

Nocturnal vertical CO₂ accumulation in two Amazonian ecosystems

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[1] Observations of the nocturnal vertical profile of CO₂, specific humidity, temperature, and winds over a forested and a deforested site in the Amazonian region are presented. This study aims to understand better how scalars accumulate vertically at these two distinct sites at night. The measurements also provide an alternate way to determine the nocturnal fluxes under extremely calm conditions that vex the eddy covariance method. A profiling system based on a low-cost Russian CO₂ sensor aboard a tethered balloon, developed for this study, is described. At the deforested site, accumulation of scalars is restricted to a 100-m thick layer, above which background concentrations of CO₂ and specific humidity remain unaffected during the night. Over the forest, most of the scalars accumulate within the canopy. At both sites, accumulation and cooling rates are larger during calm periods near the surface, with the scalars escaping to upper levels during windier episodes. At the deforested site, the surface fluxes estimated from the time change of the profiles are only comparable to those observed at the nearby micrometeorological tower under windier, less stable conditions. On extremely stable nights, CO₂ accumulates uniformly throughout the accumulation layer, possibly indicating convergence from the nearby forest toward the deforested region.

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1. Introduction

[2] The boundary layer budget method is an alternate technique to estimate surface fluxes when the more commonly used eddy covariance method is inadequate. In this approach, one measures the vertical profile of a given scalar, up to the height to which the vertical fluxes converge, the accumulation layer. The vertically integrated scalar difference for a specified period is assumed to relate to the average surface flux during that period as:

$$F_S = \int_{\text{surface}}^h \frac{\Delta S}{\Delta t} dz. \quad (1)$$

[3] This simple budget approach is obtained by neglecting horizontal transport, by assuming that there are no local sources or sinks of the scalar S within the accumulation layer and no exchange of the scalar between the accumulation layer and the atmosphere above. These conditions practically restrict the use of this approach to cases with very weak winds or to sites with such long horizontally

homogeneous fetch that there is little influence of horizontal advection. The accumulation layer may reach as much as 500 m, making the profile measurement challenging, especially when seeking CO₂ fluxes. Though estimating nocturnal CO₂ surface fluxes, which reflect the ecosystem respiration rate, is crucial for carbon budget studies, very few studies to date have applied the boundary layer budget method to determine them [Culf *et al.*, 1999; Levy *et al.*, 1999; Eugster and Siegrist, 2000; Patey *et al.*, 2002; Mathieu *et al.*, 2005].

[4] At night, the eddy covariance technique appears to be severely limited at certain locations due to low turbulent mixing in the surface layer [Massman and Lee, 2002; Baldocchi, 2003]. These are precisely the conditions under which respired carbon dioxide may accumulate locally near the surface or be transported horizontally by drainage currents [Staebler and Fitzjarrald, 2004; Aubinet *et al.*, 2005] undetected by an eddy covariance system, which only measures turbulent fluxes.

[5] In recent years, our understanding of the capabilities of the eddy covariance technique at night has increased. Given proper analysis, eddy observations can correctly quantify the turbulent exchange even during very stable surface layer conditions [Mahrt and Vickers, 2006; Acevedo *et al.*, 2007]. However, the temporal scales on which the transfer occurs are much smaller than those usually associated with the eddy flux, leading to discrepancies observed in attempts at energy budget closure. Therefore, the usual culprit identified to explain perceived nocturnal CO₂ flux underestimates—“insufficient turbulent mixing” [Baldocchi,

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2003]—may not be the real problem. Even when the turbulent intensity is extremely weak, turbulent exchange can be quantified. What is lacking is better understanding of genuine physical processes responsible for the scalar exchange. Such processes include drainage, circulations attached to local topography or land cover patterns and other very local systematic circulations. These are, sometimes, broadly referred to as “mesoscale fluxes,” motions that occur on timescales longer than those that can be used to define the eddy flux.

[6] In this study, we examine observations from a campaign in which the nocturnal vertical profiles of carbon dioxide, temperature, water vapor, and winds were measured at two sites in the eastern Amazon, one in the forest, the other in a cleared area. The observations aimed: (1) to identify the surface accumulation layer; and (2) to compare the fluxes obtained from the boundary layer budget to those determined from the eddy covariance at the nearby micrometeorological towers. We expected that careful observations would improve understanding of the physical processes driving the nocturnal exchange in such environments. We use the approach used by *Mahrt and Vickers* [2006] and by *Acevedo et al.* [2007] to decompose turbulent exchange into temporal scales, allowing the proper identification of the turbulent exchange and how it interacts with the entire accumulation layer. While the case studies that we report are necessarily limited in duration, our larger aim is to identify the thickness of the relevant CO₂ accumulation layer in two distinct situations in an ecologically important region. This is a step toward developing a plausible method to make estimates for longer periods based on continuous surface observations, much as we did previously for water vapor and heat [e.g., *Acevedo et al.*, 2004; *Sakai et al.*, 2004].

2. Profiling System

[7] At the core of the CO₂ profiling system is a small CO₂ gas analyzer (DX6100, RMT, Ltd., Moscow, Russia). This is a differential, nondispersive infrared gas analyzer that works on detection of the selective absorption of infrared radiation by the gas molecules. The most important advantages of this sensor over similar units commonly used at micrometeorological towers are its low cost and low energy consumption. It weighs 0.3 kg, is small (10 cm × 8 cm × 3 cm), and consumes only 300 mA at 12 VDC. The highest sampling frequency is 1 Hz. The manufacturer specifies precision to be 1 ppm. The sampling cell volume is 4.7 ml and the pump flow rate used was 1 l min⁻¹. To estimate accuracy, this sensor was compared with a model LI-7000 gas analyzer (Li-Cor, Inc., USA) both in the laboratory and in the field and with a LI-820 gas analyzer during profiling (see below).

[8] Even though both temperature and pressure could potentially influence the measurements from the IRGA, our tests indicated that only temperature compensation needed to be applied here to the DX6100 signal. We found that the temperature influence on the CO₂ concentration data may be significant, a consequence of the small dimensions of the optical chamber and the fact that the small aluminum instrument body is in direct contact with the chamber that provides the readings. The corrections for the temperature were done by comparing the DX6100 signal to

the outputs provided by a Licor LI-7000 IRGA. This instrument corrects for both temperature and pressure, and its signal was considered as a reference during the laboratory tests. These tests showed that a temperature correction was sufficient to reproduce the LI-7000 outputs. This correction consists of a four-step process:

[9] 1. First, the temperature compensation is determined as $Y_T = Y(T_{env}/T_{calib})$, where Y is the raw concentration output, T_{env} is the observed temperature and T_{calib} is a constant value, used for the calibration.

[10] 2. The corrected concentration Y_T is then adjusted to the observations by the LI-7000, using a linear regression equation.

[11] 3. The ratio R_Y/Li between the concentration that results from the previous correction and the Li-7000 concentration still shows a linear dependence on temperature. This dependence is removed by adjusting a linear equation to find the function $f(T) = R_Y/Li$ and applying the correction $R_T = R_Y/f(T)$.

[12] 4. Finally, a last linear adjustment is applied between the corrected concentration from the DX6100 and the LI-7000 observation.

[13] The quality of the correction is confirmed by field comparisons to the tower data at the deforested site. Furthermore, at higher levels, the corrected data obtained at both sites with the DX6100 are in good agreement with those observed at two 65-m towers, located above the nearby forest, both within 15 km of distance from the deforested site.

[14] Consult *da Silva* [2006] for further details on these efforts, which led to the operational calibration curves applied to the field data. During the field campaigns, further comparisons were also done between the system output and observations taken by a LI-820 (Li-Cor, Inc., USA). Profiles made with the two distinct CO₂ sensors were nearly identical, adding confidence to our correction procedure.

[15] Pressure, temperature and humidity were determined by the PTH module, developed at the Atmospheric Sciences Research Center (ASRC) by J. Berndt. The pressure observation is used for the determination of the sounding height. The pressure sensor is a model OMEGA PX72-030AV (Omega Engineering, Inc., USA). Relative humidity was determined by a sensor HIH3605 (Honeywell, Inc., USA) and for the temperature observations a thermoresistor SI44006 (YSI, Inc., USA) was used. The temperature and humidity measured by the PTH module were calibrated against values measured independently provided by a Humitter 50Y/50U. The calibrations for these sensors are described in detail by *da Silva* [2006].

[16] The data are stored during sounding by a Tattletale 5F-LCD data logger (Onset Computer Corporation, USA). The sounding signal is transmitted by a radio system consisting of a transmitter AM-TXHP-433 and a receiver AM-HRR6-433 (ABACOM Technologies, USA), which is connected to a computer, at the ground. It allows the real-time monitoring of the observations and provides a backup to the data stored in the data logger. Data were also recorded on board the sonde as a backup.

[17] The combined sensors were fitted into a sonde that was installed below a tethered balloon, model Blimp 13' (Blimp Works, USA). The balloon can operate up to 1000-m height, carry a payload up to 1 kg, and operate in horizontal

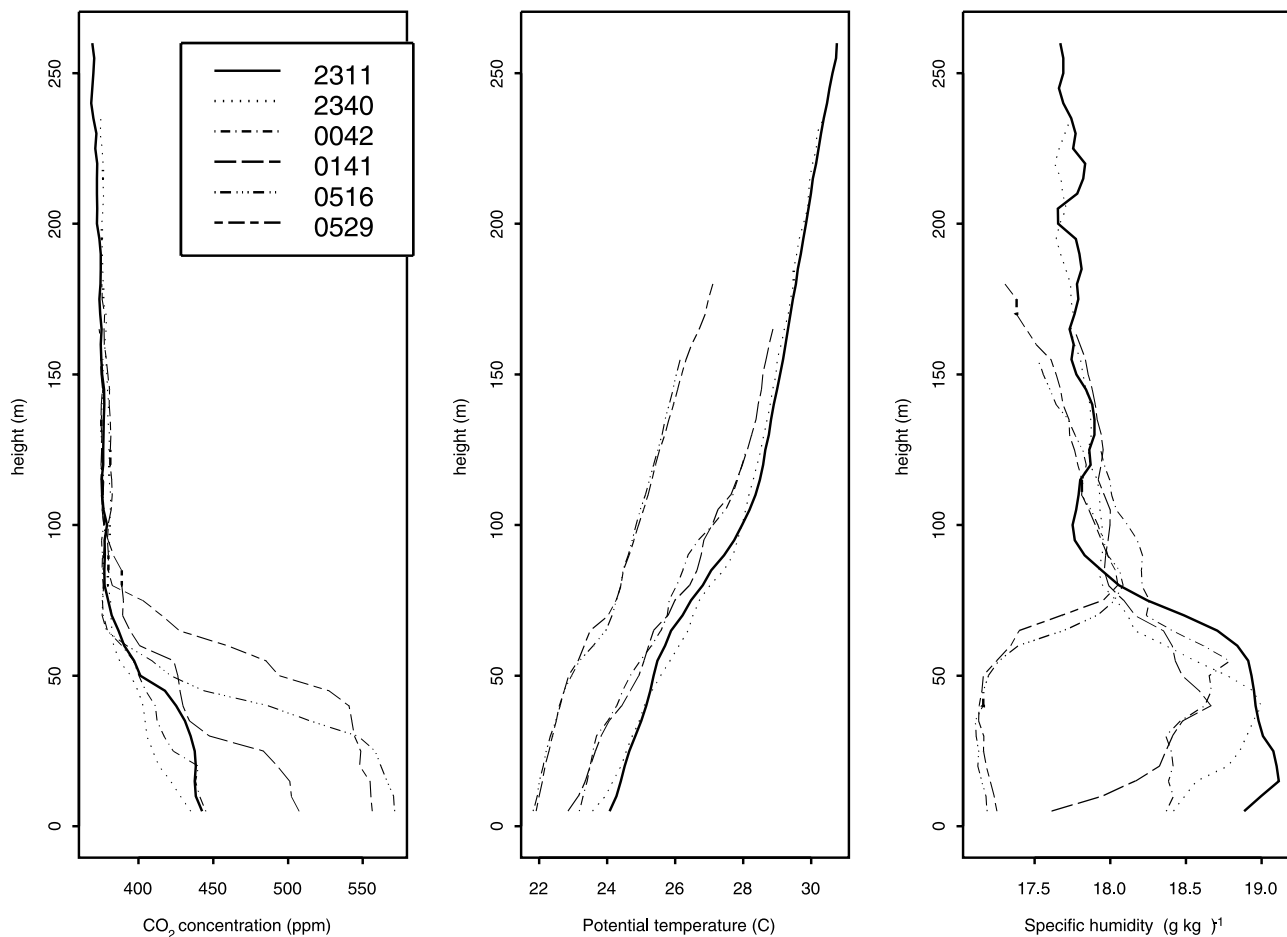


Figure 1. Vertical profiles of (left) CO₂, (middle) potential temperature, and (right) specific humidity over the deforested site, at different times of the night 11/12 November 2003, as given by legend.

winds up to 12 m s^{-1} . A Tethersonde (AIR, Inc., USA) provided wind speed and direction observations and an alternate set of temperature, humidity and pressure measurements. These data were recorded by a ground receiver.

3. Field Sites and Observation Campaigns

[18] The agricultural (deforested) site consists of a 500-ha area of forest that was converted into pasture in 1992. It is surrounded by primary and secondary forest, 25 km east of the Tapajós River. Topography, soil properties and vegetation are described by *Sakai et al.* [2004]. Originally used as pasture for cattle ranching, the pasture was burned in November 2001 and the land was tilled and prepared for the planting of first rice and later soybeans. Between November 2000 and July 2006, a 20-m micrometeorological tower operated continuously, measuring atmospheric variables and turbulent heat, water vapor, momentum and CO₂ fluxes using the eddy covariance technique. Details can be found in *Sakai et al.* [2004].

[19] Three intensive tethered balloon campaigns were performed at the agricultural site, with the purpose of observing the vertical structure of the nocturnal boundary layer. No CO₂ observations were made during the first two campaigns in 2001, whose results were presented by *Acevedo et al.* [2004]. During the third campaign, the focus of this study, profiles including CO₂ were made during the

period 11–18 November 2003. The land was tilled during the week of the observations. Soundings were performed approximately 500 m from the micrometeorological tower. At this time, the field had recently been plowed and there was no vegetation above the surface. Profiles were obtained from sunset until the first hours after sunrise. During the night, the soundings were taken every hour, going either to 300 m altitude, or to the level at which the wind speed reached 12 m s^{-1} . The balloon ascended at 1 m s^{-1} .

[20] The measurements on the forested site were made 23–27 November 2003, with the balloon based in a 50 m by 80 m clearing surrounded by secondary forest with an approximately 35-m high canopy. These measurements were made 5 km from the LBA-ECO km83 flux towers, where sensors on two towers have monitored the surface flux evolution in an area subject to selective logging [*Miller et al.*, 2004].

4. Case Studies

[21] In this section, we analyze some results from specific nights to infer the physical processes controlling CO₂ accumulation near the surface at the two sites. In the next section, these results will be generalized.

[22] At the deforested site, observations from the night of 11/12 November 2003 (Figure 1) show that most of the CO₂ and specific humidity variability at night is confined to a

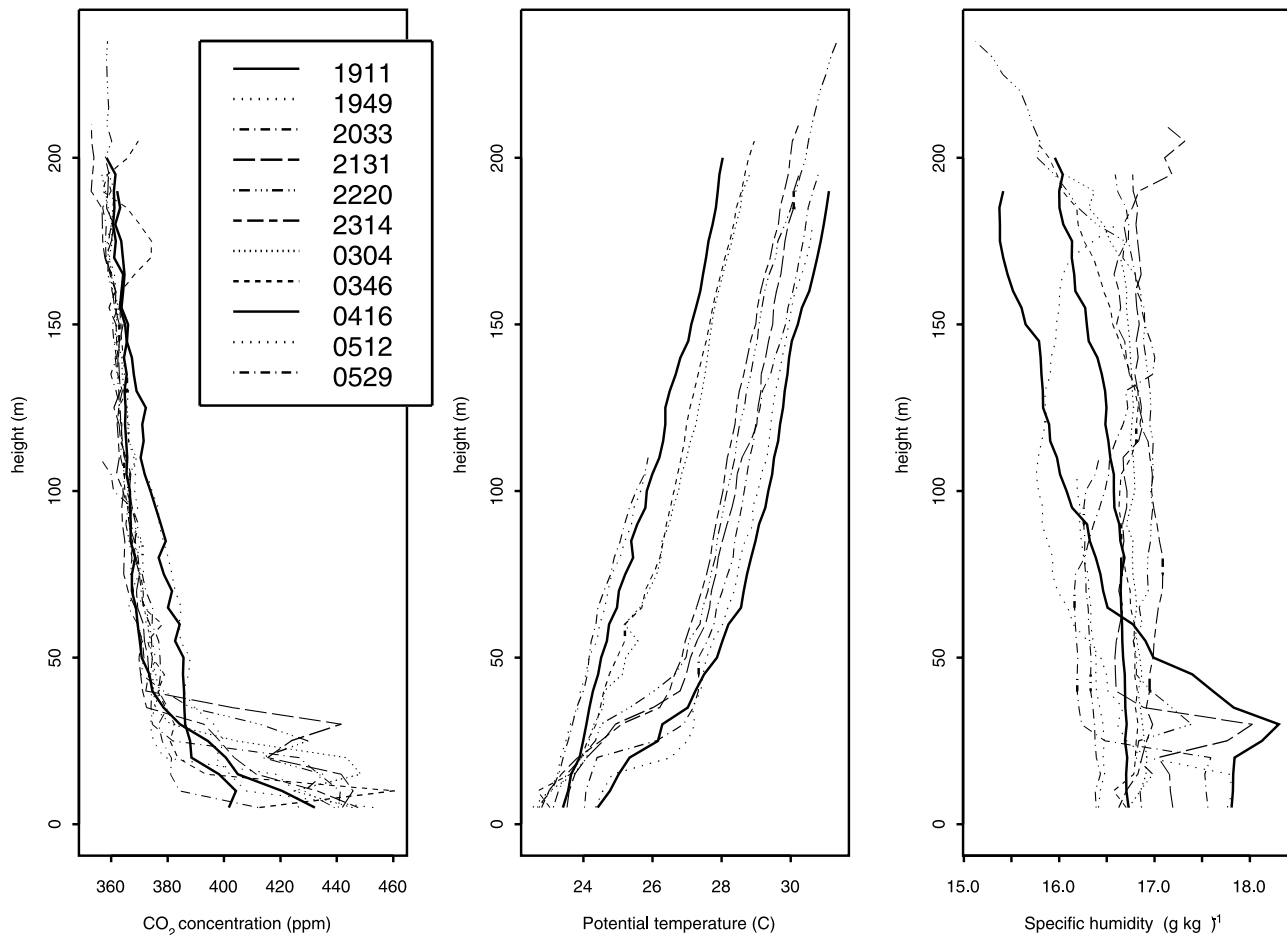


Figure 2. Same as Figure 1, but over the forested site, night 23/24 November 2003.

shallow layer, 50-m thick. Smaller variability can be observed as high as 100 m above the surface and above this height the scalar concentrations tend to background atmospheric values characteristic of the previous afternoon's convective boundary layer. This pattern, however, is not observed every night, being dependent on the wind direction within the accumulation layer (see next section). A very stable nocturnal boundary layer is typically observed, with a vertical temperature gradient approximately of 0.02 K m^{-1} throughout the night. The temperature profile shows an inflection point, characterizing a level with a stronger stability. At the beginning of the night, the inflection point is near 100-m high, shifting to near 60 m at later periods. The height of this stronger inversion may be used as an indication of the accumulation layer thickness.

[23] At the forested site, the accumulation of CO₂ and specific humidity is largely restrained to a 40-m layer, defined by the canopy height (Figure 2). Nevertheless, there is exchange between the canopy layer and the atmosphere above during specific periods, characterized by CO₂ increase at higher levels, especially at 0416 and 0512 LST (Figure 2). The thermal structure above the canopy is similar to that observed above the accumulation layer at the deforested site. An inflection point in the temperature profile occurs during earlier periods of the night. This represents an evolution from the daytime conditions, when

there is radiative heat absorption by the leaves at canopy top, to nocturnal conditions with net radiation losses. The inflection point disappears as the night proceeds, so that a uniform temperature gradient appears by the end of the period.

[24] *Mathieu et al.* [2005] show that the occurrence of a low level jet restrains the accumulation of surface emitted scalars to the calm layer underneath it. They also show that the scalars escape to upper levels when the stability at the surface is reduced. In the present case, the observation of a low level jet was often not possible, as the soundings did not go high enough. Nevertheless, a very calm layer was typical near the surface. In many cases, the winds within this layer were below the threshold of the AIR tethersonde anemometer, which indicated zero wind speed from the surface up to near 50 m. The calm layer was at times destroyed by the onset of winds near the surface, and when it occurred the scalars escaped to upper levels, a behavior similar to that described by *Mathieu et al.* [2005].

[25] Such a process is exemplified for the deforested site during the night 17/18 November 2003 (Figure 3). On this night, the very calm layer existed at sunset, as shown by the 1849 LST profile. During the first hours of the night the weak winds allowed large CO₂ accumulation. Between 2137 and 2211 LST, increased surface winds lead to CO₂ decrease near the surface. An appreciable change was

17/18 November 2003: deforested site

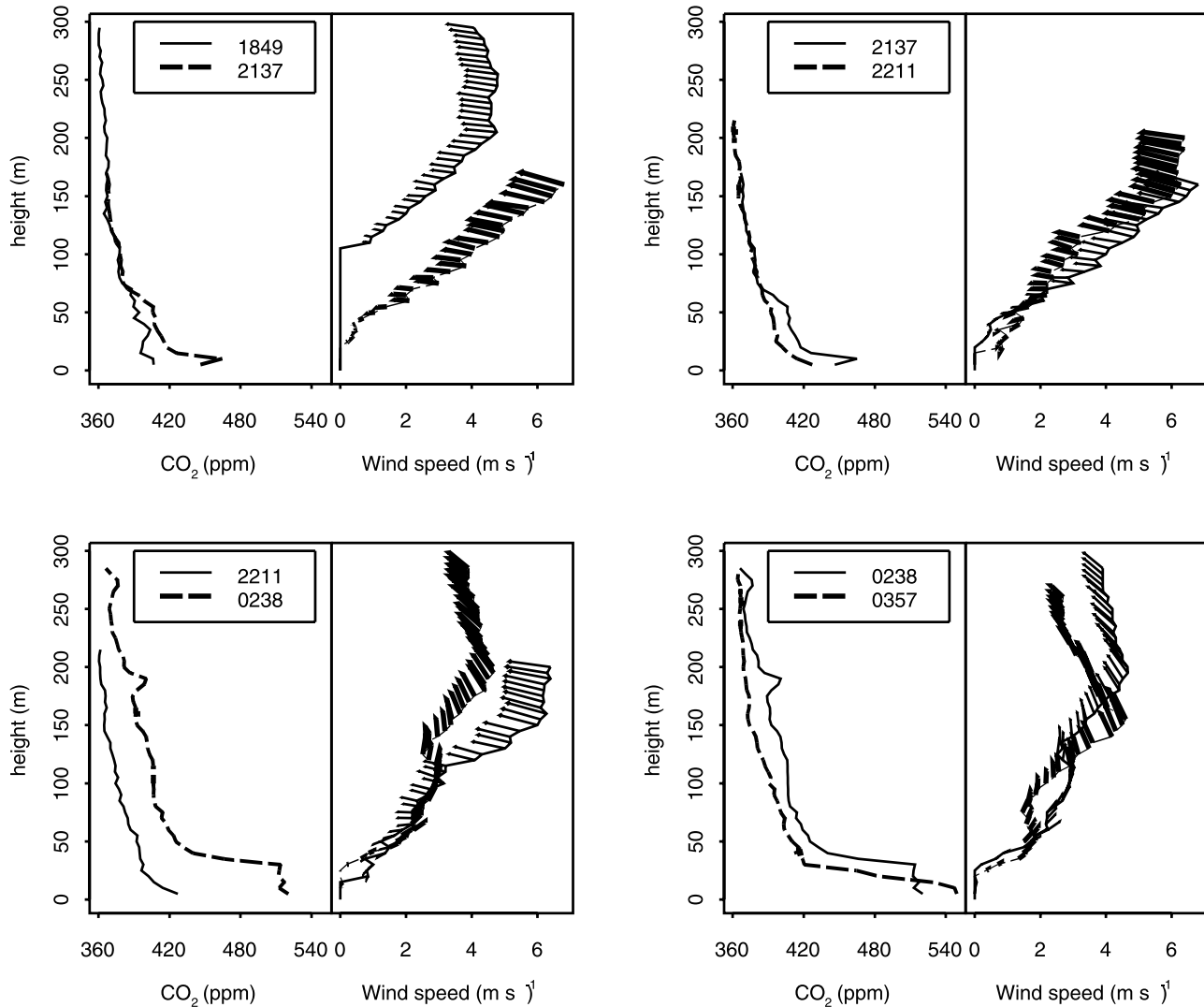


Figure 3. Evolution of CO₂ profile during the night 17/18 November 2003. On each panel two successive profiles are shown, with times indicated in the legend. (left) Corresponding wind profiles, with the wind direction indicated by arrows.

observed in the subsequent profile, at 0238 LST, which showed CO₂ increase both at the surface and at higher levels. During the same period, the wind direction within the accumulation layer shifted, presenting a southerly component. We, therefore, speculate that the southerly winds led to the large CO₂ increase through advective transport. Similar behavior occurred in the night of 14/15 November 2003 (see next section). At 0238 LST, a CO₂ concentration peak happens at a height of 190 m, coinciding with a local jet. Finally, from 0238 to 0357 LST, the persistence of southerly winds, with a calm layer near the surface favored CO₂ accumulation near the surface and decreased concentrations in the layer above.

[26] For the forest, a similar process is observed (Figure 4). The main difference regards the fact that there is a larger difference of wind magnitude between the accumulation layer (the canopy layer) and the air above it. In the night

23/24 November 2003, very calm winds existed within the canopy during the first hours, favoring large accumulation. At 0304 LST, a weak jet within the canopy could be observed, leading to small accumulation at lower levels and some CO₂ escaping to above the canopy. The transfer of CO₂ escaping from the canopy to the air above it becomes appreciable from 0304 to 0416 LST, when increased winds are observed within the canopy. Between 0416 and 0512 LST, large accumulation is observed in a shallow layer close to the surface.

[27] The control exerted by the wind speed on scalar accumulation during both nights described above is summarized in Figure 5, where the accumulation rates are classified in terms of the mean wind speed in the layer from the surface to a 40-m height. This height was chosen because this is a typical thickness for the calm layer on both sites, but the results are not sensitive to this value. At each

23/24 November 2003: forested site

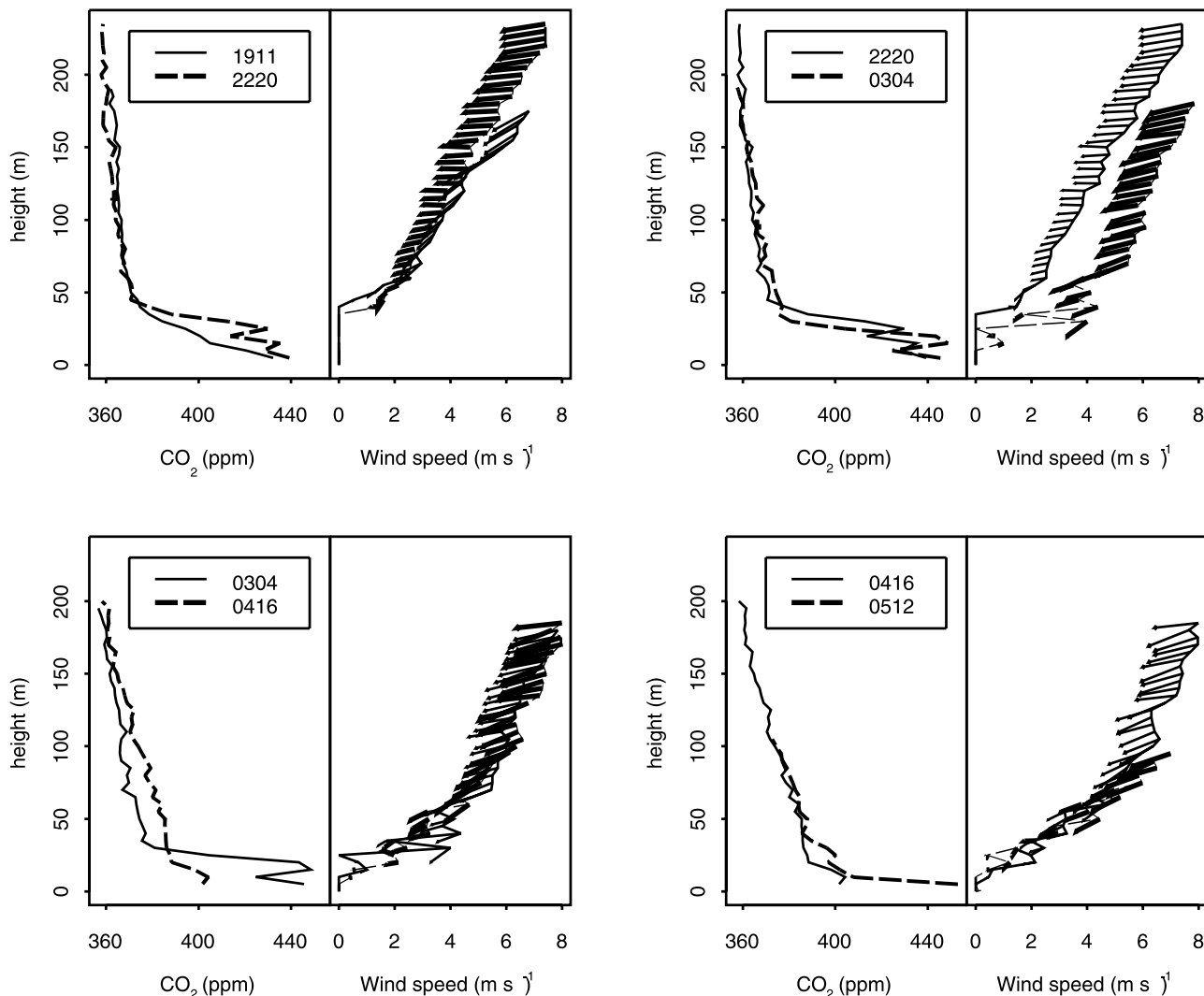


Figure 4. Same as Figure 3, but for 23/24 November 2003.

site, CO₂ accumulates near the surface during calm conditions and decreases when windy situations prevail. Furthermore, the cooling rate is also larger in calm conditions. These results indicate that mixing between the accumulation layer and higher levels occurs in specific, intermittent events, during which the air penetrates the surface layer from aloft.

5. Overall Behavior and Surface Fluxes

[28] To investigate the average behavior of the CO₂ accumulation at nighttime above the chosen sites, we constructed composite time-height plots, using the data from all nights for which vertical profiles were measured (Figure 6). Such composites mask the variability among the nights, but show the overall behavior at each location, allowing the comparison between the sites. Surface accumulation is larger at the deforested area, with the CO₂ concentration reaching in average 540 ppm at early morning,

while it reaches only 480 ppm above the forest surface. Furthermore, the accumulation at the forest is largely confined to the canopy layer, while at the deforested site it reaches levels as high as 200 m, especially after 0200 LST, when the wind shifts to a southerly component on some of the nights, as described in Figure 3.

[29] The surface CO₂ fluxes inferred by applying equation 1 from the first to the last profile at each night are larger at the deforested site (Table 1). Estimated respiration rates from the forest floor are much smaller than the value of 0.37 mg CO₂ m⁻² s⁻¹ reported by *Hutyra et al.* [2007] for November 2003 at the km 67 forest site. The difference may be caused by genuine variability caused by temperature and precipitation fluctuations, but the location of the observations at a disturbed clearing may also be important. Furthermore, the estimated fluxes at the deforested site show large variability among the nights. To understand how the vertical profiles interact with the local turbulent surface fluxes there, we consider several cases for CO₂ accumula-

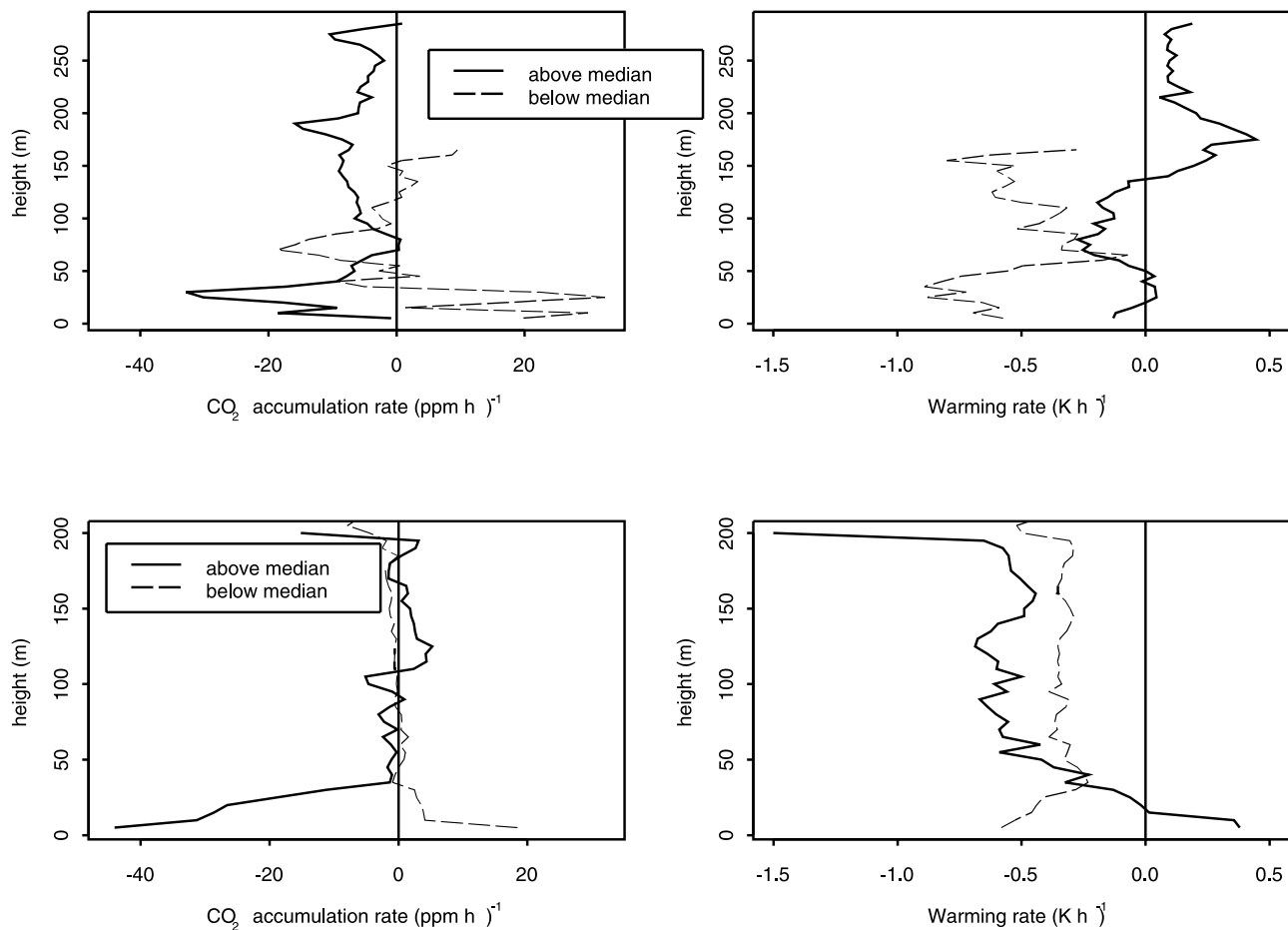


Figure 5. (left) Carbon dioxide accumulation rates and (right) warming rates classified according to the average winds in the layer from the surface up to 40 m. Upper panels refer to the night of 17/18 November 2003 at the deforested site, and lower panels refer to 23/24 November 2003 at the forested site. In each night, the threshold for classification was the median value observed throughout the night.

tion, analyzing both the observed profiles and the eddy correlation tower data. Such comparison is not possible at the forested site, since no tower data are available for the observation period there.

[30] Two distinct behaviors describe nocturnal CO₂ accumulation at the deforested site. The first occurred in the nights of 11 and 16 November 2003 (Figure 7). A nocturnal surface layer approximately 50-m thick developed with the very weak winds during this period. CO₂ accumulated uniformly over the entire calm layer, despite the very calm conditions near the surface. On these nights, CO₂ fluxes obtained from the vertically integrated profiles (Table 1) are higher than 0.30 mg CO₂ m⁻² s⁻¹. This value is much larger than the 0.08 mg CO₂ m⁻² s⁻¹ local respiration rates reported by Sakai *et al.* [2004] for a longer period. Furthermore, on each night, the CO₂ flux observed at the tower was negative on the smaller temporal scales, associated with the turbulent exchange. The flux decomposition on its temporal scales was obtained by applying the multiresolution decomposition [Vickers and Mahrt, 2003]. The decomposition has the important property that the fluxes integrated up to a given temporal scale T equal the eddy covariance flux determined with a temporal window

equal to T . It is important to note that downward CO₂ turbulent fluxes during the night are not a rare occurrence during the dry season. In fact, during three months analyzed, they occurred 49% of the time, generally in association with an inversion of the CO₂ profile.

[31] A second mode of CO₂ vertical accumulation was observed on the nights of 14 and 17 November 2003 (Figure 8). In each case, although there was a very calm surface layer at the beginning of the night, stronger surface winds were observed later, with significant southerly component. In these cases, the CO₂ accumulation was largest near the surface, and the CO₂ concentrations decreased with height throughout the night. Turbulent fluxes were positive, as expected. In these cases, the integration of the averaged multiresolution cospectrum for the whole night up to a 54.6-min window, shows that the fluxes under these conditions are more comparable to those obtained from the vertically integrated profiles. On 14 November 2003, the flux is 0.13 mg-CO₂ m⁻² s⁻¹ from the profile, and matches the value observed at the tower. On 17 November 2003, a flux of 0.16 mg-CO₂ m⁻² s⁻¹ was inferred from the vertical profile, comparing well to the 0.13 mg-CO₂ m⁻² s⁻¹ seen at the tower. These values are also similar to the respiration

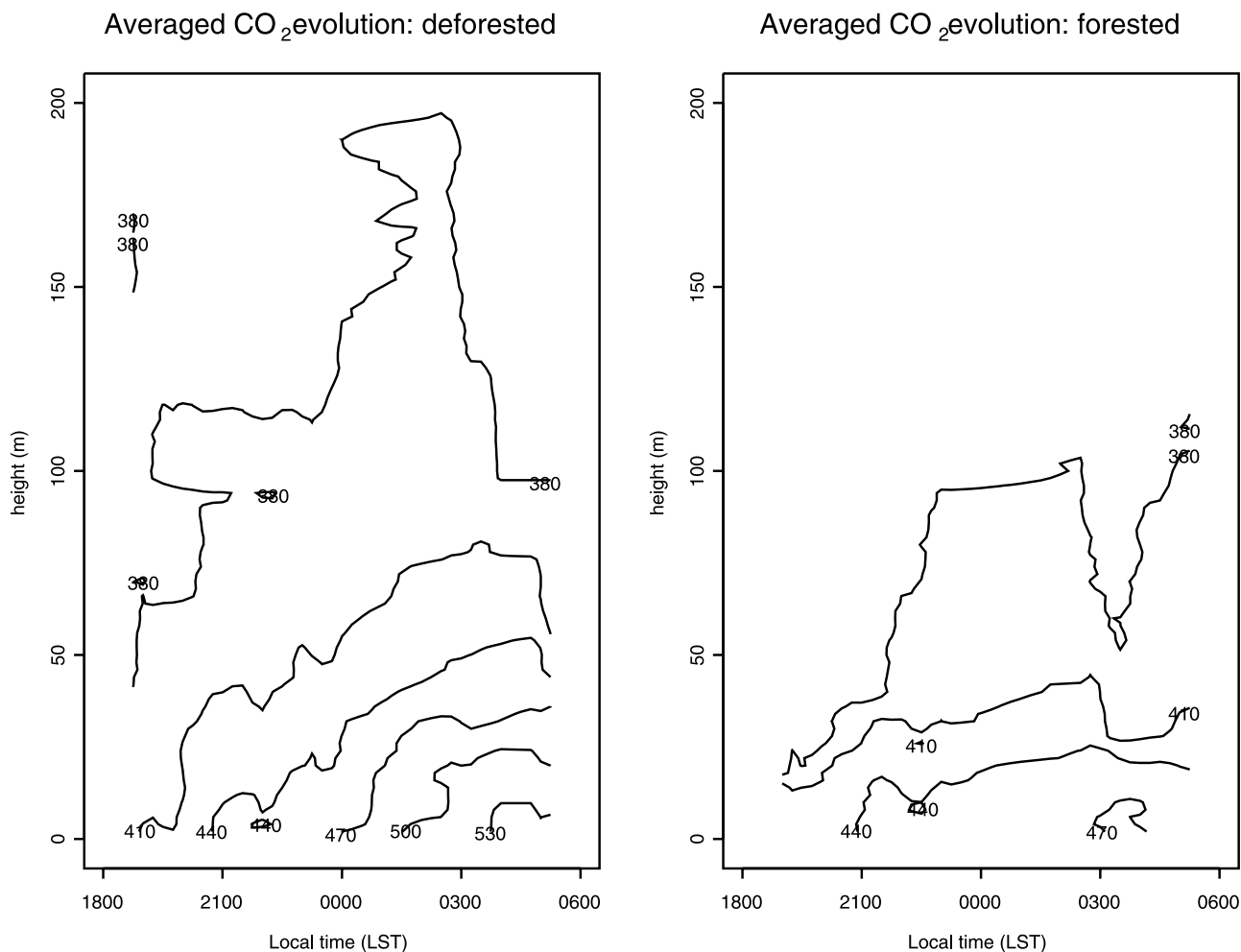


Figure 6. Time-height composites of CO₂ concentration at each site.

rate limit for fully turbulent conditions determined by Sakai *et al.* [2004], of $0.12 \text{ mg-CO}_2 \text{ m}^{-2} \text{ s}^{-1}$.

[32] It is not yet clear what drives these distinct observations, characterized by surface CO₂ fluxes of opposite sign. It is possible that the large deviations between the values observed in the first situation and the average are a mere consequence of the relative frequency of occurrence of nights with large respiration rates. However, we speculate that there may be a genuine physical process being observed in that case. It may occur during more stable conditions,

when the deforested area acts as a pool toward which a good portion of the CO₂ respired in the surrounding forest converges. In this case, advection plays an important role, in a similar manner to what was observed by Eugster and Siegrist [2000]. The deforested region tends to be colder, due to the increased long-wave radiative heat loss. Therefore, the warmer air advected from the forest remains above the surface, in a layered structure, driving the inversion of the CO₂ vertical gradients, and subsequent onset of downward fluxes at the level of the eddy covariance observations.

Table 1. Average CO₂ Fluxes Estimated at Each Night From the Vertical CO₂ Accumulation Between the Times Indicated as First Time and Last Time

Night	Site	First Time (LST)	Last Time (LST)	Flux ($\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)
11/12 Nov 2003	Deforested	2311	0529	0.32
14/15 Nov 2003	Deforested	1835	0450	0.13
16/17 Nov 2003	Deforested	1953	0335	0.31
17/18 Nov 2003	Deforested	1849	0357	0.16
18/19 Nov 2003	Deforested	1903	2246	0.19
23/24 Nov 2003	Forested	1825	0449	0.044
25/26 Nov 2003	Forested	1856	0505	0.144
27/28 Nov 2003	Forested	2103	2251	0.071

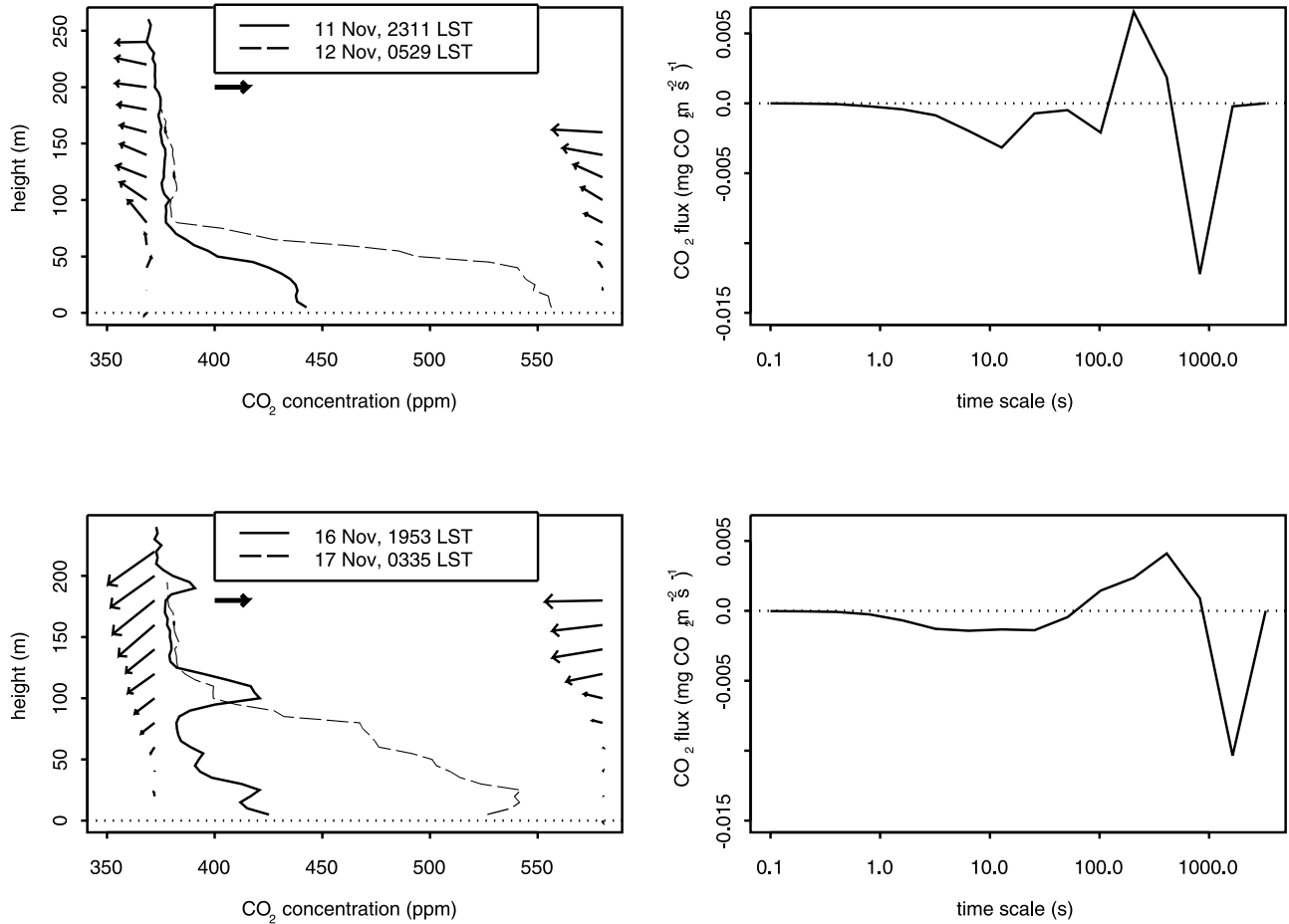


Figure 7. (left) Vertical profiles of carbon dioxide at two different times, according to legend. The arrows at the left side indicate the wind profile at the earlier time, and those at the right side are the wind profile at the later time. The thick arrow at the upper right side indicates a wind magnitude of 3 m s⁻¹. (right) Turbulent carbon dioxide flux as a function of timescale. Both profiles are from the deforested site.

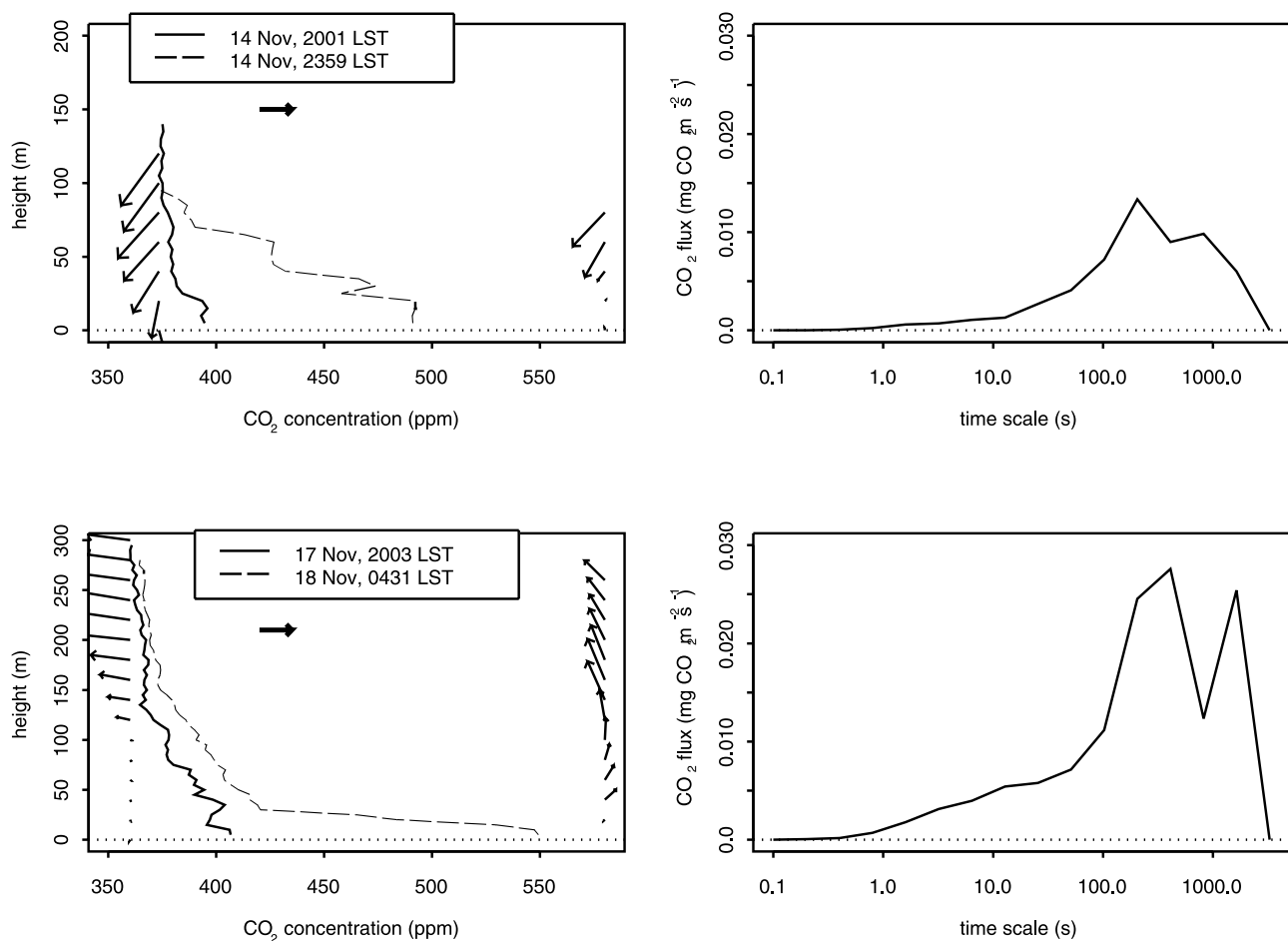


Figure 8. Same as Figure 7, but for two different nights.

The second type of observed behavior is closer to an intuitive conceptual model of upward surface CO₂ fluxes at night, along with a decreasing concentration with height.

6. Conclusions

[33] The main findings of the present study are:

[34] 1. At an Amazonian cleared site, a very stable layer is common near the surface, causing local CO₂ accumulation to be confined to a shallow layer, approximately 100-m thick, above which there is no perturbation on the background atmosphere.

[35] 2. At a forested site, the locally emitted carbon dioxide accumulated mostly within the canopy.

[36] 3. Scalar accumulation is favored under calm wind conditions near the surface, and there is episodic escape of CO₂ to higher levels with stronger winds near the surface.

[37] 4. The estimated CO₂ fluxes at the deforested site are in some cases much larger than typical respiration rates, indicating that there is horizontal advection of CO₂.

[38] The results described here suggest that the correct determination of the nocturnal respiration rates at sites such as the cleared site described is a very complex task. Local circulations may be responsible for downward CO₂ surface flux and inversion of the vertical gradients. During the dry

season, when very stable stratification and fog are common, such behavior may be the more the rule than the exception. At the forest, on the other hand, the higher ventilation indicates that upward fluxes are the rule and that the commonly used methods used for flux determination, such as the eddy covariance may be less of a problem. Since the forest profiles are tightly connected to canopy top, tower-based estimates of the CO₂ storage terms are not likely to be in error because of missed storage. This would only be the case under the very special conditions of substantial accumulation above the tower flux observation level.

[39] The occurrence of downward nocturnal CO₂ fluxes must be further investigated. The mechanisms suggested here need to be corroborated by more detailed studies. In particular, it is necessary to address whether or not there is enhanced lateral advection during the most stable nights when the surface turbulent CO₂ flux is negative. Similarly, it is important to quantify the early morning exchange following these nights and test whether it is enhanced.

[40] We showed that the quantification of the surface fluxes from the application of equation (1) is not always possible. On the other hand, the data provided good evidence on how local circulations affect the carbon dioxide exchange between the surface and the atmosphere at an environment where both forested and cleared areas coexist.

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