

UC Irvine

UC Irvine Previously Published Works

Title

Turbulence regimes in the nocturnal roughness sublayer: Interaction with deep convection and tree mortality in the Amazon

Permalink

<https://escholarship.org/uc/item/91s864tb>

Authors

Mendonça, Anne CS
Dias-Júnior, Cléo Q
Acevedo, Otávio C
et al.

Publication Date

2023-08-01

DOI

10.1016/j.agrformet.2023.109526

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Turbulence regimes in the nocturnal roughness sublayer: interaction with deep convection and tree mortality in the Amazon

Anne C. S. Mendonça^a, Cléo Q. Dias-Júnior^{a,b,*}, Otávio C. Acevedo^c, Raoni A. Santana^d, Felipe D. Costa^e, Robinson I. Negrón-Juarez^f, Antônio O. Manzi^g, Susan E. Trumbore^h, Daniel. M. Marra^h

^a*Amazonian National Research Institute (INPA-CLIAMB), Manaus, AM, Brazil*

^b*Department of Physics, Federal Institute of Pará (IFPA), Belém, PA, Brazil*

^c*Departamento de Física, Universidade Federal de Santa Maria, Santa Maria, RS, Brazil*

^d*Institute of Engineering and Geosciences, Federal University of West Pará (UFOPA), Santarém, PA, Brazil*

^e*Universidade Federal do Pampa, Alegrete, Brazil*

^f*Lawrence Berkeley National Laboratory, Berkeley, CA, USA*

^g*National Institute for Spatial Research (INPE), Cachoeira Paulista, SP, Brazil*

^h*Biogeochemical Processes Department, Max Planck Institute for Biogeochemistry, Jena, Germany*

Abstract

We investigated the influence of seasonality and proximity to the forest canopy on nocturnal turbulence regimes in the roughness sublayer of a Central Amazon forest. Since convective systems of different scales are common in this region, we also analyzed the effect of extreme wind gusts (propagated from convective downdrafts) on the organization of the turbulence regimes, and their potential to cause the mortality of canopy trees. Our data include high-frequency winds, temperature and ozone concentration at different heights during the dry and wet seasons of 2014. In addition, we

*Corresponding Author

Email address: cleo.quaresma@ifpa.edu.br (Cléo Q. Dias-Júnior)

used critical wind-speed data derived from a tree-winch experiment and a modeling study conducted in the same study site. Two different turbulence regimes were identified at three heights above the canopy: a weakly stable (WS) and a very stable regime (VS). The threshold wind speeds that mark the transition between turbulence regimes were larger during the dry season and increased as a function of the height above the canopy. The turbulent fluxes of sensible heat and momentum during the WS accounted for 88% of the entire nighttime flux. Downdrafts occurred only in the WS and favored a fully coupled state of wind flow along the canopy profile. The destructive potential of winds was four times higher than on nights without downdrafts.

Keywords: Downdrafts, Extreme wind speed, Seasonality, Tropical forest, Turbulence regimes, Wind disturbance

1. Introduction

A growing number of observational and modeling studies show that the world's forests plays a key role in global climate (Malhi et al., 2002; Bonan, 2008; Alves et al., 2016) and emphasize its importance to the water, radiation and surface-energy balance. All these are affected by exchanges of mass (water vapor, carbon dioxide, methane, ozone, and a variety of gases and particles), heat (sensible and latent) and momentum between the forest and the atmosphere (Von Randow et al., 2004; Thomas and Foken, 2007; Knohl and Baldocchi, 2008; Gerken et al., 2016, among others). This near-surface boundary layer that is dynamically influenced by vegetation is called the roughness sublayer (RSL). Particularly at night, the transport efficiency decreases above the forest, which inhibits its penetration into the canopy (Cava

13 [et al., 2022](#)) and leads to a decoupling between the sub- and upper canopy
14 flows ([Thomas et al., 2013](#); [Freundorfer et al., 2019](#); [Cava et al., 2022](#))

15 Assessments of turbulent flow are challenging in the nocturnal RSL, par-
16 ticularly during the occurrence of intense downdrafts that typically originate
17 within a convective system (e.g. squall lines, super-cell and single-cell thun-
18 derstorms). Intense downdrafts can develop when cooled air from evaporat-
19 ing precipitation sinks rapidly towards the ground. Such events transport
20 relatively cooler and drier air from the troposphere to the lower levels lead-
21 ing to changes in the thermodynamic and kinematic properties of the near-
22 surface air mass ([Wakimoto, 2015](#)). These downdrafts can extend to the
23 surface in the form of sudden variations in the values of the wind, pressure,
24 turbulent fluxes and a drop in equivalent potential temperature ([Garstang
25 and Fitzjarrald, 1999](#); [Betts et al., 2002](#); [Dias-Júnior et al., 2017a](#); [Melo et al.,
26 2019](#); [D’Oliveira et al., 2022](#)). Such phenomena can gain an interesting phys-
27 ical interpretation when the turbulence is classified into distinct turbulent
28 nocturnal regimes. In mid-latitude regions for example, [Mahrt \(1998\)](#) cate-
29 gORIZED turbulence as “weakly stable” and “very stable” to differentiate the
30 conditions of sustained and non-sustained turbulence, respectively. [Sun et al.
31 \(2012\)](#) classified the turbulence regimes as either weak or strong, according to
32 the relationship between Turbulent Kinetic Energy (TKE) and wind speeds.
33 Subsequently, such terms have been widely used to refer to the regimes.

34 The weakly stable regime follows Monin-Obukhov similarity theory, which
35 is used in most atmospheric models for expressing the surface layer. On the
36 other hand, the same is not true in the very stable regime ([Mahrt, 1998,
37 2014](#)). In general, numerical schemes such as those used in numerical weather

38 prediction and atmospheric models reproduce the occurrence of both noc-
39 turnal turbulence regimes, but conditions that mark the transition between
40 them depend on the parameterizations used to represent the eddy diffusivity
41 (Costa et al., 2020). The transition between regimes is not universal, vary-
42 ing from one site to another. Such differences may be associated with local
43 factors, for example by increased cloudiness (Acevedo and Fitzjarrald, 2003),
44 surface roughness (Mahrt et al., 2013) and net nocturnal radiative loss (Sun
45 et al., 2020; Acevedo et al., 2021).

46 Recent studies (Santos et al., 2016; Cava et al., 2022) have evidenced
47 that the nature of the nocturnal-scalar exchange between the canopy and the
48 overlying atmosphere is contrastingly dependent on the turbulence regime.
49 While the weakly stable regime is dominated by turbulence, under very stable
50 conditions a relatively larger fraction of the exchange is produced by non-
51 turbulence motion with long time scales. This fact is particularly important
52 for quantifying these fluxes since under very stable conditions the typical
53 eddy-covariance methods might not properly capture the total exchange.
54 Therefore, when assessing exchange patterns it is important to consider the
55 following: Is the exchange seasonally dependent? If so, what seasonal pro-
56 cesses affect the regimes? Is the nocturnal turbulence regime influenced by
57 the frequency of convective downdrafts, which can affect the total canopy-
58 atmosphere exchange of scalars? Therefore, experimental results obtained
59 at different sites, such as in dense tropical forests, are essential to better
60 understand the biosphere-atmosphere interaction and to improve existing
61 knowledge on the nocturnal boundary layer.

62 From another perspective, in regions often covered by intense convective

63 systems and convective cloud clusters, such as the Amazon region (Betts
64 et al., 2002, 2003; Machado et al., 2002, 2004), the downdrafts may propa-
65 gate strong downward wind gusts with high velocities (Fujita, 1985; Nelson,
66 1994; Garstang et al., 1998; Negrón-Juárez et al., 2010, 2017, 2018). When
67 they reaches the surface, strong wind outflow with horizontal dimensions is
68 propagated (Fujita, 1985; Garstang et al., 1998). These wind gusts can cause
69 widespread tree damage and mortality through snapping and/or uprooting.
70 These modes of tree mortality occur when the mechanical load caused by
71 wind exceeds the resistance of the trunk or the root-soil anchorage (Nelson,
72 1994; Marra et al., 2014; Ribeiro et al., 2016).

73 The severity of damage/mortality caused by extreme wind events influ-
74 ences biomass balance and the functional composition of *terra-firme* forests
75 in Central and Northwestern Amazon (Urquiza Muñoz et al., 2021; Negrón-
76 Juárez et al., 2018; Marra et al., 2018, 2014). While some of the carbon
77 contained in dead or damaged trees is decomposed and incorporated into
78 the soil rather than directly emitted into the atmosphere (dos Santos et al.,
79 2016), dead trees represent future CO_2 emissions (Chambers et al., 2004) and
80 potentially methane (CH_4), which contributes to global warming. Using field
81 data (Ribeiro et al., 2016) combined with static and dynamic biomechanical
82 models, Peterson et al. (2019) estimated that wind speeds $> 10.75 \text{ m s}^{-1}$
83 are critical and can snap or uproot trees in *terra-firme* forests of Central
84 Amazon.

85 Current knowledge about the effects of wind disturbances in the Ama-
86 zon forest derives from studies that have quantified the spatial extent of
87 these events using satellite imagery, in particular Landsat (Nelson, 1994;

88 [Negrón-Juárez et al., 2010](#); [Chambers et al., 2013](#); [Espírito-Santo et al., 2014](#)),
89 or from post-perturbation forest inventories to assess associated tree dam-
90 age/mortality and their effects on forest structure and diversity in subsequent
91 years to decades ([Marra et al., 2014, 2018](#); [Schwartz et al., 2017](#); [Silvério et al.,](#)
92 [2019](#); [Urquiza Muñoz et al., 2021](#)). The estimated time to recover 90% of
93 pre-disturbance biomass is up to 40 years ([Marra et al., 2018](#)) in the Central
94 Amazon and 30 years in the northwestern Amazon ([Urquiza Muñoz et al.,](#)
95 [2021](#)).

96 The goal of our study was to identify the existence of different noctur-
97 nal turbulence regimes above a *terra-firme* forest in the Central Amazon
98 and their possible association with seasonality and proximity to the forest
99 canopy. Furthermore, to assess the effect of extreme winds associated with
100 convective downdrafts on the organization of turbulence regimes in the noc-
101 turnal RSL and the potential of observed winds to cause damage/mortality
102 of canopy trees. We recognize that damaging winds and downdrafts in this
103 region are also associated with convective storms and with fronts that can
104 pass during the day, but that is beyond the scope of the current analysis. To
105 our knowledge, this is the first assessment of the influence of extreme winds
106 on turbulence regimes and of the potential of associated wind to promote
107 tree damage/mortality. Apart from a better understanding of the processes
108 of turbulent exchange between the biosphere and the atmosphere, especially
109 in rainforests with dense canopies, our study provides insights into the vul-
110 nerability of Amazon forests to ongoing shifts on the intensity and frequency
111 of convective storms resulting from climate change ([Feng et al., 2023](#)).

112 2. Material and methods

113 2.1. Study site and data acquisition

114 Our data were collected at the *Estação Experimental de Silvicultura Trop-*
115 *ical* (EEST, also known as ZF2), Central Amazon, Brazil (Figure 1). The
116 EEST is located about 60 km northwest of Manaus ($2^{\circ} 36' S$, $60^{\circ} 12' W$,
117 $130 m a.s.l.$) (Araújo et al., 2002) and is predominantly covered by old-
118 growth *terra-firme* forest with closed canopy (e.g. 593 ± 28 trees ha^{-1}),
119 dense understory and high tree-species diversity (Braga, 1979; Marra et al.,
120 2014). Trees are relatively tall and slender (Oliveira et al., 2008; Ribeiro
121 et al., 2016). The proportion of trees reaching the canopy increased with
122 diameter at breast height (DBH): from 21% for trees 10-20 cm DBH, and
123 57% for 20-30 cm DBH, up to 100% for trees above 70 cm DBH (Araujo
124 et al., 2020).

125 The topography at the study area comprises a mosaic of plateaus, slopes
126 and valleys with elevation differences of about 50 m. The vegetation cover
127 on the plateau and slope areas is composed by forest with height varying
128 between 30 to 40 m, maximum surface area density of $0.35 m^2m^{-3}$. In
129 valley areas, the vegetation is smaller with heights from 15 to 25 m, but
130 with significant surface area density more than the $0.35 m^2m^{-3}$ (Tóta et al.,
131 2012). The average values of leaf area index for the local vegetation was 6.1
132 m^2m^{-2} (Marques Filho et al., 2005).

133 Oxisols rich in kaolinite clay dominate plateaus and the upper portions
134 of slopes. The soils on slope bottoms and valleys are sandy and mixed with
135 organic matter (Spodosol) (Telles et al., 2003). The mean annual tempera-
136 ture is $27^{\circ}C$ and mean annual rainfall was about 2365 mm for the period

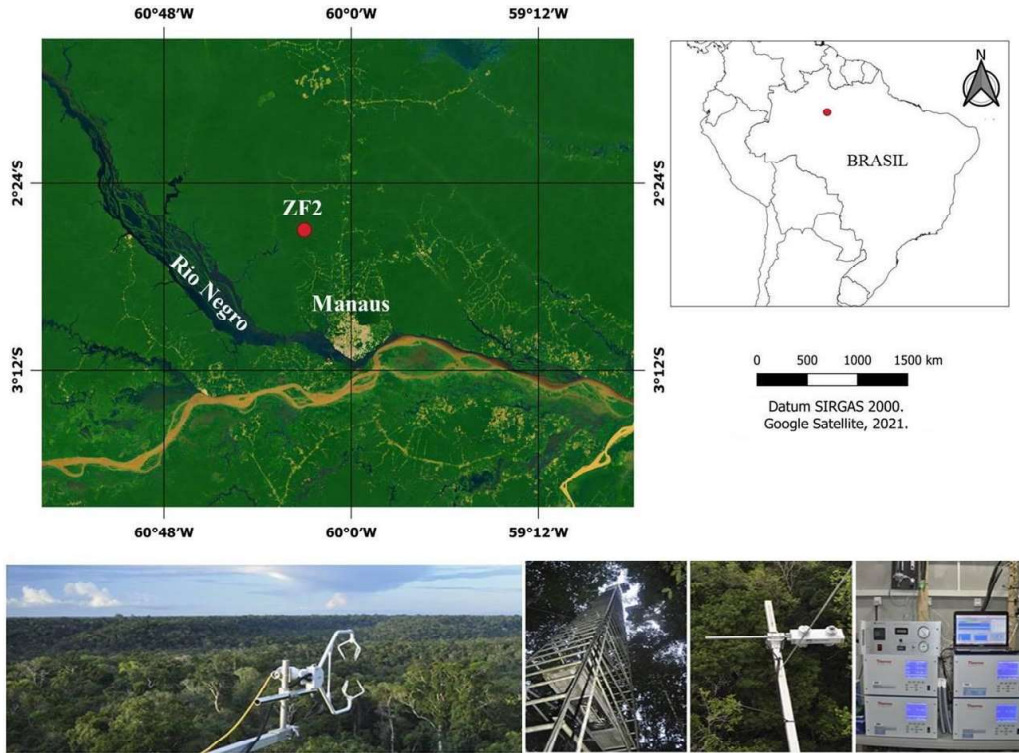


Figure 1: Study area at the *Estação Experimental de Silvicultura Tropical* (EEST) near Manaus, Brazil, and micrometeorological tower and sensors. (Top panel) Map of Brazil showing the study region. (Bottom left) A panoramic view of the forest and the employed 3D-sonic anemometer. (Bottom center left) Micrometeorological tower. (Bottom center right) Net radiometer. (Bottom right) Ozone analyzers.

137 between 1971 and 2000, with a distinct dry season between July and Septem-
 138 ber (rainfall $< 100 \text{ mm month}^{-1}$) (Negrón-Juárez et al., 2017).

139 Our data were collected using sensors installed on a micrometeorological
 140 tower of 54 m height. We used the sonic virtual temperature (T) and wind
 141 components (u, v and w) measured at 10 different heights (i.e. 1.5, 7.0,
 142 13.5, 18.4, 22.1, 24.5, 31.6, 34.9, 40.4 and 48.2 m above ground) by 3D-sonic
 143 anemometers (model CSAT3, Campbell Scientific Inc., Logan, UT, USA) at

144 a rate of 20 Hz. For analyzing the vertical temperature gradient, we used
145 thermo-hygrometer data from sensors (HMP45AC, Vaisala) installed at 35.5
146 m and 51 m height. These data were available at a 30 min resolution. Net
147 radiation (R_N) was measured with a net-radiometer (model CNR1, Kipp &
148 Zonen, Delft, Netherlands) installed at 39 m height. We used data from April
149 2014 to January 2015 collected in the course of the Green Ocean Amazon
150 Experiment (GoAmazon). For more details about instruments and respective
151 measurements, see [Fuentes et al. \(2016\)](#).

152 Ozone concentration (O_3) was measured continuously at 40 m height
153 at a frequency of 1 Hz using an ultraviolet light absorbed gas analyzer
154 (model 49i, Thermo Fisher Scientific Inc., Waltham, MA). For more de-
155 tails on ozone measurements see [Gerken et al. \(2016\)](#). Convective cloud
156 coverage over the study site was assessed with GOES-13 (Geostationary Op-
157 erational Environmental Satellites) satellite imagery data available at the
158 Brazilian National Institute for Space Research (INPE) database (<http://satelite.cptec.inpe.br/acervo/>,
159 accessed on 30 May 2021).

160 Our data were analyzed for two time periods: (i) 55 days in the wet sea-
161 son (from April to May) and (ii) 36 days during the dry season (from July
162 to September). To avoid transitional periods, we used data from 2000 to
163 0500 local standard time (LST). The dry and wet seasons were character-
164 ized based on the seasonality of precipitation using the Global precipitation
165 Mission (GPM) level-3 product ($mm\ h^{-1}$). Estimates were carried out us-
166 ing data downloaded from the website of National Aeronautics and Space
167 Administration (NASA) (<https://giovanni.gsfc.nasa.gov>, accessed on
168 28 october 2020) for the period between 1st April and 31st December 2014.

169 Overall, we used a product of the Integrated Multi-satellitE Retrievals for
170 GPM (IMERG) at a spatial resolution of $0.1^\circ \times 0.1^\circ$ and at temporal resolu-
171 tion of 1 month (Final Run IMERG v06). The IMERG algorithm combines
172 information from the GPM satellite constellation and precipitation gauges.
173 The system “final run” uses monthly gauge data to create research-level
174 products.

175 Local estimates of critical wind-speed (CWS) were compiled from [Peter-](#)
176 [son et al. \(2019\)](#). According to these authors, the CWS is the wind speed
177 necessary to generate a turning moment at the base of the trunk greater
178 than or equal to the turning moment that results in tree failure. CWS were
179 modeled based on critical turning moments measured locally in a winching
180 experiment that included 60 trees from different species and varying sizes
181 ([Ribeiro et al., 2016](#)). We considered CWS values estimated from a dy-
182 namic model (i.e. profile method) assuming that tree mortality associated
183 with convective systems can create canopy gaps that contribute to increasing
184 turbulence and wind propagation into the forest. In this model, tree spac-
185 ing/density, leaf-area index and wind profiles are updated progressively after
186 each tree failure ([Peterson et al., 2019](#)). The reported CWS ranged from
187 10.75 ms^{-1} to 34.5 ms^{-1} .

188 Before analyzing the micrometeorological, meteorological and profile data,
189 we conducted the following quality control: (i) testing for record complete-
190 ness and checking for the presence of error flags as proposed by [Zahn et al.](#)
191 ([2016](#)) and (ii) detection of spikes and dropouts with eventual removal of
192 corrupted/damaged data as suggested by [Vickers and Mahrt \(1997\)](#).

193 *2.2. Turbulence regimes and flux estimates*

194 In this study we examine the turbulence regimes at three heights. The
195 first one was defined as near as possible to the top of the forest canopy (i.e.
196 ≈ 35 m; [Fuentes et al. \(2016\)](#)), and the other two at the maximum heights
197 where the sensors were installed on the tower (40 and 48 m, respectively).
198 We focused only on the nighttime period (i.e., nocturnal boundary layer)
199 because the diurnal relationship between wind speed and turbulence rarely
200 deviates from linearity (not shown here), since typical daytime conditions at
201 our study site are close to neutrality.

202 We used two methods for identifying the nocturnal turbulence regimes.
203 The method proposed by [Sun et al. \(2012, 2016\)](#) considers the possibility of
204 external agents (e.g. convective clouds) acting on the atmospheric boundary
205 layer and disturbing its turbulent fields ([Garstang et al., 1998](#); [Garstang
206 and Fitzjarrald, 1999](#); [Betts et al., 2002](#); [Dias-Júnior et al., 2017a](#)). Sun's
207 method accounts for the average relationship between the turbulent velocity
208 scale (V_{TKE}) and the mean horizontal wind speed (V). Where $V_{TKE} =$
209 $\sqrt{TKE} = [0.5(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)]^{1/2}$ and $V = \sqrt{u^2 + v^2}$, in which u, v and w are
210 zonal, meridional and vertical wind components, σ represents the standard
211 deviation of each variable and TKE represents the Turbulent Kinetic Energy.
212 Sun's method identifies the wind speed threshold value (V_L) from the slope
213 change of a straight line around which the data are clustered. For this, we
214 performed a segmented linear regression and selected the V_L with the best
215 coefficient of determination (R^2). In this case, turbulence is compared at a
216 given level with the wind speed at that level.

217 The second method, reported by [Acevedo et al. \(2016\)](#) is based on the

218 sign inversion of the vertical gradient of V_{TKE} (ΔV_{TKE}). This procedure
 219 accounts for the relationship between V_{TKE} and V , but in contrast to Sun's
 220 method, turbulence is examined at all levels in terms of the wind speeds at
 221 a fixed reference level. When classified by the V at a reference level, the
 222 wind speed crossover threshold (V_T) lies where the average ΔV_{TKE} reverses
 223 sign for the entire tower layer. This change occurs because in very stable
 224 regime the V_{TKE} increase with height and the importance of low-frequency
 225 (sub mesoscale fluctuations) phenomena at higher levels contributes to this
 226 pattern. In weakly stable regime, on the other hand, the classical pattern of
 227 decreasing turbulence with height is dominant. Therefore, the parameters V_L
 228 and V_T are the wind speed values that determine the change from very stable
 229 (decoupled boundary layer) to weakly stable regime (the classical boundary
 230 layer coupled to the surface). Here, we assumed ΔV_{TKE} as the difference
 231 between 48 m and 35 m.

232 Fluxes were estimated by the Eddy Covariance method. We calculated
 233 the turbulent fluxes of sensible heat as $H = \rho c_p \overline{\theta' w'}$ and momentum as $\tau =$
 234 $\rho (\overline{u'w'^2} + \overline{v'w'^2})^{1/2}$, where ρ is the density of air (assumed to be 1.225 kgm^{-3})
 235 and c_p is the specific heat of air at a constant pressure. The variables θ' and
 236 w' , represent the fluctuations of virtual temperature ($^{\circ}\text{C}$) and vertical wind
 237 speed (ms^{-1}), respectively. As suggested by Sun et al. (2002) and Vickers
 238 et al. (2010), we used mean values over 5 min intervals for all the different
 239 statistical moments of the turbulence.

240 To investigate statistical differences between the very stable and weakly
 241 stable regimes, we first used the Mann Whitney U-test considering the iden-
 242 tified regimes as grouping variables. Therefore, six tests were performed, one

243 at each height (48 m, 40 m and 35 m) and for the dry and wet seasons.
244 In a second analysis, we applied a factorial analysis of variance (ANOVA)
245 followed by Tukey tests to assess the effects of the interaction between the
246 seasons, heights and turbulence regimes on observed patterns of atmospheric
247 turbulence. Here we use V_{TKE} as dependent variable. For all tests we con-
248 sidered a significance level of 5% and used the software Matlab and Jamovi
249 for data processing and analysis.

250 In this work V_{TKE} was only used in the analysis of the transition of
251 turbulence regimes, but not as an indicator of the tree damage/mortality.
252 To assess the potential of extreme wind gusts as a mechanism of tree dam-
253 age/mortality, we compared the CWS data available for our study site and
254 the maximum wind speed observed within our study period, as detailed in
255 section 2.4.

256 *2.3. Identification of convective cloud downdrafts*

257 Previous studies have demonstrated that convective downdrafts transport
258 air with high O_3 concentrations and lower T (cold pool) rapidly from the
259 lower-middle troposphere to the surface (Betts et al., 2002; Gerken et al.,
260 2016; Dias-Júnior et al., 2017a; Bezerra et al., 2021).

261 It is known that in environments with high moisture and strong con-
262 vection such as in the Amazon, the equivalent potential temperature (θ_e) is
263 also important under unstable atmospheric conditions. Since θ_e changes as a
264 function of moisture (through mixing ratio) and temperature, the downward
265 transport of cold and dry air leads to an important decrease of θ_e (Garstang
266 and Fitzjarrald, 1999; Betts et al., 2002). However, moisture data were not
267 available for our study site. Alternatively, we used virtual temperatures.

268 The identification of convective cloud downdrafts in our study was per-
269 formed using a two-step procedure. We first analyzed the time series of
270 horizontal wind speed, air temperature and surface concentration of O_3 to
271 investigate atmospheric dynamics and the occurrence of gust fronts associ-
272 ated with convective clouds. For this analysis, we averaged data at 48 m (V
273 and T) and 40 m (O_3) height for 5-minute intervals. The data series were
274 mapped by an algorithm that identifies a subtle increase of O_3 concentra-
275 tions of at least 3 parts per billion (ppb), and a simultaneous decrease of T
276 values of 2 °C within a 1h time window of respective events (Gerken et al.,
277 2016; Dias-Júnior et al., 2017a). During these events, the highest horizontal
278 wind speed registered within one second interval and the five minutes average
279 comprising such an interval were retained. False detections were manually
280 identified and removed. In the next step, GOES-13 imagery were visually
281 inspected for the presence of convective clouds over the study site. Here,
282 we only considered images acquired on days for which abrupt changes in
283 weather variables were detected as described in the previous step. We ana-
284 lyzed the effect of downdrafts associated with turbulence regimes by checking
285 the relationship between V_{TKE} and V . Here, we assumed the minimum and
286 maximum V values to determine the start and end time of respective wind
287 gusts.

288 2.4. *Extreme winds as a mechanism of tree mortality*

289 To assess the potential of extreme wind gusts as a mechanism of tree dam-
290 age/mortality, we compared the CWS data and the maximum wind speed
291 (V_o) measured by our anemometers. The V_o is the maximum horizontal wind
292 speeds (or extremes winds) measured at 5 min time-intervals at 48 m height.

293 These data were analyzed for the different seasons (dry and wet).

294 Since downdrafts can last from few seconds to (rarely) minutes, we calcu-
295 lated V_o at two other time intervals: 1-minute and 30-seconds windows. To
296 check if V_o differs with the size of time-intervals, we compared computed val-
297 ues (response variable) using ANOVA of repeated measures. Subsequently,
298 we executed an ANOVA to verify potential variations of V_o as a function of
299 seasonality.

300 **3. Results**

301 *3.1. Turbulence regimes in the nocturnal boundary layer*

302 We found a positive relationship between V_{TKE} and V for both dry and
303 wet seasons, and a clear distinction between the two turbulence regimes
304 (Figure 2). For events classified as weak turbulence (very stable regime),
305 V_{TKE} increased less than V as indicated by a smaller slope. As V reached a
306 threshold value (V_L), turbulence changed from weak to strong (weakly stable
307 regime) as indicated by a larger increase of V_{TKE} as a function of V and larger
308 slope. V_L increased nonlinearly with the distance from the forest canopy in
309 both seasons. The observed values of V_L at 35 m and 48 m were near 0.7
310 and 2.3 ms^{-1} (dry) and 0.5 and 1.9 ms^{-1} (wet), respectively. These results
311 are in agreement with previous studies that found that V_L increases nearly
312 logarithmically with height (Sun et al., 2012; Acevedo et al., 2016).

313 Although the observed increase of V_L with height supports previous re-
314 search on non-vegetated surfaces, the thresholds identified at 35 m in our
315 study site were significantly smaller than those observed at a pasture area at
316 the Federal University of Santa Maria (in south Brazil) (V_L of 3.0 ms^{-1} at

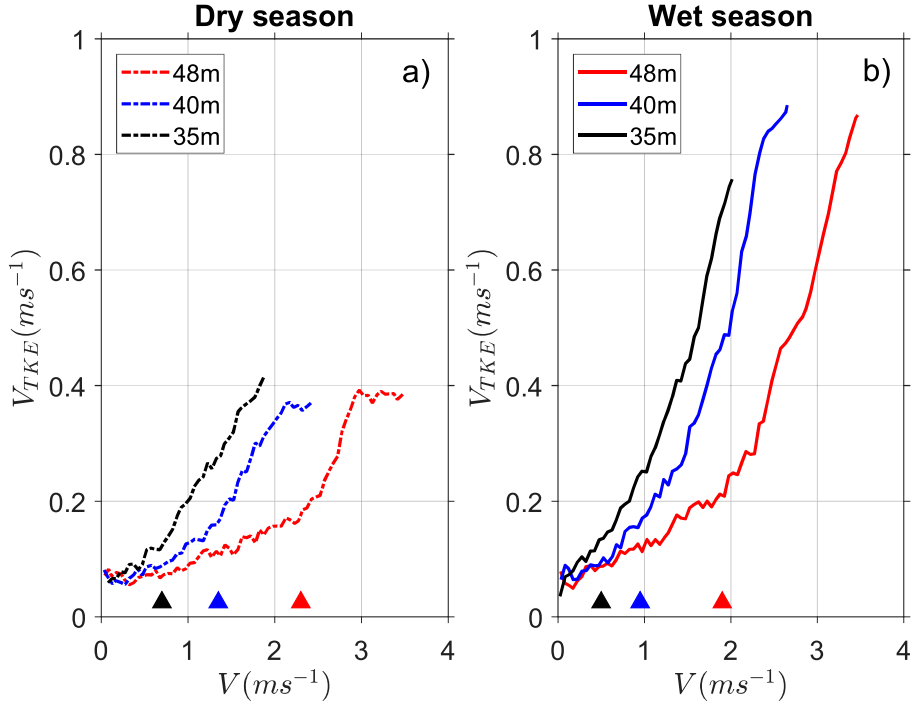


Figure 2: Relationship between turbulence velocity scale (V_{TKE}) and mean wind speed (V) at different heights in the (a) dry and (b) wet season during the nighttime at the EEST, Manaus, Central Amazon. Triangles indicate the threshold wind speed (V_L) at which the very stable changed to weakly stable regime.

317 30 m height) (Acevedo et al., 2021) and at project FLOSS II (Fluxes over
 318 Snow Surfaces) conducted in Colorado (US) (V_L of 5.3 m s^{-1} at 30 m height)
 319 (Acevedo et al., 2016). Such differences show that the structure and rough-
 320 ness of dense forests influence the change of the turbulence regime. For a
 321 proper comparison we considered the observation level with respect to the
 322 zero plane displacement height (d). We used $d=31.5 \text{ m}$ based on estimates
 323 provided by Viswanadham et al. (1990) and Chor et al. (2017) for central
 324 Amazon, in which $d=0.88h$ and $d=0.9h$, respectively, where h is the canopy

325 height (35 m at our study site). Doing that, the V_L values found at 35 m
326 ($z-d = 3.5$ m) in both seasons are smaller than the value of 2.04 ms^{-1} found
327 at 2 m in FLOSS II (Acevedo et al., 2016) and that of 1.5 ms^{-1} found at 1.5
328 m in the CASES-99 (experiment carried out in southeast Kansas, US) (Sun
329 et al., 2012). Similarly, the V_L found for both seasons at the EEST at 48 m
330 ($z-d=16.5$ m) are smaller than those at 15 m in FLOSS (5.04 ms^{-1}) and at 10
331 m in CASES-99 (4.5 ms^{-1}). The V_L found at 48 m at EEST site in the wet
332 season is also smaller than the value reported by Acevedo et al. (2021) at 14
333 m in Santa Maria (2.2 ms^{-1}). Still, this value is close to that we found during
334 the dry season at the EEST. In general, the V_L values between turbulence
335 regimes was smaller at the EEST site than that reported in previous studies
336 at similar heights, even when the zero-plane displacement height is taken
337 into account. This relates to V_L being generally smaller above rough surfaces
338 compared to smooth surfaces (Mahrt et al., 2013; Vignon et al., 2017; Guerra
339 et al., 2018), a simple consequence of turbulent mixing being larger above a
340 rough surface than above a smooth one at a same mean wind speed.

341 From the nighttime turbulence regimes identified at 48 m height, around
342 77% (dry) and 65% (wet) of them were associated with very stable regime.
343 In contrast, weakly stable regime corresponded to 23% (dry) and 35% (wet)
344 of the events. Furthermore, V_L was larger during the dry season than in
345 the wet season at the three investigated heights (Figure 2 and Table 1).
346 This result is in agreement with Acevedo et al. (2021), who showed that
347 V_L increases linearly with net radiative loss at the surface at three mid-
348 latitude sites. According to these authors, the fully turbulence regime occurs
349 when the mean wind speed is large enough to support heat fluxes capable of

350 transferring back to the surface part of the energy lost radiatively. Therefore,
 351 such a minimum heat flux and corresponding minimum wind speeds must be
 352 larger when the net radiative loss is also larger. The relationship between V_L
 353 and R_N is further discussed in Section 4.

Table 1: Wind speed threshold (V_L) at studied heights for the dry and wet seasons at the EEST, Manaus, Central Amazon.

Season	V_L at 48m (ms^{-1})	V_L at 40m (ms^{-1})	V_L at 35m (ms^{-1})
Dry	2.3	1.35	0.7
Wet	1.9	0.95	0.5

354 We also identified the transition between regimes as a function of V at 35
 355 m, for which the ΔV_{TKE} reverses sign for both dry and wet seasons ([Acevedo
 356 et al., 2021](#)). Figure 3 show that the V_{TKE} increased with height for weak
 357 winds in both seasons. When V at 35 m exceeds a sharp threshold, this
 358 pattern is reversed, so that V_{TKE} decreases with height under sufficiently
 359 strong winds. Such a threshold was approximately $0.65 ms^{-1}$ and $0.50 ms^{-1}$
 360 for the dry and wet seasons, respectively. However, when the same analysis
 361 is performed in terms of V at 48 m (Figure 4), there was no gradient reversal
 362 and V_{TKE} decreased with height for all observed wind speeds.

363 These findings suggest that the relationship between V and V_{TKE} at the
 364 different heights is not trivial and may be associated with the occurrence of
 365 phenomena such as low-level jets and density currents ([Greco et al., 1992](#);
 366 [Dias-Júnior et al., 2017b](#); [Corrêa et al., 2021](#)). When the wind speeds are
 367 weak at higher levels, the wind profile is often distorted and maximum values
 368 can occur near the surface ([Acevedo et al., 2016](#)).

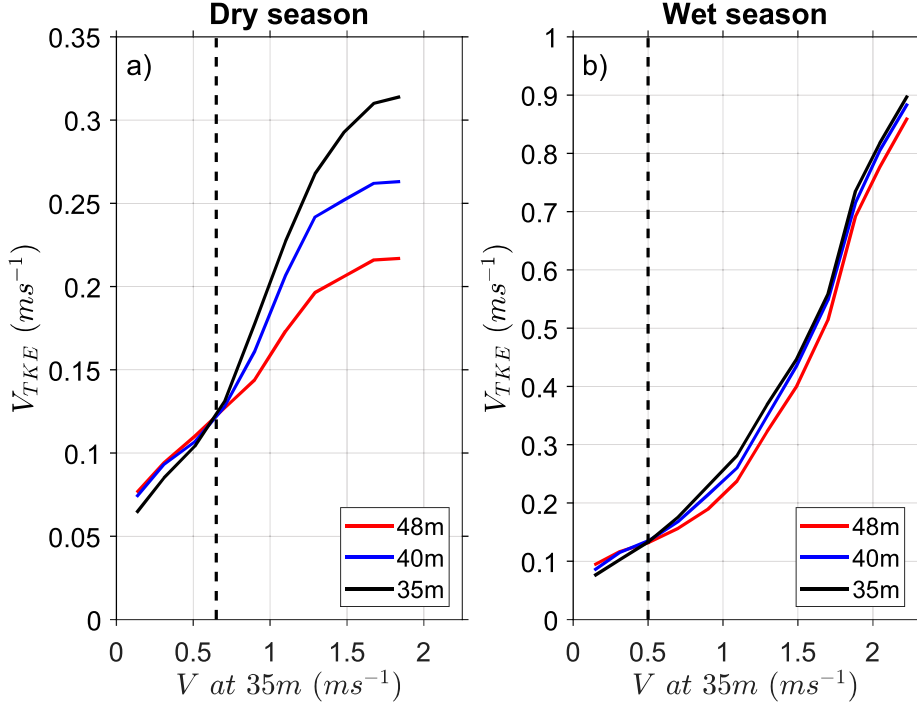


Figure 3: Turbulence velocity scale (V_{TKE}) as a function of the mean wind speed (V) at 35 m during the nighttime at the EEST, Manaus, Central Amazon. The solid lines are V_{TKE} at different heights in the (a) dry and (b) wet season. Black vertical dashed line indicates when V_{TKE} reverses its sign and exceeds the crossover threshold (V_T) at which the very stable changed to weakly stable regime

369 The V_T values identified by the vertical gradient method at 35 m height
 370 during the dry (0.65 m s^{-1}) and wet (0.50 m s^{-1}) seasons were similar to the
 371 V_L values obtained with Sun's method. This result corroborates the existence
 372 of nighttime turbulence regimes at the EEST during the two seasons. As the
 373 values of V_T and V_L were similar, hereafter we used the values of V_L as an
 374 indication for changes of turbulence regimes, since it was possible to identify
 375 it at all heights investigated here.

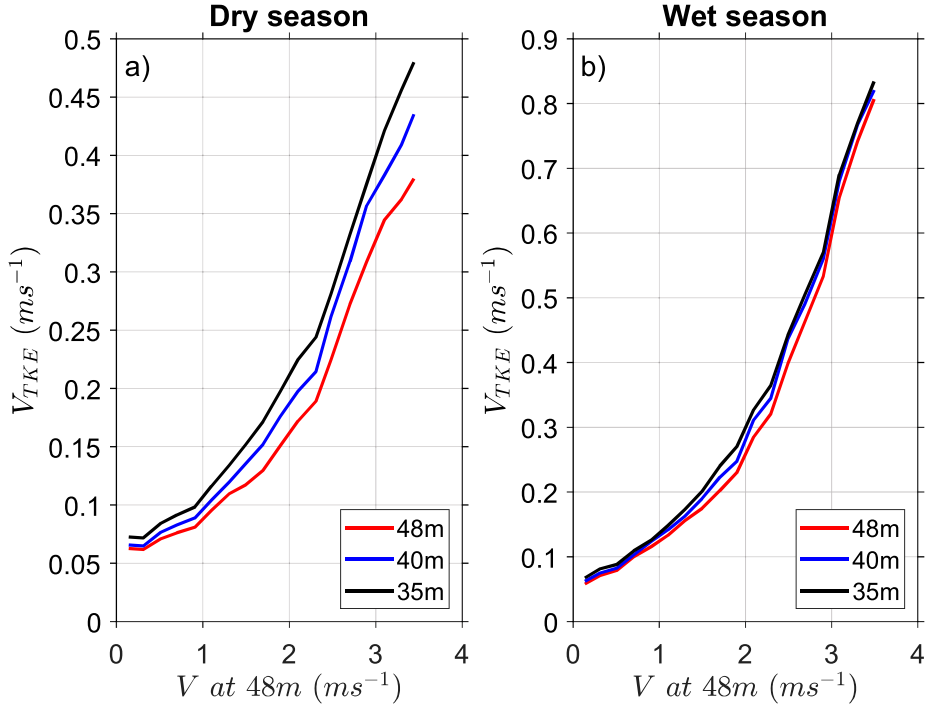


Figure 4: Turbulence velocity scale (V_{TKE}) as a function of the mean wind speed (V) at 48 m during the nighttime at the EEST, Manaus, Central Amazon. The solid lines are V_{TKE} at different heights in the (a) dry and (b) wet season

376 Our results evidenced the existence of different nocturnal turbulence
 377 regimes in the *terra-firme* Amazon forests. Moreover, they indicated that
 378 turbulence intensity decreased with the proximity to the canopy (Figure 5a).
 379 V_{TKE} during weakly stable regime was larger than in the very stable regime
 380 (Figure 5b). Overall, the wet season had larger values of V_{TKE} than the dry
 381 season (Figure 5c).

382 These larger values of V_{TKE} in the wet season are likely associated with
 383 a lower wind speed threshold between regimes in the wet season (Figure 2).
 384 Since the threshold is smaller, it is plausible considering that it is easier to

385 overcome this threshold and establish “large” V_{TKE} in this case. Another
 386 reason that could result in larger values of V_{TKE} in the wet season would be
 387 simply because the wet season has higher wind speeds values than the dry
 388 season. Nonetheless, this was not the case, as can be seen in Figure 5d-f.
 389 Our result may be related to other factors, such as radiative loss, thermal
 390 gradient, among others.

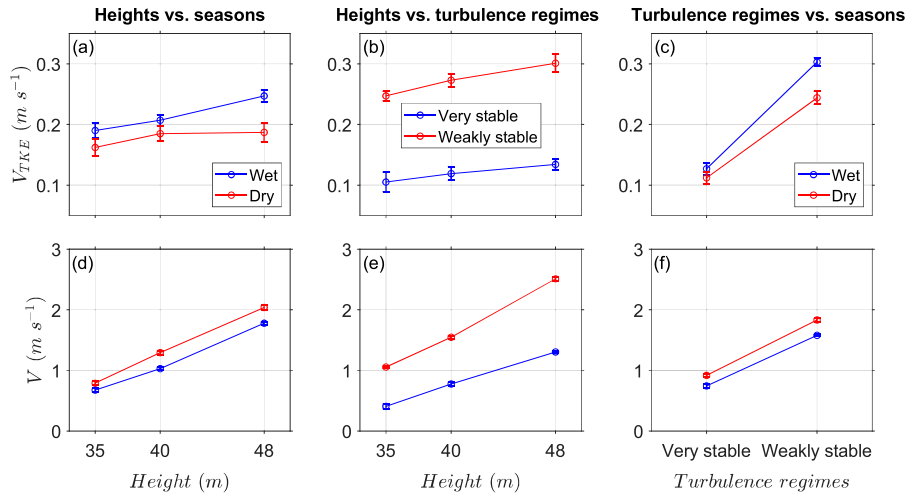


Figure 5: Turbulence velocity scale (V_{TKE}) and mean wind speed (V) as a function of (a,d) heights vs. seasons, (b,e) heights vs. turbulence regimes and (c,f) turbulence regimes vs. seasons during nighttime at the EEST, Manaus, Central Amazon. Legend: circles and vertical bars indicate mean values and the 95% confidence intervals, respectively

391 3.2. Turbulent fluxes in the nocturnal boundary layer

392 We investigated the differences between the turbulent fluxes during the
 393 occurrence of very stable and weakly stable regimes, and found an interesting
 394 relationship between V and the sensible heat (H), and momentum (τ) fluxes
 395 at 35 m height during both seasons. Bins of V each $0.2 m s^{-1}$ were used

396 to calculate the average values and standard deviations of the fluxes. H
397 values (Fig. 6a and Fig. 6b) changed in response to the turbulence shifting
398 from the weak to the strong in both seasons (Table 2). On average, the H
399 flux in the weakly stable regime corresponded to about 88% of the total H
400 observed in both seasons. Our findings corroborate those of previous research
401 conducted in Eastern Amazon (Dias-Júnior et al., 2017b). Importantly, H
402 values were more intense during the dry season ($p = 0.001$). This result is
403 possibly associated to larger net radiative loss due to reduced cloud cover
404 and atmospheric column water vapor load (Collow and Miller, 2016), which
405 leads to less longwave radiation reaching the canopy.

Table 2: Mean values (\pm 95% confidence interval) of sensible heat flux (H) and momentum flux (τ) for the dry and wet seasons at the EEST, Central Amazon, Brazil.

Turbulence regimes	H Dry (Wm^{-2})	H Wet (Wm^{-2})	τ Dry (10^{-2}) (Nm^{-2})	τ Wet (10^{-2}) (Nm^{-2})
Very stable	-1.8 ± 2.5	-1.3 ± 2.0	-0.3 ± 0.4	-0.5 ± 0.6
Weakly stable	-13.4 ± 17	-9.8 ± 9.6	-2.3 ± 3.0	-4.1 ± 5.4

406 The τ fluxes showed a similar behavior to that of H , in which the flux
407 in the weakly stable regime was larger than in the very stable regime ($p \leq$
408 0.001), and reached on average 89% of the total τ flux in each season (Fig.
409 6c and Fig. 6d). Such variations may be related to atmospheric stability
410 conditions. The wet season is less stable (on average), that is, the strong
411 turbulence events (i.e. weakly stable regime) occurs more frequently and,
412 consequently, the momentum fluxes are greater. Overall, the weakly stable

413 regime contributed more significantly to sensible heat and momentum fluxes
 414 than the very stable regime (Table 2), in both seasons.

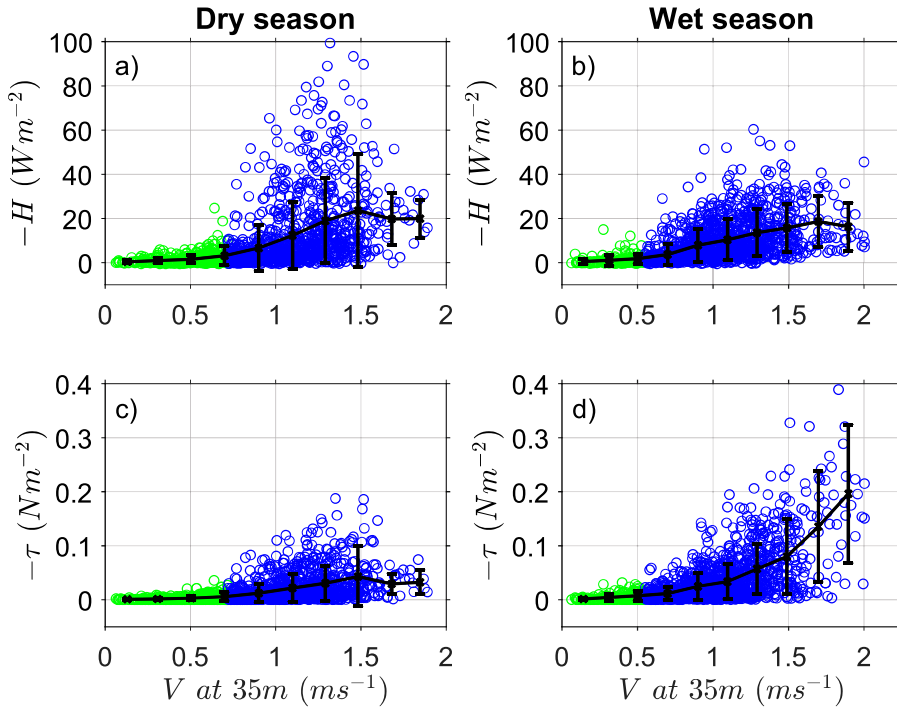


Figure 6: Mean and standard deviation of sensible heat flux (H) and momentum flux (τ) as a function of the wind speed (V) at 35 m during nighttime at the EEST, Manaus, Central Amazon. The left and right panels indicate the dry and wet season, respectively. Green and blue circles indicate the very stable and weakly stable regimes, respectively.

415 3.3. Relationship between deep convection and nocturnal turbulence regimes

416 During the night of 06 August 2014 and 12 April 2014, gust fronts from
 417 downdrafts reached the tower around 2110 LST (dry season) and 2325 LST
 418 (wet season), respectively (Figure 7). These events were evidenced from
 419 observations of (i) decreasing T (around 2 °C at both seasons) and (ii) si-

420 multaneous increasing O_3 of approximately 12 ppb (dry) and 15 ppb (wet).
421 The pre-gust measurements of V ($\approx 2 \text{ ms}^{-1}$) were similar in both nights
422 (Fig. 7c and Fig. 7g). However, V reached maximums of 7.5 (dry) and
423 15 ms^{-1} (wet) during the observed downdrafts. At this time, the standard
424 deviation of wind vertical velocity (σ_w) increased substantially (Fig. 7d and
425 Fig. 7h). As the surface cools and uncouples the boundary layer from the
426 above troposphere, the near-surface O_3 values are low (3-5 ppb). This pat-
427 tern allows for a clear recognition of night downdrafts transporting air with
428 higher ozone and lower temperature to the surface. We observed this pattern
429 on other nights and identified 16 downdrafts (eight different nights in each
430 season) over the studied period. Overall, these events occurred between 2000
431 LST and 2300 LST. Finally, the GOES-13 imagery indicates the existence
432 of cloudiness at the times of the events (Figure 8) and also on the other 16
433 nights that we studied here.

434 These results support previous studies, such as that by [Betts et al. \(2002\)](#)
435 who found that nighttime convective downdrafts coupled the surface to the
436 lower troposphere and transported down air with larger O_3 and lower equiv-
437 alent potential temperature. [Dias-Júnior et al. \(2017a\)](#) also reported that
438 the downdrafts produce O_3 enhancement events and an increase in V val-
439 ues, in addition to the occurrence of air divergence during the horizontal
440 propagation of density currents.

441 We observed that all downdrafts happened during or after the transition
442 to the weakly stable regime (Figure 9). This pattern evidenced that down-
443 drafts may influence the turbulence characteristics near the surface since they
444 are associated with a weakly stable regime (strong turbulence). However,

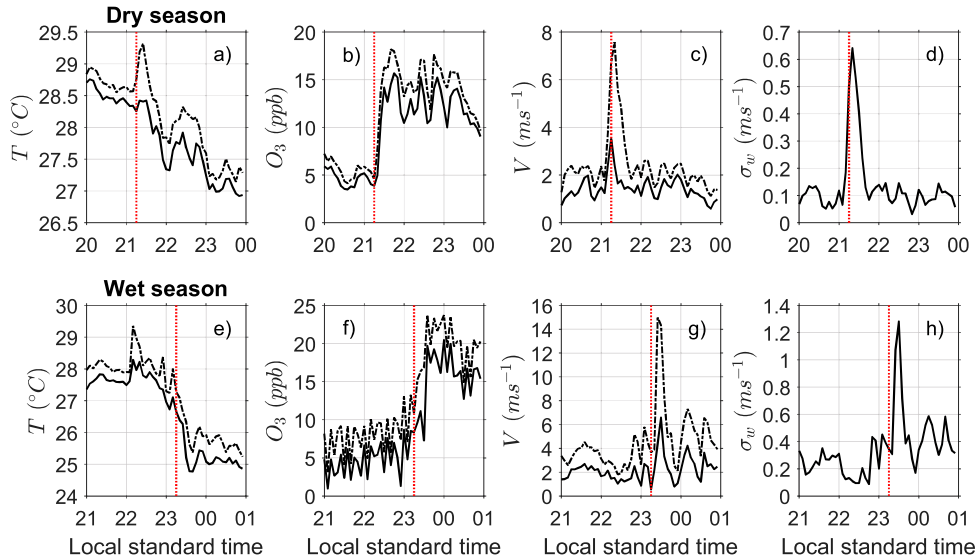


Figure 7: Times series of key variables used to identify downdrafts at the EEST, Central Amazon, Brazil. The upper and bottom panels show the downdrafts from 06 August 2014 and 12 April 2014, respectively. Legend: virtual temperature (T), ozone (O_3), horizontal wind speed (V) and standard deviation of wind vertical velocity (σ_w). Solid and dashed lines indicate the mean and maximum values, respectively. Vertical red-dotted lines indicate the starting time of downdrafts.

445 weakly stable regime was not represented completely by these events, which
 446 suggest that the strong turbulence may be associated with the occurrence
 447 of other phenomena. Similar results were previously reported for Central
 448 Amazon by [Bezerra et al. \(2021\)](#), who observed that downdrafts generated
 449 by a squall line occurred only during the strong turbulence regime.

450 3.4. Extreme winds as a mechanism of tree mortality

451 During the weakly stable regime associated with nocturnal downdraft
 452 events, the speeds and thus destructive potential of winds varied between

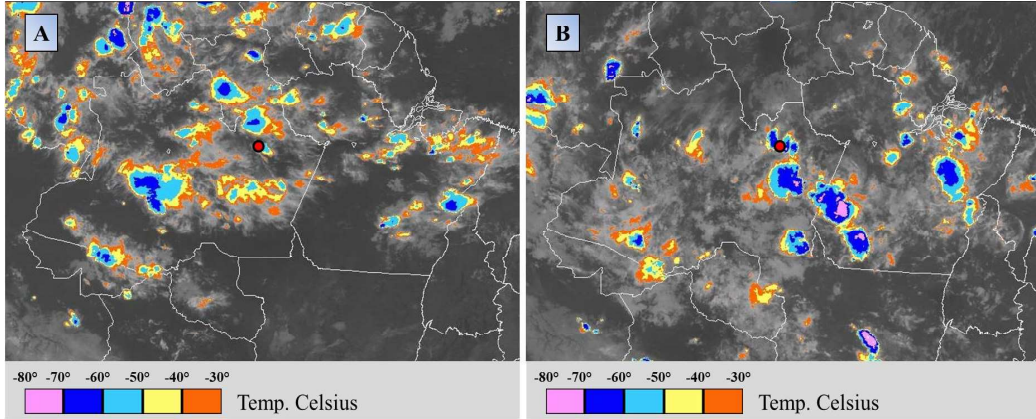


Figure 8: GOES 13 imagery for (a) 07 August 2014 at 0100 UTC and (b) 13 April 2014 at 0300 UTC when downdrafts reached the micrometeorology tower at the EEST (red dot), Central Amazon, Brazil.

453 seasons. The greatest wind speeds were identified during the wet season
 454 ($V_o = 14.96 \text{ m s}^{-1}$). This value was approximately four times higher than on
 455 nights without downdrafts, and exceed the CWS of three out of the studied
 456 trees by Peterson et al. (2019). In contrast, maximum wind speeds in the
 457 nocturnal period of the dry season ($V_o = 7.57 \text{ m s}^{-1}$) did not exceed the CWS
 458 of the studied trees.

459 Here we did not assess the direct effect of high wind-speeds on trees,
 460 but rather evaluated the destructive potential of these based on observa-
 461 tional data acquired at the same study site. Importantly, the occurrence of
 462 excessive wind speeds does not necessarily result in trees damage and mortal-
 463 ity. Further studies are needed to understand the link between wind speeds,
 464 canopy structure and tree motion in these diverse forests. Still, the strong
 465 dissipation of air to layers below the forest canopy (presented in Section 4)
 466 are rarely observed in the absence of downdrafts. Therefore, the wind gusts

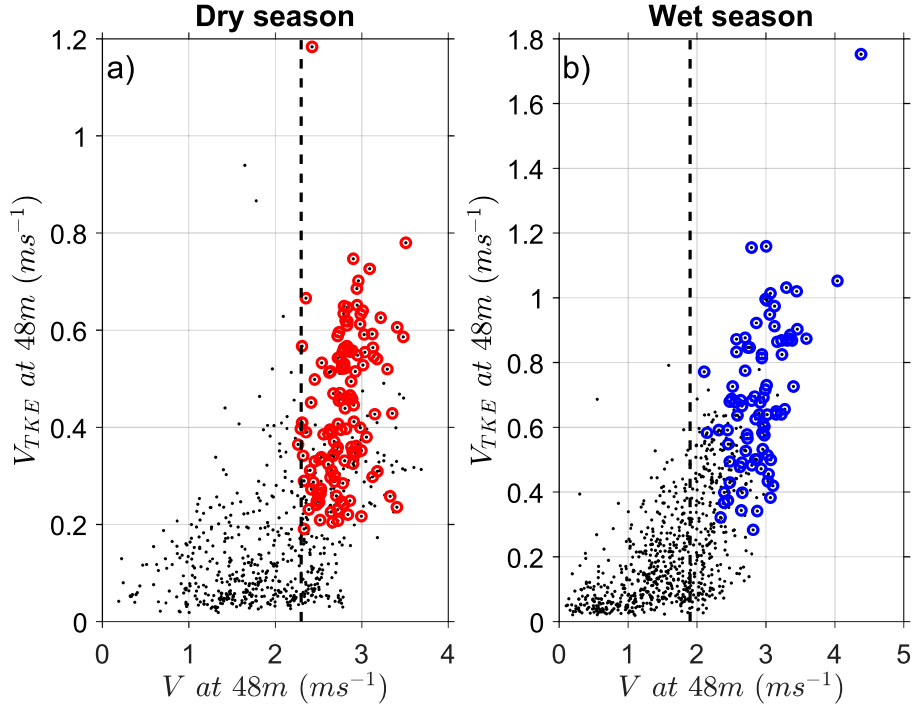


Figure 9: Turbulence velocity scale (V_{TKE}) as a function of the mean wind speed (V) measured at 48 m in the (a) dry and (b) wet season during nighttime at the EEST, Manaus, Central Amazon. The dots correspond to mean values calculated over 5-min periods. Thick circles indicate the range of occurrence of the downdrafts. Vertical black-dashed lines mark the threshold wind speed (V_L) at which the very stable changed to weakly stable regime.

467 described in our study not only reached extreme speeds but also penetrated
 468 the forest canopy, and had the potential to cause damage and mortality of
 469 trees of different sizes, both directly and indirectly.

470 The mean V_o values varied significantly between the analyzed time-intervals
 471 ($p \leq 0.001$, Fig. 10a). As expected, the values were higher for the 30 seconds
 472 interval ($5.97 \pm 2.85 \text{ ms}^{-1}$, mean \pm 95% confidence interval). For the 1 min

473 and 5 min intervals, V_o was $5.35 \pm 2.68 \text{ m s}^{-1}$ and $3.63 \pm 2.45 \text{ m s}^{-1}$, respec-
 474 tively. Results from subsequent ANOVA showed that the interaction between
 475 seasons and time intervals was significant ($p \leq 0.001$, Fig. 10b). Post-hoc
 476 Tukey tests showed that observed variations in V_o were not significantly dif-
 477 ferent between seasons at both 1 min ($p = 0.057$) and 5 min ($p = 1.000$)
 478 intervals. Nonetheless, V_o varied as a function of seasonality for our shorter
 479 time interval (i.e. 30 seconds). These result shows that for extreme wind
 480 gusts that may last a few seconds such as those causing tree damage and
 481 mortality in the Amazon, our 30 second interval is likely too large and may
 482 have underestimated maximum V_o values.

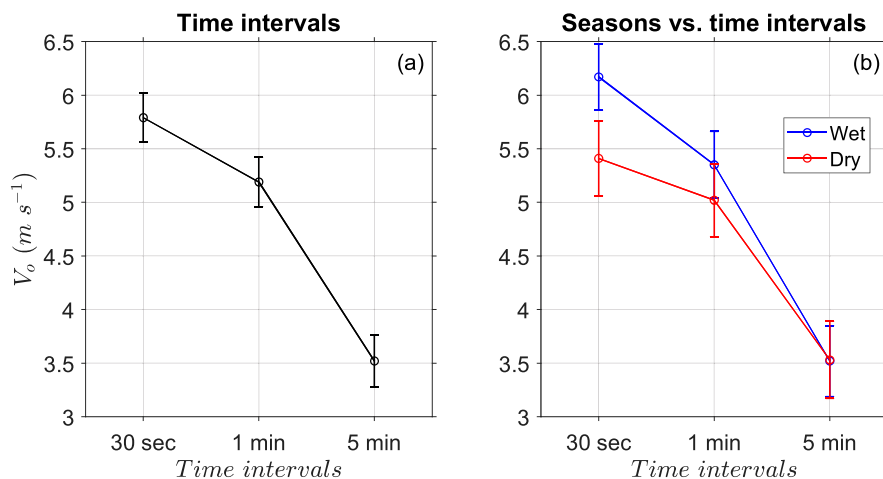


Figure 10: Observed wind speed (V_o) as a function of the (a) three time intervals and (b) seasons vs. time intervals at the EEST, Manaus, Central Amazon. Legend: circles and vertical bars indicate mean values and the 95% confidence intervals, respectively.

483 Although daytime patterns were not a focal aspect in our study, wind
 484 speed reached the highest values (up to 22 m s^{-1}) during this period, in the
 485 dry season. In contrast to the relatively low destructive potential of nocturnal

486 winds, this value could topple 73% of trees previously investigated in our
487 study site (Ribeiro et al., 2016; Peterson et al., 2019). These observations
488 reinforce the importance of extreme wind as a major natural mechanism of
489 tree damage and mortality in these forests (Nelson, 1994; Chambers et al.,
490 2009, 2013; Negrón-Juárez et al., 2017, 2018; Marra et al., 2018).

491 In fact, a higher destructive potential of diurnal winds may be expected,
492 since in moist environments such as the Amazon forest, surface warming pro-
493 motes upward movements that increase the low-level moisture convergence
494 and intensify convection. Moreover, the results from the nighttime period
495 provide evidence on the importance of downdrafts on the propagation of
496 extreme winds downward below the canopy.

497 **4. Discussion**

498 Coupling between the canopy and the atmosphere occurs when turbu-
499 lence provides continuous mixing. At nighttime, however, the mixing can
500 be inhibited by the presence of a stable layer. Therefore, two contrasting
501 regimes are observed. In the weakly stable regime, the wind speed provides
502 heat fluxes that are large enough to continuously transfer the energy lost
503 by radiation back to the surface. In the very stable regime, heat fluxes are
504 not transferred continuously to the surface, leading to strong temperature
505 drops. This allows for the establishment of an enhanced thermal gradient,
506 which further inhibits mixing. Thus, the coupling between the forest and the
507 atmosphere is favored by the continuous turbulence observed in the weakly
508 stable regime.

509 We evaluated the degree of coupling in two ways. First, a comparison of

510 σ_w on above (48 m) and sub-canopy heights following [Thomas et al. \(2013\)](#).
511 Figure 11 shows the comparison between such variables but it is not easy
512 to visualize the trends with only plotting the data points. Thus, we added
513 a Locally Weighted Regression (LOWESS) to the graph (solid line). Here
514 we focus on 4 forest understory heights (1.5 m, 7.0 m, 18.4 m and 31.6
515 m) and on datasets with and without downdrafts. During weak winds (i.e.
516 without downdrafts), the turbulence strength at 1.5 m and 7.0 m was largely
517 independent of that observed above canopy. After 18 m height, the σ_{wsub}
518 was linearly correlated with σ_{wtop} (Fig. 11c) indicating the occurrence of a
519 coupled canopy condition. On the other hand, the extreme winds associated
520 with downdrafts were propagated into the canopy at all heights, and the
521 threshold of σ_{wtop} (i.e., when the correlation became linear) increased as
522 flow above the canopy reached the ground.

523 Second, in order to quantify the coupling between the canopy and the
524 atmosphere we calculated the temperature gradient (ΔT) between 51 m and
525 35 m height, in the dry and wet seasons. The dependence of ΔT on V
526 (Fig. 12) shows the differences of coupling and subsequent mixing for the
527 two regimes. A large thermal gradient occurs under the lowest wind speeds.
528 This was observed when ΔT averaged 0.58 °C and 0.25 °C during the dry
529 and wet seasons, respectively.

530 In the dry and wet seasons, ΔT peaked at V_L and reached 0.73 °C and
531 0.25 °C, respectively. Similar ΔT maxima at the transition between regimes
532 was observed by [Acevedo et al. \(2016\)](#) for the FLOSS II dataset. These
533 authors argue that this pattern was associated with an enhanced heat-flux
534 convergence at similar ranges of wind speed reported by [Acevedo et al. \(2021\)](#)

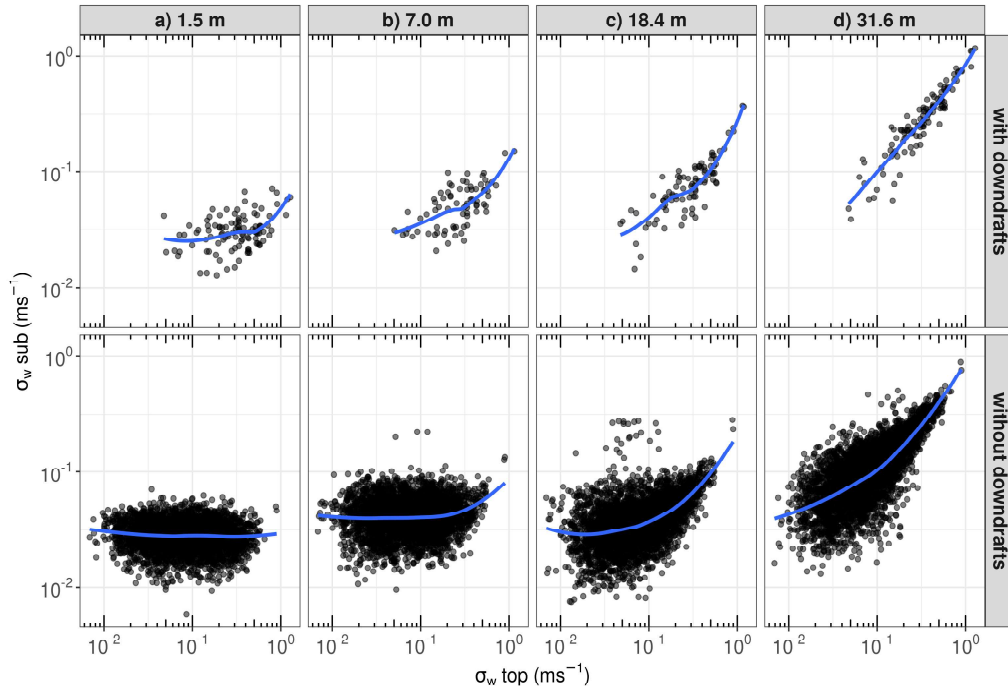


Figure 11: Standard deviation of wind vertical velocity (σ_w) between the forest understory (sub) and above-canopy (top at 48 m) heights. The dots correspond to periods of 5 min data. Dataset in which downdrafts occurred (Top panels). Dataset without the occurrence of downdrafts (Bottom panels). The columns a, b, c and d indicated the investigated sub-canopy heights.

535 for the CASES-99 dataset. Smaller gradients typical of mixed conditions
 536 occur when wind speeds are higher.

537 The relationship between turbulence and net radiation is a reliable cri-
 538 terium for distinguishing regimes. When the radiative loss is high, wind
 539 speeds tend to grow proportionally to allow compensative heat-fluxes (Acevedo
 540 et al., 2021). It is known that cloud cover plays an important role in R_N .
 541 Von Randow et al. (2004) showed that in the southern Amazon, reduced

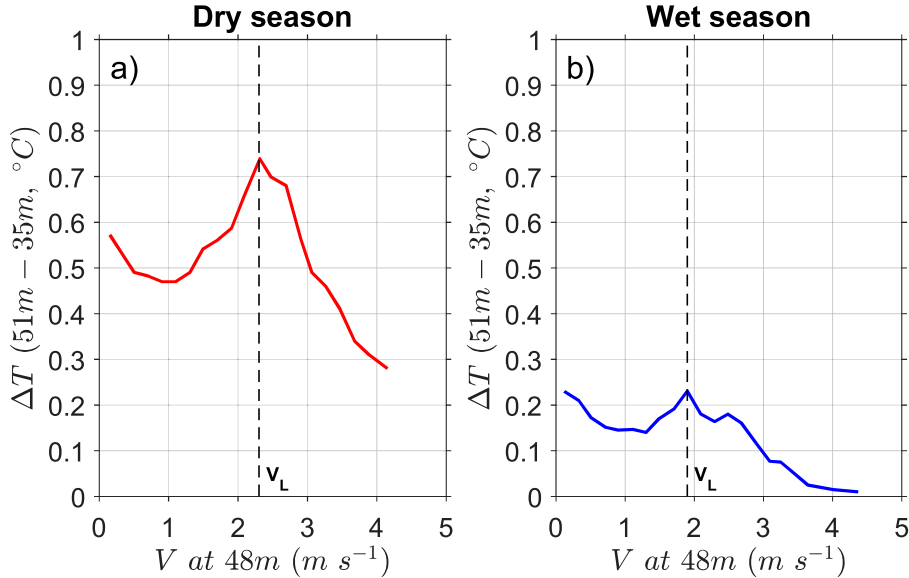


Figure 12: Differences of mean virtual temperature between 51 m and 35 m height as a function of the mean wind speed (V) at 48 m in the dry (a) and wet (b) season at the EEST, Manaus, Central Amazon. Dashed lines indicate the threshold wind speed (V_L) at which very stable changed to weakly stable regime.

542 cloud cover in the dry season results in increased radiative loss. The oppo-
 543 site occurs in the wet season. In this context, we have assessed the frequency
 544 distribution of R_N (30-min averages) for our studied period (from 8pm to
 545 5am) and only for the nights in which downdrafts occurred (2h before and
 546 after respective events). In the dry season, the two lowest values of R_N (high-
 547 est radiative loss) were observed between -40 and -60 $W \text{ m}^{-2}$ (Fig. 13a). This
 548 variation indicates that there were relatively fewer clouds over the site. By
 549 contrast, R_N was more uniform during the wet season, with values ranging
 550 from -10 to -50 $W \text{ m}^{-2}$ (Fig. 13b). Radiative loss was also higher in the
 551 2-hour interval before and after downdrafts observed in the dry season (Fig.

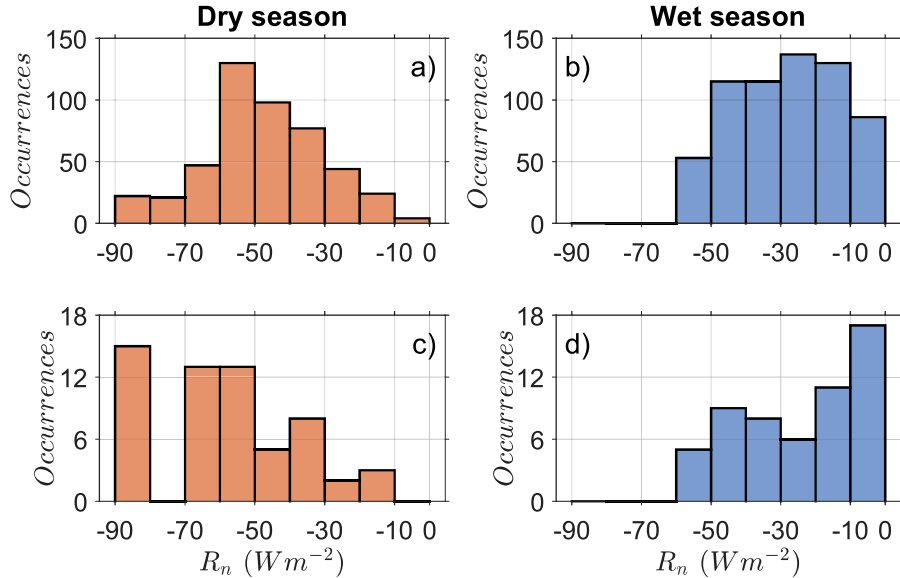


Figure 13: Distribution of the net radiation (R_n) for all studied days (top panels) and for those on which downdraft were identified (bottom panels) in the dry (red bars) and wet (blue bars) season during the nighttime.

552 13c,d).

553 This R_n pattern is related to the change in cloud cover and moisture
 554 loads at each season (Collow and Miller, 2016). Above the Amazon forest,
 555 single-cell clouds are frequent in the dry season. This contrasts mesoscale
 556 convective-systems (multiple cell) that are more frequent during the wet sea-
 557 son (Gerken et al., 2016). Multiple cells and water vapor can trap some of
 558 the outgoing infrared radiation emitted by the Earth and radiate it back
 559 downward, which can reduce the radiative loss at the surface. This explains
 560 why the transition between regimes occurs at higher wind speed V_L in the
 561 dry season. During this period, the shallower cloud cover and the lower wa-
 562 ter vapor load of the atmospheric column allows for a larger loss of radiation

563 than that observed in the wet period.

564 Both single and multiple cells are known to produce downdrafts (Gerken
565 et al., 2016; Dias-Júnior et al., 2017b). Furthermore, we showed in this study
566 that downdrafts are one of the main causes of transition from turbulence
567 regimes above the Amazon forest (Fig. 9). We investigated the profile of
568 four turbulent parameters during a night-time downdraft (July 24, 2014).
569 H values, which were initially close to zero, turned strongly negative when
570 the downdraft reached the tower at around 11 pm local time (Fig. 14a).
571 Similarly, there was an increase in parameters associated with the intensity
572 of turbulence, such as σ_w , TKE and friction velocity (u_*) (Figures 14b, c and
573 d, respectively). Furthermore, this strong dissipation of air to strata/layers
574 below the forest canopy are rarely observed in the absence of downdrafts.
575 The air layer from the soil surface is largely decoupled from layers above the
576 canopy (Thomas et al., 2013; Freundorfer et al., 2019; Cava et al., 2022).
577 Santana et al. (2018) provided evidence that atmospheric eddies generated
578 above the canopy can hardly penetrate the region below 0.5 h (h is the canopy
579 top). This pattern was reported for different sites in the Amazon. However,
580 observations (Bezerra et al., 2021) and numerical simulations (Serra-Neto
581 et al., 2021) showed that under strong wind conditions, turbulence below the
582 forest canopy was intensified and the scalar mixing more efficient.

583 The penetration of wind gusts inside the canopy increases the probability
584 of tree damage and mortality. However, since the peak velocities may be
585 underestimated when using single tower-measurements and we did not have
586 data on risk of tree mortality, further studies are needed to describe the
587 return frequency of such gusts and the relationship between speed and the

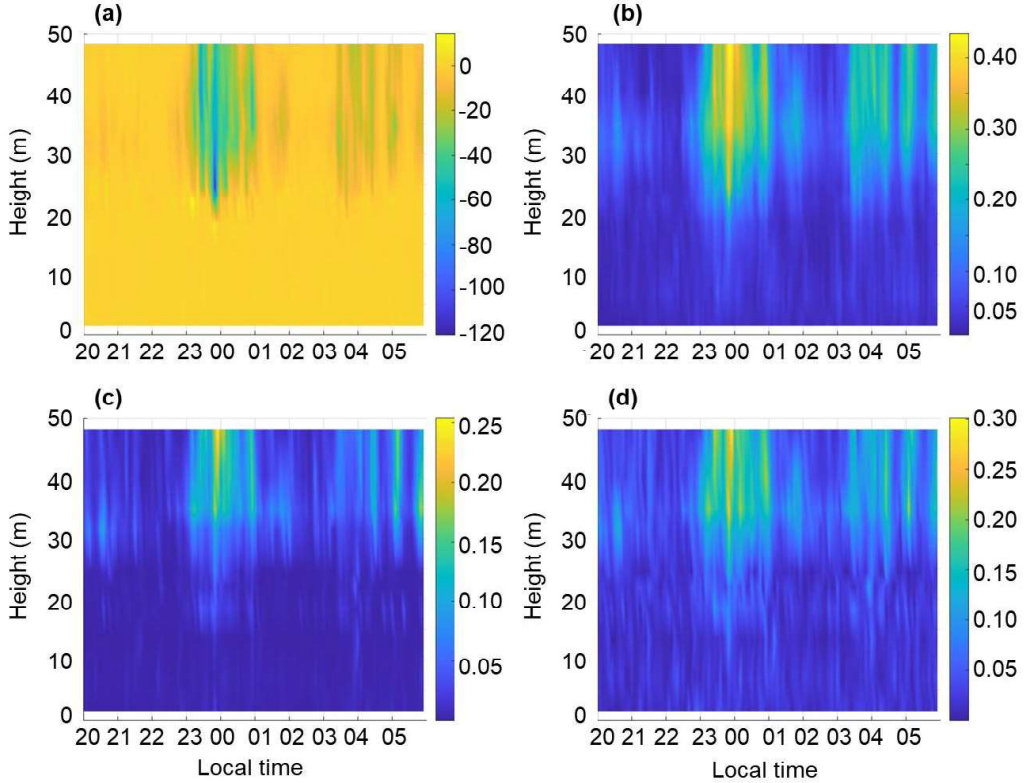


Figure 14: Vertical profile of: a) sensible heat flux (Wm^{-2}), b) standard deviation of vertical wind (ms^{-1}), c) Turbulent Kinetic Energy (m^2s^{-2}) and d) friction velocity (ms^{-1}) at the night of July 24, 2014.

588 disturbance severity.

589 Our study has limitations which shall be addressed in future research.
 590 First, the patterns we described for central Amazon may not occur in other
 591 regions with different vegetation structure. This highlights the need of stud-
 592 ies based on extended datasets from other regions and for heights above 48 m.
 593 Second, when analyzing fast-response data from a single tower, the down-
 594 drafts may be not fully captured, and their magnitude and duration may

595 be underestimated. Last, the link between wind speed, canopy structure
596 and tree motion in these diverse forests is currently unknown. Nonetheless,
597 our study stress the importance of datasets including a range of heights and
598 seasons for detecting processes and mechanisms regulating turbulence and
599 wind-tree interactions in dense tropical forests. A better understanding of
600 these interactions is key for the parameterization of more robust and realis-
601 tic in numerical models. In addition, our findings provided insights into the
602 importance of wind gusts to the ecology and dynamics of Amazon forest.

603 **5. Conclusions**

604 This study provides three novel contributions. The first is the identifi-
605 cation of different turbulence regimes and their patterns in terms of season-
606 ality and proximity to the forest canopy in the nocturnal RSL. The second
607 is the assessment of the effects of near surface wind gusts (propagated from
608 downdrafts) on the organization of turbulence regimes. Finally, it provides
609 evidences on the occurrence of extreme wind gusts associated with convec-
610 tive downdrafts, with potential do promote damage and mortality of canopy
611 trees. These aspects highlight the strong interactions between atmospheric
612 and biospheric processes and mechanisms regulating forest structure and dy-
613 namics.

614 Two turbulence regimes were identified: the very stable (weak turbulence)
615 and weakly stable regime (strong turbulence). The wind speed threshold
616 that mark the transition between the regimes increases nonlinearly with the
617 distance from the ground under non-vegetated surfaces ([Sun et al., 2012](#);
618 [Acevedo et al., 2021](#)). Our study provides evidence that such pattern also

619 occurs in closed canopy forests. In addition, new knowledge was obtained:

620 i) The average wind speed threshold for turbulence regime varies season-
621 ally, and was relatively larger in the dry season at all heights as a consequence
622 of a higher radiative loss from the surface during this period. Furthermore,
623 the change of turbulence regime was influenced by the structure and rough-
624 ness of the forest. This pattern was highlighted by relatively lower thresholds
625 of wind speed compared to previous studies at mid-latitudes, and can be ex-
626 plained by the greater turbulent mixing above rough surfaces for a given
627 mean wind speed.

628 ii) Near-surface wind gusts (convective downdrafts) occurred only during
629 the weakly stable regime and were one of the main drivers of the observed
630 turbulence regimes transition. Nevertheless, not all weakly stable regime
631 were associated to such events.

632 iii) Full coupling state of wind flow among layers above and within the
633 canopy occur during downdrafts. At nights without extreme winds, coupling
634 along the canopy profile occurred only above 18 m height.

635 iv) The destructive potential of winds propagated during downdrafts was
636 approximately four times higher than on nights without downdrafts in the
637 wet season. By contrast, the wind speeds during daytime downdrafts were
638 more intense in the dry season (not reported). These gusts would be suf-
639 ficient to topple 73% of the previously investigated trees at our study site,
640 which emphasize the importance of wind disturbances on controlling forest
641 structure and diversity in central Amazon.

642

643 **Acknowledgments**

644 ACSM thanks the Conselho Nacional de Desenvolvimento Científico e
645 Tecnológico (CNPq) for the Master grant awarded through the Programa de
646 Pós-graduação em Clima e Ambiente. This study is part of the Wind-Tree
647 Interaction Project (INVENTA) and the Amazon Tall Tower Observatory
648 (ATTO), funded by the German Federal Ministry of Education and Research
649 (BMBF, contracts 01LB1001A and 01LK1602A), the Brazilian Ministry of
650 Science, Technology and Innovation (MCTI/FINEP, contract 01.11.01248.00)
651 and the Max Planck Society (MPG). ATTO is also supported by the Fundação
652 de Amparo à Pesquisa do Estado do Amazonas (FAPEAM), Fundação de
653 Amparo à Pesquisa do Estado de São Paulo (FAPESP), Universidade do
654 Estado do Amazonas (UEA), Instituto Nacional de Pesquisas Amazônia
655 (INPA), Programa de Grande Escala da Biosfera-Atmosfera na Amazônia
656 (LBA) and the SDS/CEUC/RDS-Uatumã. We thank Marcelo Chameki and
657 his team for the efforts in obtaining and making available the GoAmazon
658 data.

659 **References**

- 660 Acevedo, O.C., Costa, F.D., Maroneze, R., Carvalho, Jr, A.D., Puhales,
661 F.S., Oliveira, P.E.S., 2021. External controls on the transition between
662 stable boundary-layer turbulence regimes. *Quarterly Journal of the Royal*
663 *Meteorological Society* 147, 2335–2351. doi:[10.1002/qj.4027](https://doi.org/10.1002/qj.4027).
- 664 Acevedo, O.C., Fitzjarrald, D.R., 2003. In the core of the night-effects of
665 intermittent mixing on a horizontally heterogeneous surface. *Boundary-*
666 *layer meteorology* 106, 1–33. doi:[10.1023/A:1020824109575](https://doi.org/10.1023/A:1020824109575).

- 667 Acevedo, O.C., Mahrt, L., Puhales, F.S., Costa, F.D., Medeiros, L.E., De-
668 grazia, G.A., 2016. Contrasting structures between the decoupled and cou-
669 pled states of the stable boundary layer. *Quarterly Journal of the Royal*
670 *Meteorological Society* 142, 693–702. doi:[10.1002/qj.2693](https://doi.org/10.1002/qj.2693).
- 671 Alves, E.G., Jardine, K., Tota, J., Jardine, A., Yáñez Serrano, A.M., Karl,
672 T., Tavares, J., Nelson, B., Gu, D., Stavrou, T., Martin, S., Artaxo,
673 P., Manzi, A., Guenther, A., 2016. Seasonality of isoprenoid emissions
674 from a primary rainforest in central amazonia. *Atmospheric Chemistry*
675 *and Physics* 16, 3903–3925. doi:[10.5194/acp-16-3903-2016](https://doi.org/10.5194/acp-16-3903-2016).
- 676 Araujo, R.F., Chambers, J.Q., Celes, C.H.S., Muller-Landau, H.C., Santos,
677 A.P.F.d., Emmert, F., Ribeiro, G.H.P.M., Gimenez, B.O., Lima, A.J.N.,
678 Campos, M.A.A., Higuchi, N., 2020. Integrating high resolution drone
679 imagery and forest inventory to distinguish canopy and understory trees
680 and quantify their contributions to forest structure and dynamics. *PLOS*
681 *ONE* 15, 1–16. doi:[10.1371/journal.pone.0243079](https://doi.org/10.1371/journal.pone.0243079).
- 682 Araújo, A.C., Nobre, A.D., Kruijt, B., Elbers, J.A., Dallarosa, R., Stefani,
683 P., von Randow, C., Manzi, A.O., Culf, A.D., Gash, J.H.C., Valentini,
684 R., Kabat, P., 2002. Comparative measurements of carbon dioxide fluxes
685 from two nearby towers in a central amazonian rainforest: The manaus lba
686 site. *Journal of Geophysical Research: Atmospheres* 107, LBA 58–1–LBA
687 58–20. doi:[10.1029/2001JD000676](https://doi.org/10.1029/2001JD000676).
- 688 Betts, A.K., Gatti, L.V., Cordova, A.M., Silva Dias, M.A., Fuentes, J.D.,
689 2002. Transport of ozone to the surface by convective downdrafts at night.

- 690 Journal of Geophysical Research: Atmospheres 107, LBA–13. doi:[10.](https://doi.org/10.1029/2000JD000158)
691 [1029/2000JD000158](https://doi.org/10.1029/2000JD000158).
- 692 Betts, A.K., et al., 2003. The diurnal cycle over land. *Forests at the Land-*
693 *Atmosphere Interface* 79, 93.
- 694 Bezerra, V.L., Dias-Júnior, C.Q., Vale, R.S., Santana, R.A., Botía, S., Manzi,
695 A.O., Cohen, J.C.P., Martins, H.S., Chamecki, M., Fuentes, J.D., 2021.
696 Near-surface atmospheric turbulence in the presence of a squall line above
697 a forested and deforested region in the central amazon. *Atmosphere* 12.
698 doi:[10.3390/atmos12040461](https://doi.org/10.3390/atmos12040461).
- 699 Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the
700 climate benefits of forests. *science* 320, 1444–1449. doi:[10.1126/science.](https://doi.org/10.1126/science.1155121)
701 [1155121](https://doi.org/10.1126/science.1155121).
- 702 Braga, P.I.S., 1979. Subdivisão fitogeográfica, tipos de vegetação, con-
703 servação e inventário florístico da floresta amazônica. *Acta amazonica*
704 9, 53–80.
- 705 Cava, D., Dias-Júnior, C.Q., Acevedo, O., Oliveira, P.E., Tsokankunku, A.,
706 Sörgel, M., Manzi, A.O., de Araújo, A.C., Brondani, D.V., Toro, I.M.C.,
707 et al., 2022. Vertical propagation of submeso and coherent structure in a
708 tall and dense amazon forest in different stability conditions part i: Flow
709 structure within and above the roughness sublayer. *Agricultural and Forest*
710 *Meteorology* 322, 108983. doi:[10.1016/j.agrformet.2022.108983](https://doi.org/10.1016/j.agrformet.2022.108983).
- 711 Chambers, J.Q., Negron-Juarez, R.I., Marra, D.M., Di Vittorio, A., Tews, J.,
712 Roberts, D., Ribeiro, G.H.P.M., Trumbore, S.E., Higuchi, N., 2013. The

- 713 steady-state mosaic of disturbance and succession across an old-growth
714 central amazon forest landscape. *Proceedings of the National Academy of*
715 *Sciences* 110, 3949–3954. doi:[10.1073/pnas.1202894110](https://doi.org/10.1073/pnas.1202894110).
- 716 Chambers, J.Q., Robertson, A.L., Carneiro, V.M., Lima, A.J., Smith, M.L.,
717 Plourde, L.C., Higuchi, N., 2009. Hyperspectral remote detection of
718 niche partitioning among canopy trees driven by blowdown gap distur-
719 bances in the central amazon. *Oecologia* 160, 107–117. doi:[10.1007/
720 s00442-008-1274-9](https://doi.org/10.1007/s00442-008-1274-9).
- 721 Chambers, J.Q., Tribuzy, E.S., Toledo, L.C., Crispim, B.F., Higuchi, N.,
722 Santos, J.d., Araújo, A.C., Kruijt, B., Nobre, A.D., Trumbore, S.E., 2004.
723 Respiration from a tropical forest ecosystem: Partitioning of sources and
724 low carbon use efficiency. *Ecological Applications* 14, 72–88. doi:[10.1890/
725 01-6012](https://doi.org/10.1890/01-6012).
- 726 Chor, T.L., Dias, N.L., Araújo, A., Wolff, S., Zahn, E., Manzi, A., Trebs, I.,
727 Sá, M.O., Teixeira, P.R., Sörgel, M., 2017. Flux-variance and flux-gradient
728 relationships in the roughness sublayer over the amazon forest. *Agricultural*
729 *and Forest Meteorology* 239, 213–222. doi:[10.1016/j.agrformet.2017.
730 03.009](https://doi.org/10.1016/j.agrformet.2017.03.009).
- 731 Collow, A.B.M., Miller, M.A., 2016. The seasonal cycle of the radiation bud-
732 get and cloud radiative effect in the amazon rain forest of brazil. *Journal*
733 *of Climate* 29, 7703–7722. doi:[10.1175/JCLI-D-16-0089.1](https://doi.org/10.1175/JCLI-D-16-0089.1).
- 734 Corrêa, P.B., Dias-Júnior, C.Q., Cava, D., Sörgel, M., Botía, S., Acevedo,
735 O., Oliveira, P.E., Ocimar Manzi, A., Toledo Machado, L.A., dos Santos

- 736 Martins, H., Tsokankunku, A., de Araújo, A.C., Lavric, J.V., Walter, D.,
737 Mortarini, L., 2021. A case study of a gravity wave induced by amazon
738 forest orography and low level jet generation. *Agricultural and Forest*
739 *Meteorology* 307, 108457. doi:[https://doi.org/10.1016/j.agrformet.](https://doi.org/10.1016/j.agrformet.2021.108457)
740 [2021.108457](https://doi.org/10.1016/j.agrformet.2021.108457).
- 741 Costa, F.D., Acevedo, O.C., Medeiros, L.E., Maroneze, R., Puhales, F.S.,
742 Jr., A.D.C., Camponogara, L.F., dos Santos, D.M., Mortarini, L., 2020.
743 Stable boundary layer regimes in single-column models. *Journal of the*
744 *Atmospheric Sciences* 77, 2039 – 2054. doi:[10.1175/JAS-D-19-0218.1](https://doi.org/10.1175/JAS-D-19-0218.1).
- 745 Dias-Júnior, C.Q., Dias, N.L., Fuentes, J.D., Chamecki, M., 2017a. Convec-
746 tive storms and non-classical low-level jets during high ozone level episodes
747 in the amazon region: An arm/goamazon case study. *Atmospheric Envi-*
748 *ronment* 155, 199–209. doi:[10.1016/j.atmosenv.2017.02.006](https://doi.org/10.1016/j.atmosenv.2017.02.006).
- 749 Dias-Júnior, C.Q., Sá, L.D., Marques Filho, E.P., Santana, R.A., Mauder,
750 M., Manzi, A.O., 2017b. Turbulence regimes in the stable boundary layer
751 above and within the amazon forest. *Agricultural and Forest Meteorology*
752 233, 122–132. doi:[10.1016/j.agrformet.2016.11.001](https://doi.org/10.1016/j.agrformet.2016.11.001).
- 753 D'Oliveira, F.A., Cohen, J.C., Spracklen, D.V., Medeiros, A.S., Cirino, G.G.,
754 Artaxo, P., Dias-Júnior, C.Q., 2022. Simulation of the effects of biomass
755 burning in a mesoscale convective system in the central amazon. *Atmo-*
756 *spheric Research* 278, 106345.
- 757 Espírito-Santo, F.D., Gloor, M., Keller, M., Malhi, Y., Saatchi, S., Nelson,
758 B., Junior, R.C.O., Pereira, C., Lloyd, J., Frohling, S., et al., 2014. Size

759 and frequency of natural forest disturbances and the amazon forest carbon
760 balance. *Nature communications* 5, 1–6. doi:[10.1038/ncomms4434](https://doi.org/10.1038/ncomms4434).

761 Feng, Y., Negrón-Juárez, R.I., Romps, D.M., Chambers, J.Q., 2023. Ama-
762 zon windthrow disturbances are likely to increase with storm frequency
763 under global warming. *Nature Communications* 14, 101. doi:[10.1038/
764 s41467-022-35570-1](https://doi.org/10.1038/s41467-022-35570-1).

765 Freundorfer, A., Rehberg, I., Law, B.E., Thomas, C., 2019. Forest wind
766 regimes and their implications on cross-canopy coupling. *Agricultural
767 and Forest Meteorology* 279, 107696. doi:[https://doi.org/10.1016/j.
768 agrformet.2019.107696](https://doi.org/10.1016/j.agrformet.2019.107696).

769 Fuentes, J.D., Chamecki, M., dos Santos, R.M.N., Randow, C.V., Stoy, P.C.,
770 Katul, G., Fitzjarrald, D., Manzi, A., Gerken, T., Trowbridge, A., Freire,
771 L.S., Ruiz-Plancarte, J., Maia, J.M.F., Tóta, J., Dias, N., Fisch, G., Schu-
772 macher, C., Acevedo, O., Mercer, J.R., Yañez-Serrano, A.M., 2016. Link-
773 ing meteorology, turbulence, and air chemistry in the amazon rain for-
774 est. *Bulletin of the American Meteorological Society* 97, 2329 – 2342.
775 doi:[10.1175/BAMS-D-15-00152.1](https://doi.org/10.1175/BAMS-D-15-00152.1).

776 Fujita, T., 1985. The downburst: Microburst and macroburst. *Satellite
777 and Mesometeorology Research Project, Department of the Geophysical
778 Sciences, University of Chicago* 210, 122.

779 Garstang, M., Fitzjarrald, D.R., 1999. *Observations of surface to atmosphere
780 interactions in the tropics*. Oxford University Press, USA. doi:[10.1016/
781 S0168-1923\(03\)00003-0](https://doi.org/10.1016/S0168-1923(03)00003-0).

- 782 Garstang, M., White, S., Shugart, H., Halverson, J., 1998. Convective cloud
783 downdrafts as the cause of large blowdowns in the amazon rainforest. *Meteo-*
784 *rology and Atmospheric Physics* 67, 199–212. doi:[10.1007/BF01277510](https://doi.org/10.1007/BF01277510).
- 785 Gerken, T., Wei, D., Chase, R.J., Fuentes, J.D., Schumacher, C., Machado,
786 L.A., Andreoli, R.V., Chamecki, M., Ferreira de Souza, R.A., Freire, L.S.,
787 Jardine, A.B., Manzi, A.O., Nascimento dos Santos, R.M., von Randow,
788 C., dos Santos Costa, P., Stoy, P.C., Tóta, J., Trowbridge, A.M., 2016.
789 Downward transport of ozone rich air and implications for atmospheric
790 chemistry in the amazon rainforest. *Atmospheric Environment* 124, 64–
791 76. doi:[10.1016/j.atmosenv.2015.11.014](https://doi.org/10.1016/j.atmosenv.2015.11.014).
- 792 Greco, S., Ulanski, S., Garstang, M., Houston, S., 1992. Low-level nocturnal
793 wind maximum over the central amazon basin. *Boundary-layer meteorol-*
794 *ogy* 58, 91–115. doi:[10.1007/BF00120753](https://doi.org/10.1007/BF00120753).
- 795 Guerra, V.S., Acevedo, O.C., Medeiros, L.E., Oliveira, P.E., Santos, D.M.,
796 2018. Small-scale horizontal variability of mean and turbulent quantities in
797 the nocturnal boundary layer. *Boundary-Layer Meteorology* 169, 395–411.
798 doi:[10.1007/s10546-018-0381-3](https://doi.org/10.1007/s10546-018-0381-3).
- 799 Knohl, A., Baldocchi, D.D., 2008. Effects of diffuse radiation on canopy gas
800 exchange processes in a forest ecosystem. *Journal of Geophysical Research:*
801 *Biogeosciences* 113. doi:[10.1029/2007JG000663](https://doi.org/10.1029/2007JG000663).
- 802 Machado, L., Laurent, H., Dessay, N., Miranda, I., 2004. Seasonal and diur-
803 nal variability of convection over the amazonia: A comparison of different

- 804 vegetation types and large scale forcing. *Theoretical and Applied Clima-*
805 *tology* 78, 61–77. doi:[10.1007/s00704-004-0044-9](https://doi.org/10.1007/s00704-004-0044-9).
- 806 Machado, L.A.T., Laurent, H., Lima, A.A., 2002. Diurnal march of the
807 convection observed during trmm-wetamc/lba. *Journal of Geophys-*
808 *ical Research: Atmospheres* 107, LBA 31–1–LBA 31–15. doi:[10.1029/
809 2001JD000338](https://doi.org/10.1029/2001JD000338).
- 810 Mahrt, L., 1998. Nocturnal boundary-layer regimes. *Boundary-layer meteo-*
811 *rology* 88, 255–278.
- 812 Mahrt, L., 2014. Stably stratified atmospheric boundary layers.
813 *Annual Review of Fluid Mechanics* 46, 23–45. doi:[10.1146/
814 annurev-fluid-010313-141354](https://doi.org/10.1146/annurev-fluid-010313-141354).
- 815 Mahrt, L., Thomas, C., Richardson, S., Seaman, N., Stauffer, D., Zeeman,
816 M., 2013. Non-stationary generation of weak turbulence for very stable and
817 weak-wind conditions. *Boundary-layer meteorology* 147, 179–199. doi:[10.
818 1007/s10546-012-9782-x](https://doi.org/10.1007/s10546-012-9782-x).
- 819 Malhi, Y., Meir, P., Brown, S., 2002. Forests, carbon and global cli-
820 mate. *Philosophical Transactions of the Royal Society of London. Se-*
821 *ries A: Mathematical, Physical and Engineering Sciences* 360, 1567–1591.
822 doi:[10.1098/rsta.2002.1020](https://doi.org/10.1098/rsta.2002.1020).
- 823 Marques Filho, A.d.O., Dallarosa, R.G., Pachêco, V.B., 2005. Radiação
824 solar e distribuição vertical de área foliar em floresta-reserva biológica
825 do cuieiras zf2, manaus. *Acta Amazonica* 35, 427–436. doi:[10.1590/
826 S0044-59672005000400007](https://doi.org/10.1590/S0044-59672005000400007).

- 827 Marra, D.M., Chambers, J.Q., Higuchi, N., Trumbore, S.E., Ribeiro,
828 G.H.P.M., dos Santos, J., Negrón-Juárez, R.I., Reu, B., Wirth, C., 2014.
829 Large-scale wind disturbances promote tree diversity in a central amazon
830 forest. PLOS ONE 9, 1–16. doi:[10.1371/journal.pone.0103711](https://doi.org/10.1371/journal.pone.0103711).
- 831 Marra, D.M., Trumbore, S.E., Higuchi, N., Ribeiro, G.H.P.M., Negrón-
832 Juárez, R.I., Holzwarth, F., Rifai, S.W., dos Santos, J., Lima, A.J.N.,
833 Kinupp, V.F., Chambers, J.Q., Wirth, C., 2018. Windthrows control
834 biomass patterns and functional composition of amazon forests. Global
835 Change Biology 24, 5867–5881. doi:[10.1111/gcb.14457](https://doi.org/10.1111/gcb.14457).
- 836 Melo, A.M., Dias-Junior, C.Q., Cohen, J.C., Sá, L.D., Cattanio, J.H., Kuhn,
837 P.A., 2019. Ozone transport and thermodynamics during the passage of
838 squall line in central amazon. Atmospheric Environment 206, 132–143.
839 doi:<https://doi.org/10.1016/j.atmosenv.2019.02.018>.
- 840 Negrón-Juárez, R.I., Chambers, J.Q., Guimaraes, G., Zeng, H., Raupp,
841 C.F.M., Marra, D.M., Ribeiro, G.H.P.M., Saatchi, S.S., Nelson, B.W.,
842 Higuchi, N., 2010. Widespread amazon forest tree mortality from a
843 single cross-basin squall line event. Geophysical Research Letters 37.
844 doi:[10.1029/2010GL043733](https://doi.org/10.1029/2010GL043733).
- 845 Negrón-Juárez, R.I., Holm, J.A., Marra, D.M., Rifai, S.W., Riley, W.J.,
846 Chambers, J.Q., Koven, C.D., Knox, R.G., McGroddy, M.E., Vittorio,
847 A.V.D., Urquiza-Muñoz, J., Tello-Espinoza, R., Muñoz, W.A., Ribeiro,
848 G.H.P.M., Higuchi, N., 2018. Vulnerability of amazon forests to storm-
849 driven tree mortality 13, 054021. doi:[10.1088/1748-9326/aabe9f](https://doi.org/10.1088/1748-9326/aabe9f).

- 850 Negrón-Juárez, R.I., Jenkins, H.S., Raupp, C.F.M., Riley, W.J., Kueppers,
851 L.M., Magnabosco Marra, D., Ribeiro, G.H.P.M., Monteiro, M.T.F., Can-
852 dido, L.A., Chambers, J.Q., Higuchi, N., 2017. Windthrow variability in
853 central amazonia. *Atmosphere* 8. doi:[10.3390/atmos8020028](https://doi.org/10.3390/atmos8020028).
- 854 Nelson, B.W., 1994. Natural forest disturbance and change in the brazil-
855 ian amazon. *Remote Sensing Reviews* 10, 105–125. doi:[10.1080/02757259409532239](https://doi.org/10.1080/02757259409532239).
- 857 Oliveira, A.N.d., Amaral, I.L.d., Ramos, M.B.P., Nobre, A.D., Couto,
858 L.B., Sahdo, R.M., 2008. Composição e diversidade florístico-estrutural
859 de um hectare de floresta densa de terra firme na amazônia cen-
860 tral, amazonas, brasil. *Acta amazônica* 38, 627–641. doi:[10.1590/S0044-59672008000400005](https://doi.org/10.1590/S0044-59672008000400005).
- 862 Peterson, C.J., Ribeiro, G.H.P.d.M., Negrón-Juárez, R., Marra, D.M., Cham-
863 bers, J.Q., Higuchi, N., Lima, A., Cannon, J.B., 2019. Critical wind
864 speeds suggest wind could be an important disturbance agent in Ama-
865 zonian forests. *Forestry: An International Journal of Forest Research* 92,
866 444–459. doi:[10.1093/forestry/cpz025](https://doi.org/10.1093/forestry/cpz025).
- 867 Ribeiro, G., Chambers, J., Peterson, C., Trumbore, S., Magnabosco Marra,
868 D., Wirth, C., Cannon, J., Négron-Juárez, R., Lima, A., de Paula, E.,
869 Santos, J., Higuchi, N., 2016. Mechanical vulnerability and resistance to
870 snapping and uprooting for central amazon tree species. *Forest Ecology*
871 *and Management* 380, 1–10. doi:[10.1016/j.foreco.2016.08.039](https://doi.org/10.1016/j.foreco.2016.08.039).
- 872 Santana, R.A., Dias-Júnior, C.Q., da Silva, J.T., Fuentes, J.D., do Vale,

- 873 R.S., Alves, E.G., dos Santos, R.M.N., Manzi, A.O., 2018. Air turbu-
874 lence characteristics at multiple sites in and above the amazon rainforest
875 canopy. *Agricultural and Forest Meteorology* 260, 41–54. doi:[10.1016/j.
876 agrformet.2018.05.027](https://doi.org/10.1016/j.agrformet.2018.05.027).
- 877 Santos, D.M., Acevedo, O.C., Chamecki, M., Fuentes, J.D., Gerken, T.,
878 Stoy, P.C., 2016. Temporal scales of the nocturnal flow within and above
879 a forest canopy in amazonia. *Boundary-Layer Meteorology* 161, 73–98.
880 doi:[10.1007/s10546-016-0158-5](https://doi.org/10.1007/s10546-016-0158-5).
- 881 dos Santos, L.T., Magnabosco Marra, D., Trumbore, S., de Camargo, P.B.,
882 Negrón-Juárez, R.I., Lima, A.J.N., Ribeiro, G.H.P.M., dos Santos, J.,
883 Higuchi, N., 2016. Windthrows increase soil carbon stocks in a central ama-
884 zon forest. *Biogeosciences* 13, 1299–1308. doi:[10.5194/bg-13-1299-2016](https://doi.org/10.5194/bg-13-1299-2016).
- 885 Schwartz, N.B., Uriarte, M., DeFries, R., Bedka, K.M., Fernandes, K.,
886 Gutiérrez-Vélez, V., Pinedo-Vasquez, M.A., 2017. Fragmentation in-
887 creases wind disturbance impacts on forest structure and carbon stocks
888 in a western amazonian landscape. *Ecological Applications* 27, 1901–1915.
889 doi:[10.1002/eap.1576](https://doi.org/10.1002/eap.1576).
- 890 Serra-Neto, E.M., Martins, H.S., Dias-Júnior, C.Q., Santana, R.A., Bron-
891 dani, D.V., Manzi, A.O., de Araújo, A.C., Teixeira, P.R., Sörgel, M., Mor-
892 tarini, L., 2021. Simulation of the scalar transport above and within the
893 amazon forest canopy. *Atmosphere* 12, 1631. doi:[10.3390/atmos12121631](https://doi.org/10.3390/atmos12121631).
- 894 Silvério, D.V., Brando, P.M., Bustamante, M.M.C., Putz, F.E., Marra, D.M.,
895 Levick, S.R., Trumbore, S.E., 2019. Fire, fragmentation, and windstorms:

- 896 A recipe for tropical forest degradation. *Journal of Ecology* 107, 656–667.
897 doi:[10.1111/1365-2745.13076](https://doi.org/10.1111/1365-2745.13076).
- 898 Sun, J., Burns, S.P., Lenschow, D.H., Banta, R., Newsom, R., Coulter, R.,
899 Frasier, S., Ince, T., Nappo, C., Cuxart, J., et al., 2002. Intermittent
900 turbulence associated with a density current passage in the stable bound-
901 ary layer. *Boundary-Layer Meteorology* 105, 199–219. doi:[10.1023/A:
902 1019969131774](https://doi.org/10.1023/A:1019969131774).
- 903 Sun, J., Lenschow, D.H., LeMone, M.A., Mahrt, L., 2016. The role of large-
904 coherent-eddy transport in the atmospheric surface layer based on cases-
905 99 observations. *Boundary-layer meteorology* 160, 83–111. doi:[10.1007/
906 s10546-016-0134-0](https://doi.org/10.1007/s10546-016-0134-0).
- 907 Sun, J., Mahrt, L., Banta, R.M., Pichugina, Y.L., 2012. Turbulence
908 regimes and turbulence intermittency in the stable boundary layer dur-
909 ing cases-99. *Journal of Atmospheric Sciences* 69, 338–351. doi:[10.1175/
910 JAS-D-11-082.1](https://doi.org/10.1175/JAS-D-11-082.1).
- 911 Sun, J., Takle, E.S., Acevedo, O.C., 2020. Understanding physical pro-
912 cesses represented by the monin–obukhov bulk formula for momen-
913 tum transfer. *Boundary-Layer Meteorology* 177, 69–95. doi:[10.1007/
914 s10546-020-00546-5](https://doi.org/10.1007/s10546-020-00546-5).
- 915 Telles, E.d.C.C., de Camargo, P.B., Martinelli, L.A., Trumbore, S.E.,
916 da Costa, E.S., Santos, J., Higuchi, N., Oliveira Jr., R.C., 2003. Influe-
917 nce of soil texture on carbon dynamics and storage potential in tropical

- 918 forest soils of amazonia. *Global Biogeochemical Cycles* 17. doi:[10.1029/
919 2002GB001953](https://doi.org/10.1029/2002GB001953).
- 920 Thomas, C., Foken, T., 2007. Flux contribution of coherent structures
921 and its implications for the exchange of energy and matter in a tall
922 spruce canopy. *Boundary-Layer Meteorology* 123, 317–337. doi:[10.1007/
923 s10546-006-9144-7](https://doi.org/10.1007/s10546-006-9144-7).
- 924 Thomas, C.K., Martin, J.G., Law, B.E., Davis, K., 2013. Toward biologically
925 meaningful net carbon exchange estimates for tall, dense canopies: Multi-
926 level eddy covariance observations and canopy coupling regimes in a mature
927 douglas-fir forest in oregon. *Agricultural and forest meteorology* 173, 14–
928 27. doi:[10.1016/j.agrformet.2013.01.001](https://doi.org/10.1016/j.agrformet.2013.01.001).
- 929 Tóta, J., Fitzjarrald, D.R., da Silva Dias, M.A., 2012. Exchange of carbon be-
930 tween the atmosphere and the tropical amazon rainforest, in: Sudarshana,
931 P., Nageswara-Rao, M., Soneji, J.R. (Eds.), *Tropical Forests*. IntechOpen,
932 Rijeka. chapter 16. doi:[10.5772/29716](https://doi.org/10.5772/29716).
- 933 Urquiza Muñoz, J.D., Magnabosco Marra, D., Negrón-Juarez, R.I., Tello-
934 Espinoza, R., Alegría-Muñoz, W., Pacheco-Gómez, T., Rifai, S.W., Cham-
935 bers, J.Q., Jenkins, H.S., Brenning, A., Trumbore, S.E., 2021. Recovery
936 of forest structure following large-scale windthrows in the northwestern
937 amazon. *Forests* 12. doi:[10.3390/f12060667](https://doi.org/10.3390/f12060667).
- 938 Vickers, D., Göckede, M., Law, B., 2010. Uncertainty estimates for 1-h
939 averaged turbulence fluxes of carbon dioxide, latent heat and sensible heat.

- 940 Tellus B: Chemical and Physical Meteorology 62, 87–99. doi:[10.1111/j.](https://doi.org/10.1111/j.1600-0889.2009.00449.x)
941 [1600-0889.2009.00449.x](https://doi.org/10.1111/j.1600-0889.2009.00449.x).
- 942 Vickers, D., Mahrt, L., 1997. Quality control and flux sampling problems for
943 tower and aircraft data. *Journal of Atmospheric and Oceanic Technology*
944 14, 512 – 526. doi:[10.1175/1520-0426\(1997\)014<0512:QCAFSP>2.0.CO;](https://doi.org/10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2)
945 [2](https://doi.org/10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2).
- 946 Vignon, E., van de Wiel, B.J.H., van Hooijdonk, I.G.S., Genthon, C., van der
947 Linden, S.J.A., van Hooft, J.A., Baas, P., Maurel, W., Traullé, O., Casas-
948 anta, G., 2017. Stable boundary-layer regimes at dome c, antarctica: obser-
949 vation and analysis. *Quarterly Journal of the Royal Meteorological Society*
950 143, 1241–1253. doi:[10.1002/qj.2998](https://doi.org/10.1002/qj.2998).
- 951 Viswanadham, Y., Molion, L., Manzi, A., Sá, L., Filho, V.S., André, R.,
952 Nogueira, J., Santos, R.d., 1990. Micrometeorological measurements in
953 amazon forest during gte/able 2a mission. *Journal of Geophysical Re-*
954 *search: Atmospheres* 95, 13669–13682. doi:[10.1029/JD095iD09p13669](https://doi.org/10.1029/JD095iD09p13669).
- 955 Von Randow, C., Manzi, A.O., Kruijt, B., De Oliveira, P., Zanchi, F.B., Silva,
956 R.d., Hodnett, M.G., Gash, J.H., Elbers, J.A., Cardoso, F.L., et al., 2004.
957 Comparative measurements and seasonal variations in energy and carbon
958 exchange over forest and pasture in south west amazonia. *Theoretical and*
959 *Applied Climatology* 78, 5–26. doi:[10.1007/s00704-004-0041-z](https://doi.org/10.1007/s00704-004-0041-z).
- 960 Wakimoto, R., 2015. Mesoscale meteorology— microbursts .
- 961 Zahn, E., Chor, T., Dias, N., 2016. A simple methodology for quality control

962 of micrometeorological datasets. Am J Environ Eng 6, 135–142. doi:[10.](https://doi.org/10.5923/s.ajee.201601.20)
963 [5923/s.ajee.201601.20](https://doi.org/10.5923/s.ajee.201601.20).

Highlights

Turbulence regimes in the nocturnal roughness sublayer: interaction with deep convection and tree mortality in the Amazon

Anne C. S. Mendonça, Cléo Q. Dias-Júnior, Otávio C. Acevedo, Raoni A. Santana, Felipe D. Costa, Robinson I. Negrón-Juarez, Antônio O. Manzi, Susan E. Trumbore, Daniel. M. Marra

- The transition threshold of turbulence regimes is different between dry and wet seasons.
- Downdrafts are one of the main drives of the observed turbulence regimes transition.
- Extreme winds associated with downdrafts are propagated into the canopy at all heights.
- **The destructive potential of winds was four times higher during downdrafts events** ~~Vulnerability of Amazon forests to extreme winds.~~

Turbulence regimes in the nocturnal roughness sublayer: interaction with deep convection and tree mortality in the Amazon

Anne C. S. Mendonça^a, Cléo Q. Dias-Júnior^{a,b,*}, Otávio C. Acevedo^c, Raoni A. Santana^d, Felipe D. Costa^e, Robinson I. Negrón-Juarez^f, Antônio O. Manzi^g, Susan E. Trumbore^h, Daniel. M. Marra^h

^a*Amazonian National Research Institute (INPA-CLIAMB), Manaus, AM, Brazil*

^b*Department of Physics, Federal Institute of Pará (IFPA), Belém, PA, Brazil*

^c*Departamento de Física, Universidade Federal de Santa Maria, Santa Maria, RS, Brazil*

^d*Institute of Engineering and Geosciences, Federal University of West Pará (UFOPA), Santarém, PA, Brazil*

^e*Universidade Federal do Pampa, Alegrete, Brazil*

^f*Lawrence Berkeley National Laboratory, Berkeley, CA, USA*

^g*National Institute for Spatial Research (INPE), Cachoeira Paulista, SP, Brazil*

^h*Biogeochemical Processes Department, Max Planck Institute for Biogeochemistry, Jena, Germany*

Abstract

We investigated the influence of seasonality and proximity to the forest canopy on nocturnal turbulence regimes in the roughness sublayer of a Central Amazon forest. Since convective systems of different scales are common in this region, we also analyzed the effect of extreme wind gusts (propagated from convective downdrafts) on the organization of the turbulence regimes, and their potential to cause the mortality of canopy trees. Our data include high-frequency winds, temperature and ozone concentration at different heights during the dry and wet seasons of 2014. In addi-

*Corresponding Author

Email address: cleo.quaresma@ifpa.edu.br (Cléo Q. Dias-Júnior)

tion, we used critical wind-speed data derived from a tree-winch experiment and a modeling study conducted in the same study site. Two different turbulence regimes were identified at three heights above the canopy: a weakly stable (WS) and a very stable regime (VS). The threshold wind speeds that mark the transition between turbulence regimes were larger during the dry season and increased as a function of the height above the canopy. The turbulent fluxes of sensible heat and momentum during the WS accounted for 88% of the entire nighttime flux. Downdrafts occurred only in the WS and favored a fully coupled state of wind flow along the canopy profile. The destructive potential of winds was four times higher than on nights without downdrafts. We investigated the influence of seasonality and proximity to the forest canopy on nocturnal turbulence regimes in the roughness sublayer of a Central Amazon forest. For that, we applied different methods associated with the turbulent velocity scale, and analyzed the effect of convective downdrafts propagating extreme wind gusts above and within the forest canopy. Our data include monthly measurements of precipitation and high-frequency winds, temperature and ozone concentration at different heights during the dry and wet seasons of 2014. In addition, we used critical wind-speed data derived from a tree-winch experiment and a modeling study conducted in the same study site. Our results show that the threshold wind speeds that separate the very stable from weakly stable regimes were larger during the dry season, and increased as a function of the height above the canopy. Downdrafts occurred only in the weakly stable regime. The turbulent fluxes of sensible heat and momentum during the weakly stable regime accounted for 88% of the entire nighttime flux. The maximum

wind-speed observed during the weakly stable regime was approximately four times higher than the values registered on nights without downdrafts.

Keywords: Downdrafts, Extreme wind speed, Seasonality, Tropical forest, Turbulence regimes, Wind disturbance

1. Introduction

A growing number of observational and modeling studies show that the Amazon world's forests plays a key role in regional and global climate (Malhi et al., 2002; Bonan, 2008; Alves et al., 2016) and emphasize its importance to the water, radiation and surface-energy balance. All these are affected by exchanges of mass (water vapor, carbon dioxide, methane, ozone, and a variety of gases and particles), heat (sensible and latent) and momentum between the forest and the atmosphere (Von Randow et al., 2004; Thomas and Foken, 2007; Knohl and Baldocchi, 2008; Gerken et al., 2016, among others). This near-surface boundary layer that is dynamically influenced by vegetation is called the roughness sublayer (RSL). Particularly at night, the transport efficiency decreases above the forest, which inhibits its penetration into the canopy (Cava et al., 2022) and leads to a decoupling between the sub- and upper canopy flows (Thomas et al., 2013; Freundorfer et al., 2019; Cava et al., 2022). Exchange processes of mass, heat and momentum are driven by turbulent vertical motions, which are produced by air warming over the surface (i.e. thermal component) and the interactions between atmospheric flow and surface roughness (i.e. mechanical component).

Studies carried out in the Amazon region highlight the difficulties in correctly estimating turbulent fluxes, which can vary significantly for different

21 wind speeds ([Dias-Júnior et al., 2017b](#); [Dias-Júnior et al., 2018](#); [Dias-Júnior et al., 2020](#); [Dias-Júnior et al., 2020](#);
22 It is also known that the turbulent flow within and above forest canopies is
23 more complex compared to those found for flat and homogeneous surfaces
24 ([Raupach et al., 1996](#); [Raupach et al., 2000](#); [Raupach et al., 2007](#); [Raupach et al., 2020](#); [Raupach et al., 2020](#);
25 Assessments of turbulent flow are challenging in the NBL nocturnal RSL,
26 particularly during the occurrence of intense downdrafts that cause significant
27 changes in atmospheric dynamics and can interact with forest canopies causing
28 widespread tree mortality. that typically originate within a convective system
29 (e.g. squall lines, super-cell and single-cell thunderstorms). Intense
30 downdrafts can develop when cooled air from evaporating precipitation sinks
31 rapidly towards the ground. Such events transport relatively cooler and drier
32 air from the troposphere to the lower levels leading to changes in the thermo-
33 dynamic and kinematic properties of the near-surface air mass ([Wakimoto,
34 2015](#)). These downdrafts can extend to the surface in the form of sudden
35 variations in the values of the wind, pressure, turbulent fluxes and a drop
36 in equivalent potential temperature ([Garstang and Fitzjarrald, 1999](#); [Betts
37 et al., 2002](#); [Dias-Júnior et al., 2017a](#); [Melo et al., 2019](#); [D'Oliveira et al.,
38 2022](#)). Such phenomena can gain an interesting physical interpretation when
39 they are the turbulence is classified into distinct turbulent nocturnal regimes.
40 In mid-latitude regions for example, [Mahrt \(1998\)](#) categorized turbulence as
41 “weakly stable” and “very stable” to differentiate the conditions of sustained
42 and non-sustained turbulence, respectively. [Sun et al. \(2012\)](#) classified the
43 turbulence regimes as either weak or strong, according to the relationship
44 between Turbulent Kinetic Energy (TKE) and wind speeds. Subsequently,
45 such terms have been widely used to refer to the regimes.

46 The weakly stable regime follows Monin-Obukhov similarity theory, which
47 is used in most atmospheric models for expressing the surface layer. On the
48 other hand, the same is not true in the very stable regime (Mahrt, 1998,
49 2014). In general, numerical schemes such as those used in numerical weather
50 prediction and atmospheric models reproduce the occurrence of both NBL
51 nocturnal turbulence regimes, but conditions that mark the transition be-
52 tween them depend on the parameterizations used to represent the eddy dif-
53 fusivity (Costa et al., 2020). The transition between regimes is not universal,
54 varying from one site to another. Such differences may be associated with
55 local factors, for example by increased cloudiness (Acevedo and Fitzjarrald,
56 2003), surface roughness (Mahrt et al., 2013) and net nocturnal radiative loss
57 (Sun et al., 2020; Acevedo et al., 2021).

58 Recent studies (Santos et al., 2016; Cava et al., 2022) have evidenced
59 that the nature of the nocturnal-scalar exchange between the canopy and the
60 overlying atmosphere is contrastingly dependent on the turbulence regime.
61 While the weakly stable regime is dominated by turbulence, under very stable
62 conditions a relatively larger fraction of the exchange is produced by non-
63 turbulence motion with long time scales. This fact is particularly important
64 for quantifying these fluxes since under very stable conditions the typical
65 eddy-covariance methods might not properly capture the total exchange.
66 Therefore, when assessing exchange patterns it is important to consider the
67 following: Is the exchange seasonally dependent? If so, what seasonal pro-
68 cesses affect the regimes? Is the nocturnal turbulence regime influenced by
69 the frequency of convective downdrafts, which can affect the total canopy-
70 atmosphere exchange of scalars? Therefore, experimental results obtained

71 at different sites, such as in dense tropical forests, are essential to better
72 understand the biosphere-atmosphere interaction and to improve existing
73 knowledge on the nocturnal boundary layer. provide a better understanding
74 and better parameterization of the NBL.

75 From another perspective, in regions often covered by intense convective
76 systems and convective cloud clusters, such as the Amazon region (Betts
77 et al., 2002, 2003; Machado et al., 2002, 2004), the downdrafts may propa-
78 gate strong downward wind gusts with high velocities (Fujita, 1985; Nelson,
79 1994; Garstang et al., 1998; Negrón-Juárez et al., 2010, 2017, 2018). When
80 they reaches the surface, strong wind outflow with horizontal dimensions is
81 propagated (Fujita, 1985; Garstang et al., 1998). These wind gusts can cause
82 widespread tree damage and mortality through snapping and/or uprooting.
83 These modes of tree mortality occur when the mechanical load caused by
84 wind exceeds the resistance of the trunk or the root-soil anchorage (Nelson,
85 1994; Marra et al., 2014; Ribeiro et al., 2016).

86 It is also known that the Amazon region is often covered by convective
87 cloud clusters and intense convective systems (Betts et al., 2002, 2003; Betts et al., 2002; Betts et
88 Deep/strong convection may produce downdrafts, which propagate strong
89 downward wind gusts with high velocities (Fujita, 1985; Fujita, 1994; Fujita, 1998; Fujita, 2010; F
90 When a downdraft reaches the surface, strong wind outflow with horizontal
91 dimensions is propagated (Fujita, 1985; Fujita, 1998). Such events transport
92 relatively cooler and drier air to the lower levels leading to changes in the
93 thermodynamic and kinematic properties of the near-surface air mass (Wakimoto, 2015).
94 Apart from that, downdrafts can cause widespread tree damage and mortality
95 through snapping and/or uprooting. These modes of tree mortality occur

96 when the mechanical load caused by wind exceeds the resistance of the trunk
97 or the root-soil anchorage (Nelson, 1994; Nelson, 2014; Nelson, 2016).

98 The severity of damage/mortality caused by extreme wind events influ-
99 ences biomass balance and the functional composition of *terra-firme* forests
100 in Central and Northwestern Amazon (Urquiza Muñoz et al., 2021; Negrón-
101 Juárez et al., 2018; Marra et al., 2018, 2014). While some of the carbon
102 contained in dead or damaged trees is decomposed and incorporated into
103 the soil rather than directly emitted into the atmosphere (dos Santos et al.,
104 2016), dead trees represent future CO_2 emissions (Chambers et al., 2004) and
105 potentially methane (CH_4), which contributes to global warming. Using field
106 data (Ribeiro et al., 2016) combined with static and dynamic biomechanical
107 models, Peterson et al. (2019) estimated that wind speeds $> 10.75 \text{ m s}^{-1}$
108 are critical and can snap or uproot trees in *terra-firme* forests of Central
109 Amazon.

110 Current knowledge about the effects of wind disturbances in the Ama-
111 zon forest derives from studies that have quantified the spatial extent of
112 these events using satellite imagery, in particular Landsat (Nelson, 1994;
113 Negrón-Juárez et al., 2010; Chambers et al., 2013; Espírito-Santo et al., 2014),
114 or from post-perturbation forest inventories to assess associated tree dam-
115 age/mortality and their effects on forest structure and diversity in subsequent
116 years to decades (Marra et al., 2014, 2018; Schwartz et al., 2017; Silvério et al.,
117 2019; Urquiza Muñoz et al., 2021). The estimated time to recover 90% of
118 pre-disturbance biomass is up to 40 years (Marra et al., 2018) in the Central
119 Amazon and 30 years in the northwestern Amazon (Urquiza Muñoz et al.,
120 2021).

121 The goal of our study was to identify the existence of different noctur-
122 nal turbulence regimes above a *terra-firme* forest in the Central Amazon
123 and their possible association with seasonality and proximity to the forest
124 canopy. Furthermore, to assess the effect of extreme winds associated with
125 convective downdrafts on the organization of turbulence regimes in the noc-
126 turnal boundary layer **RSL** and the potential of observed winds to cause
127 damage/mortality of canopy trees. We recognize that damaging winds and
128 downdrafts in this region are also associated with convective storms and with
129 fronts that can pass during the day, but that is beyond the scope of the cur-
130 rent analysis. To our knowledge, this is the first assessment of the influence
131 of extreme winds on turbulence regimes and of the potential of associated
132 wind to promote tree damage/mortality. Apart from a better understanding
133 of the ~~Amazon boundary layer structure and processes of turbulent exchange~~
134 between the biosphere and the atmosphere, **especially in rainforests with**
135 **dense canopies**, our study provides insights into the vulnerability of Amazon
136 forests to ongoing shifts on the intensity and frequency of convective storms
137 resulting from climate change (Feng et al., 2023).

138 2. Material and methods

139 2.1. Study site and data acquisition

140 Our data were collected at the *Estação Experimental de Silvicultura Trop-*
141 *ical* (EEST, also known as ZF2), Central Amazon, Brazil (Figure 1). The
142 EEST is located about 60 km northwest of Manaus ($2^{\circ} 36' S$, $60^{\circ} 12' W$,
143 $130 m a.s.l.$) (Araújo et al., 2002) and is predominantly covered by old-
144 growth *terra-firme* forest with closed canopy (e.g. 593 ± 28 trees ha^{-1}),

145 dense understory and high tree-species diversity (Braga, 1979; Marra et al.,
146 2014). Trees are relatively tall and slender (Oliveira et al., 2008; Ribeiro
147 et al., 2016). The proportion of trees reaching the canopy increased with
148 diameter at breast height (DBH): from 21% for trees 10-20 cm DBH, and
149 57% for 20-30 cm DBH, up to 100% for trees above 70 cm DBH (Araujo
150 et al., 2020).

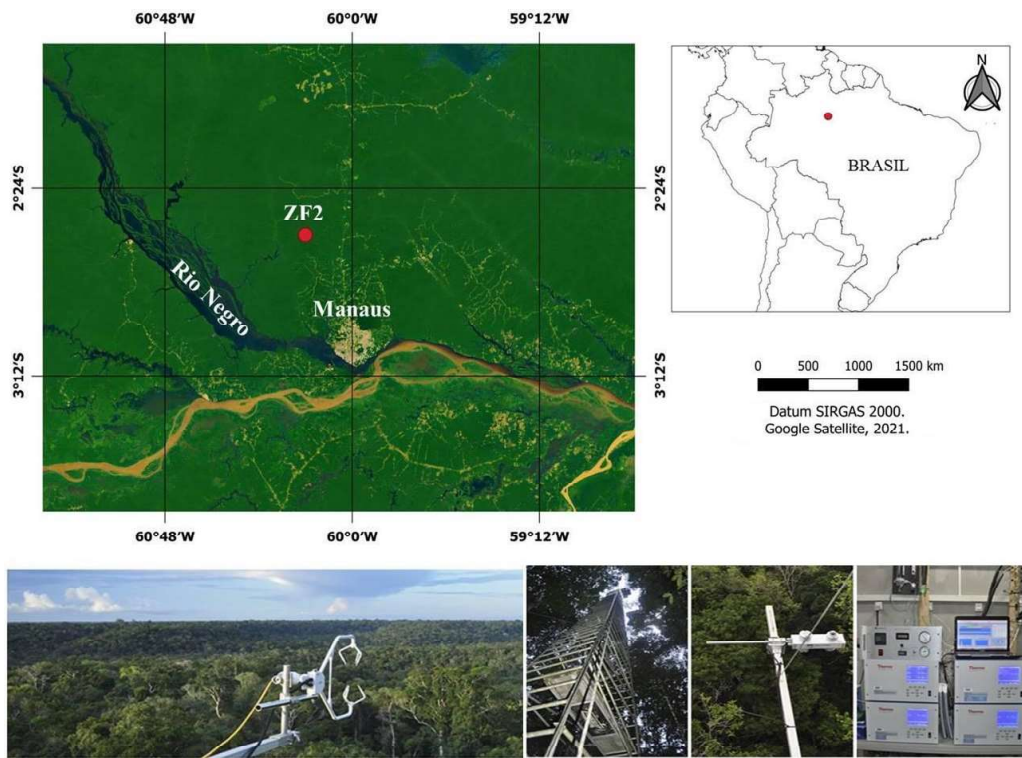


Figure 1: Study area at the *Estação Experimental de Silvicultura Tropical* (EEST) near Manaus, Brazil, and micrometeorological tower and sensors. (Top panel) Map of Brazil showing the study region. (Bottom left) A panoramic view of the forest and the employed 3D-sonic anemometer. (Bottom center left) Micrometeorological tower. (Bottom center right) Net radiometer. (Bottom right) Ozone analyzers.

151 The topography at the study area comprises a mosaic of plateaus, slopes

152 and **valleys** with elevation differences of about 50 *m*. The vegetation cover
153 on the plateau and slope areas is composed by forest with height varying
154 between 30 to 40 *m*, maximum surface area density of $0.35 \text{ m}^2\text{m}^{-3}$. In
155 valley areas, the vegetation is smaller with heights from 15 to 25 *m*, but
156 with significant surface area density more than the $0.35 \text{ m}^2\text{m}^{-3}$ (Tóta et al.,
157 2012). The average values of leaf area index for the local vegetation was 6.1
158 m^2m^{-2} (Marques Filho et al., 2005).

159 Oxisols rich in kaolinite clay dominate plateaus and the upper portions
160 of slopes. The soils on slope bottoms and valleys are sandy and mixed with
161 organic matter (Spodosol) (Telles et al., 2003). The mean annual tempera-
162 ture is 27 °C and mean annual rainfall was about 2365 *mm* for the period
163 between 1971 and 2000, with a distinct dry season between July and Septem-
164 ber (rainfall $< 100 \text{ mm month}^{-1}$) (Negrón-Juárez et al., 2017).

165 Our data were collected using **sensors** installed on a micrometeorological
166 tower of 54 *m* height. We used the sonic virtual temperature (T) and wind
167 components (u, v and w) measured at 10 different heights (i.e. 1.5, 7.0,
168 13.5, 18.4, 22.1, 24.5, 31.6, 34.9, 40.4 and 48.2 *m* above ground) by 3D-sonic
169 anemometers (model CSAT3, Campbell Scientific Inc., Logan, UT, USA) at
170 a rate of 20 *Hz*. For analyzing the vertical temperature gradient, we used
171 thermo-hygrometer data from sensors (HMP45AC, Vaisala) installed at 35.5
172 *m* and 51 *m* height. These data were available at a 30 *min* resolution. Net
173 radiation (R_N) was measured with a net-radiometer (model CNR1, Kipp &
174 Zonen, Delft, Netherlands) installed at 39 *m* height. We used data from April
175 2014 to January 2015 collected ~~on the scope~~ **in the course** of the Green Ocean
176 Amazon Experiment (GoAmazon). For more details about instruments and

177 respective measurements, see [Fuentes et al. \(2016\)](#).

178 Ozone concentration (O_3) was measured continuously at 40 m height
179 at a frequency of 1 Hz using an ultraviolet light absorbed gas analyzer
180 (model 49i, Thermo Fisher Scientific Inc., Waltham, MA). For more de-
181 tails on ozone measurements see [Gerken et al. \(2016\)](#). Convective cloud
182 coverage over the study site was assessed with GOES-13 (Geostationary Op-
183 erational Environmental Satellites) satellite imagery data available at the
184 Brazilian National Institute for Space Research (INPE) database (<http://satelite.cptec.inpe.br/acervo/>, accessed on 30 May 2021).

186 Our data were analyzed for two time periods: (i) 55 days in the wet sea-
187 son (from April to May) and (ii) 36 days during the dry season (from July to
188 September). To avoid transitional periods, we used data from 2000 to 0500
189 local standard time (LST). ~~for NBL~~. The dry and wet seasons were character-
190 ized based on the seasonality of precipitation using the Global precipitation
191 Mission (GPM) level-3 product ($mm\ h^{-1}$). Estimates were **carried out** us-
192 ing data downloaded from the website of National Aeronautics and Space
193 Administration (NASA) (<https://giovanni.gsfc.nasa.gov>, accessed on
194 28 october 2020) for the period between 1st April and 31st December 2014.
195 Overall, we used a product of the Integrated Multi-satellitE Retrievals for
196 GPM (IMERG) at a spatial resolution of $0.1^\circ \times 0.1^\circ$ and at temporal resolu-
197 tion of 1 month (Final Run IMERG v06). The IMERG algorithm combines
198 information from the GPM satellite constellation and precipitation gauges.
199 The system “final run” uses monthly gauge data to create research-level
200 products.

201 Local estimates of critical wind-speed (CWS) were compiled from [Peter-](#)

202 [son et al. \(2019\)](#). According to these authors, the CWS is the wind speed
203 necessary to generate a turning moment at the base of the trunk greater
204 than or equal to the turning moment that **results** in tree failure. CWS were
205 modeled based on critical turning moments measured locally in a winching
206 experiment that included 60 trees from different species and varying sizes
207 ([Ribeiro et al., 2016](#)). We considered CWS values estimated from a dy-
208 namic model (i.e. profile method) assuming that tree mortality associated
209 with convective systems can create canopy gaps that contribute to increasing
210 turbulence and wind propagation into the forest. In this model, tree spac-
211 ing/density, leaf-area index and wind profiles are updated progressively after
212 each tree failure ([Peterson et al., 2019](#)). The reported CWS ranged from
213 10.75 ms^{-1} to 34.5 ms^{-1} .

214 Before analyzing the micrometeorological, meteorological and profile data,
215 we conducted the following quality control: (i) testing for record complete-
216 ness and checking for the presence of error flags as proposed by [Zahn et al.](#)
217 ([2016](#)) and (ii) detection of spikes and dropouts with eventual removal of
218 corrupted/damaged data as suggested by [Vickers and Mahrt \(1997\)](#).

219 *2.2. Turbulence regimes and flux estimates*

220 In this study we examine the turbulence regimes at three heights. The
221 first one was defined as near as possible to the top of the forest canopy (i.e.
222 $\approx 35 \text{ m}$; [Fuentes et al. \(2016\)](#)), and the other two at the maximum heights
223 where the sensors were installed on the tower (40 and 48 m, respectively).
224 **We focused only on the nighttime period (i.e., nocturnal boundary layer)**
225 **because the diurnal relationship between wind speed and turbulence rarely**
226 **deviates from linearity (not shown here), since typical daytime conditions at**

227 ~~our study site are close to neutrality. Since the physical processes associated~~
228 ~~with turbulence are completely different during daytime, here we focused only~~
229 ~~on the nighttime period (stable boundary layer). During daytime, the state~~
230 ~~of stable stratification is regularly overturned by the heating of the air layers~~
231 ~~that are in contact with the surface (i.e., boundary layer and surface are~~
232 ~~strongly coupled).~~

233 We used two methods for identifying the nocturnal turbulence regimes.
234 The method proposed by Sun et al. (2012, 2016) considers the possibility of
235 external agents (e.g. convective clouds) acting on the atmospheric boundary
236 layer and disturbing its turbulent fields (Garstang et al., 1998; Garstang
237 and Fitzjarrald, 1999; Betts et al., 2002; Dias-Júnior et al., 2017a). Sun’s
238 method accounts for the average relationship between the turbulent velocity
239 scale (V_{TKE}) and the mean horizontal wind speed (V). Where $V_{TKE} =$
240 $\sqrt{TKE} = [0.5(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)]^{1/2}$ and $V = \sqrt{u^2 + v^2}$, in which u, v and w are
241 zonal, meridional and vertical wind components, σ represents the standard
242 deviation of each variable and TKE represents the Turbulent Kinetic Energy.
243 Sun’s method identifies the wind speed threshold value (V_L) from the slope
244 change of a straight line around which the data are clustered. ~~For this, we~~
245 ~~performed a segmented linear regression and selected the V_L with the best~~
246 ~~coefficient of determination (R^2).~~ In this case, turbulence is compared at a
247 given level with the wind speed at that level.

248 The second method, reported by Acevedo et al. (2016) is based on the
249 sign inversion of the vertical gradient of V_{TKE} (ΔV_{TKE}). This procedure
250 accounts for the relationship between V_{TKE} and V , but in contrast to Sun’s
251 method, turbulence is examined at all levels in terms of the wind speeds at

252 a fixed reference level. When classified by the V at a reference level, the
 253 wind speed crossover threshold (V_T) lies where the average ΔV_{TKE} reverses
 254 sign for the entire tower layer. This change occurs because in very stable
 255 regime the V_{TKE} increase with height and the importance of low-frequency
 256 (sub mesoscale fluctuations) phenomena at higher levels contributes to this
 257 pattern. In weakly stable regime, on the other hand, the classical pattern of
 258 decreasing turbulence with height is dominant. Therefore, the parameters V_L
 259 and V_T are the wind speed values that determine the change from very stable
 260 (decoupled boundary layer) to weakly stable regime (the classical boundary
 261 layer coupled to the surface). Here, we assumed ΔV_{TKE} as the difference
 262 between 48 m and 35 m.

263 **Fluxes were estimated by the Eddy Covariance method.** We calculated
 264 the turbulent fluxes of sensible heat as $H = \rho c_p \overline{\theta' w'}$ and momentum as $\tau =$
 265 $\rho(\overline{u'w'^2} + \overline{v'w'^2})^{1/2}$, where ρ is the density of air (assumed to be 1.225 kgm^{-3})
 266 and c_p is the specific heat of air at a constant pressure. The variables θ' and
 267 w' , represent the fluctuations of virtual temperature ($^{\circ}\text{C}$) and vertical wind
 268 speed (ms^{-1}), respectively. As suggested by [Sun et al. \(2002\)](#) and [Vickers](#)
 269 [et al. \(2010\)](#), we used mean values over 5 min intervals for all the different
 270 statistical moments of the turbulence.

271 To investigate statistical differences between the very stable and weakly
 272 stable regimes, we first used the Mann Whitney U-test considering the iden-
 273 tified regimes as grouping variables. Therefore, six tests were performed, one
 274 at each height (48 m, 40 m and 35 m) and for the dry and wet seasons.
 275 In a second analysis, we applied a factorial analysis of variance (ANOVA)
 276 followed by Tukey tests to assess the effects of the interaction between the

277 seasons, heights and turbulence regimes on observed patterns of atmospheric
278 turbulence. Here we use V_{TKE} as dependent variable. For all tests we con-
279 sidered a significance level of 5% and used the software Matlab and Jamovi
280 for data processing and analysis.

281 In this work V_{TKE} was only used in the analysis of the transition of
282 turbulence regimes, but not as an indicator of the tree damage/mortality.
283 To assess the potential of extreme wind gusts as a mechanism of tree dam-
284 age/mortality, we compared the CWS data available for our study site and
285 the maximum wind speed observed within our study period, as detailed in
286 section 2.4.

287 2.3. Identification of convective cloud downdrafts

288 Previous studies have demonstrated that convective downdrafts transport
289 air with high O_3 concentrations and lower T (cold pool) rapidly from the
290 lower-middle troposphere to the surface (Betts et al., 2002; Gerken et al.,
291 2016; Dias-Júnior et al., 2017a; Bezerra et al., 2021).

292 It is known that in environments with high moisture and strong con-
293 vection such as in the Amazon, the equivalent potential temperature (θ_e) is
294 also important under unstable atmospheric conditions. Since θ_e changes as a
295 function of moisture (through mixing ratio) and temperature, the downward
296 transport of cold and dry air leads to an important decrease of θ_e (Garstang
297 and Fitzjarrald, 1999; Betts et al., 2002). However, moisture data were not
298 available for our study site. Alternatively, we used virtual temperatures.

299 The identification of convective cloud downdrafts in our study was per-
300 formed using a two-step procedure. We first analyzed the time series of
301 horizontal wind speed, air temperature and surface concentration of O_3 to

302 investigate atmospheric dynamics and the occurrence of gust fronts associ-
303 ated with convective clouds. For this analysis, we averaged data at 48 m (V
304 and T) and 40 m (O_3) height for 5-minute intervals. The data series were
305 mapped by an algorithm that identifies a subtle increase of O_3 concentra-
306 tions of at least 3 parts per billion (ppb), and a simultaneous decrease of T
307 values of 2 °C within a 1h time window of respective events (Gerken et al.,
308 2016; Dias-Júnior et al., 2017a). During these events, the highest horizontal
309 wind speed registered within one second interval and the five minutes average
310 comprising such an interval were retained. False detections were manually
311 identified and removed. In the next step, GOES-13 imagery were visually
312 inspected for the presence of convective clouds over the study site. Here,
313 we only considered images acquired on days for which abrupt changes in
314 weather variables were detected as described in the previous step. We ana-
315 lyzed the effect of downdrafts associated with turbulence regimes by checking
316 the relationship between V_{TKE} and V . Here, we assumed the minimum and
317 maximum V values to determine the start and end time of respective wind
318 gusts.

319 *2.4. Extreme winds as a mechanism of tree mortality*

320 To assess the potential of extreme wind gusts as a mechanism of tree dam-
321 age/mortality, we compared the CWS data and the maximum wind speed
322 (V_o) measured by our anemometers. The V_o is the maximum horizontal wind
323 speeds (or extremes winds) measured at 5 min time-intervals at 48 m height.
324 These data were analyzed for the different seasons (dry and wet).

325 Since downdrafts can last from few seconds to (rarely) minutes, we calcu-
326 lated V_o at two other time intervals: 1-minute and 30-seconds windows. To

327 check if V_o differs with the size of time-intervals, we compared computed val-
328 ues (response variable) using ANOVA of repeated measures. Subsequently,
329 we executed an ANOVA to verify potential variations of V_o as a function of
330 seasonality.

331 **3. Results**

332 *3.1. Turbulence regimes in the nocturnal boundary layer*

333 We found a positive relationship between V_{TKE} and V for both dry and
334 wet seasons, and a clear distinction between the two turbulence regimes (Fig-
335 ure 2). For events classified as weak turbulence (very stable regime), V_{TKE}
336 increased less than V as indicated by a ~~relatively~~ smaller slope. As V reached
337 a threshold value (V_L), turbulence changed from weak to strong (weakly sta-
338 ble regime) as indicated by a ~~relatively~~ larger increase of V_{TKE} as a function
339 of V and larger slope. V_L increased nonlinearly with the distance from the
340 forest canopy in both seasons. The observed values of V_L at 35 m and 48 m
341 were near 0.7 and 2.3 ms^{-1} (dry) and 0.5 and 1.9 ms^{-1} (wet), respectively.
342 These results are in agreement with previous studies that found that V_L in-
343 creases nearly logarithmically with height (Sun et al., 2012; Acevedo et al.,
344 2016).

345 Although the observed increase of V_L with height supports previous re-
346 search on non-vegetated surfaces, the thresholds identified at 35 m in our
347 study site were significantly smaller than those observed at a pasture area at
348 the Federal University of Santa Maria (in south Brazil) (V_L of 3.0 ms^{-1} at
349 30 m height) (Acevedo et al., 2021) and at project FLOSS II (Fluxes over
350 Snow Surfaces) conducted in Colorado (US) (V_L of 5.3 ms^{-1} at 30 m height)

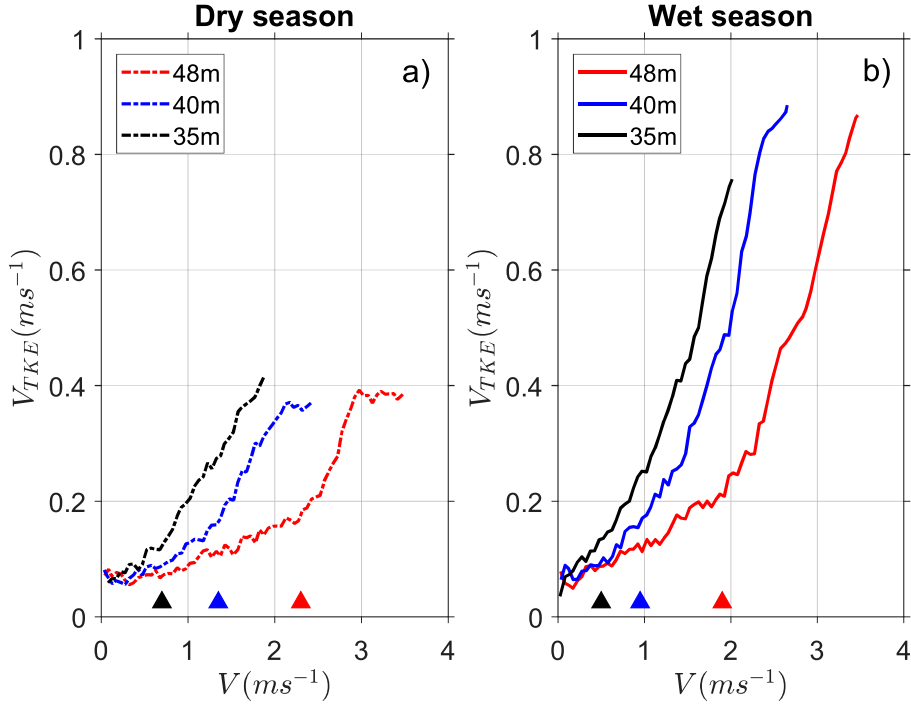


Figure 2: Relationship between turbulence velocity scale (V_{TKE}) and mean wind speed (V) at different heights in the (a) dry and (b) wet season during the nighttime at the EEST, Manaus, Central Amazon. Triangles indicate the threshold wind speed (V_L) at which the very stable changed to weakly stable regime.

351 (Acevedo et al., 2016). Such differences show that the structure and rough-
 352 ness of dense forests influence the change of the turbulence regime. Similar
 353 to the analysis performed by Chor et al. (2017) for the Amazon Tall Tower
 354 Observatory (ATTO) site, we also used the zero-plane displacement height
 355 (d) equal to $d = 0.9 h = 31.5$ m (where h is the canopy height) at our
 356 study site. Therefore, a proper comparison must consider the observation
 357 level with respect to d . For a proper comparison we considered the observa-
 358 tion level with respect to the zero plane displacement height (d). We used

359 $d=31.5$ m based on estimates provided by Viswanadham et al. (1990) and
360 Chor et al. (2017) for central Amazon, in which $d=0.88h$ and $d=0.9h$, re-
361 spectively, where h is the canopy height (35 m at our study site). Doing
362 that, the V_L values found at 35 m ($z-d = 3.5$ m) in both seasons are smaller
363 than the value of 2.04 m s^{-1} found at 2 m in FLOSS II (Acevedo et al., 2016)
364 and that of 1.5 m s^{-1} found at 1.5 m in the CASES-99 (experiment carried
365 out in southeast Kansas, US) (Sun et al., 2012). Similarly, the V_L found for
366 both seasons at the EEST at 48 m ($z-d=16.5$ m) are smaller than those at
367 15 m in FLOSS (5.04 m s^{-1}) and at 10 m in CASES-99 (4.5 m s^{-1}). The V_L
368 found at 48 m at EEST site in the wet season is also smaller than the value
369 reported by Acevedo et al. (2021) at 14 m in Santa Maria (2.2 m s^{-1}). Still,
370 this value is close to that we found during the dry season at the EEST. In
371 general, the V_L values between turbulence regimes was smaller at the EEST
372 site than that reported in previous studies at similar heights, even when the
373 zero-plane displacement height is taken into account. This relates to V_L being
374 generally smaller above rough surfaces compared to smooth surfaces (Mahrt
375 et al., 2013; Vignon et al., 2017; Guerra et al., 2018), a simple consequence
376 of turbulent mixing being larger above a rough surface than above a smooth
377 one at a same mean wind speed.

378 From the nighttime turbulence regimes identified at 48 m height, around
379 77% (dry) and 65% (wet) of them were associated with very stable regime.
380 In contrast, weakly stable regime corresponded to 23% (dry) and 35% (wet)
381 of the events. Furthermore, V_L was larger during the dry season than in
382 the wet season at the three investigated heights (Figure 2 and Table 1).
383 This result is in agreement with Acevedo et al. (2021), who showed that

384 V_L increases linearly with net radiative loss at the surface at three mid-
 385 latitude sites. According to these authors, the fully turbulence regime occurs
 386 when the mean wind speed is large enough to support heat fluxes capable of
 387 transferring back to the surface part of the energy lost radiatively. Therefore,
 388 such a minimum heat flux and corresponding minimum wind speeds must be
 389 larger when the net radiative loss is also larger. The relationship between V_L
 390 and R_N is further discussed in Section 4.

Table 1: Wind speed threshold (V_L) at studied heights for the dry and wet seasons at the EEST, Manaus, Central Amazon.

Season	V_L at 48m (ms^{-1})	V_L at 40m (ms^{-1})	V_L at 35m (ms^{-1})
Dry	2.3	1.35	0.7
Wet	1.9	0.95	0.5

391 We also identified the transition between regimes as a function of V at 35
 392 m, for which the ΔV_{TKE} reverses sign for both dry and wet seasons (Acevedo
 393 et al., 2021). Figure 3 show that the V_{TKE} increased with height for weak
 394 winds in both seasons. When V at 35 m exceeds a sharp threshold, this
 395 pattern is reversed, so that V_{TKE} decreases with height under sufficiently
 396 strong winds. Such a threshold was approximately $0.65 ms^{-1}$ and $0.50 ms^{-1}$
 397 for the dry and wet seasons, respectively. However, when the same analysis
 398 is performed in terms of V at 48 m (Figure 4), there was no gradient reversal
 399 and V_{TKE} decreased with height for all observed wind speeds.

400 These findings suggest that the relationship between V and V_{TKE} at the
 401 different heights is not trivial and may be associated with the occurrence of
 402 phenomena such as low-level jets and density currents (Greco et al., 1992;

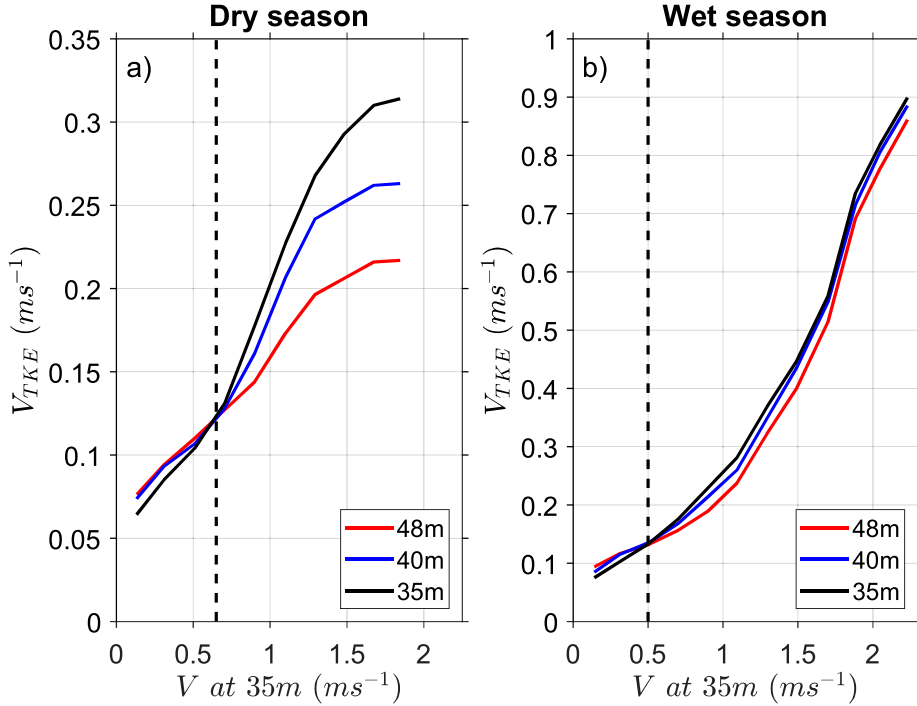


Figure 3: Turbulence velocity scale (V_{TKE}) as a function of the mean wind speed (V) at 35 m during the nighttime at the EEST, Manaus, Central Amazon. The solid lines are V_{TKE} at different heights in the (a) dry and (b) wet season. Black vertical dashed line indicates when V_{TKE} reverses its sign and exceeds the crossover threshold (V_T) at which the very stable changed to weakly stable regime

403 [Dias-Júnior et al., 2017b](#); [Corrêa et al., 2021](#)). When the wind speeds are
 404 weak at higher levels, the wind profile is often distorted and maximum values
 405 can occur near the surface ([Acevedo et al., 2016](#)).

406 The V_T values identified by the vertical gradient method at 35 m height
 407 during the dry (0.65 m s^{-1}) and wet (0.50 m s^{-1}) seasons were similar to the
 408 V_L values obtained with Sun's method. This result corroborates the existence
 409 of nighttime turbulence regimes at the EEST during the two seasons. As the

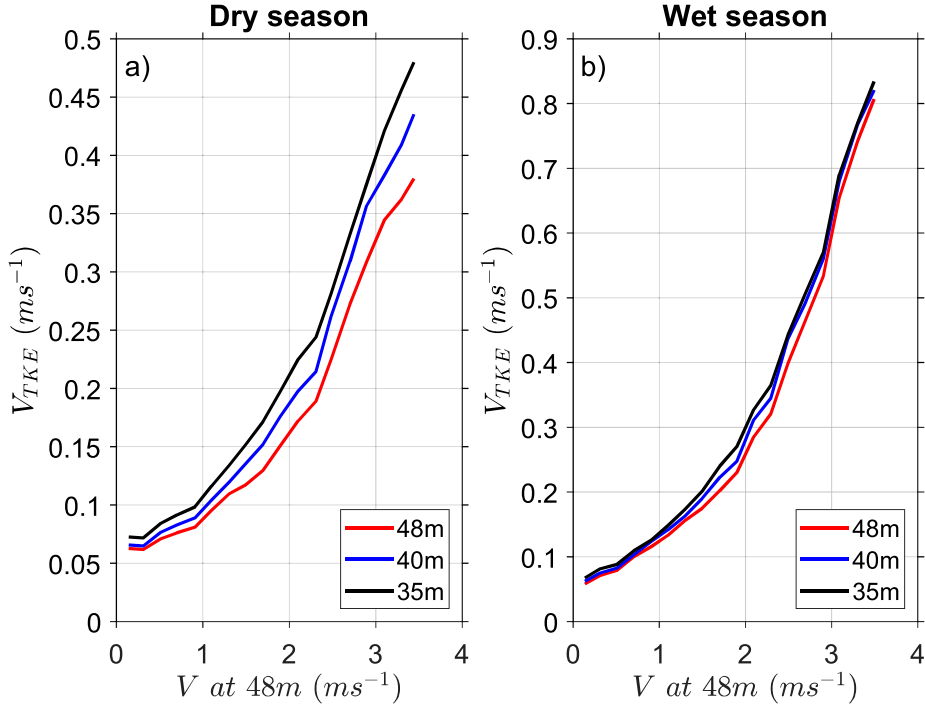


Figure 4: Turbulence velocity scale (V_{TKE}) as a function of the mean wind speed (V) at 48 m during the nighttime at the EEST, Manaus, Central Amazon. The solid lines are V_{TKE} at different heights in the (a) dry and (b) wet season

410 values of V_T and V_L were similar, hereafter we used the values of V_L as an
 411 **indication for** changes of turbulence regimes, since it was possible to identify
 412 it at all heights investigated here.

413 Our results evidenced the existence of different nocturnal turbulence
 414 regimes in the *terra-firme* Amazon forests. Moreover, they indicated that
 415 turbulence intensity decreased with the proximity to the canopy (Figure 5a).
 416 V_{TKE} during weakly stable regime was larger than in the very stable regime
 417 (Figure 5b). Overall, the wet season had larger values of V_{TKE} than the dry
 418 season (Figure 5c).

419 These larger values of V_{TKE} in the wet season are likely associated with
 420 a lower wind speed threshold between regimes in the wet season (Figure 2).
 421 Since the threshold is smaller, it is plausible considering that it is easier to
 422 overcome this threshold and establish “large” V_{TKE} in this case. Another
 423 reason that could result in larger values of V_{TKE} in the wet season would be
 424 simply because the wet season has higher wind speeds values than the dry
 425 season. Nonetheless, this was not the case, as can be seen in Figure 5d-f.
 426 Our result may be related to other factors, such as radiative loss, thermal
 427 gradient, among others.

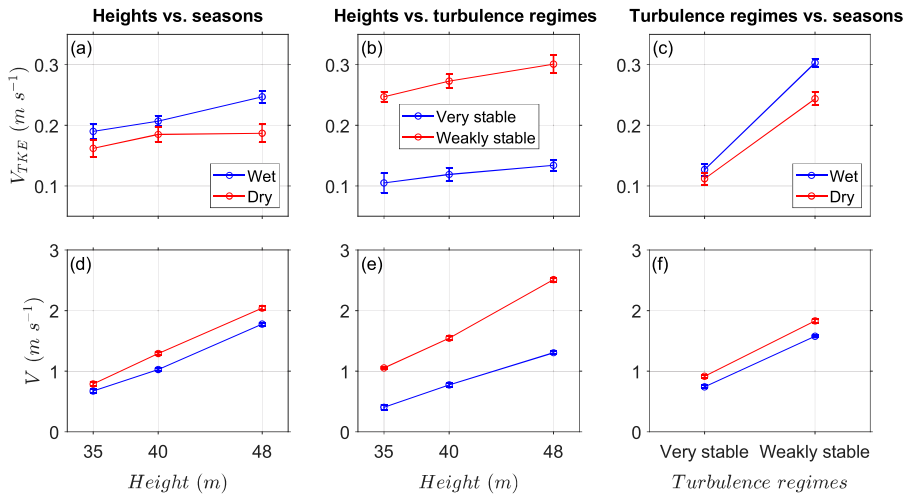


Figure 5: Turbulence velocity scale (V_{TKE}) and mean wind speed (V) as a function of (a,d) heights vs. seasons, (b,e) heights vs. turbulence regimes and (c,f) turbulence regimes vs. seasons during nighttime at the EEST, Manaus, Central Amazon. Legend: circles and vertical bars indicate mean values and the 95% confidence intervals, respectively

428 *3.2. Turbulent fluxes in the nocturnal boundary layer*

429 We investigated the differences between the turbulent fluxes during the
 430 occurrence of very stable and weakly stable regimes, and found an interesting
 431 relationship between V and the sensible heat (H), and momentum (τ) fluxes
 432 at 35 m height during both seasons. Bins of V each 0.2 ms^{-1} were used
 433 to calculate the average values and standard deviations of the fluxes. H
 434 values (Fig. 6a and Fig. 6b) changed in response to the turbulence shifting
 435 from the weak to the strong in both seasons (Table 2). On average, the H
 436 flux in the weakly stable regime corresponded to about 88% of the total H
 437 observed in both seasons. Our findings corroborate those of previous research
 438 conducted in Eastern Amazon (Dias-Júnior et al., 2017b). Importantly, H
 439 values were more intense during the dry season ($p = 0.001$). This result is
 440 possibly associated to larger net radiative loss due to reduced cloud cover
 441 and atmospheric column water vapor load (Collow and Miller, 2016), which
 442 leads to less longwave radiation reaching the canopy.

Table 2: Mean values (\pm 95% confidence interval) of sensible heat flux (H) and momentum flux (τ) for the dry and wet seasons at the EEST, Central Amazon, Brazil.

Turbulence regimes	H Dry (Wm^{-2})	H Wet (Wm^{-2})	τ Dry (10^{-2}) (Nm^{-2})	τ Wet (10^{-2}) (Nm^{-2})
Very stable	-1.8 ± 2.5	-1.3 ± 2.0	-0.3 ± 0.4	-0.5 ± 0.6
Weakly stable	-13.4 ± 17	-9.8 ± 9.6	-2.3 ± 3.0	-4.1 ± 5.4

443 The τ fluxes showed a similar behavior to that of H , in which the flux
 444 in the weakly stable regime was larger than in the very stable regime ($p \leq$

445 0.001), and reached on average 89% of the total τ flux in each season (Fig.
 446 6c and Fig. 6d). Such variations may be related to atmospheric stability
 447 conditions. The wet season is less stable (on average), that is, the strong
 448 turbulence events (i.e. weakly stable regime) occurs more frequently and,
 449 consequently, the momentum fluxes are greater. Overall, the weakly stable
 450 regime contributed more significantly to sensible heat and momentum fluxes
 451 than the very stable regime (Table 2), in both seasons.

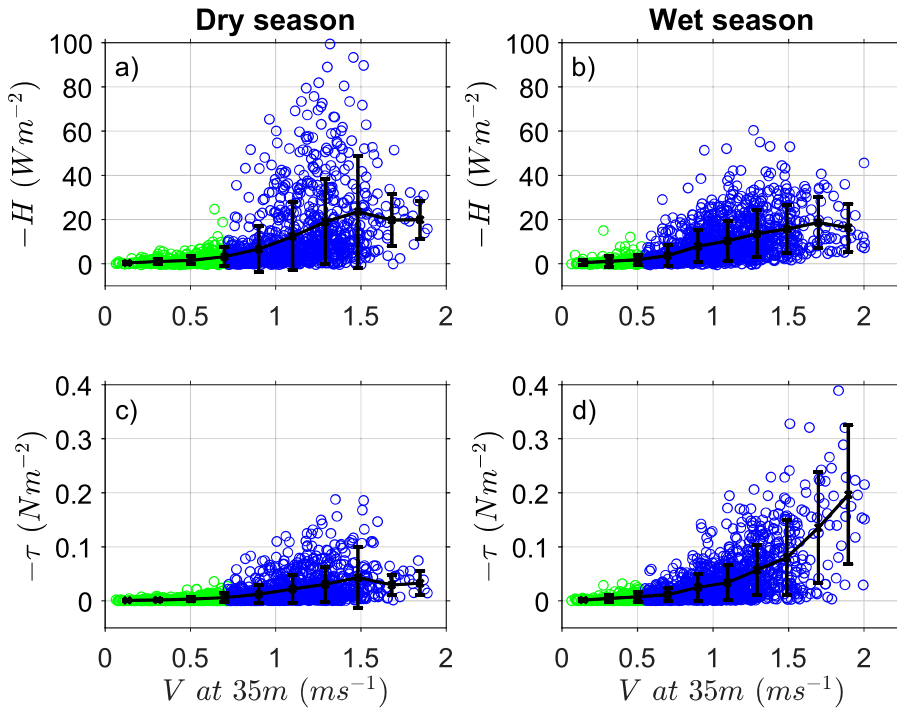


Figure 6: Mean and standard deviation of sensible heat flux (H) and momentum flux (τ) as a function of the wind speed (V) at 35 m during nighttime at the EEST, Manaus, Central Amazon. The left and right panels indicate the dry and wet season, respectively. Green and blue circles indicate the very stable and weakly stable regimes, respectively.

452 *3.3. Relationship between deep convection and nocturnal turbulence regimes*

453 During the night of 06 August 2014 and 12 April 2014, gust fronts from
454 downdrafts reached the tower around 2110 LST (dry season) and 2325 LST
455 (wet season), respectively (Figure 7). These events were evidenced from
456 observations of (i) decreasing T (around 2 °C at both seasons) and (ii) si-
457 multaneous increasing O_3 of approximately 12 ppb (dry) and 15 ppb (wet).
458 The pre-gust measurements of V ($\approx 2 \text{ ms}^{-1}$) were similar in both nights
459 (Fig. 7c and Fig. 7g). However, V reached maximums of 7.5 (dry) and 15
460 ms^{-1} (wet) during the observed downdrafts. At this time, the standard devi-
461 ation of wind vertical velocity (σ_w) increased substantially (Fig. 7d and Fig.
462 7h). ~~As the surface cools and uncouples the boundary layer from the above~~
463 ~~troposphere, the near-surface O_3 values are low (3-5 ppb). This pattern al-~~
464 ~~lows for a clear recognition of night downdrafts transporting air with higher~~
465 ~~ozone and lower temperature to the surface. Since the surface cools the NBL~~
466 ~~uncoupling. It from the layer above and thus reducing O_3 values (3-5 ppb),~~
467 ~~downdrafts are more easily recognized at night.~~ We observed this pattern
468 on other nights and identified 16 downdrafts (eight different nights in each
469 season) over the studied period. Overall, these events occurred between 2000
470 LST and 2300 LST. Finally, the GOES-13 imagery indicates the existence
471 of cloudiness at the times of the events (Figure 8) and also on the other 16
472 nights that we studied here.

473 These results support previous studies, such as that by [Betts et al. \(2002\)](#)
474 who found that nighttime convective downdrafts coupled the surface to the
475 lower troposphere and transported down air with larger O_3 and lower equiv-
476 alent potential temperature. [Dias-Júnior et al. \(2017a\)](#) also reported that

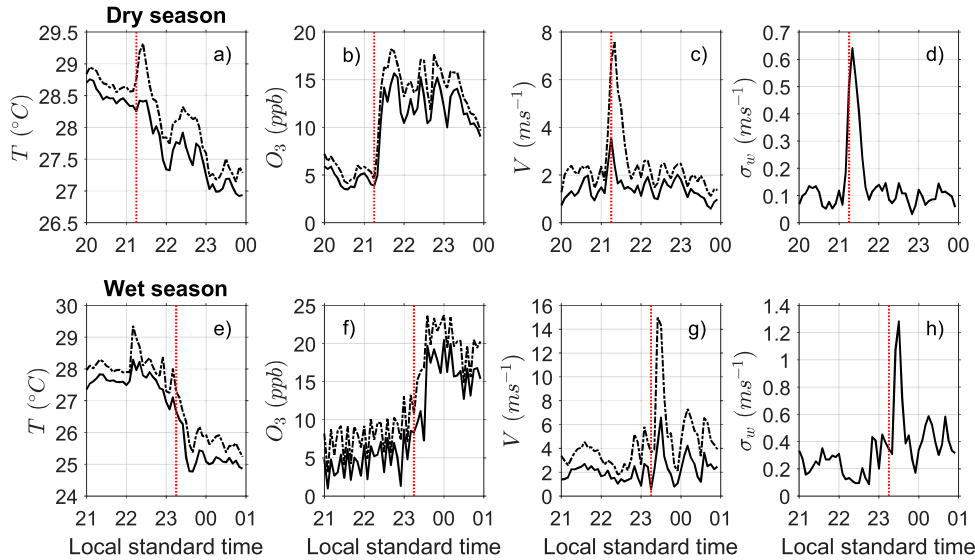


Figure 7: Times series of key variables used to identify downdrafts at the EEST, Central Amazon, Brazil. The upper and bottom panels show the downdrafts from 06 August 2014 and 12 April 2014, respectively. Legend: virtual temperature (T), ozone (O_3), horizontal wind speed (V) and standard deviation of wind vertical velocity (σ_w). Solid and dashed lines indicate the mean and maximum values, respectively. Vertical red-dotted lines indicate the starting time of downdrafts.

477 the downdrafts produce O_3 enhancement events and an increase in V val-
 478 ues, in addition to the occurrence of air divergence during the horizontal
 479 propagation of density currents.

480 We observed that all downdrafts happened during or after the transition
 481 to the weakly stable regime (Figure 9). This pattern evidenced that down-
 482 drafts may influence the turbulence characteristics near the surface since they
 483 are associated with a weakly stable regime (strong turbulence). However,
 484 weakly stable regime was not represented completely by these events, which
 485 suggest that the strong turbulence may be associated with the occurrence

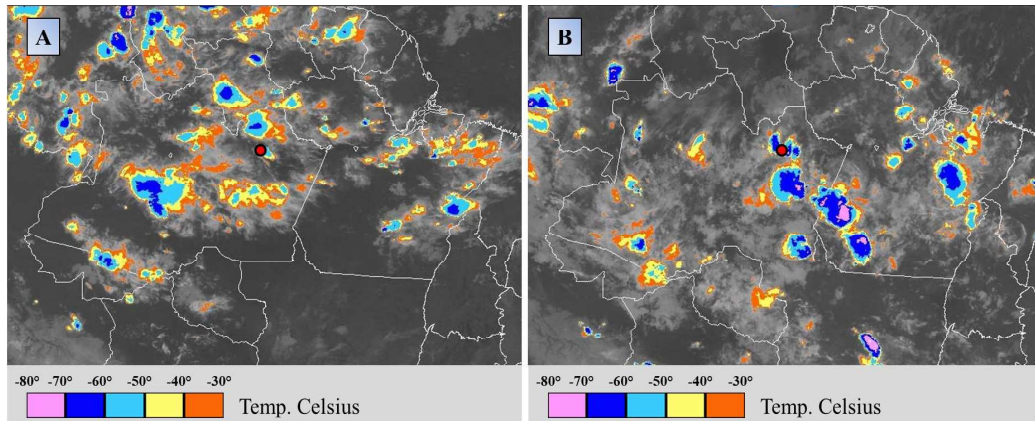


Figure 8: GOES 13 imagery for (a) 07 August 2014 at 0100 UTC and (b) 13 April 2014 at 0300 UTC when downdrafts reached the micrometeorology tower at the EEST (red dot), Central Amazon, Brazil.

486 of other phenomena. Similar results were previously reported for Central
 487 Amazon by [Bezerra et al. \(2021\)](#), who observed that downdrafts generated
 488 by a squall line occurred only during the strong turbulence regime.

489 3.4. *Extreme winds as a mechanism of tree mortality*

490 During the weakly stable regime associated with nocturnal downdraft
 491 events, the speeds and thus destructive potential of winds varied between
 492 seasons. The greatest wind speeds were identified during the wet season
 493 ($V_o = 14.96 \text{ ms}^{-1}$). This value was approximately four times higher than on
 494 nights without downdrafts, and exceed the CWS of three out of the studied
 495 trees by [Peterson et al. \(2019\)](#). In contrast, maximum wind speeds in the
 496 nocturnal period of the dry season ($V_o = 7.57 \text{ ms}^{-1}$) did not exceed the CWS
 497 of the studied trees.

498 Here we did not assess the direct effect of high wind-speeds on trees,

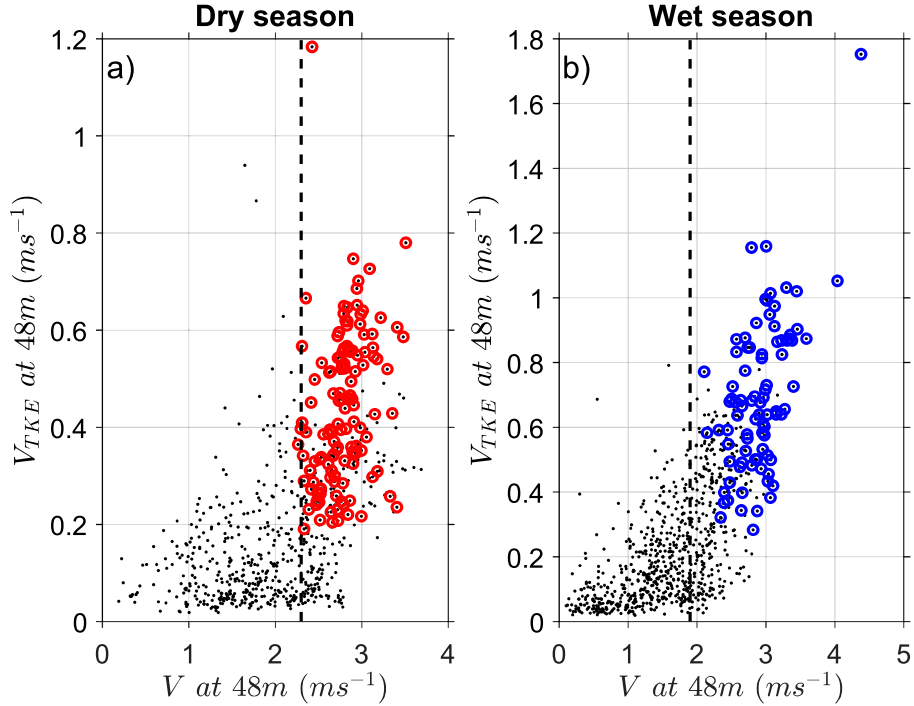


Figure 9: Turbulence velocity scale (V_{TKE}) as a function of the mean wind speed (V) measured at 48 m in the (a) dry and (b) wet season during nighttime at the EEST, Manaus, Central Amazon. The dots correspond to mean values calculated over 5-min periods. Thick circles indicate the range of occurrence of the downdrafts. Vertical black-dashed lines mark the threshold wind speed (V_L) at which the very stable changed to weakly stable regime.

499 but rather evaluated the destructive potential of these based on observa-
500 tional data acquired at the same study site. Importantly, the occurrence of
501 excessive wind speeds does not necessarily result in trees damage and mortal-
502 ity. Further studies are needed to understand the link between wind speeds,
503 canopy structure and tree motion in these diverse forests. Still, the strong
504 dissipation of air to layers below the forest canopy (presented in Section 4)

505 are rarely observed in the absence of downdrafts. Therefore, the wind gusts
506 described in our study not only reached extreme speeds but also penetrated
507 the forest canopy, and had the potential to cause damage and mortality of
508 trees of different sizes, both directly and indirectly.

509 The mean V_o values varied significantly between the analyzed time-intervals
510 ($p \leq 0.001$, Fig. 10a). As expected, the values were higher for the 30 seconds
511 interval ($5.97 \pm 2.85 \text{ ms}^{-1}$, mean \pm 95% confidence interval). For the 1 min
512 and 5 min intervals, V_o was $5.35 \pm 2.68 \text{ ms}^{-1}$ and $3.63 \pm 2.45 \text{ ms}^{-1}$, respec-
513 tively. Results from subsequent ANOVA showed that the interaction between
514 seasons and time intervals was significant ($p \leq 0.001$, Fig. 10b). Post-hoc
515 Tukey tests showed that observed variations in V_o were not significantly dif-
516 ferent between seasons at both 1 min ($p = 0.057$) and 5 min ($p = 1.000$)
517 intervals. Nonetheless, V_o varied as a function of seasonality for our shorter
518 time interval (i.e. 30 seconds). These result shows that for extreme wind
519 gusts that may last a few seconds such as those causing tree damage and
520 mortality in the Amazon, our 30 second interval is likely too large and may
521 have underestimated maximum V_o values.

522 Although daytime patterns were not a focal aspect in our study, wind
523 speed reached the highest values (up to 22 ms^{-1}) during this period, in the
524 dry season. In contrast to the relatively low destructive potential of nocturnal
525 winds, this value could topple 73% of trees previously investigated in our
526 study site (Ribeiro et al., 2016; Peterson et al., 2019). These observations
527 reinforce the importance of extreme wind as a major natural mechanism of
528 tree damage and mortality in these forests (Nelson, 1994; Chambers et al.,
529 2009, 2013; Negrón-Juárez et al., 2017, 2018; Marra et al., 2018).

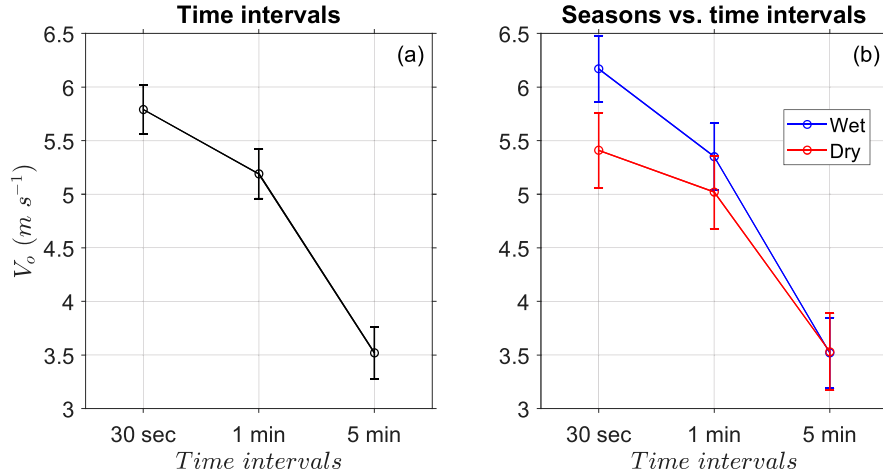


Figure 10: Observed wind speed (V_o) as a function of the (a) three time intervals and (b) seasons vs. time intervals at the EEST, Manaus, Central Amazon. Legend: circles and vertical bars indicate mean values and the 95% confidence intervals, respectively.

530 In fact, a higher destructive potential of diurnal winds may be expected,
 531 since in moist environments such as the Amazon forest, surface warming pro-
 532 motes upward movements that increase the low-level moisture convergence
 533 and intensify convection. Moreover, the results from the nighttime period
 534 provide evidence on the importance of downdrafts on the propagation of
 535 extreme winds downward below the canopy.

536 4. Discussion

537 Coupling between the canopy and the atmosphere occurs when turbu-
 538 lence provides continuous mixing. At nighttime, however, the mixing can
 539 be inhibited by the presence of a stable layer. Therefore, two contrasting
 540 regimes are observed. In the weakly stable regime, the wind speed provides
 541 heat fluxes that are large enough to continuously transfer the energy lost

542 by radiation back to the surface. In the very stable regime, heat fluxes are
543 not transferred continuously to the surface, leading to strong temperature
544 drops. This allows for the establishment of an enhanced thermal gradient,
545 which further inhibits mixing. Thus, the coupling between the forest and the
546 atmosphere is favored by the continuous turbulence observed in the weakly
547 stable regime.

548 We evaluated the degree of coupling in two ways. First, a comparison of
549 σ_w on above (48 m) and sub-canopy heights following [Thomas et al. \(2013\)](#).
550 **Figure 11 shows the comparison between such variables but it is not easy**
551 **to visualize the trends with only plotting the data points. Thus, we added**
552 **a Locally Weighted Regression (LOWESS) to the graph (solid line).** Here
553 we focus on 4 forest understory heights (1.5 m, 7.0 m, 18.4 m and 31.6
554 m) and on datasets with and without downdrafts. During weak winds (i.e.
555 without downdrafts), the turbulence strength at 1.5 m and 7.0 m was largely
556 independent of that observed above canopy. After 18 m height, the $\sigma_w sub$
557 was linearly correlated with $\sigma_w top$ (Fig. 11c) indicating the occurrence of a
558 coupled canopy condition. On the other hand, the extreme winds associated
559 with downdrafts were propagated into the canopy at all heights, and the
560 threshold of $\sigma_w top$ (i.e., when the correlation became linear) increased as
561 flow above the canopy reached the ground.

562 Second, in order to quantify the coupling between the canopy and the
563 atmosphere we calculated the temperature gradient (ΔT) between 51 m and
564 35 m height, in the dry and wet seasons. The dependence of ΔT on V
565 (Fig. 12) shows the differences of coupling and subsequent mixing for the
566 two regimes. A large thermal gradient occurs under the lowest wind speeds.

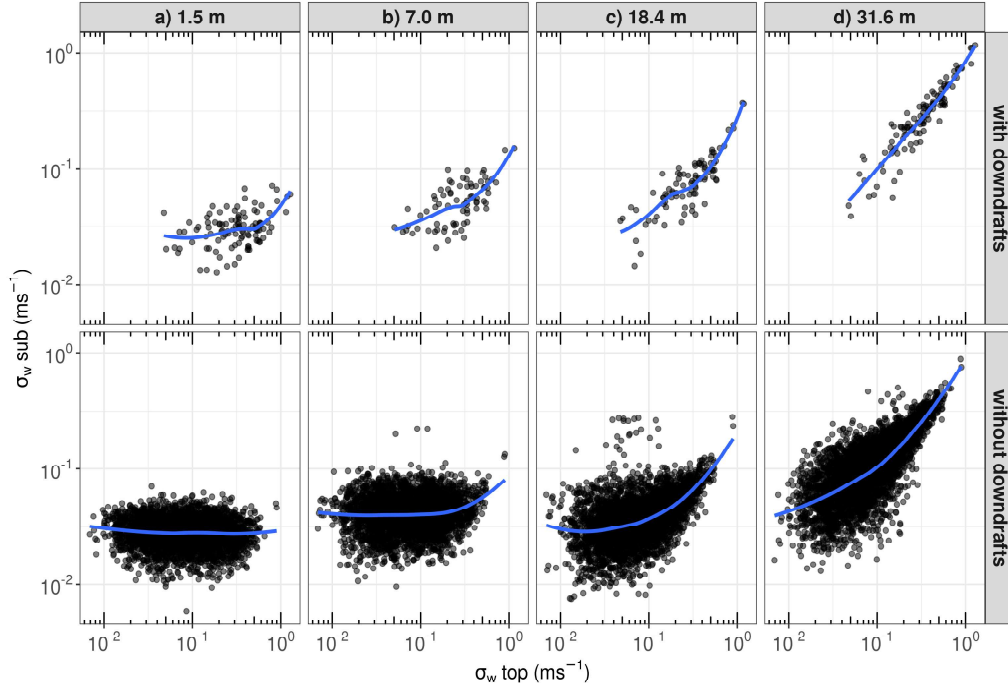


Figure 11: Standard deviation of wind vertical velocity (σ_w) between the forest understory (sub) and above-canopy (top at 48 m) heights. The dots correspond to periods of 5 min data. Dataset in which downdrafts occurred (Top panels). Dataset without the occurrence of downdrafts (Bottom panels). The columns a, b, c and d indicated the investigated sub-canopy heights.

567 This was observed when ΔT averaged $0.58\text{ }^\circ\text{C}$ and $0.25\text{ }^\circ\text{C}$ during the dry
 568 and wet seasons, respectively.

569 In the dry and wet seasons, ΔT peaked at V_L and reached $0.73\text{ }^\circ\text{C}$ and
 570 $0.25\text{ }^\circ\text{C}$, respectively. Similar ΔT maxima at the transition between regimes
 571 was observed by [Acevedo et al. \(2016\)](#) for the FLOSS II dataset. These
 572 authors argue that this pattern was associated with an enhanced heat-flux
 573 convergence at similar ranges of wind speed reported by [Acevedo et al. \(2021\)](#)

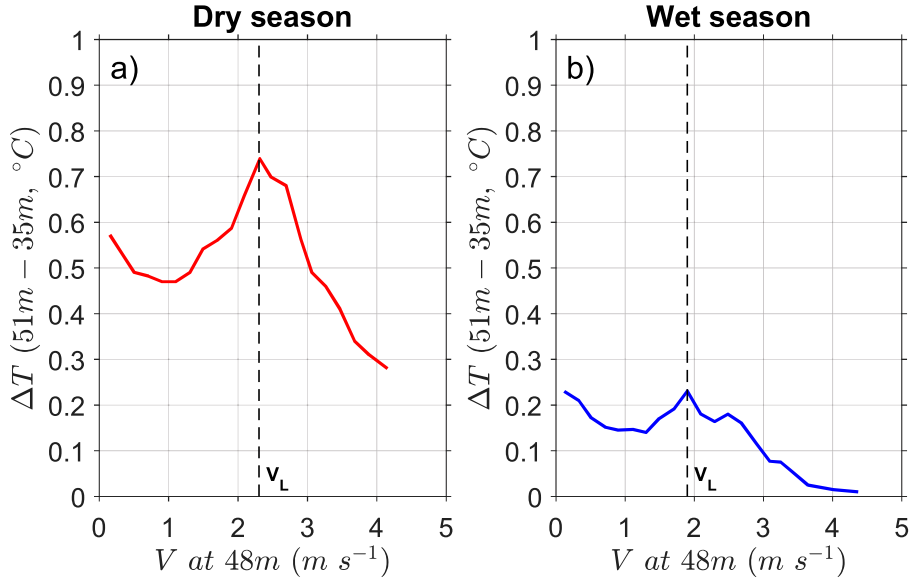


Figure 12: Differences of mean **virtual** temperature between 51 m and 35 m height as a function of the mean wind speed (V) at 48 m in the dry (a) and wet (b) season at the EEST, Manaus, Central Amazon. Dashed lines indicate the threshold wind speed (V_L) at which very stable changed to weakly stable regime.

574 for the CASES-99 dataset. Smaller gradients typical of mixed conditions
 575 occur when wind speeds are higher.

576 The relationship between turbulence and net radiation is a reliable cri-
 577 terium for distinguishing regimes. When the radiative loss is high, wind
 578 speeds tend to grow proportionally to allow compensative heat-fluxes (Acevedo
 579 et al., 2021). It is known that cloud cover plays an important role in R_N .
 580 Von Randow et al. (2004) showed that in the southern Amazon, reduced
 581 cloud cover in the dry season results in increased radiative loss. The oppo-
 582 site occurs in the wet season. In this context, we have assessed the frequency
 583 distribution of R_N (30-min averages) for our studied period (from 8pm to

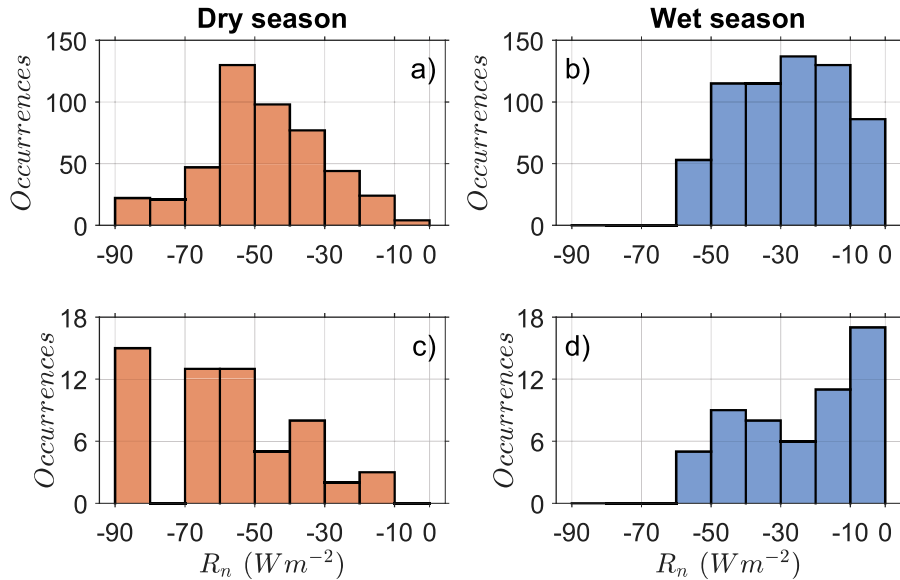


Figure 13: Distribution of the net radiation (R_n) for all studied days (top panels) and for those on which downdraft were identified (bottom panels) in the dry (red bars) and wet (blue bars) season during the nighttime.

584 5am) and only for the nights in which downdrafts occurred (2h before and
 585 after respective events). In the dry season, the two lowest values of R_N (high-
 586 est radiative loss) were observed between -40 and -60 $W m^{-2}$ (Fig. 13a). This
 587 variation indicates that there were relatively fewer clouds over the site. By
 588 contrast, R_N was more uniform during the wet season, with values ranging
 589 from -10 to -50 $W m^{-2}$ (Fig. 13b). Radiative loss was also higher in the
 590 2-hour interval before and after downdrafts observed in the dry season (Fig.
 591 13c,d).

592 This R_n pattern is related to the change in cloud cover and moisture
 593 loads at each season (Collow and Miller, 2016). Above the Amazon forest,
 594 single-cell clouds are frequent in the dry season. This contrasts mesoscale

595 convective-systems (multiple cell) that are more frequent during the wet sea-
596 son (Gerken et al., 2016). Multiple cells and water vapor can trap some of
597 the outgoing infrared radiation emitted by the Earth and radiate it back
598 downward, which can reduce the radiative loss at the surface. This explains
599 why the transition between regimes occurs at higher wind speed V_L in the
600 dry season. During this period, the shallower cloud cover and the lower wa-
601 ter vapor load of the atmospheric column allows for a larger loss of radiation
602 than that observed in the wet period.

603 Both single and multiple cells are known to produce downdrafts (Gerken
604 et al., 2016; Dias-Júnior et al., 2017b). Furthermore, we showed in this
605 study that downdrafts are one of the main causes of transition from turbu-
606 lence regimes above the Amazon forest (Fig. 9). We investigated the profile
607 of four turbulent parameters during a night-time downdraft (July 24, 2014).
608 H values, which were initially close to zero, turned strongly negative when
609 the downdraft reached the tower at around 11 pm local time (Fig. 14a).
610 Similarly, there was an increase in parameters associated with the intensity
611 of turbulence, such as σ_w , TKE and friction velocity (u_*) (Figures 14b, c and
612 d, respectively). Furthermore, this strong dissipation of air to strata/layers
613 below the forest canopy are rarely observed in the absence of downdrafts. ~~It~~
614 ~~is known that~~ The air layer from the soil surface to 0.5 h (h is the canopy
615 ~~top~~) is largely decoupled from layers above the canopy (Thomas et al., 2013;
616 Freundorfer et al., 2019; Cava et al., 2022). Santana et al. (2018) provided
617 evidence that atmospheric eddies generated above the canopy can hardly
618 penetrate the region below 0.5 h (h is the canopy top). This pattern was
619 reported for different sites in the Amazon. However, observations (Bezerra

620 et al., 2021) and numerical simulations (Serra-Neto et al., 2021) showed that
 621 under strong wind conditions, turbulence below the forest canopy was inten-
 622 sified and the scalar mixing more efficient.

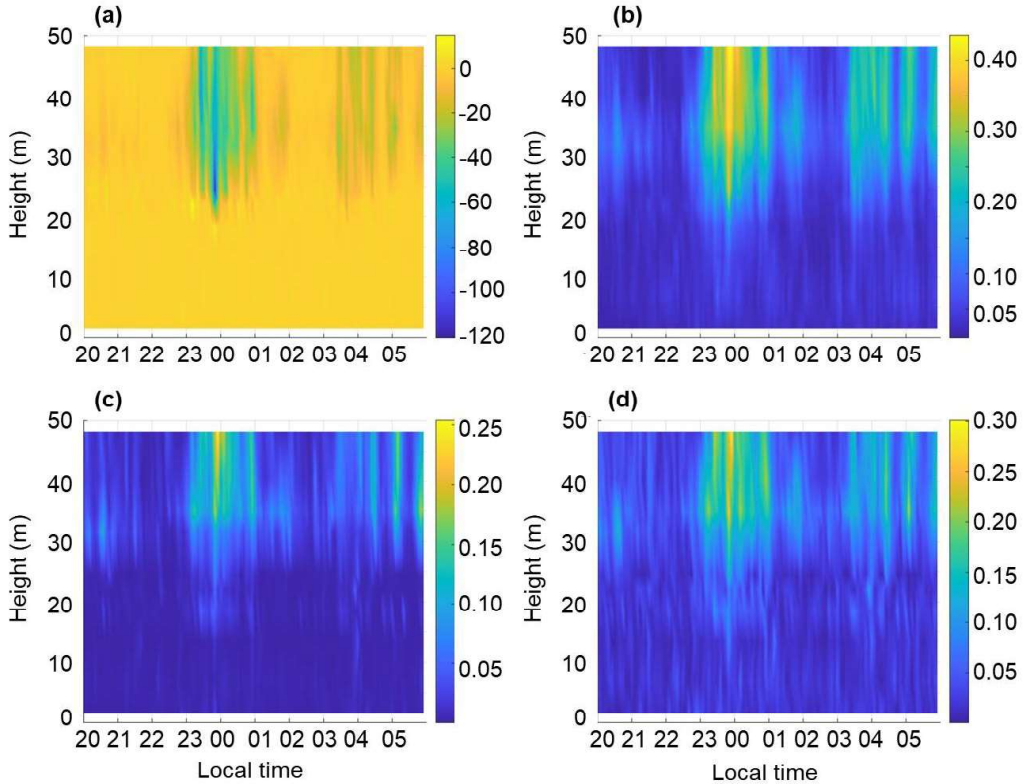


Figure 14: Vertical profile of: a) sensible heat flux (Wm^{-2}), b) standard deviation of vertical wind (ms^{-1}), c) Turbulent Kinetic Energy (m^2s^{-2}) and d) friction velocity (ms^{-1}) at the night of July 24, 2014.

623 The penetration of wind gusts inside the canopy increases the probability
 624 of tree damage and mortality. However, since the peak velocities may be
 625 underestimated when using single tower-measurements and we did not have
 626 data on risk of tree mortality, further studies are needed to describe the

627 return frequency of such gusts and the relationship between speed and the
628 disturbance severity.

629 Our study has limitations which shall be addressed in future research.
630 First, the patterns we described for central Amazon may not occur in other
631 regions with different vegetation structure. This highlights the need of stud-
632 ies based on extended datasets from other regions and for heights above 48 m.
633 Second, when analyzing fast-response data from a single tower, the down-
634 drafts may be not fully captured, and their magnitude and duration may
635 be underestimated. Last, the link between wind speed, canopy structure
636 and tree motion in these diverse forests is currently unknown. Nonetheless,
637 our study stress the importance of datasets including a range of heights and
638 seasons for detecting processes and mechanisms regulating turbulence and
639 wind-tree interactions in dense tropical forests. A better understanding of
640 these interactions is key for the parameterization of more robust and realis-
641 tic in numerical models. In addition, our findings provided insights into the
642 importance of wind gusts to the ecology and dynamics of Amazon forest.

643 **5. Conclusions**

644 This study provides three novel contributions. The first is the identifica-
645 tion of different turbulence regimes and their patterns in terms of seasonality
646 and proximity to the forest canopy in the ~~NBL~~ **nocturnal RSL**. The second
647 is the assessment of the effects of near surface wind gusts (propagated from
648 downdrafts) on the organization of turbulence regimes. Finally, it provides
649 evidences on the occurrance of extreme wind gusts associated with convec-
650 tive downdrafts, with potential do promote damage and mortality of canopy

651 trees. These aspects highlight the strong interactions between atmospheric
652 and biospheric processes and mechanisms regulating forest structure and dy-
653 namics.

654 Two turbulence regimes were identified: the very stable (weak turbulence)
655 and weakly stable regime (strong turbulence). The wind speed threshold
656 that mark the transition between the regimes increases nonlinearly with the
657 distance from the ground under non-vegetated surfaces (Sun et al., 2012;
658 Acevedo et al., 2021). Our study provides evidence that such pattern also
659 occurs in closed canopy forests of central Amazon . In addition, new knowl-
660 edge was obtained:

661 i) The average wind speed threshold for turbulence regime varies season-
662 ally, and was relatively larger in the dry season at all heights as a consequence
663 of a higher radiative loss from the surface during this period. Furthermore,
664 the change of turbulence regime was influenced by the structure and rough-
665 ness of the forest. This pattern was highlighted by relatively lower thresholds
666 of wind speed compared to previous studies at mid-latitudes, and can be ex-
667 plained by the greater turbulent mixing above rough surfaces for a given
668 mean wind speed.

669 ii) Near-surface wind gusts (convective downdrafts) occurred only during
670 the weakly stable regime and were one of the main **drivers** of the observed
671 turbulence regimes transition. Nevertheless, not all weakly stable regime
672 were associated to such events.

673 iii) Full coupling state of wind flow among layers above and within the
674 canopy occur during downdrafts. At nights without extreme winds, coupling
675 along the canopy profile occurred only above 18 m height.

676 iv) The destructive potential of winds propagated during downdrafts was
677 approximately four times higher than on nights without downdrafts in the
678 wet season. By contrast, the wind speeds during daytime downdrafts were
679 more intense in the dry season (not reported). These gusts would be suf-
680 ficient to topple 73% of the previously investigated trees at our study site,
681 which emphasize the importance of wind disturbances on controlling forest
682 structure and diversity in central Amazon.

683

684 **Acknowledgments**

685 ACSM thanks the Conselho Nacional de Desenvolvimento Científico e
686 Tecnológico (CNPq) for the Master grant awarded through the Programa de
687 Pós-graduação em Clima e Ambiente. This study is part of the Wind-Tree
688 Interaction Project (INVENTA) and the Amazon Tall Tower Observatory
689 (ATTO), funded by the German Federal Ministry of Education and Research
690 (BMBF, contracts 01LB1001A and 01LK1602A), the Brazilian Ministry of
691 Science, Technology and Innovation (MCTI/FINEP, contract 01.11.01248.00)
692 and the Max Planck Society (MPG). ATTO is also supported by the Fundação
693 de Amparo à Pesquisa do Estado do Amazonas (FAPEAM), Fundação de
694 Amparo à Pesquisa do Estado de São Paulo (FAPESP), Universidade do
695 Estado do Amazonas (UEA), Instituto Nacional de Pesquisas Amazônia
696 (INPA), Programa de Grande Escala da Biosfera-Atmosfera na Amazônia
697 (LBA) and the SDS/CEUC/RDS-Uatumã. We thank Marcelo Chameki and
698 his team for the efforts in obtaining and making available the GoAmazon
699 data.

700 **References**

- 701 Acevedo, O.C., Costa, F.D., Maroneze, R., Carvalho, Jr, A.D., Puhales,
702 F.S., Oliveira, P.E.S., 2021. External controls on the transition between
703 stable boundary-layer turbulence regimes. *Quarterly Journal of the Royal*
704 *Meteorological Society* 147, 2335–2351. doi:[10.1002/qj.4027](https://doi.org/10.1002/qj.4027).
- 705 Acevedo, O.C., Fitzjarrald, D.R., 2003. In the core of the night-effects of
706 intermittent mixing on a horizontally heterogeneous surface. *Boundary-*
707 *layer meteorology* 106, 1–33. doi:[10.1023/A:1020824109575](https://doi.org/10.1023/A:1020824109575).
- 708 Acevedo, O.C., Mahrt, L., Puhales, F.S., Costa, F.D., Medeiros, L.E., De-
709 grazia, G.A., 2016. Contrasting structures between the decoupled and cou-
710 pled states of the stable boundary layer. *Quarterly Journal of the Royal*
711 *Meteorological Society* 142, 693–702. doi:[10.1002/qj.2693](https://doi.org/10.1002/qj.2693).
- 712 Alves, E.G., Jardine, K., Tota, J., Jardine, A., Yáñez Serrano, A.M., Karl,
713 T., Tavares, J., Nelson, B., Gu, D., Stavrakou, T., Martin, S., Artaxo,
714 P., Manzi, A., Guenther, A., 2016. Seasonality of isoprenoid emissions
715 from a primary rainforest in central amazonia. *Atmospheric Chemistry*
716 *and Physics* 16, 3903–3925. doi:[10.5194/acp-16-3903-2016](https://doi.org/10.5194/acp-16-3903-2016).
- 717 Araujo, R.F., Chambers, J.Q., Celes, C.H.S., Muller-Landau, H.C., Santos,
718 A.P.F.d., Emmert, F., Ribeiro, G.H.P.M., Gimenez, B.O., Lima, A.J.N.,
719 Campos, M.A.A., Higuchi, N., 2020. Integrating high resolution drone
720 imagery and forest inventory to distinguish canopy and understory trees
721 and quantify their contributions to forest structure and dynamics. *PLOS*
722 *ONE* 15, 1–16. doi:[10.1371/journal.pone.0243079](https://doi.org/10.1371/journal.pone.0243079).

- 723 Araújo, A.C., Nobre, A.D., Kruijt, B., Elbers, J.A., Dallarosa, R., Stefani,
724 P., von Randow, C., Manzi, A.O., Culf, A.D., Gash, J.H.C., Valentini,
725 R., Kabat, P., 2002. Comparative measurements of carbon dioxide fluxes
726 from two nearby towers in a central amazonian rainforest: The manaus lba
727 site. *Journal of Geophysical Research: Atmospheres* 107, LBA 58–1–LBA
728 58–20. doi:[10.1029/2001JD000676](https://doi.org/10.1029/2001JD000676).
- 729 Betts, A.K., Gatti, L.V., Cordova, A.M., Silva Dias, M.A., Fuentes, J.D.,
730 2002. Transport of ozone to the surface by convective downdrafts at night.
731 *Journal of Geophysical Research: Atmospheres* 107, LBA–13. doi:[10.](https://doi.org/10.1029/2000JD000158)
732 [1029/2000JD000158](https://doi.org/10.1029/2000JD000158).
- 733 Betts, A.K., et al., 2003. The diurnal cycle over land. *Forests at the Land-*
734 *Atmosphere Interface* 79, 93.
- 735 Bezerra, V.L., Dias-Júnior, C.Q., Vale, R.S., Santana, R.A., Botía, S., Manzi,
736 A.O., Cohen, J.C.P., Martins, H.S., Chamecki, M., Fuentes, J.D., 2021.
737 Near-surface atmospheric turbulence in the presence of a squall line above
738 a forested and deforested region in the central amazon. *Atmosphere* 12.
739 doi:[10.3390/atmos12040461](https://doi.org/10.3390/atmos12040461).
- 740 Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the
741 climate benefits of forests. *science* 320, 1444–1449. doi:[10.1126/science.](https://doi.org/10.1126/science.1155121)
742 [1155121](https://doi.org/10.1126/science.1155121).
- 743 Braga, P.I.S., 1979. Subdivisão fitogeográfica, tipos de vegetação, con-
744 servação e inventário florístico da floresta amazônica. *Acta amazonica*
745 9, 53–80.

- 746 Brunet, Y., 2020. Turbulent flow in plant canopies: Historical perspective
747 and overview. *Boundary-Layer Meteorology* 177, 315–364.
- 748 Cava, D., Dias-Júnior, C.Q., Acevedo, O., Oliveira, P.E., Tsokankunku, A.,
749 Sörgel, M., Manzi, A.O., de Araújo, A.C., Brondani, D.V., Toro, I.M.C.,
750 et al., 2022. Vertical propagation of submeso and coherent structure in a
751 tall and dense amazon forest in different stability conditions part i: Flow
752 structure within and above the roughness sublayer. *Agricultural and Forest*
753 *Meteorology* 322, 108983. doi:[10.1016/j.agrformet.2022.108983](https://doi.org/10.1016/j.agrformet.2022.108983).
- 754 Chambers, J.Q., Negron-Juarez, R.I., Marra, D.M., Di Vittorio, A., Tews, J.,
755 Roberts, D., Ribeiro, G.H.P.M., Trumbore, S.E., Higuchi, N., 2013. The
756 steady-state mosaic of disturbance and succession across an old-growth
757 central amazon forest landscape. *Proceedings of the National Academy of*
758 *Sciences* 110, 3949–3954. doi:[10.1073/pnas.1202894110](https://doi.org/10.1073/pnas.1202894110).
- 759 Chambers, J.Q., Robertson, A.L., Carneiro, V.M., Lima, A.J., Smith, M.L.,
760 Plourde, L.C., Higuchi, N., 2009. Hyperspectral remote detection of
761 niche partitioning among canopy trees driven by blowdown gap distur-
762 bances in the central amazon. *Oecologia* 160, 107–117. doi:[10.1007/
763 s00442-008-1274-9](https://doi.org/10.1007/s00442-008-1274-9).
- 764 Chambers, J.Q., Tribuzy, E.S., Toledo, L.C., Crispim, B.F., Higuchi, N.,
765 Santos, J.d., Araújo, A.C., Kruijt, B., Nobre, A.D., Trumbore, S.E., 2004.
766 Respiration from a tropical forest ecosystem: Partitioning of sources and
767 low carbon use efficiency. *Ecological Applications* 14, 72–88. doi:[10.1890/
768 01-6012](https://doi.org/10.1890/01-6012).

- 769 Chor, T.L., Dias, N.L., Araújo, A., Wolff, S., Zahn, E., Manzi, A., Trebs, I.,
770 Sá, M.O., Teixeira, P.R., Sörgel, M., 2017. Flux-variance and flux-gradient
771 relationships in the roughness sublayer over the amazon forest. *Agricultural
772 and Forest Meteorology* 239, 213–222. doi:[10.1016/j.agrformet.2017.
773 03.009](https://doi.org/10.1016/j.agrformet.2017.03.009).
- 774 Collow, A.B.M., Miller, M.A., 2016. The seasonal cycle of the radiation bud-
775 get and cloud radiative effect in the amazon rain forest of brazil. *Journal
776 of Climate* 29, 7703–7722. doi:[10.1175/JCLI-D-16-0089.1](https://doi.org/10.1175/JCLI-D-16-0089.1).
- 777 Corrêa, P.B., Dias-Júnior, C.Q., Cava, D., Sörgel, M., Botía, S., Acevedo,
778 O., Oliveira, P.E., Ocimar Manzi, A., Toledo Machado, L.A., dos Santos
779 Martins, H., Tsokankunku, A., de Araújo, A.C., Lavric, J.V., Walter, D.,
780 Mortarini, L., 2021. A case study of a gravity wave induced by amazon
781 forest orography and low level jet generation. *Agricultural and Forest
782 Meteorology* 307, 108457. doi:[https://doi.org/10.1016/j.agrformet.
783 2021.108457](https://doi.org/10.1016/j.agrformet.2021.108457).
- 784 Costa, F.D., Acevedo, O.C., Medeiros, L.E., Maroneze, R., Puhales, F.S.,
785 Jr., A.D.C., Camponogara, L.F., dos Santos, D.M., Mortarini, L., 2020.
786 Stable boundary layer regimes in single-column models. *Journal of the
787 Atmospheric Sciences* 77, 2039 – 2054. doi:[10.1175/JAS-D-19-0218.1](https://doi.org/10.1175/JAS-D-19-0218.1).
- 788 Dias-Júnior, C.Q., Dias, N.L., Fuentes, J.D., Chamecki, M., 2017a. Convec-
789 tive storms and non-classical low-level jets during high ozone level episodes
790 in the amazon region: An arm/goamazon case study. *Atmospheric Envi-
791 ronment* 155, 199–209. doi:[10.1016/j.atmosenv.2017.02.006](https://doi.org/10.1016/j.atmosenv.2017.02.006).

- 792 Dias-Júnior, C.Q., Sá, L.D., Marques Filho, E.P., Santana, R.A., Mauder,
793 M., Manzi, A.O., 2017b. Turbulence regimes in the stable boundary layer
794 above and within the amazon forest. *Agricultural and Forest Meteorology*
795 233, 122–132. doi:[10.1016/j.agrformet.2016.11.001](https://doi.org/10.1016/j.agrformet.2016.11.001).
- 796 D’Oliveira, F.A., Cohen, J.C., Spracklen, D.V., Medeiros, A.S., Cirino, G.G.,
797 Artaxo, P., Dias-Júnior, C.Q., 2022. Simulation of the effects of biomass
798 burning in a mesoscale convective system in the central amazon. *Atmo-
799 spheric Research* 278, 106345.
- 800 Espírito-Santo, F.D., Gloor, M., Keller, M., Malhi, Y., Saatchi, S., Nelson,
801 B., Junior, R.C.O., Pereira, C., Lloyd, J., Frohking, S., et al., 2014. Size
802 and frequency of natural forest disturbances and the amazon forest carbon
803 balance. *Nature communications* 5, 1–6. doi:[10.1038/ncomms4434](https://doi.org/10.1038/ncomms4434).
- 804 Feng, Y., Negrón-Juárez, R.I., Romps, D.M., Chambers, J.Q., 2023. Ama-
805 zon windthrow disturbances are likely to increase with storm frequency
806 under global warming. *Nature Communications* 14, 101. doi:[10.1038/
807 s41467-022-35570-1](https://doi.org/10.1038/s41467-022-35570-1).
- 808 Finnigan, J., 2000. Turbulence in plant canopies. *Annual Review of Fluid
809 Mechanics* 32, 519–571. doi:[10.1146/annurev.fluid.32.1.519](https://doi.org/10.1146/annurev.fluid.32.1.519).
- 810 Freundorfer, A., Rehberg, I., Law, B.E., Thomas, C., 2019. Forest wind
811 regimes and their implications on cross-canopy coupling. *Agricultural
812 and Forest Meteorology* 279, 107696. doi:[https://doi.org/10.1016/j.
813 agrformet.2019.107696](https://doi.org/10.1016/j.agrformet.2019.107696).

- 814 Fuentes, J.D., Chamecki, M., dos Santos, R.M.N., Randow, C.V., Stoy, P.C.,
815 Katul, G., Fitzjarrald, D., Manzi, A., Gerken, T., Trowbridge, A., Freire,
816 L.S., Ruiz-Plancarte, J., Maia, J.M.F., Tóta, J., Dias, N., Fisch, G., Schu-
817 macher, C., Acevedo, O., Mercer, J.R., Yañez-Serrano, A.M., 2016. Link-
818 ing meteorology, turbulence, and air chemistry in the amazon rain for-
819 est. *Bulletin of the American Meteorological Society* 97, 2329 – 2342.
820 doi:[10.1175/BAMS-D-15-00152.1](https://doi.org/10.1175/BAMS-D-15-00152.1).
- 821 Fujita, T., 1985. The downburst: Microburst and macroburst. *Satellite*
822 *and Mesometeorology Research Project*, Department of the Geophysical
823 *Sciences*, University of Chicago 210, 122.
- 824 Garstang, M., Fitzjarrald, D.R., 1999. *Observations of surface to atmosphere*
825 *interactions in the tropics*. Oxford University Press, USA. doi:[10.1016/](https://doi.org/10.1016/S0168-1923(03)00003-0)
826 [S0168-1923\(03\)00003-0](https://doi.org/10.1016/S0168-1923(03)00003-0).
- 827 Garstang, M., White, S., Shugart, H., Halverson, J., 1998. Convective cloud
828 downdrafts as the cause of large blowdowns in the amazon rainforest. *Meteo-*
829 *rology and Atmospheric Physics* 67, 199–212. doi:[10.1007/BF01277510](https://doi.org/10.1007/BF01277510).
- 830 Gerken, T., Wei, D., Chase, R.J., Fuentes, J.D., Schumacher, C., Machado,
831 L.A., Andreoli, R.V., Chamecki, M., Ferreira de Souza, R.A., Freire, L.S.,
832 Jardine, A.B., Manzi, A.O., Nascimento dos Santos, R.M., von Randow,
833 C., dos Santos Costa, P., Stoy, P.C., Tóta, J., Trowbridge, A.M., 2016.
834 Downward transport of ozone rich air and implications for atmospheric
835 chemistry in the amazon rainforest. *Atmospheric Environment* 124, 64–
836 76. doi:[10.1016/j.atmosenv.2015.11.014](https://doi.org/10.1016/j.atmosenv.2015.11.014).

- 837 Greco, S., Ulanski, S., Garstang, M., Houston, S., 1992. Low-level nocturnal
838 wind maximum over the central amazon basin. *Boundary-layer meteorol-*
839 *ogy* 58, 91–115. doi:[10.1007/BF00120753](https://doi.org/10.1007/BF00120753).
- 840 Guerra, V.S., Acevedo, O.C., Medeiros, L.E., Oliveira, P.E., Santos, D.M.,
841 2018. Small-scale horizontal variability of mean and turbulent quantities in
842 the nocturnal boundary layer. *Boundary-Layer Meteorology* 169, 395–411.
843 doi:[10.1007/s10546-018-0381-3](https://doi.org/10.1007/s10546-018-0381-3).
- 844 Knohl, A., Baldocchi, D.D., 2008. Effects of diffuse radiation on canopy gas
845 exchange processes in a forest ecosystem. *Journal of Geophysical Research:*
846 *Biogeosciences* 113. doi:[10.1029/2007JG000663](https://doi.org/10.1029/2007JG000663).
- 847 Machado, L., Laurent, H., Dessay, N., Miranda, I., 2004. Seasonal and diur-
848 nal variability of convection over the amazonia: A comparison of different
849 vegetation types and large scale forcing. *Theoretical and Applied Clima-*
850 *tology* 78, 61–77. doi:[10.1007/s00704-004-0044-9](https://doi.org/10.1007/s00704-004-0044-9).
- 851 Machado, L.A.T., Laurent, H., Lima, A.A., 2002. Diurnal march of the
852 convection observed during trmm-wetamc/lba. *Journal of Geophys-*
853 *ical Research: Atmospheres* 107, LBA 31–1–LBA 31–15. doi:[10.1029/
854 2001JD000338](https://doi.org/10.1029/2001JD000338).
- 855 Mahrt, L., 1998. Nocturnal boundary-layer regimes. *Boundary-layer meteo-*
856 *rology* 88, 255–278.
- 857 Mahrt, L., 2014. Stably stratified atmospheric boundary layers.
858 *Annual Review of Fluid Mechanics* 46, 23–45. doi:[10.1146/
859 annurev-fluid-010313-141354](https://doi.org/10.1146/annurev-fluid-010313-141354).

- 860 Mahrt, L., Thomas, C., Richardson, S., Seaman, N., Stauffer, D., Zeeman,
861 M., 2013. Non-stationary generation of weak turbulence for very stable and
862 weak-wind conditions. *Boundary-layer meteorology* 147, 179–199. doi:[10.
863 1007/s10546-012-9782-x](https://doi.org/10.1007/s10546-012-9782-x).
- 864 Malhi, Y., Meir, P., Brown, S., 2002. Forests, carbon and global cli-
865 mate. *Philosophical Transactions of the Royal Society of London. Se-
866 ries A: Mathematical, Physical and Engineering Sciences* 360, 1567–1591.
867 doi:[10.1098/rsta.2002.1020](https://doi.org/10.1098/rsta.2002.1020).
- 868 Marques Filho, A.d.O., Dallarosa, R.G., Pachêco, V.B., 2005. Radiação
869 solar e distribuição vertical de área foliar em floresta-reserva biológica
870 do cuieiras zf2, manaus. *Acta Amazonica* 35, 427–436. doi:[10.1590/
871 S0044-59672005000400007](https://doi.org/10.1590/S0044-59672005000400007).
- 872 Marra, D.M., Chambers, J.Q., Higuchi, N., Trumbore, S.E., Ribeiro,
873 G.H.P.M., dos Santos, J., Negrón-Juárez, R.I., Reu, B., Wirth, C., 2014.
874 Large-scale wind disturbances promote tree diversity in a central amazon
875 forest. *PLOS ONE* 9, 1–16. doi:[10.1371/journal.pone.0103711](https://doi.org/10.1371/journal.pone.0103711).
- 876 Marra, D.M., Trumbore, S.E., Higuchi, N., Ribeiro, G.H.P.M., Negrón-
877 Juárez, R.I., Holzwarth, F., Rifai, S.W., dos Santos, J., Lima, A.J.N.,
878 Kinupp, V.F., Chambers, J.Q., Wirth, C., 2018. Windthrows control
879 biomass patterns and functional composition of amazon forests. *Global
880 Change Biology* 24, 5867–5881. doi:[10.1111/gcb.14457](https://doi.org/10.1111/gcb.14457).
- 881 Melo, A.M., Dias-Junior, C.Q., Cohen, J.C., Sá, L.D., Cattanio, J.H., Kuhn,
882 P.A., 2019. Ozone transport and thermodynamics during the passage of

883 squall line in central amazon. *Atmospheric Environment* 206, 132–143.
884 doi:<https://doi.org/10.1016/j.atmosenv.2019.02.018>.

885 Miranda, F.O., Ramos, F.M., von Randow, C., Dias-Júnior, C.Q., Chamecki,
886 M., Fuentes, J.D., Manzi, A.O., de Oliveira, M.E., de Souza, C.M., 2020.
887 Detection of extreme phenomena in the stable boundary layer over the
888 amazonian forest. *Atmosphere* 11. doi:[10.3390/atmos11090952](https://doi.org/10.3390/atmos11090952).

889 Negrón-Juárez, R.I., Chambers, J.Q., Guimaraes, G., Zeng, H., Raupp,
890 C.F.M., Marra, D.M., Ribeiro, G.H.P.M., Saatchi, S.S., Nelson, B.W.,
891 Higuchi, N., 2010. Widespread amazon forest tree mortality from a
892 single cross-basin squall line event. *Geophysical Research Letters* 37.
893 doi:[10.1029/2010GL043733](https://doi.org/10.1029/2010GL043733).

894 Negrón-Juárez, R.I., Holm, J.A., Marra, D.M., Rifai, S.W., Riley, W.J.,
895 Chambers, J.Q., Koven, C.D., Knox, R.G., McGroddy, M.E., Vittorio,
896 A.V.D., Urquiza-Muñoz, J., Tello-Espinoza, R., Muñoz, W.A., Ribeiro,
897 G.H.P.M., Higuchi, N., 2018. Vulnerability of amazon forests to storm-
898 driven tree mortality 13, 054021. doi:[10.1088/1748-9326/aabe9f](https://doi.org/10.1088/1748-9326/aabe9f).

899 Negrón-Juárez, R.I., Jenkins, H.S., Raupp, C.F.M., Riley, W.J., Kueppers,
900 L.M., Magnabosco Marra, D., Ribeiro, G.H.P.M., Monteiro, M.T.F., Can-
901 dido, L.A., Chambers, J.Q., Higuchi, N., 2017. Windthrow variability in
902 central amazonia. *Atmosphere* 8. doi:[10.3390/atmos8020028](https://doi.org/10.3390/atmos8020028).

903 Nelson, B.W., 1994. Natural forest disturbance and change in the brazil-
904 ian amazon. *Remote Sensing Reviews* 10, 105–125. doi:[10.1080/
905 02757259409532239](https://doi.org/10.1080/02757259409532239).

- 906 Oliveira, A.N.d., Amaral, I.L.d., Ramos, M.B.P., Nobre, A.D., Couto,
907 L.B., Sahdo, R.M., 2008. Composição e diversidade florístico-estrutural
908 de um hectare de floresta densa de terra firme na amazônia cen-
909 tral, amazonas, brasil. *Acta amazônica* 38, 627–641. doi:[10.1590/
910 S0044-59672008000400005](https://doi.org/10.1590/S0044-59672008000400005).
- 911 Peterson, C.J., Ribeiro, G.H.P.d.M., Negrón-Juárez, R., Marra, D.M., Cham-
912 bers, J.Q., Higuchi, N., Lima, A., Cannon, J.B., 2019. Critical wind
913 speeds suggest wind could be an important disturbance agent in Ama-
914 zonian forests. *Forestry: An International Journal of Forest Research* 92,
915 444–459. doi:[10.1093/forestry/cpz025](https://doi.org/10.1093/forestry/cpz025).
- 916 Raupach, M., Finningan, J., Brunet, Y., 1996. Coherent eddies and turbu-
917 lence in vegetation canopies; the mixing. layer analogy. *Boundary-Layer*
918 *Meteorology* 78, 351–382.
- 919 Ribeiro, G., Chambers, J., Peterson, C., Trumbore, S., Magnabosco Marra,
920 D., Wirth, C., Cannon, J., Négron-Juárez, R., Lima, A., de Paula, E.,
921 Santos, J., Higuchi, N., 2016. Mechanical vulnerability and resistance to
922 snapping and uprooting for central amazon tree species. *Forest Ecology*
923 *and Management* 380, 1–10. doi:[10.1016/j.foreco.2016.08.039](https://doi.org/10.1016/j.foreco.2016.08.039).
- 924 Santana, R.A., Dias-Júnior, C.Q., da Silva, J.T., Fuentes, J.D., do Vale,
925 R.S., Alves, E.G., dos Santos, R.M.N., Manzi, A.O., 2018. Air turbu-
926 lence characteristics at multiple sites in and above the amazon rainforest
927 canopy. *Agricultural and Forest Meteorology* 260, 41–54. doi:[10.1016/j.
928 agrformet.2018.05.027](https://doi.org/10.1016/j.agrformet.2018.05.027).

- 929 Santos, D.M., Acevedo, O.C., Chamecki, M., Fuentes, J.D., Gerken, T.,
930 Stoy, P.C., 2016. Temporal scales of the nocturnal flow within and above
931 a forest canopy in amazonia. *Boundary-Layer Meteorology* 161, 73–98.
932 doi:[10.1007/s10546-016-0158-5](https://doi.org/10.1007/s10546-016-0158-5).
- 933 dos Santos, L.T., Magnabosco Marra, D., Trumbore, S., de Camargo, P.B.,
934 Negrón-Juárez, R.I., Lima, A.J.N., Ribeiro, G.H.P.M., dos Santos, J.,
935 Higuchi, N., 2016. Windthrows increase soil carbon stocks in a central ama-
936 zon forest. *Biogeosciences* 13, 1299–1308. doi:[10.5194/bg-13-1299-2016](https://doi.org/10.5194/bg-13-1299-2016).
- 937 Schwartz, N.B., Uriarte, M., DeFries, R., Bedka, K.M., Fernandes, K.,
938 Gutiérrez-Vélez, V., Pinedo-Vasquez, M.A., 2017. Fragmentation in-
939 creases wind disturbance impacts on forest structure and carbon stocks
940 in a western amazonian landscape. *Ecological Applications* 27, 1901–1915.
941 doi:[10.1002/eap.1576](https://doi.org/10.1002/eap.1576).
- 942 Serra-Neto, E.M., Martins, H.S., Dias-Júnior, C.Q., Santana, R.A., Bron-
943 dani, D.V., Manzi, A.O., de Araújo, A.C., Teixeira, P.R., Sörgel, M., Mor-
944 tarini, L., 2021. Simulation of the scalar transport above and within the
945 amazon forest canopy. *Atmosphere* 12, 1631. doi:[10.3390/atmos12121631](https://doi.org/10.3390/atmos12121631).
- 946 Silvério, D.V., Brando, P.M., Bustamante, M.M.C., Putz, F.E., Marra, D.M.,
947 Levick, S.R., Trumbore, S.E., 2019. Fire, fragmentation, and windstorms:
948 A recipe for tropical forest degradation. *Journal of Ecology* 107, 656–667.
949 doi:[10.1111/1365-2745.13076](https://doi.org/10.1111/1365-2745.13076).
- 950 Sun, J., Burns, S.P., Lenschow, D.H., Banta, R., Newsom, R., Coulter, R.,
951 Frasier, S., Ince, T., Nappo, C., Cuxart, J., et al., 2002. Intermittent

- 952 turbulence associated with a density current passage in the stable bound-
953 ary layer. *Boundary-Layer Meteorology* 105, 199–219. doi:[10.1023/A:](https://doi.org/10.1023/A:1019969131774)
954 [1019969131774](https://doi.org/10.1023/A:1019969131774).
- 955 Sun, J., Lenschow, D.H., LeMone, M.A., Mahrt, L., 2016. The role of large-
956 coherent-eddy transport in the atmospheric surface layer based on cases-
957 99 observations. *Boundary-layer meteorology* 160, 83–111. doi:[10.1007/](https://doi.org/10.1007/s10546-016-0134-0)
958 [s10546-016-0134-0](https://doi.org/10.1007/s10546-016-0134-0).
- 959 Sun, J., Mahrt, L., Banta, R.M., Pichugina, Y.L., 2012. Turbulence
960 regimes and turbulence intermittency in the stable boundary layer dur-
961 ing cases-99. *Journal of Atmospheric Sciences* 69, 338–351. doi:[10.1175/](https://doi.org/10.1175/JAS-D-11-082.1)
962 [JAS-D-11-082.1](https://doi.org/10.1175/JAS-D-11-082.1).
- 963 Sun, J., Takle, E.S., Acevedo, O.C., 2020. Understanding physical pro-
964 cesses represented by the monin–obukhov bulk formula for momen-
965 tum transfer. *Boundary-Layer Meteorology* 177, 69–95. doi:[10.1007/](https://doi.org/10.1007/s10546-020-00546-5)
966 [s10546-020-00546-5](https://doi.org/10.1007/s10546-020-00546-5).
- 967 Telles, E.d.C.C., de Camargo, P.B., Martinelli, L.A., Trumbore, S.E.,
968 da Costa, E.S., Santos, J., Higuchi, N., Oliveira Jr., R.C., 2003. Influe-
969 nce of soil texture on carbon dynamics and storage potential in tropical
970 forest soils of amazonia. *Global Biogeochemical Cycles* 17. doi:[10.1029/](https://doi.org/10.1029/2002GB001953)
971 [2002GB001953](https://doi.org/10.1029/2002GB001953).
- 972 Thomas, C., Foken, T., 2007. Flux contribution of coherent structures
973 and its implications for the exchange of energy and matter in a tall

- 974 spruce canopy. *Boundary-Layer Meteorology* 123, 317–337. doi:[10.1007/
975 s10546-006-9144-7](https://doi.org/10.1007/s10546-006-9144-7).
- 976 Thomas, C.K., Martin, J.G., Law, B.E., Davis, K., 2013. Toward biologically
977 meaningful net carbon exchange estimates for tall, dense canopies: Multi-
978 level eddy covariance observations and canopy coupling regimes in a mature
979 douglas-fir forest in oregon. *Agricultural and forest meteorology* 173, 14–
980 27. doi:[10.1016/j.agrformet.2013.01.001](https://doi.org/10.1016/j.agrformet.2013.01.001).
- 981 Tóta, J., Fitzjarrald, D.R., da Silva Dias, M.A., 2012. Exchange of carbon be-
982 tween the atmosphere and the tropical amazon rainforest, in: Sudarshana,
983 P., Nageswara-Rao, M., Soneji, J.R. (Eds.), *Tropical Forests*. IntechOpen,
984 Rijeka. chapter 16. doi:[10.5772/29716](https://doi.org/10.5772/29716).
- 985 Urquiza Muñoz, J.D., Magnabosco Marra, D., Negrón-Juarez, R.I., Tello-
986 Espinoza, R., Alegría-Muñoz, W., Pacheco-Gómez, T., Rifai, S.W., Cham-
987 bers, J.Q., Jenkins, H.S., Brenning, A., Trumbore, S.E., 2021. Recovery
988 of forest structure following large-scale windthrows in the northwestern
989 amazon. *Forests* 12. doi:[10.3390/f12060667](https://doi.org/10.3390/f12060667).
- 990 Vickers, D., Göckede, M., Law, B., 2010. Uncertainty estimates for 1-h
991 averaged turbulence fluxes of carbon dioxide, latent heat and sensible heat.
992 *Tellus B: Chemical and Physical Meteorology* 62, 87–99. doi:[10.1111/j.
993 1600-0889.2009.00449.x](https://doi.org/10.1111/j.1600-0889.2009.00449.x).
- 994 Vickers, D., Mahrt, L., 1997. Quality control and flux sampling problems for
995 tower and aircraft data. *Journal of Atmospheric and Oceanic Technology*

996 14, 512 – 526. doi:[10.1175/1520-0426\(1997\)014<0512:QCAFSP>2.0.CO;](https://doi.org/10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2)
997 [2](https://doi.org/10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2).

998 Vignon, E., van de Wiel, B.J.H., van Hooijdonk, I.G.S., Genthon, C., van der
999 Linden, S.J.A., van Hooft, J.A., Baas, P., Maurel, W., Traullé, O., Casas-
1000 anta, G., 2017. Stable boundary-layer regimes at dome c, antarctica: obser-
1001 vation and analysis. Quarterly Journal of the Royal Meteorological Society
1002 143, 1241–1253. doi:[10.1002/qj.2998](https://doi.org/10.1002/qj.2998).

1003 Viswanadham, Y., Molion, L., Manzi, A., Sá, L., Filho, V.S., André, R.,
1004 Nogueira, J., Santos, R.d., 1990. Micrometeorological measurements in
1005 amazon forest during gte/able 2a mission. Journal of Geophysical Re-
1006 search: Atmospheres 95, 13669–13682. doi:[10.1029/JD095iD09p13669](https://doi.org/10.1029/JD095iD09p13669).

1007 Von Randow, C., Manzi, A.O., Kruijt, B., De Oliveira, P., Zanchi, F.B., Silva,
1008 R.d., Hodnett, M.G., Gash, J.H., Elbers, J.A., Cardoso, F.L., et al., 2004.
1009 Comparative measurements and seasonal variations in energy and carbon
1010 exchange over forest and pasture in south west amazonia. Theoretical and
1011 Applied Climatology 78, 5–26. doi:[10.1007/s00704-004-0041-z](https://doi.org/10.1007/s00704-004-0041-z).

1012 Wakimoto, R., 2015. Mesoscale meteorology— microbursts .

1013 Zahn, E., Chor, T., Dias, N., 2016. A simple methodology for quality control
1014 of micrometeorological datasets. Am J Environ Eng 6, 135–142. doi:[10.](https://doi.org/10.5923/s.ajee.201601.20)
1015 [5923/s.ajee.201601.20](https://doi.org/10.5923/s.ajee.201601.20).