

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

185,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Exchange of Carbon Between the Atmosphere and the Tropical Amazon Rainforest

Julio Tóta¹, David Roy Fitzjarrald² and Maria A. F. da Silva Dias³

¹Universidade do Estado do Amazonas,

²State University of New York,

³Universidade de São Paulo,

^{1,3}Brasil

²USA

1. Introduction

The terrestrial biosphere is an important component of the global carbon system. The long term exchanges estimates of terrestrial biosphere is a challenge and has resulted in ongoing debate [Baldocchi, 2008; Aubinet, 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, 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 [Goulden *et al.*, 1996; Black *et al.*, 1996; Baldocchi *et al.*, 2001; Massman and Lee, 2002; Loescher *et al.*, 2006; Aubinet, 2008, Tóta *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 night's 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 on the u^* threshold value used to correct the flux tower data at Santarem LBA site (Easterly Amazon Region - Brazil), the area can change from carbon sink to neutral or carbon source to the atmosphere.

The transport of CO₂ by advection process has been suggested by several studies as the principle reason for the "missing" CO₂ 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 CO₂ 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; Sun *et al.*, 2007; 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 CO₂ respiration as past studies have asserted [Froelich and Schmid, 2006]. The Manaus LBA site (Central Amazon Region – Brazil), is an example of moderately complex terrain covered by dense tropical forest. The NEE bias is reported by previous works [Kruijt *et al.*, 2004; 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-circulation features and how they relate to spatial and temporal distribution of CO₂ on the Manaus LBA Project site. The contribution of exchange of carbon between the atmosphere and the tropical Amazon Rainforest is discussed and correlated with the present work.

2. Material and methods

2.1 Site description

The study site is located in the Cuieiras Biological Reserve (54° 58'W, 2° 51'S), 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 monitor long term microclimate, energy, water and carbon exchanges (Araújo *et al.*, 2002), and various studies 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.

The vegetation cover on the plateau and slope areas is composed by tall and dense terra firme (non-flood) tropical forest with height varying between 30 to 40m, maximum surface area density of 0.35 m²m⁻³ (Figure 2b, see also Parker *et al.*, [2004]), and average biomass of 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 m²m⁻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].

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] and Cuartas *et al.* [2007].

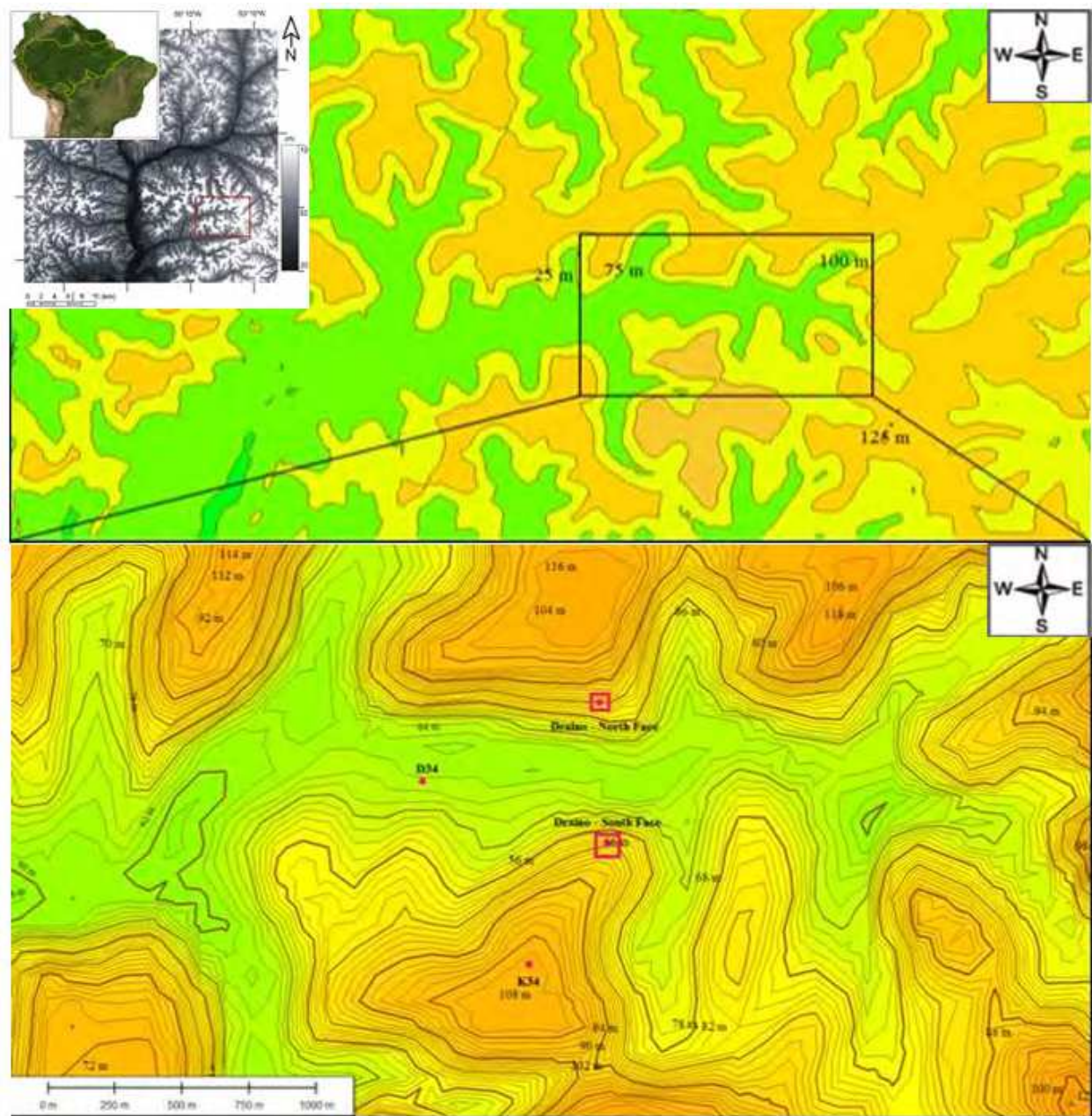


Fig. 1. Detailed measurements towers’s view in the ZF-2 Açu catchment (East-West valley orientation) from SRTM-DEM datasets. The large view in the above panel and below panel the points of measurements (B34 – Valley, K34 – Plateau, and subcanopy Drainio system measurements over slopes in south and north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

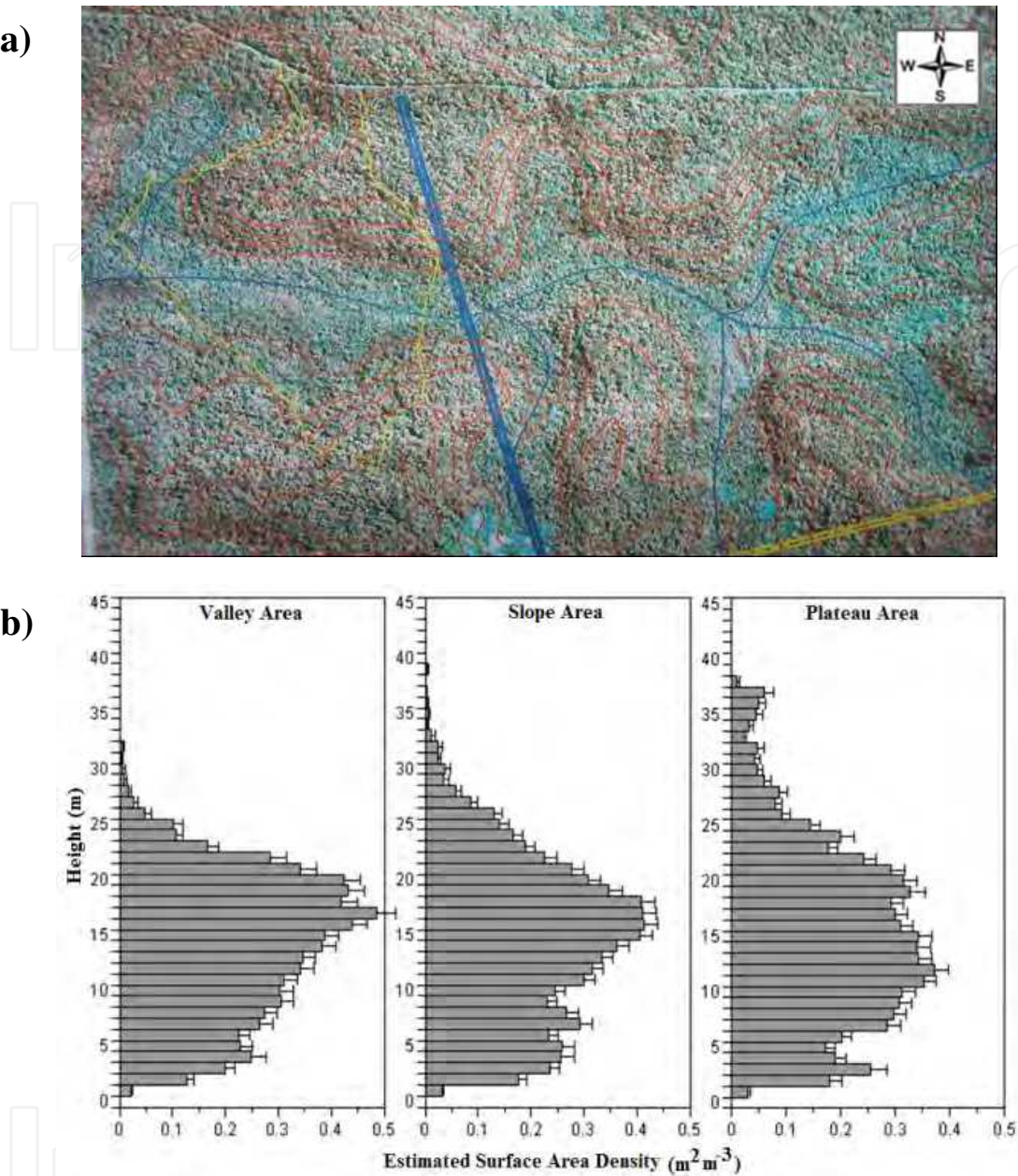


Fig. 2. (a) IKONOS’s image of the site at Açú Cachment with level terrain cotes and vegetation cover and (b) vegetation structure measured from LIDAR sensor over yellow transect in (a). From (a) the valley vegetation (blue color) and vegetation transition to plateau areas (red colors).

2.2 Measurements and instrumentation

The datasets used in this study include a measurement system to monitor airflow above and below the forest, horizontal gradients of CO₂, and the thermal structure of the air below the canopy, named “DRAINOS 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 $\text{CO}_2/\text{H}_2\text{O}$ 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].

- DRAINNO 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).



Fig. 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 (CO_2 , H_2O , air temperature and humidity) 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).

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.

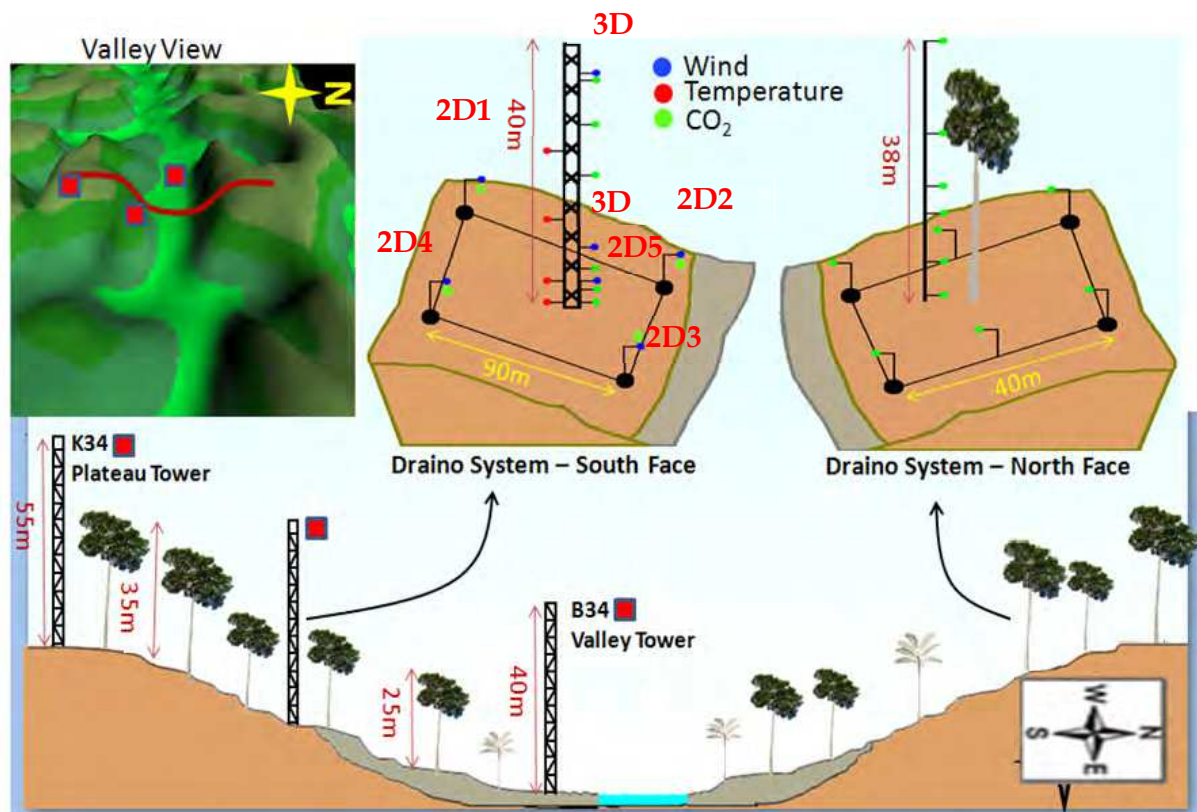


Fig. 4. Draino measurement system (South and North Slope face) implemented at Manaus LBA Site, including topographic view and instrumentation deployed.

The result was similar to that obtained by *Tóta et al.* [2008], with CO₂ 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 CO₂ 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 CO₂/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 CO₂ 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 10 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 CO₂.

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 O analyzer
38,26,15,3,2,1	CO ₂ , H ₂ O Profile (South face)	LI-7000 CO ₂ /H ₂ O analyzer
35,20,15,11,6,1	CO ₂ , H ₂ O Profile (North face)	LI-7000 CO ₂ /H ₂ O analyzer
18,10,2,1	Air Temperature and Humidity	Aspirated thermocouples

u', v', w': wind components and T', air temperature fluctuation

Table 1. DRAINNO system Sensors at ZF2 LBA Manaus Site

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) seasons of 2006. Figure 5 presents an example of the datasets cover, with 10 days composite statistic, for CO₂ concentration and air temperature at south face area of the DRAINNO system and the total precipitation on the plateau K34 tower measurements.

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 DRAINNO System was higher, as expected, in the dry season. A good relationship is observed between CO₂ 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 CO₂ 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). During the nighttime, stable conditions dominates during 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]).

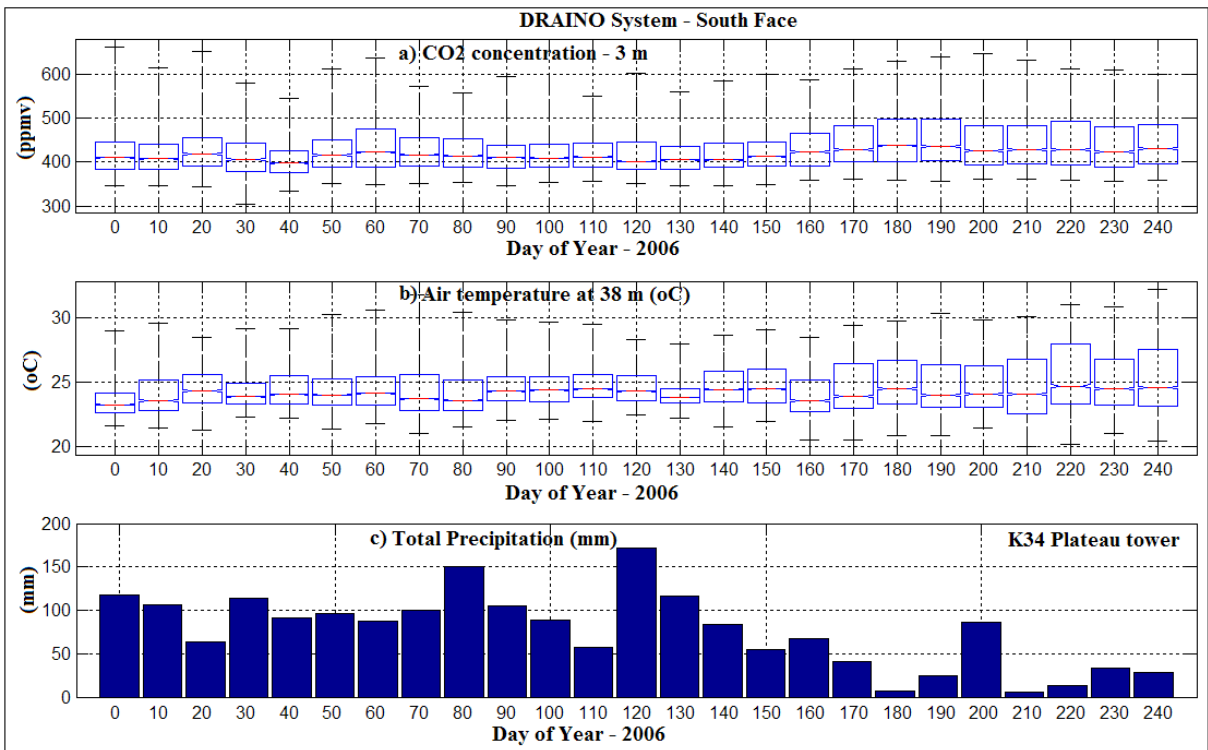


Fig. 5. 10 days time series of the CO₂ concentration (a), air temperature (b) (DRAINO System) and total precipitation (c) (plateau tower).

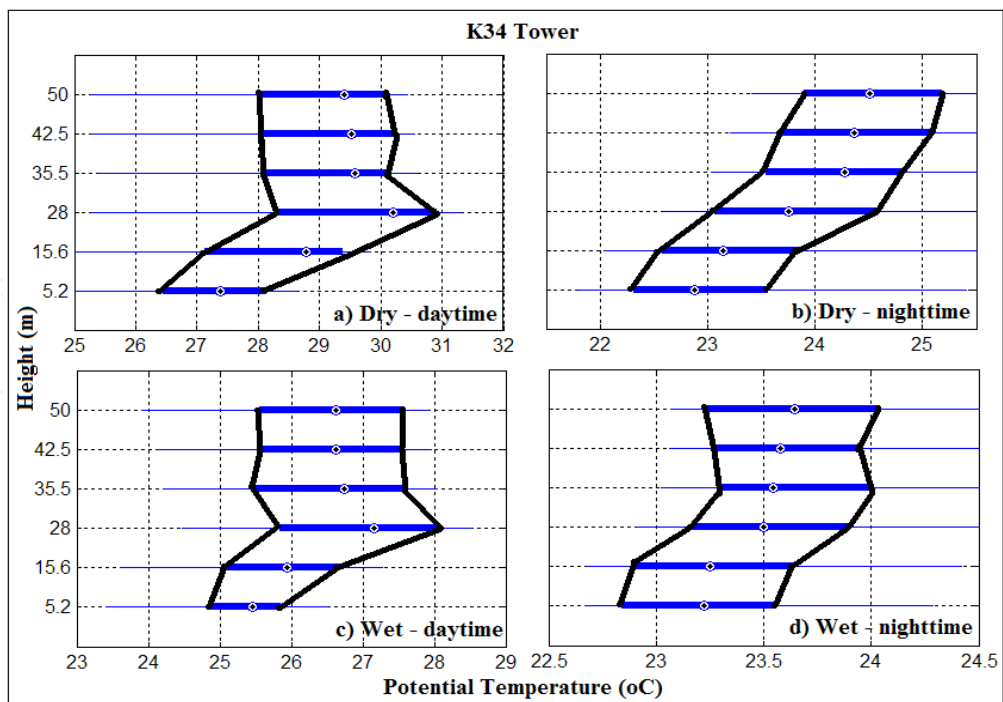


Fig. 6. Boxplot of the virtual potential temperature vertical profile for dry (a, b) and wet periods (c, d) of the 2006 during night (b, d) and daytime (a, c), on the plateau K34 tower.

The below-canopy layer of 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.

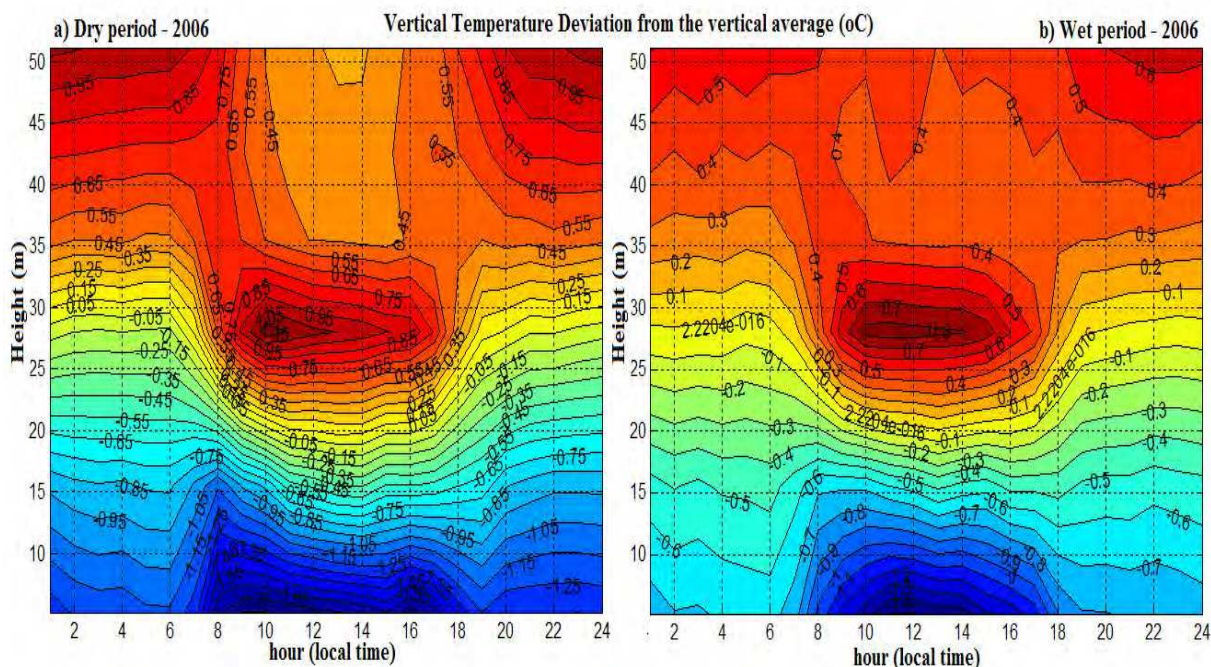


Fig. 7. Daily course of the vertical deviation of the virtual potential temperature $([\theta'_v = \theta_v(z) - \overline{\theta_v(z)}_{5.2}^{55}])$, during dry (a) and wet (b) periods of the 2006, over plateau K34 tower.

The Figure 7 presents daily course of the vertical deviation of the virtual potential temperature, e.g., $([\theta'_v = \theta_v(z) - \overline{\theta_v(z)}_{5.2}^{55}])$, 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. The 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]].

3.1.2 DRAIN 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.

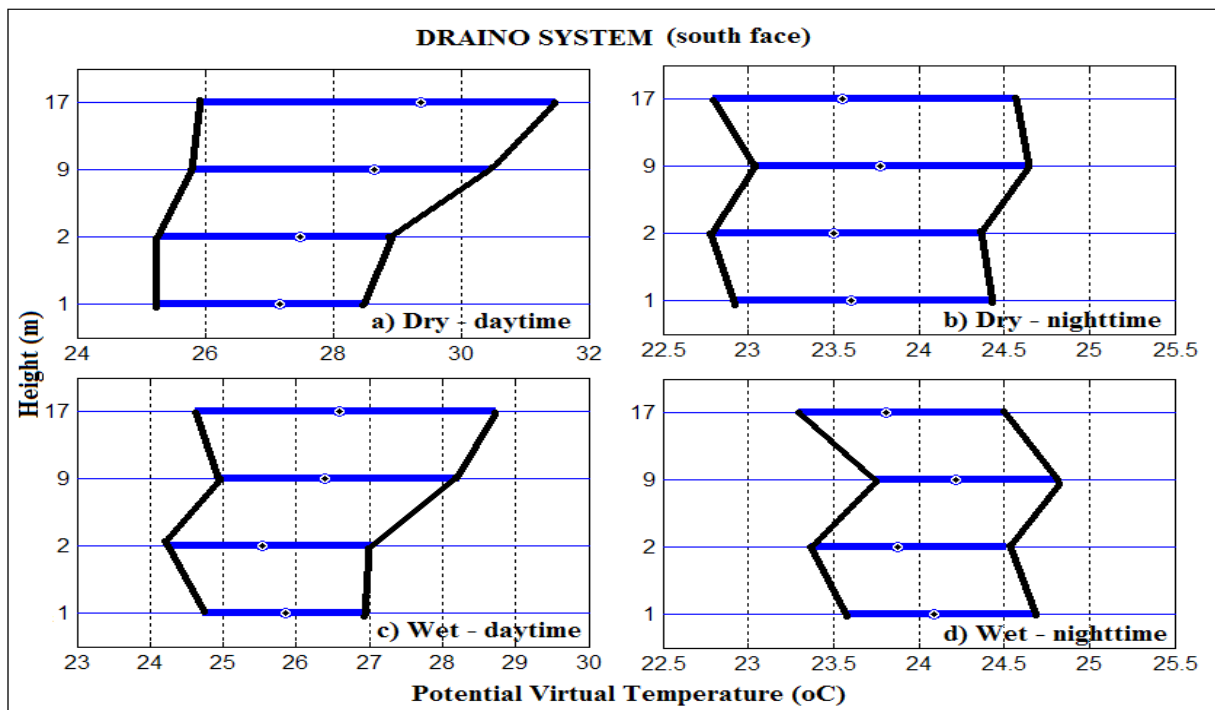


Fig. 8. Boxplot of the virtual potential temperature vertical profile for dry (a, b) and wet periods (c, d) of the 2006 during night (b, d) and daytime (a, c), on the slope area DRAIN0 System tower (south face, see Figure 2).

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 9 presents a daily cycle composite of the virtual potential temperature deviation from the vertical average ($[\theta_v(z) - \overline{\theta_v(z)}_1^{18}]$). 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 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 found on the sloping open areas without dense vegetation. This general pattern was present at several specific study cases not show here due limited size paper. A similar pattern was reported by *Froelich and Schmid* [2006] during “leaf on” season.

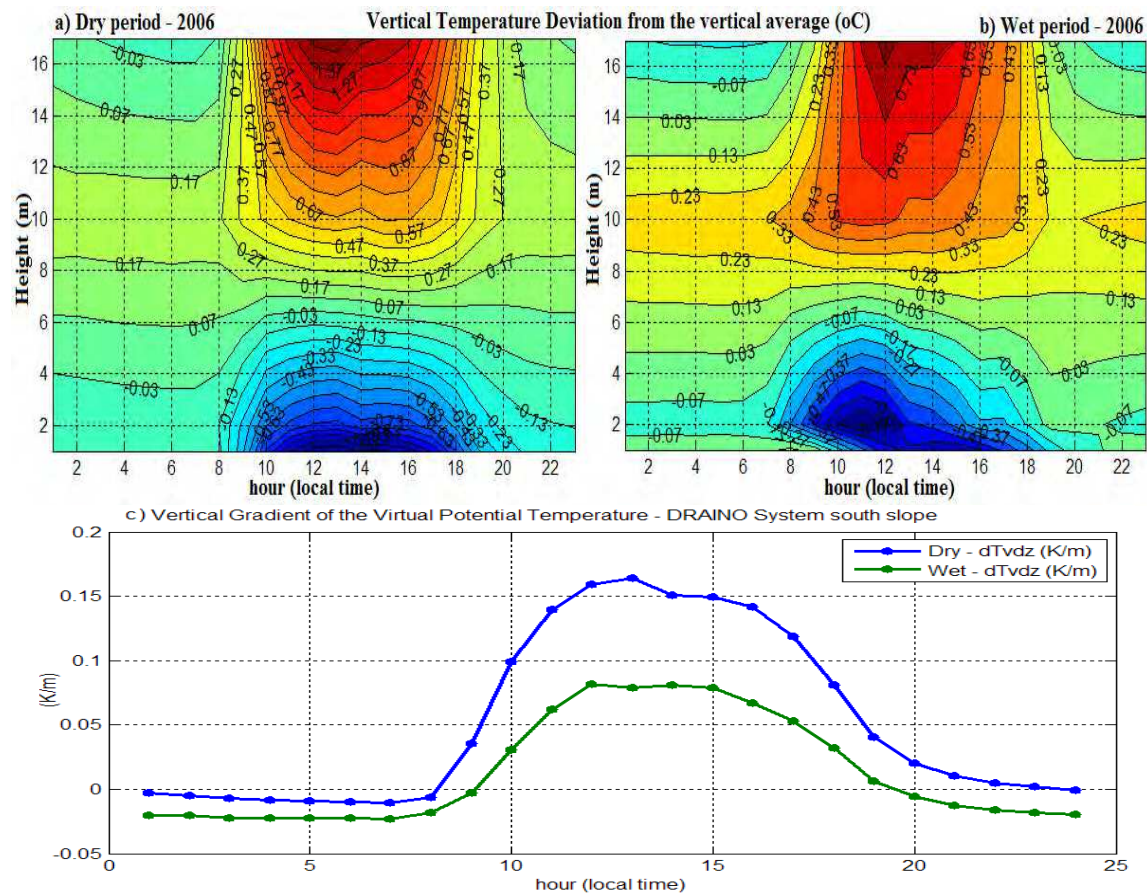


Fig. 9. Daily course of the vertical deviation of the virtual potential temperature for dry (a) and wet (b) periods of the year 2006, and the virtual potential temperature vertical gradient (c), over slope area DRAINOSystem tower.

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. It is important to 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].

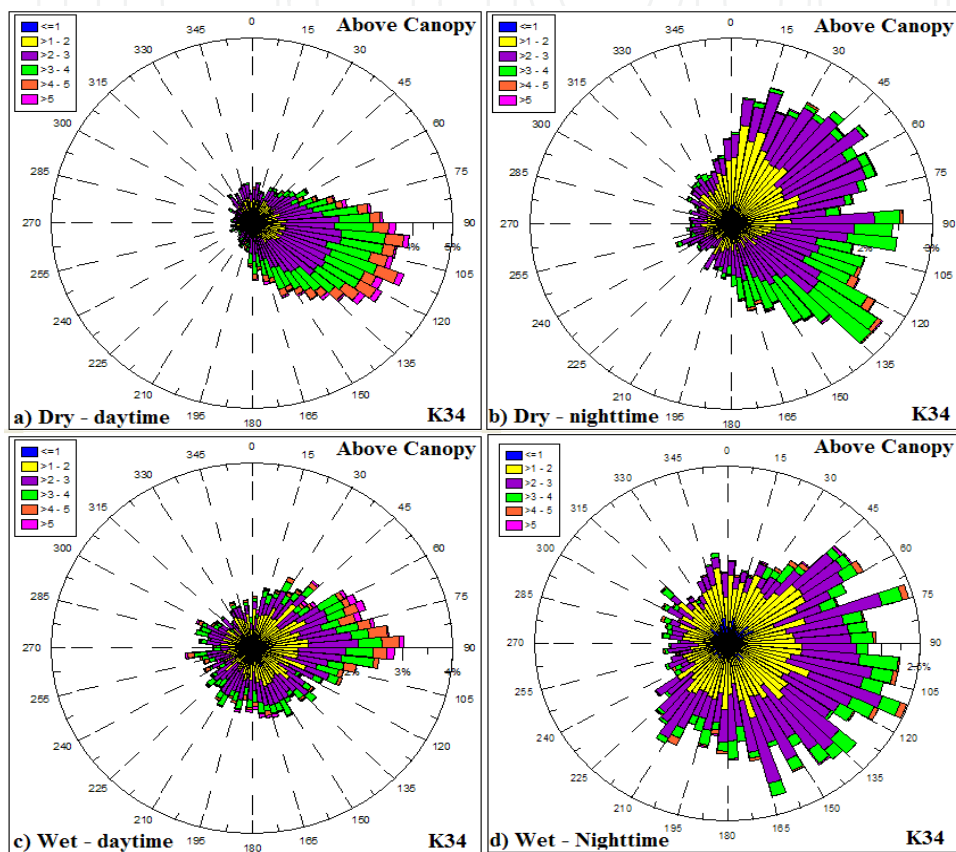


Fig. 10. Frequency distribution of the wind speed and direction. For dry (a, b) and wet (c, d) periods from the year 2006 during day (a, c) and nighttime (b, d), on the plateau K34 tower.

3.2.1.2 DRAINOS System slope tower

The above canopy (38 m above ground level – a.g.l.) on the slope area DRAINOS 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).

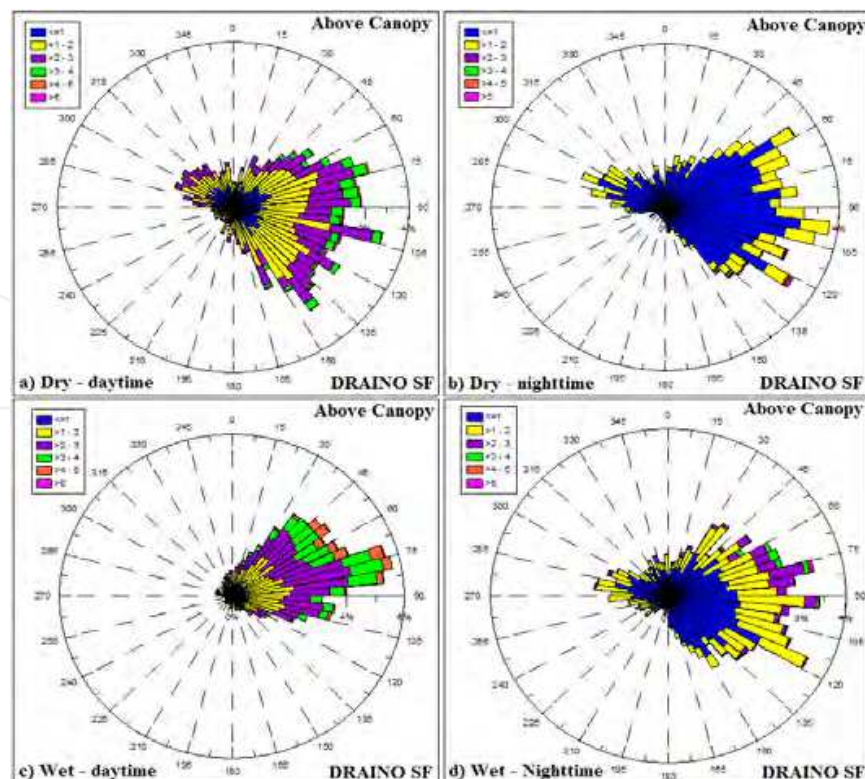


Fig. 11. Frequency distribution of the wind speed and direction above canopy (38 m above ground level – a.g.l). For dry (a, b) and wet (c, d) periods from the year 2006 during day (a, c) and nighttime (b, d), on the slope area at DRAINNO system tower.

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 year 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 the year 2006. It is important to observe that the south slope area in the DRAINNO 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 slope 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.

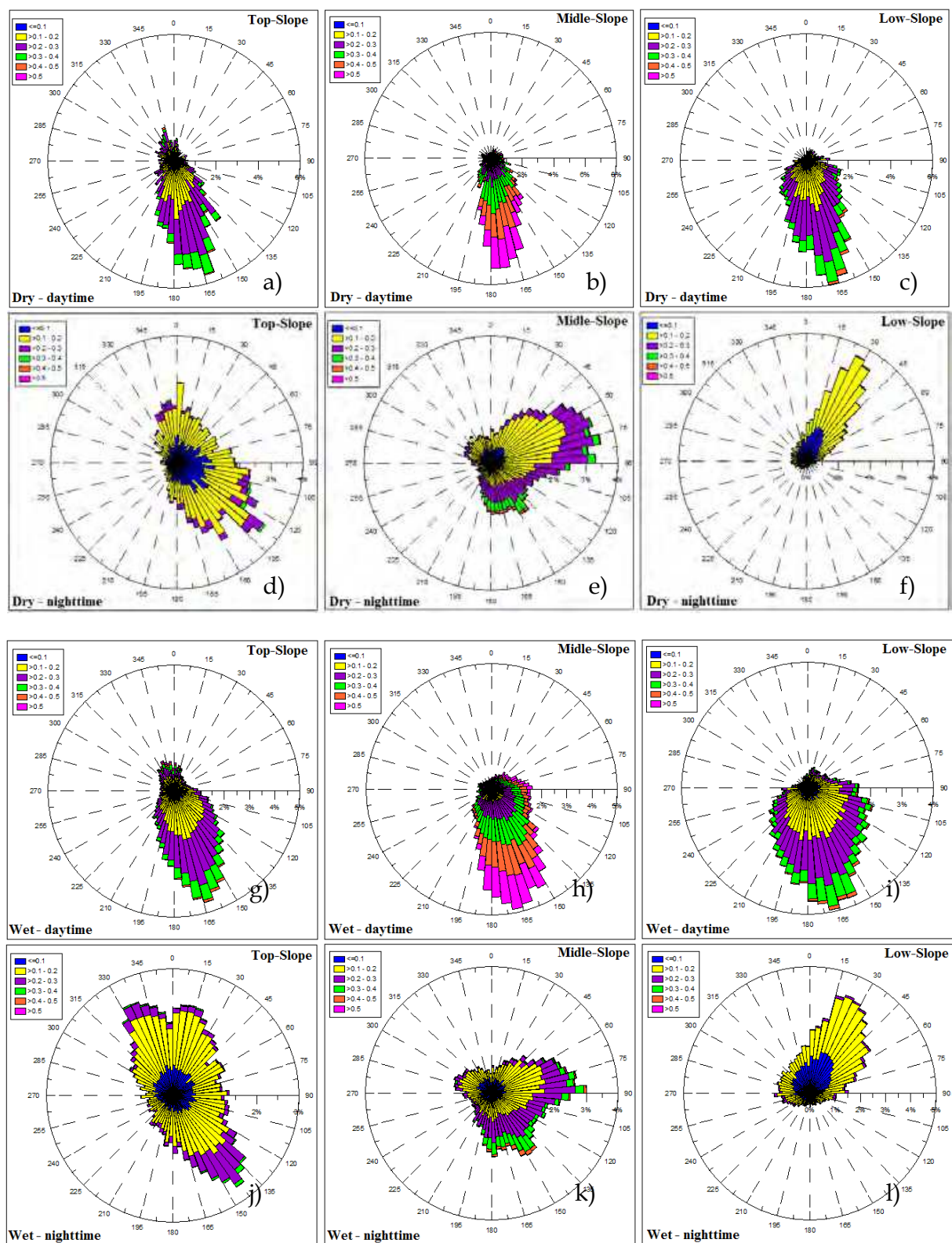


Fig. 12. Frequency distribution of the wind speed and direction in the subcanopy array (2 m above ground level – a.g.l) on the microbasin south face slope area at DRAINO horizontal array system (see Figure 4). For dry (a-f) and wet (g-l) periods from the year 2006, during day (a, b, c, g, h, i) and nighttime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

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); 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]*.

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. On the lower-part of the slope area (Figure 12f, l) the wind direction prevailed from the northeast (10°-70°), indicating upsloping pattern (anabatic). It 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 has been suggested by *Staebler [2003]* and reported by simulations using fluid dynamic models [*Katul and Finnigan, 2003; Poggi et al., 2008*].

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, as commented previously (section 3.1.2), this is an example of non-classical microscale slope flow. *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.

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: $\bar{w} = w - a(\alpha_i) - b(\alpha_i)u$, where ‘*a*’ and ‘*b*’ are coefficients to be determined, for each α_i (10° 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, not only low but non-zero values were observed for all points of measurements.

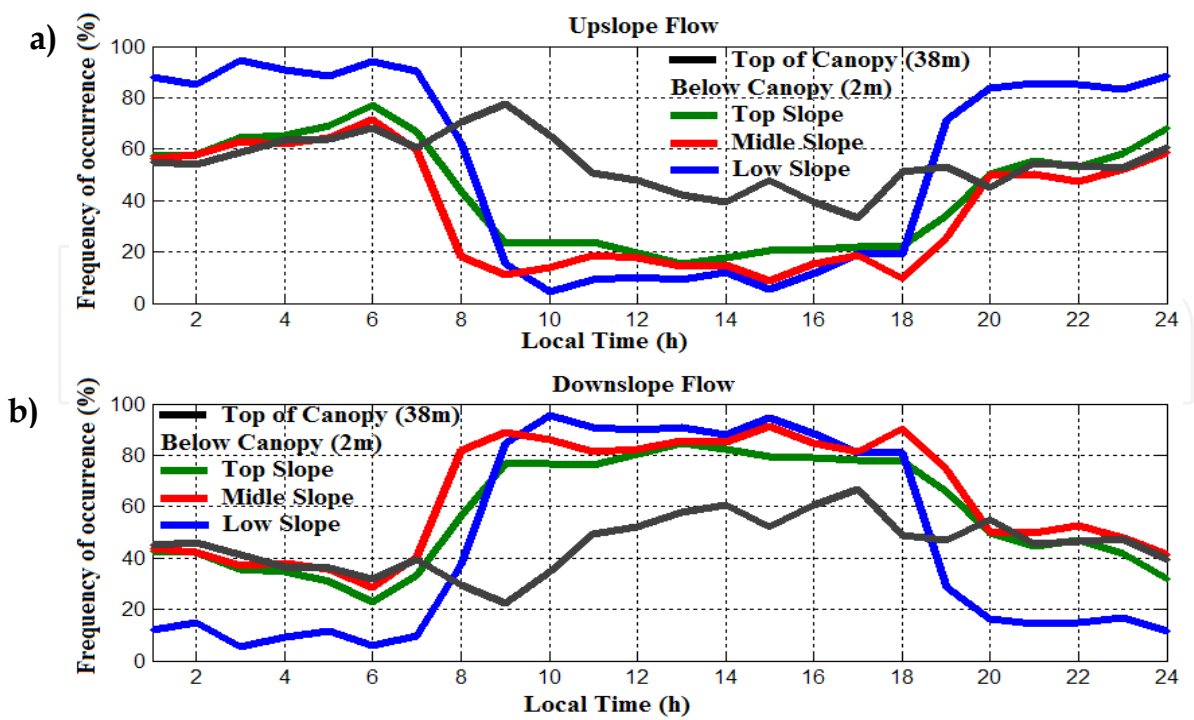


Fig. 13. Frequency distribution of the subcanopy wind direction (a) upsloping (from north quadrant) and (b) downsloping (from south quadrant) on the south face slope area at DRAINNO horizontal array system (see Figure 4).

On the plateau area, the mean vertical velocity was always positive indicating upward motion or vertical convergence at the top of the 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].

However, 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 by the DRAINNO 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). 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.

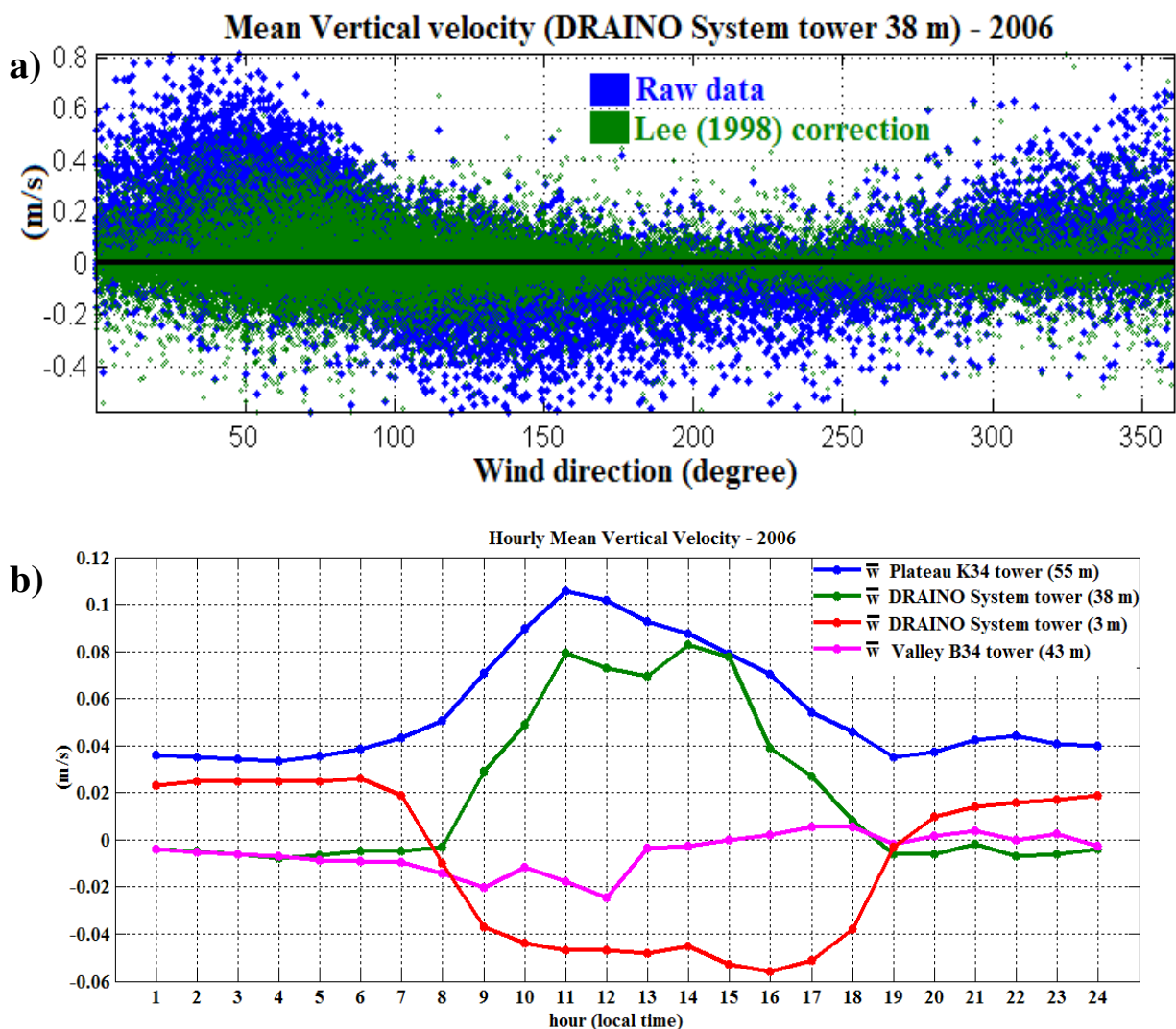


Fig. 14. Mean vertical velocity raw and correct vertical velocity (a) for DRAINNO system slope tower (38 m), and hourly mean vertical velocity (b) for: plateau K34 tower (55 m), DRAINNO system slope tower (above canopy - 38 m and subcanopy - 3 m) and for valley B34 (43 m) towers (see Figure 4, for details).

In Figure 15a is show the above canopy airflow over valley space (red arrow) and correspondent (induced) the most probable airflow above canopy over slope areas (blue arrow). In the same figure is show the main physical mechanisms (pressure gradient force) producing that micro-scale circulations. The observations result from preview 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 the ground, associated with positive mean vertical velocity (indicating upward movement). Also, above canopy, there is a downslope flow associated with negative mean vertical velocity, with downward convergence above the canopy. The microcirculation along the plateau-slope-valley is promoted by an feedback mechanism of accumulation of cold air drainage above canopy into the valley center (Figure 15b), creating the forcing needed to sustain nighttime pattern. The air temperature structure above canopy in the valley (see de

Araújo, 2009) is a good indication of cold air pool in the center of the valley. Maybe the local pressure gradient force due to the cold air accumulation promotes the upward airflow in both the 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.

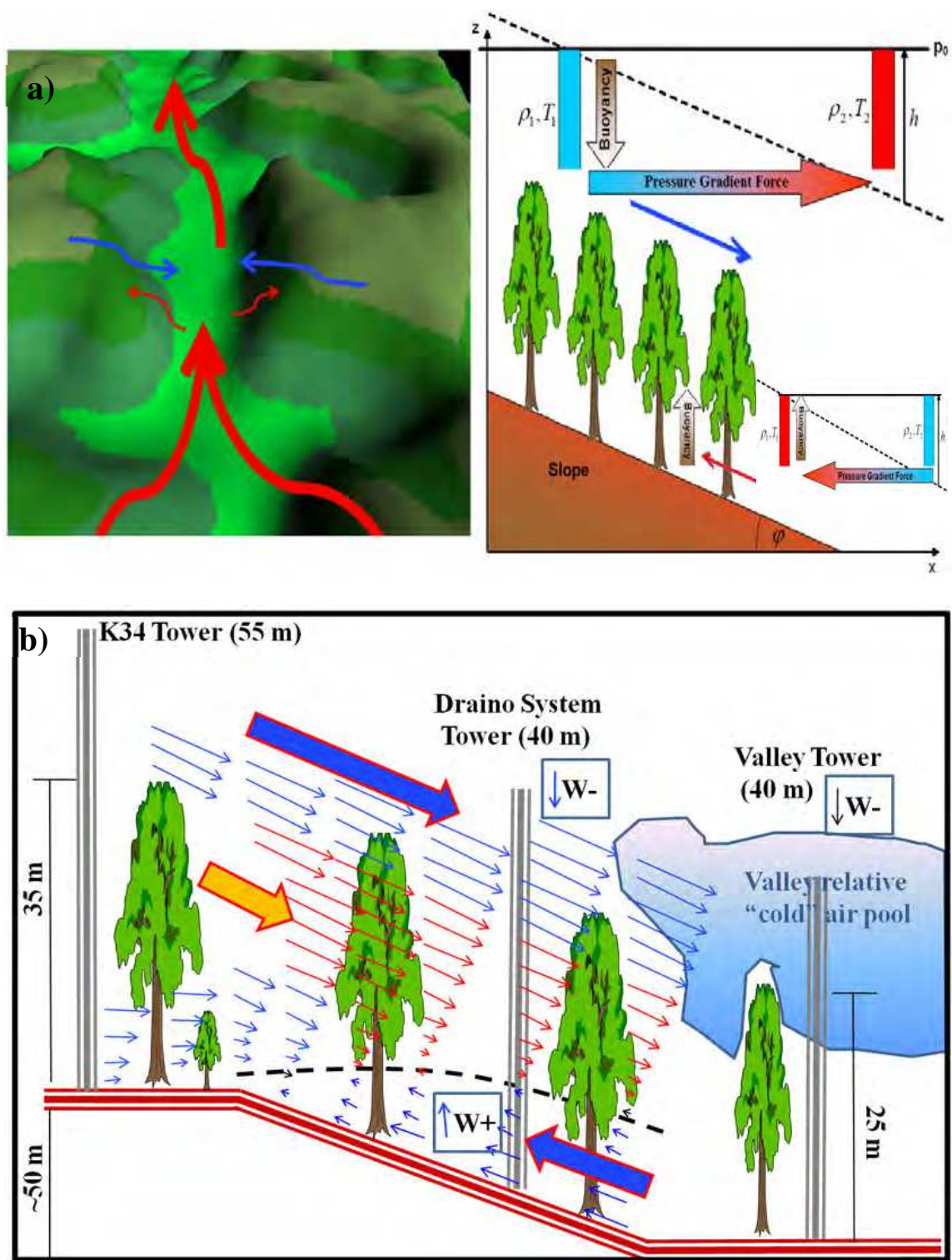


Fig. 15. Schematic local circulations in the site studied, valley and slopes flow (a), 2D view from suggested below and above canopy airflow (b).

3.4 CO₂ concentration and subcanopy horizontal wind field

The CO₂ concentration was measured by DRAINNO system on the south face slope area for dry and wet periods of the year 2006, and on the north face slope during the dry period (Figure 4). The Figure 16 presents an example, for midnight (local time), of the horizontal wind field and spatial CO₂ concentration over the DRAINNO 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 an important role in modulating the horizontal spatial distribution of CO₂ concentration (Figure 16).

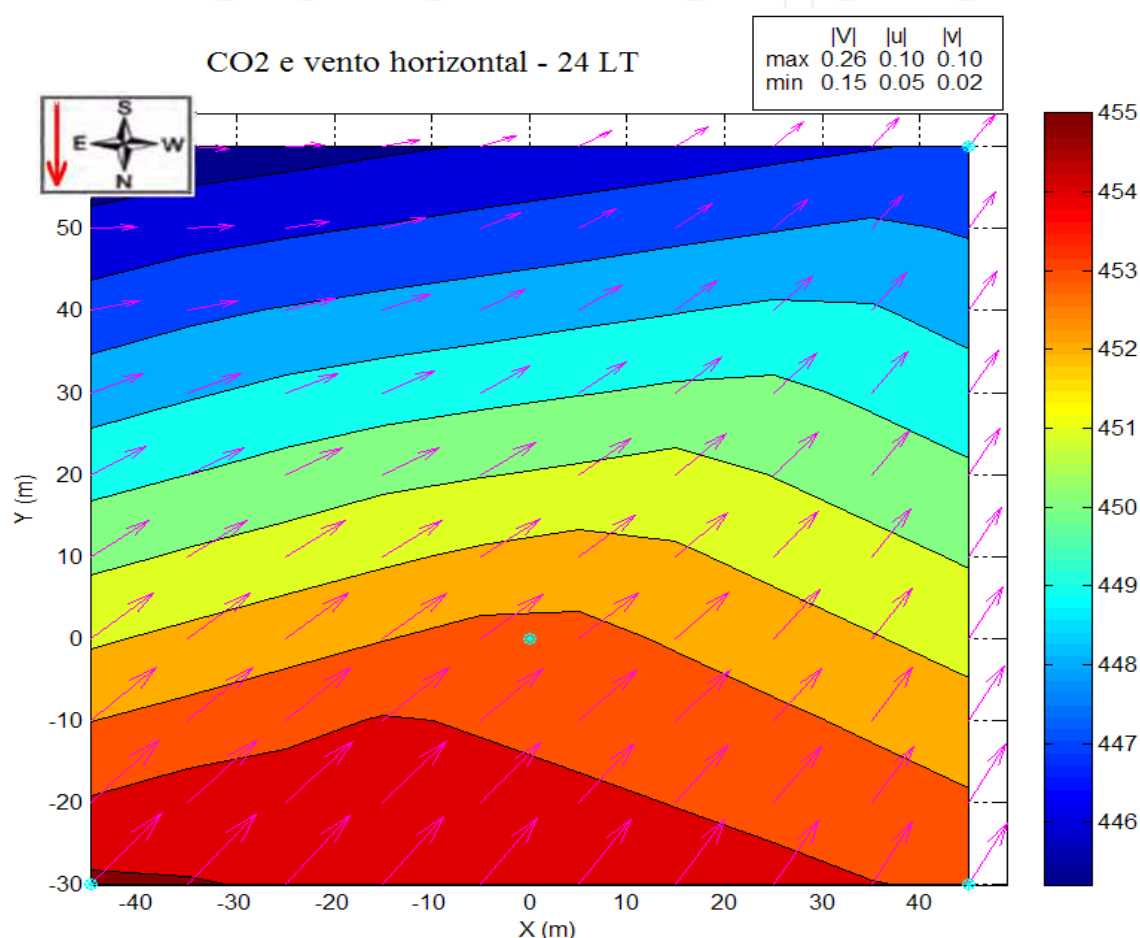


Fig.16. Example at midnight (local time) of the horizontal CO₂ concentration (ppmv) over the DRAINNO System south face domain including an interpolated horizontal wind field (10 m grid). Note the geographic orientation and the red arrow indicating slope inclination (see Figure 4).

In Figure 17 (a, b, c) the typical pattern observed is shown for both dry and wet periods of the year 2006 measured by the DRAINNO system on the south-facing slope area. During the daytime (Figure 17c), the wind prevailed downslope inducing a strong horizontal gradient of CO₂ 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 CO₂ concentration. Later during the night, the upsloping regime is well established and also the horizontal gradient of CO₂ is growing from lower part of the 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.

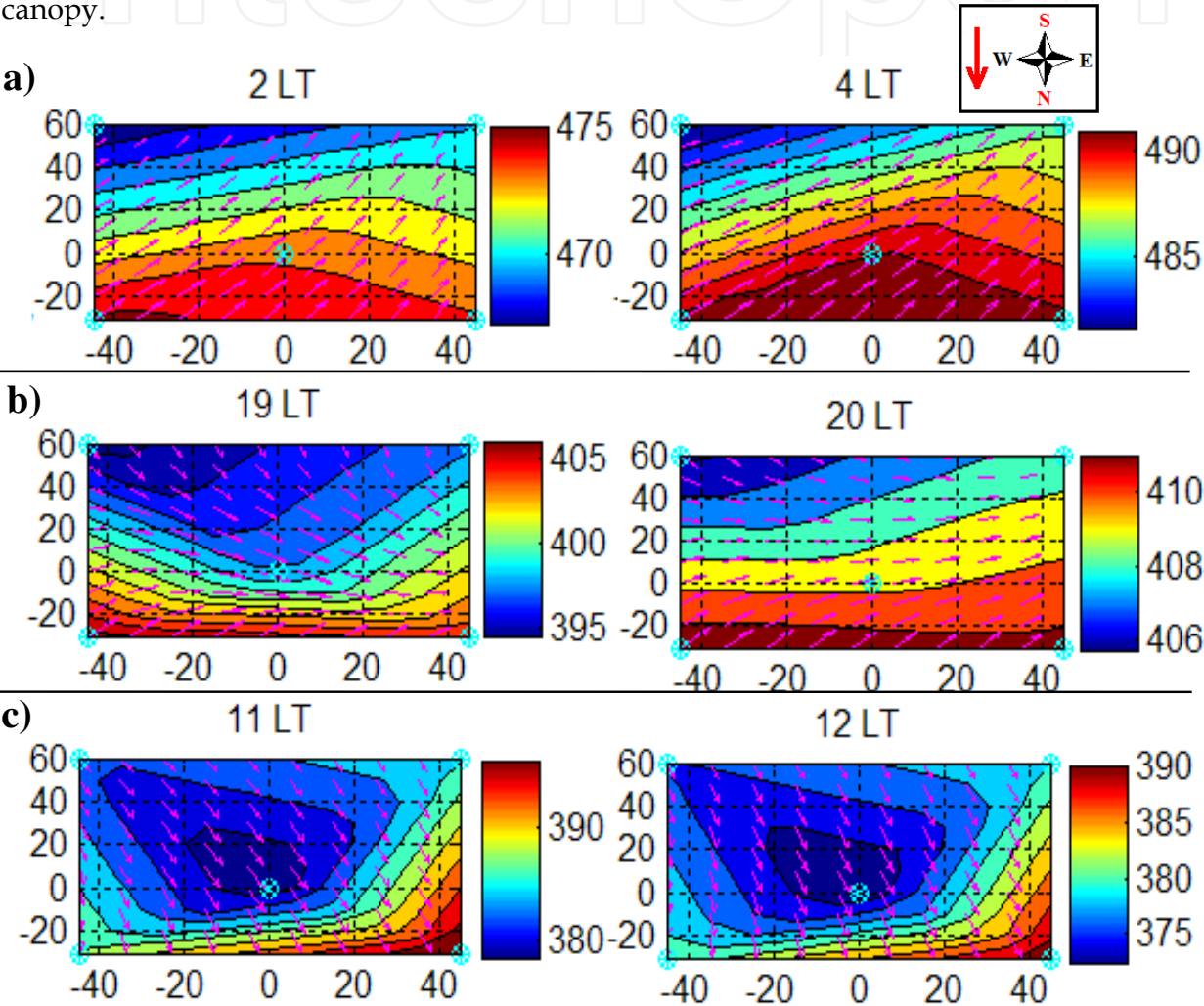


Fig. 17. Hourly average of the subcanopy (2 m) CO₂ concentration and horizontal wind speed over DRAINO System south face area during dry period of the year 2006, note the geographic orientation and the red arrow indicating slope inclination (see Figure 4). The axis represents distances from center of the main tower. Daytime (a), transition period - evening (b), established nighttime (c).

The spatial distribution of the horizontal CO₂ concentration, Figure 18 along the north face, shows a similar pattern than the south face described previously. Despite there being no wind information in that area, if one assumes the same spatial correlation between

horizontal wind and CO₂ concentration, it is possible predict that the wind should present an inverse pattern from the south face suggesting that during daytime the downslope wind direction should be from the northeast (Figure 18c, from blue to red color).

During evening period (Figure 18b), it 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.

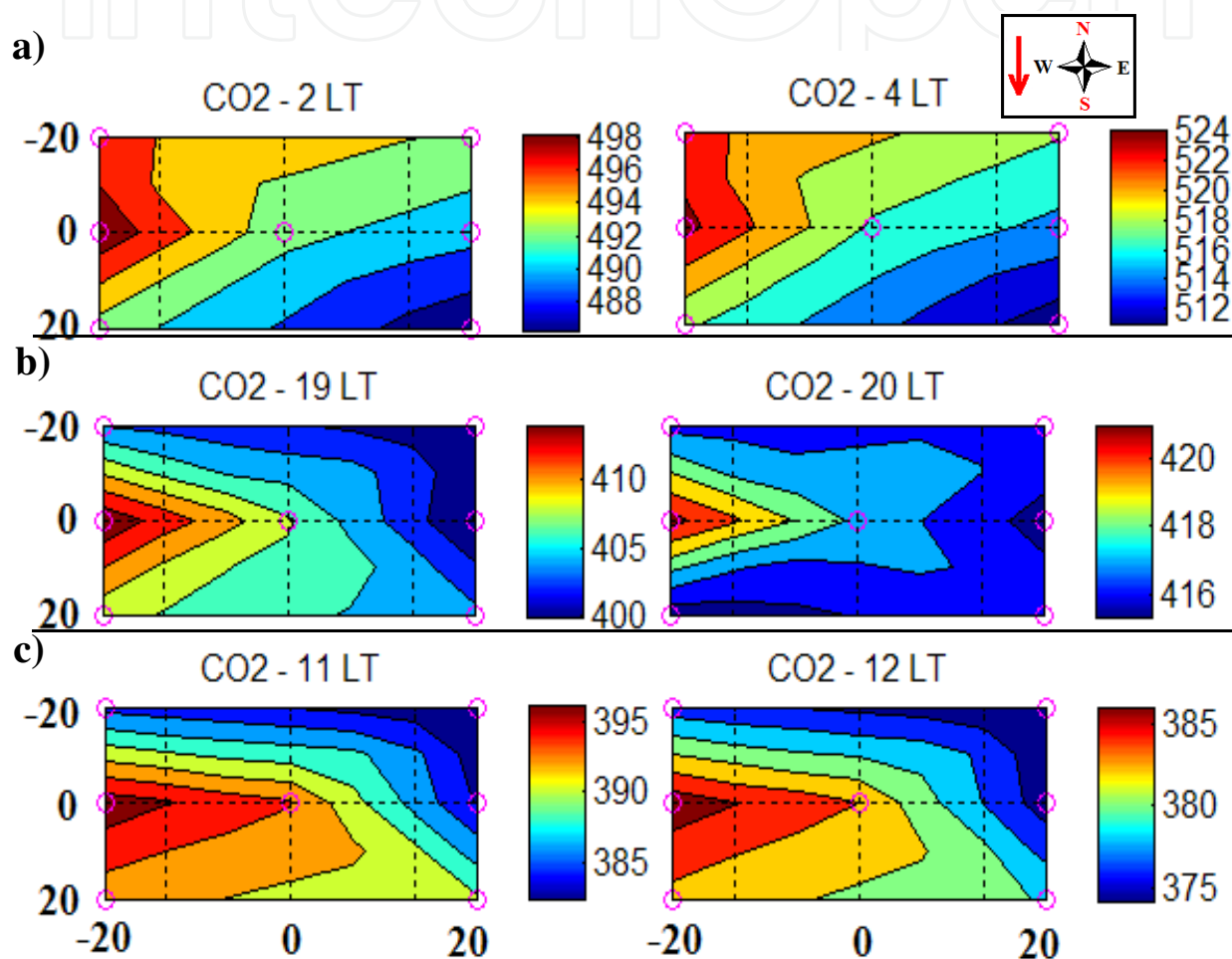


Fig. 18. Hourly average of the subcanopy (2 m) CO₂ concentration on the DRAINOS System north face area during dry period of the year 2006. Note the geographic orientation and the red arrow indicating slope inclination (see Figure 4). The axis represents distances from center of the main tower. Daytime (a), transition period - evening (b), established nighttime (c).

One possible explanation to this subcanopy slopes wind regime and spatial distribution of CO₂ concentration, is the valley wind channeling effect and how it is meandering when it enters in the valley topography [as described by de Araújo, 2009]. This valley wind pattern, probably causes oscillations as those observed on the CO₂ 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 discussed in preview sections, it was identified as 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 the one observed here. The study highlighted that the local micro-circulation was complicated 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; Belcher *et al.*, 2008).

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] and more research is warranted. 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; Schmid, 2006]. The representativeness of the eddy flux tower is most in question for complex terrain, especially on calm nights).

5. Acknowledgments

This work is part of the LBA-ECO project, supported by the NASA Terrestrial Ecology Branch under grants NCC5-283 and NNG-06GE09A to the Atmospheric Sciences Research Center, University at Albany, SUNY, LBA-ECO team CD-03. The latter grant included a subcontract to the Fundação Djalma Batista, Manaus. Julio Tóta was also supported by FAPEAM RH-POSGRAD and by MCT-INPA - Fundacao Djalma Batista during 2006–2007, with a fellowship. Thanks to LBA Manaus team for support and during the field work.

6. References

- 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.
- de Araújo, A. C., (2009), Spatial variation of CO₂ 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 CO₂ storage and advection conditions at night at different Carboeuroflux sites. *Boundary Layer Meteorol.*, 116: 63–94.

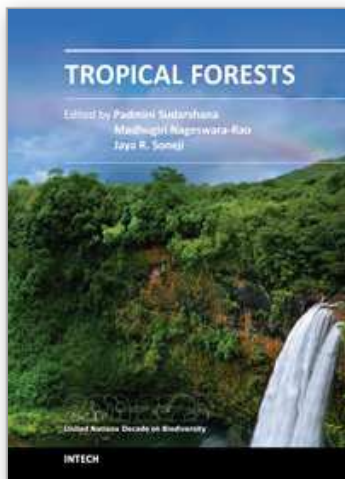
- Aubinet, M., B. Heinesch, and M. Yernaux (2003), Horizontal and vertical CO₂ advection in a sloping forest, *Boundary Layer Meteorol.*, 108(3), 397–417.
- Aubinet, Marc. (2008), Eddy Covariance CO₂ flux measurements in nocturnal conditions: An analysis of the problem. *Ecological Applications*, 18:1368–1378. [doi: <http://dx.doi.org/10.1890/06-1336.1>]
- 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.D. (2008). ‘Breathing’ of the Terrestrial Biosphere: Lessons Learned from a Global Network of Carbon Dioxide Flux Measurement Systems. *Australian Journal of Botany*. 56, 1-26.
- Belcher, S. E., J. J. Finnigan, and I. N. Harman. (2008). Flows through forest canopies in complex terrain. *Ecological Applications*, 18:1436–1453. [doi: <http://dx.doi.org/10.1890/06-1894.1>]
- 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.
- Castilho, C., (2004), Variação espacial e temporal da biomassa arbórea viva em 64 km² de floresta de terra-firme na Amazônia Central. 87p. Doctoral Thesis, ecology, Instituto Nacional de Pesquisa da Amazônia, Manaus-AM.
- 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.
- Feigenwinter, C., C. Bernhofer, and R. Vogt, (2004), The influence of advection on the short term CO₂-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 CO₂ fluxes at three forest sites, *Agric. Forest. Meteorol.*, 145, 1–21.
- Feigenwinter, C., et al. (2009a), Spatiotemporal evolution of CO₂ 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 CO₂ modified by a persistent slope wind system in and above an alpine forest. *Agric. Forest Meteorol.*, doi:10.1016/j.agrformet.2009.05.009.
- 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.
- Finnigan JJ. 1999. A comment on the paper by Lee (1998): On micrometeorological observations of surface-air exchange over tall vegetation. *Agricultural and Forest Meteorology*. 97: 55-64.
- 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. Sclor, 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.

- Foken, T. (2008), The energy balance closure problem: An overview. *Ecological Applications*: Vol. 18, No. 6, pp. 1351-1367.
- 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.
- 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., 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.
- 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.
- Katul, G. G., Finnigan, J. J., Poggi, D., Leuning, R. and Belcher, S. E. (2006) The influence of hilly terrain on canopy-atmosphere carbon dioxide exchange. *Boundary-Layer Meteorology*, 118 (1). pp. 189-216. ISSN 0006-8314.
- Kossmann, M., and F. Fiedler, (2000) Diurnal momentum budget analysis of thermally induced slope winds. *Meteor. Atmos. Phys.*, 75, 195–215.
- Kruijt, B. J., A. Elbers, C. von Randow, A. C. Araujo, 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.
- Leuning, R., Zegelin, S. J., Jones, K., Keith, H., Hughes, D., (2008), Measurement of horizontal and vertical advection of CO₂ within a forest canopy. *Agricultural and Forest Meteorology*, Volume 148, Issue 11, Pages 1777-1797.
- Loescher, H.W., Law, B.E., Mahrt, L., Hollinger, D.Y., Campbell, J. and Wofsy, S.C. (2006). Uncertainties in, and interpretation of, carbon flux estimates using the eddy covariance technique. *Journal of Geophysical Research* 111(D21): doi: 10.1029/2005JD006932. issn: 0148-0227.
- 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.
- Manins, P. C., and B. L. Sawford, (1979) Katabatic winds: A field case study. *Quart. J. Roy. Meteor. Soc.*, 105, 1011–1025.
- Marcolla, B, A. Cescatti, L. Montagnani, G. Manca, G. Kerschbaumer and S. Minerbi, (2005), Importance of advection in the atmospheric CO₂ exchanges of an alpine forest. *Agric. For. Meteorol.*, 130, 193-206.

- Massman, W.J.; Lee, X. (2002) Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. *Agricultural and Forest Meteorology*. 113: 121-144.
- 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.
- 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.
- Papadopoulos, K. H. and Helmis, C. G.: (1999) Evening and Morning Transition of Katabatic Flows, *Boundary-Layer Meteorol.* 92, 195–227.
- Papale D., Reichstein M., Aubinet M., Canfora E., Bernhofer C., Longdoz B., Kutsch W., Rambal S., Valentini R., Vesala T., Yakir D. (2006). Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation. *Biogeosciences*, 3, 571-583.
- 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.
- 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.
- 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.
- 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.
- 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., (2006), Wind velocity above and inside Amazonian Rain Forest in Rondônia. *Revista Brasileira de Meteorologia*, v.21, n.3a, 50-58, 2006.
- Schmid, H.P. (2006): On the "Dos" and "Don't"s of footprint analysis in difficult conditions. *iLEAPS Specialist Workshop Flux Measurement in Difficult Conditions*. 26-28 January, 2006, Boulder, USA.
- Schuepp, P. H., Leclerc, M. Y., MacPherson, J. I. and Desjardins, R. L.: 1990, Footprint Prediction of Scalar Fluxes from Analytical Solutions of the Diffusion Equation', *Boundary-Layer Meteorol.* 50, 355-373.
- Spiegel, R. H., and J. Imberger. (1980) The classification of mixed layer dynamics in lakes of small to medium size. *J. Phys. Oceanogr.* 10: 1104–1121.
- 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 CO₂ 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.
- Sturman, A.P., 1987. Thermal influences on airflow in mountainous terrain. *Prog. Phys. Geog.* 11, 183-206.
- 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), CO₂ transport over complex terrain. *Agric. Forest. Meteorol.*, 145,1-21.
- 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.
- 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.
- 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.

IntechOpen



Tropical Forests

Edited by Dr. Padmini Sudarshana

ISBN 978-953-51-0255-7

Hard cover, 388 pages

Publisher InTech

Published online 14, March, 2012

Published in print edition March, 2012

The astounding richness and biodiversity of tropical forests is rapidly dwindling. This has severely altered the vital biogeochemical cycles of carbon, phosphorus, nitrogen etc. and has led to the change in global climate and pristine natural ecosystems. In this elegant book, we have defined "Tropical Forests" broadly, into five different themes: (1) tropical forest structure, synergy, synthesis, (2) tropical forest fragmentation, (3) impact of anthropogenic pressure, (4) Geographic Information System and remote sensing, and (5) tropical forest protection and process. The cutting-edge synthesis, detailed current reviews, several original data-rich case studies, recent experiments/experiences from leading scientists across the world are presented as unique chapters. Though, the chapters differ noticeably in the geographic focus, diverse ecosystems, time and approach, they share these five important themes and help in understanding, educating, and creating awareness on the role of "Tropical Forests" for the very survival of mankind, climate change, and the diversity of biota across the globe. This book will be of great use to the students, scientists, ecologists, population and conservation biologists, and forest managers across the globe.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Julio Tóta, David Roy Fitzjarrald and Maria A.F. da Silva Dias (2012). Exchange of Carbon Between the Atmosphere and the Tropical Amazon Rainforest, Tropical Forests, Dr. Padmini Sudarshana (Ed.), ISBN: 978-953-51-0255-7, InTech, Available from: <http://www.intechopen.com/books/tropical-forests/exchange-of-carbon-between-the-atmosphere-and-the-tropical-amazon-rainforest>

INTECH
open science | open minds

InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

© 2012 The Author(s). Licensee IntechOpen. This is an open access article distributed under the terms of the [Creative Commons Attribution 3.0 License](https://creativecommons.org/licenses/by/3.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

IntechOpen

IntechOpen