Global Change Biology (2004) **10**, 1–9, doi: 10.1111/j.1529-8817.2003.00755.x

Inferring nocturnal surface fluxes from vertical profiles of scalars in an Amazon pasture

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Abstract

Ecosystem carbon budgets depend on there being good representative surface flux observations for all land use types during the entire diurnal cycle. In calm conditions that often occur at night, especially in areas of small roughness (such as pastures), ecosystem respiration rate is poorly measured using the eddy covariance (EC) technique. Nocturnal vertical profiles of temperature, humidity and winds were observed using tethered balloon soundings in a pasture in the eastern Amazon during two campaigns in 2001. The site is characterized by very weak winds at night, so that there is insufficient turbulence for the EC technique to determine fluxes accurately. To compensate, the time evolution of the profiles is used to determine surface fluxes at early morning and these are compared with those observed by EC at a nearby micrometeorological tower. The nocturnal boundary layer thickness h is determined as the height to which the surface fluxes must converge so that energy budget closure is achieved. The estimated values range from 30 m, around 22:00 hours LST, to more than 100 m just before dawn. These are in good agreement with the observed thickness of a frequently observed fog layer during the middle of the night. During the early portion of the night, when the accumulation layer is shallow, there is appreciable decrease of dCO_2/dt with height. On calm nights, CO_2 accumulation rate is larger near the surface than at higher levels. On windier nights, this accumulation rate is vertically uniform. Hence, extrapolation of tower profiles for estimating fluxes must be done carefully. Although uncertainties remain large, an alternate approach to the EC method is described for measuring nighttime surface CO_2 fluxes under stable atmospheric conditions.

Keywords: carbon budget, noctumal fluxes, stable boundary layer, CO_2 accumulation, energy budget

Received 3 December 2002; revised version received 2 June 2003 and accepted 17 July 2003

Introduction

The use of eddy covariance (EC) technique to determine surface fluxes is very successful in daytime or weakly stable conditions, but it fails to predict the fluxes accurately when the turbulence is too small or intermittent (Pattey *et al*., 2002). This limitation is critical in determining carbon balances in many terrestrial ecosystems, since respiratory fluxes can only be measured this way at night, when conditions are typically calmer than in daytime. On calm nights, over relatively smooth surfaces like pastures, a temperature inversion develops close to the ground and mixing virtually vanishes in many instances. For the weak mixing case, a number of screening criteria to filter the data have been suggested for application over rough surfaces, such as forests.

In the so-called u^* correction (Goulden *et al*., 1996), one neglects data from nights for which the turbulent velocity scale is lower than a given threshold (u^*, the friction velocity is a measure of turbulent mixing intensity). Carbon dioxide emission is estimated using data from other, windier nights for which soil temperatures are similar. We note that this technique was developed for use for measurements made over rough surfaces like forests.

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Undersampling turbulent mixing affects the observed energy budget closure, which can serve as a test for the quality of flux measurement. For convective conditions over forests, Sakai *et al.* (2001) showed that including the contributions of low frequency eddies causes all turbulent flux estimates to increase. They verified that heat and water vapor flux estimates increase enough that energy budget closure can be obtained. Thus, improving estimates of turbulent sensible and latent heat fluxes by investigating observational energy budget closure indirectly leads to better understanding of the problems in finding ecosystem respiration. The Sakai *et al.* finding that daytime fluxes are underestimated simply exacerbated the problem of apparently undersampling nocturnal CO_2 flux. Apparently there is a larger amount of missing flux than previously thought.

In LBA-ECO (Large Scale Biosphere–Atmosphere Experiment in Amazonia – Ecology component), flux measurements are being made at both forested and pasture sites. At one forest site, Goulden *et al.* (2002), reported that 70% of nocturnal observations fell below a $u^* < 0.2\,\mathrm{m\,s^{-1}}$ criterion during the wet season, and 77% during the dry season. Further, at the same site, Miller *et al.* (2003) found that estimates of annual net carbon exchange varied from being a strong sink to being a weak source depending on the u^* criterion chosen. More severe problems occur at locations with shorter vegetation where there is a preponderance of calm nights. At the LBA-ECO agricultural field site described in this paper (see the Description of Site and Measurements below), Sakai *et al.* (2003) find a u^* threshold of $0.08\,\mathrm{m\,s^{-1}}$ below which the net ecosystem exchange (NEE) cannot be determined from the EC method. To estimate the ecosystem respiration rate using meteorological methods, storage in the stable surface and boundary layers must be understood. In this case 'storage' refers to scalar buildup in the stable boundary layer (SBL), but it is not obvious the relevant thickness of the SBL for budget purposes. Here we analyze detailed observations of the build-up of heat and water vapor in the stable boundary layer, with the aim to understand the effective level to which CO_2 accumulates.

The temporal evolution of a scalar C (such as CO_2) at a given point is:

$$\underset{(1)}{\frac{\partial \overline{C}}{\partial t}} = -\overline{U}\underset{(2)}{\frac{\partial \overline{C}}{\partial x}} - \underset{(3)}{\frac{\partial \overline{w'C'}}{\partial z}} + \underset{(4)}{S}. \qquad (1)$$

Term (1) represents the local evolution, or storage of C; term (2) is the advection (horizontal transport) by the mean wind; term (3) is the convergence of the vertical turbulent flux of C; and term (4) includes any sources or sinks of C. In Eqn (1), x is the direction of the mean horizontal wind vector, and the turbulent fluxes in the horizontal directions are neglected. If advective effects are also neglected and there are no other sources or sinks within the layer, the temporal evolution of the mean concentration is given by $\partial\overline{C}/\partial t \approx -\partial F_C/\partial z$, where $F_0 \equiv \overline{w'C'}$is the surface flux of C given by:

$$F_0 - F_h \approx \int_0^h \frac{\partial \overline{C}}{\partial t}\mathrm{d}z = h_\mathrm{a}\frac{\partial \overline{C}}{\partial t}, \qquad (2)$$

where h_a represents an accumulation height. It is not the same as the upper limit of integration h, because $\partial C/\partial t$ is not necessarily constant with height. The height h_a is, therefore an equivalent height to which accumulation would occur, if it was constant at all levels.

Strengths and weaknesses of this 'boundary layer budget' method are discussed by Fitzjarrald (2003). A key difficulty is the problem of finding the relevant height at which turbulent fluxes above the SBL approach zero, thereby creating the upper boundary of the SBL. Surface fluxes not advected horizontally converge into this layer. It is difficult to identify the proper level to which surface emissions accumulate in the stable boundary layer. André and Mahrt (1982) presented several alternative definitions for the thickness of the stable boundary layer, and these are repeated in recent boundary layer textbooks (e.g. Stull, 1988; Garratt, 1992). The thickness of the stable surface inversion (h) extends some tens of meters. A low-level wind maximum (h_u) often appears at 50–200 m. The nocturnal boundary layer (NBL) height h_i, is also sometimes regarded as the highest level at which strong potential temperature inversion often reaches several hundreds of meters. For budget purposes, there is less ambiguity. If we assume that surface fluxes are confined vertically h is the layer over which surface flux convergence determines $\frac{\partial C}{\partial t}$ in (2).

Nocturnal mixing can be very localized, both in time and space, in the form of intermittent breakdowns of turbulence (Nappo, 1991), and this may have an appreciable effect on average regional surface fluxes. Mahrt (1987) showed that the average flux from an area does not relate linearly to the average thermodynamical state of that area. During the breakdowns, the surface connects to an upper level. Acevedo and Fitzjarrald (2003) found that surface stations in open areas surrounded by higher vegetation do not appear to mix to levels as high as the SBL. They observed that mixing events were infrequent, and at one location the events served to connect the surface to the lowest 30 m.

Culf *et al.* (1999) used the accumulation method (Eqn (2)) to estimate CO_2 fluxes from an Amazonian forest canopy for 10 nights. They show that the NEE calculated from this technique can differ substantially from that determined by EC. Similarly, Pattey *et al.* (2002) used (2) to replace EC observations on calm nights (65% of the total number of nights in their study) for boreal and agricultural canopies.

The main purpose of the present study is to estimate respiratory CO_2 fluxes from tower concentration data. This can be done from Eqn (2) if one knows the SBL thickness h and how the CO_2 accumulation rate varies with height. Both points are addressed in the present paper. We use tethered balloon measurements of temperature (T) and specific humidity (q) vertical profiles to identify the level to which scalars emitted from or deposited at the surface at night affect concentration profiles. The SBL thickness is then estimated through a budget method (see The Energy Budget Method for Determination of h) as the height to which the integrated T and q tendencies match the difference between net radiation and soil heat storage and the estimated value is compared with the thickness of the fog layer. The dCO_2/dt profile is addressed in the CO_2 Accumulation Layer, along with its evolution and dependence on mean wind magnitude. Finally, these results along with the estimated value of SBL thickness, allow the proper extrapolation of tower profiles of CO_2 concentration to the top of the accumulation layer and subsequent estimation of nocturnal CO_2 surface emissions.

Description of the site and measurements

The tethered balloon data were collected as a part of LBA-ECO project, at the pasture flux tower site (S03°01′11.4″, W54°53′39.3″), near Santarém, PA, Brazil. The site is located on a farm, at km 77 along the Santarém-Cuiabá highway. At the time of the campaigns, the surface cover was 1 m high grass (*Brachiara brizantha*).

A micrometeorological tower has operated continuously at the site since 2000 (Sakai *et al.*, 2003). The measurements at the tower include profiles of wind, temperature, humidity, and CO_2 concentrations, as well as turbulence and fast-response sensors of CO_2 and water vapor. It allows estimates of sensible and latent heat and CO_2 fluxes. The components of the radiative budget and soil properties are also measured. Turbulent fluxes were estimated using the EC technique for periods of 30 min. Further details are given by Sakai *et al.* (2003).

The tethered balloon soundings were done in the field 500 m from the pasture tower, near enough to allow comparison between sounding profiles and tower data. Each sounding provided information on temperature, humidity, horizontal wind magnitude and direction as the balloon went up and down. The data acquisition was done remotely at the surface, via radio transmission, using an ADAS (Atmospheric Data Acquisition System, AIR Inc., Boulder, CO, USA). Typical soundings went up to 300–400 m, as the main purpose of the study was the temporal evolution of the properties near the surface. During most of the night, soundings were performed hourly. The balloon rose at a rate of 0.5 m s^{-1} in the first 100 m, and 2 m s^{-1} above it. The time between successive samplings was 10 s. Intensive periods of shallow, successive soundings were performed starting at dawn (Fig. 1), to catch the early development of the convective boundary layer (CBL). These early morning soundings went up only to the capping inversion (see the Estimation of the SBL Thickness).

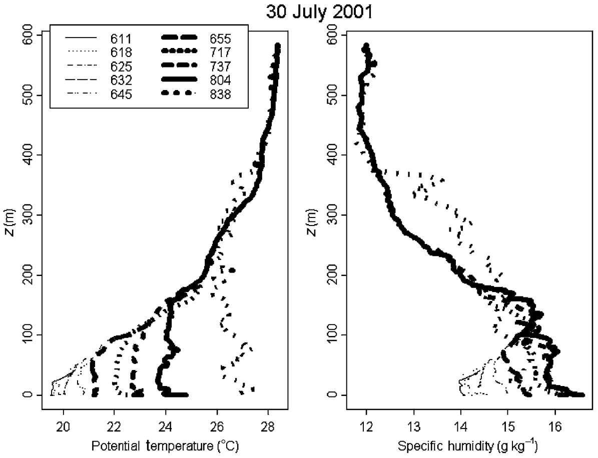
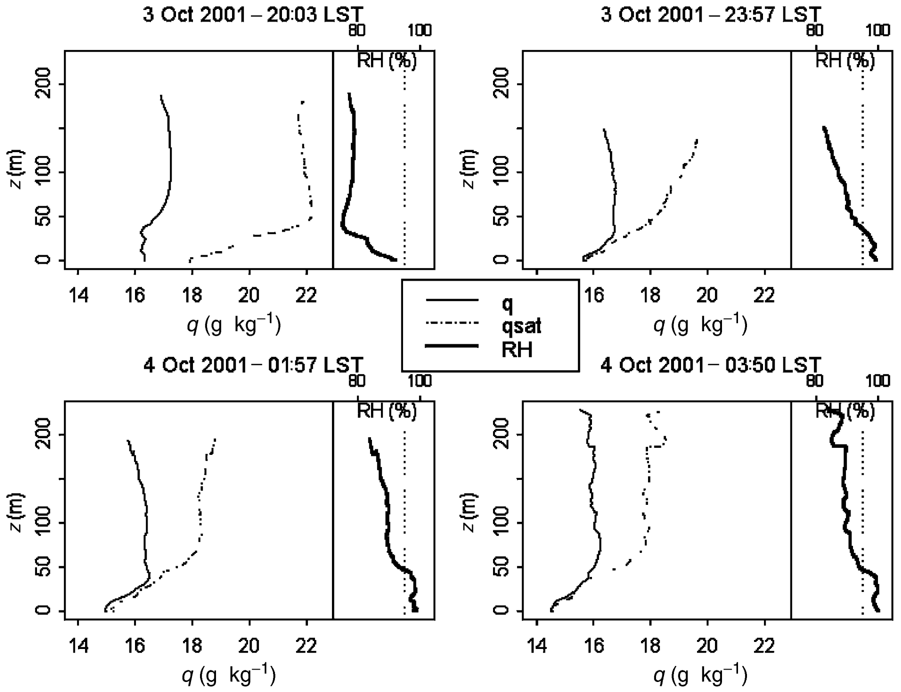


Fig. 1 Vertical profiles observed by the tethered balloon sounding at different times (according to legend) on the morning of 30 July 2001. Left panes shows potential temperature, right panel shows specific humidity.

Two tethered balloon campaigns were performed. The first went from 24 to 30 July 2001. The weather during this period (Silva Dias, pers. commun.) includes the passage of a squall line on the night of 24 July 2001. Normally steady easterly winds were weaker than normal, owing to penetration of a cold air mass into the western Amazon basin (Silva Dias *et al.*, 2003). Northerly winds were observed before the passage of the system, and in the following nights the usual pattern of easterlies dominated. The second campaign occurred from 4 to 11 October 2001. No major synoptic events happened in this period, and a consistent pattern was observed from night to night.

Estimation of the SBL thickness

Is the height h to which the surface fluxes converge at night constant or does it evolve during the night? Is there a typical pattern of evolution during the night? Two different methods were used to the determination of h.


3 Oct 2001 – 20:03 LST

3 Oct 2001 – 23:57 LST

4 Oct 2001 – 01:57 LST

4 Oct 2001 – 03:50 LST

Fig. 2 Each panel show the vertical profile of specific humidity (solid), saturation specific humidity (dash-dotted) and relative humidity (thick, scale on top) for different times, identified on panel top.

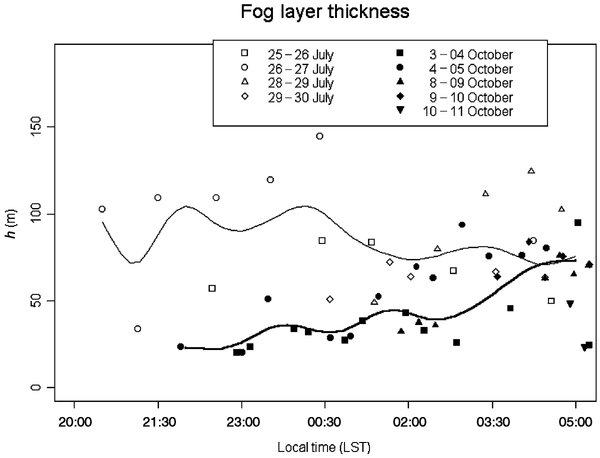

Fog layer thickness

Fig. 3 Thickness of fog layer occurrences. The different nights are identified by different symbols, according to legend. Open symbols are used for the July campaign, solid symbols for October. Thin solid line is a smoothed median for the July observations; thick solid line is the smoothed median of the October occurrences.

The fog layer as an estimation of h

Fog occurs at the site on most nights. The thickness of the fog layer is a good measure of the height up to which most dew deposition has an effect, because little specific humidity variation is observed above this layer (Fig. 2). Radiative flux divergence at the interface between fog and the clear air above leads to a strong temperature inversion, and this effectively damps out turbulent mixing. This height was objectively determined from the analysis of the tethered balloon temperature and humidity profiles. An example (Fig. 2) shows the saturation value of specific humidity (q_{sat}) decreasing during the night of 3–4 October 2001, approaching q, and creating the fog layer next to the surface. The threshold used to determine fog presence was a relative humidity (RH) of 95%, chosen (rather than 100%) to allow for instrumental errors on the soundings. A sharp decrease of RH is observed above the fog layer (Fig. 2), so that its thickness is not very sensitive to the choice of threshold. The fog layer was thicker in July than in October (Fig. 3). Distinct regimes were observed in the different nights in July (Fig. 3, open symbols). As an example, on the night of 26–27 July 2002, fog was observed as high as 150 m early at night, an occurrence not observed on any other night. In October, on the other hand, there was less variability among nights (Fig. 3, solid symbols). Typically, its thickness evolved from around 30 m at 21:00 hours LST to 70 m at 05:00 hours LST. Much more variability was observed in later periods.

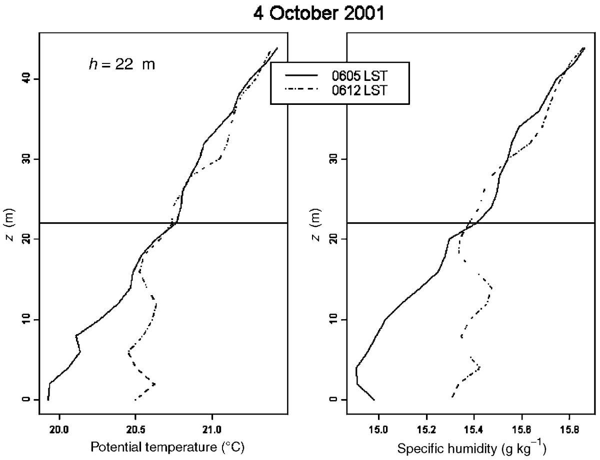


Fig. 4 Vertical profiles of potential temperature (left panel) and specific humidity (right panel), at two different times, according to legend.

The energy budget method for determination of h

Flux estimates at early morning During the initial stages of the convective period, both the EC and the boundary layer budget techniques should work well. There is sufficient turbulence to provide adequate mixing, but the accumulation is confined to a shallow, more easily determined layer. Therefore, the observations along this period are a good indication of the viability of estimating surface fluxes from the scalar profiles sequences.

Eight mornings of intensive observation describe the initial development of the CBL: 26, 29, and 30 July and 4, 5, 9, 10, and 11 October. On each day, the intensive observation periods began at dawn (around 05:30 hours LST) and ended around 08:30 hours LST. To identify the capping inversion describing the SBL top but also insure adequate time resolution of the changing state, balloon descent began as the initial strongly stable layer was detected. Each subsequent sounding was made to incrementally higher levels. This procedure led to remarkably detailed description of the early stages of the CBL, as the evolving convective layer eroded the surface stable layer.

The height h to which the surface fluxes converge was objectively determined from the analysis of soundings adjacent in time (Fig. 4). Height h is taken to be the lowest level at which both temperature and specific humidity tendencies are equal to or less than zero, that is, the lowest level at which no increase in temperature and humidity was observed in subsequent soundings. Surface fluxes were determined using Eqn 2 for three cases in July and five cases in October. The agreement of the estimated fluxes and those observed by the EC method is better for the sensible heat flux (Fig. 5, upper right panel), than for the latent one (Fig. 5, lower right panel). The correlation coefficient between the observed and estimated fluxes is 0.86 for sensible heat and 0.37 for latent. The low correlation coefficient for latent heat flux can be a consequence of larger uncertainties on the sounding specific humidity measurements to those of temperatures, but also of spurious large fluxes observed at the tower early in the morning. In general, the growth tendencies along the period are confirmed both by the tower and the tethered balloon estimates. Furthermore, there is no consistent bias, with the scatter spreading around the 1 : 1 line, so that errors will tend to be averaged out when the averages for different nights are taken, as is done in the next subsection.

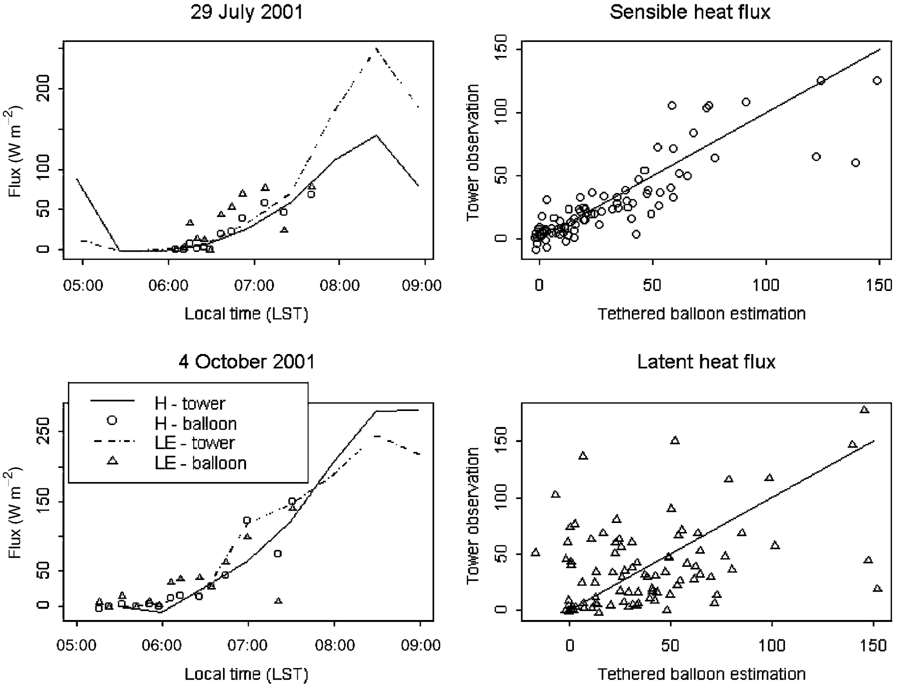
Nocturnal flux estimates The energy budget equation for the current study is:

$$-Q^{*} = H + LE + G + S, \tag{3}$$

where Q^{*} is the net radiative flux, H and LE are, respectively, the sensible and latent heat fluxes, G is the soil heat flux and S is the soil heat storage. The budget is determined inside a box, whose bottom face is located at -0.19 m, and top face is at the stable boundary layer height h.

The term S is determined from the soil temperature profile (Oke, 1995, pp. 46–47), and represents the heat storage from the surface down to the bottom of the box. The atmospheric heat storage is accounted from the surface up to h, in the terms H and LE (Eqn (6)). The flux at the bottom of the box is given by G, and the flux at the box top is assumed to be zero (from the definition of h). Advective terms are neglected, so that no contribution from the sides of the boxes is being accounted. This neglection is supported by the extremely light winds observed during the period both at the tower (median nocturnal wind speed at 5.7 m was lower than 1 m s^{-1} at all nights of the campaigns) and by the soundings, up to the 50 m level (figure not shown). Net radiation is measured at 11 m, a height that is likely below h. If radiative flux divergence exists, it should be included in the budget equation. Sun *et al.* (2002) performed detailed observations of radiative flux divergence at a midlatitude site, finding that this term has a significant contribution to cooling rates only during the evening transition, decreasing to near zero afterwards. Since we are here interested only in the period when the stable boundary layer is already well established, we assume the radiative flux divergence to be negligible.

The sensible and latent heat fluxes are determined from integration of the temperature and specific humidity vertical profiles, respectively, similar to what was done in the Flux Estimates at Early


29 July 2001

Sensible heat flux

4 October 2001

Latent heat flux

Fig. 5 Left panels show the comparison of estimated sensible and latent heat fluxes to those observed by the eddy covariance (EC) technique at the nearby micrometeorological tower, according to legend. The EC measurements were performed for 30 min intervals and the points are connected by lines for clarity; right panels show the comparison of all estimated and observed sensible and latent heat fluxes.

Morning. Only the October nights are analyzed, due to more constant large-scale patterns during this campaign, which allow the determination of composites and average patterns. Differently than the morning, at night the boundary layer thickness is unknown and, therefore, we find this value as the height to which *H* and *LE* converge so that closure of the energy budget is achieved. Despite the large variability observed among the nights, a common pattern of evolution shows small *h* at the middle of the night (sometimes below 50 m), increasing towards its end, reaching as much as 150 m just before dawn (Fig. 6). The median *h* that closes the energy budget agrees very well with the median fog layer thickness (Fig. 6, circles) in the middle of the night, until about 02:00 hours LST. In the later periods of the night, *h* is larger than the fog layer thickness, but both techniques indicate a growth of the layer relative to earlier periods.

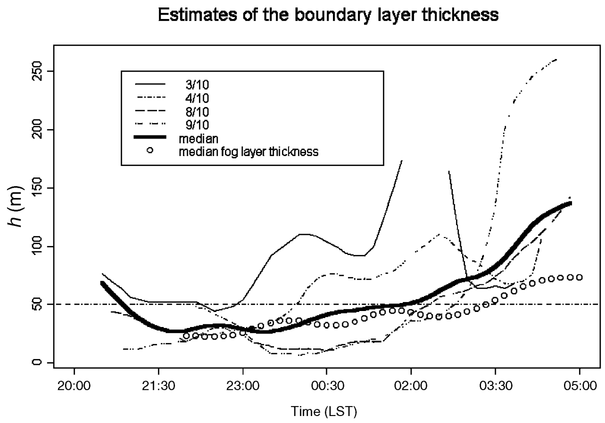

Estimates of the boundary layer thickness

Fig 6 Time evolution of the height of the nocturnal boundary layer for which closure of the energy budget is achieved for the different nights, according to legend. Thick line represents the median for the four nights; circles show the median thickness of the fog layer in October, from Fig. 3.

CO_2 accumulation layer

Micrometeorological towers measure CO_2 concentrations only up to a certain level, usually below the height *h* up to which the surface emissions accumulate. If *h* is known, the surface flux can be estimated from Eqn (2) only if one knows how the accumulation rate varies with height. If enough mixing exists, a surface emitted scalar may accumulate uniformly over the entire layer from the surface to *h* and, in this case, the scalar flux varies linearly from its surface value to zero, at *h*. However, this is not necessarily the case under calm

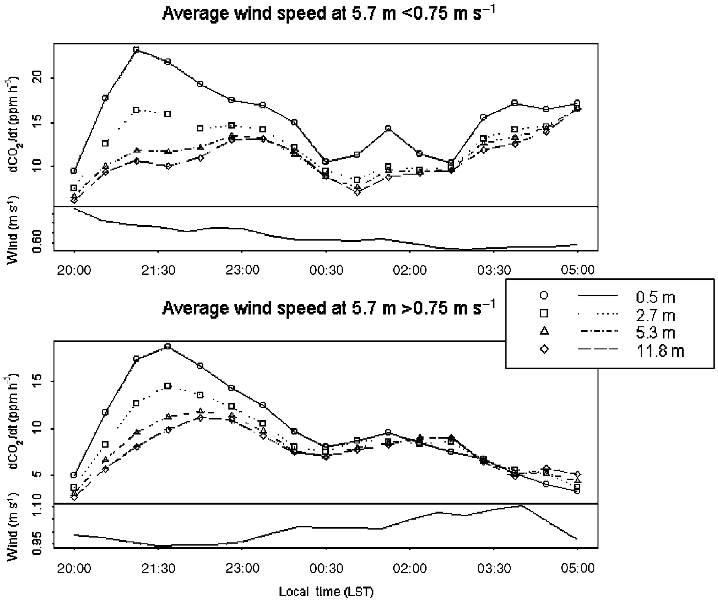


Fig. 7 At each frame, the upper panel shows the average evolution of CO_2 accumulation rate at each tower observation level, according to legend, and the lower level is the average evolution of the wind speed at 5.7 m. Upper frame represents the cases for which the average nocturnal wind at 5.7 m was lower than $0.75\,\mathrm{m\,s^{-1}}$, and the lower frame shows the average for the remaining nights.

conditions, when the accumulation rate may be larger near the surface and the scalar flux profile may be strongly curved.

Although very light winds were the typical condition on the pasture site, the profile of nocturnal CO_2 accumulation rate can be classified according to the mean nocturnal wind speed. A total of 367 nights over the years of 2001 and 2002 were analyzed and the median wind speed at the 5.7 m level at night was observed to be $0.75\,\mathrm{m\,s^{-1}}$. This value was used as a threshold. On nights for which the average wind at 5.7 m falls below the median, the accumulation rate near the surface, at the 0.5 m level, is consistently larger than at the higher observation levels (Fig. 7, upper panel), a consequence of the low mixing activity, which does not transfer the surface emissions effectively to above. On the other hand, on nights with average winds above the median, the CO_2 accumulation rate is uniform with height from 00:00 hours LST to the end of the night (Fig. 7, lower panel). In any case, however, the behavior before 00:00 hours LST is peculiar, with a consistent accumulation peak, around 22:00 hours LST, a possible consequence of the shallower SBL thickness. Furthermore, in this period, dCO_2/dt shows a larger vertical variation, and can be assumed to be constant with height only above the 5.3 m level.

The nocturnal CO_2 flux was determined at four times (22:00, 00:00, 02:00, and 04:00 hours LST) from Eqn (2) and the estimated value for the boundary layer height (the Estimation of the SBL Thickness). At 22:00 hours LST, the accumulation rate was assumed to be constant with height above 5.3 m, and equal to the average observed at the two highest tower observation levels. At 00:00, 02:00, and 04:00 hours LST, it was assumed to be constant with height above 2.7 m, and its value was its average over the three highest observation levels. This was done from the behavior shown in Fig. 7, considering that during the period of the tethered balloon campaigns the average winds at 5.7 m was consistently below $0.75\,\mathrm{m\,s^{-1}}$. The boundary layer thickness was given from the two methods described in the CO_2 Accumulation Layer, and the results are shown in Table 1. The agreement between the two methods is larger at the earlier portions of the night. Later, Figs 3 and 5 indicate the growth of the boundary layer thickness along with a larger variability of its value among the different nights, and this is the cause of the discrepancy between the methods.

Sakai *et al.* (2003) report on long-term CO_2 observations at the Santarém pasture tower where the tethered balloon measurements were made. During the period of observations, the field changed from pasture to upland rice cultivation, planted in February 2002. It has been burned and plowed in November 2001, shortly after the second tethered balloon campaign was conducted. The period after the plowing but before the rice was planted is of special interest. The absence of vegetation determines that there is little or no CO_2 uptake. Therefore, daytime observations of CO_2 flux in the period represent an estimate of the nighttime

Table 1 Estimated boundary layer thickness from the fog method (h_1) and energy budget method (h_2) and CO_2 surface flux estimates from both methods for four times along the night

Time (hours LST)	h_1 (m)	h_2 (m)	F_1 (mg CO_2 m^{-2} s^{-1})	F_2 (mg CO_2 m^{-2} s^{-1})
22:00	23.2	27.7	0.089	0.10
00:00	35.6	32.9	0.14	0.13
02:00	42.9	50.9	0.13	0.16
04:00	65.0	109.0	0.30	0.51

emissions at the site, considering that during the day there is enough turbulent activity at the site for the EC technique to work. This, however, is a crude estimate, as the respiratory fluxes can differ from the plowed field to the pasture because the soil has been tilled. The average daytime emission of CO_2 in the bare soil period observed by Sakai *et al.* (2003) is 0.08 ± 0.02 mg CO_2 m^{-2} s^{-1}. This value is similar to that estimated in Table 1 at the earlier periods of the night. On later periods, the estimated respiratory flux increases, reaching large values at 04:00 hours LST.

These results suggest that the average nocturnal CO_2 flux at the pasture site exceeds the estimation by Sakai *et al.* (2003) based on the measurements over the bare period. This difference may be related to the different surface condition and to errors associated with the technique. The boundary layer thickness *h* estimated from both methods described in the Estimation of the SBL Thickness shows large variability towards the end of the night and it may affect the flux estimates on the period.

Conclusion

On calm nights, ecologically credible nocturnal CO_2 fluxes are often not found using the EC technique. This paper concerns the estimation of the surface nocturnal CO_2 flux on calm nights, when the eddy correlation technique is not useful. Extrapolation of the tower profiles is not simple because of uncertainties about the thickness of the accumulation layer and on the shape of the CO_2 accumulation profile. We addressed both questions in this study, and the main findings are discussed below.

1. The thickness of the nocturnal accumulation layer (*h*) evolves during the night from a very shallow value (around 30 m) in the early nocturnal stages to a thicker layer (around 100 m) just before dawn. Two methods were used to determine *h*, and both indicate a larger variability of its value at the later stages of the night. The growth of the stable boundary layer may be understood as a response to the mixing activity at the site. The nights can be classified in two distinct classes, according to the mean wind speed. Nights for which the mean wind speed falls below its median value (Fig. 7, upper panel) show a constant decay of the winds from its early evening value until the end of the night. On the second class of nights (those that are windier than the median), the average behavior shows a continuous increase of the wind magnitude along the night. Therefore, on earlier stages of the night, in any case, there is very little mixing, and the accumulation layer remains shallow. Towards the end of the night, this layer may or may not grow, depending on the wind evolution, causing the larger variability of the *h* values observed on the period. The generality of this result is not yet known, and further measurements and studies are necessary, especially for a quantitative confirmation. On similar locations with a smooth surface, that favor very calm nighttime conditions, the general behavior shown here should be observed: a shallow accumulation layer that tends to grow along the night. The present study provides not only an estimate of the boundary layer thickness on such a site but also a methodology for its estimation in other situations.
2. The profile of CO_2 accumulation evolves with time, but also depends on the nighttime wind magnitude. In any case, the accumulation peaks at earlier periods of the night, when the SBL is shallow and in this period dCO_2/dt decreases strongly with height. For later periods, typically after 00:00 hours LST, the main difference regards the wind magnitude: on windier nights the accumulation is similar at all levels, while under calmer conditions, much larger CO_2 increase is observed at the lowest observation level (0.5 m). Therefore, extrapolation of the tower profiles must be done carefully. Large overestimation of the estimated fluxes can occur if one assumes that the whole layer evolves as the levels close to the surface do.

Sakai *et al.* (2003) report that during a period for which no vegetation covered the ground of the site, the average CO_2 emissions measured by the EC technique during the daytime is 0.08 ± 0.02 mg CO_2 m^{-2} s^{-1}. Our estimated fluxes are larger than those, but generally within a factor of 2. The differences are caused by the uncertainties regarding the differences on the bare soil nighttime surface fluxes to the pasture fluxes and the *h* estimation technique.

Plans for continuing this work include direct observation of the CO_2 profiles and their evolution.

Acknowledgements

This work is part of the LBA-ECO project, supported by the Terrestrial Ecology Branch under grant NCC5-283 to the authors' institutions. The UFSM authors are supported by CNPq and CAPES, the Brazilian Science Agencies. Jorge Nogueira, engineer from INPE (Brazilian Spatial Institute) provided valuable technical support during the campaigns. We are grateful to the team at the LBA-ECO Logistics Support Office, Santarém, for their fine efforts. Finally, we thank editor Eric Davidson and two anonymous reviewers for their valuable suggestions.

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