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Cloud streets and land–water interactions in the Amazon

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Abstract Cloud streets are common feature in the Amazon Basin. They form from the combination of the vertical trade wind stress and moist convection. Here, satellite imagery, data collected during the COBRA-PARÁ (Caxiuanã Observations in the Biosphere, River and Atmosphere of Pará) field campaign, and high resolution modeling are used to understand the streets′ formation and behavior. The observations show that the streets have an aspect ratio of about 3.5 and they reach their maximum activity around 15:00 UTC when the wind shear is weaker, and the convective boundary layer reaches its maximum height. The simulations reveal that the cloud streets onset is caused by the local circulations and convection produced at the interfaces between forest and rivers of the Amazon. The satellite data and modeling show that the large rivers anchor the cloud streets producing a quasi-stationary horizontal pattern. The streets are associated with horizontal roll vortices parallel to the mean flow that organizes the turbulence causing advection of latent heat flux towards the upward branches. The streets have multiple warm plumes that promote a connection between the rolls. These spatial patterns allow fundamental insights on the interpretation of the Amazon exchanges between surface and atmosphere with important consequences for the climate change understanding.

Keywords Caxiuanã · COBRA-PARA · Latent flux · LES · Roll vortices

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Introduction

In recent years, several instrumented meteorological towers were deployed over the Amazon basin for monitoring fluxes of heat, moisture, carbon along with several other meteorological parameters. One of the greatest questions is to understand how the Amazon exchanges carbon and water with the environment (Ometto et al. 2005). The real picture of carbon balance of this region is still under debate. Some studies suggest moderate carbon sink (Grace et al. 1995), large forest carbon uptake (Araujo et al. 2002; Carswell et al. 2002), and even possible neutral carbon balance which could be explained by the river flux evasions (Richey et al. 2002). Furthermore, there is a consensus that carbon fluxes have a strong relationship with climatic conditions, soil nutrients and local environmental conditions (Davidson and Artaxo 2004).

Since clouds are important on controlling solar and thermal radiation reaching the surface, cloud streets may be fundamental to the surface energy balance and to the surface carbon and water budget in the Amazon. Furthermore, the presence of the roll vortices seems to organize local fluxes of heat, moisture and momentum (Le Mone 1976) with potential implications on the fluxes of the carbon and water vapor.

Cloud streets are quasi-two-dimensional lines of cumulus clouds that are produced by the combination of steady wind shear and buoyant fluid parcels rising from the surface (Etling and Brown 1993; Weckwerth et al. 1997). These coherent structures are observed in several regions of the globe, such as under cold air outbreaks over the Greenland Sea (Chlond 1992), coastal areas of Florida (Dailey and Fovel 1999; Weckwerth et al. 1999), over the Michigan Lake (Young et al. 2002; Kristovich et al. 1999), and over the Arctic (Brummer 1999). The observed clouds form over the upward branch of rotors that function to transport warm moist air in its upward branch and drier air in its downward branch. The existence of those roll vortices and cloud streets was previously predicted by the use of boundary layer models (Brown 1970), and have been modeled with cloud resolving models (Dailey and Fovel 1999; Liu et al. 2004), and Large Eddy Simulations [LES] (Chlond 1992; Glendening 2000).

In the tropical Amazon this phenomena occurs throughout over the year due to the presence of two mechanisms: the steady easterly trade winds and the moist convection caused by the strong solar radiation reaching the surface and the surface fluxes of sensible and latent heat. Figure 1 shows six snapshot satellite images for the years 2004–2009 of Moderate Resolution Imaging Spectroradiometer (MODIS) TERRA Satellite for the eastern Amazon region for early November around 14:00 UTC (11:00 LT). The images show the presence of cloud streets that can be seen aligned with the northeasterly predominant boundary layer trade winds for all the cases. This quasi-two-dimensional cloud pattern shows the locations where moist hot air rises forming the clouds. Although these images show cloud streets in the eastern Amazon for November, this phenomena occurs during other periods of the year and over other regions of the Amazon.

Figure 2 shows a TERRA Satellite image for 07 November 2006 around 14:00 UTC. The estimated distance between the streets is about 3.3 km, which is comparable to other observations taken world-wide (Young et al. 2002). Further analysis of these pictures reveals that the cooler water surfaces inhibit cloud formation mainly at the center of the domain over the Caxiuanã Bay, at the west over the Xingu River, and at the north over the Amazon River. This is caused by the subsidence associated with the local circulations (Silva Dias et al. 2004). The image shows also that water surfaces can function to anchor the location of several cloud streets. At the time the above image was obtained, a field campaign was taking place in the Caxiuanã Reserve Forest. This field experiment named Caxiuanã Observations in the Biosphere River and Atmosphere in the Pará state (COBRA-PARA) collected meteorological and hydrological data to understand the local meso- and micro-scale processes. During this campaign atmospheric profiles, water and air samples, and instrumented tower data were collected.

The aim of this study is to understand the physical mechanisms associated with the formation of cloud streets over the Amazon and to better understand the effect of those patterns of the flux exchange between the surface and the boundary layer.

COBRA-pará field campaign

During the COBRA-PARA a series of meteorological, hydrological, and aerological instruments were deployed in the Brazilian Forest Reserve of Caxiuanã. This nearly pristine forest is located in the state of Pará (Brazil), about 350 km inland (Andreae et al. 2002). The campaign occurred between 30 October and 15 November 2006. Vaisalla radiosondes were launched from a clearing in the middle of the forest and atmospheric profiles were obtained every 3 h for the period between 06 and 12 November corresponding to a total of 60 soundings. Figure 3 presents the wind profiles and estimated boundary layer height observed during 07 November 2006. It shows the predominant northeasterly trade wind over most of the boundary layer. Around 600 m a northeasterly

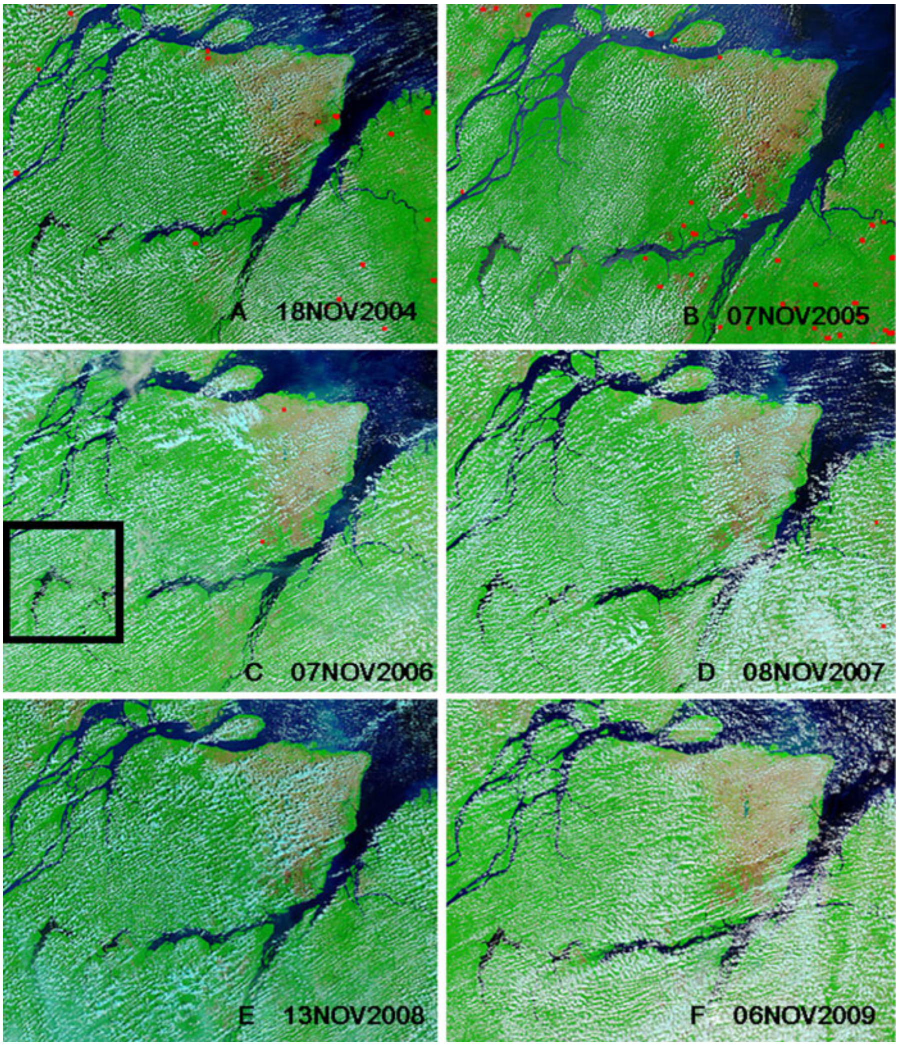


Fig. 1 MODIS Terra satellite image, snapshots for years 2004–2009. The *box* in **c** highlights the Caxiuanã Bay and the Reserve Forest where the COBRA-PARA field campaign was conducted. Image courtesy of MODIS Rapid Response Project at NASA/GSFC. Data available at rapidfire.sci.gsfc.nasa.gov

low level jet with speed on the order of 14 ms^{-1} is noticed during the night time and the early hours of the day, but weakens in the afternoon. At the low levels ($\sim$200 m) a southeast component is observed, producing a directional wind shear in the boundary layer. The estimated shear below 200 m was 0.048, 0.050, 0.042, 0.028, 0.018, and 0.021 s^{-1}, for 03:00, 06:00, 09:00, 12:00, 15:00 and 18:00 UTC, respectively. These soundings show that the directional and intensity of near-surface wind shear reaches its minimum around noon time (15:00 UTC), when the boundary layer reached its maximum height of about 1000 m.

Cloud streets can be characterized by their aspect ratio defined as the ratio between the streets wavelength and the boundary layer height (Young et al. 2002). Based on the satellite image (Fig. 2) and considering a measured boundary layer height of about 950 m at around 14:00 UTC, the estimated aspect ratio of these Amazonian cloud streets is about of 3.5.

Numerical modeling design

To better understand the cloud streets dynamics over the Caxiuanã Reserve region, the Regional

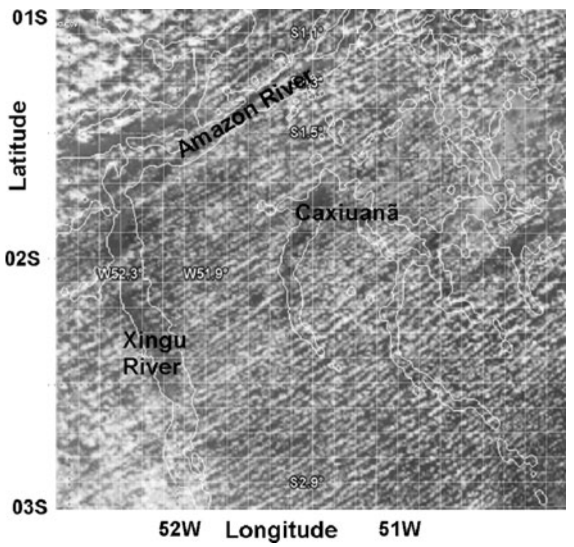


Fig. 2 MODIS Terra satellite image, 07 November 2006, 14:00 UTC. The distance between the cloud streets is about 3.3 km. Image courtesy of MODIS Rapid Response Project at NASA/GSFC. Data available at rapidfire.sci.gsfc.nasa.gov

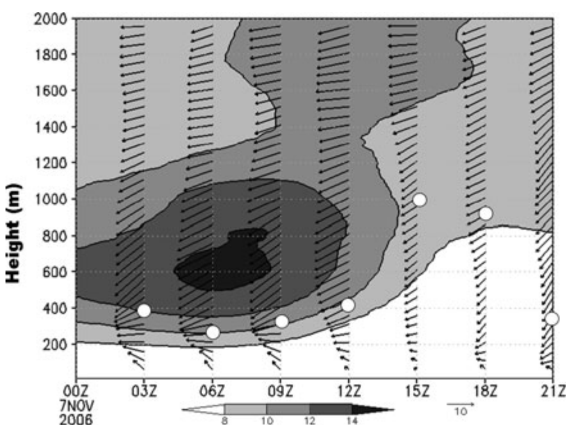


Fig. 3 Horizontal wind profile obtained from radiosondes during the COBRA-PARA field campaign for 07 November 2006 at latitude 1.74S and longitude 51.46W. The size of the vector represents the magnitude and the inclination the wind direction. The shaded areas represent the wind speed (ms^{-1}) and the white balls represent the estimated boundary layer height (m)

Atmospheric Modeling System (RAMS) model (Cotton et al. 2003) version 6.0 is used together with data collected during the COBRA-PARA field experiment. RAMS is a three dimensional model that solves the Navier–Stokes equations using the finite difference approach on an Arakawa-C type of grid. The model consists of several interacting sub-models that simulate the atmosphere dynamics, the soil–vegetation–atmosphere exchange of heat and moisture (Walko et al. 1995, 2000a), the surface layer turbulent processes (Louis 1979), the boundary layer turbulent processes (Mellor and Yamada 1974; Deardorff 1980), the solar and thermal radiation transfer and its interactions with the hydrometeors (Harrington 1997), and cloud microphysics and precipitation (Walko et al. 2000b). RAMS was used recently in several studies to understand the Amazon region clouds formation and rainfall (Ramos da Silva and Avissar 2006; Baidya Roy and Avissar 2002; Silva Dias et al. 2002), and on the impacts of land-cover change (Ramos da Silva et al. 2008; Gandu et al. 2004).

In this study, the model was set up with a nesting grid approach with a coarse grid covering nearly the same domain shown in the satellite image (Fig. 2). Initially, a coarse grid was designed as having a total of 250 × 250 grid points in the horizontal with grid cells spaced by 1.2 km (Fig. 4). This domain is adopted because it represents the major land surface characteristics, their interactions with the atmosphere, and it has enough resolution to simulate the major mesoscale meteorological processes observed in the area. In the vertical, the model was set up with a total of 35 layers having higher resolution near the ground surface. The layers are stretched vertically starting with a size of 50 m and reaching a maximum size of 800 m at the top of the model. Then, a second grid was nested in the coarse grid having 200 × 200 grid cells spaced by 400 meters to better represent the dynamics of the cloud streets. For grids 1 and 2 the Mellor and Yamada (1974) turbulent fluxes parametrization was adopted. Finally, a third grid was set up nested in the second grid with Large Eddy Simulation (LES) capability having 200 × 200 grid cells spaced by 100 meters (Fig. 4). The LES grid domain set up adopt the Deardorff (1980) parametrization for the turbulent fluxes, which is more suitable for the very high resolution simulations.

Two surface types were adopted for the modeling domain, the broadleaf evergreen forest and water surfaces. The parameters used in the vegetation characterization in the soil-vegetation model parametrization were adopted according to previous modeling tests performed for the Amazon region (Ramos da Silva and Avissar 2006). The water temperature

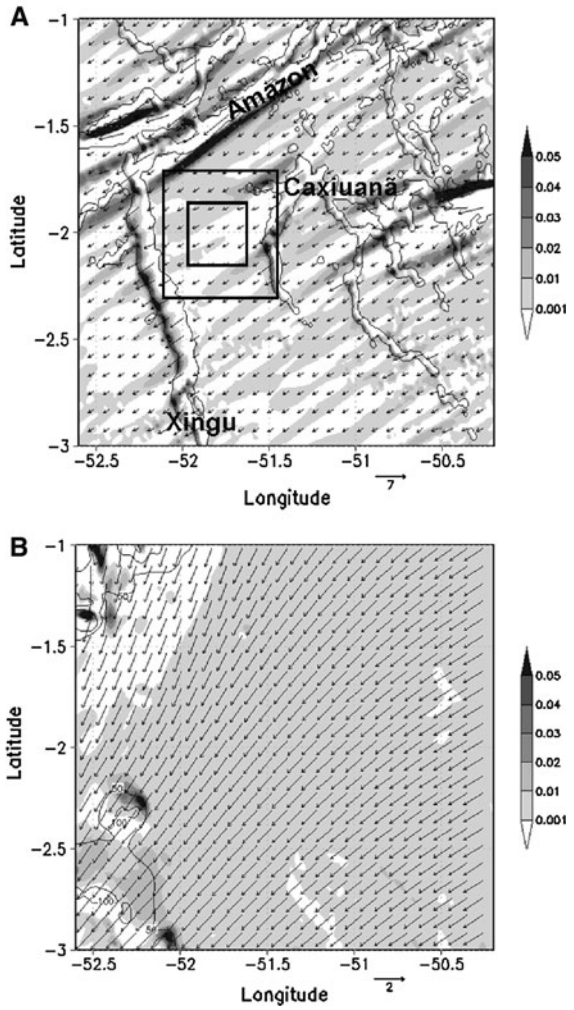


Fig. 4 RAMS model grid domains, simulated vertical velocity at 270 meters height (ms^{-1}) and surface wind vectors for 07 November 2006 at 14:30 UTC. The contour lines represent the interface between forest and surface water. The wind vectors are skipped every 10 grid points for clarity

for lakes and rivers were set at 31°C, based on local measurements obtained during the COBRA-PARA field campaign. The soil texture was assumed to be sandy clay loam, which represents the predominant soil type for the region (Andreae et al. 2002). The model is initialized with homogeneous layers from an atmospheric radiosounding obtained during the COBRA-Pará field campaign for 07 November 2006, at 09:00 UTC (Fig. 3), which is the same day of the retrieved satellite image shown in Fig. 2. This day was chosen, due to the absence of large scale perturbations, as representative of a typical day in the Amazon. At that moment, a northeasterly low level jet was acting over the region (Fig. 3) that may have an influence on the cloud streets observed from the satellite image (Fig. 2). A time step of 10 s was used for the numerical integration and the simulation lasted 12 h representing the growth of the convective boundary layer.

Model results

Figure 4 shows the RAMS results obtained with the coarse grid at 14:30 UTC for vertical motion at the height of 270 meters and the surface wind vectors. The results reveal that the surface heterogeneity is very important for the onset and location of the warm plumes and roll vortices. The onset of convection at the boundaries between the forest and the rivers are the major location for the warm elongated plumes formation (Fig. 4a). This process is well represented mainly in the borders of the Xingu River located in the west region of the domain. The large water surfaces anchors the location of the elongated warm plumes producing quasi-predictable spatial patterns. This feature is well represented in the northwest region near the Amazon River where the river boundaries coincides with the direction of the north-easterly trade wind flow. The surface wind vectors converge at the warm plumes producing horizontal roll vortices parallel to the wind direction. A further simulation (Fig. 4b) with identical set up but imposing a homogeneous forest surface boundary without rivers and lakes produced a wind flow without the presence of warm plumes and convection.

Composite maps obtained from hourly vertical velocity (at 270 m height) snapshots between 13:00 and 17:00 UTC reveals that cloud streets are produced over preferable locations (Fig. 5). The surface heterogeneity has important role on their distribution. Cooler advected air from water surfaces inhibits the stronger vertical motion and cloud formation. This feature is observed west of the water surfaces due to the advection produced by the easterly trade winds and is well captured by the high resolution grid located at the west side of the Caxiuanã Bay (Fig. 5b). These results reveal also important mesoscale influence on the local micro-scale processes.

The cloud streets have life-time stages that correspond to formation, maturation and dissipation. Fig. 6

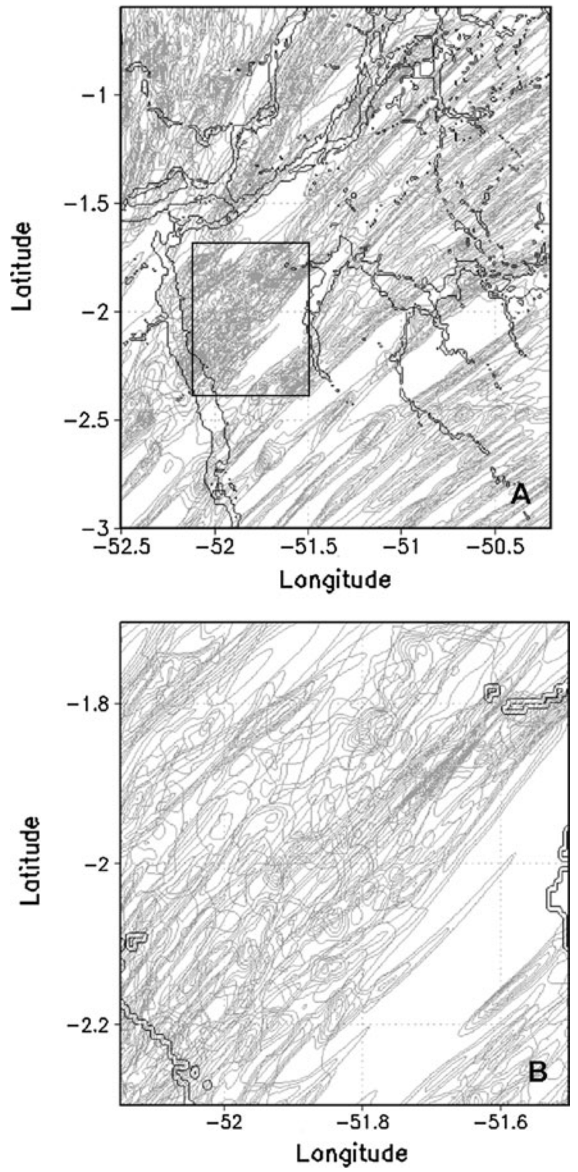


Fig. 5 Model results for cloud fraction combined from snapshots for 07 November 2006 at 13:00, 14:00, 15:00, 16:00 and 17:00 UTC obtained with contours greater than 0.2, for **a** grid 01 and **b** grid 2. The *black contour lines* represent the interfaces between forest and water surfaces

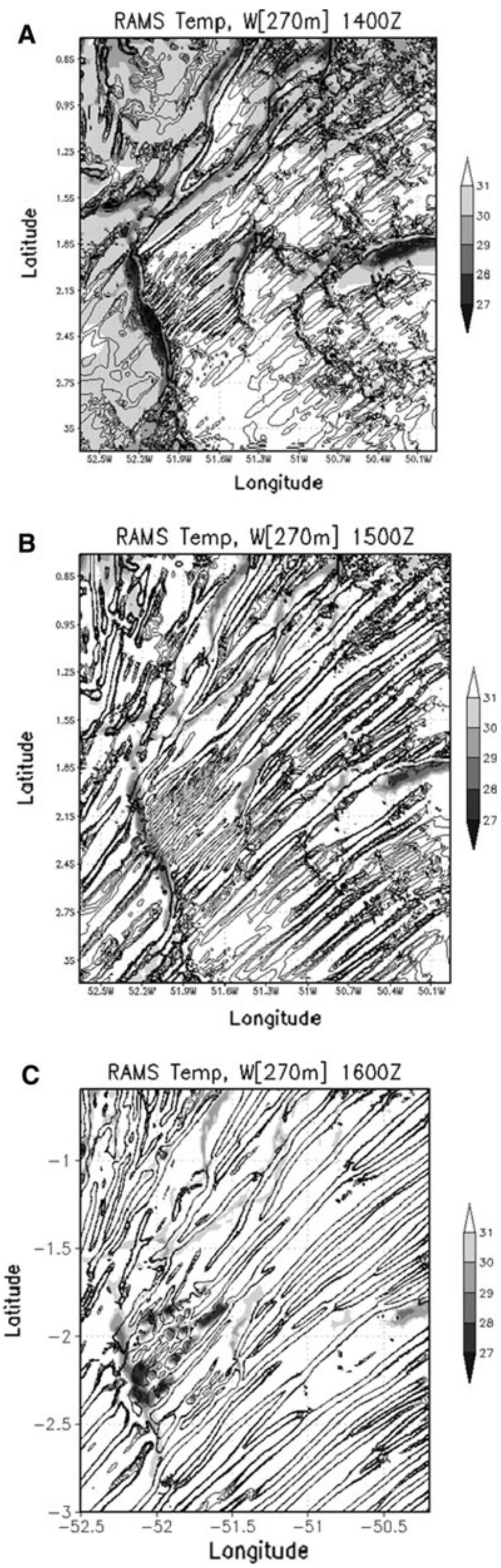
shows that the formation occurs at around 14:00 UTC. At this stage, the combination between the trade winds and local convection are important physical processes for production. Around 15:00 UTC the streets are in their maximum activity (Fig. 6b). This stage is represented by the well established streets of strong upward vertical motion. The observed soundings reveal that at this time the boundary layer height reaches its maximum and the wind shear reaches its minimum (Fig. 3). Around 16:00 UTC strong convection induces to the streets dissipation (Fig. 6c). These stages are better captured with the simulation performed with grid 2 that shows the transition from a quasi-two-dimensional convection pattern to formation of closed cells (Fig. 7).

The high resolution Large Eddy Simulation (LES) shows that the cloud streets have multiple warm upward plumes (Fig. 8a). This feature was also detected in the rolls observed during the winter cold air outbreak in the Arctic (Brummer 1999). Furthermore, several plumes act to promote a connection between the neighboring cloud streets. The presence of the streets causes advection of turbulent latent heat flux towards the upward branches of the row (Fig. 8b). This lateral advection has important implications for the surface flux estimates.

Discussion and final remarks

The new high resolution satellite images obtained from the MODIS sensor onboard Terra satellite is providing clear evidence of the presence of cloud streets in the Amazon all through the year. Analysis of those images shows that large rivers are important to the spatial cloud cover mainly through river breezes that create clear sky and subsiding circulations over the river surfaces, and through anchoring the cloud streets. These features shows up well at the Caxiuanã region where cloud streets occur aligned with the Amazon River and the Caxiuanã Bay and are absent over the cooler surface waters. The estimated distance between the cloud streets is about 3.3 km, which is comparable to other observations taken overland, but is less than the ones observed from the cold air outbreaks over warm water (Young et al. 2002; Chlond 1992).

A cloud resolving simulation for the Caxiuanã region reveals that the Amazonian surface heterogeneity produced by the presence of forest and rivers are fundamental to the onset and evolution of the convection and cloud streets. The daytime local circulations caused by the river-forest boundaries sets the location of the first warm plumes and convective cells. This interaction between the river-forest circulations and the roll vortices is similar to the cloud streets observed by radar during the Convection and



◀**Fig. 6** RAMS model grid 01 surface temperature (°C), vertical upward velocity at 270 m for 07 November 2006 at **a** 14:00 UTC, **b** 15:00 UTC, and **c** 16:00 UTC

Precipitation/Eletrification (CaPE) Experiment along the sea-breeze fronts (Atkins et al. 1995) and cloud resolving model results for the coastal regions (Dailey and Fovell 1999). During the LBA campaign in the state of Rondonia (Brazil) it was found that the local initiation of convective clouds occurred preferentially over high elevations (Laurent et al. 2002) and at the interfaces of forest-pasture deforested regions (Baidya Roy 2009). Here, we show that in the eastern Amazon, the initiation of those clouds occur preferentially over the upward branches of the roll vortices forming cloud streets. The warm plumes interact with the trade winds vertical shear producing the cloud streets parallel to the mean wind flow. River edges that coincide with the northeasterly trade winds are favored to develop the atmospheric streets along the flow.

Figure 9 shows simulated vertical velocity representing streets aligned with the Amazon River. The surface wind flow has components that cross the river boundaries towards the streets. Figure 10 shows an illustration of the interaction between cloud streets and the land–water surfaces. Since the rivers are stationary, they anchor the streets producing a quasi-stationary horizontal spatial cloud pattern. The anchoring of the cloud streets is fundamental for understanding the Amazon functioning.

The observed cloud streets aspect ratio of 3.5 is comparable to other estimates overland that is about 3.2 (Young et al. 2002). The combination of satellite data, radiosondes and high resolution modeling shows that the streets reach the maximum activity around 15:00 UTC (i. e. noon time), when the boundary layer reaches its maximum height. It shows that surface flux of heat and moisture has fundamental importance on the streets formation. Thus, the surface heterogeneity is fundamental to set the most likely regions for cloud street formation. More stable cooler near-surface boundary layer inhibits the streets formation. The maximum activity occurs when the wind shear reaches its minimum and little directional shear. This characteristic of the Amazonian streets are different from the streets observed in the Lake Michigan where the rolls form after increases in the

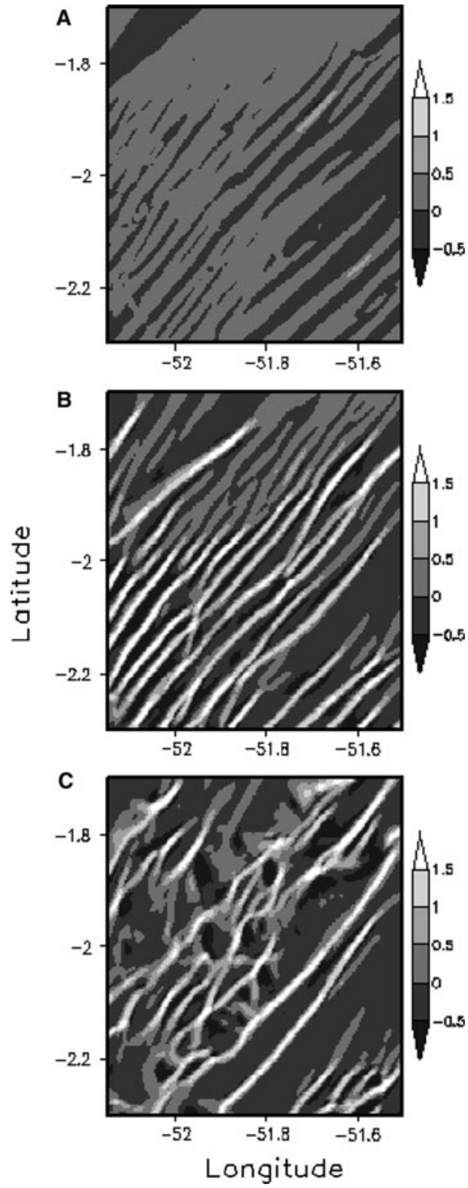


Fig. 7 RAMS model results from grid 2 for vertical motion at 270 m for 07 November 2006 at **a** 14:00, **b** 15:00 and **c** 16:00 UTC

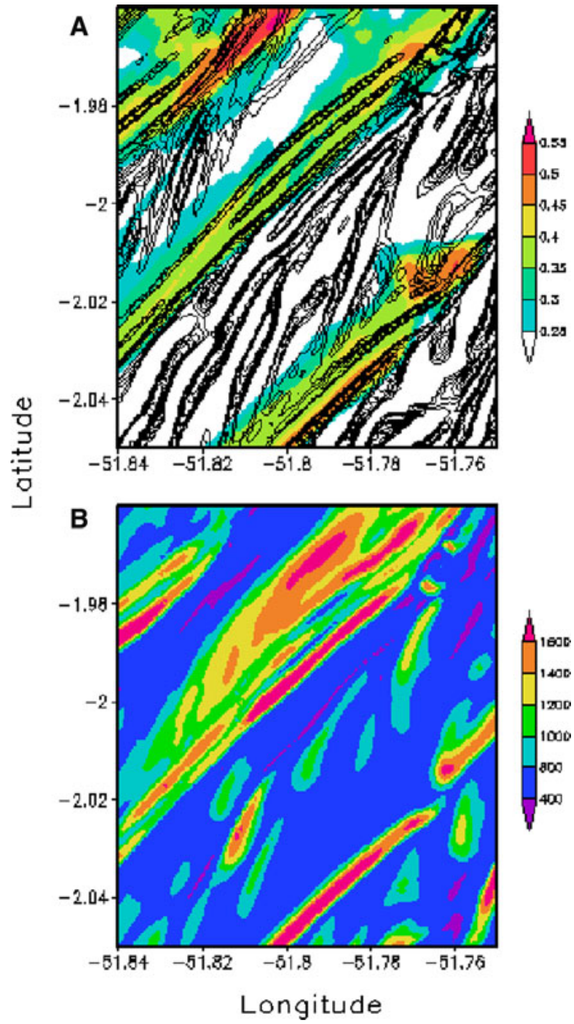


Fig. 8 RAMS LES (Large Eddy Simulation) results for 07 November 2006 at 14:25 UTC for **a** cloud fraction (*shaded*) and vertical motion (*contour lines*), and **b** Latent heat fluxes

low-level wind speed (Kristovich et al. 1999), but is similar to observations in the east-center Florida and during the CaPE Project that shows an optimal combination of wind shear and buoyancy (Weckwerth et al. 1997, 1999).

The roll vortices re-organize the turbulent fluxes through advection causing higher surface-atmosphere transfer at the upward branch. For instance, latent heat fluxes are higher over the upward region of the roll vortices. Other fluxes, such as carbon, heat and momentum, should be strongly controlled by these vortices. This type of turbulence flux redistribution was also detected over the Lake Michigan by data collected from airplanes (Le Mone 1976, Le Mone and Pennell 1976). This type of fluxes redistribution should also affect the Amazonian instrumented tower fluxes and other in situ measurements. For example, a tower located under an upward branch of a quasi-stationary roll vortex may provide very different surface flux as compared to another located at the downward branch. Furthermore, data collected over water surfaces (e.g. rivers and lakes) should be interpreted through the presence of cloud streets.

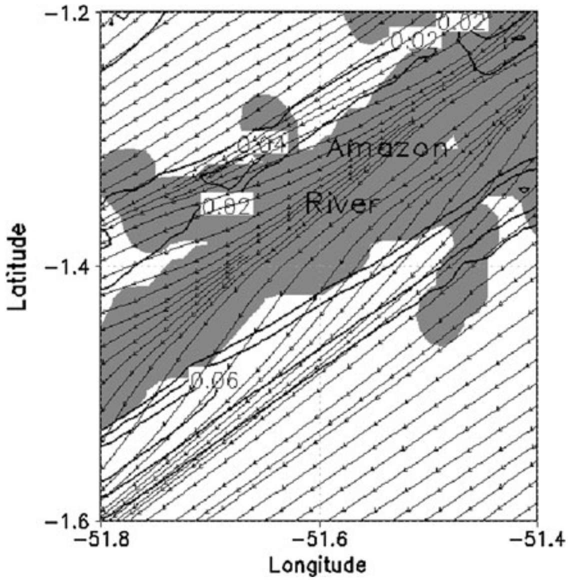


Fig. 9 RAMS model surface wind streamlines sub-set from Fig. 4a near the Amazon River for 07 November 2006 at 14:30 UTC. The contour lines over land represent vertical velocity (ms^{-1}) at 270 meters height

Thus, this numerical experiment highlights important spatial features that help on interpretation of the ongoing fluxes measurements.

In this study, we focused on a well documented case that was observed during the COBRA-PARA field campaign in Caxiuanã region. Other studies should explore different synoptic conditions. However, these conclusions can be generalized based on the available satellite data that provides similar behavior during other times of the year and locations. Thus, the interpretation performed in this study for Caxiuanã can be extended to other regions of the Amazon, improving the overall picture of its functioning. Furthermore, there is still room for new studies and would be important to produce a climatology of cloud streets for the Amazon.

The presence of those cloud streets can affect not only the climate variables, but can also affect the local ecosystem. For example, vegetation located under quasi-stationary cloud streets receives less solar radiation affecting the local photosynthesis and perhaps the vegetation growth, biomass production, carbon uptake, and species distribution. Furthermore, the quasi-stationary streets are likely to influence the local habitat dynamics, such as the insects and birds traveling. Thus the knowledge of these land–atmosphere streets can help on the Amazon monitoring and on the possible reserve boundaries settings to provide sustainable bio-diverse corridors.

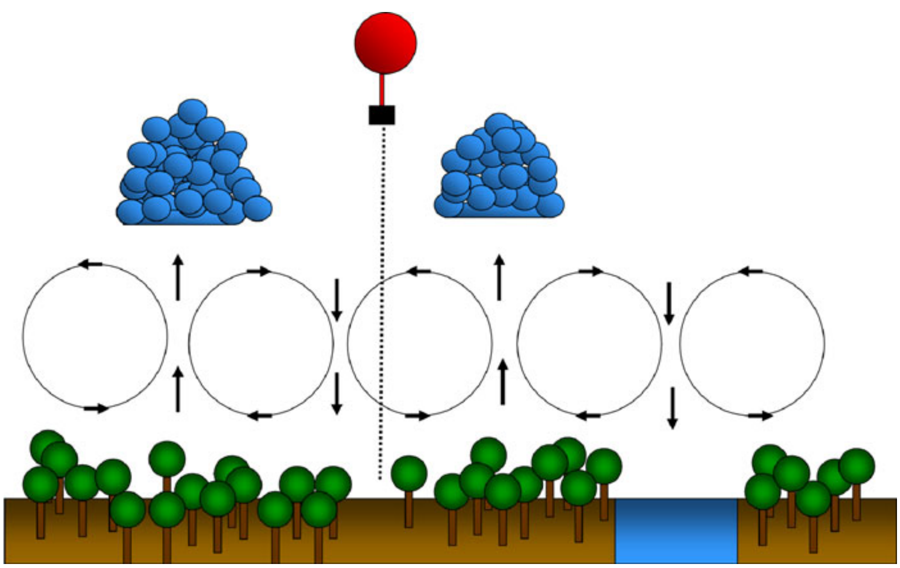


Fig. 10 Illustration of the Amazon cloud streets, the land–water interfaces and the effects of the river breeze circulations on the streets and its likely influence on local measurements such as atmospheric radiosondes

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