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Air turbulence characteristics at multiple sites in and above the Amazon rainforest canopy

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ABSTRACT

Atmospheric turbulence characteristics within and above rain forest canopies are investigated at several sites located in the Amazon region of Brazil. Turbulence data provided by bi- and three-dimensional sonic anemometers, which were deployed at heights ranging from near the forest floor to about 80 m, are analyzed to describe the principal features of atmospheric turbulence, sensible heat flux (H), and components of the turbulent kinetic energy (TKE) budget equation. The analyses focused on weak (WW) and strong (SW) wind conditions to achieve the research objectives of evaluating the turbulence structure above and below the rain forest canopy and estimating the degree of coupling between air layers above the forest and deep in the canopy. Turbulence statistical moments show that atmospheric eddies, generated above the canopy, hardly penetrate the region below 0.5h (h is the canopy height). Forest-atmosphere exchanges of heat differ depending on the observed wind regimes. Sensible heat fluxes decrease with canopy depth for SW conditions and are approximately constant with the height for WW above the canopy. Sensible heat flux profiles reveal a transition layer (around 0.6h) which sometimes exchanges heat with the upper and sometimes with the lower forest canopy, depending on time of day and weather conditions. TKE balance results show that during the daytime period in SW conditions the shear production is at least an order of magnitude greater than the buoyancy above the forest canopy. This turbulence, however, is practically all dissipated in the region above 0.5h. Thus, the air layer from the soil surface to 0.5h is largely decoupled from the upper part of the forest canopy. This feature of having the bottom of the canopy mostly decoupled from the air aloft in the dense and tall rain forest can exert control on the residence times and turbulent transport of plant-emitted gases out of the forest canopy.

1. Introduction

The study of the energy, mass and momentum exchanges between vegetated landscapes and the atmosphere is an essential part of the understanding of the processes associated with biosphere–atmosphere interactions (Raupach and Thom, 1981; Finnigan, 2000). In particular, tropical forests such as the Amazon play a key role not only in these exchanges (Fitzjarrald et al., 1988; Kruijt et al., 2000; Fuentes et al., 2016), but also in the carbon cycling related to biomass accumulation contributing to carbon stocks (Gloor et al., 2012). For instance, due to the forest physiology and evapotranspiration processes, the Amazon forest can recycle about 20–35% of the moisture available for precipitation (Rocha et al., 2015). This moisture source is important to the occurrence of precipitation in the southern regions of South America (Rocha et al., 2015). The forest is also known to play a role in the carbon cycling related to biomass – an important carbon stock (Gloor et al., 2012), and the emissions of volatile organic compounds (VOCs) such as isoprene and monoterpenes (Jardine et al., 2011, 2015), which can react with other gases to form secondary organic aerosols that are important for the formation of cloud condensation nuclei (Andreae, 2009; Pöschl et al., 2010).

Turbulent vertical motions govern the transport of scalars (e.g., CO_2, H_2O, among others) from the forest to the free atmosphere. Thermal and mechanical effects generate turbulence. In the Amazon

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Table 1
Measurement levels, variables, sampling rates and instrument models used in the K34 and ATTO experimental sites.

Levels (m)	Variables	Sampling rate (Hz)	Instruments
K34			
1.5, 7.0, 13.5, 18.4, 22.1, 24.5, 31.6, 34.9, 40.4 and 48.2	Virtual temperature and wind speed components	20	Three-dimensional sonic anemometer (CSAT)
ATTO Triangular Tower			
78, 41 and 30	Virtual temperature and wind speed components	10	Three-dimensional sonic anemometer (Gill)
57, 60 and 72	Air temperature, humidity, pressure and wind speed and direction	1	Metpak-automatic weather station coupled to a two dimensional sonic anemometer (Gill)
23, 36, 45 and 50	Wind, speed and direction	4	Two-dimensional sonic anemometer (Gill)

rain forest little incident solar radiation can reach the forest floor (about 1–3%, according to Shuttleworth et al. (1984)). As a consequence, statically stable layers form within the forest canopy that persist for almost the entire diurnal cycle (Fitzjarrald and Moore, 1990; Santos et al., 2016; Dias-Júnior et al., 2017a). This thermodynamic condition promotes a limited or a non-existing coupling (i.e., a time period in which turbulent mixing occurs between different levels of the atmosphere (Acevedo and Fitzjarrald, 2003; Freire et al., 2017) between the top and bottom of the forest canopy. The mechanical turbulence generated above the forest, or even the one that comes from high levels in the atmosphere, reaches the surface by downward vertical movements (Santana et al., 2015; Gerken et al., 2016; Dias-Júnior et al., 2017b), and becomes the important mechanism driving energy and mass exchanges between the dense forest and the atmosphere. During the daytime, coherent eddies (or coherent structures) have the ability to penetrate the interior of the forest canopy (Lu and Fitzjarrald, 1994). Such eddies may be directly related to the aerodynamic instability caused by the inflection point in the vertical wind speed profile (Raupach et al., 1996). Dias-Júnior et al. (2013) showed that there is a direct relationship between the temporal scales of occurrences of those structures and the inflection point height in the wind speed profile in the Amazonia forests.

Although previous studies (Fitzjarrald et al., 1988, 1990; Fitzjarrald and Moore, 1990; Kruijt et al., 2000; Santos et al., 2016; Dias-Júnior et al., 2017a) provided a critical understanding of atmospheric turbulence in and above the Amazon forest canopy, further analysis is needed to answer questions related to the characteristic size and frequency of the eddies reaching different levels of the forest canopy. Some analyses are still needed to determine the extent of air turbulence transfer in the lower depths of the forest canopy. Equally important is the identification of the processes responsible for the coupling between the upper and bottom of the Amazon rain forest canopy. Therefore, the objectives of this study are to evaluate the turbulence structure above and below the rain forest canopy and to estimate the degree of coupling between air layers above the forest and deep in the canopy. To address the objectives, air turbulence data sets obtained at two experimental sites in the Amazon are analyzed and interpreted. At each site, air turbulence measurements made at ten different levels were carried out over long-term periods. The vertical variability of turbulence statistics was calculated and compared with results obtain by Kruijt et al. (2000) (hereafter, KJ2000) for moderately unstable atmospheric conditions. These profiles were also analyzed under weak and strong wind conditions over the forest. Other analyses were also conducted based on weak and strong wind classes to evaluate the diurnal cycle of turbulence statistics, sensible heat flux, and terms of the turbulent kinetic energy budget equation for different levels within and above the rain forest.

2. Material and methods

2.1. Experimental sites and data

The data used in this research were collected at two experimental sites, both located in the state of Amazonas, Brazil. These sites are areas of dense forest with trees ranging from 30 to 40 m in height. The first, called K34, is located in the Biological Reserve of Cuieiras (2°51′ S, 54°58′ W) which is about 60 km northwest of Manaus city (Araújo et al., 2002). The forest had a leaf area index of 6.1 (Marques Filho et al., 2005) and 7.3 $m^2\,m^{-2}$ (Tóta et al., 2012). The second site is known as ATTO (Amazon Tall Tower Observatory) and is located in the city of São Sebastião do Uatumã, within the Sustainable Development Reserve of Uatumã (2°8′32.42″ S, 59°0′3.50″ W) (Andreae et al., 2015). The leaf area index estimated for this site in September 2013 was 5.7 ± 0.37 $m^2\,m^{-2}$ (Santana et al., 2017).

At the K34 site, 10 three-dimensional sonic anemometers (model CSAT3, Campbell 128 Scientific Inc., Logan, UT) were installed from 1.5 to 48.2 m above ground during the period from April 2014 to January 2015 as part of the GoAmazon project (Fuentes et al., 2016), see Table 1 and Fig. 1 for detailed information. The data were collected at the sampling frequency of 20 Hz, included the three wind components (u, v, and w) and the virtual sonic temperature (T_V).

ATTO data were collected from February to April 2012, on a triangular tower of 84 m height, as part of the ATTO-CLAIRE (Cooperative LBA Airborne Regional Experiment)/IOP-1-2012 experiment Santana et al. (2017). In this experiment, three-dimensional and two-dimensional sonic anemometers were deployed over 10 different heights on the tower. At some heights two-dimensional sonic anemometers were coupled to temperature and humidity sensors, and this set is referred to as “metpak”. These metpaks (MetPak, Gill Instruments Ltd, UK) were installed above the forest canopy at 57, 62 and 70 m height, with 1 Hz sampling rate. Three-dimensional sonic anemometers (WindMaster, Gill Instruments Ltd., Lymington, Hampshire, UK) were installed at 30, 41 and 78 m height and collected data at a 10 Hz sampling rate. In turn, the two-dimensional sonic anemometers were installed at 23, 36, 45 and 50 m in height, at a sampling rate of 4 Hz (Table 1).

ATTO data have advantages and disadvantages compared to K34 data. At the ATTO site, not all instruments were three-dimensional as in K34, which means that vertical velocity data are not available at all heights. In addition, the low sampling rate of two-dimensional sonics may not capture all eddies, especially those of smaller length scales. However, ATTO data are relevant as they provide information on heights above the canopy that were not considered at the K34 site due to the limitation of the measurement tower, which is only 50 m high.

2.2. Methodology

To compare the results with those found by KJ2000, we calculated the variables of the so-called ‘family portraits’ of turbulence (Raupach et al., 1996), for each measurement height. The time interval used to calculate these quantities was 5 min for the nighttime period, in order to minimize the effects of non-turbulent scales, and 30 min for the daytime period (Vickers and Mahrt, 1997). The overall horizontal wind speed was obtained by the equation $\overline{U} = \sqrt{u^2 + v^2}$, where u and v are zonal and meridional wind components. The u standard deviation was calculated as $\sigma_u = (\overline{u'^2})^{1/2}$, with u oriented along with the mean wind direction. Similarly, the standard deviation of the wind vertical component, w, was defined as $\sigma_w = (\overline{w'^2})^{1/2}$. We also calculated the