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A large eddy simulation model applied to analyze the turbulent flow above Amazon forest

Cleo Q. Dias-Junior [a,b,*], Edson P. Marques Filho [c], Leonardo D.A. Sá [d]

[a] Federal Institute of Education Science and Technology of Pará/Bragança, Brazil
[b] National Institute of Amazonian Research / CLIAMB, Manaus, Brazil
[c] Federal University of Bahia, Salvador, Brazil
[d] National Institute for Space Research/CRA, Belém, Brazil

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ABSTRACT

The occurrence of coherent structures (CS) above the Amazon forest is analyzed. To perform this study, a large eddy simulation (LES) model is used, which has been improved by the introduction of a drag force which is representative of a typical Amazon forest canopy. The results show that the flow is sensitive to the presence of canopy and an inflexion point is simulated in wind profiles. On the region between $1h$ and $4h$ several CS features associated with turbulent flow regarding pressure, momentum fluxes, skewness and vorticity fields are detected suggesting that “roll” structures arranged perpendicularly to the mean wind direction populate this region. Other interesting LES results were: (i) the skewness of the wind velocity has also a maximum value on the region, what indicates an asymmetric distribution of the wind velocity relatively to its mean value, a fact that might be associated with the generation process of the “roll” structures; (ii) the horizontal vorticity component transversal to the mean wind direction is greater than the vorticity components on the other orthogonal directions suggesting that “roll” structures move perpendicularly to the mean wind direction.

1. Introduction

It is well known that forests play an important role in the mass, energy, and momentum exchange processes between vegetation and the atmosphere (Fitzjarrald et al., 1990; Kruijt et al., 2000; von Randow et al., 2004). Tropical forests, such as the Amazonian, require special attention because they are characterized by an energy balance at the forest canopy where latent heat fluxes are greater than sensible heat fluxes, with low values of the Bowen ratio (generally < 0.4), contributing to the warming of the tropical troposphere (Betts et al., 2009; Silva Dias et al., 2002; von Randow et al., 2002). Furthermore, the availability of water for evaporation processes directly affects several feedback processes encompassing cloud generation, turbulent transport, irradiative exchanges, hydrological processes, and ecophysiological issues (Betts, 2004; Betts et al., 2009; Restrepo-Coupe et al., 2013; Zeri et al., 2014).

In recent decades, many researchers have worked for a better understanding of the exchanges between the Amazonian forest and the atmosphere, particularly the turbulent processes. For example, Fitzjarrald et al. (1990) showed that the Amazonian forest canopy acts as a low-pass filter such that high-frequency turbulent fluctuations are not observed within the canopy. In addition, they observed that during the day, the sign of the vertical velocity skewness both above and within the canopy are explained fully by considering the skewness budget. Kruijt et al. (2000) found sharp attenuation of turbulence within the Amazonian canopy during the day, which resulted in little movement and a near-Gaussian probability distribution of wind speed. However, they also showed that findings from within the canopy contrasted with the strongly skewed and kurtotic distribution above the canopy. Silva Dias et al. (2002) showed that momentum flux is altered considerably at the Amazonian rainforest–atmosphere interface. von Randow et al. (2002) found that mesoscale motions can contribute up to 30% to the total covariances under weak wind conditions above the Amazonian forest. Zeri and Sá (2011) showed that the passage of waves during nighttime conditions could cause negative turbulent fluxes of carbon dioxide and positive sensible heat flux above the Amazonian forest. Dias-Junior et al. (2013) established a time scale associated with the height of the inflection point in the wind profile above the Amazonian rainforest, and found it correlated closely with the time scales of coherent structures (CS).

* Corresponding author at: Federal Institute of Education Science and Technology of Pará/Bragança, Brazil.
E-mail address: cleo.quaresma@ifpa.edu.br (C.Q. Dias-Junior).

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Large-scale experimental projects such as the Amazonian Region Micrometeorological Experiment (ARME) (Shuttleworth et al., 1991), Global Troposphere experiments/Amazon Boundary Layer Experiment (GTE-ABLE) (Viswanadham et al., 1990), Brazilian Amazonian Climate Observation Study (ABRACOS) (Gash and Nobre, 1997), and Large-scale Biosphere–Atmosphere Experiment in Amazonia (LBA) (Avissar and Nobre, 2002) have been undertaken to obtain a more systematic view of the exchange processes that occur in the Amazonian forest environment. However, studies based on experimental data still present certain restrictions, i.e.: (i) difficulties in accurately determining the height of the roughness sublayer and its diurnal and seasonal variability; (ii) questions concerning aspects of the turbulence structure at different heights above the canopy, particularly regarding the characteristics of the existing eddies within the inner, outer, and transition layers (Malhi et al., 2004; McNaughton and Laubach, 2000) and their possible interrelationships; and (iii) difficulties in understanding why, under certain conditions, there might be cases involving active turbulence or non-active turbulence (Högström, 1990).

One alternative is to investigate such problems numerically using the large-eddy simulation (LES) model, which resolves directly the dominant scales of the turbulent flow of the atmospheric boundary layer and parameterizes only subgrid-scale processes (Sagaut et al., 2006). This three-dimensional model is based on the assumption that the structures of subgrid-scale flows, such as those in the inertial subrange of developed turbulence, tend to be more homogeneous and isotropic and therefore, they are affected less by the actual boundary conditions (Smagorinsky, 1984). Thus, it can be expected that the parameterization of subgrid-scale processes have a universal characteristic, i.e., lower dependency on the type of flow being simulated (Maruyama et al., 1999; Pope, 2004).

Few studies of the Amazonia region based on the LES have been published in the international literature. da Silva et al. (2011) used the LES to investigate the role of latent heat flux and the consequent formation of clouds above a fluvial bay in the eastern Amazon, and Vilà-Guerau de Arellano et al. (2011) used it to investigate the diurnal variability of the concentration of some chemical species in the Amazonian region. However, no previous studies have used the LES to characterize the organization of turbulent flow above the Amazonian forest, to obtain information regarding features of the turbulent flow within the roughness sublayer above the vegetation.

The objective of this work was to use the LES model to investigate the influence of the canopy layer on turbulent flow over the Amazonian rainforest. This research commenced by introducing a vertical profile of the leaf area index (LAI) into the LES model. This was incorporated to obtain a better understanding both of the organization of turbulence and its statistical moments, and of the wind velocity and vorticity fields and their vertical variability above and within the forest environment. In addition, CS, in its sweep and ejection phases, were investigated for predominantly neutral conditions.

2. Site description and data

The experimental data used in this work were collected during the 1999 Amazonian wet season as part of the activities of the LBA Project in the Jarú Forest Reserve (Rebio Jarú) (Silva Dias et al., 2002). The LBA project was a multinational interdisciplinary research program designed to realize a better understanding of the climatological, ecological, biogeochemical, and hydrological issues of the Amazon as a regional entity, but from the perspective of global climate change.

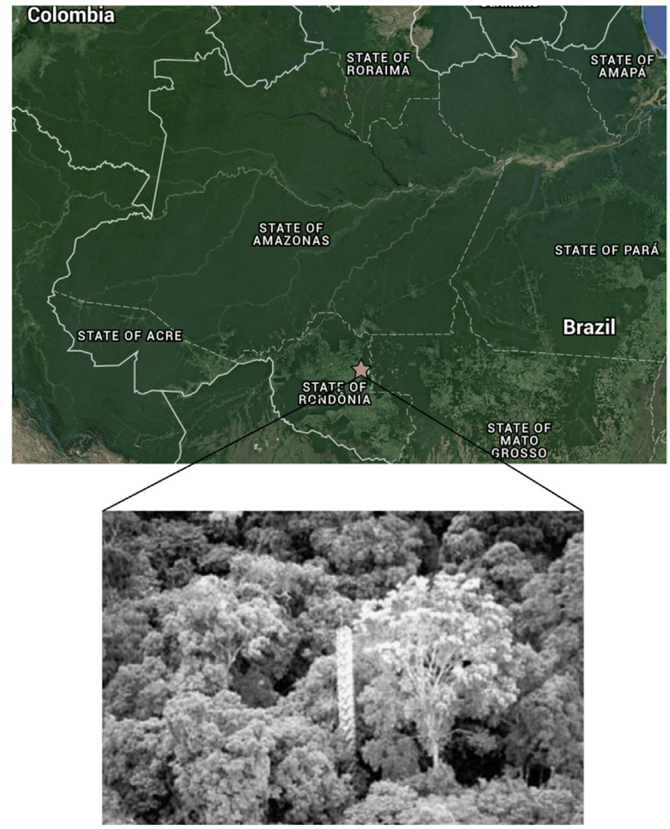

Fig. 1. Schematic map of Amazonia, with the location of the experimental site of the Rebio Jaru, in south west Amazonia.
Source: Google Maps.

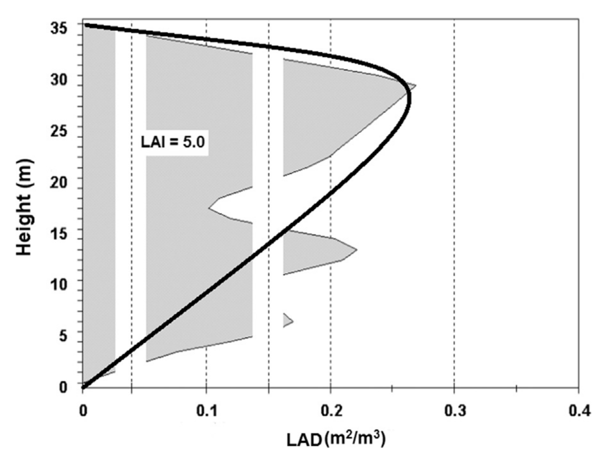

Fig. 2. Vertical profiles of leaf area density (LAD) of the Rebio Jarú Forest Reserve (for leaf area index (LAI)=5.0): after Marques Filho et al. (2005) (gray region), and the modifications inserted in the large-eddy simulation model used in this work (black line).

The Rebio Jarú is located at the southwest of the Amazon and has an area of approximately 268,150 ha between 10°05′–10°19′S and 61°35′–61°57′W, with elevations ranging from 100 to 150 m above sea level. According to Andreae et al. (2002), this forest reserve is characterized by areas of native tropical forest with an average height of 30–35 m but with some species reaching up to 45 m high. Fig. 1 shows the location of the Rebio Jarú and 60-m-high aluminum tower (10°4.706′S, 61°56.027′W) upon which the micrometeorological instruments were installed; full descriptions of the instrumentation can be found in Zeri and Sá (2010).