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The convective boundary layer over pasture and forest in Amazonia

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With 9 Figures

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Summary

The coupling between different types of surface (tropical forest or grass) and the Convective Boundary Layer (CBL) has been investigated using observational (rawinsoundings) data collected over Rondônia in southwest Amazonia. The data reported here support the notion that deforestation may modify the dynamics of the boundary layer, in particular during the dry season. In this period the sensible heat fluxes are very high over pasture, creating a CBL around 550 m deeper compared to that over the forest. The measurements showed the height of the fully developed CBL for pasture to be 1650 m, compared to around 1100 m for forest. During the wet season the height of the CBL is lower than during the dry season and has the same height (around 1000 m) for forest and pasture sites. The CBL over pasture is hotter and drier than over forest during the dry season, but during the wet season the air temperatures and humidities are similar. Comparing the CBL growth during the dry and wet season, there is evidence that the CBL properties over the forest are not dependent on the surface characteristics, but over the pasture they are.

1. Introduction

Energy, momentum and scalar properties are transported to and from the land surface through the Atmospheric Boundary Layer (ABL), the lower part of the atmosphere which acts as the link between the surface and the large-scale circulation above. Understanding the behaviour of the ABL is thus a critical prerequisite to understanding how changes in the land surface will translate into changes in the dynamics and thermodynamics of the large-scale circulation and, in the other direction, how changes in the atmospheric circulation will modify the surface climate and in turn the surface fluxes.

The ABL is characterized by thermal and mechanical turbulence processes which are controlled by the interactions with the surface and by entrainment with the free atmosphere above. At the same time, the ABL may also modify the surface fluxes through the influence of the ambient temperature and humidity on the surface energy partition. The phase of the ABL that is dominated by thermal (buoyancy) and mechanical (wind shear) turbulence is called the Convective Boundary Layer (CBL). The CBL is important because it transports momentum, energy, water vapour and trace gases (such as CO_2) from the surface to a height of 1–2 km, where these species can then be linked to the general circulation of the atmosphere.

Despite its importance, relatively little is known about the CBL in Amazonia, although a few measurements have been made in previous experiments such as the Atmospheric Boundary Layer Experiment – ABLE-2 (see Garstang et al., 1990) and the joint Anglo-Brazilian Amazonian Climate Observational Study – ABRACOS (see Gash and Nobre, 1997) and the Rondônia Boundary Layer Experiment – RBLE (see Fisch, 1995; or Fisch and Nobre, 1997). The first comprehensive dataset of the boundary layer over tropical forest during the dry season was presented by Martin et al. (1988). They obtained maximum CBL heights around 1200 m during undisturbed conditions and pointed out that the entrainment flux can be very important for the growth of the CBL, as well as for drying the whole boundary layer. The diurnal cycle of the specific humidity showed a maximum in the early morning with a subsequent drying. This feature is strongly coupled with the decrease of the temperature jump at the base of the inversion layer, as dry and hot air from above is entrained into the CBL.

Although Amazonia is still mainly covered by tropical forest it is suffering from a high rate of deforestation. The impact of the deforestation on climate is likely to depend strongly on the scale of the deforested area. For large-scale deforestation, several numerical studies (among them Nobre et al., 1991; Hahmann and Dickinson, 1997; and Gandu et al., 2004) have postulated that large scale deforestation will increase air temperature, decrease rainfall and evaporation and result in a longer dry season. However the meso-scale impact of deforestation and its effect on the ABL is not so well understood. Fu et al. (1999) demonstrated the importance of moisture convergence in the ABL in triggering convection and also in the initiation of the wet season. On the other hand, knowledge of the comparative thermodynamic profiles over forest and pasture is limited to the ABRACOS/RBLE field campaigns mentioned above. Fisch (1995) carried out a detailed analysis on the characteristics of profiles of potential temperature and humidity during the dry season. He found that the CBL developed to a greater height over the pasture (by about 600 m) than over the forest and that there is also enhanced turbulence over the pasture, perhaps due to the thermal circulation created by the juxtaposition of fragments of forest and large deforested areas. There is no equivalent analysis for the wet season as the results presented by Martin et al. (1988) refer to the dry season in the central Amazonia.

Previous modelling studies during the dry season predicted that the juxtaposition of forest and pasture might result in circulations at meso-α (Silva Dias and Regnier, 1996) and meso-γ (Fisch, 1995) scales: both from dry and hot pasture to the wet and cool forest during daytime. However for the wet season, the lack of good and detailed data has limited this modelling approach to the work of Wang et al. (2000). Their study predicted that in the wet season the synoptic conditions would dominate the flow and prevent local circulations from developing.

In general, CBL development appears to have one-dimensional dependence but some events can modify this structure. Cold front invasions into Amazonia during the winter (known locally as a *friagem*) strongly modify the ABL because they bring dry and cold air to the area, as well as an intensification of the windspeed. So far, the current knowledge about the modification on the ABL structure by a *friagem* is not well known and this is the reason why a case study is shown here. Some characteristics of a *friagem* event observed in 1993 are presented in Section 3.3.

The Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) (*http://lba.cptec.inpe.br/lba*) is an international research initiative led by Brazil. It was designed to understand the climatological, ecological, biogeochemical and hydrological functioning of Amazonia and how the land use and cover modify these cycles. Two coupled experiments were carried out during the first Intensive Observing Period of LBA (LBA-IOP1): the Wet Season Atmospheric Mesoscale Campaign (WETAMC-LBA, hereafter LBA) and the ground validation of the Tropical Rainfall Measuring Mission (TRMM) in a tropical region (see Silva Dias et al., 2002). The combination of these two experiments will be referred to as LBA/TRMM.

This paper describes the growth of the CBL over forest and pasture in Amazonia, presenting

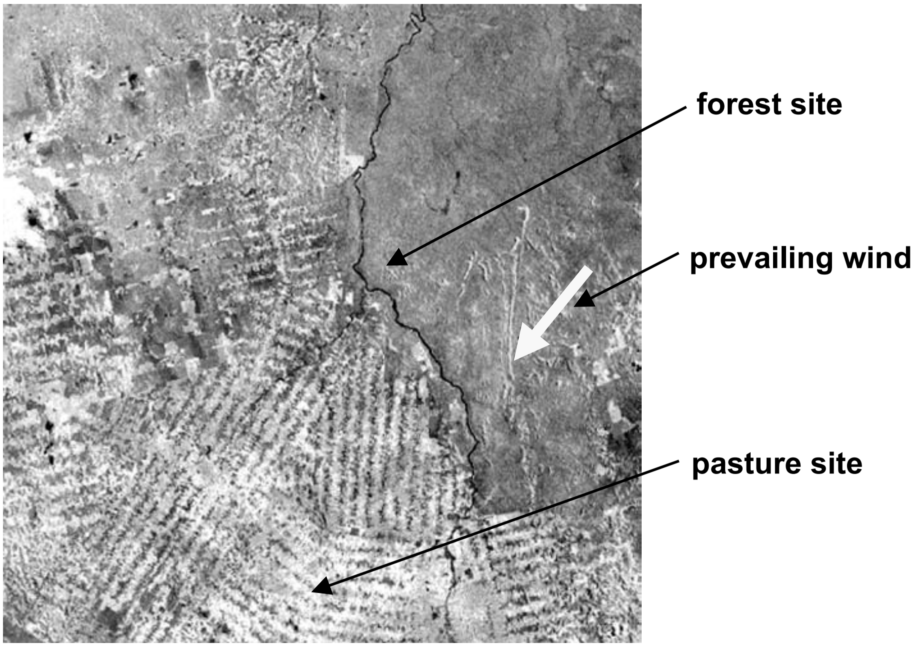

Fig. 1. The location of the forest and the pasture experimental sites. The distance between forest and pasture site is 80 km

and comparing some differences in the CBL properties during wet and dry seasons. Some examples of CBL evolution are also presented, with some discussion on the thermodynamic processes governing the convection.

2. Sites

The sites were chosen to represent two contrasting surfaces: an undisturbed tropical forest and a deforested area (pasture) in the Ji-Paraná area of Rondônia in southwestern Amazonia. These sites were set up as part of the ABRACOS Project (see Gash and Nobre, 1997) and have been collecting meteorological data since 1991. The forest site (hereafter called Rebio Jaru) was in a reserve located at 10° 5′S, 61° 55′W, 120 MSL. The surface meteorological measurements were made at a height of 65 m, on a tower, surrounded by 30 m high trees, with the shortest fetch being approximately 1 km. There was an automatic weather station (AWS) and turbulent fluxes were measured. The balloons (rawinsoundings) were launched in a clearing about 5 km from the tower.

The pasture site Fazenda Nossa Senhora da Aparecida (hereafter called Fazenda N.S. Aparecida) was located at 10° 45′S, 62° 21′W, 290 MSL, on a cattle ranch that was originally cleared in the 1980s. The ranch is situated in a cleared strip about 4 km wide and several tens of kilometres long, in the centre of an area of about 50 km in radius, which has undergone large scale clearance. The two sites are approximately 80 km apart. Figure 1 shows the geographic position of the two sites as well as the fragmentation of the area around the pasture site (small strips of tropical forest embedded within a large area of clearing). The deforestation rate around Ji-Paraná area has been very high (the latest figures of Amazonian deforestation can be seen at *http://www.inpe.br/amz.html*): the portion of native tropical forest in Rebio Jaru is 95%, which contrasts with Fazenda N.S. Aparecida which is 93% deforested.

3. Dataset and methods

LBA/TRMM was carried out during January and February 1999 when average rainfall is approximately 300 mm per month (Fig. 2a) (Ferreira da Costa et al., 1998). In 1999 this period had slightly above average precipitation (Tota et al., 2000), but the data collected are considered as being representative of the wet season (Fig. 2b). Most of the rainfall is due to convective systems (both local and mesoscale). During the dry period, only a few rain events occur and they are associated with a *friagem* penetration of a cold air mass. The dry season dataset was obtained from the ABRACOS/RBLE experi-

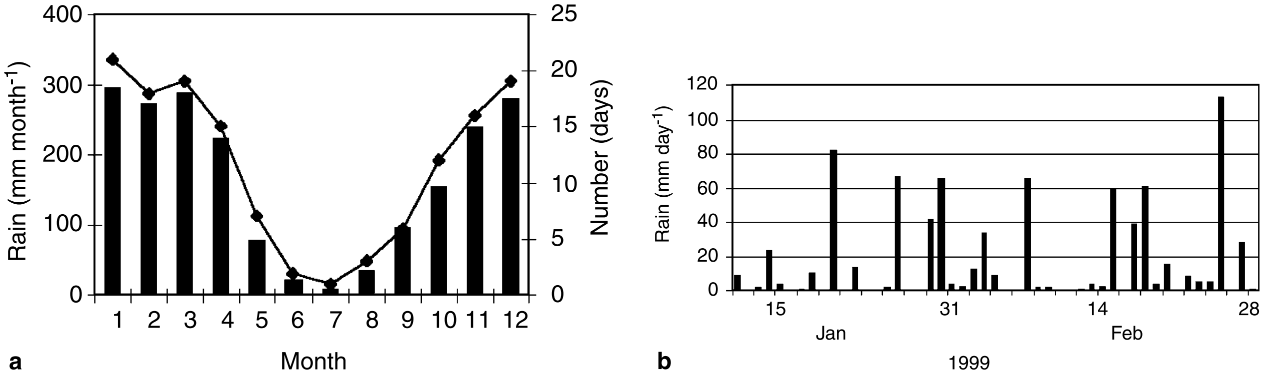

Fig. 2. Climatology of the rainfall for the Ji-Paraná area (left) and the time series of the rainfall during the LBA/TRMM (right)

ment (see Fisch, 1995; or Fisch and Nobre, 1997) and it consists of simultaneous soundings made between 14 and 25 August 1994 at Rebio Jaru and Fazenda N. S. Aparecida. For the dry season two Vaisala (Helsinki, Finland) rawinsounding systems were used with RS80 sondes. For the wet season a Vaisala system was used in the forest and a Viz – Mark II Microsonde (Philadelphia, USA) was used in the pasture. Soundings were made at 08:00, 11:00, 14:00 and 17:00 Local Time (LT) for both wet and dry experiments. The soundings were linearly interpolated between each 50 m level in the vertical. The rawinsounding dataset has been passed through a data quality control (identification checks, pressure monotonically decreasing with height, temperature and relative humidity within a specified range, etc).

There are several alternative methods for computing the depth of the CBL (for instance the lift air parcel method, or the use of the Richardson number (Stull, 1988)). However, Seibert et al. (2000), recommend that whenever detailed measurements (vertical (50 m) and high-resolution temporal (2 s) data) are available, the analysis of the profile measurements (temperature and specific humidity) is to be preferred. The depth of the CBL has therefore been computed as the height of the inversion layer, estimated as the first point where the gradient of potential temperature (θ) is positive instead of zero (assuming that neutral conditions represent the mixed layer inside the CBL). This method also gives a criterion which is proportional to Richardson number and represents the real mixing inside the CBL. Mathematically this point was determined as: $|\partial\theta/\partial z| \geq 2\,\mathrm{K\,km^{-1}}$. This value has been decided upon after taking into account the error in the temperature sensor (0.1 K) and the vertical resolution (50 m), and also following extensive comparisons between this method and visual inspection of the ABRACOS/RBLE dataset (Fisch and Tota, 1999). A similar procedure could be employed using the specific humidity profiles but the CBL heights computed (data not shown) are nearly the same as those obtained with θ. The horizontal distance inside the boundary layer from the sounding to the reception and launch point was at all times less than 8 km, which guarantees that the measurements are representative of forest and pasture biomes.

4. Results and discussion

4.1 Development of the CBL

Table 1 compares the heights of the CBL for the forest and pasture sites. The standard deviation and the number of profiles used are also shown in this table. During the dry season the CBL heights over forest and pasture are higher than 900 m at 14:00 LT, growing up to 1641 m over the pasture and 1092 m over the forest by the late afternoon (17:00 LT). This represents a layer 550 m deeper over pasture, which is hot and dry relative to the forest. For both sites, the highest growth rates occur between 11:00 and 14:00 LT, when the atmosphere has strong buoyancy and the sensible heat flux is very high. Typical values of sensible heat fluxes measured by the ABRACOS project ranged from 80 up to 110 W m^{-2} in the forest and 150 up to 180 W m^{-2} in the pasture between

Table 1. The height (m) statistics (average values and standard deviation) of the CBL over the pasture and the forest sites during the dry and wet season

Local time	Pasture		Forest	
	Dry	Wet	Dry	Wet
08:00	62 ± 31 (10)	94 ± 29 (25)	75 ± 28 (12)	124 ± 50 (16)
11:00	517 ± 241 (13)	475 ± 99 (26)	267 ± 114 (13)	491 ± 133 (26)
14:00	1471 ± 479 (13)	775 ± 127 (28)	902 ± 307 (13)	813 ± 128 (19)
17:00	1641 ± 595 (13)	927 ± 166 (12)	1094 ± 385 (13)	1002 ± 195 (16)

The numbers in brackets represent the number of profiles used to compute the height

11:00 and 14:00 LT (Culf et al., 1996; Galvão and Fisch, 2000). After that time, although the surface fluxes decrease, the CBL still grows and the entrainment flux at the inversion base is very active. The typical values for vertical scale are 1.8 m s^{-1} in the pasture and 1.4 m s^{-1} for the forest. For the wet season the values of the sensible heat fluxes were smaller than during the dry season, especially for the pasture. Typical wet season fluxes are 70–80 W m^{-2} in the forest and 80–100 W m^{-2} in the pasture. The vertical scale is around 1.2 m s^{-1} for both sites. Consequently there is a tendency for the CBL to show similar heights over forest and pasture sites. For instance, the final development of the CBL was on average 1002 m for the forest and 927 m in the pasture at 17:00 LT. There is some uncertainty about these numbers, as can be seen by the standard deviation of the sample. However, they show similar values and trends. The role of the sensible heat fluxes is very important in defining the depth of the CBL. The pasture shows a strong seasonality in the sensible heat fluxes, but this is not the case for the forest: the sensible heat fluxes vary from 26.6 W m^{-2} (wet period) to 59.0 W m^{-2} (dry season) for pasture, while it is 23.1 W m^{-2} (wet period) and 28.9 W m^{-2} (dry season) for the forest (data extracted from Galvão and Fisch, 2000). Von Randow et al. (2004) observed this pattern for the same forest and pasture sites using data collected during 1999–2000: while the Bowen ratio over forest is almost seasonally constant (typical values between 0.3–0.4), there is a large variation of the Bowen ratio over pasture, ranging from 0.3–0.6 during the wet season to 0.6–0.8 during the dry season. This behaviour is a consequence of the soil moisture conditions. Galvão (1999) presented figures of the soil moisture for the wet to the dry season transition period of 1993 and the soil moisture content (integrated value from the surface down to 2.0 m depth) ranged from 650 mm to 580 mm for forest, and from 650 mm to 450 mm for the pasture. This is an indication that in the pasture the soil dries much faster than the forest, with important consequences to the partition of energy. Alvala et al. (2002) presented the soil moisture data for both forest and pasture during the LBA/TRMM (February 1999) and also during the dry season (July 1999). Although they are restricted to a shallow layer (surface down to 400 mm depth), the results confirmed the strong seasonality between wet (typical values of 0.2 $m^3\,m^{-3}$) and dry (0.1 $m^3\,m^{-3}$) conditions (see also Hodnett et al., 1996). Figure 3 presents the diurnal cycle

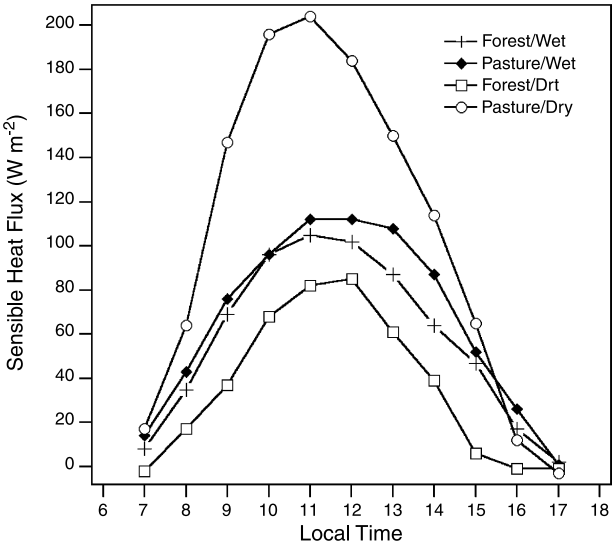

Fig. 3. The time evolution of the sensible heat flux over forest and pasture for dry and wet periods. Legend: forest/wet (cross), forest/dry (squares), pasture/wet (diamond) and pasture/dry (circles)

of the sensible heat fluxes for forest and pasture for both periods. The important difference is the sensible heat flux for pasture during dry conditions, when the values are almost twice the others measurements. This strong flux results in the deep boundary layer (around 2000 m) and the very effective mixing. Recently, Esau and Lyons (2002) discussed the growth of the CBL over native and agricultural crops in Australia and they suggested that this is not a direct dependence of the type of surface; rather it is achieved through the formation of coherent structure over the regions with higher surface sensible heat flux.

It is interesting to note that the largest growth rates occur between 11:00 and 14:00 LT for both sites and in both periods. However, there is a significant change in this rate from the dry to the wet period, especially in the pasture: during the dry period the growth rate is 320 m h^{-1}, but this diminishes to 100 m h^{-1} for the wet season (a factor of 3). Over the forest site, this variation is from 210 m h^{-1} to 110 m h^{-1} (a factor of 2). For the others times of day both sites present equivalent growth rates (around 100 m h^{-1} in the early morning and about 60 m h^{-1} during late afternoon). Considering only the wet season, both sites show similar growth rates at all times, indicating that the CBL structure and dynamics are triggered by the same mechanisms. Machado et al. (2002) observed that the convection is deeper over the pasture, but the fraction of clouds and its associated area is larger for forest. The growth rates have been computed from the numbers in Table 1.

The height of the CBL, $h(t)$, at time t can be estimated from the simple mixed layer "slab" model (Tennekes, 1973) as:

$$h(t) = \frac{2(1+2C_F)}{S_0}\int_{t_6}^{t_{17}} \overline{w'\theta'}dt \qquad (1)$$

where C_F is the ratio between the entrainment and surface fluxes and S_0 is the lapse rate above the inversion. This height is a solution of a differential equation assuming horizontally homogenous (no-advection) conditions and neglecting the mechanical turbulence (Garratt, 1992). For this calculation C_F was assumed to be 0.2 (Driedonks, 1982). For the wet season, this height was 1026 m for forest and 1040 m for pasture, while considering the dry period the heights are 835 m and 1310 m for forest and pasture, respectively. These estimates agree quite well with the observations (Table 1), especially during the wet season. For the dry season, they are lower, possibly due to the underestimation of the mechanical turbulence.

As the height of the CBL over pasture is so different between the dry and wet seasons, a 2-D simulation was done using the RAMS model (Pielke et al., 1992), which is depicted in Fig. 4. Basically, these results were obtained from a simulation carried out for 60 hours (the first 12 hours were disregarded due to the spin-up problems) with a wet soil moisture (Fig. 4a) with a constant profile (0.65 m^3 m^{-3}) and a profile varying with the depth – dry conditions (0.1 m^3 m^{-3} at the depth 10 cm and 0.28 m^3 m^{-3} at 80 cm depth). The domain was a grid with 16 km

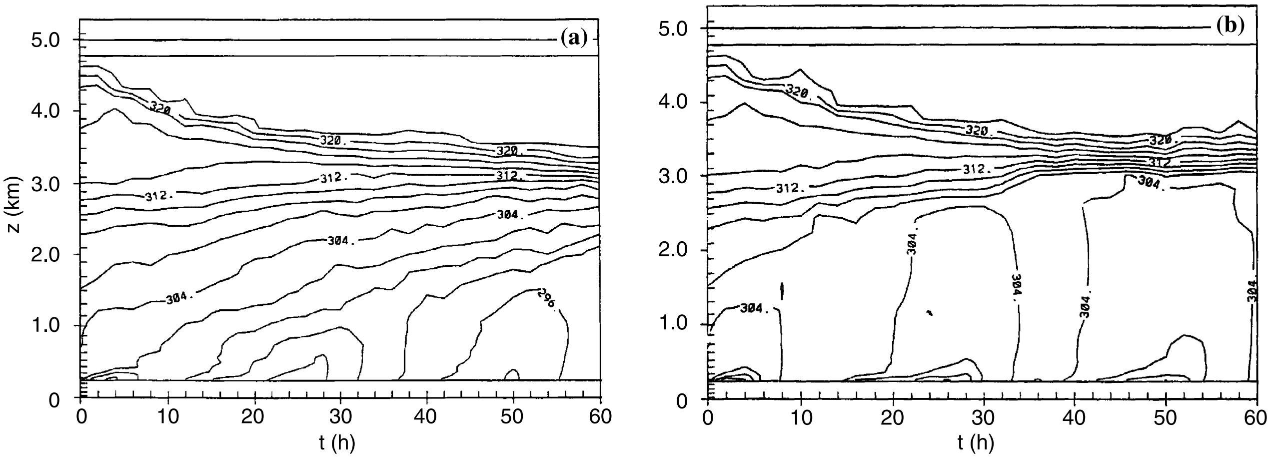

Fig. 4. The 2D simulation of the CBL development (from potential temperature) using the model RAMS for wet (**a**) and dry (**b**) soil moisture conditions

(250 m horizontal grid with 35 levels) mainly covered with pasture biome (there are few strips of tropical forest inserted in this domain). Turbulent transport (isotropic deformation by Smagorinski) and cumulus (Kuo modified) parametrizations were included, with a homogeneous initialization. Further details of the initial and boundary conditions for this simulation are given by Fisch (1995). The main difference between the two simulations is due to the soil moisture conditions. For the wet period (Fig. 4a), the height of the CBL over pasture grows up to 1100 m, while for the dry season (Fig. 4b) it is much higher (almost 2500 m). Obviously this is a consequence of the dryness of the soil moisture and the associated sensible heat fluxes (see Fig. 3).

Using the two available datasets (RBLE and LBA/TRMM), several average moist thermodynamic parameters have been computed, to describe the difference in convective activity. These figures are depicted in Table 2. The lifting condensation level (LCL) is always higher over the pasture than over the forest. During the dry season, it is 57.8 hPa (almost 600 m) higher, this difference decreasing to 15.7 hPa (around 150 m) in the wet period. The atmosphere over the forest is moister than over the pasture in the dry period (the specific humidity difference is typically 2–2.5 g kg^{-1}), but the humidities are similar during the wet season. The air is warmer over the pasture (almost 0.6 °C) during the dry season, but is of similar temperature during the wet period. The convective available potential energy (CAPE) shows similar values for the wet season over both surfaces, but a significant difference for the dry period: the CAPE over the pasture is 1/3 of the value over forest. These values include day and nighttime observations. If only a daytime observation (sounding at 14:00 LT) is considered to represent the time of most vigorous convection, this situation still persists and the difference is even bigger. Figure 5 shows the correlation between the specific humidity over forest and pasture for both periods: during the wet season there is no difference between the sites; but for the dry season the air over the forest is moister. Figure 6 presents the relationship between the specific humidity and temperature for each of the sites and for both seasons. During the wet season, the data from forest and pasture are mixed and it is difficult to separate the forest and pasture conditions. For the dry period, there is a clear separation between the characteristics from forest and pasture.

Table 2. Moist thermodynamics variables computed over the pasture and forest for both dry and wet periods

	Pasture		Forest	
	Dry	Wet	Dry	Wet
LCL (hPa)	841.1	927.1	898.9	942.8
Q (g kg^{-1})	12.4	17.1	14.5	17.2
Temperature (°C)	27.0	24.9	26.4	25.1
CAPE (J kg^{-1})	180	1194	571	1084
CAPE 14:00 LT (J kg^{-1})	31	1205	734	1487

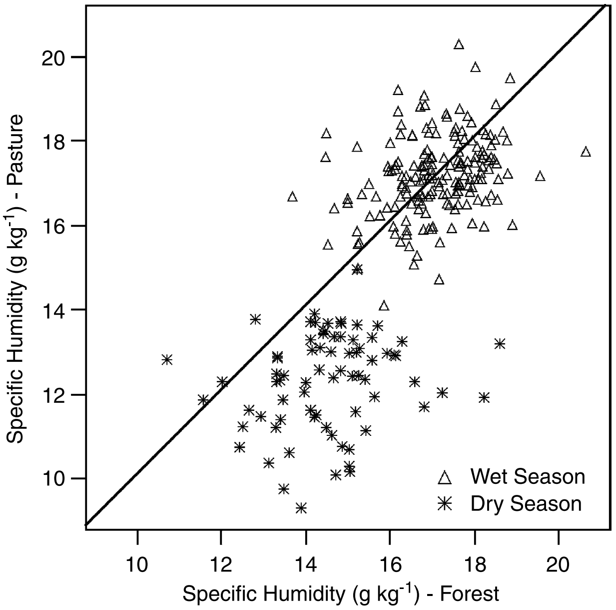

Fig. 5. The scatter plot between the specific humidity from forest and pasture sites and for wet and dry seasons

The thermodynamic differences between the forest and pasture sites must be understood, as they will have a key role in triggering the convection (Table 3). During the dry season, it is clear that the forest site is wetter (by a value of approximately 2.0 g kg^{-1}) than the pasture, although the pasture is hotter (by a value around 1.5–2.0 °C). The forest CBL shows a maximum temperature of about 32 °C, with a specific humidity ranging from 11 up to 14 g kg^{-1}. The pasture presents a similar behaviour, with a higher value of temperature (34 °C) and a drier layer (specific humidity ranging from 9.5 up to

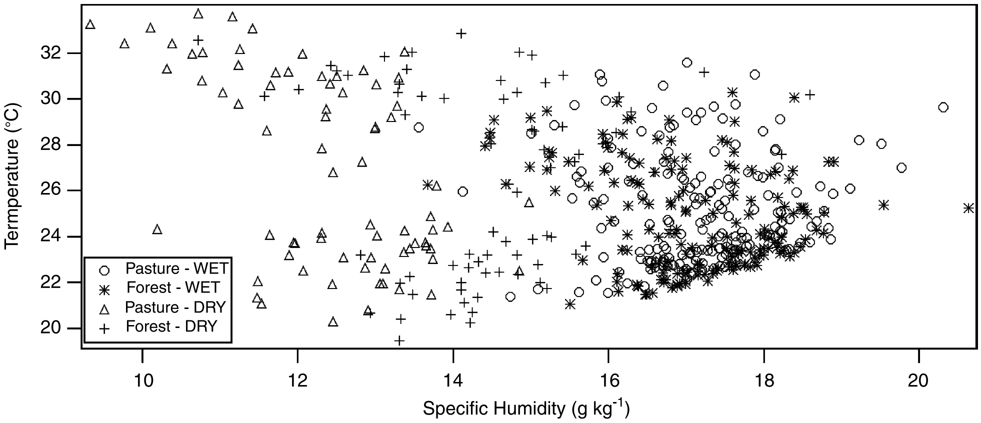

Fig. 6. The correlation between specific humidity and temperature for both sites (forest and pasture) for wet and dry seasons

Table 3. Average values of temperature and specific humidity for the whole CBL during the dry and wet season for forest and pasture

Time (LT)	Pasture		Forest	
	Dry	Wet	Dry	Wet
08:00	25.7/12.4	27.2/17.6	21.0/14.6	–
11:00	30.9/11.1	29.8/17.2	28.2/13.5	29.6/15.8
14:00	33.6/9.3	32.2/16.0	31.8/11.0	32.0/15.1
17:00	34.0/9.5	32.9/16.5	32.3/11.1	32.8/15.0

OBS: Values are Temperature (°C)/Specific Humidity (g kg^{-1})

12.5 g kg^{-1}). For the wet period, the profiles are almost the same, considering the bias (in particular for the specific humidity) found during the intercomparison of the soundings. They showed temperatures around 33 °C (1 degree less than the dry season value) and specific humidities around 16.0–17.0 g kg^{-1}.

4.2 Contrasting days (disturbed versus undisturbed days) for wet and dry season

Figure 7 shows the development of the CBL for two representative days during LBA/TRMM: a dry day (5 February 1999) and a very wet day (18 February 1999). The first point in each of the forest profiles (surface measurements) has been disregarded as this observation represents the meteorological conditions inside the small clearing where the balloons were released. The daily rainfall was zero for 5 February for both sites: because synoptic scale subsidence over the Ji-Paraná area allowed only shallow cumulus clouds to develop. 18 February 1999 had a daily rainfall of 60.4 mm and 48.6 mm for pasture and forest respectively, and this precipitation was due to a mesoscale system reaching the Ji-Paraná area, probably linked with a coastal squall line coming from the eastern coast of the continent (Betts et al., 2002). Tota et al. (2000) have shown that this system passed over the Ji-Paraná area during the night of 17–18 February. These selected days were also chosen to represent the growth of the CBL with a sunny (5 February) and cloudy day (18 February). In terms of daily average solar radiation, 5 February had 290 and 315 W m^{-2} for forest and pasture respectively, but these figures decreased to 147 W m^{-2} for forest and 141 W m^{-2} for pasture on 18 February 1999. Machado et al. (2002) found that the cloud cover was lower than average on 5 February, and higher than average on 18 February.

The different incoming energy produces very different CBL growth at the two sites. On 5 February 1999, the pasture CBL was 75 m at 08:00 LT, 475 m at 11:00 LT, 900 m at 14:00 LT and 1075 m at 17:00 LT. The CBL height at the forest site showed a similar growth: 750 m at 11:00 LT, 950 m at 14:00 LT and 1150 m at 17:00 LT. These numbers characterized the CBL growth with high solar energy, some of which returned to the atmosphere as sensible and latent heat fluxes. For the day with the lowest available energy (18 February 1999), the CBL development was very different: over the pasture it was 90 m at 08:00 LT, 350 m at 11:00 LT, 600 m at 14:00 LT. The forest showed a similar

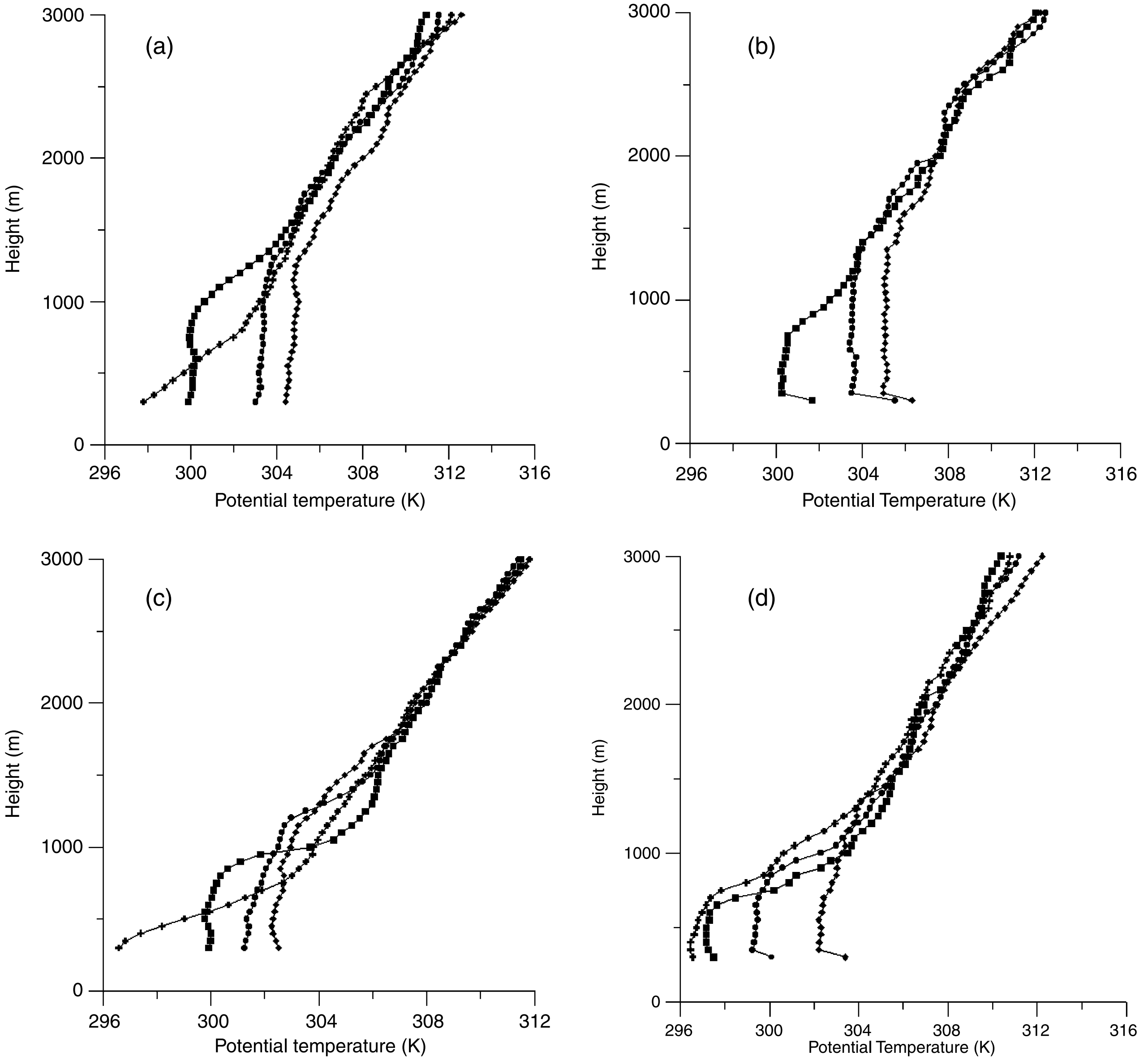

Fig. 7. Typical development of the CBL over the forest and the pasture for two representative days during the LBA/TRMM at 08:00 LT (cross), 11:00 LT (square), 14:00 LT (circles) and 17:00 LT (diamond) over the forest (**a**, **c**) and the pasture (**b**, **d**)

growth: 80 m at 08:00 LT, 550 m at 11:00 LT, 650 m at 14:00 LT and 800 m at 17:00 LT. It seems that the CBL grew almost 300 m less for both sites on 18 February 1999 due to there being less energy available. At the pasture, the boundary layer average temperature and specific humidity were 27.3 °C and 16.6 g kg^{-1} at 08:00 LT, changing to 31.9 °C and 15.6 g kg^{-1} in the late afternoon (17:00 LT) on 5 February. The forest shows the same pattern, changing the temperature from 28.8 °C to 33.6 °C, with the specific humidity almost constant around 13.8 g kg^{-1}. On 18 February 1999, the range of temperature was 3 °C at the pasture and 2.5 °C in the forest. The range for specific humidity was less than 0.5 g kg^{-1}.

The dry season observations contain no disturbed day conditions, as there was no rain during the whole period of the experiment. Figure 8 shows the time evolution of the CBL for a typical day (18 August 1994). For the pasture case, the height of the CBL in the early morning was 90 m at 08:00 LT, growing to 480 m at 11:00 LT, producing a rapid growth rate with an estimated height of 1630 m at 14:00 LT, and a final height of 1880 m at 17:00 LT. For the forest site, the

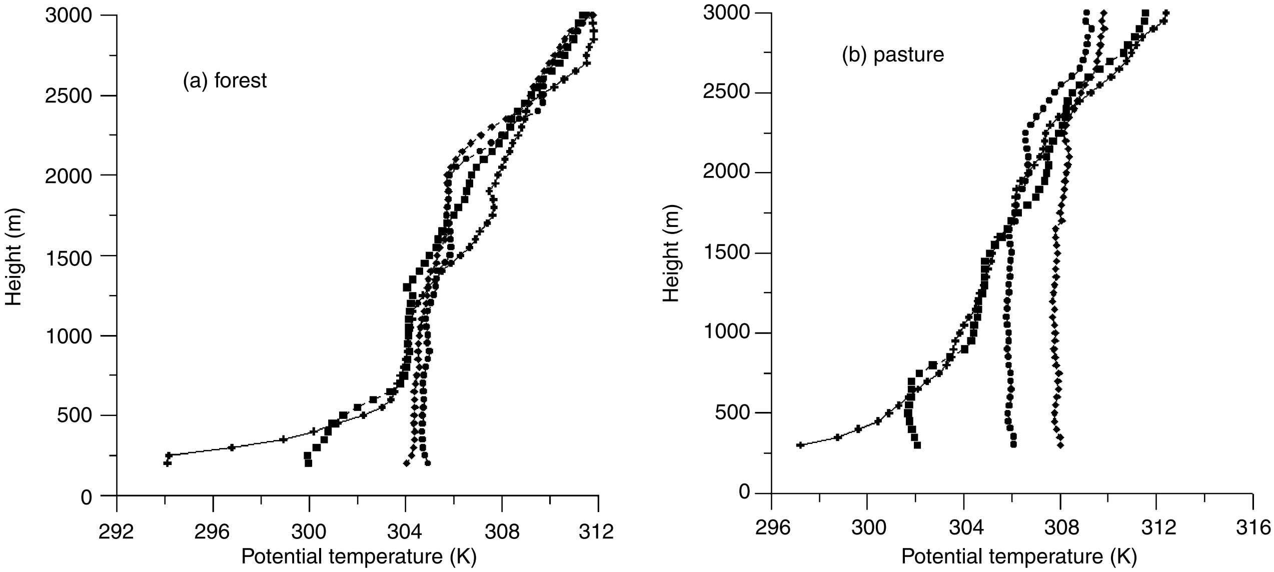

Fig. 8. Typical development of the CBL over the forest (**a**) and the pasture (**b**) for a representative day during the ABRACOS/RBLE at 08:00 LT (cross), 11:00 LT (square), 14:00 LT (circles) and 17:00 LT (diamond) over the forest (**a**) and the pasture (**b**)

CBL height was 90 m at 08:00 LT, 280 m at 11:00 LT, 980 m at 14:00 LT and reaching a final height of 1230 m at 17:00 LT. At the pasture site, the boundary layer average temperature and specific humidity were 23.2 °C and 13.2 g kg^{-1} at 08:00 LT, changing to 33.1 °C and 10.6 g kg^{-1} in the late afternoon (17:00 LT). The forest shows the same pattern, changing the temperature from 19.7 °C to 31.6 °C and the specific humidity from 14.3 g kg^{-1} to 11.8 g kg^{-1}. The solar radiation fluxes are almost the same for the pasture (206 W m^{-2}) and the forest (208 W m^{-2}), although this energy has been partitioned in a very different way. In the pasture the sensible heat flux was 49 W m^{-2} with a Bowen ratio of 0.93 and in the forest it was 22 W m^{-2} with a Bowen ratio of 0.23. This difference in the sensible heat flux explains why the CBL is deeper over pasture than over forest. Also, this energy flux and the consequent thermal buoyancy, produces an early mixing of the CBL over the pasture (Oliveira and Fisch, 2000).

4.3 *A friagem event – case study*

This case study is an example of how external forcing can modify the structure of the CBL. During the field campaign of RBLE 2 (July 1993), there was an event classified as a moderate *friagem*: the minimum surface temperature was 15.1 °C, 6.6 °C less than that on the previous day. Analysing the 1992–1993 ABRACOS dataset for the Ji-Paraná area, Fisch (1995) found an average of 6-7 *friagem* events from April to September. This invasion of a cold air system occurred during the night of 6–7 July, 1993, with a small amount of rainfall (3.6 mm) at sunrise (06:00 LT). According to *Climanalise* (1993) and satellite images, this sypnotic system had passed the south of Brazil (Rio Grande do Sul and Santa Catarina) on 5 July. In the next 2 days, it moved northward (a distance of almost 2000 km), covering most parts of Brazil. On 8 July, the cold front dissipated, with only minor activity occurring on the east coast (about 1500 km from Ji-Paraná). Daily averages of the surface climatic variables (solar and net radiation, sensible heat flux, air temperature, specific humidity and windspeed) for the period of *friagem* (6–8 July 1993) are shown in Table 4. The fluxes showed typical behaviour on 6 July, but they changed remarkably on the next day, when the fluxes were less than half the values of the previous day. There were 8 oktas of cloud cover (stratus – visual observations reported by the rawinsounding operators) during most of the event and the solar radiation showed a maximum (instantanous) value of around 320 W m^{-2}. On 8 July the cloud cover had decreased (6 oktas of stratus at 11:00 LT and 3 oktas of shallow

Table 4. Daily average values of the surface climatic elements (Solar radiation – S, net radiation – R_n, sensible heat flux – H), air temperature – T, specific humidity – Q and windspeed (WS) during the *friagem* event. These data were obtained from the top of the micromet tower (65 m) at the forest site (Rebio Jaru)

Variable Date	S ($W\,m^{-2}$)	R_n ($W\,m^{-2}$)	H ($W\,m^{-2}$)	T °C	Q ($g\,kg^{-1}$)	WS ($m\,s^{-1}$)
July 6	17.1	11.8	1.8	25.3	16	1.0
July 7	7.1	5.2	0.7	18.7	11	3.2
July 8	17.2	11.9	3.5	19.3	14	1.6

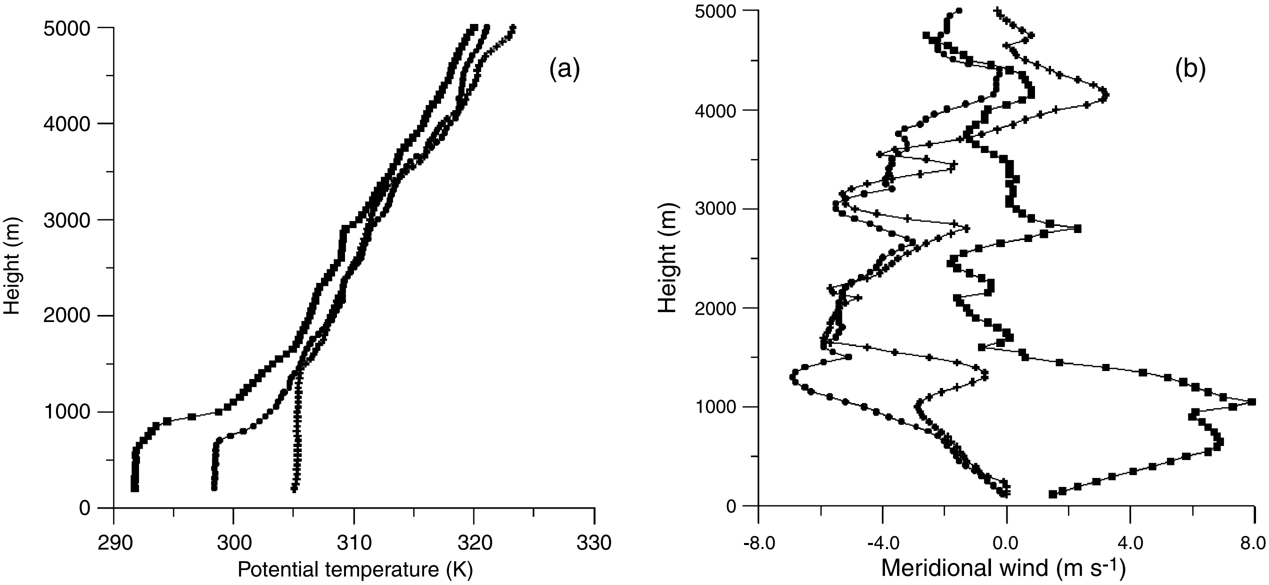

Fig. 9. The time evolution of the potential temperature (**a**) and meridional wind (**b**) during the *friagem* event for July 5 (cross), 7 (squares) and 8 (circles) over tropical forest during RBLE 2 (July 1993, Rondônia)

cumulus at 14:00 LT) and the insolation began to warm the surface. The daily (24 hour) average of solar radiation dropped from 198 $W\,m^{-2}$ (6 July) to a value of 82 $W\,m^{-2}$ on 7 July, recovering to 199 $W\,m^{-2}$ by 8 July. The net radiation flux followed the same pattern. The average sensible heat flux is also interesting: it was 21 $W\,m^{-2}$ on 6 July, decreasing to 8 $W\,m^{-2}$ on 7 July but climbing to the high value of 41 $W\,m^{-2}$ on 8 July. In this situation, the partition of energy was mainly by sensible heat transfer, instead of the usual latent heat flux. The ABL structure (both potential temperature and meridional wind component) is shown in Fig. 9a. The 6 July profile has been discarded due to the appearance of some cirrus clouds and an intensification of the winds that could be a signal of the penetration of the cold air. On 5 July, the height of the CBL was estimated to be 1350 m, with an average potential temperature of 305.3 K. These characteristics are typical for ABL over tropical forest. On 7 July, there was a cooling of the layer by 13.5 K (with a minimum value of 291.8 K) and only a shallow CBL developed (height around 420 m). This value is about one third of the typical values of 1100 m and the mechanical turbulence is important due to the high windspeed (on 7 July the friction velocity is around 0.6–0.8 $m\,s^{-1}$ instead of the typical values of 0.2–0.4 $m\,s^{-1}$). The temperature jump at the top of the mixed layer was 9 K, indicating a strong inversion. The next day (8 July), the solar insolation heats the layer and the average potential temperature has increased to 298.5 K. The temperature discontinuity decreased to 3.5 K and the CBL was still shallow (height was estimated to be 500 m). Probably the cooling of the atmosphere was so intense during in the lower 1–2 km that the solar insolation on 8 July was primarily used to warm the layer instead of moistening it by evapotranspiration. Also, the jump of the temperature was so strong that it may have inhibited the entrainment from above that contributes to the development of the CBL. The time series of the meridional component of the wind are shown at Fig. 9b and this component was chosen because its rotation, from north (the prevailing wind is from NE) to the south, indicates the penetration of this cold extratropical front. There was a significant modification when the *friagem* reached the site, changing from $-2.0\,\mathrm{m\,s^{-1}}$ at 1000 m on 5 July to $+8.0\,\mathrm{m\,s^{-1}}$ on 7 July. This intensification can also be seen at the surface, where the average windspeed (data not shown) increased from 1.0 to $3.2\,\mathrm{m\,s^{-1}}$. The *friagem* also reduced the specific humidity of the layer by $5.0\,\mathrm{g\,kg^{-1}}$ at the surface and around $3.0\,\mathrm{g\,kg^{-1}}$ inside the CBL (data not shown).

5. Concluding remarks

The CBL development shows different patterns for different surface wetness conditions: for the forest site the CBL grows up to approximately 1000 m, independent of the season (dry or wet). In contrast, the CBL at the pasture site shows strong seasonality with heights of 1650 m during the dry season and around 1000 m in the wet season. The soil moisture conditions in these situations determine the partitioning of surface energy and hence the sensible heat fluxes. This feature has a strong effect on the cloud formation regime and also for the energy budget. There is evidence from previous studies (Silva Dias and Regnier, 1996; Fisch, 1995) that during the dry season the land-use/land cover (forest versus pasture) can determine the structure of the CBL. In this situation, the synoptic situation is very weak and the surface is strongly coupled with the ABL. Conversely, for the wet season the large-scale convection seems to be the dominant factor in shaping the development of the CBL, as both surfaces have similar characteristics (height and growth of the CBL, convection properties, etc). The CBL can be critically modified by the external forcings (like *friagem*). The associated time scale is about 2–3 days. This cold air penetration reduces the development of the CBL by a factor of 3, despite the fact that the higher windspeeds increase the contribution of mechanical turbulence. Under these conditions, the low incoming solar energy (due to the cloud cover) and the associated temperature jump at the top of the boundary layer reduce the development of the CBL.

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