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River breeze circulation in eastern Amazonia: observations and modelling results

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With 10 Figures

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Summary

The CIRSAN/LBA field campaign was conducted close to two major rivers of the Amazon Basin, the Tapajós and the Amazon. The observations indicate that during weak trade wind episodes the Tapajós River breeze actually induces a westerly flow at the eastern margin with an associated line of shallow cumulus. The atmospheric circulation induced by the river has been interpreted with the help of a high resolution numerical simulation. A single cell forms during late morning over the Tapajós River and evolves into the afternoon with ascending motion in the eastern margin and a descending branch in the western margin suppressing cloud formation. During the night, convergence is seen along the centre of the River Tapajós . The implications of the particular geometry of the river with respect to the trade winds for the generalization of the surface measurements of turbulent fluxes of heat, moisture and CO_2 in the Tapajós eastern margin of the Amazon Basin as a whole are discussed.

1. Introduction

During the beginning of the Amazon Region dry season of 2001, an atmospheric intensive field campaign called CIRSAN/LBA (Circulation in Santarém) was carried out close to Santarém (see Fig. 1 for locations). The campaign was part of the Large Scale Biosphere Atmosphere Experiment in Amazonia – LBA. Boundary layer and upper air measurements were carried out with the objective of studying the local circulation in the region around the confluence of two major Amazonian rivers, the Tapajós and the Amazon (Fig. 2). Eastward of the Tapajós River, in a narrow strip of forest about (20 km wide), instrumented towers of several LBA projects measure fluxes of heat, moisture and trace gases as well as pressure temperature, humidity, windspeed and radiation profiles below and above the forest canopy. In deforested areas to the east of the forest, a network of automatic weather stations, as well as a flux tower, are also part of the LBA network and are described in detail by Fitzjarrald et al. (2003). The intensive field campaign intended to gather upper air data to help understanding the local circulation and thus contribute to the interpretation of the tower measurements.

The large scale situation during the experiment included an event of a cold air intrusion into western Amazonia. Frontal systems in South America have been seen to intrude into the tropical regions with a significant effect on temperature and moisture and on boundary layer features (Hamilton and Tarifa, 1978; Parmenter, 1976;

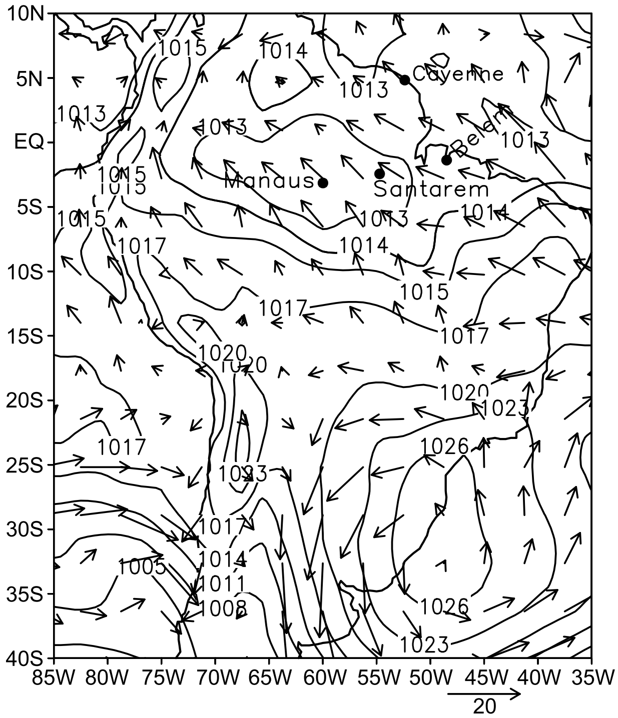

Fig. 1. Sea level pressure and 925 hPa winds from CPTEC analysis 29 July, 2001, 06 UTC, including the location of a few towns

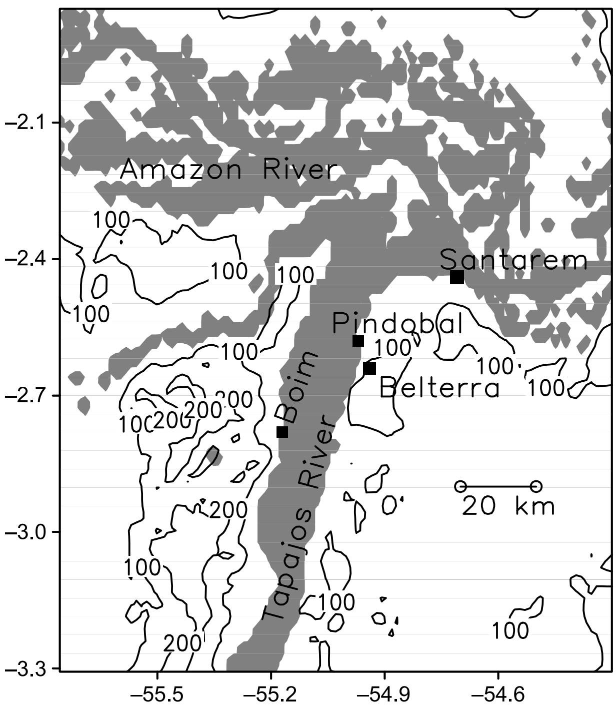

Fig. 2. Topography contours (in metres). The River Tapajós (north south) and River Amazon (east west direction) are shaded. The location of main stations mentioned in the text is indicated

Marengo et al., 1997a, b). A cold air mass intrusion into Amazonia is known locally as a *friagem*. The typical sequence of events, described in several case studies, begins with a mid-latitude progression of a high amplitude upper level trough, with accompanying surface front and high-pressure area behind it, the latter with a northward continental trajectory. The south to south-easterly flow ahead of the high reaches western Amazonia, lowering average daily temperatures in Manaus, by about 5 °C, an unusual occurrence for an equatorial region. During the period from 24 to 31 July 2001, the daily-averaged low level winds in eastern Amazonia diminished from 6 m s^{-1} to about 3–4 m s^{-1} associated with a *friagem* event. As shown by Fitzjarrald et al. (2003), low-level prevailing winds in eastern Amazonia during July and August are basically the trades, with some day to day variability from south-easterlies to north-easterlies. Figure 1 shows the 925 hPa winds and sea level pressure for 29 July 2001 at 0600 UTC (UTC is 4 hours ahead of local time). It can be seen that southerly winds reach western Amazonia while Santarém is dominated by the trade winds. A confluence of the air mass coming from the south and the tropical air mass advected by the trade winds is seen, southwest of Santarém, as the north-westward extension of a cold front going through south-eastern Brazil. The effect of the cold air intrusion was to lower the surface temperature and increase the sea level pressure in western Amazonia. The difference in the sea level pressure in the global CPTEC (Brazilian Center for Weather Forecasts and Climate Studies) analysis between grid points close to Santarém and Manaus (not shown) is of about 1.3 hPa on the afternoon of 28 July. A positive value indicates a pressure gradient force pointing due east which is coherent with a reduction in the trade wind speed. This period of weak trade wind presented an opportunity to study the evolution of the local circulation, in a situation not dominated by the large-scale winds. As shown by Fitzjarrald et al. (2003), in weak wind situations, the automated weather stations in the Santarém region show a reversal of the wind direction indicating the effect of the river breeze.

The river and land breezes, which are a feature of the large rivers of Amazonia, are basically a result of the different surface heat capacity of water and land, transmitted to the boundary layer by the surface sensible heat flux, and are similar to coastal sea and land breezes. The resulting differences in boundary layer temperature, warmer during daytime over land and during nighttime over water, generate a low level pressure over the warmer surface which results in ascending motion over the warmer side, low level flow from cold to warm, return flow at some level above and a descending branch over the cold side, defining a local circulation cell in a vertical plane. Without the presence of a large scale flow, the local circulation is seen as a 180° change in the horizontal wind direction from day to night. Wide rivers have been documented to induce a diurnal cycle of the wind direction as by Oliveira and Fitzjarrald (1993).

The objective of this paper is to present and interpret the local circulation evolution close to the confluence of the River Tapajós and the River Amazon, embedded in weak trade winds during an Amazonian *friagem* event. Section 2 describes the CIRSAN/LBA data used here, Section 3 presents the observed local circulation features; Section 4 uses a mesoscale numerical simulation to analyse the observed features and Section 5 draws the conclusions.

2. Data

The CIRSAN/LBA data collected during July/August 2001 and used here are listed in Table 1. Radiosondes were released from Belterra every 6 hours, with a few intensive periods when a sounding was performed every three hours. Pilot balloons (pibals) were released and tracked on both sides of the Tapajós, in the small villages of Pindobal and Boim, while and an acoustic sounder was operated at Santarém airport close to the south bank of the River Amazon. Locations may be seen in Fig. 2.

Table 1. CIRSAN/LBA sites (geographical locations in Fig. 2)

Site	Instrument/vertical resolution/depth reached	Data period	Temporal frequency	Variables measured
Belterra	Vaisala RS-80 radiosonde/ approx. 10 hPa/ approx. 20 km	25 July to 15 August	6 hours, and occasionally 3 hours	Pressure, temperature, relative humidity, wind speed and direction
Santarém Airport	Remtech Acoustic Sounder–Sodar/ 50 m/1500 m	15 July to 15 August	30 minutes	Height, wind speed and direction, vertical velocity, Standard deviation of the 3 wind components, C_T (turbulence intensity), height of thermal inversion
Pindobal	Pibal with optical theodolite/100 m/ variable, usually up to 4000 m	20 to 31 July	Hourly from 07:00 to 18:00 LT	Height, elevation and azimuth angle, converted into position, using constant rate of ascent of 250 m
Boim	Pibal with optical theodolite/100 m/ variable, usually up to 4000 m	24 to 31 July	Hourly from 07:00 to 18:00 LT	Height, elevation and azimuth angle, converted into position, using constant rate of ascent of 250 m
Belterra	Pibal with optical theodolite/100 m/ variable, usually up to 4000 m	3 to15 August	Hourly from 07:00 to 18:00 LT	Height, elevation and azimuth angle, converted into position, using constant rate of ascent of 250 m

The radiosonde data quality control is the same used for other LBA radiosonde data and is described by Longo et al. (2002). The data goes through three steps of quality control whereby it is screened for large errors when compared to climatology, for continuity errors in the vertical structure, superadiabatic layers and temporal continuity at each level. Flagged data are subject to further investigation and either maintained or removed according to the presence of phenomena such as cloudiness or rainfall.

The pilot balloon data also go through a procedure of data quality control. The vertical velocity of the balloon was previously calibrated with the use of two theodolites located at the ends of a 300 m baseline and synchronous observations of elevation and azimuth angles. The payload for filling the balloon was determined as an average of several launches to give a vertical velocity of 250 metres per minute. The balloon position, obtained at 20 seconds interval from the elevation and azimuth angles, was smoothed out by a 5 point running average and then the horizontal vector components were calculated. The quality control was performed by examining the vertical continuity of zonal and meridional components. Strong level to level variations were flagged and re-examined for indications of operational problems, such as when the lens is changed from large to small field of view or when the pibal trajectory goes over the theodolite. When the problems encountered where defined as errors, the corresponding azimuth, elevation angles were removed and positions were calculated with the remaining points. Finally the zonal and meridional components were interpolated to a regular 50 m resolution vertical coordinate above the local surface. The sodar data was processed by the manufacturer's software (REMTECH, Inc) to produce wind profiles, acoustic echo intensity and an estimate of the lowest inversion height every 30 minutes.

Since local circulations forced by a river are theoretically a function not only of the river width but also of the river temperature, two daytime boat trips were taken along the Tapajós and Amazon rivers to measure water temperature. The boat was stopped for a few minutes for each measurement and the position was recorded using a hand held GPS. A set of 4 equally spaced thermistors connected to a data logger was attached to a 1 m pole, with a weight on one end. When the pole was lowered in the water, it left the first thermistor between 5 and 10 cm below the surface. The first trip, on 23 July, was from Pindobal to Boim and back. The second trip, on 28 July, was from south to north on the Tapajós and then due west up the Amazon and back, several times, crossing the confluence were the Tapajós flows into the Amazon. Figure 3 shows the water temperature measured as a function of time. The dashed line in Fig. 3b indicates the temperature at the merging of the two rivers. As seen in Fig. 3, the Tapajós had an average temperature of about 30.5 °C while the Amazon was cooler averaging about 27.5 °C. There is a small variation in water temperature during the day and in the vertical in the Tapajós, as seen in Fig. 3a. However, for the purpose of the numerical simulations described in Section 4, the water temperatures will be assumed to be different in the two rivers, but constant and equal to the average temperatures mentioned above.

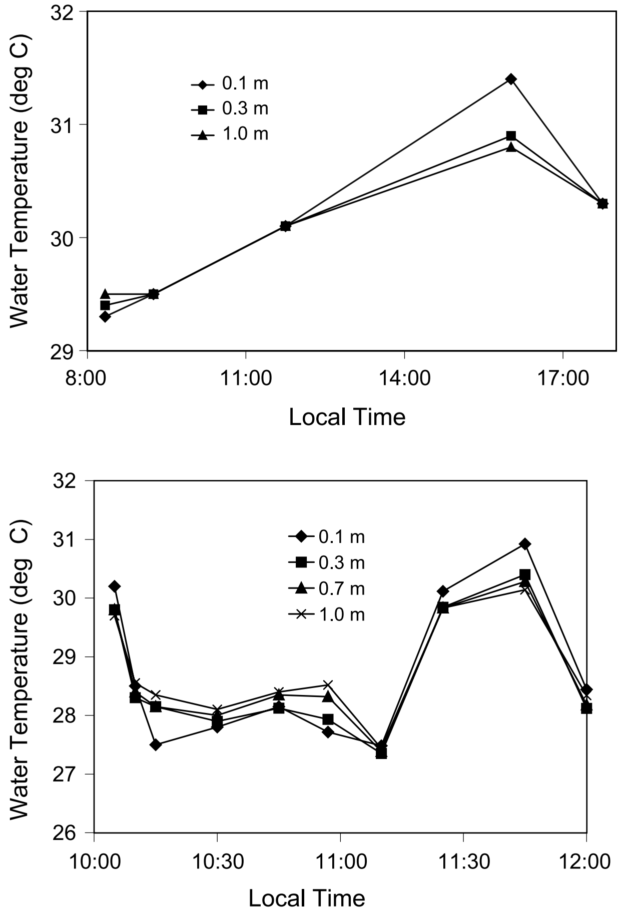

Fig. 3. Water temperature of the River Amazon and Tapajós (see text for details)

3. Observed features of the local circulation

The radiosonde station at Belterra is located at 176 m above sea level on a plateau which is approximately 100 m above the level of the River Tapajós and about 7 km to the east of the river margin. The pibal station of Pindobal was located at the river margin while the Boim station was 100 m from the margin and about 5 m above the river level. Being at opposite sides of the Tapajós River, the Boim and Pindobal stations should be able to capture the different impact of the river breeze with the same large-scale wind. An indication of the river breeze in Belterra and Pindobal is a positive zonal wind component, a westerly wind, while in Boim a negative zonal component corresponds to an easterly component. Oliveira and Fitzjarrald (1993, 1994) explained the rotation of the wind vector and a low level nocturnal wind maximum close to the confluence of the Negro and Solimões rivers in central Amazonia as a result of the river breeze. Figure 4 shows the wind vector and zonal windspeed for the layer from 990 to 850 hPa for 25 to 31 July, obtained from the Belterra sounding. The wind is seen to become westerly or almost westerly, in most of the days in a layer of 40 to 50 hPa (400 to 500 m above ground level). Figure 5 shows the zonal wind profile at

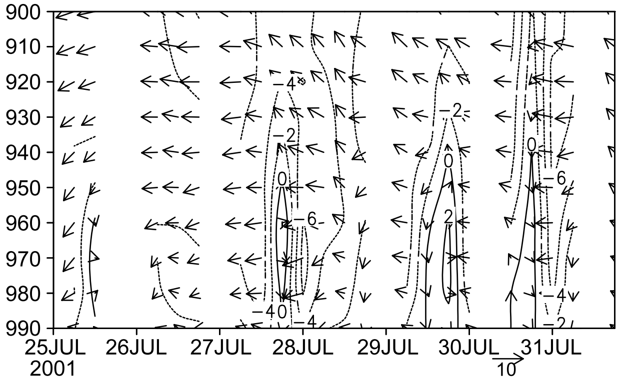

Fig. 4. Belterra radiosonde; wind vector and contours of zonal wind component for 25 to 31 July from 990 hPa to 850 hPa

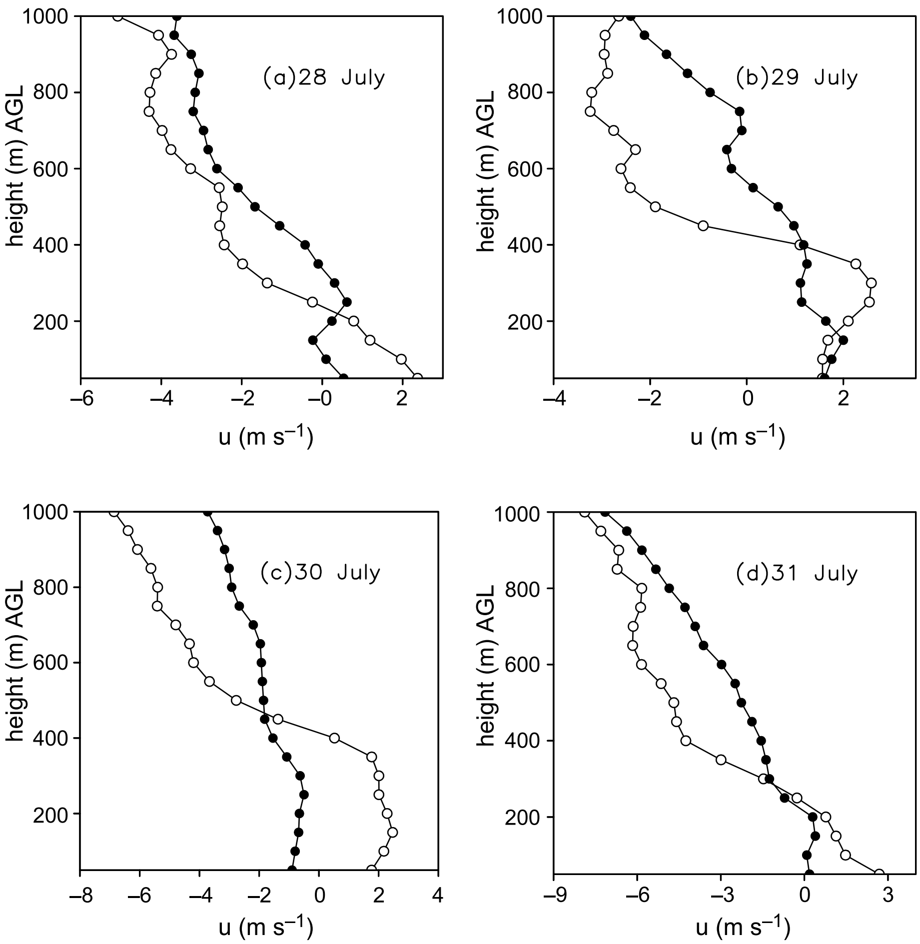

Fig. 5. Zonal wind profile from pilot balloon soundings at Pindobal (empty circle) and Boim (full circle) at 1500 UTC (1100 local time) for (**a**) 28 July, (**b**) 29 July, (**c**) 30 July and (**d**) 31 July

Boim and Pindobal for the period from 28 to 31 July at 1500 UTC (1100 local time). On all days the behaviour of the wind profile is consistent with a river breeze. Even when the Pindobal wind does not turn to westerly there is a considerable reduction of the easterly component at low levels and an increase of the easterly component in a superimposed layer above. The reverse is true for Boim.

At the margin of the River Amazon, the mean sodar wind vector and echo time-height sections for the period 24–31 July (Fig. 6, top panel) illustrate marked diurnal variation. In the mean, the meridional component indicates southerly (land breeze) circulation only in the early evening (19–24 LT). For much of the day, the combination of the slightly north-easterly trade wind flow and the river breeze keeps the wind onshore. The boundary layer over the River Amazon is convective both day and night. This is evident in the sodar echo time-height section (Fig. 6, bottom panel). The sodar detection software locates an inversion at between 400 and 500 m. This is consistent not only with the LCL (Lifted Condensation Level) of surface air measured at Santarém airport at night, but also with the weather observer's estimate of the lowest cloud base ("C" in Fig. 6, bottom panel) and the LCL of fluvial surface layer air, using the observed surface temperature and assuming saturation at water temperature ("R" in Fig. 6, bottom panel). Calculated in this way, the Tapajós surface layer air LCL is at 417 m and the Amazon's at 394 m. In the middle of the day, the LCL for surface air at Santarém airport reaches about 1100 m, comparable to the convective cloud base measured inland, slightly lower than the inversion base typically observed in the Belterra radiosonde profile. Incipient cloud seen at the airport as the northerly river breeze commences, grows early in the day and is

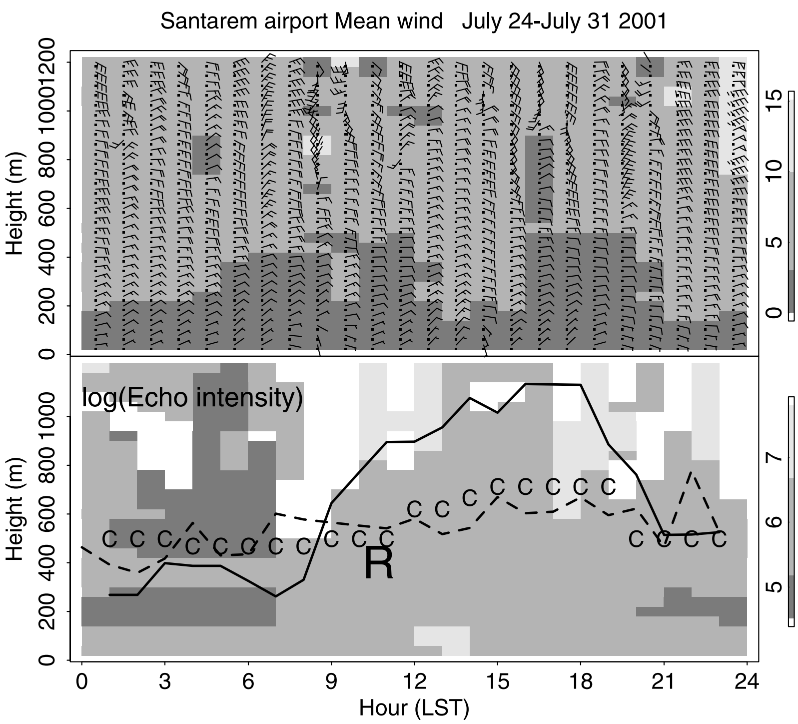

Fig. 6. Hourly averages of the sodar data at Santarém airport for the week 24 to 31 July, 2001. Top panel: Mean wind vectors (averaged by components and then reassembled into wind speed/direction. The shading is the windspeed ($m\,s^{-1}$), with the legend at right. Each full barb on wind model is $3\,m\,s^{-1}$. Bottom panel: echo strength presented as the log ($C_T{}^2$), the temperature structure function obtained from the Remtech Inc software, in shading with scale on the right. Solid black line is the median hourly LCL from the Santarém airport weather station temperature and dew point. The dashed line is the median hourly Remtech inversion base parameter; a length scale obtained through estimates of the dominant horizontal scale of eddies sampled by the sodar. The symbols "C" are the median hourly observer's report, at the airport station, of the lowest cloud base. The big "R" indicates the LCL for the air near the river surface

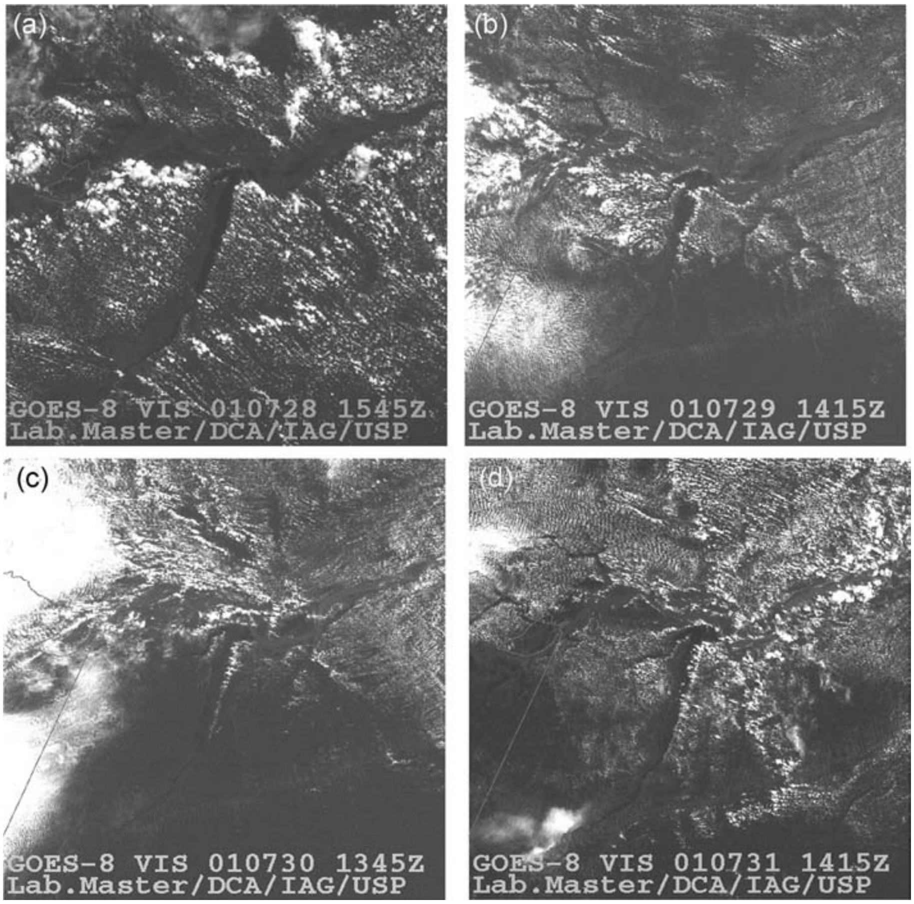

Fig. 7. GOES-8 visible satellite images for July 2001 (**a**) 28, 1545 UTC, (**b**) 29, 1415 UTC (**c**) 30, 1345 UTC and (**d**) 31, 1415 UTC

clearly present in the GOES visible band satellite images (e.g. Fig. 7a, upper left panel). These observations make it clear that measurements taken very close to the great rivers of Amazonia, the situation with most long-term climate stations, must be interpreted very carefully.

Visible satellite images for the 28 to 31 July period shown in Fig. 7 indicate that the effect of the river breeze in the eastern margin of the River Tapajós is seen as a line of cumulus. No clouds are seen in the western margin at the time of the start of shallow cumulus. The numerical model results in the next section will be used to understand the difference in cloudiness in the two margins of the River Tapajós.

4. Numerical simulation of the local circulation

The Regional Atmospheric Modelling System (RAMS) as described by Walko et al. (2000), Version 4.3, has been used to simulate the local circulation in the Santarém area. The initial and boundary conditions were given by the analysis of the National Center for Environmental Prediction (NCEP) and the model was run with three nested grids with resolutions of 32, 8 and 2 km. Grid 3 covers the area shown in Fig. 2. Vertical resolution starts at 50 m close to the surface and progressively increases by a factor of 1.2 until reaching 1000 m resolution, which is then kept constant up to model top located at 19 km. Several tests with vertical spacing indicated the need for very high resolution close to the surface. In the horizontal, the 2 km resolution of Grid 3 was defined with the idea of having 10 points over the river, which allows a good representation of the derived circulation. A soil model with 11 levels between the surface and 1.25 m below the surface was used. The model was initialized on 28 July 2001 at 0600 UTC. Kuo's cumulus parameterization was used in Grid 1, while a full microphysical parameterization was used in Grids 2 and 3. Topography and vegetation from IGBP files were used. The initial soil moisture used was 0.56 of

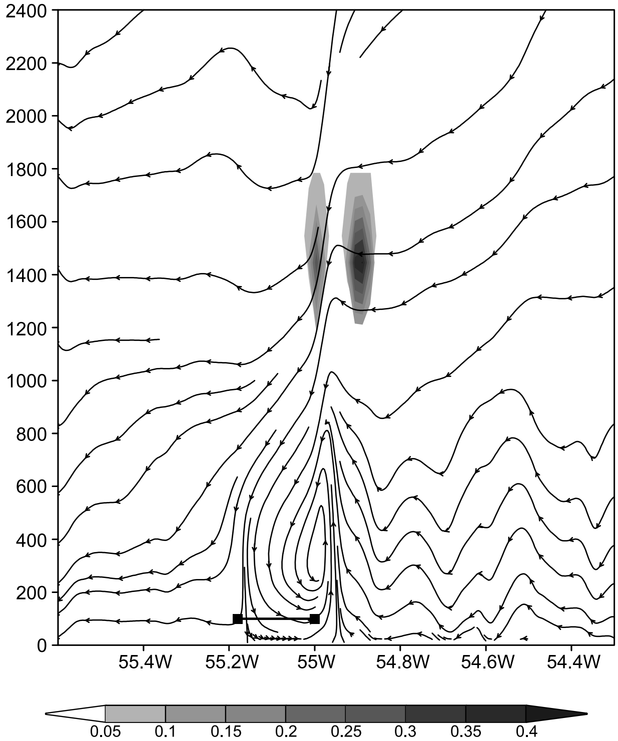

Fig. 8. Numerical simulation for a vertical cross section at 2.7° S, at 21 UTC on 28 July 2001. Streamlines of u, w and liquid water content (in shaded) in $g \cdot kg^{-1}$. The slab indicates the position of the River Tapajós

saturation at 1.25 m depth decreasing to 0.40 at the surface. This profile was obtained after adjustment to provide a good match with the mixed layer height observed by the Belterra sounding.

Only a few results of the simulation will be shown here since the main objective is to help understanding the observations. Figure 8 shows a vertical cross section of cloud liquid water and streamlines of the zonal and vertical wind components at latitude 2.7° S at 2100 UTC (1700 local time on 28 July). Figure 9 shows a time evolution for the first 24 hours of simulation of the horizontal wind vector at the first model level (25 m above ground level) and the liquid water content at 1000 m above ground level. At 1000 m only the cloud base value of the liquid water mixing ratio is seen (c.f. Fig. 8). The Tapajós river breeze in Fig. 8 is seen as a single cell with upward motion on the east margin, producing shallow clouds, and descending motion on the western margin suppressing cloudiness. The well developed closed cell over the river is about 1 km deep, but the background trade wind flow is disturbed through a layer more than 3 km deep along the eastern margin. Figure 9 shows the propagation of the river breeze front on the eastern side of the Tapajós and the formation of the land breeze at night with convergence in the centre of the river. Experiments with the river water temperature indicate, as expected, that the warmer River Tapajós induces a weaker breeze circulation during daytime and a stronger one at night than the colder River Amazon. Sensitivity tests were performed with respect to the water temperature. Using the same temperature in the two rivers (and equal to the cooler Amazon water temperature) has an effect (not shown) of up to $1\,m\,s^{-1}$ in lower levels close to the Tapajós.

The one-cell nature of the river breeze over the Tapajós is due to the fact that the river is approximately perpendicular to the background trade wind flow. This is consistent with the need for convergence east of the river and divergence west of the river. Above the River Amazon, which is more parallel to the trades, the model simulates the expected two cell structure and the visible images in Fig. 7 also show a line of shallow clouds on both sides of the river, with different intensities on each side and each day since the river is not always exactly parallel to the trade winds. Figure 10 shows the temporal evolution of water vapour mixing ratio at 100 m above the surface. The isoline of $17\,g\,kg^{-1}$ traces the flow from the river associated with the winds in Fig. 9. While the river breeze front progresses the mixing ratios over the Tapajós are lowered due to the transport of drier air by the descending branch of the local circulation cell.

The enhanced cloudiness over the east bank of the River Tapajós, also detected by Moore et al. (2001), may have a significant ecological impact, in this case arising from the geometry of the river and the trade wind regime. The confluence between the two river breezes southeast of Santarém is also likely to have an effect. Enhanced cloudiness and rainfall over the east bank and suppressed cloudiness and rainfall over the west bank suggest that horizontal mesoscale differences in climatology may hinder our ability to generalize from the Tapajós flux and ecosystem sites to the larger region and the Amazon Basin as a whole.

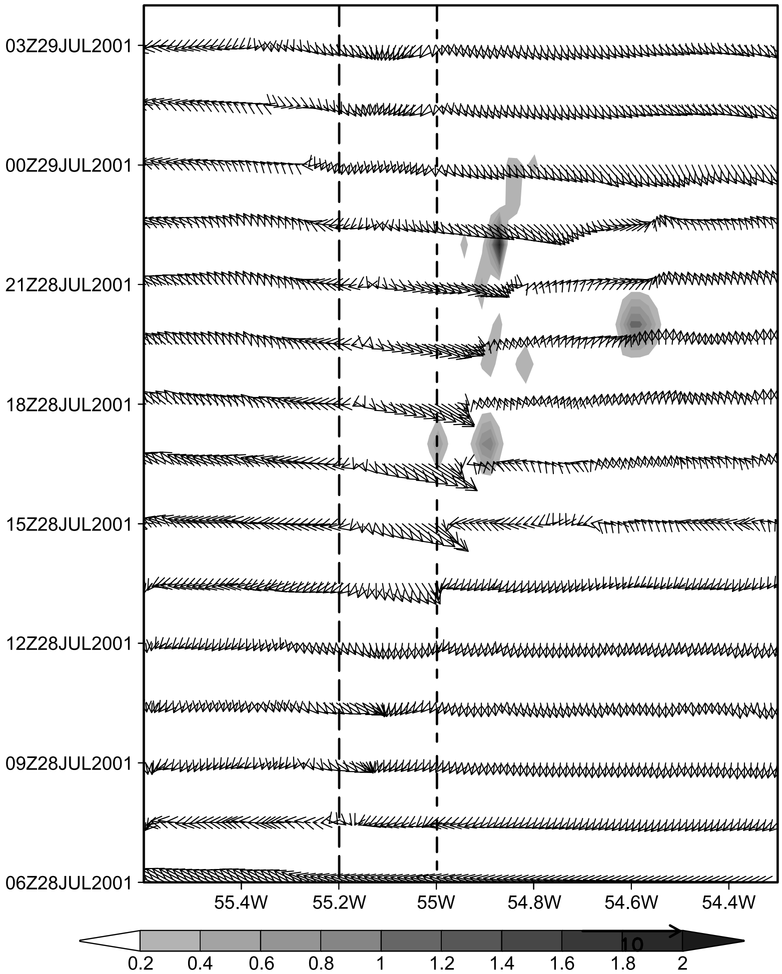

Fig. 9. Numerical simulation of the time evolution of surface wind vectors and 1000 m liquid water content different from zero (shaded, $10^{-3}\ g \cdot kg^{-1}$) at 2.7° S. The dashed lines indicate the east and west banks of the River Tapajós at this latitude

5. Conclusion

The reversal of the wind on the River Tapajós eastern margin in a weak trade wind situation has been documented through the data of CIRSAN/LBA, and a high resolution RAMS simulation has been used to understand the coupling of the circulation with the observed cloudiness. It is seen that during daytime a single circulation cell develops. This single cell is contrary to what might be expected, i.e. a double circulation with sinking in the river centre and rising motion in both margins. This explains the formation of clouds on the eastern margin during the morning and their absence on the western margin. The impacts of the river discussed in this paper make it clear that measurements taken very close to the great rivers of Amazonia, the situation for most long-term climate stations, must be interpreted very carefully. The observed horizontal mesoscale differences may hinder our ability to generalize from the Tapajós flux and ecosystem sites to the larger region and the Amazon Basin as a whole.

From another perspective, the presence of a regular and coherent circulation like the river breeze observed near the River Tapajós may provide an opportunity to investigate the recent suggestion by Ritchey et al. (2002) that CO_2 gas evasion from wetlands and water bodies plays an important role in the carbon budget of Amazonia. The presence of a climatological zone of slow windspeed and convergence on the east bank of the Tapajós suggests that this is a likely place to look for differences in atmospheric concentrations and isotopic ratios of CO_2 that might result from a strong gas evasion flux. Steady efflux by gas evasion in the presence of such a coherent circulation feature might allow quantitative evaluation of the evasion hypothesis if atmospheric measurements could be made in the lowest 1000 m of the atmosphere over the east bank of the river. The circulation observed

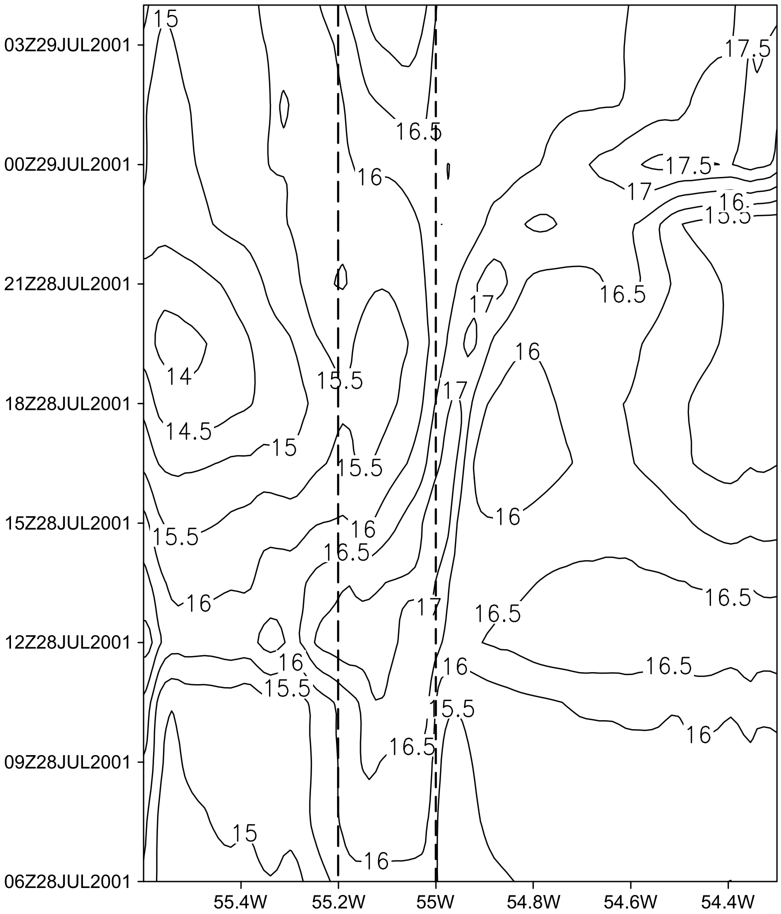

Fig. 10. Same as Fig. 9 but for the water vapour mixing ratio (g kg^{-1}) at 100 m above the surface

and simulated would be expected to produce an observable concentration maximum to the east of the river in the confluence zone.

Acknowledgements

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