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SOME CHARACTERISTICS OF THE NOCTURNAL ATMOSPHERIC SURFACE LAYER STRUCTURE AND CO_2 RELEASING ABOVE CAXIUANÃ AMAZONIAN RAIN FOREST

Leonardo Deane de Abreu Sá[1,2,3*] Daniele Santos Nogueira[4] Julia Clarinda Paiva Cohen[4] Alessandro Lechinoski[2] Renata Leitão da Conceição[2] Cintya de Azambuja Martins[5] Carlos José Capela Bispo[4]

1) Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais; 2) Museu Paraense Emílio Goeldi; 3) Conselho Nacional de Pesquisas e Desenvolvimento Tecnológico; 4) Departamento de Meteorologia da Universidade Federal do Pará; 5) Laboratório de Micrometeorologia, Universidade Federal de Santa Maria

1. INTRODUCTION

Even though the Nocturnal Boundary Layer (NBL) has been object of many analyses based on Monin-Obukhov's Similarity Theory (Sorbjan, 1989), the investigation of its characteristics has been stimulated by the results from the Field Experiment CASES-99 (Poulos et al., 2002), the study about the early-evening transition (Acevedo and Fitzjarrald, 2001) and the action of low level jets in the "upside down" mixture of the lower atmosphere (Mahrt, 1999). They emphasized the complex aspect of the NBL evolution, in which various phenomena participate interactively, such as density currents, wind gusts, gravity waves, solitary waves, local circulations, etc. (Sun et al., 2002; 2004).

The flow above forests is an important domain of the NBL studies (Cava et al., 2004). The investigation of forest-atmosphere interaction, especially in Amazonia, has become more important in determining the carbon balance.

In the research developed in the eastern Amazonia, in Caxiuanã National Forest, relative maxima in the wind speed time series were detected near the surface, known as "wind gusts". The importance of these gust events is shown by the considerable increase in the vertical and horizontal transports of CO_2, humidity and sensible heat. Most of the times, they last about ten minutes and are responsible for exchange amounts comparable to those verified during the rest of the night.

Furthermore, the precise determination of the turbulent fluxes is very important in the study of forest-atmosphere interaction processes.

It is shown that during gust events the sampling errors associated with flux calculation increase significantly. Gust events are also responsible for very peculiar forest-atmosphere heat and water vapor exchanges, with upward heat flux during short duration time intervals.

Therefore, the investigation of errors in fluxes estimation is presented in this work.

* Corresponding author address: Leonardo D. A. Sá, Museu Paraense Emílio Goeldi, CCTE, INPE's Office, Av. Perimetral 1901, 66077-530, Belém, PA, Brazil, ldsa@museu-goeldi.br

2. MATERIAL AND METHODOLOGY

The data were collected at Caxiuanã Forest (1º42'30''S, 51º31'45''W), in Melgaço, Pará, in 2003 (dry season) and 2005 (dry and wet seasons). The measurements were: vertical soundings of the atmosphere with VAISALA radiosondes in, at least, four daily times; 30-second horizontal wind measurements by four cup anemometers "Vektor", installed in different heights (20,6 m, 40,8 m, 48,1 m and 52,8 m) of a meteorological tower of 56 m, localized in the forest (average height of the canopy is 32 m); and fast response measurements (16 Hz), at 54 m in the tower, of the three wind velocity components, temperature, specific humidity and carbon dioxide concentration.

A statistical characterization of the nocturnal gusts and an investigation of the variability patterns in the covariance between wind speed components and the other available variables were developed. Dumped oscillation patterns were also identified. They generally occurred after the investigated events and seemed to present complexity (Fritts et al., 2003).

In this work, wind gusts are defined as wind speed relative maxima, identified in cup and sonic anemometers data. They have minimum wind speed of 4 m/s and last from 2 to 14 minutes. In addition, their occurrence begins, generally, at 8 pm (LT), and they show characteristic patterns in the evolution of statistical parameters associated to turbulent micrometeorological variables.

Sampling errors associated with eddy-correlation flux calculation are calculated according with Wyngaard(1983).

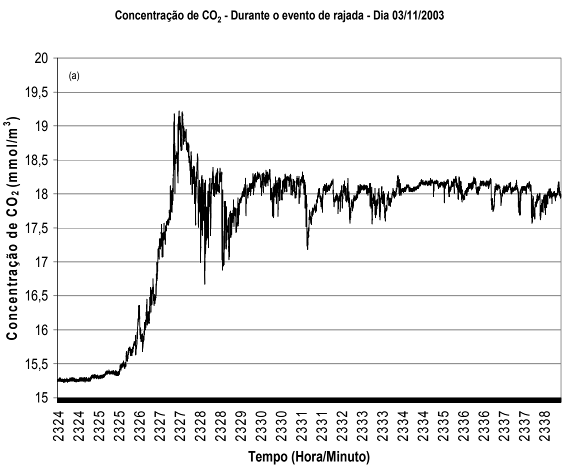
Time-frequency analyses of turbulent time series data have been performed using marlet complex wavelet methodology (Daubechies, 1992).

3. RESULTS AND DISCUSSION

All the available 15 day-long data presented gust events at the highest measuring level, and also, in most of the times, in the other available anemometers.

Plots from the available fast response data of 2003 dry season were made to those days and times when the wind gusts were observed. These plots clearly showed developed turbulence characteristics. The variability of the wind speed components presented sharp change during the occurrence of the gusts, as u and v increased in magnitude and w oscillations augmented in amplitude. On the other hand, scalars like water vapor and CO_2 concentration had similar variability, with a sharp increase, and temperature presented the opposite, decreasing during the gust event, as shown by Figure 1, for CO_2 and temperature data.

(a)



(b)

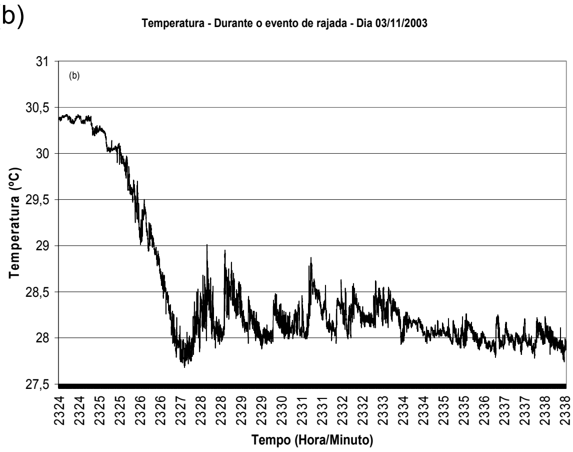


Figure 1 – Turbulent time series of sonic anemometer data during the gust of 11/03/2003: (a) CO_2 concentration and (b) temperature.

It is possible to note the occurrence of ramp-like coherent structures in the scalars turbulent time series. They are associated to the classic sweep-ejection cycle, which is more active during their occurrence and allows very efficient forest-atmosphere exchanges. These structures occur synchronically in CO_2, water vapor and temperature time series, with "inverted" ramps for temperature. This happens because the canopy is a sink of heat and a source of carbon dioxide and humidity, during the night (Cava et al., 2004). The variability pattern of the coherent structures in Figure 1 shows a decrease in the oscillations amplitude and an increase in their frequency. This is different from what is expected from "classic" dumped oscillations that do not present temporal variation of frequency. Therefore, it is suggested that these oscillations are regulated by non-linear dynamics (Fritts et al., 2003), phenomena associated to feedback processes, with a complex nature.

This suggests the existence of different NBL evolution classes in Caxiuanã. The classification methodology proposed by Cava et al. (2004), which considers the nocturnal variability of the radiation balance in order to detect changes generated by cloudiness alterations upon the turbulent data has been applied to Caxiuanã forest nocturnal data measured during 2005 wet and dry seasons, as shown in table 1.

Number	Day	Class I	Class II	Class III	Class IV	Class V	
1	109-110	5	1	1	4	1	
2	115-116	1	0	1	7	1	
3	112-113	0	0	0	4	4	
4	108-109	2	2	0	6	2	
5	99-100	5	0	0	1	4	
6	97-98	0	0	0	5	4	
7	87-88	2	0	0	5	4	
8	83-84	3	1	0	6	1	
9	81-82	2	1	0	4	2	
10	79-80	4	0	0	4	3	TOTAL
	TOTAL	24	5	2	46	26	103
	PERC.	23,3%	4,8%	1,9%	44,6%	25,2%	

Table 1 – Number of events distribution during night time classified according with Cava et al (2004) methodology, for ten analised days.

The data show that organized turbulent coherent structures are often observed at night, irrespectively of the the nocturnal variability of the net radiation. The first three classes are cloud-free so that net radiation Rn keeps almost constant or with no sharp changes. They are: (I) occurrence of ramp-like coherent structures in the scalars time series; (II) wave shape oscillation above the canopy typical of gravity waves; (III) existence of fine-structure turbulence. The two last categories refer to the simultaneous occurrence of organized coherent structures and cloudiness conditions with Rn variations greater than $10W/m^2$. They are: (IV) the radiation balance induces an organized movement; (V) the variation in the radiation balance is not correlated with organized movement alterations. The results showed that in almost all the studied cases (more than 90%) there was organized turbulence in the form of scalar ramp-like structures. Moreover, episodes with considerable variations in the radiation balance (greater than $10W/m^2$) corresponded to about 70% of the cases.

Analyzing a typical night during the wet season of 2005, the variations in the thermodynamic structure were investigated. Therefore, the variability patterns of virtual potential temperature θ_v and mixing ratio q are analyzed. This is important to identify factors that may contribute to identify the nocturnal exchanges between forest and atmosphere.

It was found that the wind gusts, after 9 pm (local time), are responsible for a sudden decrease in θ_v under the canopy and interfere in the humidity variability. The wind velocity, potential virtual temperature and mixing ratio variability, all measured above and below forest canopy during a gust event are shown in figure 2a. As it observed, during a wind gust event lasting a few minutes after a sudden and small increase, θ_v decreases in all the analyzed levels, as shown in figure 2b. The cool air associated to the wind gust generates a strong upward humidity flux during a brief period shown in Figure 2c. These gust events bring cooler and drier air which can be observed in all levels.

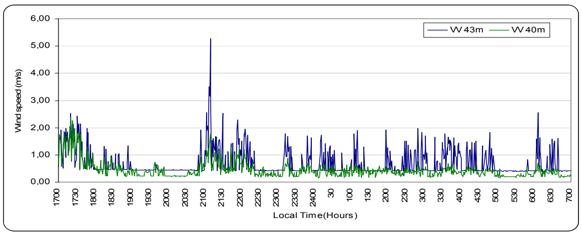


Figure 2a) – Wind speed variability in the levels of 40 and 43m during gust event.

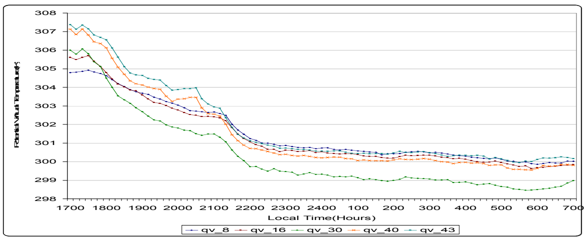


Figure 2b) – Potential virtual temperature temporal variation in the levels of 8, 16, 30, 40 and 43m during gust event.

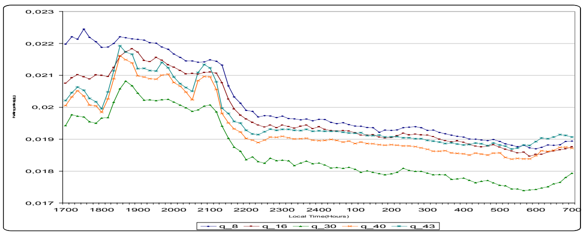


Figure 2c) – Mixing ratio temporal variation in the levels of 8, 16, 30, 40 and 43m during gust event.

The existence of regions with negative θ_v vertical gradients under the canopy and positive above it from 7 pm on, suggests the occurrence of nocturnal convective mixture inside the canopy above 8 m and stable conditions above the canopy. In addition, there is a decrease of θ_v in all levels of about 2 K after the gust event.

These cooling effects caused by wind gusts were not observed in precedent studies regarding the thermal structure of the forest reserve canopies of Ducke, in Manaus (Shuttleworth et al., 1985) and Rebio Jaru, in Rondônia (Pachêco, 2001). This can be a indication that the wind gusts may be related to breeze fronts that might influence the local circulation in Caxiuanã Forest area .

The observed gusts direction was calculated with sonic anemometer data. Their direction and the direction of the covariance of u'w', v'w', u'c', v'c', u'q', v'q', u'T' e v'T' are always from the Northeast during the event. This direction is the same of that where thunderstorms were observed minutes before the nocturnal radiosonde launchings, for the same days when the gusts were registered.

Based on that, the variation of the equivalent potential temperature vertical profiles, θ_e, were investigated, before and after the occurrence of the gusts. The results presented considerable drop in the θ_e values in the Superficial Boundary Layer (SBL), as shown by the typical case in Figure 3. However, considering the vertical extension of the drop region, two different situations were observed: (i) considerable and almost uniform drop of θ_e along the whole region sounded by the radiosonde; (ii) considerable drop of θ_e only until a height of a few hundreds of meters, characterized by the existence of a pronounced local maximum in θ_e.

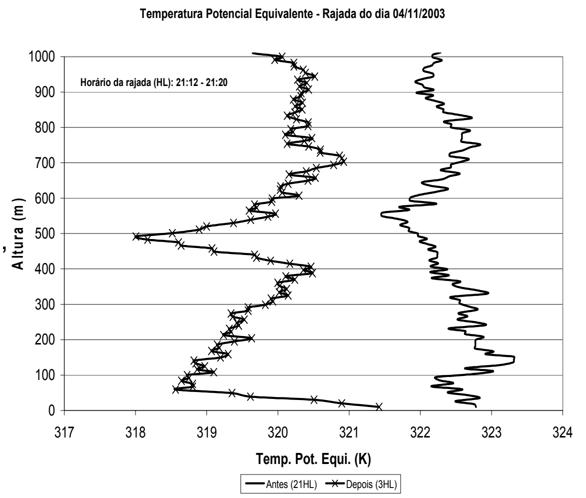


Figure 3 – Vertical profiles of equivalent potential temperature before and after the gust event of 11/04/2003, which represent the typical drop in θ_e after the episode.

This suggests the importance of descending air currents (outflows) associated to the convective activity (in class 1) and river breezes (in class 2) in the gusts occurrence. In both cases, density currents would act in the NBL, that have, in many times, different origins, as mentioned by Sun et al. (2002; 2004) in their study of the nocturnal flow in the central region of the USA. Towards the meteorological tower, the arrival of these downdrafts is noticed as a colder air current, detected as a sudden increase in wind speed and a drop in θ_e. The temperature difference would generate a free convection motion, which transports upwards the sensible heat, CO_2 and humidity in larger quantities than those in the level immediately above.

To prove the importance of the gusts related to the whole night, a simple time integration of the vertical and horizontal transports of each available scalar was made, based on Cava et al. (2004). The calculus considered two different periods: the first, corresponding to the period associated to the event (half an hour before, during and half an hour after the gust); the other, corresponding to the rest of the night.

It is important to emphasize that, even though the gust episodes correspond to about 10% of the whole night period, they contribute with mass and heat exchanges in percentages much higher than 10% in comparison to the rest of the night. Sometimes, they correspond to almost 50% of the nocturnal exchanges. Such result has a considerable importance to a better comprehension of the nocturnal variability of the turbulent fluxes. Indeed, during gust events eddy-correlation flux calculations have shown the biggest sampling errors using Wyngaard's methodology (1983), as presented in Figure 4. It shows the average day-time and night-time the error estimates of the CO_2 flux for different periods.

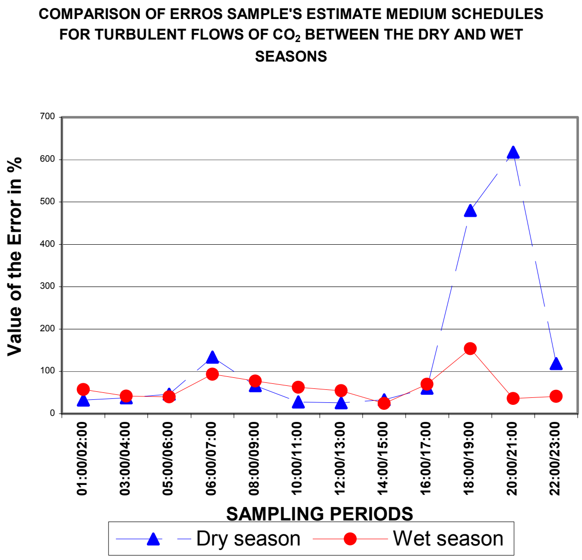


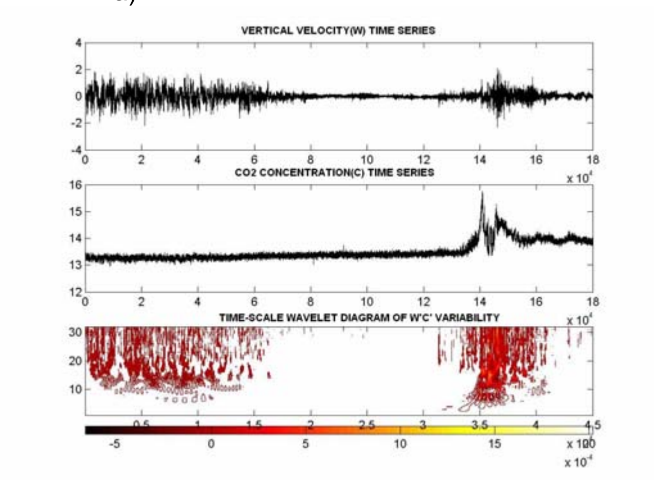
Figure 4 – Average values for the error associated to CO_2 flux in different sampling periods, calculated according to Wyngaard (1983) methodology, for the dry and wet seasons.

The results obtained for the 2005 wet and dry seasons, present a great variability in the sampling error of the CO_2 fluxes (from 20% to 500%).

It is interesting to emphasize that the greater estimated error values have been observed during the dry season in early evening periods, probably due to the strong gust events which occur in such periods.

Wavelet analysis applied to turbulent data have shown that, during nocturnal gust events, sensible heat fluxes present positive values, at least, in the scales around 30 s typical of coherent structure occurrence. During an intense nocturnal wind gust episode, the co-spectral characteristics of the CO_2 flux were determined. In Figure 5(a), there are the vertical velocity, w, and the CO_2 concentration, c, time series (data from 4:00 to 8:30 pm, local time), where a strong fluctuation is observed around 7 pm. In the lower part of Figure 5(a), there is a scalogram, which clearly shows the time-scale location of the gust. From Figures 5(b) to 5(d), there are the projection products of w' and c' are shown (where c' is the CO_2 fluctuation) in the temporal scales of 22,5 s, 17 s and 13,6 s during the gust event. This allows a quantitative investigation of the CO_2 fluxes contribution in several scales and the determination of the ones in which there was a greater effective contribution for flux. The results show intense positive CO_2 fluxes concerning three time scales in the range from 22,5 s to 13,6 s.

a)



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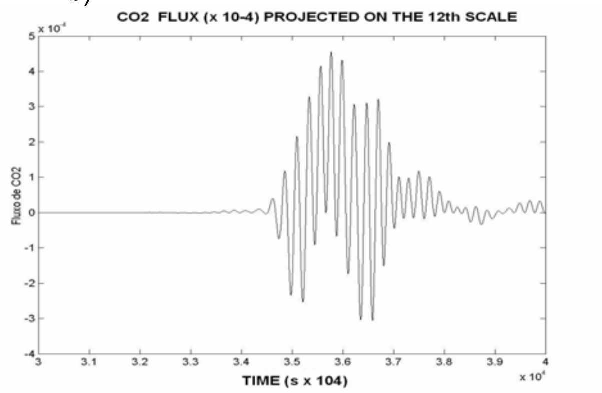

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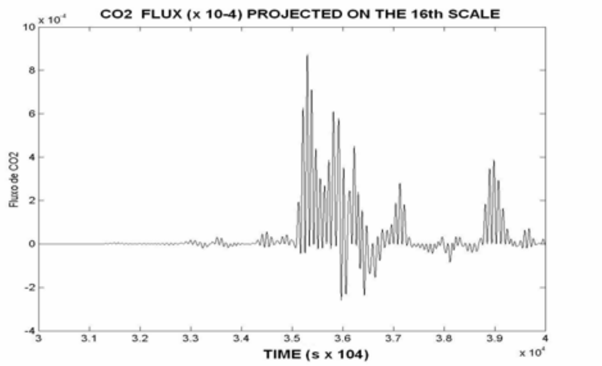

d)

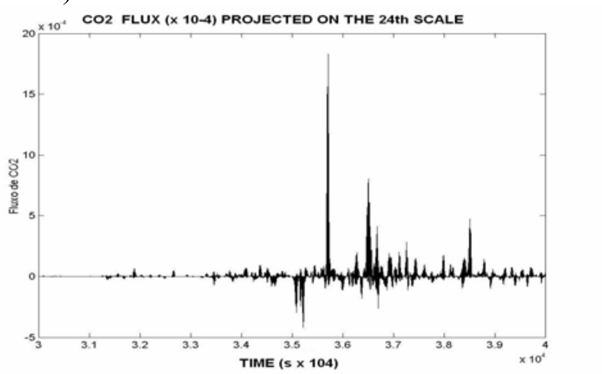

Figure 5 – Gust event: (a) Vertical velocity(w) time series, CO_2 concentration(c) time series and time-scale wavelet diagram of (w'c') variability; (b) wavelet projection on the scale 12 (22.5s) ; (c) wavelet projection on the scale 16 of the flow of CO_2; (d) wavelet projection on the scale 20 (13.6s) of the CO_2 concentration time series.

These results should offer an experimental basis for future investigation upon better parameterizations of the forest-atmosphere exchange processes in numerical models that simulate the NBL evolution.

4. CONCLUSION

Intense nocturnal gust occurrences were observed above the Amazon Forest in Caxiuanã. They always occur once a day and may reach more than 10 m/s at the top of the 56m-height tower. They are from Northeast and last about 10 minutes. These events are associated to strong turbulence in the scalar variables time series, which present ramp-like coherent structures during their occurrences. During the wind gusts, the momentum, sensible heat, water vapor and CO_2 fluxes show a pronounced increase and are responsible for a considerable fraction of the forest-atmosphere exchanges relative to the whole night period. A remarkable characteristic of the lower part of the nocturnal boundary layer vertical structure in its is the drop in temperature and equivalent potential temperature after the gust events. This suggests that descending air currents (outflows) participate in the gusts generation process, which would explain the temperature drop and the increase in stabilization observed in the layers above the canopy after the events. During gust events the turbulent flux estimation presented the greater sampling errors.

5. ACKNOWLEDGMENTS

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