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Carbon dioxide measurements in the nocturnal boundary layer over Amazonian forest.

Alistair D. Culf,[1] Gilberto Fisch,[2] Yadvinder Malhi,[3] Rafael Carvalho Costa,[4] Antonio D. Nobre,[5] Ari de O. Marques Filho,[4] John H.C. Gash[1] and John Grace[3]

[1] Institute of Hydrology, Wallingford, OX10 8BB, U.K.
[2] Centro Técnico Aeroespacial, São José dos Campos, 12228–904, SP, Brazil
[3] Institute of Ecology and Resource Management, University of Edinburgh, EH9 3JU, U.K.
[4] Centro de Previsão de Tempo e Estudos Climaticos, Cachoeira Paulista, 12630–000, SP, Brazil
[5] Instituto Nacional de Pesquisas da Amazônia, Manaus, CP478, 69011, AM, Brazil

Abstract

Measurements of carbon dioxide concentration, temperature and windspeed were made in the nocturnal boundary layer over a tropical forest near Manaus, Brazil using a tethered balloon system. The measurements were made up to a maximum height of 300 m on ten consecutive nights in November 1995. Simultaneous surface flux and in-canopy concentration measurements were made at the surface close to the site. The observation period included several different types of conditions. Generally strong windshear and relatively weak temperature gradients prevented the formation of a strong capping inversion to the nocturnal boundary layer. On some nights, however, the inversion was sufficiently strong that the CO_2 concentration at 100 m above the surface exceeded 400 ppm. The concentration within the canopy was largely controlled by the presence of an inversion very close to the canopy surface. The temperature and wind profiles are contrasted with conditions in Rondônia, Brazil, where the windshear was found to be weaker and higher carbon dioxide concentrations were observed in the early morning. The difference in carbon dioxide concentrations in the nocturnal boundary layer between dusk and dawn is used to estimate the regional nighttime flux of carbon dioxide. The value obtained generally exceeds the measured surface flux and sometimes exceeds the sum of the surface flux and the in-canopy storage made at the tower site. The reasons for the discrepency are not clear; either one of the methods is in error or the regional carbon dioxide budget differs significantly from the local budget measured at the tower site.

Introduction

At night, temporal variations of concentrations and fluxes of trace gases observed near the surface may be strongly influenced by the structure of the atmosphere aloft. Recent studies in Amazonia (Grace *et al.*, 1995), for example, observed high concentrations of carbon dioxide above the canopy at night suggesting that the layer was effectively decoupled from the atmosphere above, resulting in a build-up of respired carbon dioxide close to the canopy. On some nights, CO_2 has been observed to leave the canopy in bursts—events linked to wind and temperature structure (Fitzjarrald and Moore, 1990)—whilst on others, it remained within the canopy until early morning when thermally driven convection developed. Until now, such studies have not included measurements of CO_2 in the nocturnal boundary layer (NBL). Explanations of observed variations of fluxes and concentrations based on boundary layer properties and processes have had to rely on estimates or model output for testing hypotheses (Culf *et al.*, 1997 for example). The present paper presents concentrations of carbon dioxide measured in the NBL over an area of tropical forest in Brazil during the Manaus Atmospheric Carbon Dioxide Experiment (MACOE) in November 1995. The measurements are compared with simultaneous measurements of fluxes and concentrations made above and within the canopy.

Tropical forest covers such a large proportion of the earth's surface that it is important to establish whether it is a significant source or sink in the global budgets of carbon dioxide and other trace gases. However, there has been relatively little work to date on the exchange of carbon dioxide between tropical forests and the atmosphere. Delmas *et al.* (1992) made measurements over tropical forest in the Congo basin, whilst the first measurements in Amazonia were made by Fan *et al.* (1990) during the Amazon Boundary Layer Experiment (ABLE–2B). Over the last few years, advances in instrumentation have made longer term, continuous measurements in remote sites more practical. Recent carbon dioxide flux measurements (Grace *et al.*, 1995) and allied modelling (Lloyd *et al.*,

1995) have shown one area of tropical forest in south-west Amazonia (Reserva Jaru, Rondônia) to be a sink for carbon dioxide. Similar measurements in central Amazonia at the site described in this paper show that the forest there is also a sink for carbon dioxide (Malhi *et al.*, 1999). These results have been derived from eddy correlation measurements of the flux above the canopy (F_{ec}) and concentration measurements (C_z) within the canopy to determine the storage term (S). The net ecosystem exchange (NEE) can then be derived as

$$NEE = F_{ec} + \frac{d}{dt}\int_0^{z_i} C(z)\,dz \qquad (1)$$

Typically, for forest eddy correlation measurements, 50% of the measured flux derives from an area of ~20 ha upwind of the site whilst 90% of the flux originates from an area of about 250 ha. The in-canopy concentrations are samples of a much smaller area. To take account of spatial variability in the surface flux and so to enable such patch-scale measurements to be scaled up to larger areas, methods of measuring the regional scale flux (10–100 km length scale) are required. At night, when vegetated areas are strong sources of carbon dioxide, changes in the concentration profiles measured in the NBL can, under some atmospheric conditions, be used to derive an estimate of the nocturnal regional surface flux (Denmead *et al.*, 1996). In the present work, the nocturnal surface flux is estimated from concentration profiles measured through the NBL and compared with values obtained from eddy correlation instrumentation above the canopy.

Site

The site of the experiment was in the Reserva Biológica do Cuieiras (2°35′ S, 60°07′ W), a forest reserve belonging to the Instituto Nacional de Pesquisas da Amazonia (INPA), about 70 km north of the city of Manaus. The site, accessed by a dirt track, is some 10 km west of the main Manaus—Boa Vista (BR 174) road, along which there are frequent small clearings. About 30 km to the north of the site, some larger scale clearing has been carried out to create a pasture area of some 400 km^2 in area. The Reserva Biológica do Cuieiras is part of an area of continuous dense lowland terra firme evergreen tropical forest which first became accessible in the 1970s and was subsequently selected for a representative basin study in the 1980s. The area is relatively flat, although dissected by numerous small streams. The mean canopy height of the forest is 30m and the above ground biomass density is 300 to 400t ha^{-1}. The climate of the area is hot and humid, with average air temperature of 25.6°C and little seasonal variation. The rainfall has some seasonality with the wettest part of the year being the period from December until May, but there is still, on average, more than 100mm per month throughout the rest of the year. The average rainfall in November is 211mm but November 1995, when the measurements discussed here were made, was unusually wet with 331 mm of rainfall. However, during the actual field campaign there was little rain.

Operation of the tethered balloon used to measure atmospheric profiles requires a small clearing if it is not to be damaged by trees. The clearing used was approximately 50 by 50m and contained an abandoned meteorological site and a small building which was used to house the equipment and for accommodation. In the early 1980s, when this meteorological site was in use, the cleared area was approximately 250m by 250m. Subsequently, the vegetation has grown back to a large extent, although it is shorter than the surrounding untouched areas. Approximately 750m south east of the clearing is a 45m high tower which was used for an associated programme of long-term measurements of the carbon dioxide flux above the canopy (Malhi *et al.*, 1998), the measurements from which have been used in the current work.

Instrumentation and methods

ATMOSPHERIC PROFILES

The atmospheric profiles were measured using a tethered balloon system (AIR, Boulder Colorado, USA) augmented with an airline, pump and infra-red gas analyser (IRGA). The balloon system consists of a tethered balloon (volume 5.25 m^3), a winch, a tethersonde which measures and transmits pressure, temperature and wind data at ten second intervals and a receiver station. A wet bulb temperature sensor is also included in the package allowing humidity to be calculated. During this work, however, the wet bulb sensor proved to be unreliable and so no humidity data are presented here. The measurements were logged immediately on a portable computer. In addition to the standard winch and tetherline, a swivelling, sprung elbow was used to absorb shocks on the tetherline and winch and to allow the winch operator to sit in a position from which the balloon could be seen easily. The balloon could be winched up and down easily in windspeeds of less than about 7m s^{-1} but it was not operated in greater windspeeds to avoid damage or loss of the balloon.

The airline was a 300m long nylon tube (3.5 mm id, 4.3 mm od, A.J. Cope, London) chosen for its high bore to wall thickness ratio and its low weight. Choosing the length of the airline involved compromising between sampling at as great a height as possible and being able to lift the weight of tube with the balloon available. However, as any strong vertical gradient in the nocturnal boundary layer profile was expected to be within 300m of the surface (Culf *et al.*, 1997) this length was chosen. The tube had a filter attached to the inlet to prevent insects or other contaminants from being sucked into the system. The inlet end of the tube was attached to the balloon rigging at the top of the tetherline. The rest of the tubing was wound onto a reel positioned next to the elbow in the tetherline. The connection of the tube to the IRGA (CIRAS 1, PP Systems, Hitchin, UK) was made via a swivel joint forming the axle of the reel and a second length of tubing connected to a vacuum pump (Model B105 DE, Charles Austin Pumps, West Byfleet, UK) and a flask. The IRGA sampled the air in this flask using its own internal pump. The IRGA compensates for pressure changes in the sample and reference cells by using its built-in transducers and, regularly, automatically checks its zero by passing CO_2 free air through all its cells. The span was checked throughout the course of the experiment using a cylinder of compressed air of known CO_2 concentration. During a balloon ascent the tubing was attached to the tetherline at approximately 10m intervals using adhesive tape. During a descent, this tape was removed. At every 50m level, judged from the tethersonde height calculation, the balloon ascent was stopped and the air sampled with the IRGA until a steady reading was obtained. Typically, this would take 2 to 3 minutes. The concentration values were recorded manually. It was not possible to measure a continuous profile because of the relatively slow flow of air through the tubing (~3 l min^{-1}) and the volume of the flask (~1.5 l). Before and after each balloon flight, the flow of air through the IRGA was switched to an airline running to the top of a 5m mast on the abandoned meteorological site at the edge of the clearing. This provided the lowest point of the profile at a point away from the personnel working on the tetherline and air intake, and checked that the concentrations before and after the profile were similar and that the system was operating satisfactorily. As is shown below, these extra data proved more useful than was expected initially. The equipment was powered by a diesel-powered generator, positioned some 50m to the west of the balloon, (the normal downwind direction) under the canopy of the trees on the edge of the clearing.

Profiles of CO_2, temperature and wind were measured at 1800, 2100, 0000, 0300, 0530 and 0800 local time (conditions permitting) on ten consecutive nights beginning on 16 November 1995 (Day of the Year 320). In addition, a further ascent without the carbon dioxide measurements was carried out each day at 1000. Logistical constraints meant that the final profile on the last night of measurements took place at 0300.

SURFACE MEASUREMENTS

Throughout MACOE, an eddy correlation system, situated at the top of the micrometeorological tower at a height of 46.5 m, measured fluxes of carbon dioxide, water vapour, heat and momentum. This system (Edisol, Edinburgh University, see Moncrieff *et al.*, 1997) consisted of a fast response closed path IRGA to measure water vapour and carbon dioxide (Li 6262, Li-Cor, Lincoln, Nebraska, USA), a three dimensional sonic anemometer to measure the vertical component of wind (Solent A1002R, Gill Instruments, Lymington, UK), a pumping unit to draw air through the IRGA at a constant rate and a laptop computer to calculate and log the fluxes in real time. A second eddy correlation system built up from similar components, but different in detail (Institute of Hydrology, UK), was operated level with the top of the canopy at a height of 33m from 17 November until 26 November. The horizontal windspeed data from the sonic anemometer used in this second system have been used in the calculation of Richardson numbers discussed below.

The concentration of carbon dioxide at various heights within the canopy $C(z)$ was also measured to enable the storage of carbon dioxide to be calculated. The measurement system consisted of an IRGA, a pump and a switching unit which sampled air sequentially from heights 5.3 m, 9.0 m, 17.4 m, 25.25 m, 33.25 m and 46.5 m, spending five minutes at each level and cycling through the entire profile once every 30 minutes. The time rate of change of this storage component added to the flux of CO_2 measured by the eddy correlation instrumentation above the canopy gives the net ecosystem exchange (from Eqn. 1). An automatic weather station (Didcot Instruments, Abingdon, UK) at the top of the tower recorded hourly averages of solar and net radiation, dry and wet bulb temperatures, wind speed and direction, and rainfall.

BACKGROUND CARBON DIOXIDE CONCENTRATION

The programme of measurements described here did not include any measurements of the background, tropospheric carbon dioxide concentration—which would have required sampling above 300m by aircraft. This value has therefore been estimated. There are no long-term background measurements available in this region, but Wofsy *et al.* (1988) measured an average value of 344.1 ppm for the mean concentration in the mixed layer during the afternoon over forested surfaces in the same region in the ABLE programme in July and August 1985. Over the intervening period, the CO_2 concentration at Mauna Loa has increased by 1.5 ppm per year (Keeling and Whorf, 1996). Assuming the same rate of increase over Amazonia gives an estimated background concentration of ~359 ppm, and this value has been used in the present work.

Discussion of observations

HOW TYPICAL WERE THE MEASUREMENT NIGHTS?

Ten days is a relatively short period for an atmospheric measurement campaign and therefore determining the more general significance of the results is difficult. However, it is possible to gain an impression of how the measurement period relates to general conditions by comparing the atmospheric conditions during MACOE to long term automatic weather station data collected at the same site. Figure 1 shows the frequency distribution of nocturnal net radiation and nocturnal wind run for the site, two

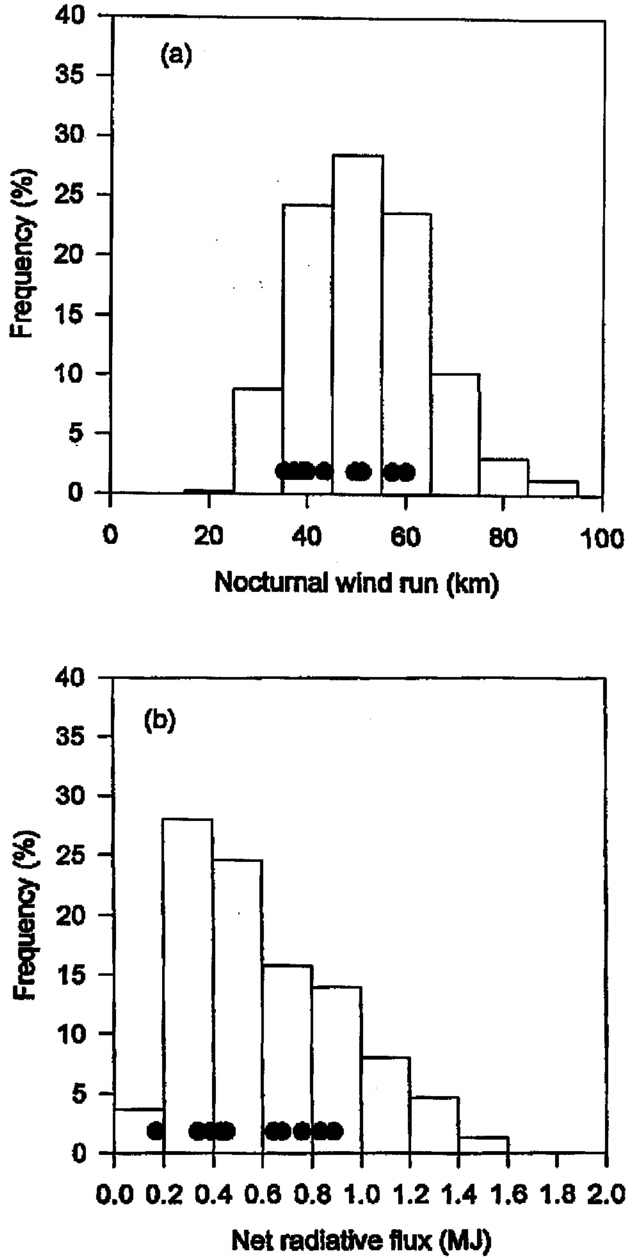


Fig. 1. *Frequency distribution of radiation and wind at the tower site. The dots show the conditions during the 10 nights of MACOE.*

of the factors which most influence the development of the NBL and the nocturnal turbulent transfer. The dots show the values occuring during MACOE. Although the data cover a range of values, they are all sufficiently common for the data to be regarded as representative of much of the year at this site.

COMPARISON OF BALLOON CONCENTRATIONS WITH TOWER DATA

Before and after each atmospheric profile measurement, the air inlet was switched to the top of a 5m mast positioned at the northern edge of the clearing. These 5m data are presented in Fig. 2a along with the concentration measurements made at the 5.3m level on the micrometeorological tower. The tower system failed between Day of the Year (DOY) 325 and the end of DOY 326 resulting in the gap in the data displayed in the figure. The agreement between the concentration measured by the two systems is excellent, particularly on calm nights when there is a large build-up of carbon dioxide within the canopy. These measurements were taken by systems separated by a distance of around 750 m, one in the heart of the forest and one at the edge of an overgrown clearing. The agreement is surprising and suggests that, close to the surface, the CO_2 concentration is remarkably uniform across the forest. Estimates of storage from a single profile may be representative of an area larger than the footprint of eddy correlation instrumentation, thus enabling a representative storage measurement to be made with a single profile system.

Figure 2b shows the concentration measurements made by the eddy correlation instrumentation on the tower at 46.5m and the concentration measured by the balloon system at the first height on each profile—nominally 50 m—but in fact

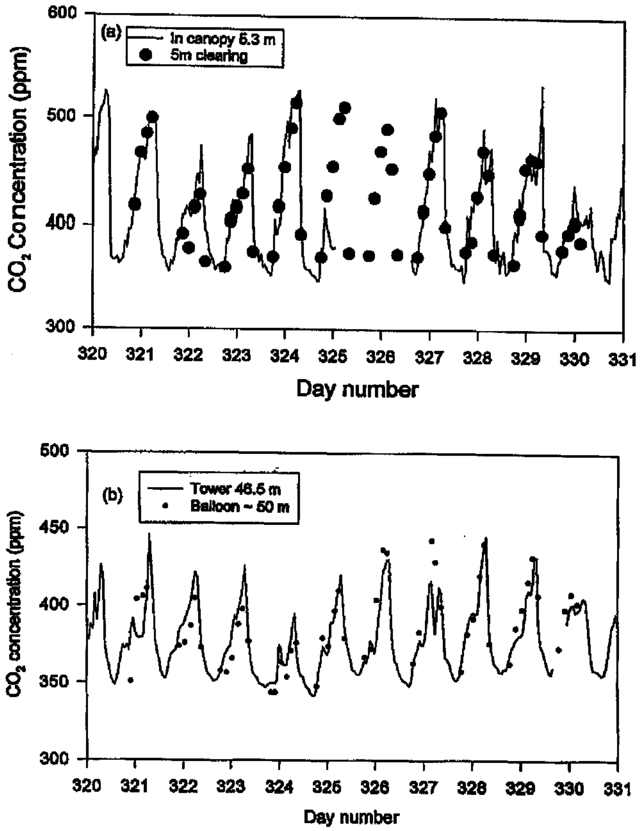


Fig. 2. *Comparison of concentration measurements made by the balloon system (dots) and the tower instrumentaion (solid lines). (a) 5 m balloon profile measurement and 5.3 m tower measurement. (b) Nominal 50 m balloon profile measurement (actually a range between 45 and 65 m) and 46.5 m tower measurement.*

varying between 45 and 60 m. The tower measurements are hourly averages whilst the balloon measurement is a sample of about 1 minute. Nevertheless the agreement between the systems is good. The largest differences occur on Nights 320 and 326.

ATMOSPHERIC PROFILES OF CO_2

The profiles of carbon dioxide measured by the tethered balloon system during the ten nights of MACOE are shown in Fig. 3. There is considerable night-to-night variation in the evolution of the carbon dioxide concentration profile from the well mixed profiles of Night 329, to the large variations with height on Night 326. Some of the individual nights will be addressed in more detail below. Common to nearly all the nights, however, is the initial relatively well mixed profile at 1800, at the end of the convective activity. The CO_2 concentration in the top half of the 1800 profile is usually less than the estimated background concentration of 359 ppm. Averaging the concentrations from above 150m on the 6 nights when it was possible to make measurements at these heights gives a value of 353 ppm; 6 ppm below the estimated background value (Night 329 is excluded from this calculation as the concentration is much greater due to other processes discussed below). This value may suggest that there is a small photosynthetic drawdown of carbon dioxide during the day. In the present work, the background concentration is only an estimate and so no firm conclusions can be drawn on this point but Wofsy *et al.* (1988) measured a 4–6 ppm reduction below free tropospheric values in the mixed layer during the afternoons over Amazonian forest. This magnitude of photosynthetic drawdown has also been simulated by general circulation model runs (Denning *et al.* 1996).

Apparent on several nights is the rapid fall in concentration between 0530 and 0800 indicating the onset of convective activity when the nocturnal boundary layer is rapidly mixed with air from above. This process is particularly clear on Nights 324 and 327 when the concentration at 100m falls from 391 to 377 ppm and 374 to 359 ppm respectively over this 2.5 hour period and the shape of the profile changes substantially. On all of the measurement nights, there was variation from the 1800 profile during the night at all sampling levels, although the strong winds made it rarely possible to measure to the maximum height of 300m permitted by the length of the airline. At the 100m level, CO_2 concentrations often rose to more than 400 ppm by 0530. A well defined 'lid' or capping layer on the nocturnal boundary layer was not observed in the CO_2

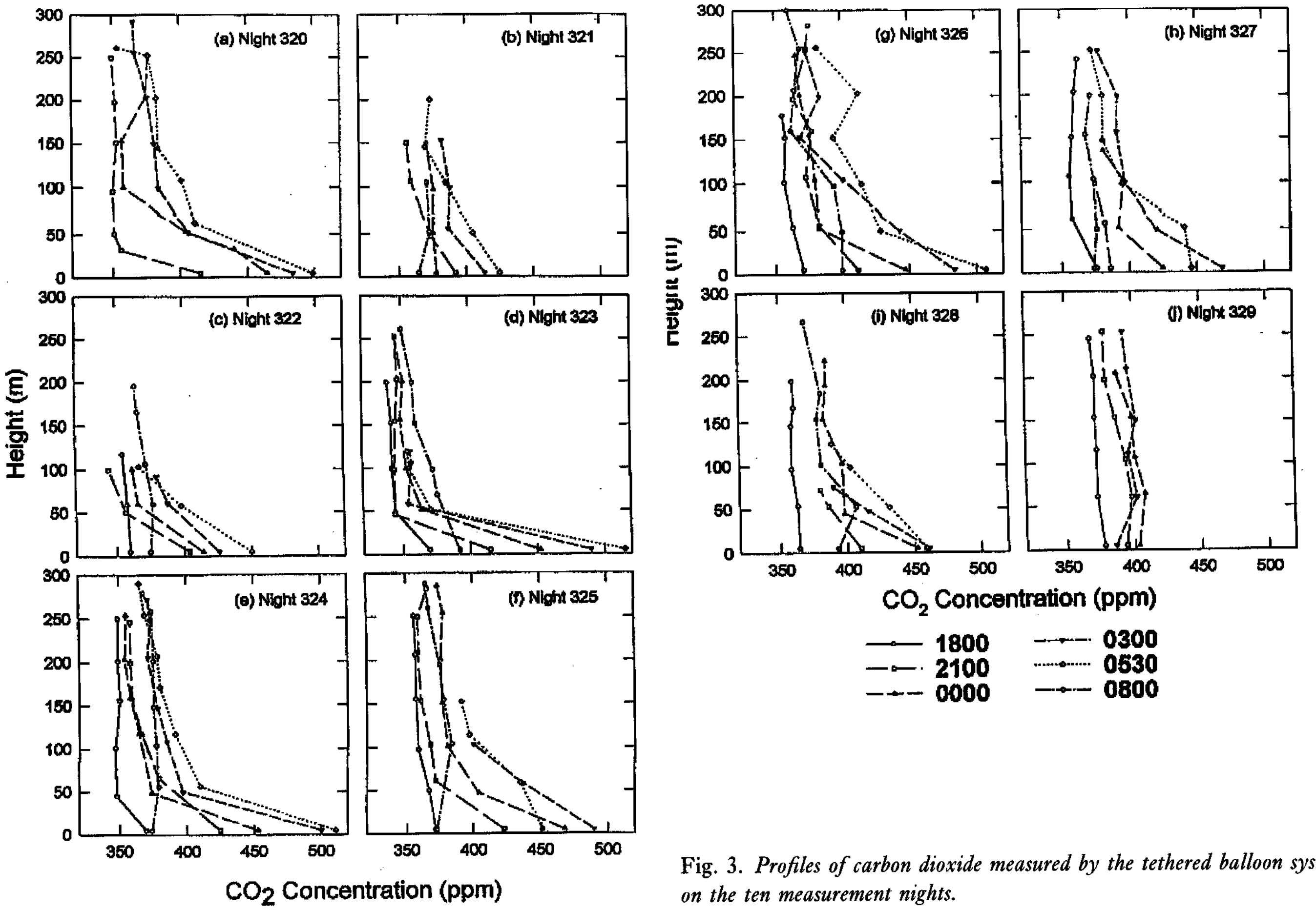


Fig. 3. *Profiles of carbon dioxide measured by the tethered balloon system on the ten measurement nights.*

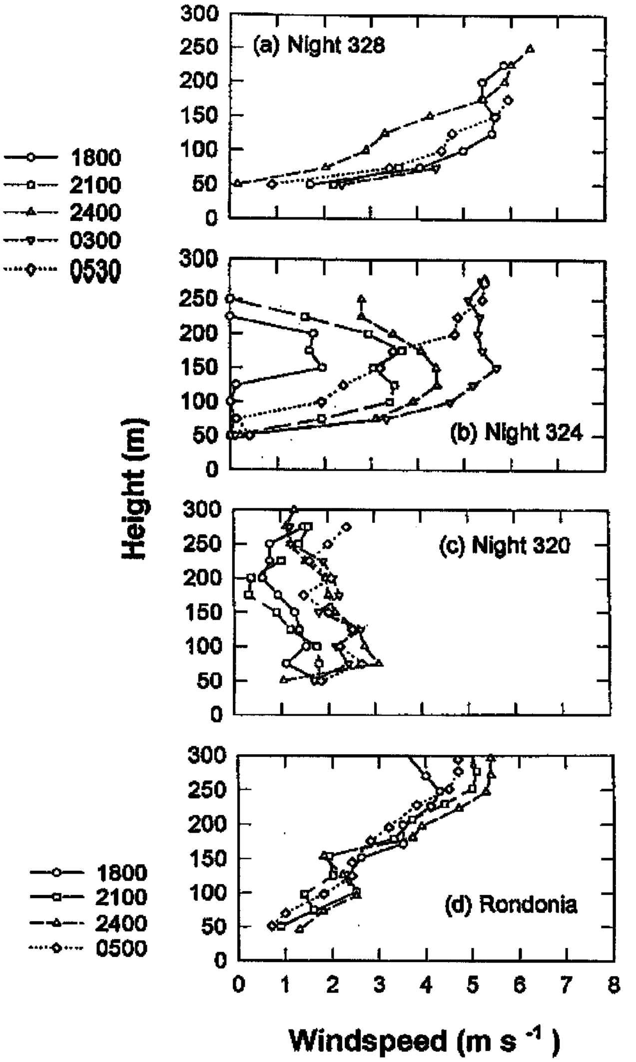


Fig. 4. *Profiles of wind measured by the tethered balloon system. a) Night 328, a typical night during the experiment. b) Night 324, an example of a jet wind profile. c) Night 320, unusually light winds with little shear. d) Typical nocturnal wind profiles measured in Rondônia over tropical forest during the Rondônia Boundary Layer Experiment (RBLE3).*

profiles, but the measurement interval of 50m does limit the possibility of detecting such a layer in the data. However, the temperature and wind data discussed below also suggest that in general there was no strong capping layer aloft during this experiment.

WIND AND TEMPERATURE PROFILES

The wind profiles shown in Fig. 4a are typical of the measurements made during MACOE. There is strong shear in the 50 to 100m layer with the wind speed often reaching 5m s^{-1} at the 100m level, even when the windspeed recorded at 50m was close to zero. On three of the ten measurement nights, a jet profile developed. This was exceptionally marked on Night 324 as shown in Fig. 4b. The windspeed reaches a maximum of 6m s^{-1} at a height of 150 m, again implying strong shear in the lowest levels of the boundary layer. Such low level nocturnal wind maxima have often been observed over central Amazonia (Greco *et al.*, 1992; Oliveira and Fitzjarrald, 1993) and are thought to be due to a thermal breeze effect caused by the Amazon and Negro rivers. Figure 4c shows the wind profiles measured on Night 320 which had a completely different form from those on the other nine nights. Light winds persisted throughout the 300m profile with very little shear developing.

Typical potential temperature profiles observed during MACOE are shown in Fig. 5a. The potential temperature gradient across the 50 to 100m layer increases from 0.015 to 0.043 °C m^{-1} during the night. Above 100 m, the profile has only weak stable stratification, with a gradient of 0.012 °C m^{-1} even at dawn. Figure 5b shows the profiles on Night 323, the night with the highest stability recorded by the eddy correlation instrumentation at the top of the tower. The most stable layer is confined to a thin layer close to the canopy. Figure 5c shows the profiles measured on the least stable night. The profile shows weak stable stratification up to 200 m.

The wind and temperature profiles discussed above combine to produce an NBL with relatively low Richardson numbers and generally no marked capping layer above 50 m. The Richardson numbers have been calculated for 10m layers from smoothed wind and temperature profiles. The distributions of Richardson numbers for all ten nights in different layers of the NBL are given in Table 1. These results contrast with the observations made during the Rondônia Boundary Layer Experiment (RBLE) (Nobre *et al.*, 1996; Fisch, 1995). Typical wind profiles recorded during that experiment showed much weaker wind shear as shown in Fig. 4d, whilst temperature profiles were typically more strongly stably stratified with potential temperature gradients of ~0.03 °C m^{-1} in the 50 to 300m layer at dawn. The distribution of Richardson numbers for the RBLE data is also shown in Table 1. Given the uncertainties in the calculation of Ri , the table suggests that there is much more likelihood of stable layers (with $Ri > 1$) aloft in the RBLE case than during MACOE when the NBL was often turbulent ($Ri < 0.25$) between 50 and 200 m. The generally more stable layers aloft in Rondônia may explain why higher values of CO_2 concentration were observed above the canopy at dawn in Rondônia (Grace *et al.*, 1995) in comparison with the present experiment, although it must be remembered that the boundary layer and carbon dioxide flux measurements were not made simultaneously at the Rondônia site. The differences in local topography at the two sites may also have influenced the observations. The Manaus tower is situated on the highest level of the local topography and is therefore well exposed to the large scale flow. At Rondônia, the tower was sited in a broad river valley with

Table 1. Number of occurrences of Richardson numbers (Ri) in the ranges Ri < 0.25, 0.25 < Ri < 1, Ri > 1 in different levels of the nocturnal boundary layer expressed as percentages of the total number of observations in each layer. Data for the Manaus Atmospheric Carbon Dioxide Experiment (MACOE) and the Rondônia Boundary Layer Experiment RBLE3 in the south west of the Amazon basin.

Layer	Ri < 0.25 (%)		0.25 < Ri < 1 (%)		Ri >1 (%)	
	MACOE	RBLE3	MACOE	RBLE3	MACOE	RBLE3
0–50	34.3	9.1	14.9	30.6	50.9	60.2
50–100	58.5	22.8	25.0	37.6	16.5	39.6
100–150	49.7	17.8	33.3	40.7	17.0	41.5
150–200	45.3	12.0	32.4	40.8	22.3	47.2
200–250	37.5	15.6	35.4	35.2	27.1	49.2

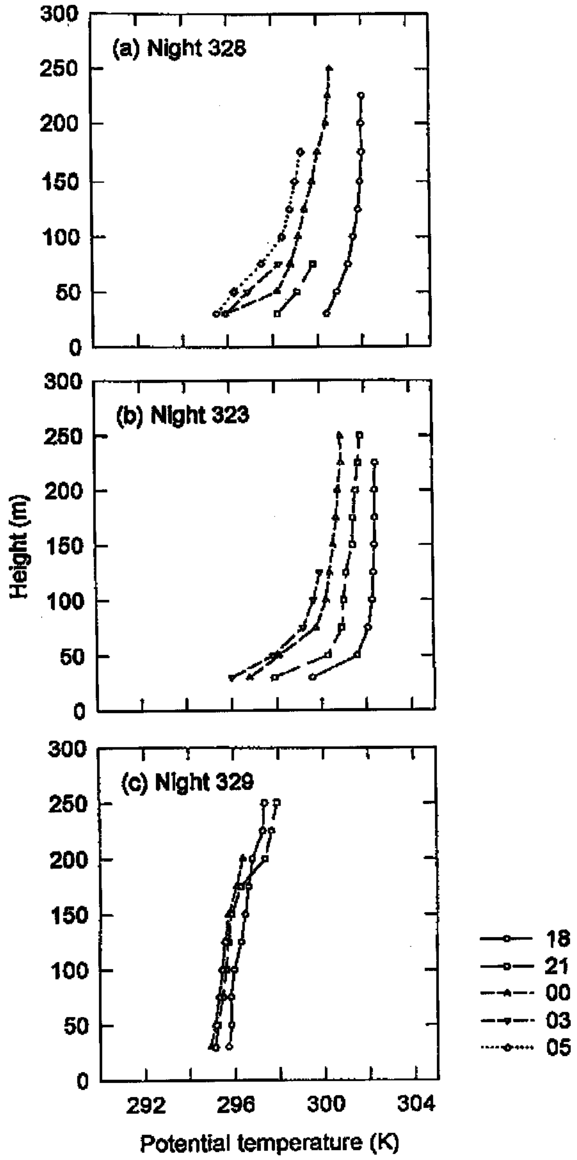


Fig. 5. *Profiles of temperature measured by the tethered balloon system. a) Night 328, typical profiles observed during the experiment, b) Night 323 the most stable conditions as measured at the top of the micrometeorological tower and c) Night 329 the least stable conditions.*

high ground to the east and may have been sheltered from the large scale flow leading to a reduction in nocturnal mixing and enabling the development of strong temperature inversions. Analysis of long term AWS records shows that more than 56% of nights at the Rondônia site have a total nocturnal radiative flux of more than 0.6 MJ m^{-2} compared with only 43% of nights at the Manaus site; this reflects Rondônia's position on the periphery of the Amazon Basin. However, the RBLE and CO_2 measurements in Rondônia were made during the dry season when nights of high outgoing radiative flux are much more common. All of the nights of the RBLE campaign and 81% of the nights of the CO_2 campaign had a total radiative flux of greater than 0.6 MJ m^{-2}. The differences in NBL development observed between the Manaus and Rondônia sites may, therefore, be largely a seasonal, rather than a general, effect.

SURFACE MEASUREMENTS

Figure 6 shows the carbon dioxide flux measured above the canopy by the eddy correlation system for each of the nights when atmospheric profiles were measured. Also shown are the net radiation and windspeed data recorded by the automatic weather station. These data facilitate classification of the nights. Nights 320, 323 and 326 have a similar form, with very little flux recorded by the eddy correlation system until 0500–0600 when there is a large flux from the canopy. Night 329 shows a prolonged period of flux from the canopy throughout the night. The differences between the nights are emphasised by comparing the values of the stability parameter $(z-d)/L$, calculated from the average values of the heat flux, friction velocity and temperature as measured at 46.5m for each night, given in Table 2. Nights 320, 323 and 326 stand out as the most stable, whilst 321, 327 and 329 are the least stable.

Case studies

NIGHT 325

Night 325 is in the middle of the range of stabilities observed during MACOE and presented in Table 2. The

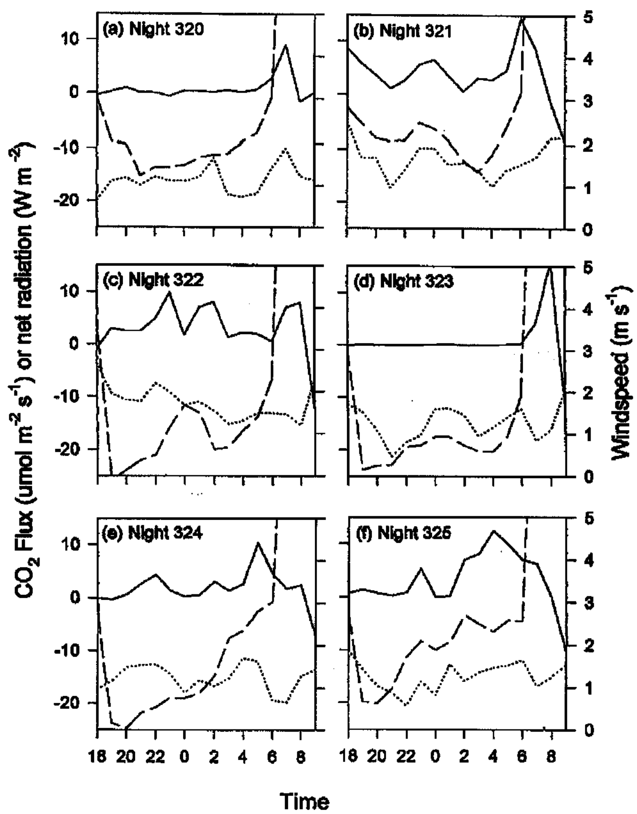
Table 2. $(z\text{–}d)/L$ calculated from average night-time values measured by the eddy correlation instrumentation at 46 m for each night of MACOE.

Day of the Year	$(z\text{–}d)/L$	Rank according to average stability
320	7.94	2
321	0.31	10
322	1.18	7
323	16.26	1
324	2.26	5
325	2.34	4
326	6.37	3
327	0.67	8
328	2.08	6
329	0.38	9

CO_2 profiles (Fig. 3f) show a build up of CO_2 in the NBL up to a height of at least 150 m. Richardson number profiles (not shown) suggest the presence of a trapping layer (Ri > 1) at about this level at 0530. Figure 6f shows that little surface flux was measured until 0100 following which there was a strong flux from the canopy until 0800. The Richardson number in the 33 to 46m layer was greater than 1 before 0100 and fell rapidly to ~0.25 after 0100 in agreement with the flux measurements. Figure 7 shows a contour plot of the average CO_2 concentrations within and above the canopy for this night and the two other nights in the same stability range (Nights 324 and 328).

NIGHT 323

Night 323 was the most stable night of MACOE as judged by the average $(z\text{–}d)/L$ figures presented in Table 2. The CO_2 profiles show little change during the night above 50 m, in comparison to the other nights, until 0800 when there is an increase in concentration. The temperature profile data (Fig. 5b) show that the strongest gradients occur below 50m with little difference from other nights above that level. The Richardson number for the 33 to 46m layer is greater than 0.9 throughout the night until 0530 when it falls rapidly. This night is the most extreme of the 3 most stable nights with the observed carbon dioxide flux above the canopy being zero throughout the night. This stability is maintained by the strong radiative cooling (~20 W m^{-2}) and windspeed of less than 2m s^{-1} throughout the night. Analysis of the AWS record shows that nights such as this, with strong radiative cooling and low windspeeds sustained throughout the night, which promote the trapping of gases within the canopy, occur on 10% of nights at this site. On the other two nights of similar average stability (320 and 326), the radiative cooling is weaker on Night 320 and less persistent, probably due to cloud cover, on Night 326.



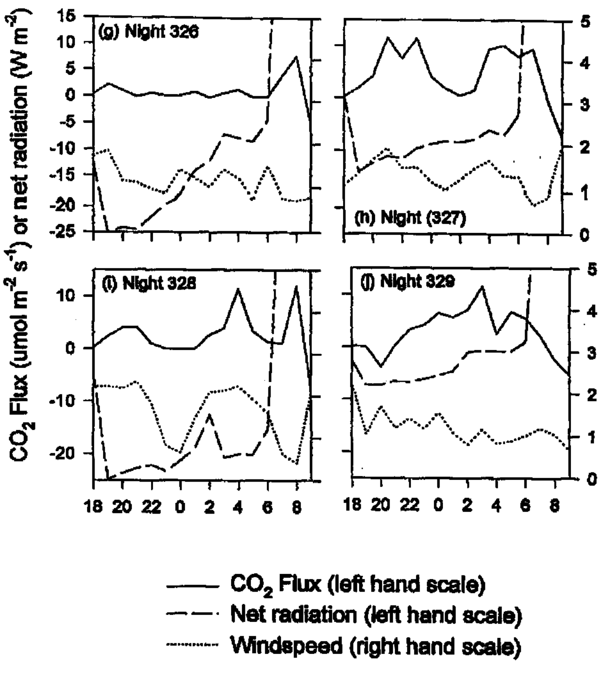


Fig. 6. *Surface fluxes of carbon dioxide (solid line, left hand scale), net radiation (dashed line, left hand scale) and windspeed (dotted line, right hand scale) for the ten measurement nights.*

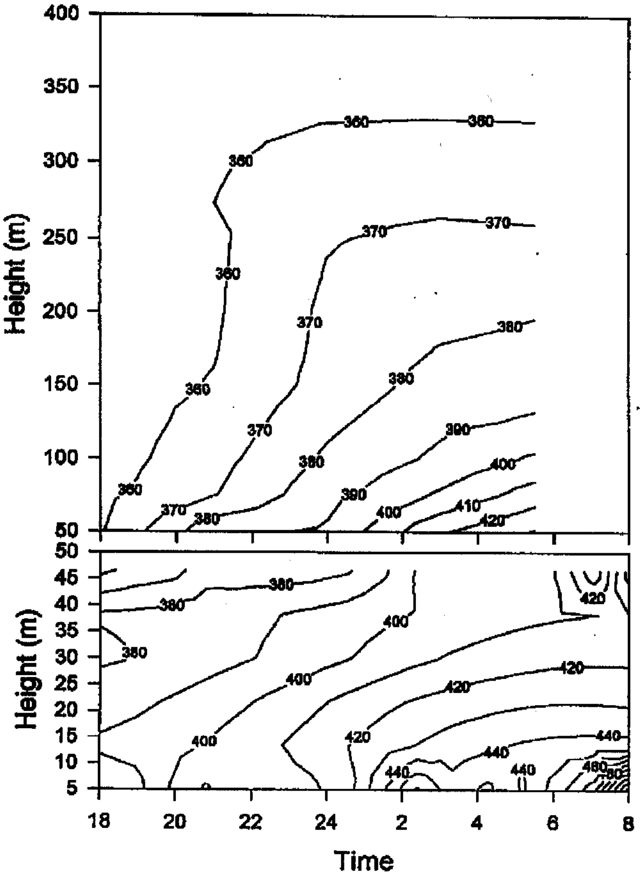


Fig. 7. *Contour plots of the average CO_2 concentration (ppm) above and within the canopy on DOY 324, 325 and 328.*

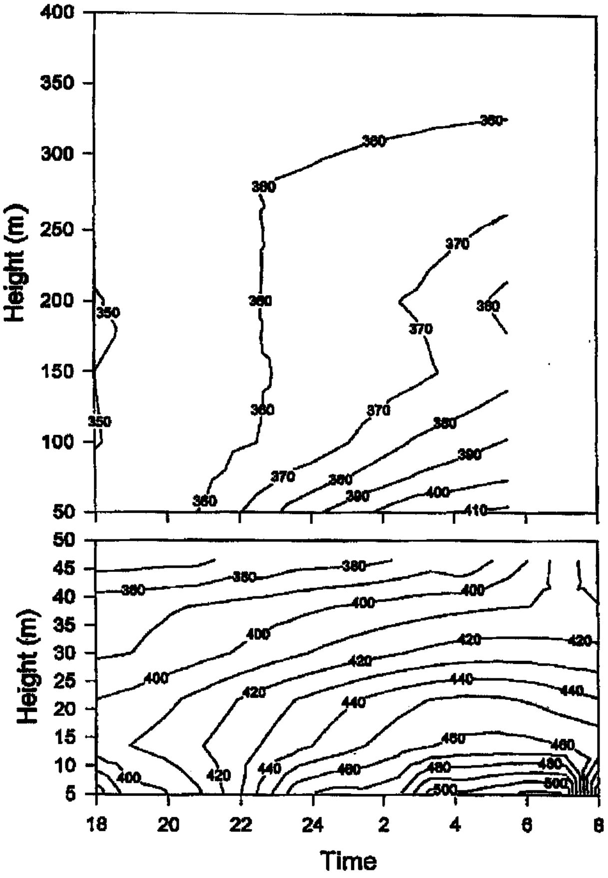


Fig. 8. *Contour plots of the average CO_2 concentration (ppm) above and within the canopy on DOY 320, 323 and 326, the nights with the strongest stable stratification. There is a strong build up of carbon dioxide within the canopy and, by dawn, in the lowest levels of the nocturnal boundary layer.*

There are bursts of flux from the canopy during the night in both cases. Similar measurements of bursts of flux from the canopy were obtained by Grace *et al.* (1995) during some nights over Reserva Jaru in south-west Amazonia. Such nocturnal periods of higher mixing between the in-canopy air and the atmosphere, resulting in an increase of the flux of CO_2 to the atmosphere have been associated with wave events by Fitzjarrald and Moore (1990). They found that the events occurred on average 5 times during the night with a time interval ranging from 25–60 minutes. Typically, the events occurred when the windspeed above the canopy was around 1.8 m s^{-1}.

Figure 8 is a contour plot of the average CO_2 concentrations throughout the canopy and in the NBL on these 3 strongly stable stratified nights. The build up of CO_2 within the canopy is clear and the NBL appears to become decoupled from the in-canopy concentrations at around 2300. The build up in concentration is in great contrast to conditions on night 329 which are discussed in detail in the next section.

NIGHT 329

Night 329 was the last night of measurements in MACOE and for logistical reasons the last balloon CO_2 profile was measured at 0300. The profiles measured on this night (see Fig. 3j) differ from those measured on all the other nights. The profile of CO_2 is relatively well mixed from the lowest (5 m) level up to the highest (250 m) level throughout the period of measurements from 1800 until 0300. The surface instrumentation recorded a relatively large flux from the canopy throughout the period from 2100 until 0700 (see Fig. 6j). On average, this night had the second weakest stability in MACOE (Table 2). There was light rain during the preceding afternoon (rainfall data are not available due to instrument failure) and humidity measurements show that the air above the canopy was saturated at 2200 and remained saturated throughout the night. The mist layer formed under these saturated conditions has reduced the radiative cooling of the canopy (Fig. 6j) and prevented the formation of a strong inversion at the top of the canopy (see Fig. 5c). Cooling probably occurred at the top of the mist layer, and downwelling of cooled air may have resulted in convective mixing between the above-canopy and the below-canopy airspace. Figure 9, a contour plot of the CO_2 concentration of the air within and

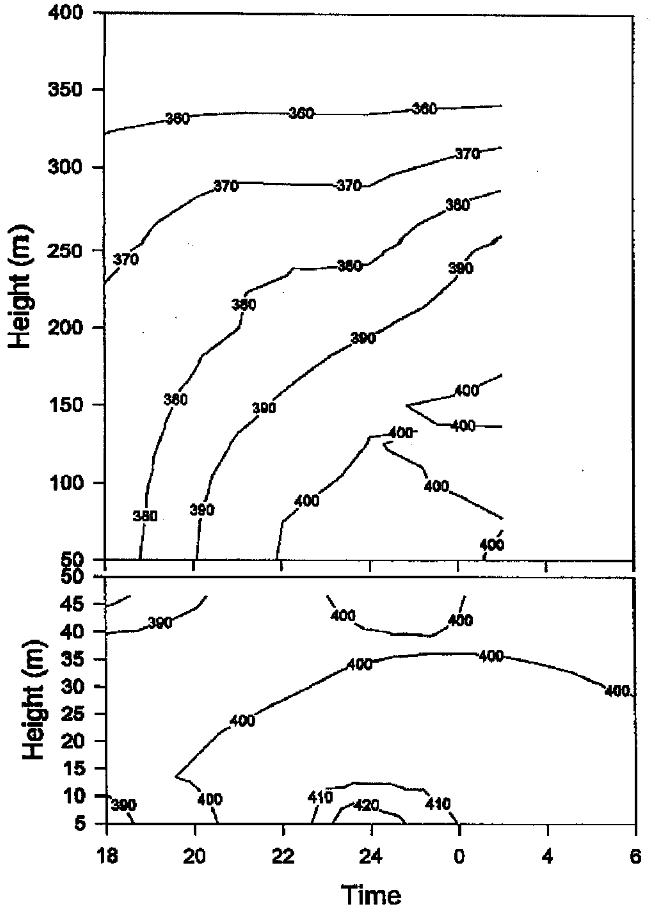


Fig. 9. *Contour plots of the CO_2 concentration (ppm) above and within the canopy on DOY 329, a night of low stability and mist, showing good agreement between the balloon profile measurements and the within canopy profiling system. The carbon dioxide concentration is relatively well mixed throughout the canopy and up to 200m.*

above the canopy, shows the CO_2 concentration being uniform at around 400 ppm throughout the depth of the canopy and for 200m above the canopy for much of the night, in stark contrast to most other nights when there was a significant build up within the canopy. Analysis of the continuous 477 day automatic weather station record currently available for this site shows that the air is saturated for more than 7 hours during the night (a similar length to night 329) on 23% of nights, with the phenomenon being most common in the wet season. On such nights the flux measured above the canopy should be a good estimate of the respiration as there is little storage within the canopy space.

Nocturnal carbon dioxide flux

ESTIMATION OF CARBON DIOXIDE FLUX FROM ATMOSPHERIC PROFILES

Estimates of the nocturnal flux of CO_2 have been made from the balloon profile data by integrating the difference between the first profile of the night (usually 1800) and the dawn profile (0530) with respect to height, in a similar way to that pointed out by Denmead *et al.* (1996), except, in the present case, over rather larger heights. Algebraically,

$$F = \int_{46.5}^{h} (C(z)_{dawn} - C(z)_{dusk})dz - A - D \qquad (2)$$

where F is the flux of CO_2 from the canopy, h is the height of the top of the nocturnal boundary layer and 46.5 is the height in metres of the eddy correlation instrumentation to allow comparison of the fluxes derived here with the tower measurements. $C(z)$ is the concentration of CO_2 in the NBL as a function of height. The term A represents horizontal advection of CO_2, whilst the term D represents movement of CO_2 across the top of the nocturnal boundary layer. The terms A and D are not measured directly, and one would wish them to be negligible if this budget method is to give results which can be related directly to the underlying surface. These terms are discussed in more detail below.

Under ideal circumstances the nocturnal boundary layer would be capped at height h by a strong inversion across which no transport of CO_2 could occur. However, as shown in Fig. 3, during this experiment, the 1800 and 0530 profiles usually had a different value of CO_2 concentration at the highest measurement level implying some transport of CO_2 across this level during the night. For the purpose of this budget work, the profiles were all assumed to return linearly to the assumed background tropospheric concentration (359 ppm) at a height of 350 m, the height at which Fisch (1995) found the vertical gradient of potential temperature to be zero in the nocturnal boundary layer during RBLE. The sensitivity of the flux to this height and the value of the background carbon dioxide concentration is addressed below.

The flux was calculated for each of the ten measurement nights using 3 different values of the tropospheric background concentration (354, 359 and 364 ppm) to get some idea of the sensitivity of the calculations to this variable. The calculations of the flux with the background concentration of 359 ppm were repeated with the height, h, of the NBL at which this background value was assumed to apply changed to 400 m. The results of these calculations are presented in Table 3. The changes in the value of the tropospheric concentration led to differences of ±3% with the average effect being less than 1%. The change in the height at which the background concentration is assumed to apply from 350 to 400 m led to an average increase in the calculated flux of 7.0%.

Table 3. Fluxes estimated from the balloon profiles using a range of values of background CO_2 concentration (C_+) and the height (h) above which the background concentration is assumed to apply.

Day of the Year	Time interval	Estimated average balloon profile flux (μmol m^{-2} s^{-1}) (C_+ = 359 ppm, h = 350 m)	(C_+ = 359 ppm, h = 400 m)	(C_+ = 354 ppm, h = 350 m)	(C_+ = 364 ppm, h = 350 m)
320	2100–0530	12.0	12.2	12.0	12.0
321	2100–0530	6.3	6.7	6.4	6.1
322	1800–0530	4.4	4.9	4.4	4.5
323	1800–0530	5.1	5.6	4.9	5.2
324	1800–0530	10.2	10.8	10.3	10.1
325	1800–0530	8.7	9.5	8.4	8.9
326	1800–0530	11.5	12.1	11.6	11.3
327	1800–0530	7.4	7.7	7.4	7.4
328	1800–0530	8.1	8.9	7.9	8.2
329	1800–0300	8.4	9.1	8.4	8.3

During this experiment, the NBL did not have a well defined capping layer and so it is likely that there was some transport of air down into the NBL from the relic mixed layer aloft, meaning that the term D in Eqn. 1 was not zero. The value of D for each night has been estimated as the flux required to raise the CO_2 concentration of the 1800 profile to the background level. The calculated fluxes with these values of D subtracted are given in Table 4. On six of the ten measurement nights, the change in the estimated flux caused by taking this effect into account is less than 10%. On Nights 320 and 324 the estimated flux is reduced by ~20% and on Night 323 by ~75%. Since there are no observations of the flux D across the top of the NBL, the choice of its value is rather arbitary. However, it is unlikely that the CO_2 concentration in the residual layer above the NBL is higher than 360 ppm, and so errors associated with the mixing of air between the residual layer and the NBL are unlikely to lead to the concentration in the NBL increasing above this value. In fact, once the concentration in the NBL has risen to that of the overlying air, mixing of air between the two layers would be expected to slow the rate of increase of CO_2 concentration in the NBL, resulting in a lower concentration at dawn and hence an underestimate of the surface flux.

The fluxes calculated from the NBL profiles and presented in Tables 3 and 4 range from 12.0 to 4.4 μmol m^{-2} s^{-1} when D is assumed to be zero and from 11.1 to 1.2 μmol m^{-2} s^{-1} when mixing down of CO_2-rich air during the early part of the night is taken into account ($D \neq 0$). These calculated fluxes (C_+ = 359 ppm, h = 350 m, $D \neq 0$) are compared with the tower eddy correlation fluxes, storage fluxes and derived net ecosystem exchange calculated for the same periods in Table 5. The data are also plotted against the average values of z/L in Fig. 10. The fluxes derived from the balloon profiles are, on average, 4.2 μmol m^{-2} s^{-1} higher than those obtained from the eddy correlation instrumentation with the difference ranging from 0.1 to 10.6 μmol m^{-2} s^{-1}. Four of the nights show relatively good agreement of within 1.5 μmol m^{-2} s^{-1}. Despite their variability, the NBL derived values are always larger than the eddy correlation measurements. The NBL fluxes are also larger than the net ecosystem exchange measured at the tower on 4 of the 8 nights for which a value of NEE is available. It is clear from Fig. 10 that the largest differences between the profile and tower measurements tend to occur at high values of z/L although there is considerable scatter and the most stable night (323) actually shows relatively good agreement between the two methods. Hence, either the CO_2 budget of the area 'seen' by the balloon system (referred to as 'regional' in the discussion below) is very different to that measured by the tower instrumentation, or one or both of the methods is in error. These alternatives are discussed below.

Table 4. Estimates of flux from profiles allowing for initial mixing down of CO_2 rich air from aloft.

Day of the Year	Time interval	Estimated average flux (μmol m^{-2} s^{-1}) (C_+ = 359 ppm, h = 350 m)	(C_+ = 364 ppm, h = 350 m)
320	2100–0530	9.4	7.8
321	2100–0530	5.8	4.5
322	1800–0530	4.0	3.5
323	1800–0530	1.2	0.2
324	1800–0530	7.7	6.4
325	1800–0530	8.3	7.7
326	1800–0530	11.1	10.0
327	1800–0530	6.5	6.3
328	1800–0530	8.0	7.4
329	1800–0300	8.1	8.0

Table 5. Balloon profile flux, surface flux, storage flux and net ecosystem exchange (surface flux + storage flux) measurements made at the surface. No storage data are available on DOY 324 and DOY 325 owing to a breakdown of the in-canopy measurement system.

Day of the Year	Time interval	Balloon profile flux F_b (μmol m^{-2} s^{-1})	Surface flux F_{ec} (μmol m^{-2} s^{-1})	Storage flux (μmol m^{-2} s^{-1})	Net Ecosystem Exchange NEE (μmol m^{-2} s^{-1})
320	2100–0530	9.4	0.34	3.37	3.71
321	2100–0530	5.8	4.27	2.71	6.98
322	1800–0530	4.0	3.94	3.19	7.13
323	1800–0530	1.2	0.07	4.74	4.81
324	1800–0530	7.7	2.51	—	—
325	1800–0530	8.3	4.31	—	—
326	1800–0530	11.1	0.47	4.0	4.47
327	1800–0530	6.5	5.89	3.76	9.65
328	1800–0530	8.0	2.92	2.69	5.61
329	1800–0300	8.1	3.85	1.36	5.21

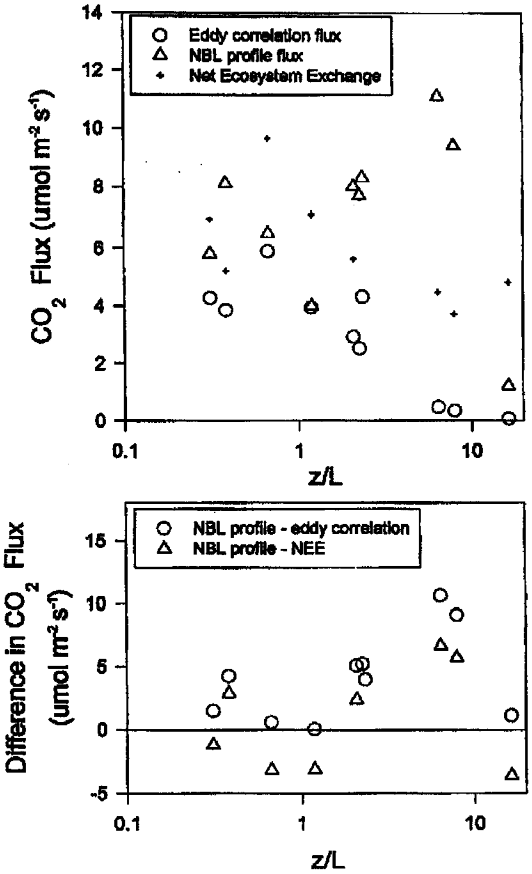


Fig. 10. *Comparison of balloon profile flux estimates and tower flux measurements. The fluxes were calculated for the period 1800 to 0530 except for Night 320 and 321 (2100 to 0530) and Nights 329 (1800 to 0300). a) Balloon profile derived flux, eddy correlation meaurements and measurements of net ecosystem exchange NEE plotted against the stability parameter z/L for the ten measurement nights. b) The differences between the balloon profile derived fluxes, the eddy correlation measurements and the NEE.*

A rough estimate of the effect of these nocturnal fluxes determined from the atmospheric profiles on the regional carbon budget has been made by computing a net 'regional' flux for each 24 hour period. This was done by adding the NBL derived flux for the nocturnal period to the flux measured by eddy correlation for the remaining hours of the day. This calculated net flux is compared to the net flux measured by eddy correlation for each entire 24 hour period. Following Malhi *et al.* (1999), the net flux in both cases has been calculated from 1700 until 1700 (when storage within the canopy is always close to zero) rather than summing the fluxes from midnight to midnight so that the storage term can be neglected. The effect of replacing most of the nocturnal period with data from the NBL estimates is to reduce the average daily net uptake of CO_2 for these 10 days from –0.18 mol m^{-2} day^{-1} to 0.02 mol m^{-2} day^{-1}. Figure 11 shows the cumulative net flux for the period of the experiment calculated in these two different ways. The fact that these data imply that the net regional carbon uptake is substantially reduced over the uptake measured at the tower site clearly makes it important to try to determine the source of the discrepancy between these two sets of measurements.

ERRORS ASSOCIATED WITH NOCTURNAL EDDY CORRELATION MEASUREMENTS

Wofsy *et al.* (1993) and Goulden *et al.* (1996) discuss the problem of measuring nocturnal fluxes using eddy correlation instrumentation and point out that errors can occur, especially at high *z*/*L*. In an experiment at Harvard Forest they concluded that there was a selective underestimation of respiration during calm conditions (defined in their case as $u_* < 0.17$ ms^{-1}) but they could not detect the cause of this underestimation. They suggest that the CO_2 may be

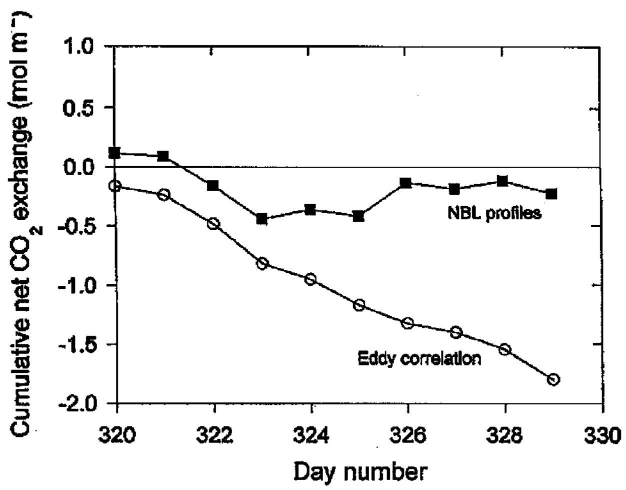


Fig. 11. *The net uptake of carbon dioxide for the 10 day period of MACOE as calculated at the tower site and discussed by Malhi et al. (1998) and the net uptake which is calculated if the balloon profile derived fluxes are substituted for the tower measurements during the period of operation of the system (generally 1800–0530).*

leaving the forest in draining cool air or be transported by eddies which are too small to be resolved by the instrumentation. A third possibility suggested is that the flux calculation algorithm is inappropriate for nocturnal conditions when transport is dominated by sporadic events. Correcting for this underestimation by using data from more turbulent nights gave a decrease in the carbon uptake from 3.7 tC ha^{-1} to 2.8 tC ha^{-1} for 1991. Figure 10 shows that for the ten day period discussed here (net ecosystem exchange data are only available on eight of the ten nights) there is some evidence that a similar effect is occurring with the net ecosystem exchange falling with increasing stability. Malhi *et al.* (1998) show that a similar trend occurs when data from a year of observations at the same site is considered. However their analysis puts this trend down to underestimation of the within canopy storage component rather than the above canopy component of the flux and suggests that the estimate of mean nocturnal respiration may have to be increased to 8 μmol m^{-2} s^{-1} from 6.5 μmol m^{-2} s^{-1} as a result. Even if the entire trend in the net ecosystem exchange with z/L shown in Fig. 10 was attributed to a shortfall in the eddy correlation measurements (Malhi *et al.*, 1998 show that this is unlikely to be the case) there would still be an average difference of ~2.7 μmol m^{-2} s^{-1} between the balloon and tower estimates of the flux. Hence there must be some additional factor accounting for the difference between the two sets of measurements.

SPATIAL VARIABILITY AND ADVECTION

The nocturnal NEE measurements made at the tower site are similar to those made previously in Amazonia and, as discussed above, the eddy correlation flux data are thought to be reliable. An alternative possibility is that the regional area behaves differently from the area sampled by the tower measurements. Respiration is usually assumed to be relatively uniform throughout the forest since it is controlled to a large extent by soil temperature which is unlikely to vary substantially in space beneath the forest canopy. However, soil moisture may also be influential (particularly during the dry to wet season transition in October and November) and it is possible that soil respiration is higher in the valley bottoms than on the plateaux and also higher in areas with substantial wind damage. Possibly, the tendency to site instruments in relatively pristine, flat areas of forest leads to a low bias in respiration measurements. Spatial variability of canopy structure and the presence of forest edges around clearings may also lead to spatial variability of the flux during the night. In areas with a less well closed canopy, there may be a substantial flux throughout the night and less build up within the canopy.

The case study of Night 329 is particularly interesting with respect to spatial variability of the carbon dioxide flux, since it shows that, under some atmospheric conditions, CO_2 may be ejected from the canopy into the NBL throughout the night. This event occurred after light showers in the preceding afternoon led to the formation of mist during the night. Small showers occur on a very patchy spatial pattern in this area of Amazonia and several may be observed from the top of the tower on most afternoons, even when no rain falls in the immediate vicinity. Possibly, such plumes of CO_2 are ejected into the atmosphere on most nights, on a spatially patchy basis, and may account for some of the excess CO_2 observed in the balloon profiles at dawn which leads to a higher calculated than measured flux. However, such processes are not likely to result in fluxes greater than the spatially-averaged NEE, unless there is a significant concentration effect due to convergence of airflow around these mist areas.

Advection of air with a high CO_2 content (represented by a non-zero value of A in Eqn. 2) originating from areas of pasture, water or from non-natural sources is also a possibility which could lead to over estimation of the NBL profile derived flux. The main area of concern in this respect is Manaus, a large city 70 km to the south of the measurement site. There is also small scale clearing along the main BR374 road and a group of 4 larger pasture areas, each approximately 10 by 10 km in size, some 30 km to the north of the site.

A simple trajectory analysis using the average windspeed and direction measured by the tethersonde in the 100–200 m layer for each night shows that air could have travelled as far as 240 km from the site in the 11.5 hours between the onset of the NBL (when the CO_2 build up begins) and 0530, the time of the dawn measurement. This simple analysis assumes that the winds measured at the balloon site are representative of the surrounding region and that

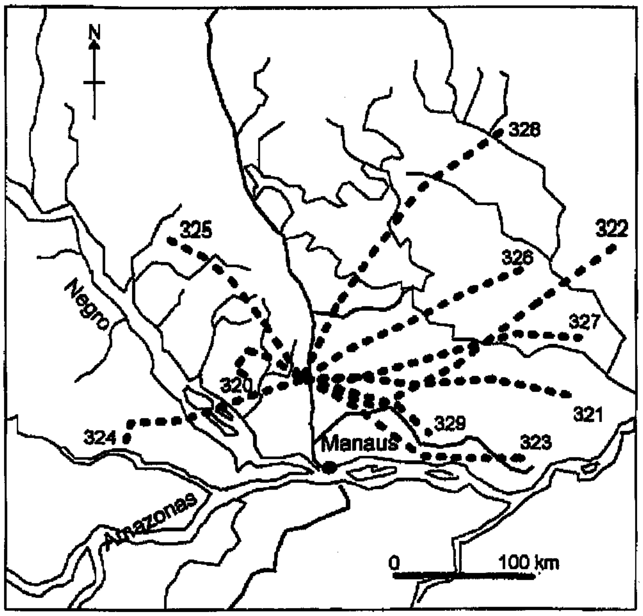


Fig. 12. *A map of the central Amazonian basin in the area surrounding the measurement site. The lines show the trajectories of air (calculated from the average 100 to 200 m layer windspeed and direction measured by the tethered balloon system) between dusk when the NBL starts to form and dawn when the last nocturnal profile of each night was measured.*

no local circulations complicate the flow patterns in the area. A more reliable analysis would require the use of a mesoscale model and initialisation data which are unavailable for the present work. Figure 12 shows that the calculated trajectories are from the east and west rather than from the urban area of Manaus to the south. It is interesting to note that the trajectories for the 4 nights which show the best agreement with the tower eddy correlation measurements all lie in a group to the east. At least two of the trajectories (328 and 324) have a substantial portion over water where the CO_2 budget would be expected to differ from that over forest and the development of the NBL is probably much weaker leading to more rapid injection of respired CO_2 into upper levels of the NBL. Trajectory 325 lies to the north west and possibly passes over some pasture areas. Whilst from this analysis it seems that the urban area of Manaus is unlikely to have influenced the measurements during this campaign, there is probably sufficient variability in the region, especially due to water bodies, to lead to variations in CO_2 concentration and NBL growth with different wind directions to account, partly, for some of the difference observed between NBL and tower based measurements.

Concluding remarks

Qualitatively, the boundary layer profiles of carbon dioxide concentrations presented here show good agreement with the surface based measurements of CO_2 concentrations, wind and temperature, and help to explain the nocturnal trends observed at the surface. Quantitatively, however, the fluxes calculated from the atmospheric concentration profiles using an NBL budget technique show large differences from the flux measured above the canopy. The fluxes calculated from the concentration profiles were, on average, 4.2 μmol m^{-2} s^{-1} higher than those measured by eddy correlation at the surface, although, on 4 of the 10 measurement nights, agreement was within 1.5 μmol m^{-2} s^{-1} . The difference implies that one of the methods is in error or that the regional carbon dioxide exchange between the atmosphere and the surface is significantly different from the balance measured at the tower site. More work of this type needs to be carried out at surface flux sites to see whether this result is general, perhaps due to the tendency to site surface measurements in relatively uniform and pristine areas of forest. If the result can be verified, then it will have a considerable impact on the techniques used to scale up the carbon budget from individual tower sites to the whole Amazon basin.

Future work of this kind should include aircraft measurements of the atmospheric concentration of CO_2 above the nocturnal boundary layer at least once and probably twice a day, in the early evening and at dawn, to determine a value for the tropospheric CO_2 concentration. A method of measuring the CO_2 concentration continuously, rather than stopping at pre-set intervals, as in this work, would also be preferable. This improvement would give a more detailed profile and thus a more accurate calculation of the nocturnal flux. Simultaneous isotopic analysis of the air sampled from different heights of the NBL might also be carried out to determine the sources of the CO_2 and help to delineate the area sampled by the balloon profiling system.

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