 2014 through January 2015 at the Cuieiras Biological Reserve (Fuentes et al. 2016; Freire et al. 2017), and the ATTO-IOP1 (Oliveira et al. 2018; Dias-Júnior et al. 2019) during October/November 2015 at the Uatumã Sustainable Development Reserve. The locations of the towers at the two sites are shown over a topographic map in Fig. 2. Both sites are located at plateaus and, given the predominance of easterly winds in the region, nearby valleys in the East-West direction were used to characterize the local topography (Fig. 2d,e). Thus, the GoAmazon K34 tower (located at 2.602° S, 60.209° W; see Fig. 2b,d) sits on a hill with height $H_h \approx 50$ m and horizontal length $4L_h \approx 1.5$ km, where L_h is the horizontal half-length of the topography (Finnigan and Belcher 2004). This geometry corresponds to an average slope of approximately $H_h/(2L_h) \approx 0.07$. The ATTO towers (located at 2.146° S, 59.006° W and 2.144° S, 59.000° W; see Fig. 2c,e) are located on a hill with height $H_h \approx 70$ m and horizontal length $4L_h \approx 2.25$ km, with average slope

187 $H_h/(2L_h) \approx 0.06$. The canopy height at the GoAmazon and ATTO sites were estimated to be
188 $h_c = 35$ m (Fuentes et al. 2016) and $h_c = 37$ m (Oliveira et al. 2018), respectively.

189 On both field campaigns, vertical arrays of sonic anemometers were deployed on tall towers with
190 the goal of profiling turbulence within and above the canopy. Only measurements obtained above
191 the forest ($z/h_c \geq 1$) were used here. In the GOAmazon campaign, 9 sonic anemometers were
192 deployed on a 50-meter tower (K34), with 3 being above canopy top. On the ATTO campaign, 8
193 sonic anemometers were deployed on two towers (a 80-meter tower and the 325-meter tall tower)
194 located 670 m apart, 5 of them being above the canopy. See Table 1 for more information about
195 the sensors employed here.

196 The data processing strategy was designed to ensure the use of high-quality data without exces-
197 sively reducing the amount of data available for analysis. Due to the short measurement period of
198 the ATTO IOP campaign, less restrictive criteria had to be applied. Data processing procedures
199 are briefly outlined here. (i) Data were separated into blocks of 30 minutes starting at 0000 h local
200 time. Up to one second of consecutive missing data were replaced by previous measurements,
201 whereas blocks with more than one second of missing data were discarded. For the ATTO data
202 only, the first two minutes of each block were also discarded, as they were mostly missing data
203 due to technical issues with data transfer (so the blocks are effectively 28-min long). (ii) Blocks
204 were selected according to the direction of mean wind. For GoAmazon, the criterion corresponded
205 to mean wind at the highest anemometer within $\pm 90^\circ$ from the anemometer axis (the mean wind
206 direction difference between anemometers is small due to the small height separation). For the
207 ATTO, data with mean wind within $\pm 135^\circ$ for each individual anemometer were selected. (iii)
208 On the remaining data, a planar fit (Wilczak et al. 2001) was performed to correct for instrument
209 tilting. (iv) Blocks with negative heat flux (measured at the top of the canopy for the GoAmazon
210 and at individual anemometers at ATTO) were filtered with a 3-min top-hat high-pass filter (i.e.,

211 a centered moving average) to remove non-turbulent oscillations usually present in stably strati-
 212 fied conditions (Mahrt 2014). This filtering had almost no effect on the results presented here, as
 213 the focus is on unstable conditions. (v) The stationarity criteria for the horizontal wind proposed
 214 by Vickers and Mahrt (1997) were used, and blocks with non-stationarity ratios R_{Nu} , R_{Nv} and
 215 $R_{NS} \geq 0.5$ were discarded (here $R_{Nu} = \delta u / \bar{u}$ is the non-stationarity ratio for the streamwise ve-
 216 locity component, with δu being the difference in streamwise velocity at the beginning and end
 217 of the block obtained from a linear regression; $R_{Nv} = \delta v / \bar{u}$ and $R_{NS} = \sqrt{\delta u^2 + \delta v^2} / \bar{u}$ are non-
 218 stationarity ratios for the crosswise wind component and the horizontal wind vector, respectively).
 219 The remaining blocks were used for data analysis.

220 The terms in the TKE budget were calculated under the usual assumption of horizontal homo-
 221 geneity over flat terrain. Shear production was calculated from $P = -\overline{u'w'}(d\bar{u}/dz)$, with the mean
 222 velocity gradient estimated from a second-order polynomial fit in $\ln(z)$ (Högström 1988). For the
 223 GoAmazon data, this fit included a fourth anemometer at $z/h = 0.90$ (see Freire et al. (2019a) for
 224 more details). Buoyancy production was calculated from $B = (g/\bar{\theta}_v)\overline{w'\theta'_v}$. The flux Richardson
 225 number $Ri_f = -B/P$ was used to characterize atmospheric stability. When assessing applicability
 226 of MOST, the Obukhov length $L_o = -u_*^3/(\kappa B)$ was estimated from the buoyancy production at
 227 canopy top (κ is the von Kármán constant). Dissipation rates were obtained from the theoretical
 228 prediction for the inertial subrange of the second-order structure function $\overline{\Delta u^2} = C_2(r\epsilon)^{2/3}$ (Kol-
 229 mogorov 1941) using the approach outlined by Chamecki and Dias (2004). The range of scales
 230 that conformed most closely to inertial subrange behavior was $0.5 \leq r \leq 2$ m for the GoAmazon
 231 and $1 \leq r \leq 5$ m for ATTO, and these ranges were used together with $C_2 = 1.97$ in the estimates.
 232 We note that dissipation rates obtained from the energy spectrum were 24% larger, likely due to
 233 aliasing effects (Freire et al. 2019b), and values obtained from structure function were considered
 234 more reliable as structure functions are not impacted by aliasing errors (using dissipation rates

from the spectrum would not have affected the conclusions of this study). The vertical turbulent transport of TKE was calculated from T_e^v by fitting a second-order polynomial in z (GoAmazon) and $\log(z)$ (ATTO) to the vertical flux of TKE ($\overline{w'e}$). From these terms of the TKE budget, the local imbalance and its non-homogeneous portion were calculated from $R = (P + B - \epsilon)$ and $R^h \approx R + T_e^v$.

After data analysis, a few criteria were employed to further select blocks used in the calculation of statistics: (i) Blocks were selected for the existence of an inertial subrange in the second-order structure function with slope within $\pm 10\%$ (GoAmazon) and $\pm 20\%$ (ATTO) of the theoretical value of $2/3$ (Kolmogorov 1941). (ii) Blocks from the GoAmazon data with very small values of TKE dissipation rate ($\epsilon \leq 5 \times 10^{-5} \text{ m}^2/\text{s}$) or with negative shear production were eliminated (for the ATTO data, no blocks had small dissipation and negative shear production only occurred in buoyancy-dominated conditions). (iii) Because the focus here is on convective conditions, blocks with stable conditions were also eliminated (here $Ri_f > 0.04$ was used). (iv) Finally, blocks from ATTO when z_i was below the highest anemometer were also discarded. The final number of blocks used hereafter is shown in Table 1.

Vertical profiles of momentum flux inside the canopy from the GoAmazon field campaign were also used to determine the displacement height (Jackson 1981), yielding $\alpha = d_0/h_c \approx 0.78$. A rough estimate of roughness length scale $z_0/h_c \approx 0.06$ was also obtained from $\bar{u}_{h_c} = (u_*/\kappa) \ln[(h_c - d_0)/z_0]$. Estimates of ABL height z_i were obtained from ceilometer data (Jenoptik CHM15k) collected during the ATTO field campaign (see Dias-Júnior et al. (2019) for more details). The ABL height estimates obtained by Dias-Júnior et al. (2019) were about 25% smaller than those obtained from the global reanalysis product ERA5, but were consistent with other observations above the Amazon forest (Fisch et al. 2004). ABL heights play a small role in our data

analysis and, in the only figure in which they are employed, we are being conservative in using the smaller values obtained by Dias-Júnior et al. (2019).

Finally, we also used tower data collected over a flat grass field during the AHATS field campaign (UCAR/NCAR - Earth Observing Laboratory 1990; Salesky and Chamecki 2012) to illustrate typical ISL behavior. For more information about the data processing, see Chamecki et al. (2017, 2018).

b. Numerical data

We employed data from three LES runs to aid the interpretation of field observations from the Amazon forest. To illustrate the behavior of the convective boundary-layer (CBL) on the TKE phase space, we used one simulation from Chor et al. (2020) of a horizontally homogeneous CBL over a rough and flat surface with $z_i/|L_o| \approx 37$ ($L_o = -41.23$ m). More information about the simulation setup can be found in Table 2.

In addition, we used two simulations with a model canopy for the Amazon forest from Chen et al. (2019), one over flat terrain and the other one over a sinusoidal ridge with amplitude $H_h = 50$ m, wavelength $4L_h = 1.0$ km and average slope $H_h/(2L_h) \approx 0.10$, which was considered representative of Amazon topography (these simulations were referred to S0.0 and S0.2 in the original paper). In the simulation with topography, the mean flow was perpendicular to the ridges and the flow was homogeneous in the crosswise direction.

Averages were calculated in time and directions of homogeneity, and fluctuations were defined with respect to these averages. Because the terms on the TKE budget are independent of the frame of reference adopted, data analysis was carried in the original cartesian coordinate system for all simulations (note that decomposition of terms into horizontal and vertical components such as $R = R^h + R^v$ do depend on the choice of coordinate system, but these decompositions were not

281 applied to the LES data). In the simulation with topography, shear production was calculated using
 282 all terms in the definition given in Eq. (1). In all simulations the subgrid-scale (SGS) dissipation
 283 rate $\epsilon_{\text{sgs}} = -\langle \tau_{ij} \tilde{S}_{ij} \rangle$ was used as a proxy for the TKE dissipation rate (here τ_{ij} is the SGS stress
 284 tensor, \tilde{S}_{ij} is the resolved strain rate tensor, and $\langle \cdot \rangle$ represents averaging in time and over directions
 285 of homogeneity).

286 4. Results

287 *a. Convective ABL and the roughness sublayer*

288 We used the AHATS observations to establish the typical pattern of measurements within the
 289 ISL (where MOST is applicable) on the TKE phase space (Fig. 3a). As shown by Chamecki
 290 et al. (2018), AHATS data occupied a small portion of the phase space, scattering around the
 291 line of local balance between production and dissipation ($R \approx 0$). Ensemble averages conditioned
 292 on values of the stability parameter ($-z/L_o$) are also shown, displaying slightly negative local
 293 imbalance ($R < 0$) and implying total production slightly smaller than dissipation within the ISL.
 294 This result is in agreement with the behavior implied by empirical functions obtained from Monin-
 295 Obukhov Similarity Theory (MOST) (Businger et al. 1971; Högström 1988, 1990), as discussed
 296 in more detail in Chamecki et al. (2018).

297 To complement this picture, results from the two LES runs for flat terrain are displayed together
 298 in Fig. 3b. The simulation of a convective ABL over a rough surface showed slightly positive
 299 imbalance within the ISL, which extended up to $z/L_o \approx -2$ (spanning the range between the “+”
 300 and the “×” in Fig. 3b). Beyond this point, the local imbalance increased significantly, marking
 301 a clear departure from ISL behavior. As expected from the large value of $z_i/|L_o|$, the ISL did
 302 not extend up to $z/z_i = 0.1$ (marked by a “o” in Fig. 3b). Above the ISL, the local imbalance

303 increases with height, reaching a maximum of $R/\varepsilon \approx 0.52$ at $z/z_i \approx 0.18$. A state of local balance
 304 between production and dissipation was reached at $z/z_i \approx 0.5$, and the local imbalance became
 305 markedly negative in the upper part of the mixed layer. These results are consistent with Fig. 1a
 306 and with aircraft measurements by Lenschow et al. (1980) suggesting that the change in the sign
 307 of turbulent transport occurs at $z/z_i \approx 0.4$. It is possible that the height where this change in the
 308 local imbalance sign occurs is influenced by the stability of the ABL (i.e., it may actually depend
 309 on $z_i/|L_o|$).

310 Finally, we used the simulation of a neutral ABL over a model of the Amazon forest to assess the
 311 effects of a horizontally homogeneous canopy on the patterns in the TKE phase space. Because
 312 the simulation had neutral stratification, all points were constrained to be on the line $B/\varepsilon = 0$. At
 313 the canopy top R/ε was very large ($R/\varepsilon > 2.5$), indicating that shear production was much larger
 314 than dissipation. The imbalance reduced with increasing distance from the canopy top, being
 315 almost zero at $z/h_c = 2$, in agreement with wind tunnel measurements by Brunet et al. (1994)
 316 and numerical simulations by Pan and Chamecki (2016). Thus, from the perspective of the TKE
 317 budget, the top of the roughness sublayer was located at $z/h_c \approx 2$.

318 The superposition of the two simulations in Fig. 3b is an idealization, which can be interpreted
 319 as a continuum by assuming that buoyancy effects are negligible within the RSL (i.e., $h_c/|L_o| \ll 1$)
 320 and that the RSL only occupies the bottom of the surface layer (i.e., $h_c/z_i \ll 0.1$). We used this
 321 superposition as a starting point to infer patterns in the phase space that would have occurred for
 322 larger canopy height h_c under the same atmospheric conditions (characterized by z_i and L_o). For
 323 practical purposes, we considered cases in which $z_i/|L_o| > 20$, so that the surface layer was split
 324 into an ISL and a matching layer. Two main cases are of interest here. In case “C1”, h_c was in-
 325 creased enough that buoyancy modified turbulence in the RSL, but the criteria for the existence of
 326 an inertial layer (Eqs. (5) and (6)) were still satisfied. The expected behavior of the reduced TKE

budget is represented by curve “C1” in Fig. 4, indicating the existence of an ISL (characterized
 by an approximate local balance between production and dissipation) above the RSL. MOST is
 expected to be applicable within this elevated ISL. A further increase in h_c would cause the cri-
 terion (5) to be violated and the RSL would merge directly into the matching layer as indicated
 by the curve “C2”. In the latter case, the ISL does not exist. Malhi et al. (2004) suggested that
 both cases are possible in the surface layer above the Amazon forest, and Dias-Júnior et al. (2019)
 concluded that the absence of a layer that followed MOST in the observations from the ATTO
 tower might have been caused by the behavior described by curve “C2”. A critical point in Fig.
 4 is that, in both cases, the local imbalance remains positive within the layer $h_c \leq z \leq 0.5z_i$, and
 for observations made above the canopy top we only anticipate a negative imbalance in the upper
 portion of the mixed layer, above $z/z_i \approx 0.5$.

b. *Observations from the Amazon*

As a starting point, we tested the criteria for the existence of the ISL in the GoAmazon and
 ATTO data sets. Discrete probability distribution functions (discrete PDFs) for h_c/L_o and h_c/z_i
 are shown in Fig. 5 together with lines corresponding to the right-hand side of Eqs. (5) and (6)
 obtained with $\alpha = 0.78$ (estimates of z_i were not available for the GoAmazon campaign). Because
 some of the near neutral blocks (as identified by the criterion based on R_{if}) had positive values
 of L_o , we displayed the PDF for h_c/L_o instead of $h_c/|L_o|$, and interpreted the condition given by
 Eq. (5) as $h_c/L_o \geq -1.64$. Note that the results shown in Fig. 5a were obtained for the periods in
 which measurements at canopy top were available. For the GoAmazon data set, 99% of the blocks
 had $h_c/L_o \geq -1.64$ (Fig. 5a) and, based on this criterion, should have at least a shallow ISL.
 However, this ISL must be located above $z = 2h_c = 70\text{m}$, and thus above the highest measurement

349 during the field campaign (located at $z = 48.2$ m). Thus, we anticipate that all measurements from
350 the GoAmazon campaign would be within the RSL.

351 The data from the ATTO site were more interesting in this respect, both because estimates of z_i
352 were available and because there were measurements above the RSL, up to $z = 8.8h_c$. Interest-
353 ingly, we found that only about 5% of the blocks had $z_i/|L_o| > 20$, corresponding to the regime
354 dominated by convective cells (and only 19% had $z_i/|L_o| > 10$). This predominance of forced
355 convection with roll structure was likely associated with the fact that a large fraction of the avail-
356 able net radiation was consumed by evapotranspiration (as an example, see Fig. 5 in Fuentes et al.
357 (2016)), promoting lower values of $z_i/|L_o|$. As a consequence, the criterion based on z_i was more
358 restrictive, and 99% of the blocks satisfied $h_c/L_o \geq -1.64$ but only 70% satisfied $h_c/z_i \leq 0.08$.
359 Based on these two criteria, 33% of the periods from ATTO had no inertial layer, 40% should have
360 had a layer that was less than 30 meters deep, and only 27% of the blocks should have an ISL
361 with depth between 30 and 100m. For the ATTO site, the RSL extended up to $z = 2h_c = 74$ m, and
362 roughly 60% of the measurements at 81 m should have been within the ISL. As for the measure-
363 ments at 150m, we expected only about 6% to be within the ISL.

364 With this information, an expected pattern arose for the measurements from the two Amazon
365 campaigns. In the GoAmazon, we expected to see RSL behavior influenced by buoyancy at all 3
366 heights, with a large positive imbalance at the first height approaching local equilibrium as height
367 increased. For the ATTO campaign, we anticipated similar behavior at the lowest two heights. At
368 81 m, we expected to see the ISL in at least 50% of the blocks. The two upper heights were mostly
369 above the ISL if one existed, and we anticipated to see mostly mixed layer behavior. However,
370 data from the two campaigns displayed on the reduced TKE phase space (Figs. 6 and 7) did not
371 conform to these expectations.

We start by discussing the GoAmazon results. Despite the very large spread of points in the phase space, the signature of the RSL with positive imbalance (points above the local balance line) was clear for measurements at $z/h_c = 1.00$ (Fig. 6a). However, measurements at $z/h_c = 1.15$ (Fig. 6b) spread around the line of local balance between production and dissipation, suggesting a very fast approach to ISL behavior (one would still expect a fairly large positive imbalance this close to the canopy top). Finally, measurements at $z/h_c = 1.38$ (Fig. 6c) were quite puzzling given the predominance of points with negative imbalance (points below the local balance line). When all heights were displayed together (Fig. 6d), the points occupied a much larger area of the phase space than in typical ISL measurements (contrast Fig. 6d to Fig. 3a). In all panels on Fig. 6, the points were colored by R^h/ϵ , indicating that the TKE budget was impacted by significant departures from horizontal homogeneity. Note that the predominant behavior with $R^h < 0$ implied that the effects of heterogeneity were mostly acting as an effective source of local TKE (recall that $R < 0$ implies local production smaller than dissipation, and transport must provide the extra energy needed to close the budget). Thus, the color pattern in the phase space was sensible: points with $(P + B)/\epsilon < 1$ had $R^h < 0$, suggesting that horizontal heterogeneity was, at least in part, responsible for providing the extra energy necessary to close the budget (one must be careful with this interpretation, though, because it does not include the effects of R^v).

The three lowest measurement heights from ATTO displayed a very similar pattern to the GoAmazon results, except that the observations were at significantly different heights z/h_c . This suggested that the patterns observed were consistent across sites, but that a different length scale (other than h_c) was required to collapse the data. In particular, a layer with negative imbalance was clearly seen at $z/h_c = 2.19$ (Fig. 7c), where we had anticipated a dominant presence of ISL behavior. While data from $z/h_c = 4.05$ (Fig. 7d) also showed more deviations from ISL behavior than expected, the highest set of measurements in Fig. 7e were a bit more as expected from obser-

396 vations in the middle of the CBL. Note that at the two top heights, blocks with smaller deviations
397 from horizontal homogeneity tended to conform more with mid-CBL expectations.

398 Before moving on to explain these deviations, we sought a more concise characterization of the
399 TKE budgets (Fig. 8). To reduce the effect of outliers on the statistics, we present results in terms
400 of median values and 25th and 75th percentiles. Without proper normalization, the profiles of TKE
401 (Fig. 8a) did not show any clear patterns. However, a clear shift in the sign of the vertical flux of
402 TKE (Fig. 8b) was observed in the interval $1.15 < z/h_c < 1.38$ (both limiting points were from
403 the GoAmazon campaign). Note that independent determination of the height at which the flux
404 changed sign for each experiment would have yielded similar results. The downward flux of TKE
405 closer to the canopy was consistent with RSL expectations (see Fig. 1b), while the upward flux
406 above was consistent with CBL expectations (see Fig. 1a). However, the transition occurred much
407 closer to the canopy than one would have anticipated. Note also that the transition from downward
408 to upward flux of TKE in both campaigns corresponded approximately to the unexpected ISL
409 behavior in the TKE phase space with points scattering around the $R = 0$ line.

410 At first sight, the TKE budget (Fig. 8c) confirmed our expectations: the RSL was dominated
411 by shear production and vertical transport of TKE, with only small buoyancy effects, while above
412 the RSL buoyancy became the dominant production mechanism. The net transport was always
413 a sink of TKE in this region, with the exception of a few points in the uppermost sonic (which
414 was sometimes in the upper portion of the CBL). As indicated by the TKE phase spaces, the
415 unexpected behavior manifested itself in the nature of the local imbalance between production
416 and dissipation. Note that the points displayed in Fig. 8c are median values, and as such, the
417 median local imbalance R cannot be calculated from the median of the P and B . Thus, median
418 values for the local imbalance R and for its horizontal component R^h are shown in Fig. 8d. Both
419 in the RSL and in the lower half of the CBL, one would have expected the residual R/ε to be

always positive and approximately equal to the negative of the vertical turbulent transport term (i.e., $R/\varepsilon \approx -T_e^v/\varepsilon$). This was the case only at the lowest measurement height near the canopy top in each campaign, where R^h was small (lowest circle and lowest square in Fig. 8d).

For the two heights that had a behavior similar to that expected for ISL on the phase space (Figs. 6b and 7b), we indeed observed $R \approx 0$ (second lowest circle and second lowest square in Fig. 8d). However, we noted that T_e^v was large at these heights (Fig. 8c), requiring a similarly large R^h . This did not conform with true ISL behavior, suggesting that the behavior on the phase space was deceiving. For the upper sonics, $-T_e^v$ had the opposite sign of R , implying large deviations from $R \approx -T_e^v$ that must be balanced by large R^h . Thus, main deviations from local balance were not due to vertical transport, but rather associated with deviations from horizontal homogeneity. In this sense, the picture that emerges from Figs. 6–8 suggests a flow in which horizontal heterogeneity has a dominant imprint on the TKE budget. For these two specific sites (and for most of the Amazon forest), the two main possible causes of deviations from horizontal homogeneity are the presence of topography and the horizontal variation in canopy structure. In the Amazon forest, vegetation in the valleys tend to be shorter and less dense than in the plateaus, due to the larger fraction of sand in the soil (Da Silva et al. 2002). Because we believe the effect of topography to be significantly more important than that of forest heterogeneity, we investigate this in the next section.

c. *Effects of idealized topography on TKE budget*

Here our goal was not to perform a complete investigation of TKE budgets over forested topography, but rather to use existing LES results to investigate if topography could explain the overall patterns in the TKE budget from the observations described in the previous section. To gain some insight on the effects of topography on the local balance of TKE production and dissipation, we

443 looked at $R/\varepsilon = P/\varepsilon - 1$ over the idealized hill covered by a model of the Amazon forest under
 444 neutral stratification. Results from the LES run described in Sec. 3b are displayed in Fig. 9. The
 445 strong effect of the topography on the TKE budget within the RSL (roughly between the two black
 446 dashed lines) is clearly seen in the figure. Note that, contrary to the situation over flat topography,
 447 portions of the RSL had strongly negative local imbalance. In particular, in the region at the top
 448 of the ridge (representative of the plateaus in the Amazon forest, where measurements were made
 449 for both campaigns), a fairly complex pattern was present in which a transition from positive to
 450 negative imbalance occurred within the RSL.

451 To draw a more direct comparison between the measurements in the Amazon and the LES results
 452 for idealized topography, LES data from the region $(x/L_h) = 2 \pm 0.2$ considered for practical
 453 purposes as the top of the ridge are shown in Fig. 10a together with results for LES over flat
 454 topography (i.e. results from the LES simulation shown in Fig. 3b). In comparison to the flat
 455 case, the presence of topography produced a much larger range of possibilities in terms of local
 456 imbalance of TKE. If we confine our observations to the top of the ridge, then the overall effect
 457 was to increase the positive imbalance in the lower half of the RSL and to reduce it in the upper
 458 half. This reduction was large enough to produce a region of negative imbalance in the upper part
 459 of the RSL. Effects of topography seemed to extend above $z/h_c = 4$ (above this height simulations
 460 results were impacted by the numerical boundary conditions at the top of the domain and were not
 461 analyzed). These conclusions are specific to the simple topography employed in the simulation,
 462 and to the specific combination of vegetation and topography scales used in this specific case.
 463 Nevertheless, the simulation did show that topographic effects can be quite strong and produce
 464 results at the top of the hill that were consistent with the observations in the previous section.
 465 This becomes clear when profiles of normalized imbalance are put side to side as done in Fig.
 466 10. The major differences between the profiles from observation and LES are likely caused by the

467 differences in topography and the absence of static stability effects in the simulation. However, the
 468 clear existence of a region with negative imbalance in the upper part of the RSL after a transition
 469 region with $R \approx 0$ in both, LES and observations, can be explained by the presence of topography.

470 To guide the interpretation of these results, we used the theoretical work on neutral flows over
 471 rough isolated hills developed by Hunt et al. (1988). In this theory, valid for small hills, the inner
 472 layer is defined as the region where $z/h_i \leq 1$, with h_i implicitly defined via

$$\frac{h_i}{L_h} \ln \left(\frac{h_i}{z_0} \right) = 2\kappa^2. \quad (7)$$

473 In the lower half of the inner layer, eddy lifetime ($\tau_\varepsilon = \bar{e}/\varepsilon$) is small compared to the advection
 474 time scale ($\tau_a = L_h/\bar{u}$), so eddies do not last long enough to experience significant changes in
 475 straining rate. In this region, turbulence is approximately homogeneous, turbulent transport and
 476 advection of TKE are small and there must be an approximate balance between production and
 477 dissipation of TKE (Belcher et al. 1993; Kaimal and Finnigan 1994). Thus, one would expect
 478 $R \approx 0$. For forest covered hills, the inner layer is the region within $d_0 \leq z \leq (d_0 + h_i)$, and it would
 479 be natural to expect the local balance in the lower half of the inner layer to be broken by vertical
 480 transport of TKE into the canopy (i.e., $R^v > 0$ but $R^h \approx 0$).

481 Using the roughness length $z_0 = 2\text{m}$ estimated from GoAmazon data and the values of L_h es-
 482 timated from the topography map (Fig. 2), Eq. (7) yielded $h_i = 40\text{m}$ for the GoAmazon and
 483 $h_i = 55\text{m}$ for the ATTO site. The profiles of the two timescales τ_ε and τ_a are shown in Fig. 11a,
 484 where the grey region corresponds to the inner layer for the ATTO site (for the GoAmazon, the in-
 485 ner layer was slightly shallower). The ratio between the two timescales is also shown in Fig. 11b,
 486 and it was in agreement with the expectations for flow over rough hills, in the sense that $\tau_\varepsilon/\tau_a < 1$
 487 within the inner layer and $\tau_\varepsilon/\tau_a > 1$ above.

488 However, our analysis suggests that the causes for local imbalance within the inner layer extends
489 beyond the vertical transport characteristic of flow over canopies. LES results show strong hori-
490 zontal variability in the local imbalance (Fig. 9). In addition, analysis of observations suggests that
491 vertical transport can only explain the local imbalance very close to the canopy top ($z/h_c = 1.00$
492 and $z/h_c = 1.08$ for GoAmazon and ATTO, respectively). At $z/h_c = 1.15$ for the GoAmazon data,
493 which is well within the inner layer, the importance of deviations from horizontal homogeneity are
494 quite strong (Fig. 8b). Together, these points suggest that advection and/or horizontal transport by
495 pressure and velocity fluctuations play a very important role within the inner layer over vegetated
496 topography. A more detailed analysis of LES results is needed to confirm the role of advection.

5. Conclusions

The goal of the present paper was to characterize the structure of the ABL over gentle topography covered by forests using daytime observations from two field campaigns in central Amazonia. We used an analysis of the TKE budget on the reduced TKE phase space (Chamecki et al. 2018), focusing on the local imbalance between production and dissipation. To facilitate interpretation, the imbalance was also split into a portion consistent with horizontal homogeneity and a portion caused by horizontal heterogeneity. The interpretation of the observational results was aided by LES simulations.

Analysis on the TKE phase space revealed two striking features in the observations: (1) a region in approximate local balance between production and dissipation, akin to an inertial sublayer, located fairly close to the canopy top ($z/h_c = 1.15$ for GoAmazon and $z/h_c = 1.49$ for ATTO), and (2) a region with local production smaller than dissipation still within the roughness sublayer ($z/h_c = 1.38$ for GoAmazon and $z/h_c = 2.19$ for ATTO). Neither can be explained by the canonical flat terrain TKE budgets in the canopy roughness layer or in the lower portion of the convective ABL. Both layers were characterized by a negative net transport of TKE, as expected from a roughness sublayer behavior, and our analysis showed that deviations from horizontal homogeneity in these layers were remarkably large. Results from LES of a model canopy over idealized (but comparable) topography suggested that the presence of topography can explain the behavior of the TKE budget in these two regions. Thus, we concluded that the boundary layer above the Amazon forest is strongly impacted by the gentle topography underneath, and that topography explains the patterns of TKE imbalance reported by Chamecki et al. (2018).

Our analysis confirmed the observation from Dias-Júnior et al. (2019) that there is no inertial sublayer at the ATTO site, and extended this observation to the GoAmazon site as well. We derived

520 two criteria for the existence of an ISL over forests in flat terrain, and most of the data satisfied
521 these criteria, suggesting that an ISL should exist in the absence of topography. Based on this
522 fact, and on the characteristics of the TKE budget, we concluded that most of the time there is
523 a layer between the canopy roughness sublayer and the mixed layer above. Over flat terrain, we
524 would expect MOST to hold in this layer. However, the horizontal flow heterogeneity produced
525 by the presence of topography modifies the TKE budget, producing more complex turbulence that
526 does not conform to MOST.

527 If one were to think about the topography as a “large-scale roughness” (e.g., from a mesoscale
528 perspective), then the layer in which the topography produces major modifications in the flow
529 would be the roughness sublayer associated with the topography itself. From this viewpoint, there
530 are two roughness sublayers superimposed on (and interacting with) each other: the roughness
531 sublayer associated with the forest and the one associated with the topography.

532 Several questions remain, and an LES investigation of the TKE budget above forests in complex
533 terrain under various atmospheric stability conditions is probably warranted. Our analysis also
534 reviewed some interesting features of the TKE budget in the inner layer of the flow over topogra-
535 phy, that seemed to differ from the behavior for flow over rough hills. In particular, the striking
536 spatial variability of the TKE imbalance seems to question some of the assumptions employed in
537 the analysis of rough hills and ridges. A better characterization of the TKE budget in this region is
538 needed. From an observational perspective, it would be useful to confirm that at the top of ridges,
539 shear production can still be accurately estimated from the vertical shear in the streamwise veloc-
540 ity, and that the other components are still small. It would also be useful to quantify the effects of
541 pressure transport, to solidify the data analysis framework developed here.

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TABLE 1. Sonic anemometer data

Site	Tower height (m)	Sonic height (m)	z/h_c	Model	Frequency (Hz)	# of blocks
GoAmazon ($h_c = 35$ m)	50	34.9	1.00	CSAT3 ^a	20	319
	50	40.4	1.15	CSAT3	20	292
	50	48.2	1.38	CSAT3	20	238
ATTO ($h_c = 37$ m)	80	41	1.08	CSAT3	10	103
	80	55	1.49	CSAT3	10	120
	80	80	2.20	Windmaster ^b	10	111
	325	150	4.06	CSAT3	10	84
	325	325	8.78	IRGASON ^a	20	45

^aCampbell Scientific Inc.^bGill Instruments Limited

TABLE 2. Setup used in the 3 numerical simulations

Variable	LES_CBL	LES_FOR	LES_TOPO
Domain size ($L_x \times L_y \times L_z$) [m]	$7680 \times 7680 \times 2700$	$2000 \times 1000 \times 520$	$2000 \times 1000 \times 540$
Grid size ($\Delta_x \times \Delta_y \times \Delta_z$) [m]	$30 \times 30 \times 6.75$	$6.25 \times 6.25 \times 2.00$	$6.25 \times 6.25 \times 2.00$
Grid points ($N_x \times N_y \times N_z$) [-]	$256 \times 256 \times 400$	$320 \times 160 \times 260$	$320 \times 160 \times 270$
Pressure gradient force [m/s^2]	6.125×10^{-4} ^a	3.11×10^{-4}	3.11×10^{-4}
Coriolis frequency [s^{-1}]	1×10^{-4}	0	0
Surface heat flux [Km/s]	3.76×10^{-2}	0	0
ABL height [m]	1570	515	515

^aApplied in the negative y-direction based on a geostrophic velocity of $U_g = 5 \text{ m/s}$

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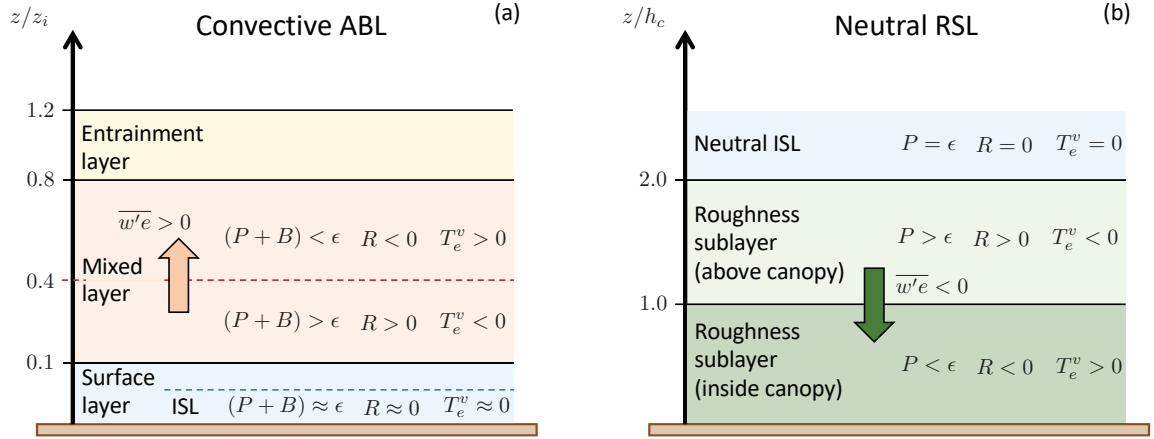


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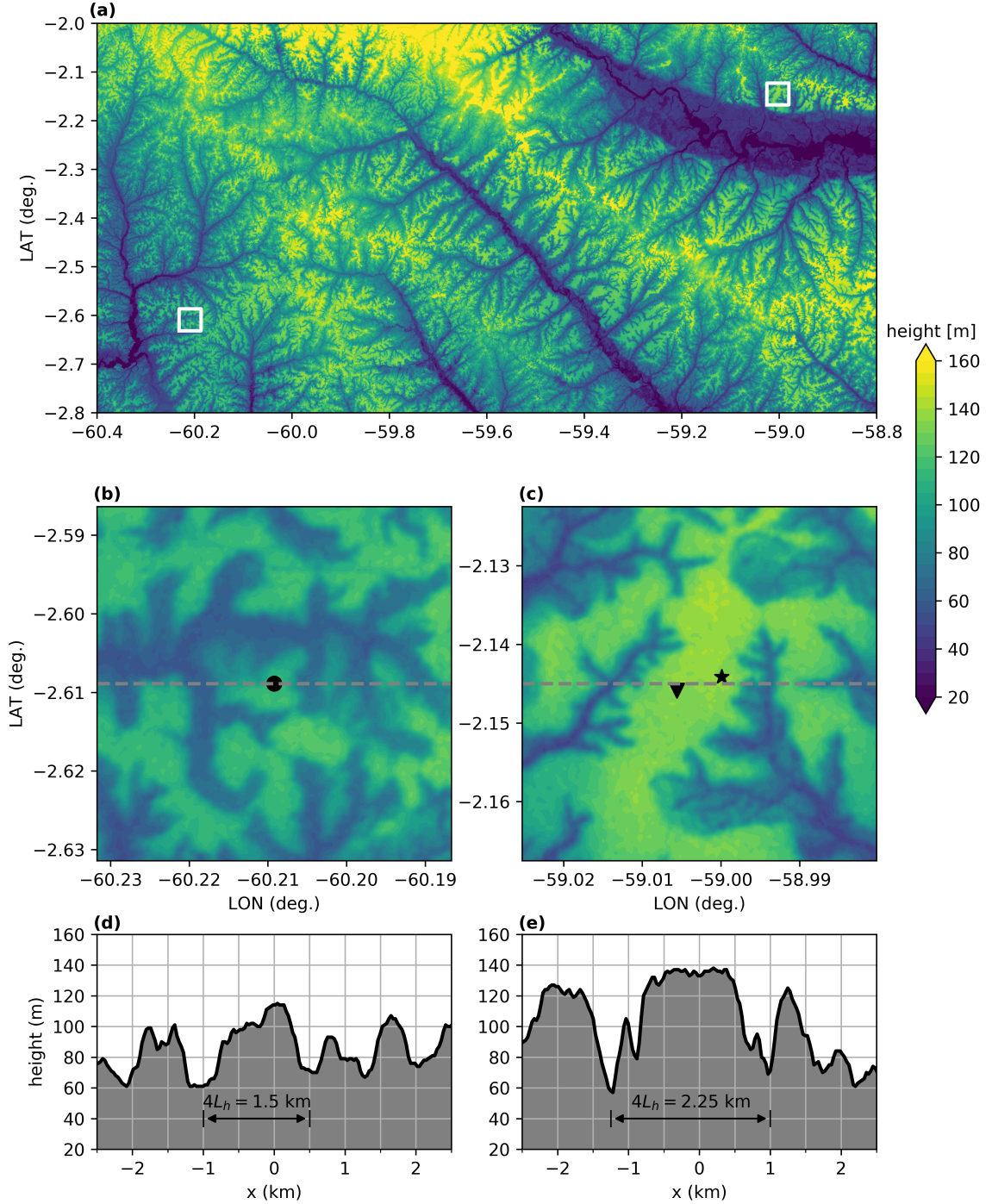


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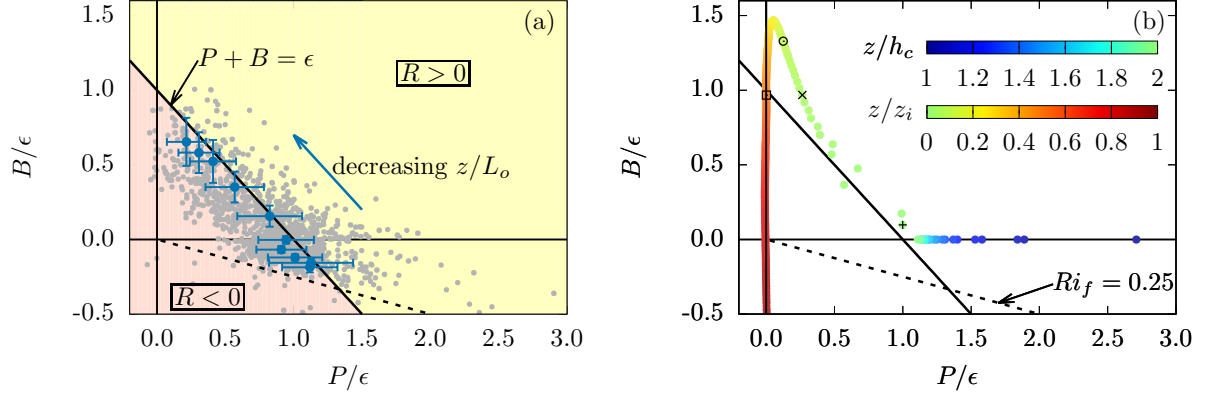


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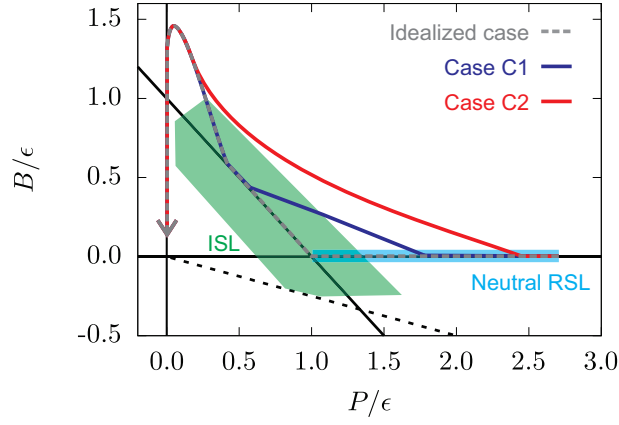


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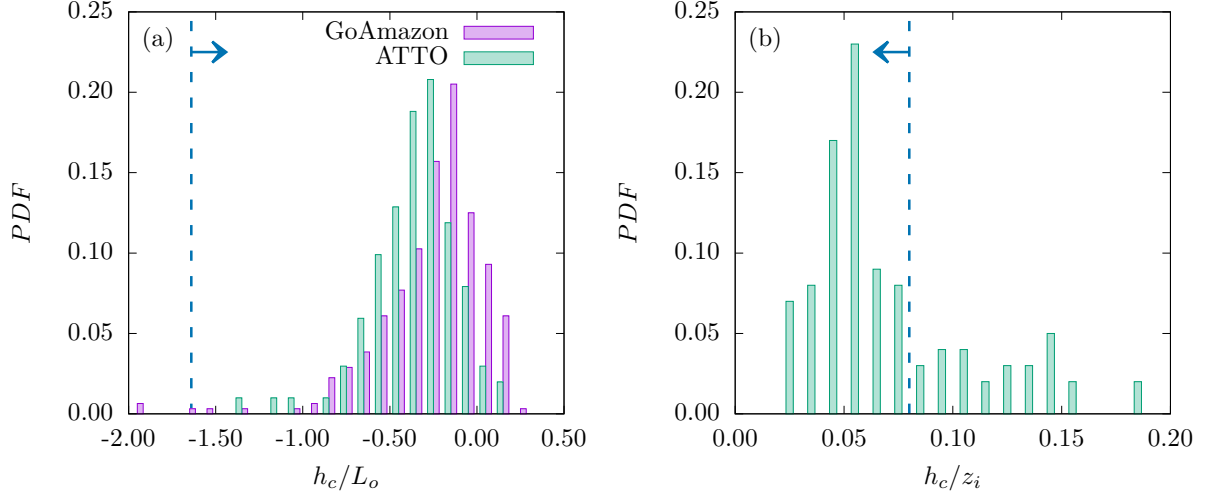
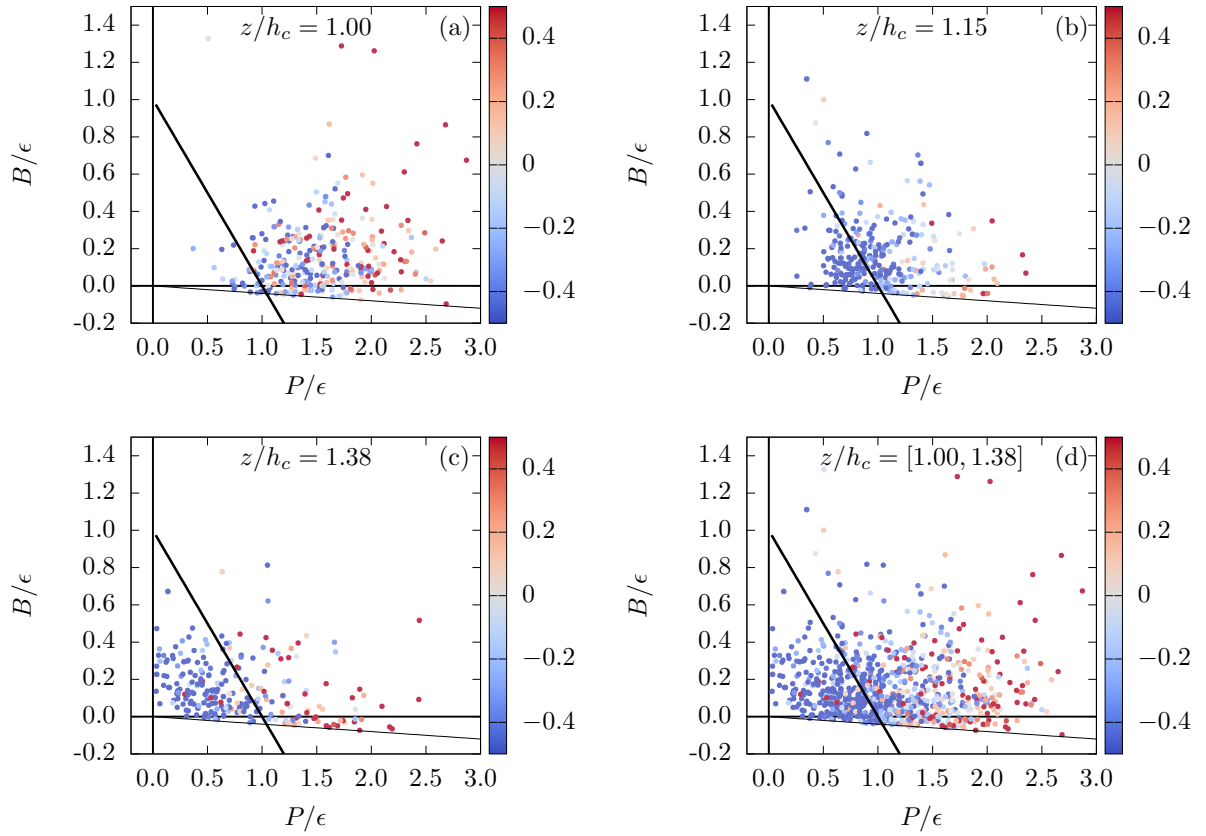
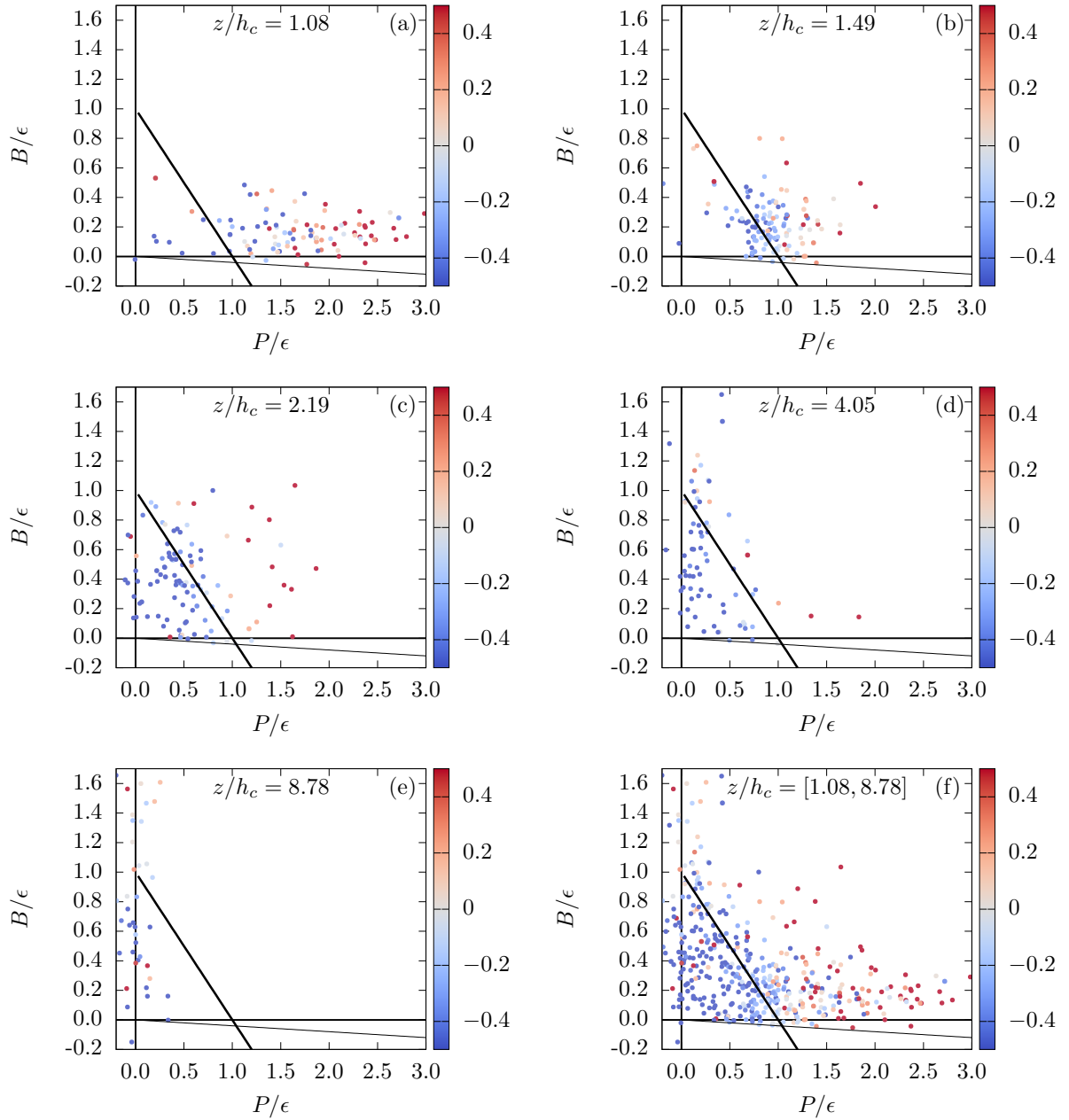


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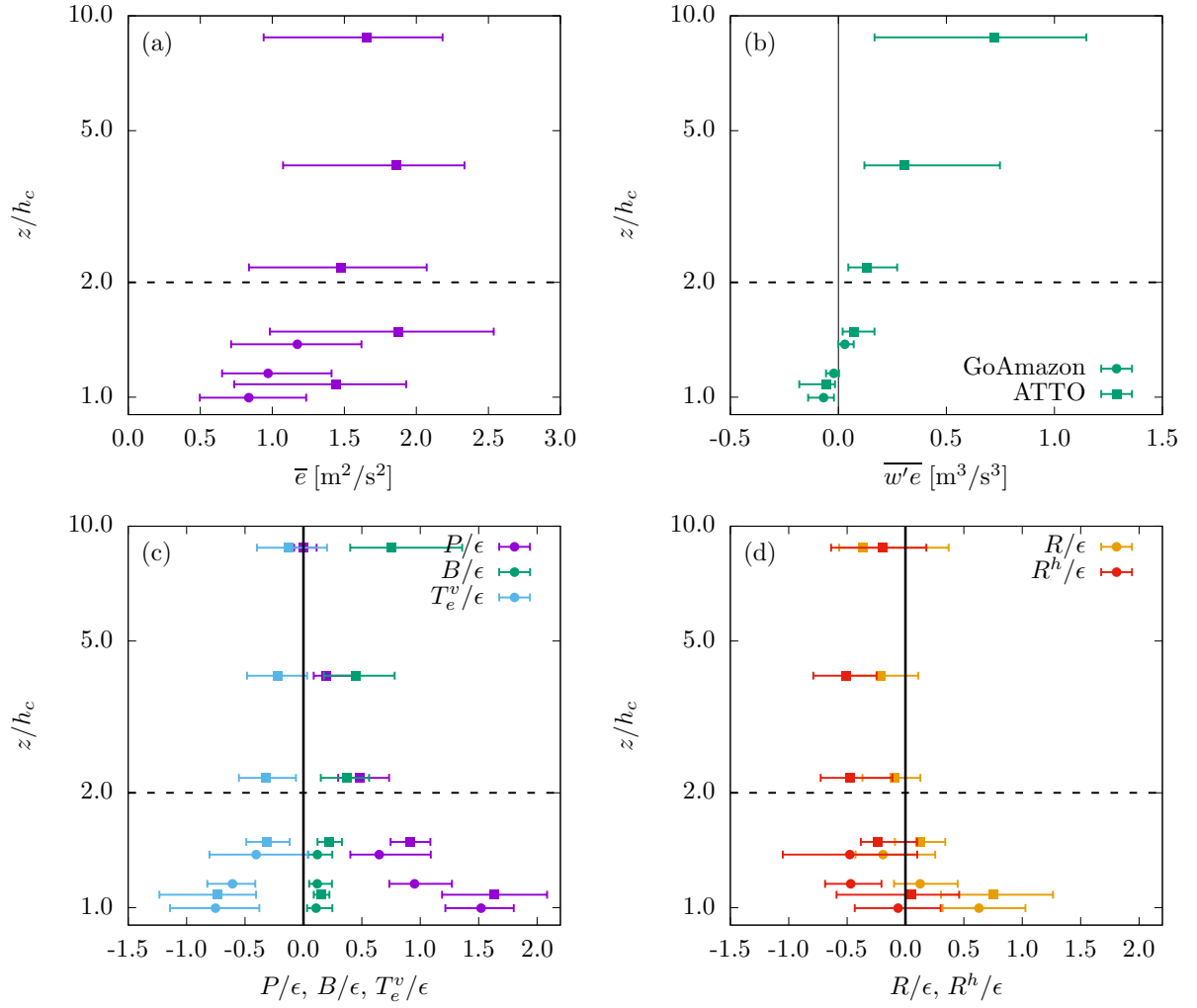
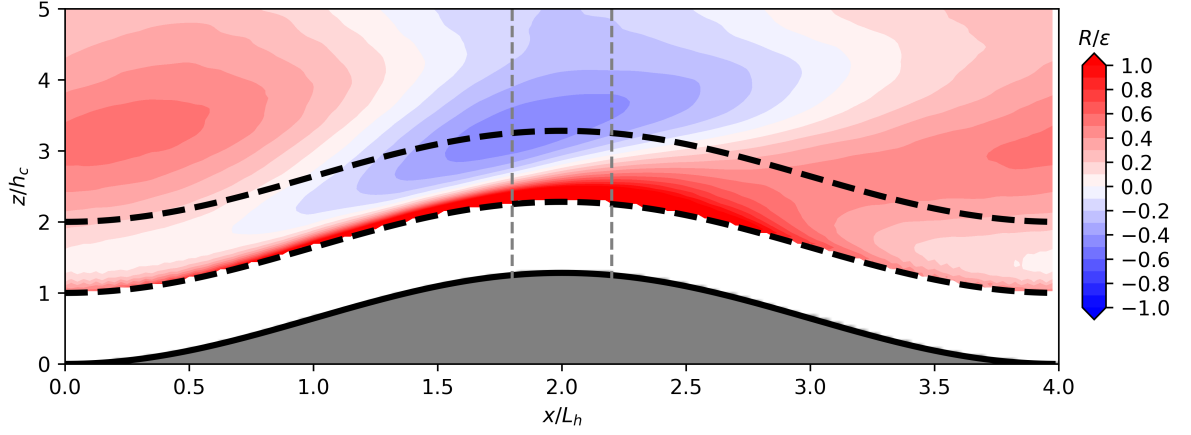


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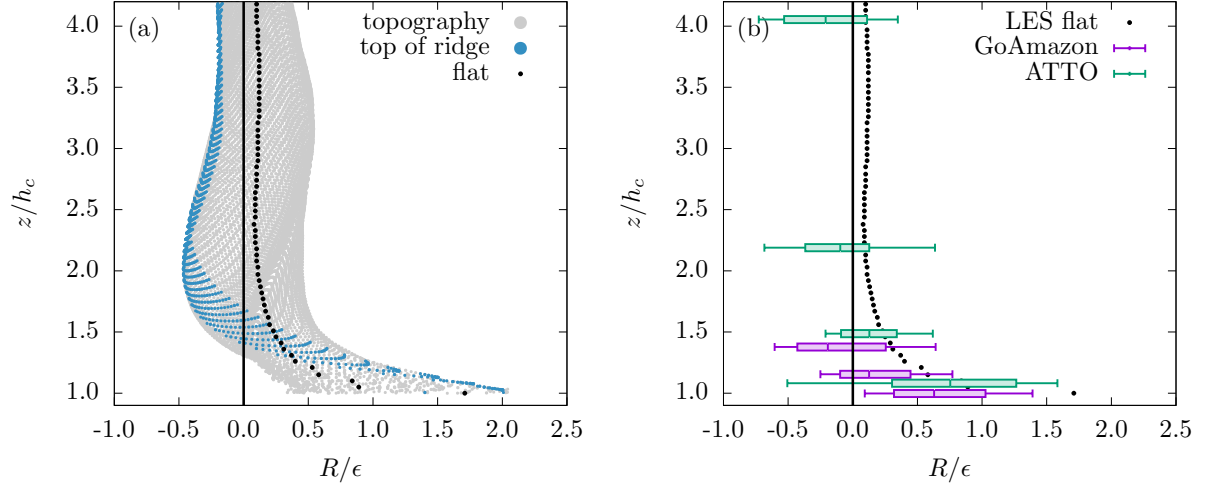


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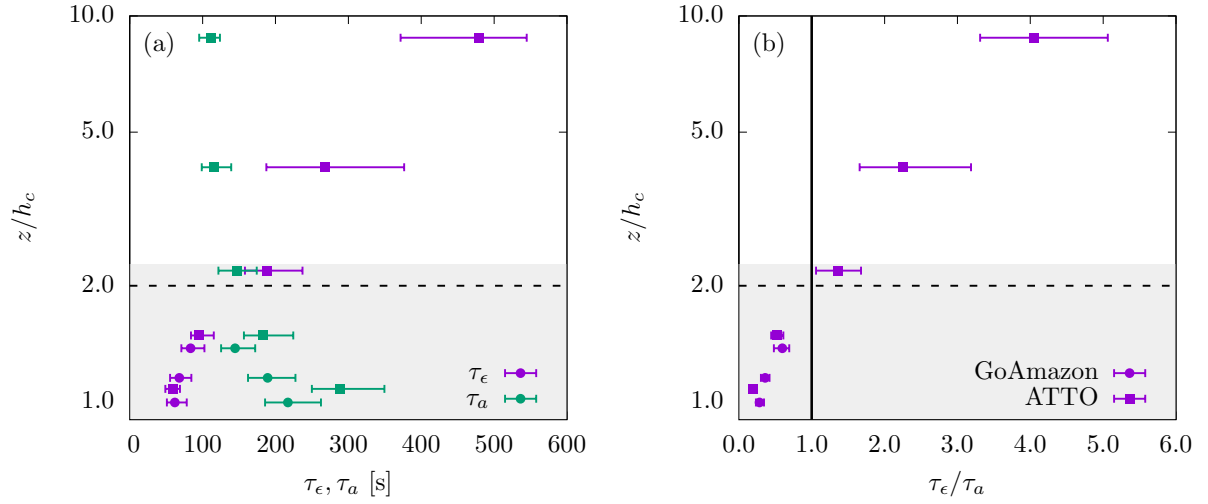


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