Capítulo II - Amazon rain forest subcanopy flow and the carbon budget: Manaus LBA Site - a complex terrain condition [2]

Abstract

On the moderately complex terrain covered by dense tropical Amazon rainforest (Reserva Biologica do Cuieiras – ZF2 - 02◦36′17.1″S, 60◦12′24.5″W) subcanopy horizontal and vertical gradients of the air temperature, CO_2 concentration and wind field were measured for dry and wet periods in 2006. We tested the hypothesis that horizontal drainage flow over this study area is significant and can affect the interpretation of the high carbon uptake rates reported by previous works. A similar experimental design as the one by *Tóta et al*. [2008] was used with a network of wind, air temperature and CO_2 sensors above and below the forest canopy. A persistent and systematic subcanopy nighttime upslope (positive buoyancy) and daytime downslope (negative buoyancy) flow pattern on a moderately inclined slope (12%) was observed. The micro-circulations observed above the canopy (38 m) over the sloping area during nighttime presents a downward motion indicating vertical convergence and correspondent horizontal divergence toward the valley area. During the daytime an inverse pattern was observed. The micro-circulations above the canopy were driven mainly by buoyancy balancing the pressure gradient forces. In the subcanopy space the micro-circulations were also driven by the same physical mechanisms but probably with the stress forcing contribution. The results also indicated that the horizontal and vertical scalar gradients (e.g., CO_2) were modulated by these micro-circulations above and below canopy, then suggesting that estimates of advection using previous experimental approaches are not appropriate due to the tri-dimensional nature of the vertical and horizontal transport locally.

Key words: Amazon Rainforest; Advection, Drainage Flow, Eddy Covariance, Subcanopy.

---

[2] Tóta, J., Fitzjarrald, D.R., Parker, G., Sakai, R.K., Silva Dias, M.A.F., Manzi, A.O., 2009. Amazon rain forest subcanopy flow and the carbon budget: Manaus LBA Site - a complex terrain condition (to be submitted).

1. Introduction

The terrestrial biosphere is an important component of the global carbon system. The uncertainty level of its long term exchanges estimates is a challenge and has resulted in ongoing debate [*Baldocchi et al.,* 2008; *Aubinet et al.*, 2008]. For monitoring long-term net ecosystem exchange (NEE) of carbon dioxide, energy and water in terrestrial ecosystems, tower-based eddy-covariance (EC) techniques have been established worldwide [*Baldocchi et al*., 2008].

It is now recognized that the EC technique has serious restrictions for application over complex terrain and under calm and stable nighttime conditions with low turbulence or limited turbulent mixing of air [e.g., *Goulden et al*., 1996; *Black et al*., 1996; *Baldocchi et al*., 2001; *Massman and Lee*, 2002; *Loescher et al*., 2006; *Aubinet et al*., 2008]. To overcome this problem, the friction velocity (u_*)-filtering approach has been formalized by the FLUXNET committee for the estimation of annual carbon balances [*Baldocchi et al.,* 2001; *Gu et al*., 2005]. This approach simply discarded calm nights flux data (often an appreciable fraction of all nights) and replaced them with ecosystem respiration rates found on windy nights [*Miller et al*., 2004]. *Papale et al*., [2006] pointed out that this approach itself must be applied with caution and the friction velocity (u_*) corrections threshold is subject to considerable concerns and is very site specific. *Miller et al*., [2004] reported that depending of the u_* threshold value used to correct the flux tower data at Santarem LBA site the area can change from carbon sink to neutral or carbon source to the atmosphere.

The transport of CO_2 by advection process has been suggested by several studies as the principle reason for the ‘‘missing’’ CO_2 at night [*Lee,* 1998; *Finnigan*, 1999; *Paw U et al*., 2000; *Aubinet et al*., 2003; *Feigenwinter et al*., 2004; *Staebler and Fitzjarrald*, 2004]. The search for this missing CO_2 has spurred a great deal of research with the goal of explicitly estimating advective fluxes in field experiments during the last decade, in order to correct the NEE bias over single tower eddy covariance measurements (*Aubinet et al*., 2003, 2005;

Staebler and Fitzjarrald, 2004, 2005; *Feigenwinter et al.*, 2004; *Marcolla et al.*, 2005; *Wang et al.*, 2005; *Sun et al.*, 2007; *Heinesch et al.*, 2008; *Leuning et al.*, 2008; *Tóta et al.*, 2008; *Yi et al.*, 2008; *Feigenwinter et al.*, 2009a, b).

The complexity of topography and the presence of the valley close to the eddy flux tower have increased the importance to investigating if subcanopy drainage flow account for the underestimation of CO_2 as past studies have asserted [*Froelich and Schmid*, 2006]. The Manaus LBA site is an example of moderately complex terrain covered by dense tropical forest. The NEE bias is reported by previews works [*Kruijt et al*., 2004*; de Araújo et al,* 2008*; de Araújo,* 2009; and references there in], and a possible explanation for this is that advection process is happening in that site. This work examines subcanopy flow dynamics and local micro-circulations features and how they relate to CO_2 spatial and temporal distribution on the Manaus LBA site in contrast with previous work done during the Santarem LBA Site experiment [see, *Tóta et al*., 2008].

2. Material and Methods

2.1. Site description

The study site (54° 58'W, 2° 51'S) is located in the Cuieiras Biological Reserve, controlled by National Institute for Amazon Research (INPA), about 100 km northeast from Manaus city. At this site, named K34, was implemented a flux tower with 65m height to monitoring long term microclimate, energy, water and carbon exchanges (*Araújo et al*., 2002), and various studies that have been conducted in its vicinity. The measurements are part of the Large-Scale Biosphere-Atmosphere experiment in Amazonia (LBA). Figure 1 presents the study site location including the topographical patterns where the maximum elevation is 120m and the total area (upper panel) is 97.26 km2, with distribution of the 31% of plateau, 26% of slope and 43% of valley [*Rennó et al*., 2008]. The site area is formed by a topographical feature with moderately complex terrain including a landscape with mosaics of plateau, valley and slopes, with elevation differences about 50m (Figure 1), and with distinct vegetation cover (Figure 2). The eddy flux tower at Manaus K34 site has footprints that encompass this plateau-valley mosaic.

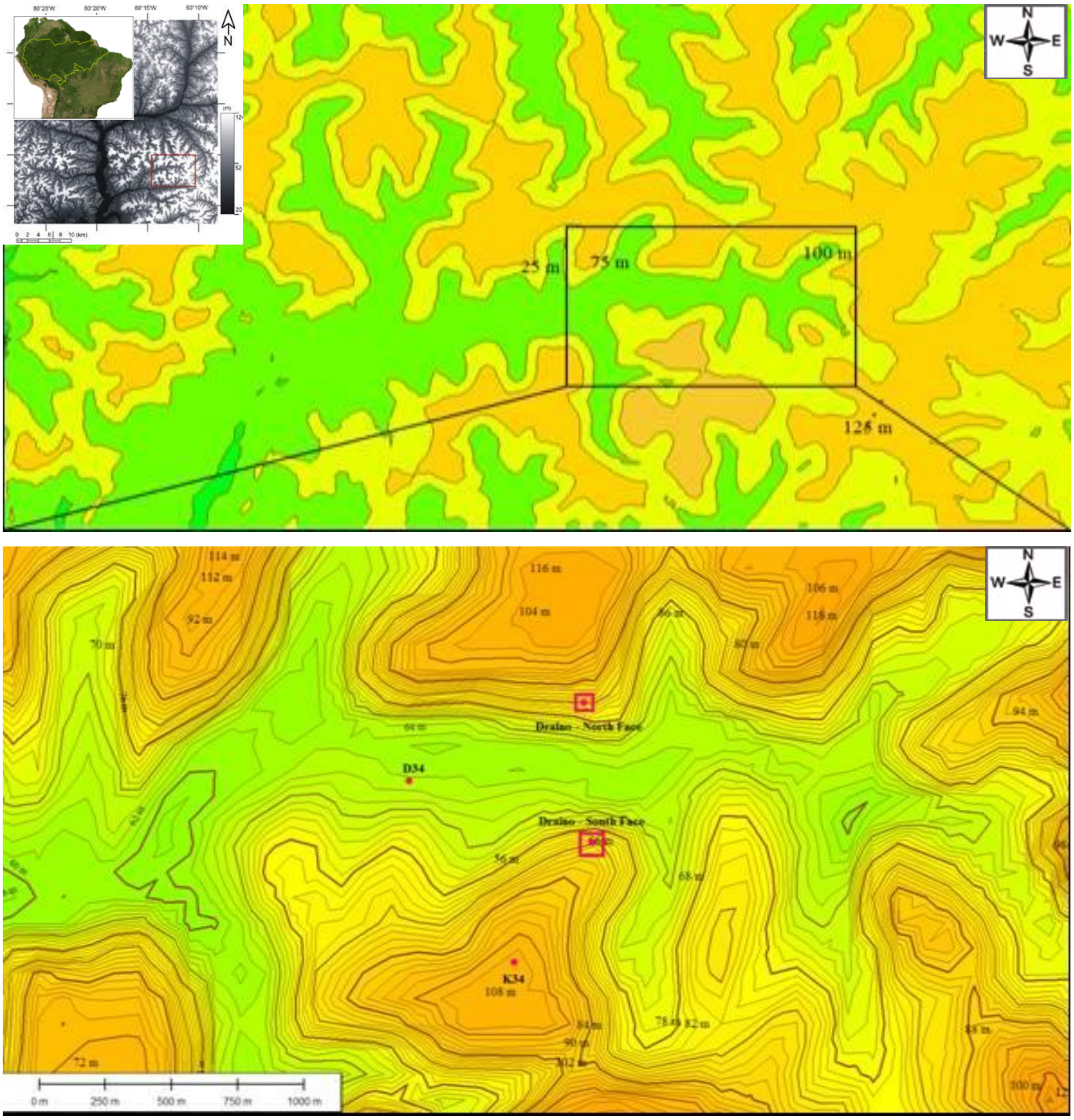

Figure 1: Detailed measurements towers's view in the ZF-2 Açu catchment (East-West valley orientation) from SRTM-DEM datasets.The large view in the above panel and below panel the points of measurements (B34 – Valley, K34 – Plateau, and subcanopy Draino system measurements over slopes in south and north faces (red square).

The vegetation cover on the plateau and slope areas is composed by tall and dense terra firme (non-flood) tropical forest with height varying 30 to 40m, maximum surface area density of the 0.35 m^2m^{-3} (Figure 2b, see also *Parker et al*., [2004]), and average biomass of the 215 to 492 ton.ha^{-1} [*Laurance et al*., 1999; *Castilho*, 2004]. On the valley area the vegetation is open and smaller with heights from 15 to 25 m, but with significant surface area density more than the 0.35 m^{2}m^{-3} (Figure 2b). The soil type on the plateau and slopes area is mainly formed by Oxisols (USDA taxonomy) or clay-rich ferrasols ultisols (FAO soil taxonomy), while on the valley area, waterlogged podzols (FAO)/spodosols (USDA) with sand soil low drained predominates. Also, in the valley area the presence of small patchy of *Campinarana* typical open vegetation with low biomass is also common [*Luizão et al*., 2004].

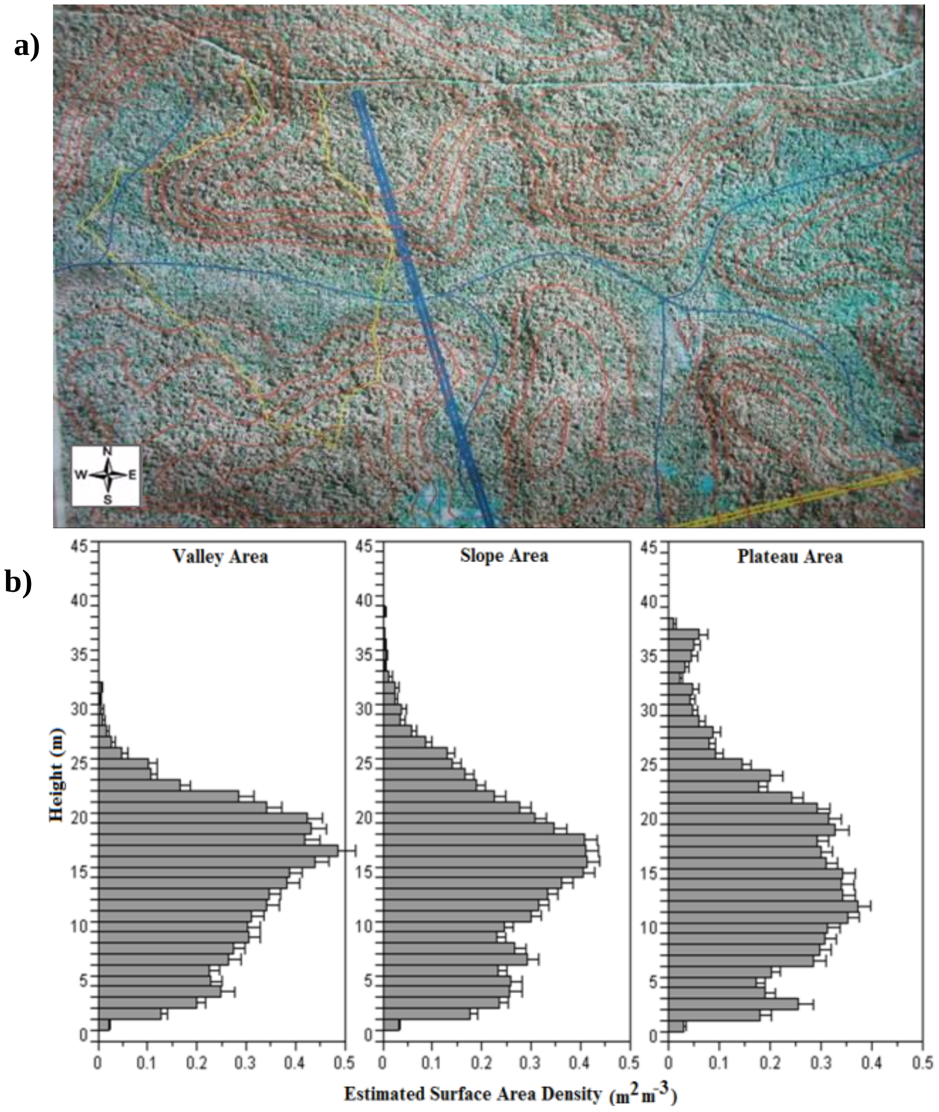

Figure 2: (a) IKONOS's image of the site at Açu Cachment with level terrain cotes and vegetation cover and (b) vegetation structure measured from LIDAR sensor over yellow transect in (a). From (a) the valley vegetation (blue color) and vegetation transition to plateau areas (red colors).

The precipitation regime on the site show wet (December to April) and dry (June to September – less than 100 mm.month^{-1}) periods. The total annual rainfall is about 2400 mm and the average daily temperature is from 26 (April) to 28˚C (September). For more detailed information about the meteorology and hydrology of this site see *Waterloo et al*. [2006], *Cuartas et al*. [2007], *Hodnett et al*. [2008], *Tomasella et al*. [2008], *Malhi et al*. [2008] and *de Araújo* [2009].

2.2. Measurements and intrumentation

The datasets used in this study include a measurement system to monitor airflow above and below the forest, horizontal gradients of CO_2, and the thermal structure of the air below the canopy, named “DRAINO System” [see, *Tóta et al*., 2008]. The data used in this study were collected during the wet season (DOY 1-151) and the dry season (DOY 152-250) of the year 2006. Complementary information was used from flux tower K34 (LBA tower) on the plateau, and sonic anemometer data collected in the valley flux tower (B34, see *de Araújo* [2009] for details).

The flux tower K34 includes turbulent EC flux and meteorological observations of the vertical profiles of the air temperature, humidity and CO_2/H_2O concentrations, and vertical profile of wind speed, as well as radiation measurements. The fast response eddy flux data were sampled at 10 Hz and slow response (air temperature and wind profiles) at 30 min average [see *Araújo et. al.*, [2002] for details information].

- DRAINO measurement System – Manaus LBA ZF2 site

The Draino measurement system used in Manaus LBA Site was similar to that developed by State University of New York, under supervision of Dr. David Fitzjarrald), and applied at Santarem LBA Site, including the same methodological procedures and sampling rates [see, *Tóta et al*., 2008]. However, due to the terrain complexity, it was modified for Manaus forest conditions including a long distance power line and duplication of CO_2 observations for different slopes areas (Figure 4). The Draino measurement system used in Manaus LBA Site was mounted in an open, naturally ventilated wooden house (Figure 3).

Figure 3: Draino measurement system used in Manaus LBA (South Face, see also Figure 4).

The system and sensors were deployed (Figure 4) with measurements of air temperature and humidity (red points), CO_2 concentration (green points), and wind speed and direction (blue points), for both south and north faces. The observations of the 3-D sonic anemometer were sampled at 10 Hz and all the other parameters (T, RH, and CO_2) were sampled at 1 Hz (Figure 4).

The acquisition system developed at ASRC was employed (Staebler and Fitzjarrald, 2005). It consists of a PC operating with Linux, an outboard Cyclades multiple serial port (CYCLOM-16YeP/DB25) collecting and merging serial data streams from all instruments in real time, the data being archived into 12-hour ASCII files. At Manaus LBA Site two systems in the both south and north valley slope faces were mounted (Figure 3 and 4).

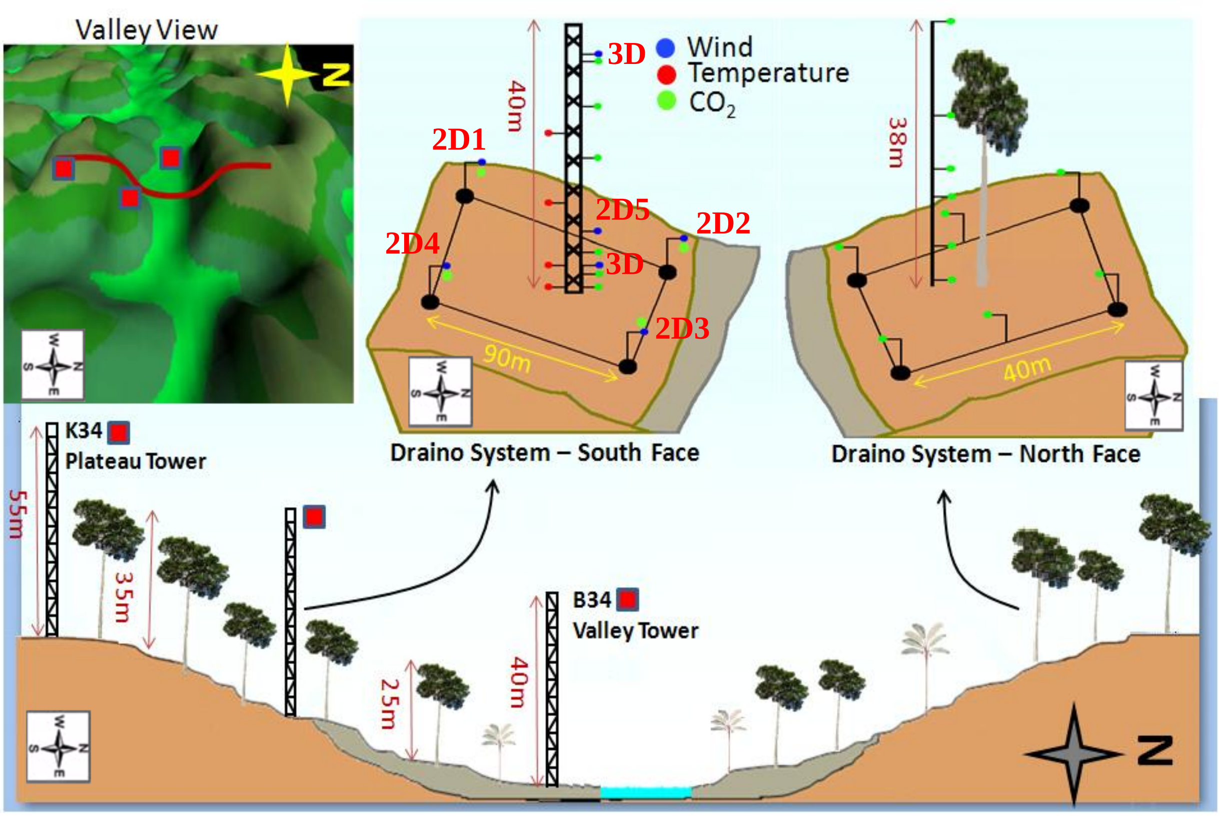

Figure 4: Draino measurement system (South and North Slope face) implemented at Manaus LBA Site, including topographic view and instrumentation deployed.

For each slope face, a single LI-7000 Infrared Gas Analyzer (LI-COR inc., Lincoln, Nebraska, USA) was used. A multi-position valve (Vici Valco Instrument Co., Inc.) controlled by a CR23x Micrologger (Campbell Scientific, Inc., Logan, Utah, USA), which also monitored flow rates was also used. This procedure minimizes the potential for systematic concentration errors to obtain the horizontal and vertical profiles. Following *Staebler and Fitzjarrald* [2004] and *Tóta et al.* [2008] a similar field calibration was performed during the observations at Manaus LBA Site, including initial instrument intercomparison. The result was similar that obtained by *Tóta et al.* [2008], with CO_2 mean standard error was < 0.05 ppm and mean standard error of about 0.005 ms-1 for wind speed measurements. After intercomparison, the sonic anemometers and the CO_2 inlet tubes were deployed as shown in Figure 4.

On the south face, the instrument network array (Figure 4 and Table 1) consisted of 6 subcanopy sonic anemometers, one 3-D ATI (Applied Technologies Inc., CO, USA) at 2m elevation in the center of the grid (named 3-D ATI), and 5 SPAS/2Y (Applied Technologies Inc., CO, USA), 2-component anemometers (1 sonic at 6m in the grid center and 4 sonic along the periphery at 2m, see Figure 4), with a resolution of 0.01 m s-1. Also, a Gill HS (Gill Instruments Ltd., Lymington, UK) 3-component sonic anemometer was installed above the canopy (38 m). The horizontal gradients of CO_2/H2O were measured in the array at 2 m above ground, by sampling sequentially from 4 horizontal points surrounding the main tower location at distances of 70-90m, and from points at 6 levels on the main Draino south face tower, performing a 3 minute cycle. On the north face, similar CO_2 measurements were mounted including a 6 level vertical profile and 6 points in the array at 2 m above ground, performing a 3 minute cycle.

On both slope faces the air was pumped continuously through 0.9 mm Dekoron tube (Synflex 1300, Saint-Gobain Performance Plastics, Wayne, NJ, USA) tubes from meshed inlets to a manifold in a centralized box. A baseline air flow of 4 LPM from the inlets to a central manifold was maintained in all lines at all times to ensure relatively “fresh” air was being sampled. The air was pumped for 20 seconds from each inlet, across filters to limit moisture effects. The delay time for sampling was five seconds and the first ten seconds of data were discarded. At the manifold, one line at a time was then sampled using an infrared gas analyzer (LI-7000, Licor, Inc.). To minimize instrument problems, only one LI-7000 gas analyzer sensor, for each slope face, was used to perform vertical and horizontal gradients of the CO_2.

Table 1. DRAINO system Sensors at ZF2 LBA Manaus Site

Level (m)	Parameter	Instrument
38	u’ v’ w’ T’	Gill 3D sonic anemometers
2	u’ v’ w’ T’	ATI 3D sonic anemometer
6,2	u’ v’ w’ T’	CATI/2 2D sonic anemometers
2	CO_2 Concentration (horizontal array)	LI-7000 CO_2/$H_2$0 analyzer
38,26,15,3,2,1	CO_2, $H_2$0 Profile (Sourth face)	LI-7000 CO_2/$H_2$0 analyzer
35,20,15,11,6,1	CO_2, $H_2$0 Profile (North face)	LI-7000 CO_2/$H_2$0 analyzer
18,10,2,1	Air Temperature and Humidity	Aspirated thermocouples

3 – Results and Discussion

The datasets analyzed in this study were obtained during the periods defined by dry (DOY 1-150 January to June) and wet (DOY 152-250 July to October) of the 2006. Figure 5 presents an example of the datasets cover, with 10 days composite statistic, for CO_2 concentration and air temperature at south face area of the DRAINO system and the total precipitation on the plateau K34 tower measurements.

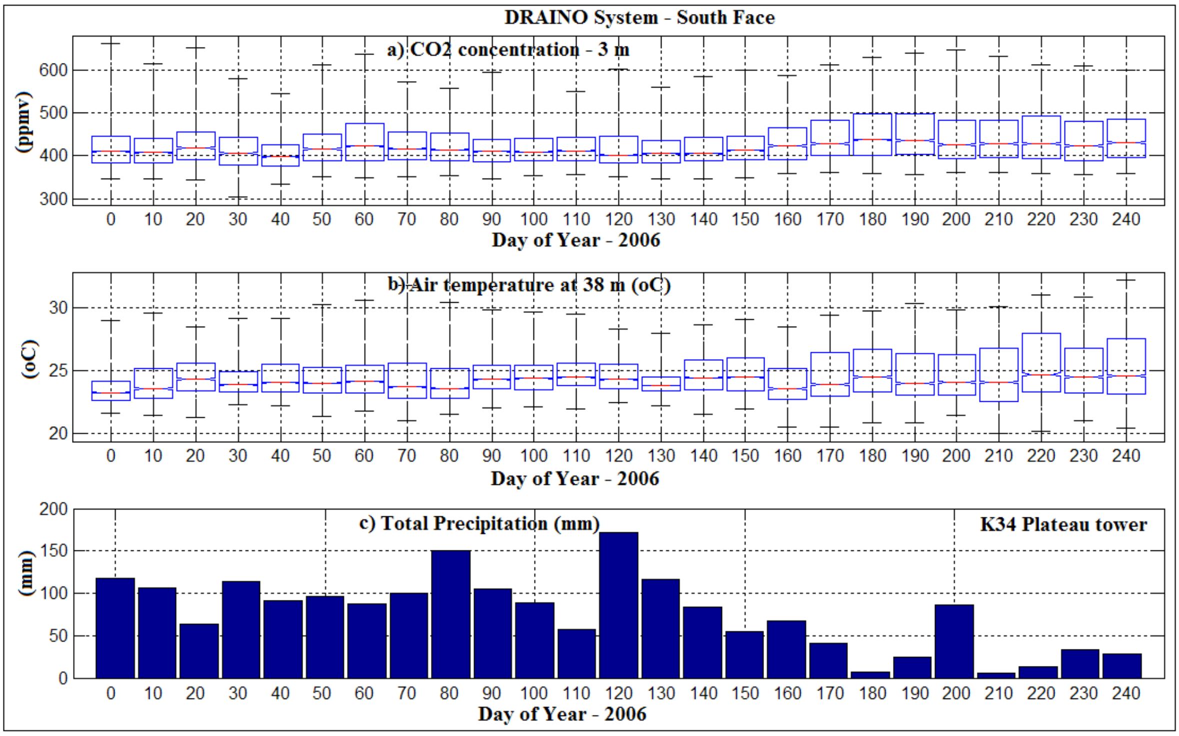

Figure 5: 10 days time series of the CO_2 concentration (a), air temperature (b) (DRAINO System) and total precipitation (c) (plateau tower).

The measurements covered almost the entire year of 2006, including dry, wet and the transition from wet to dry season. The air temperature amplitude above canopy on the slope area of the DRAINO System was higher, as expected, in the dry season. A good relationship is observed between CO_2 concentration and air temperature with much large amplitudes in the dry season than in the wet season. It is probably associates with less vertical mixing during dry than wet season producing much higher subcanopy CO_2 concentration and vertical gradient along the forest.

3.1. Air Temperature field

3.1.1 - Plateau K34 tower

The vertical profiles of air temperature from plateau K34 tower show a very different pattern from that on the slope area, probably due to canopy structure differences (Figure 2b, *Parker et al.*, [2004]). The canopy structure is important for characterizing its thermal regime as it can be seen in Figure 6. The mean canopy layer stores large quantity of heat during the daytime and distributes it downward and upward throughout the nighttime (Figure 6, 7).

Above canopy layer, over plateau area, the neutral or unstable conditions were predominant during the daytime for both seasons (Figure 6a, c). While during the nighttime stable conditions are presents for the dry period (Figure 6b) and neutral to stable conditions for the wet period (Figure 6d). Similar pattern has been reported elsewhere for plateau forests in the Amazonia (*Fitzjarrald et al.*, [1990]; *Fitzjarrald and Moore*, [1990]; *Kruijt et al.*, [2000]; *Goulden et al.*, [2006]).

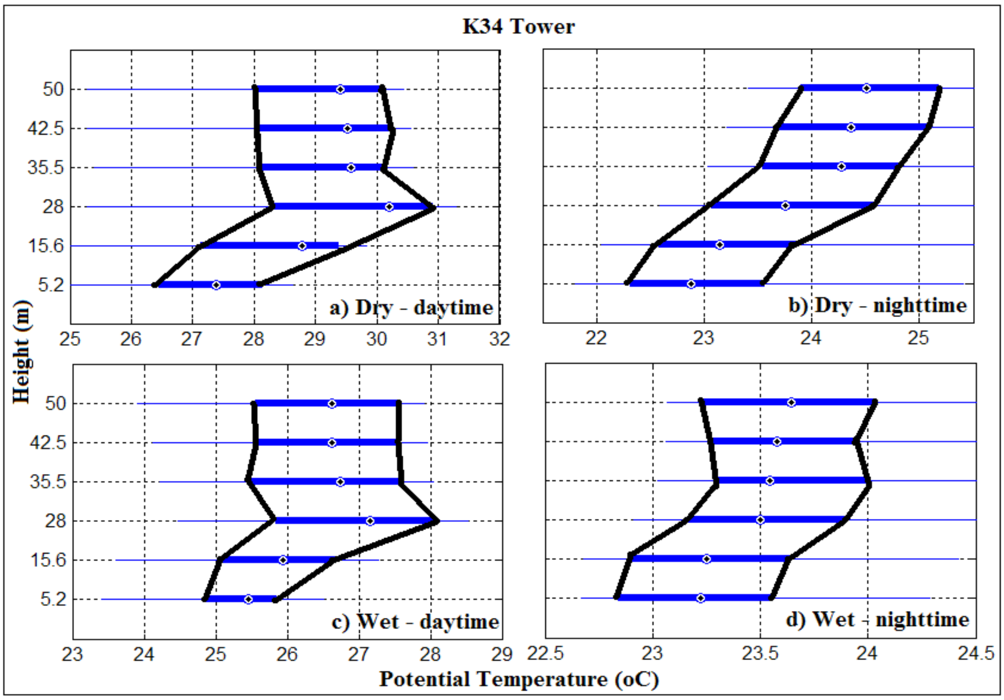

Figure 6: Boxplot of the virtual potential temperature vertical profile for dry (a, b) and wet periods (c, d) of the 2006 during night (b, d) and daytime (a, c), on the plateau K34 tower.

The below-canopy layer ambient air on the plateau area was stable at all times (Figure 6a, b, c, d), indicating that this layer is stable where the cold air concentrated in the lower part of the canopy air space as shown in Figure 7.

Figure 7 presents daily course of the vertical deviation of the virtual potential temperature, e.g., $([\boldsymbol{\theta}'_{v=}\boldsymbol{\theta}_v(\boldsymbol{z}) - \overline{\boldsymbol{\theta}_v(\boldsymbol{z})}_{5.2}^{55}])$, the temperature differences from each level in relation to the vertical average profile. The subcanopy air space was relatively colder during both dry and wet season, showing a similar feature of strong inversion. The same pattern was reported by *Kruijt et al*. [2000] measured over a tower located 11 km northeast of our site with a similar forest composition.

Note that a very interesting length scale can be extracted from the observation when the deviation is about zero. That vertical length scale has mean value of about 30 m during nighttime and 20 m during daytime (yellow color in the Figure 7a, b). Those values are comparable with above canopy hydrodynamic instability length scale used in most averaged wind profile models [*Raupach et al.*, [1996]; *Pachêco*, [2001]; *Sá e Pachêco*, [2006]; *Harman and Finnigan*, [2007]].

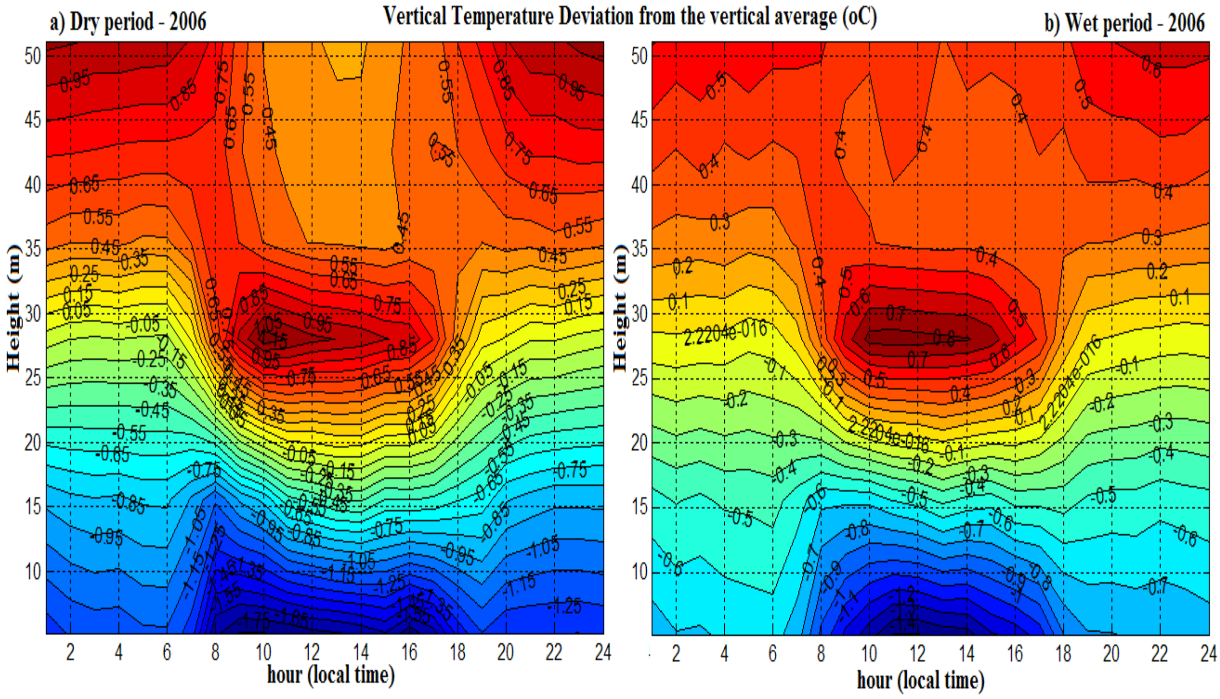

Figure 7: Daily course of the vertical deviation of the virtual potential temperature ($[\boldsymbol{\theta}'_{v=}\boldsymbol{\theta}_v(\boldsymbol{z}) - \overline{\boldsymbol{\theta}_v(\boldsymbol{z})}_{5.2}^{55}]$), during dry (a) and wet (b) periods of the 2006, over plateau K34 tower.

3.1.2 – DRAINO System Slope tower

On the slope area south face (see Figure 2) air temperature at 5 levels underneath the canopy (heights 17, 10, 3, 2, and 1 m) was measured. The observations of the air temperature profile inside canopy are used to monitor the possible cold or warm air layer that generates drainage flow on the slope area. Figure 8 presents observations of the virtual potential temperature vertical profile for both dry and wet periods, during both day and nighttime. The pattern on the slope area is clearly very different when compared with that on the plateau K34 area (Figure 6), except in dry period during daytime when the air was stable inside the canopy.

During nighttime (wet and dry periods) a very stable layer predominates with inversion at about 9 m. These can likely be interpreted as a stable layer between two convective layers is associated with cold air (Figure 8). *Yi* [2008] hypothesized about a similar ‘‘*super stable layer*’’ developing during the night in sloping terrain at the Niwot Ridge AmeriFlux site. This hypothesis suggests that above this layer, vertical exchange is most important (vertical exchange zone) and below it horizontal air flow predominates (longitudinal exchange zone). The relationship between subcanopy thermal structure and the dynamic of the airflow on the slope area will be discussed in next section.

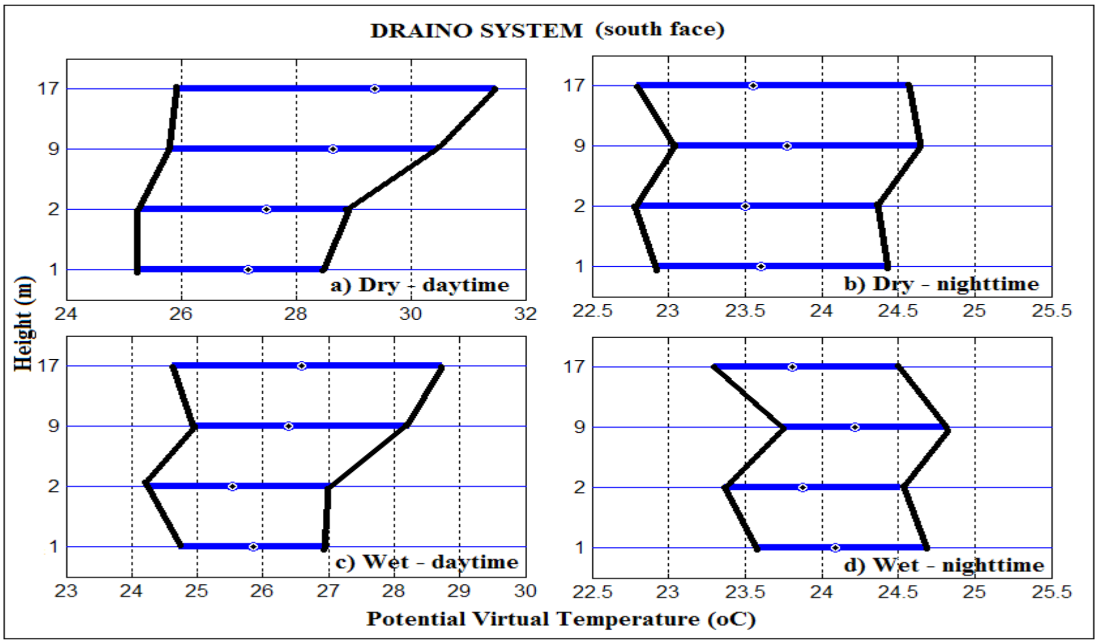

Figure 8: Boxplot of the virtual potential temperature vertical profile for dry (a, b) and wet periods (c, d) of the 2006 during night (b, d) and daytime (a, c), on the slope area DRAINO System tower (south face, see Figure 2).

Figure 9 presents a daily cycle composite of the virtual potential temperature deviation from the vertical average ($[\boldsymbol{\theta_v}(\boldsymbol{z}) - \overline{\boldsymbol{\theta_v}}(\boldsymbol{z})_1^{18}]$). There is persistent cold air entering during nighttime for both dry and wet periods, a characteristic pattern observed on the slope area. It is a very different vertical thermal structure from that of the plateau area. The cold air in the subcanopy upper layer is probably associated with top canopy radiative cooling, while the cold air just above floor layer is associated with upslope wind from the valley area (as discussed later in the next section).

The average of the vertical gradient virtual potential temperature was negative during nighttime and positive during daytime for both periods dry and wet (Figure 9). This observation shows that during the daytime a relative cooler subcanopy air layer predominates creating a inversion conditions. In contrast, a relative hotter subcanopy air layer generates a lapse conditions during nighttime. In general that is not a classical thermal condition find on the sloping open areas without dense vegetation. A similar pattern was reported by *Froelich and Schmid* [2006] during “leaf on” season.

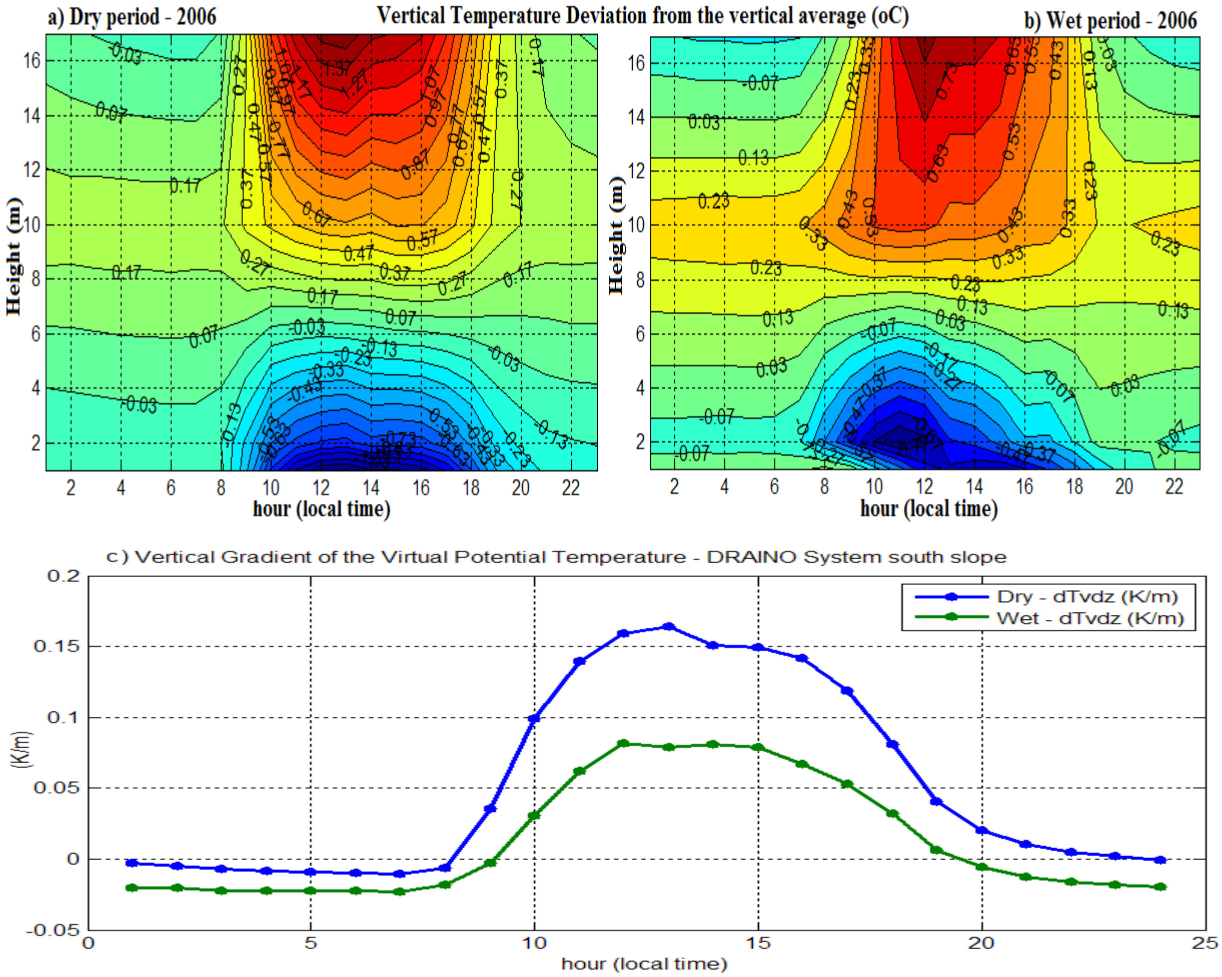

Figure 9: Daily course of the vertical deviation of the virtual potential temperature for dry (a) and wet (b) periods of the 2006, and the virtual potential temperature vertical gradient (c), over slope area DRAINO System tower.

3.2. Wind field

The LBA Manaus Site has moderately complex terrain when compared with the Santarem LBA Site (Figure 1, 2). This complexity generates a wind airflow regime much complex to be captured by standard measurement system like a single tower. At the Manaus LBA site, we implemented a complementary measurement system on the slope area to support the plateau K34 tower and better understand how the airflow above and below the canopy interact and also to describe how the valley flow influences the slope airflow regimes. Note that the valley in the microbasin is oriented from East to West (Figure 2, 4).

3.2.1 – Horizontal wind regime - ***above canopy***

3.2.1.1 - Plateau K34 tower

Above the canopy (55m above ground level – a.g.l.) on the plateau area K34 tower, the wind regime was strongest (most above 2 $m.s^{-1}$) during daytime for both dry and wet periods of 2006, with direction varying mostly from southeast and northeast for dry and wet period, respectively (Figure 10).

During nighttime, the wind regime was slower (most below 3 $m.s^{-1}$) and with same direction variation from northeast to southeast (Figure 10). As reported by *de Araújo* [2009], the above canopy valley area wind speed and direction was different from that of the plateau area, suggesting a decoupling mainly during nighttime. A clear channeling effect on the valley wind regime was observed; which was oriented by microbasin topography during both day and nighttime, with direction of the flow in the valley area determined by the valley orientation [as also reported by *de Araújo*, 2009].

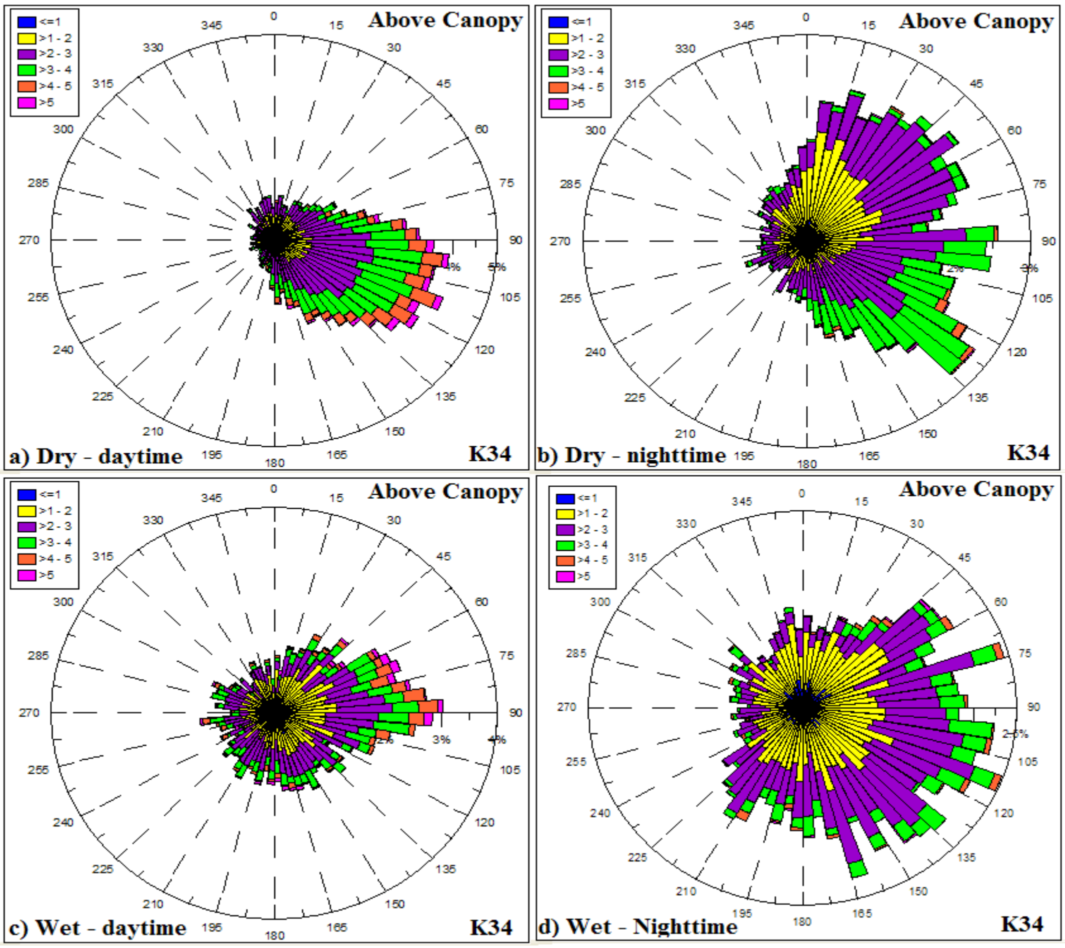

Figure 10: Frequency distribution of the wind speed and direction. For dry (a, b) and wet (c, d) periods from 2006 during day (a, c) and nighttime (b, d), on the plateau K34 tower.

3.2.1.2 -DRAINO System slope tower

The above canopy (38 m above ground level – a.g.l.) on the slope area DRAINO system south face (see Figure 4, 3D sonic), the wind regime was very persistent from East quadrant direction during day and nighttime in both dry and wet periods of the 2006 (Figure 11). The daytime wind speed during the dry season was between 1 to 3 m s^{-1} and much stronger during the wet period with values up to 4 m s^{-1}. During the nighttime the wind speed was slower than 2 m s^{-1}, except from northeast during the wet period. The wind direction pattern was similar to that on the plateau K34 tower (Figure 10) prevailing from northeast to southeast. This observation indicates that the airflow above the canopy on the slope area is related to how the synoptic flow enters in the eastern part of the microbasin (see Figure 2, 4).

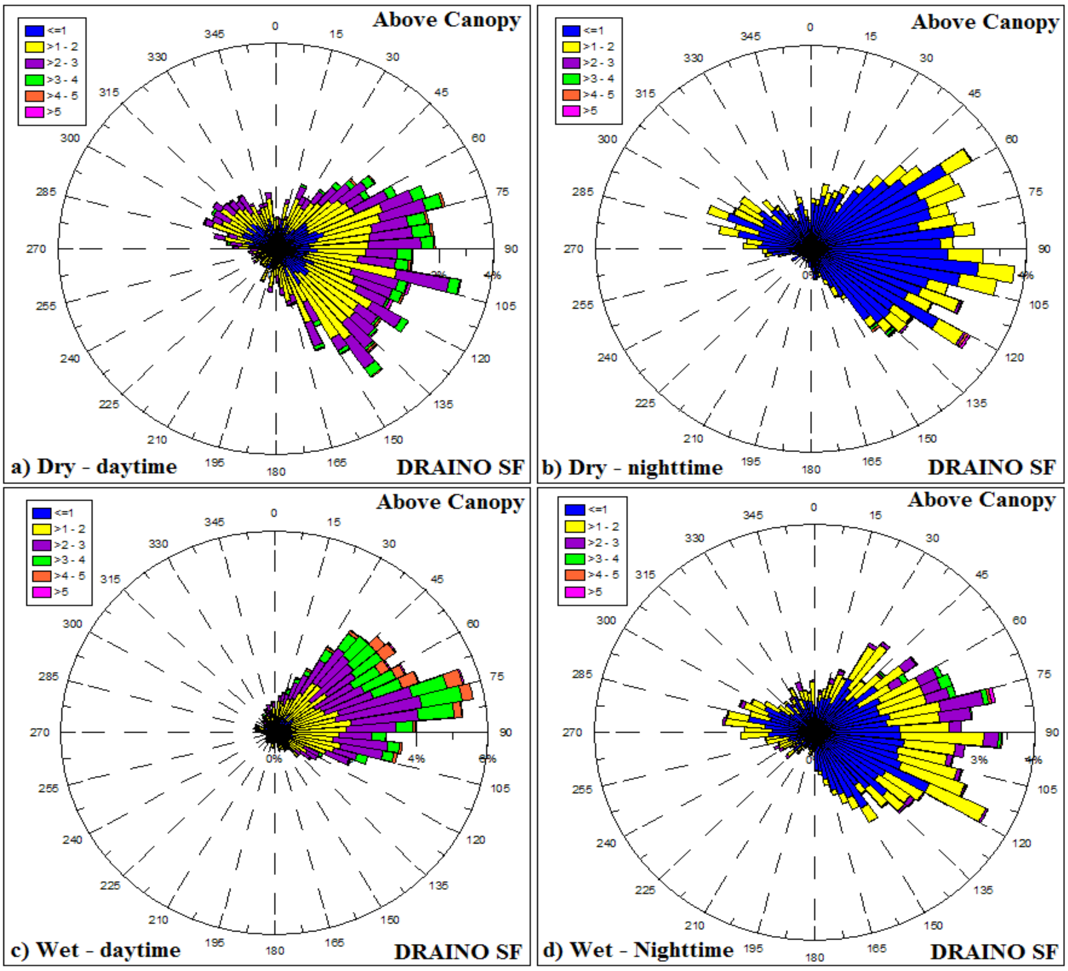

Figure 11: Frequency distribution of the wind speed and direction above canopy (38 m above ground level – a.g.l). For dry (a, b) and wet (c, d) periods from 2006 during day (a, c) and nighttime (b, d), on the slope area at DRAINO system tower.

*3.2.2 – Horizontal wind regime – **Subcanopy array measurements (2 m a.g.l)***

In Figure 12 the subcanopy array frequency distribution of the wind speed and directions is shown for both dry and wet periods of the 2006, during both day and nighttime. The observations show that the airflow in the subcanopy is very persistent and with similar pattern during both dry and wet periods of 2006. Note that the south slope area in the DRAINO System (see Figure 4) is ***downslope*** from **south** and ***upslope*** from **north** quadrants.

*Subcanopy **daytime** wind regime*

During daytime, in both dry (Figure 12a-c) and wet periods (Figure 12g-i), the wind direction prevailed from south-southeast (190-150 degrees) on the three southernslope regions [Figure 12, Top (a, d, g, j), Middle (b, e, h, k) and Low slope part (c, f, i, l)]. The airflow in the subcanopy was decoupled from the wind regime above the canopy (Figure 11) most of the time.

The wind direction in the subcanopy airflow was dominated by a daytime downslope regime during the majority of the period of study, suggesting a systematic daytime katabatic wind pattern. The wind speed in the subcanopy during the daytime was mostly from 0.1 to 0.4 m/s, and strongest at middle slope region (Figure 12b, e, h, k) about 0.3 to 0.5 m/s or above. A similar daytime katabatic wind regime was reported by *Froelich and Schmid* [2006] during “leaf on” season in Morgan-Monroe State Forest (MMSF), Indiana USA.

The daytime downslope wind was also supported by the subcanopy thermal structure (Figure 9), where the air was cooling along the day by inversion of the virtual potential temperature profile with a positive vertical gradient (Figure 9c). This results shows that subcanopy flows in a sloping dense tropical rainforest are opposite to the classical diurnal patterns of slope flows studied elsewhere in the literature [e.g.; *Manins and Sawford*, 1979; *Sturman* (1987); *Amanatidis et al*., 1992; *Papadopoulos and Helmis*, 1999; *Kossmann and Fiedler*, 2000]. It is important to note that few studies have been done in forested terrain and it is unclear why similar reversed diurnal patterns have not been observed in studies at other forested sites [*Aubinet et al*., 2003; *Staebler and Fitzjarrald*, 2004; *Yi et al*., 2005], except by a single point subcanopy measurement observed by *Froelich and Schmid* [2006].

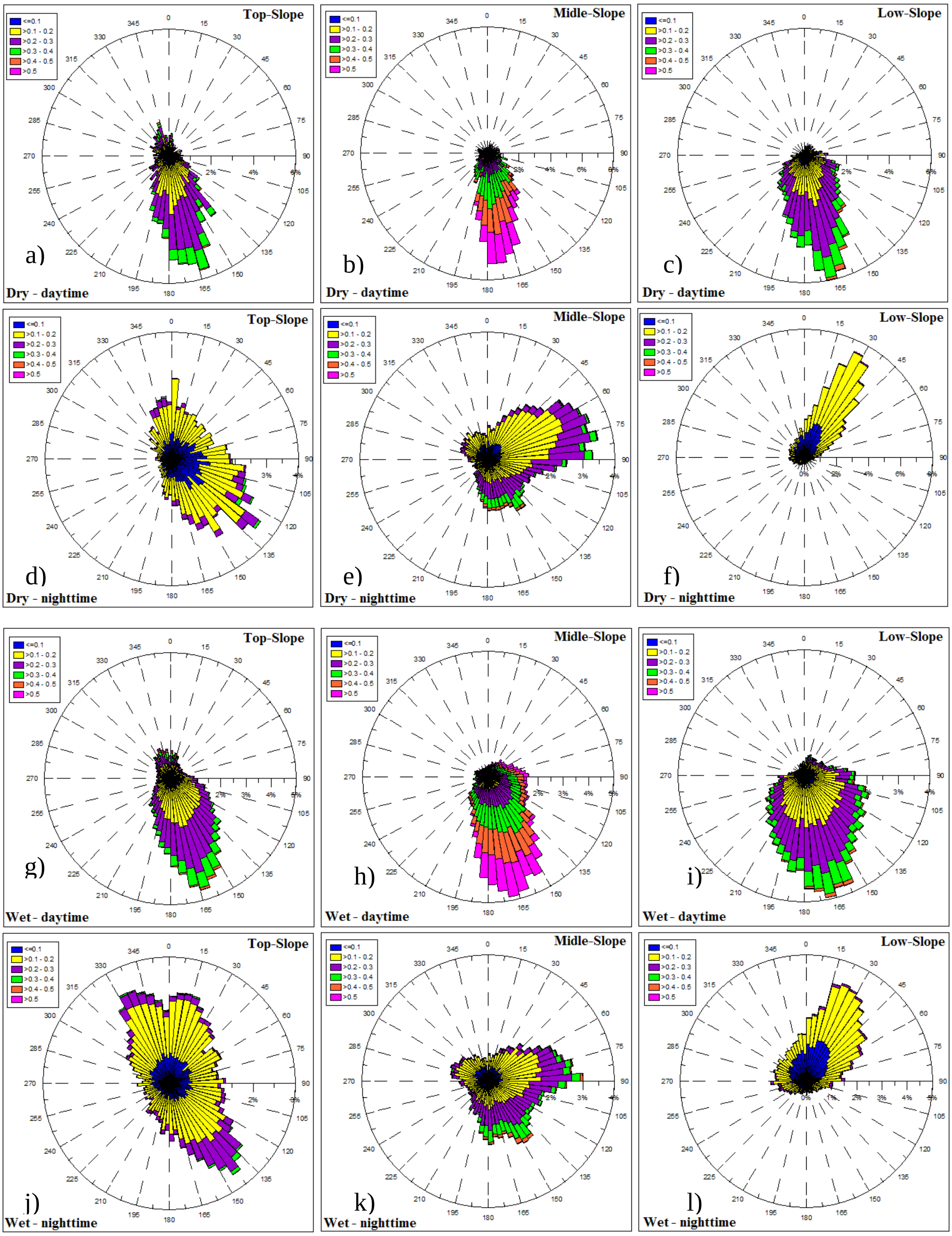

Figure 12: Frequency distribution of the wind speed and direction in the subcanopy array (2 m above ground level – a.g.l) on the microbasin south face slope area at DRAINO horizontal array system (see Figure 4). For dry (a-f) and wet (g-l) periods from 2006, during day (a, b, c, g, h, i) and nighttime (d, e, f, j, k, l).

Subcanopy ***nighttime*** *wind regime*

The nighttime subcanopy wind regime on the slope area (see the terrain on Figure 4) was very complex and differentiates from that one above the canopy vegetation.

It was observed that, on the up-slope part, the nighttime airflow was southeast downsloping direction (130°-170°) and northeast-northwest (45°-340°) uphill direction (Figure 12d, j). In the middle-part of slope area, the wind moved uphill (from northeast; 30°-90°) and also downsloping wind direction from southeast (Figure 12e, k), and with lightly higher wind speed. And finally, on the lower-part of the slope area (Figure 12f, l) the wind direction prevailed from the northeast (10°-70°), indicating upsloping pattern (anabatic).

Is interesting to note that, on the up-slope area, the wind direction regime (northeast-northwest, 45°-340°) suggest a reversal lee side airflow (re-circulation or separation zone) probably in response to the above canopy wind (see Figure 11b, d). It is has been suggest by *Staebler* [2003] and reported by simulations using fluid dynamic models [*Katul and Finnigan*, 2003; *Poggi et al*., 2008].

Also, the upsloping subcanopy flows pattern, on the lower-part the slope area, is supported by subcanopy relative heat air layer along the slope during the night, as observed by lapse rate condition of the virtual potential temperature negative vertical gradient (Figure 9c). This observation does not follow the classical concept of nighttime slope flow pattern. *Froelich and Schmid* [2006], has reported similar feature where they found anabatic wind regime during nighttime in their seasonal forest study area.

Figure 13 presents the frequency distribution of the subcanopy wind direction on the south face slope area at DRAINO horizontal array system during upsloping (from north quadrant) and downsloping (from south quadrant) events.

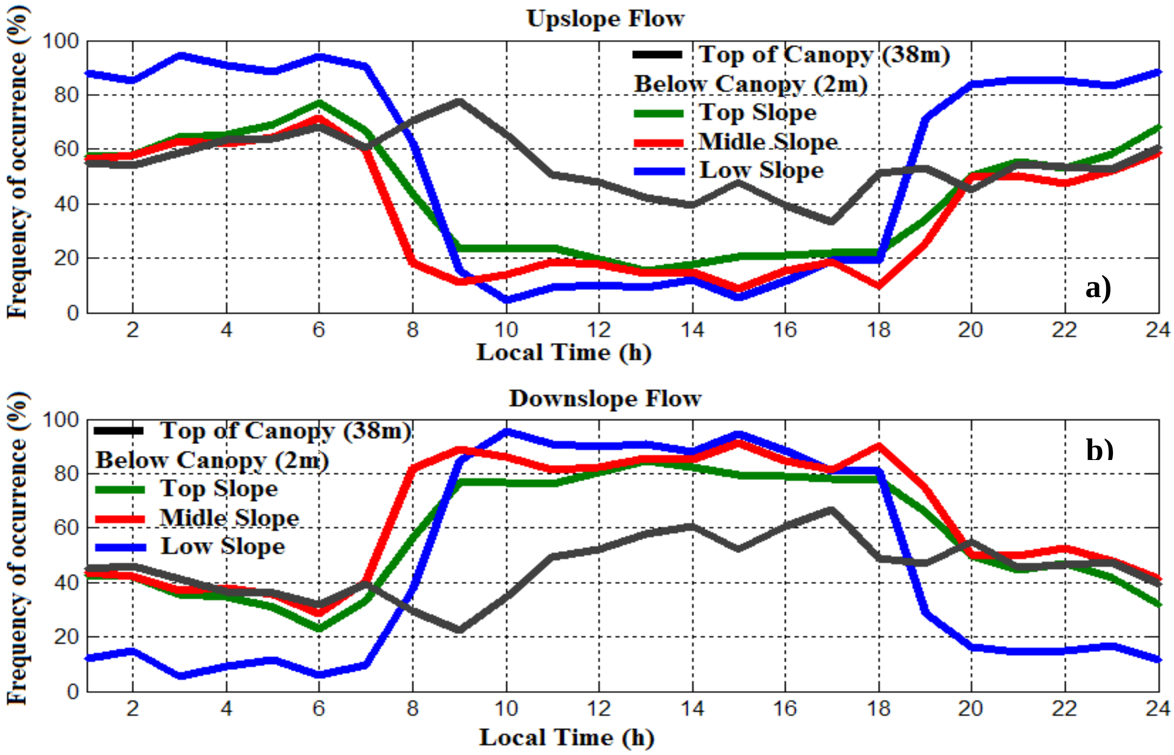

Figure 13: Frequency distribution of the subcanopy wind direction **(a) upsloping** (from north quadrant) and **(b) downsloping** (from south quadrant) on the south face slope area at DRAINO horizontal array system (see Figure 4).

3.2.3 – Mean Vertical wind velocity – ***subcanopy and above canopy***

Several correction methods have been proposed to calculate the mean vertical velocity, e.g. linear regression method [*Lee*, 1998], coordinate rotation [*Finnigan et al*., 2003] and the planar fit method [*Wilczak et al*., 2001]. We use the linear regression method by *Lee* [1998] to determine the ‘‘true’’ mean vertical velocity: $\boldsymbol{\overline{w} = w - a(\alpha_i) - b(\alpha_i)u}$, where *a* and *b* are coefficients to be determine, for each α_i (10^{o} azimuthal wind direction), by a linear regression of measured mean vertical velocity (*w*) and horizontal velocity (*u*) in the instrument coordinate system.

Figure 14a presents the original and the correction results by method application of the mean vertical velocity as function of wind direction. In Figure 14b, the results of the hourly mean vertical velocities for plateau K34, DRAINO system (above and below canopy) and valley B34 towers. As expected, low values were observed for all points of measurements, but non-zero values were also observed.

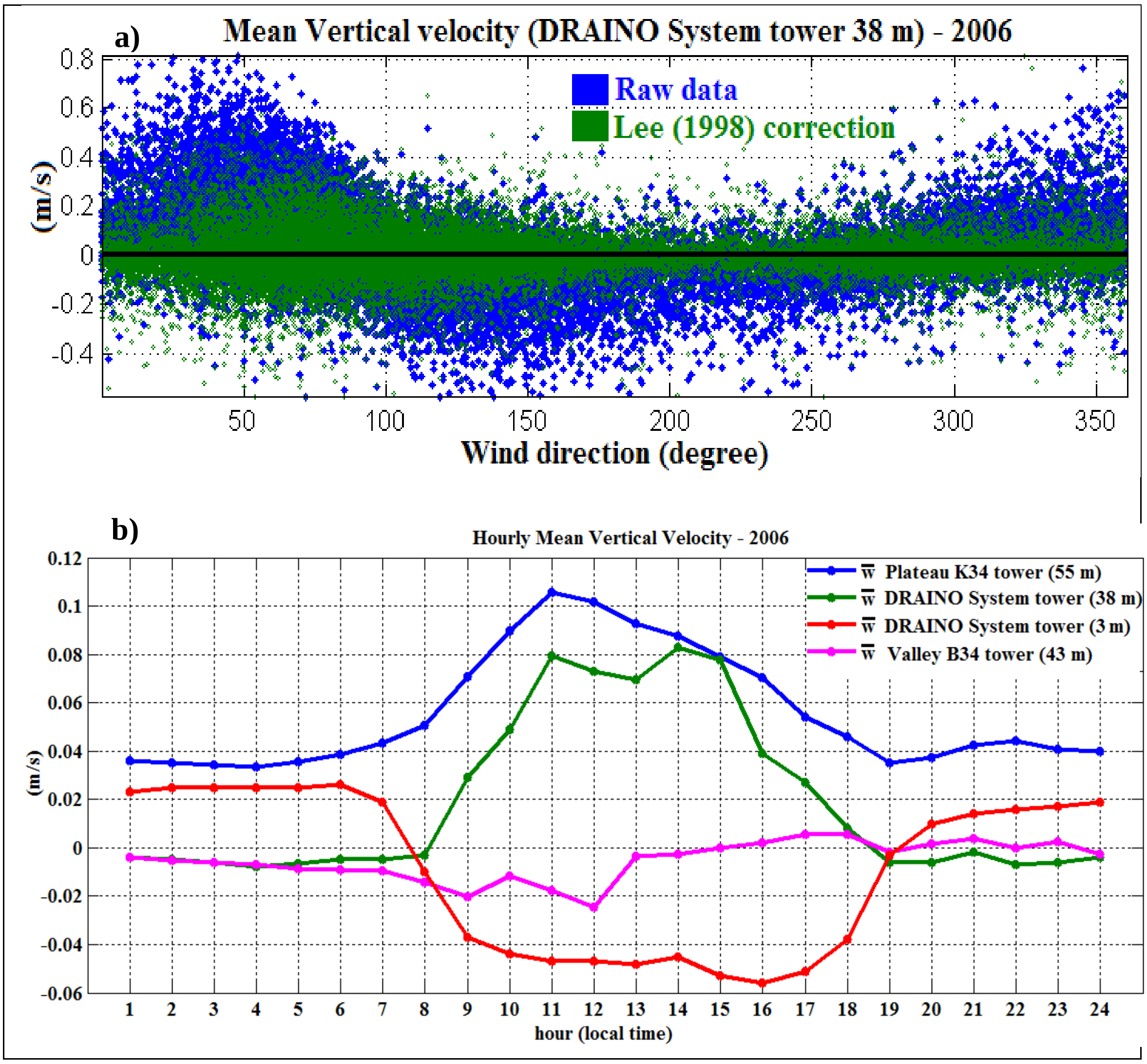

Figure 14: Mean vertical velocity raw and correct vertical velocity (a) for DRAINO system slope tower (38 m), and hourly mean vertical velocity (b) for: plateau K34 tower (55 m), DRAINO system slope tower (above canopy - 38 m and subcanopy - 3 m) and for valley B34 (43 m) towers (see Figure 4, for details).

On the plateau area, the mean vertical velocity was always positive indicating upward motion or vertical convergence at top of hill during night and daytime. In the valley area during nighttime, negative or zero values were observed, indicating a suppression of vertical motion (mixing) in the valley, as also reported by *de Araújo* [2009]. On the other hand, during the daytime a transition is observed, where beginning in the morning, downward motion is observed, changing after mid-morning to upward motion (Figure 14b). This suggests that probably the cold air pooled during night moved downslope and started to warm, resulting in a breakdown the inversion over the valley (see *de Araújo* [2009], for detailed description and references there in for this process). The mechanism of the breakdown the inversion process over the valley is consistent with positive vertical velocity observed above canopy at slope area observed by the DRAINO system tower during daytime (Figure 14b).

The subcanopy diurnal pattern of the mean vertical velocity observed shows positive values during nighttime and negative during daytime, consistent with observed up and downsloping flow regime, respectively (Figure 13 a, b). Also this is consistent with thermal vertical virtual potential temperature gradient on the slope (see Figure 9c), where during nighttime (daytime) an unstable (inversion) condition is associated with upward (downward) mean vertical velocity (see Figure 9c).

3.3. Phenomenology of the local circulations: Summary

The Figure 15 shows a schematic cartoon of local flow circulation from the previews sections observations.

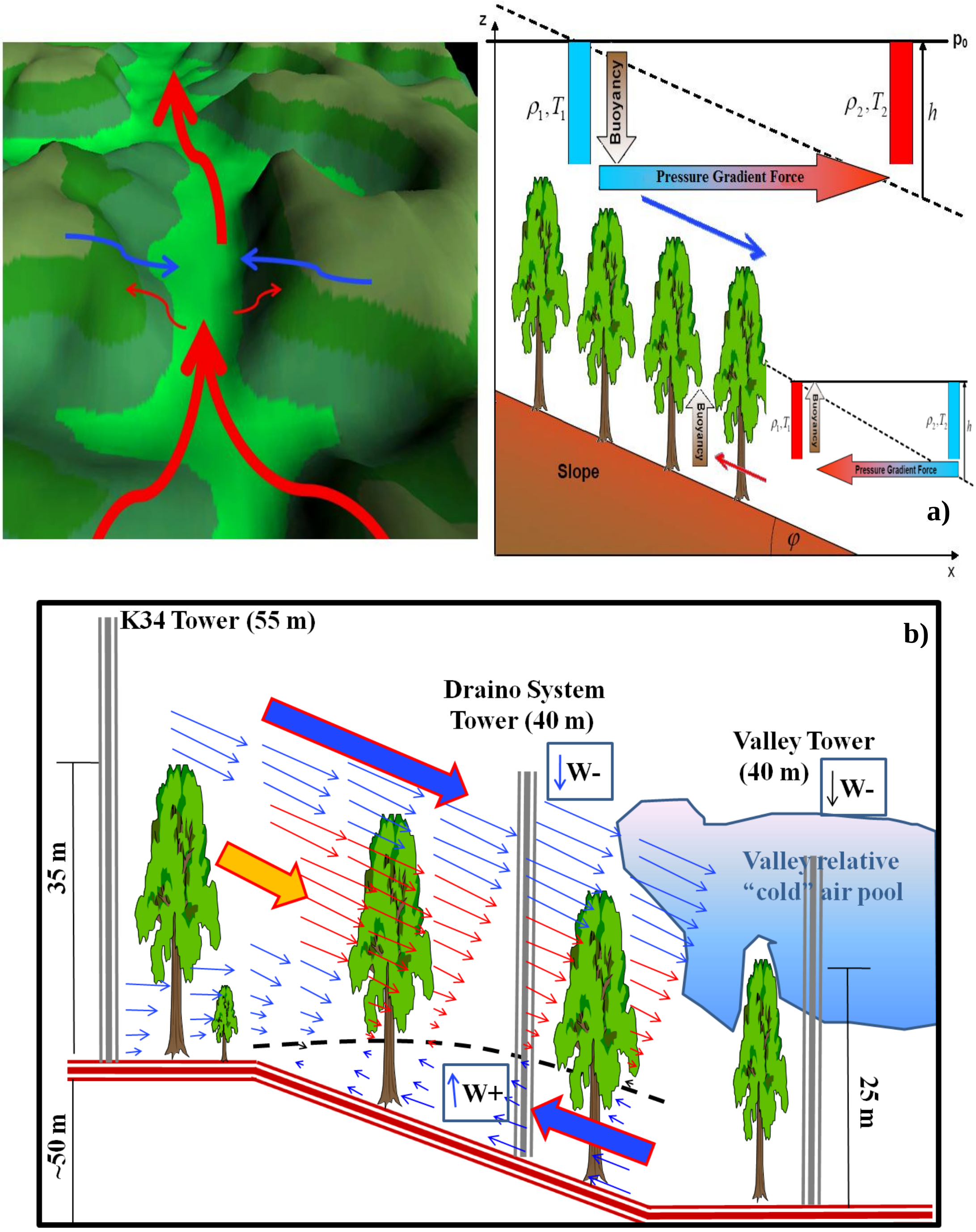

Figure 15: Schematic local circulations in the site studied, valley and slopes flow (a), 2D view from suggested below and above canopy airflow (b).

The above canopy airflow (red arrow Figure 15a) and forcing mechanisms associate. The observations result from previews sessions suggests that the balance of the buoyancy and pressure gradient forces generates the airflow or microcirculations patterns in the site studied. During nighttime (Figure 15b), in the subcanopy there is an upslope flow reaching about 10 m height above ground, associate with positive mean vertical velocity (indicating upward movement). Also, above canopy there is a downslope flow associate with negative mean vertical velocity, downward convergence above the canopy. The microcirculation along the plateau-slope-valley is promotes by an feedback mechanism of accumulation of cold air drainage above canopy into the valley center (Figure 15b), creating the forcing need to sustain nighttime pattern. The air temperature structure above canopy in the valley (see Araújo, 2009) is a good indication of cold air pool in the center of the valley. Maybe, also, the local pressure gradient force due the cold air accumulation promoting the upward airflow in the both slopes of the valley. During daytime periods an inverse pattern is found (not show), indicating that this microcirculation is a systematic pattern in the site.

3.4. CO_2 ***concentration and subcanopy horizontal wind field***

The CO_2 concentration was measured by DRAINO system on the south face slope area for dry and wet periods of the 2006, and on the north face slope during dry period (Figure 4). The Figure 16 presents an example, for midnight (local time), of the horizontal wind field and spatial CO_2 concentration over the DRAINO System south face domain. The wind field was interpolated from the blue points onto a 10 m grid. Similar procedures have been reported in the literature (*Sun et al.*, 2007; *Feigenwinter et al.*, 2008). The horizontal wind regime plays important role in modulating the horizontal spatial distribution of CO_2 concentration (Figure 16).

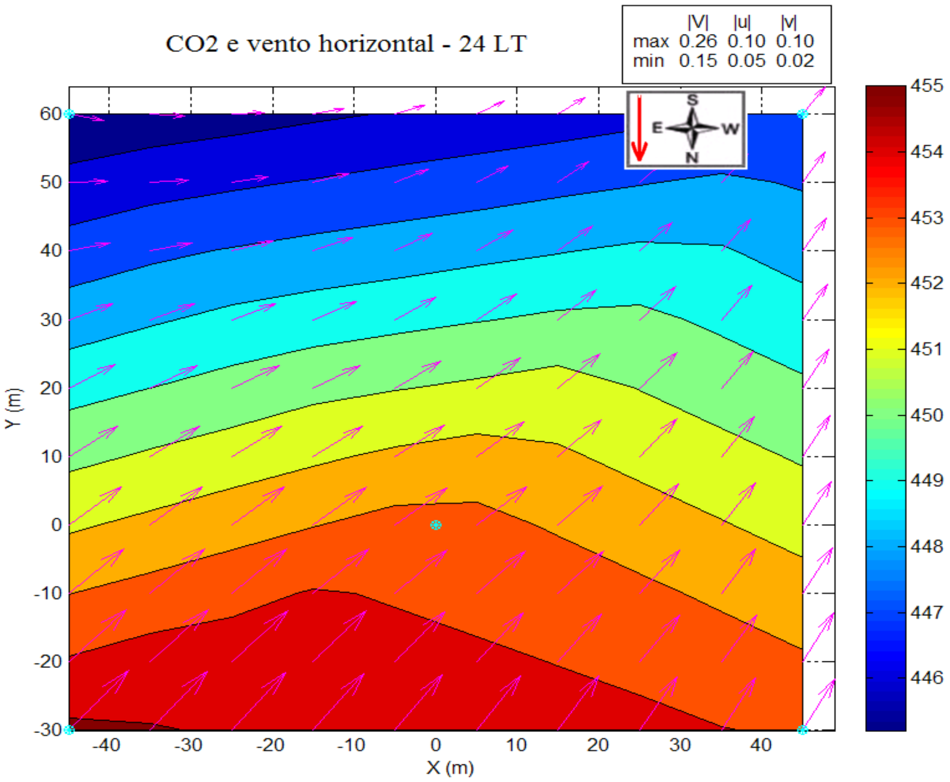

Figure 16: Example at midnight (local time) of the horizontal CO_2 concentration over the DRAINO System south face domain including an interpolated horizontal wind field (10 m grid), note the geographic orientation and the red arrow indicating slope inclination (see Figure 4).

In Figure 17 (a, b, c) the typical pattern observed is shown for both dry and wet periods of the 2006 measured by the DRAINO system on the south-facing slope area. During the daytime (Figure 17c), the wind prevailed downslope inducing a strong horizontal gradient of CO_2 in the slope area (about 0.2 ppmv m^{-1}). In the evening, periods of changes of the horizontal wind pattern (as described in section 3.1) show an upsloping regime in the lower-part and downsloping in the upper-part of the slope areas (Figure 17b). The wind regimes produce direct responses in the spatial feature of the horizontal gradient of CO_2 concentration. Later during the night, the upsloping regime is well established and also the horizontal gradient of CO_2 is growing from lower part of slope to the top (Figure 17a). These observations suggest a subcanopy drainage flow and its influence on the scalar spatial distribution. Therefore, as discussed in the previews sections, the flow above the canopy indicates a reverse pattern of downward motion (negative mean vertical velocity, see section

3.2.3) that suggests vertical convergence and possible horizontally divergent flow during nighttime. The report by *Froelich and Schmid* [2006] and more recently *Feigenwinter et al.*, [2009a, b] describing similar features of the airflow interaction between above and below canopy.

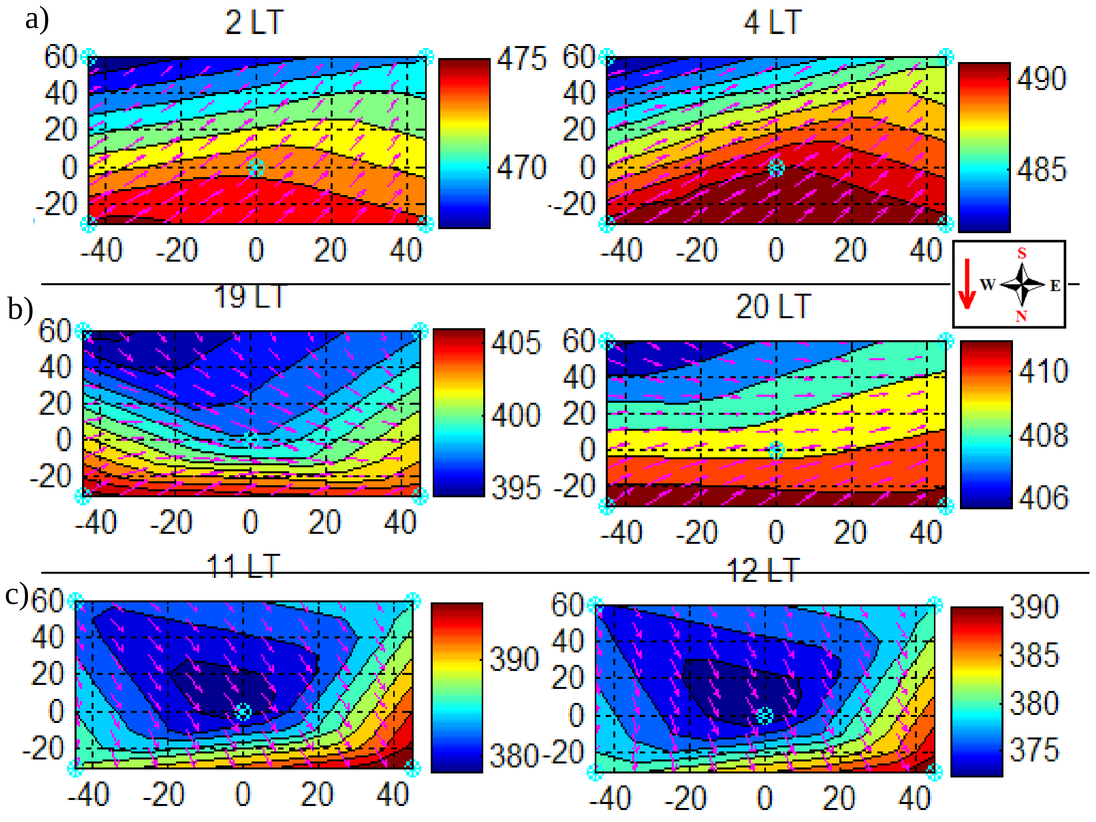

Figure 17: Hourly average of the subcanopy (2 m) CO_2 concentration and horizontal wind speed over DRAINO System south face area during dry period of the 2006, note the geographic orientation and the red arrow indicating slope inclination (see Figure 4). The axis represents distances from center of the main tower. Daytime (a), transition period - evening (b), established nighttime (c).

Along the north face, as shown in the Figure 18, the spatial distribution of the horizontal CO_2 concentration shows a similar pattern than the south face described previously. Despite, that there is no wind information in that area, if one assumes the same spatial correlation between horizontal wind and CO_2 concentration, is possible suggest that the wind should presents an inverse pattern from the south face. Its means that, during daytime the downslope wind direction should be from northeast (Figure 18c, from blue to red color).

During evening period (Figure 18b) should be indicating downslope (from northeast) in the upper part of the north face slope and upslope (from southeast) in the lower part of the slope, an inverse feature from Figure 17b. Finally, later in the night, on the north face slope, the wind pattern should present an upslope wind direction regime from southeast, an inverse regime that one from Figure 17a on the south face slope.

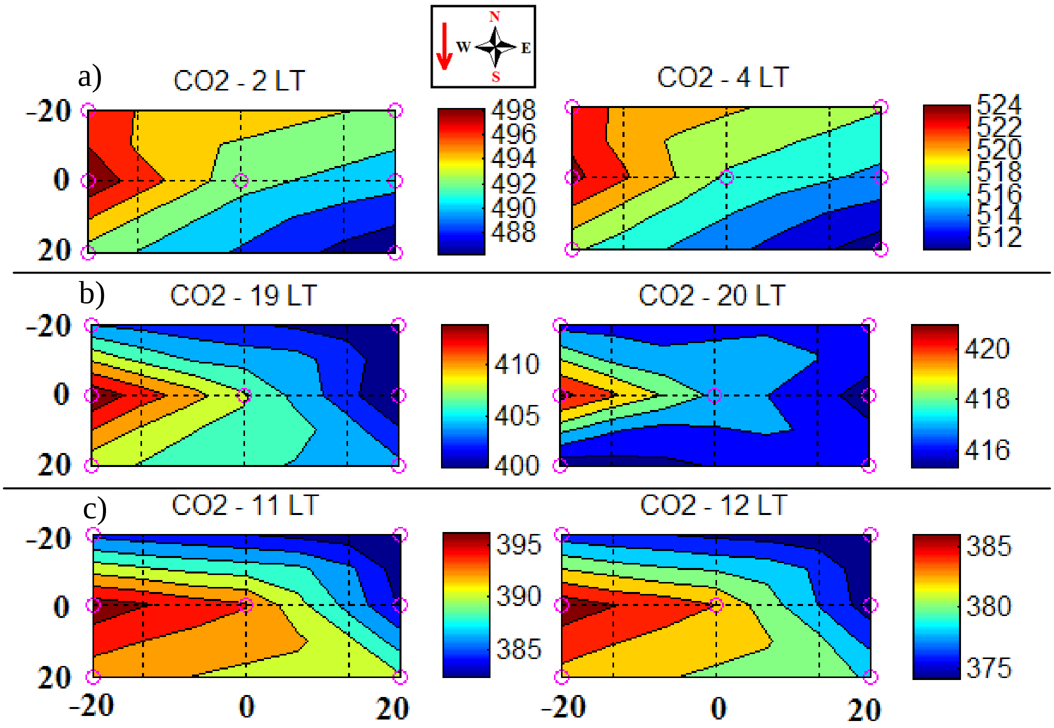

Figure 18: Hourly average of the subcanopy (2 m) CO_2 concentration on the DRAINO System north face area during dry period of the 2006, note the geographic orientation and the red arrow indicating slope inclination (see Figure 4). The axis represents distances from center of the main tower. Daytime (a), transition period - evening (b), stablished nightime (c).

One possible explanation to this subcanopy slopes wind regime and spatial distribution of CO_2 concentration, is the valley wind channeling effect and how it is meandering when enter in the valley topography [as described by *Araújo*, 2009]. This valley wind pattern, probably causes oscillations as those observed on the CO_2 concentration along the day (Figures 17, 18), the known “Seiche phenomena” (*Spigel and Imberger*, 1980).

4. Summary and Conclusions

The main objective of this study was to measure and understand the local circulation over a dense forest site in Manaus with moderately complex terrain and to verify the existence of the drainage flow regimes on slope and valley areas.

The main pattern of the airflow above and below the canopy in dense tropical forest in Amazonia was captured by a relative simple measure system, as also has been done by more sophisticated measurements system as those described recently by *Feigenwinter et al.*, [2009a, b].

As described and discuss in previews sections it was identified drainage flow in both day and nighttime periods in the site studied. Evidence of the drainage current above canopy was suggested by *Goulden et al*, (2006) similar to that one observed here.

It was identified that the local micro-circulation was complicate and presented tri-dimensional nature where to estimate the advection flux at this site seems uncertain and not possible with the limited measurement system employed.

As reported recently by *Feigenwinter et al.*, [2009a, b], even using a more sophisticated measurement design, the level of uncertainties is still high and some processes are not yet known and need more exploration perhaps using a more complete spatial observation network or even applying model resources (*Foken*, 2008; *Aubinet*, 2008, *Belcher et al*., 2008).

In summary, the drainage flow exists and is observed at K34 LBA site area and the high carbon uptake reported by previews work may be called into doubt and requires more research.

Also, the use of nighttime correction in order to save the urge necessity to estimate long term Net Ecosystem exchange is inappropriate by the using only turbulence information from above canopy, as has been pointed out here The interactions above and below canopy breakdown the footprint principle and the representativeness of the eddy flux tower in most difficult conditions (complex terrain and calm nights).

In summary, the drainage flow exists and is observed at K34 LBA site. Very large carbon uptake estimates reported previously should be questioned [*Kruijt et al*., 2004*; Araújo et al*., 2002]. More research is needed. The use of nighttime u_* correction to avoid estimating canopy storage is inappropriate. One cannot get by using only above canopy turbulence information. The interactions between motions above and below canopy question the foundations of the footprint analysis [*Schuepp et al*., 1990; *Schimid*, 2006]. The representativeness of the eddy flux tower is most in question for complex terrain, especially on calm nights).

CONCLUSÃO GERAL

No Capítulo I foi apresentado que:

- Foi realizado o primeiro esforço em determinar observacionalmente a importância dos processos de advecção noturna no balanço de CO_2 em uma densa floresta tropical na Amazônia.
- Foi testada a hipótese de que uma persistente advecção horizontal abaixo da floresta existe e transporta uma importante quantidade de CO_2 para fora do volume de controle representado pelas medidas da torre de fluxo do LBA em Santarém.
- Foi determinada a magnitude dos gradientes horizontais de CO_2 e do campo do vento abaixo da floresta e encontrado um saldo suficiente de advecção para afetar o balanço de CO_2.
- A metodologia estabelecida foi aplicada e testada para medir os gradientes horizontais de CO_2 e do vento horizontal dentro da floresta. Esses dados foram complementados pelos fluxos turbulentos e observações dos perfis médios obtidos em uma torre de 65 metros de altura no mesmo sítio experimental (sessão 2). As medidas foram realizadas durante o período das estações seca (DOY 198-238 2003 – Fase 1) e úmida (DOY 278-366 2004 e 1-32 2005 – Fase 2).
- Os gradientes horizontais médio de CO_2 e do vento horizontal foram da ordem de 0.02 ppm m^{-1} e 0.12 m s^{-1}, respectivamente (seção 3.1).
- Abaixo da floresta a direção do vento horizontal foi bem correlacionada com a inclinação suave do terreno próxima a torre de medida dos fluxos. Foi observado que a direção do escoamento abaixo da floresta foi desacoplada do escoamento acima, o que sugere um potencial para transporte lateral de CO_2 mesmo durante o período diurno (sessão 3.2).
- O principal mecanismo físico responsável pela geração do escoamento noturno abaixo da floresta foi o termo de flutuabilidade negativa (seção 3.3).

- A comparação do déficit noturno entre a respiração total do ecossistema e NEE medida no sistema de fluxo da torre foi associado à advecção noturna média de CO_2, a qual representou 73% e 71% do mesmo, para 130 noites analisados durante os períodos seco e chuvoso estudados. Isto indica um importante papel da advecção noturna no balanço total de CO_2.
- Foi observado também que, durante períodos noturnos com níveis de turbulência significativos (u* entre 0.3 a 0.6 m s^{-1}, limiares considerados suficiente para fornecer corretas medidas pelos fluxos turbulentos), o transporte de CO_2 pela advecção horizontal foi significativo.
- Esses resultados confirmam que poucos sítios de medidas de fluxos são suficientemente planos e homogêneos para ignorar *a priori* os efeitos da advecção horizontal. Estimativa observacional do efeito da velocidade vertical média no balanço de escalares aparece como a maior fonte de incertezas, e medidas continua e de longo prazo com instrumentação mais adequada são necessárias para esclarecer este tema.

No Capítulo II foi apresentado que:

- Seguindo a metodologia e design experimental desenvolvido no Capitulo I, foi possível ser aplicada também para um sitio experimental com topografia de maior complexidade.
- Foi observado que existem escoamentos de drenagem horizontal abaixo e acima da floresta, e que esses estão fortemente influenciados pela canalização do vento horizontal ao longo do vale da microbacia Asu próximo da torre de fluxo (K34) e das medidas nas encostas abaixo da floresta (Sistema DRAINO).
- Especialmente no **sítio do LBA em Manaus**, não foi possível estimar quantitativamente a magnitude da advecção horizontal de CO_2, em função da complexa heterogeneidade topográfica da área produzindo uma complicada natureza tridimensional do escoamento

abaixo e acima da floresta, que se interagem e criando uma barreira para medir em detalhe todas as informações com a metodologia e instrumentação disponível neste estudo.

- As sub-estimativas noturnas das taxas de respiração através de medidas aplicando a técnica de “Eddy Covariance” sobre vários tipos de ecossistemas e terrenos já é bem reconhecida pela comunidade científica mundialmente. Os estudos observacionais aqui apresentados suportam esta hipótese demonstrando a importância do transporte horizontal que ocorre abaixo do nível de medida das torres de fluxo de ambos **os sítios de medidas do LBA**. E finalmente adverte que correções dos fluxos turbulentos noturnos com base em condições acima da vegetação somente podem ser inapropriadas e com significante incerteza.
- Como sugestões os estudos de modelagem do tipo LES, já que foi identificado um padrão de micro circulações locais de natureza tridimencional, seriam de fundamental importância para avaliar e ajudar a entender melhor as observações aqui obtidas.

REFERÊNCIAS

Acevedo, O. C. and Fitzjarrald, D.R. (2003), In the Core of the Night - Effects of Intermittent Mixing on a Horizontally Heterogeneous Surface. *Boundary-Layer Meteorology*, Dordrecht, v. 106, n. 1, p. 1-33.

Antonia, R.A., Chambers, A.J., Frieh, C.A.E. and van Atta, C.W., (1979), Temperature ramps in the atmospheric surface layer. J. Atmos. Sci. 36, pp. 99–108.

Araújo, A. C., et al., (2002), Comparative measurements of carbon dioxide fluxes from two nearby towers in a central Amazonian rainforest: The Manaus LBA site, *Journal of Geophysical Research, 107*(D20), 8090, doi:10.1029/2001JD000676.

Araújo, A. C., et al., (2008), Interaction of micrometeorology and surface fluxes confounding the interpretation of CO_2 fluxes in Central Amazonia. *Submited to Agricultural and Forest Meteorology*.

Araújo, A. C., (2009), Spatial variaton of CO_2 fluxes and lateral transport in an area of terra firme forest in central Amazonia. PhD Thesis, Vrije Universiteit Amsterdam, VU, Holanda.

Aubinet M, P. Berbigier, C. H. Bernhofer, A. Cescatti, C. Feigenwinter, A. Granier, T. H. Grunwald, K. Havrankova, B. Heinesch, B. Longdoz, B. Marcolla, L. Montagnani, P. Sedlak (2005), Comparing CO_2 storage and advection conditions at night at different Carboeuroflux sites. *Boundary Layer Meteorol., 116*: 63-94.

Aubinet, M., B. Heinesch, and M. Yernaux (2003), Horizontal and vertical CO_2 advection in a sloping forest, *Boundary Layer Meteorol*., *108*(3), 397–417.

Aubinet, M., et al., (2000), Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. *Adv. Ecol. Res*., *30*, 113–175.

Baker I. T., Prihodko, L., Denning, A.S., Goulden, M., Miller, S., da Rocha, H.R., (2008), Seasonal drought stress in the Amazon: Reconciling models and observations, *J. Geophys. Res*., 113, G00B01, doi:10.1029/2007JG000644

Baker, T.R. et al., (2004), Increasing biomass in Amazonian forest plots. *Philosophical Transactions of the Royal Society of London*. Series B-Biological Sciences, 359(1443): 353-365.

Baldocchi, D. D., B. B. Hicks, and T. P. Meyers (1988), Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods, Ecology, *69*(5), 1331– 1340.

Baldocchi, D., et al. (2001), FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, *Bull. Am. Meteorol. Soc*., *82*(11), 2415 – 2434.

Baldocchi, D., J. Finnigan, K. Wilson, T. Paw U, and E. Falge (2000), On measuring net ecosystem carbon exchange over tall vegetation on complex terrain, *Boundary Layer Meteorol.*, *96*(1–2), 257–291.

Barr, S., (1971), A modeling study of several aspects of canopy flow. Monthly Weather Review, vol. 99, No. 6: 485-493.

Baynton, H. W., Biggs, W. G., Hamilton, H. L., Jr., Sherr, P. E., and Worth, J. J. B., (1965), Wind Structure in and Above a Tropical Forest. Journal of Applied Meteorology, Vol. 4, No. 6: 670-675.

Bergstrom, H., Hogstrom, U., (1989), Turbulent exchange above apine forest II. Organized structures. Bound.-Layer Meteorol.49: 231-263.

Bitencourt, D.P. and Acevedo, O. C., (2008), Modelling the Interaction Between a River Surface and the Atmosphere at the Bottom of a Valley. *Boundary-Layer Meteorology*, v. 129, p. 309-321.

Black, T. A., et al. (1996), Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest, *Global Change Biol.*, *2*(3), 219–229.

Bohrer, Gil, (2007), Large Eddy Simulations of Forest Canopies for Determination of Biological Dispersal by Wind. PhD Thesis. Department of Civil and Environmental Engineering, Duke University, 2007.

Castilho, C., (2004), Variação espacial e temporal da biomassa arbórea viva em64 km2 de floresta de terra-firme na Amazônia Central. 87p. Doctoral Thesis, ecology, Instituto Nacional de Pesquisa da Amazônia, Manaus-AM.

Chambers, J.Q. et al., (2004), Respiration from a tropical forest ecosystem: Partitioning of sources and low carbon use efficiency. Ecological Applications, 14(4): S72-S88.

Cionco, R. M., 1965: A mathematical model for air flow in a vegetation canopy. J. Appl. Meteor., 4, 517–522.

Clark D. B. (1996), Abolishing virginity. *Journal of Tropical Ecology, 12*, 735–739.

Cohen, J. C. P., Sá, L.D.A., Nogueira, D. S., Gandu, A.W., (2006), Jatos de baixos níveis acima da floresta amazônica em Caxiuanã. *Revista Brasileira de Meteorologia*, São Paulo, v.21, n.3b, p. 271-282.

Cuartas, L.A. et al., (2007), Interception water-partitioning dynamics for a pristine rainforest in Central Amazonia: Marked differences between normal and dry years. *Agricultural and Forest Meteorology*, 145(1-2): 69-83.

da Rocha, H. R., M. L. Goulden, S. D. Miller, M. C. Menton, L. D. V. O. Pinto, H. C. de Freitas, and A. M. E. S. Figueira (2004), Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia, *Ecol. Appl.*, *14*(4), suppl. S, S22– S32.

Denmead, O.T. and Bradley, E.F., (1985), Flux-gradient relationships in a forest canopy. *In: B.A. Hutchison and B.B. Hicks (Editors). The forest-atmosphere interaction*. D. Reidel Publishing Company, Dordrecht, Holland, pp. 421-442.

Dias, M. A. F. S. and P. Regnier., (1996), Simulation of mesoscale circulations in a deforested area of rondônia in the dry season. In Amazonian deforestation and climate, ed. J. H. C. Gash, C. A. Nobre, J. M. Roberts and R. L. Victoria:531-547. Chichester: J Weily.

Dixon, R.K., S.Brown, R.A. Houghton, A.M. Solomon, M.C. Trexler and J. Wisniewski, (1994), Carbon pools and flux of global forest ecosystems. Science, 263, 185-190.

Falge, E., et al. (2001), Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agric. For. Meteorol. 107*, 43-69.

Fan, S.M., Wofsy, S.C., Bakwin, P.S., Jacob, D.J. and Fitzjarrald, D.R., (1990), Atmosphere-biosphere exchange of CO_2 and O3 in the Central-Amazon-forest. Journal of Geophysical Research-Atmospheres, 95(D10): 16851-16864.

Feigenwinter, C., C. Bernhofer, and R. Vogt, (2004), The influence of advection on the short term CO_2-budget in and above a forest canopy, *Boundary Layer Meteorol*., *113*(2), 201–224.

Feigenwinter, C., C. et al., (2008), Comparison of horizontal and vertical advective CO_2 fluxes at three forest sites, *Agric. Forest. Meteorol*., *145*,1–21.

Feigenwinter, C., et al. (2009a), Spatiotemporal evolution of CO_2 concentration, temperature, and wind field during stable nights at the Norunda forest site. *Agric. Forest Meteorol*., doi:10.1016/j.agrformet.2009.08.005

Feigenwinter, C., Montagnani, L., Aubinet, M. (2009b), Plot-scale vertical and horizontal transport of CO_2 modified by a persistent slope wind system in and above an alpine forest. *Agric. Forest Meteorol*., doi:10.1016/j.agrformet. 2009.05.009.

Ferraz, J., Ohta, S. and Sales, S., 1988. Distribuição dos solos ao longo de dois transectos em floresta primária ao norte de Manaus. In: *N. Higuchi, M.A.A. Campos, P.T.B. Sampaio and J. dos Santos (Editors), Análise estrutural da floresta primária da bacia do rio Cuieiras, ZF-2, Manaus-AM, Brasil. MCT/INPA/JICA*, Manaus, pp. 109-144.

Finnigan, J.J., R. Clement, Y. Malhi, R. Leuning and H.A. Cleugh, (2003), A reevaluation of long-term flux measurement techniques. Part I: Averaging and coordinate rotation. Bound.-Layer Meteorol., 107, 1-48.

Fitzjarrald, D. R., and K. E. Moore, (1990), Mechanisms of nocturnal exchange between the rain-forest and the atmosphere, *Journal of Geophysical Research*, *95*(D10), 16,839–16,850.

Fitzjarrald, D. R., K. E. Moore, O. M. R. Cabral, J. Scolar, A. O. Manzi, and L. D. D. Sa (1990), Daytime turbulent exchange between the Amazon Forest and the atmosphere, *Journal of Geophysical Research*, *95*(D10), 16,825 – 16,838.

Fitzjarrald, D. R., R. K. Sakai, O. L. L. Moraes, M. J. Czikowsky, O. C. Acevedo, R. C. Oliveira, (2004), Mesoclimate of the LBA-ECO Santarém Study Area, paper presented at III LBA Scientific Conference, Braz. Minist. of Sci. and Technol., Brasilia, Brazil, July.

Fitzjarrald, D. R., Stormwind, B.L., Fisch, G., Cabral, O. M. R. (1988), Turbulent Transport Observed Just Above the Amazon Forest, Journal of Geophysical Research, 93(D2), 1,551–1,563.

Fitzjarrald, D.R., and K.M. Moore, (1995), Physical mechanisms of heat and mass exchange between forests and the atmosphere. In: M. Lowman and N. Nadkarni, eds., Forest Canopies: A Review of Research on This Biological Frontier, Academic Press, 45–72.

Foken, T. (2008), The energy balance closure problem: An overview. *Ecological Applications*: Vol. 18, No. 6, pp. 1351-1367.

Freitas, S. R., Longo, K.M., Silva Dias, M.A. F., Silva Dias, P.L., Chatfield, R., Prins, E., Artaxo, P., Grell, G., Recuero, F.S., (2005), Monitoring the transport of biomass burning emissions in South America, *Environ. Fluid Mech*., 5(1–2), doi:10.1007/s10652-0050243-7.

Freitas, S. R., M. A. F. Silva Dias, P. L. Siva Dias, K. M. Longo, P. Artaxo, M. O. Andreae, and H. Fischer (2000), A convective kinematic trajectory technique for low-resolution atmospheric models, *J. Geophys. Res.*, 105(D19), 24,375–24,386.

Froelich, N.J. and Schmid, H.P., (2006), Flow divergence and density flows above and below a deciduous forest Part II. Below-canopy thermotopographic flows. *Agricultural and Forest Meteorology*, Volume 138, Issues 1-4.

Gandu, A. W., Cohen, J.C.P., Souza, J. R. S., (2004), Simulation of deforestation in eastern Amazonia using a high-resolution model. *Theoretical and Applied Climatology*, Austria, v. 78, n. 1-3, p. 123-135.

Gao, W., Shaw, R.H., Paw U, K.T., (1989), Observation of organized structure in turbulent flow within and above a forest canopy. Bound.-Layer Meteorol. 47: 349-377.

Garratt, J. R., (1980), Surface Influnce upon Vertical Profiles in the Atmospheric near-surface layer. Quart. J. Roy. Meteorol. Soc., v.106, n.450, p. 803-819.

Goulden, M. L., J. W. Munger, S. M. Fan, B. C. Daube, and S. C. Wofsy (1996), Measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy, *Global Change Biol*., *2*(3), 169– 182.

Goulden, M. L., S. D. Miller, H. R. da Rocha, M. C. Menton, H. C. de Freitas, A. M. E. S. Figueira, and C. A. D. de Sousa (2004), Diel and seasonal patterns of tropical forest CO_2 exchange, *Ecol. Appl*., *14*(4), suppl. S, S42–S54.

Goulden, M.L., Miller, S.D. and da Rocha, H.R., (2006), Nocturnal cold air drainage and pooling in a tropical forest. *Journal of Geophysical Research-Atmospheres*, 111(D8), 10.1029/2005JD006037.

Grace, J. et al., (1995a), Carbon-Dioxide Uptake by an Undisturbed Tropical Rain-Forest in Southwest Amazonia, 1992 to 1993. *Science*, 270(5237): 778-780.

Grace, J., et al. (1995b), Carbon dioxide uptake by an undisturbed tropical rain forest in southwest Amazonia, *Science*, *270*, 778–780.

Grace, J., Y. Malhi, J. Lloyd, J. McIntyre, A. C. Miranda, P. Meir, and H. S. Miranda (1996), The use of eddy covariance to infer the net carbon dioxide uptake of Brazilian rain forest, *Global Change Biol*., *2*, 208– 217.

Gu L., E. Falge, T. Boden, D. D. Baldocchi, T. A. Black, S. R. Saleska, T. Suni, T. Vesala, S. Wofsy, L. Xu (2005), Observing threshold determination for nighttime eddy flux filtering, *Agric. For. Meteorol*., *128*:179–197.

Harman, I.N. and Finnigan, J.J., (2007), A simple unified theory for flow in the canopy and roughness sublayer. *Boundary-Layer Meteorology*, 123, 339-363.

Hodnett, M.G., Tomasella, J., Cuartas, L.A., Waterloo, M.J., and Nobre, A.D., (2007), Subsurface hydrological flow paths in a Ferralsol (Oxisol) landscape in central Amazonia. *Hydrological Sciences Journal* (in press).

Hutyra, L. R., J. W. Munger, S. R. Saleska, E. Gottlieb, B. C. Daube, A. L. Dunn, D. F. Amaral, P. B. de Camargo, and S. C. Wofsy (2007), Seasonal controls on the exchange of carbon and water in an Amazonian rain forest, *Journal of Geophysical Research*, *112*, G03008, doi:10.1029/2006JG000365.

Inoue, E., (1963), On the turbulent structure of air flow within crop canopies. J. Meteor. Soc. Japan, 41, 317–326.

IPCC 2007. Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the *Intergovernmental Panel on Climate Change*. WMO/UNEP, 18 pp.

Iwata, H., Y. Malhi, and C. Von Randow, (2005), Gap-filling measurements of carbon dioxide storage in tropical rainforest canopy airspace. Agricultural and Forest Meteorology. 132, 3-4: 305–314.

Kanda, M., R. Moriwaki, and F. Kasamatsu., (2004), Large-eddy simulation of turbulent organized structures within and above explicitly resolved cube arrays. Boundary-Layer Meteorology 112: 343-368.

Katul, G.G., J.J. Finnigan and R. Leuning, (2003), The influence of hilly terrain o canopy-atmosphere carbon dioxide exchange. Boundary Layer Meteorology.

Keller, M., et al. (2004), Ecological research in the large-scale biosphere atmosphere experiment in Amazonia: Early results, *Ecol. Appl*., *14*(4), suppl. S, S3– S16.

Kruijt, B. et al., (2000), Turbulence statistics above and within two Amazon rain forest canopies. *Boundary-Layer Meteorology*, 94(2): 297-331.

Kruijt, B. J., A. Elbers, C. von Randow, A. C. Arau'jo, P. J. Oliveira,A. Culf, A. O. Manzi, A. D. Nobre, P. Kabat, and E. J. Moors (2004), The robustness of eddy correlation fluxes for Amazon rain forest conditions, *Ecol. Appl.*, *14*, suppl. S, S101–S113.

Kruijt, B., et al., (2000), Turbulence Statistics Above and Within Two Amazon Rain Forest Canopies. *Boundary-Layer Meteorology*, v. 94, n. 2, p. 297-331.

Laurance, et al., (1999), Relationship between soils and Amazon Forest biomass: a landscape-scale study. Forest Ecology Management, 118:127-138.

Lee, X. H. (1998), On micrometeorological observations of surface-air exchange over tall vegetation, *Agric. For. Meteorol.*, *91*(1– 2), 39–49.

Lee, X. and Hu, X., (2002), Forest-air fluxes of carbon and energy over non-flat terrain, Boundary-Layer Meteorology, 103: 277-301.

Lee, X., Neumann, H.H., den Hartog, G., Fuentes, J.D., Black, T.A., Mickle, R.E., Yang, P.C. and Blanken, P.D., (1992), Observation of gravity waves in a boreal forest. Bound.-Layer Meteorol. 84, pp. 383–398.

Leuning, R., Zegelin, S. J., Jones, K., Keith, H., Hughes, D., (2008), Measurement of horizontal and vertical advection of CO_2 within a forest canopy. Agricultural and Forest Meteorology, Volume 148, Issue 11, Pages 1777-1797.

Li, B. and R. Avissar. 1994. The impact of spatial variability of land-surface characteristics on land-surface heat fluxes. Journal of Climate 7: 527-537.

Lu, C.-H., and D.R. Fitzjarrald, (1994), Seasonal and diurnal variations of coherent structures over a deciduous forest. Boundary-Layer Met., 69, 43-69.

Lu, L., Denning, A S.; Silva Dias, M.A.F., Ssilva Dias, P. L., Longo, M., Freitas, S. R., Saatchi, S., (2005), Mesoscale circulations and atmospheric CO_2 variations in the Tapajós region, Pará, Brazil. *Journal of Geophysical Research*, doi 10.1029/2004JD005757, v. 110, n. D21102.

Luizão, R.C.C., Luizão, F.J., Paiva, R.Q., Monteiro, T.F., Sousa, L.S., Kruijt, B., (2004), Variation of carbon and nitrogen cycling processes along a topographic gradient in a central Amazonian forest. *Global Change Biology*, 10: 592-600.

Mahrt, L., (1982), Momentum balance of gravity flows. J. Atmos. Sc., 39, 2701-2711.

Malhi, Y., A. D. Nobre, J. Grace, B. Kruijt, M. G. P. Pereira, A. Culf, and S. Scott, (1998), Carbon dioxide transfer over a central Amazonian rain forest. *Journal of Geophysical Research*, *103*, 31,593–31,612.

Malhi, Y., et. al. (2009), Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology*, Volume 15, Issue 5, 1255-1274.

Marcolla, B, A. Cescatti, L. Montagnani, G. Manca, G. Kerschbaumer and S. Minerbi, (2005), Importance of advection in the atmospheric CO_2 exchanges of an alpine forest. *Agric. For. Meteorol., 130*, 193-206.

Melillo, J.M. et al.,(1993), Global climate change and terrestrial net primary production. Nature 363, 234-240.

Meroney, Robert N., (1968), Characteristics of Wind and Turbulence in and Above Model Forests. Journal of Applied Meteorology, Vol. 7, NO. 5: 780-788.

Miller, S. D., M. L. Goulden, M. C. Menton, H. R. da Rocha, H. C. de Freitas, A. M. E. S. Figueira, and C. A. D. de Sousa (2004), Biometric and micrometeorological measurements of tropical forest carbon balance, *Ecol. Appl*., *14*(4), suppl. S, S114– S126.

Moncrieff, J. B., J. M. Massheder, H. deBruin, J. Elbers, T. Friborg, B. Heusinkveld, P. Kabat, S. Scott, H. Soegaard, and A. Verhoef. “A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide.” Journal of Hydrology 189, 1-4: (1997) 589–611.

Montgomery, R.B., (1948), Vertical flux of heat in the atmosphere. Journal of Meteorology, 5, 265–274.

Nogueira, D. S., Sá, L.D.A., Cohen, J. C. P., (2006), Rajadas Noturnas e Trocas de CO_2 Acima da Floresta de Caxiuanã, PA, Durante a Estação Seca. *Revista Brasileira de Meteorologia,* São Paulo, v.21, n.3b, p. 212-223.

Pachêco , V. B., (2001), Algumas Características do Acoplamento entre o Escoamento Acima e Abaixo da Copa da Floresta Amazônica em Rondônia. 2001 109f. Dissertação (*Mestrado em Meteorologia*) - *Instituto Nacional de Pesquisas Espaciais,* São José dos Campos.

Parker, G., and D. R. Fitzjarrald (2004), Canopy structure and radiation environment metrics indicate forest developmental stage, disturbance, and certain ecosystem functions, paper presented at III LBA Scientific Conference, Braz. Minist. of Sci. and Technol., Brasilia, Brazil, July.

Parotta J.A., J. K. Franci, R. R. de Almeida (1995), Trees of the Tapajos: a photographic field guide. General Technical Report IITF-1. United States Department of Agriculture, Rio Piedras, Puerto Rico, 371 pp.

Patton, E. G., (1997), Large-eddy simulation of turbulent flow above and within a plant canopy. Ph.D. Thesis, University of California Davis.

Patton, Edward (2008), Large-eddy simulation (LES); Momentum and scalar transport in canopy-covered terrain. *ADVEX Workshop*.

Paw U. K. T., D. D. Baldocchi, T. P. Meyers, and K. B. Wilson (2000), Correction of eddy covariance measurements incorporating both advective effects and density fluxes. *Boundary Layer Meteorol., 97*, 487-511.

Phillips, O.L. et al., (1998), Changes in the carbon balance of tropical forests: Evidence from long-term plots. *Science*, 282(5388): 439-442.

Poggi, D., Katul, G., Finnigan,J. J., Belcher,S. E., (2008) Analytical models for the mean flow inside dense canopies on gentle hilly terrain Q. J. R. Meteorol. Soc. 134: 1095–1112 (2008).

Prandtl, L., (1925), Uber die ausgebildete turbulenz. Z. Angew. *Math. Mech.*, 5, 136–139.

Ramos da Silva, R., Avissar, R., (2000), A Large Eddy Simulation (LES) of the Boundary Layer Evolution Over a Deforested Region of Rondonia (Brazil). In: American Geophysical Union - Fall Meeting, 2002, San Francisco. EOS Trans., San Francisco: American Geophysical Union, 2002. v. 83.

Raupach, M. R., and J. J. Finnigan., (1997), The influence of topography on meteorological variables and surface-atmosphere interactions. Journal of Hydrology 190, 3-4: 182–213.

Raupach, M. R., J. J. Finnigan, and Y. Brunet., (1996), Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy. Boundary-Layer Meteorology 78: 351-382.

Raupach, M. R., Thom, A. S., (1981), Turbulence in and above Plant Canopies. *Annual Review of Fluid Mechanics*, v. 13, p. 97-129.

Raupach, M.R., Finnigan, J.J. and Brunet, Y., (1996), Coherent eddies and turbulence in vegetation canopies: The mixing layer analogy. *Boundary-Layer Meteorology*, 78, 351-382.

Rennó, C. D., et al., (2008), HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia. Remote Sensing of Environment, doi:10.1016/j.rse.2008.03.018

Sá, L. D. A., Pachêco, V. B., (2001), Relação de Similaridade para os Perfis de Velocidade do Vento dentro da Copa da Floresta Amazônica em Rondônia. *Revista Brasileira de Meteorologia*, v.16, n. 1, p. 81-89, 2001.

Sá, L. D. A., Pachêco, V.B., (2006), Wind velocity above and inside Amazonian Rain Forest in Rondônia. *Revista Brasileira de Meteorologia*, v.21, n.3a, 50-58, 2006.

Sakai, R., D. Fitzjarrald, and K. E. Moore., (2001), Importance of low-frequency contributions to eddy fluxes observed over rough surfaces. Journal Applied Meteorology, 40: 2178–2192.

Saleska, S. R., et al. (2003), Carbon in Amazon forests: Unexpected seasonal fluxes and disturbance-induced losses, *Science*, *302*(5650), 1554– 1557.

Shaw, R. H., 1977: Secondary wind speed maxima inside plant canopies. J. Appl. Meteor., 16, 514–521.

Shuttleworth, W.J., (1989), Micrometeorology of temperate and tropical forest. *Philosophical Transactions of the Royal Society of London*, series B, 324, 1223: 299-334.

Silva Dias, M.A.F, (2006), Meteorologia , desmatamento e queimadas na Amazônia: uma síntese de resultados do LBA. *Revista Brasileira de Meteorologia*, v.21, n.3a, 190-199, 2006.

Silva Dias, M.A.F., Silva Dias, P. L., Longo, M., Fitzjarrald, D. R., Denning, A S., (2004), River breeze circulation in eastern Amazon: observations and modeling results. *Theoretical and Applied Climatology*, DOI 10.1007/s00704-004-0047-6, v. 78, n. 1-3, p. 111-121.

Silver W. L., et al., (2000), Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. *Ecosystems, 3*, 193–209.

Sousa, A.M.L. (2005), Estudo Observacional de Jatos de Baixos Níveis no Litoral Norte e Nordeste do Pará Durante o Período Chuvoso e Seco. 140 f. *Dissertação Mestrado em Meteorologia*, UFPel, Pelotas, RS.

Souza, J.S.D., (2004), Dinâmica espacial e temporal do fluxo de CO_2 do solo em floresta de terra firme na Amazônia central. *MSc Thesis, Universidade Federal do Amazonas*, Manaus, Brazil, 62 pp.

Staebler R.M., and Fitzjarrald D.R. (2005), Measuring canopy structure and kinematics of subcanopy flows in two forests. *J. Appl. Meteor., 44*, 1161-1179.

Staebler, R. M., and D. R. Fitzjarrald (2004), Observing subcanopy CO_2 advection, *Agric. For. Meteorol., 122*(3– 4), 139– 156.

Staebler, R.M., 2003. Forest subcanopy flows and micro-scale advection of carbon dioxide. Ph.D. Dissertation, SUNY Albany.

Sun J., S. P. Burns, A. C. Delany, S. P. Oncley, A. A. Turnipseed, B.B. Stephens, D. H. Lenschow, M. A. LeMone, R. K. Monson, D. E Anderson (2007), CO_2 transport over complex terrain. *Agric. Forest. Meteorol., 145*,1–21.

Swinbank, W.C., (1951), The measurements of vertical transfer of heat and water vapor by eddies in the lower atmosphere. Journal of Meteorology, 8, 135–145.

Tomasella, J. et al., (2008), The water balance of an Amazonian micro-catchment: the effect of interannual variability of rainfall on hydrological behaviour. *Hydrological Processes*, 22(13): 2133-2147.

Tóta J., Fitzjarrald, D.R., Staebler, R.M., Sakai, R.K., Moraes, O.M.M., Acevedo, O. C., Wofsy, S.C., Manzi, A.O., (2008), Amazon rain Forest subcanopy flow and the carbon budget: Santarém LBA-ECO site, *Journal Geophysical Research - Biogeosciences*, 113, G00B02, doi:10.1029/2007JG000597.

Tóta, J., Santos, R., Fisch, G., Querino, C., Silva Dias, M.A.F., Artaxo, P., Guenther, A., Martin, S., Manzi, A.O., (2008b), Nocturnal Boundary Layer measurements during the Amzonian Aeorosol Characterization Experiment - AMAZE. In: 2008 AGU Fall Meeting, A11C-0125, Dec-08, San Francisco-CA.

Turnipseed A. A., D. E. Anderson, S. Burns, P. D. Blanken, and R. K. Monson (2004), Airflows and turbulent flux measurements in mountainous terrain. Part 2. Mesoscale effects. *Agricultural and Forest Meteorology*, *125*, 187-205.

Turnipseed, A. A., D. E. Anderson, P. D. Blanken, W. M. Baugh, and R. K. Monson., (2003), Airflows and turbulent flux measurements in mountainous terrain: Part 1 - Canopy and local effects. *Agricultural and Forest Meteorology*, *119*:1–21.

Urbanski, S., Barford, C., Wofsy, S., Kucharik, C., Pyle, E., Budney, J., McKain, K., Fitzjarrald, D.R., Czikowsky, M., Munger, J.W. (2007), Factors controlling CO_2 exchange on timescales from hourly to decadal at Harvard Forest, *Journal Geophysical Research - Biogeosciences*. 112.

van Diepen, R., (2006), Spatial variability of soil respiration in a micro-scale rain forest catchment in Central Amazonia, Brazil. *MSc Thesis, Vrije Universiteit Amsterdam*, Amsterdam, the Netherlands, 68 pp.

Vickers, D., L. Mahrt, (2006), Contrasting mean vertical motion from tilt correction methods and mass continuity, *Agric. For. Meteorol.*, *138*, 93 –103.

Von Randow, C., (2007), On turbulent exchange processes over Amazonian Forest. Tese de Doutorado em Ciências Ambientais. Wageningen University and Research Centre, WUR, Holanda.

Waterloo, M.J. et al., (2006), Export of organic carbon in run-off from an Amazonian rainforest blackwater catchment. *Hydrological Processes*, 20(12): 2581-2597.

Wilczak, J.M., S.P. Oncley, and S.A. Stage (2001), Sonic anemometer tilt correction algorithms. *Bound.-Layer Meteorol.,99***,** 127-150.

Wilson, N. R., and R. H. Shaw, (1977), Higher-order closure model for canopy flow. *J. Appl. Meteor.*, 16, 1197–1205.

Wofsy, S. C., Goulden, M.L., Munger, J.W., Fan, S.M., Bakwin, P.S., Daube, B.C., Bassow, S.L., Bazzaz, F.A., (1993), Net ecosystem exchange of CO_2 in a midlattitude forest, Science 260, pp. 1314–1317.

Yang, P.C., T. A. Black, H. H. Neumann, M. D. Novak, and P. D. Blanken, (1999), Spatial and temporal variability of CO_2 concentration and flux in a boreal aspen forest. *Journal of Geophysical Research*, *104* (D22), 27653-27661.

Yi C, K. J. Davis, P. S. Bakwin, B. W. Berger, and L. Marr (2000), The influence of advection on measurements of the net ecosystem-atmosphere exchange of CO_2 from a very tall tower. *Journal of Geophysical Research*, *105*, 9991-9999.

Yi, C., (2008), Momentum transfer within canopies. *Journal of Applied Meteorology and Climatology*, 47, 262-275, doi:10.1175/2007JAMC1667.1.

Yi, C., R. K. Monson, Z. Zhai, D. E. Anderson, B. Lamb, G. Allwine, A. A. Turnipseed, and S. P. Burns (2005), Modeling and measuring the nocturnal drainage flow in a high-elevation, subalpine forest with complex terrain, *Journal of Geophysical Research*, *110,* (D22)303, doi:10.1029/2005JD006282.

Yoshino, M.M. (1984), Thermal belt and cold air drainage on the mountain slope and cold air lake in the basin at quiet, clear night. *GeoJournal*, *8* (3), 235–250.