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Seasonal and diurnal variability of convection over the Amazonia: A comparison of different vegetation types and large scale forcing

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With 8 Figures

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Summary

A climatological description of the convection over Amazonia is based on the seasonal and diurnal cycle analysis. Long series of observations are used from four sites: two sites are representative of dense rainforest, either continental (Manaus) or coastal (Belém); one site is in southeast Amazonia, in a region of ecological tension where forest has been partly replaced by pasture (Vilhena); and finally, one is in the south of Amazonia, in a region typical of savanna (Brasília). Each site has a long series of radiosonde and surface observations. Other parameters are also used: rainfall averaged from the raingauges in the vicinity of each site; vegetation monitored using NDVI averaged over 128 km $\times$ 128 km boxes centred on each site; and total and high cloud cover estimated using the 2.5° $\times$ 2.5° ISCCP products derived from satellite data. It is shown that the main differences between rainforest and savanna or deforested sites occur in the dry season, whereas the magnitude and diurnal cycle of convection as well as amount of rainfall and NDVI are quite similar during the wet season. For the savanna site the seasonal variation is well defined for every parameter, whereas for rainforest sites the vegetation and atmospheric thermodynamics show very weak seasonal variations, yet driving significant diurnal variations of the convection and precipitation. The transition season from dry to wet and the beginning of the wet season is generally the period of strongest intensity of convection.

1. Introduction

The most remarkable characteristic of tropical convection is the diurnal and seasonal variability of convective activity and hence of cloud cover. Knowledge of this diurnal and seasonal convective activity and cloud cover is essential if we are to understand the large scale and mesoscale circulation patterns and the radiation forcing on the Earth's radiation balance.

Fisch and Nobre (1998) present a general description of Amazonian climate, pointing out the paleoclimate, the characteristics of rainfall and field observations of atmospheric phenomena. Molion (1993), studying the large scale and mesoscale circulations in Amazonia depicts the following main convective mechanisms acting in Amazonia: diurnal convection, squall lines and the organized convective systems associated with the penetration of cold fronts from the South that interact with tropical convection.

Machado et al. (2002), working with the LBA Wet Season Atmospheric Mesoscale campaign (WETAMC/LBA) dataset, show that in southeast Amazonia the minimum cloud cover occurs only a few hours before the maximum precipitation in the early afternoon, whereas maximum cloud cover occurs during the night. They found, for the region of the state of Rondônia, a large lag between the maximum convective cloud cover in the afternoon, and the maximum total cloud cover occurring during the night. Betts et al. (2002), using the same dataset, study the diurnal cycle of surface temperature and humidity, lifting condensation level and surface fluxes; they found a clear diurnal modulation of the surface fluxes with maximum fluxes in the early afternoon. They also found a trend toward a cooler and wetter sub-cloud layer as the rainy season progressed. Silva Dias and Bonatti (1985) examining the diurnal variation of tropical South America using a numerical weather model, show a tropical troposphere response to diurnal forcing in Amazonia. Betts and Jakob (2002) show that the onset of precipitation in the ECMWF forecast model was earlier than observed, because the morning development of the shallow cumulus layer was not properly represented. Using rainfall data, Kousky (1980) shows that the diurnal cycle of precipitation over northeastern Brazil is very dependent on the season. He also shows that the diurnal cycle of convective cloudiness is related to the activity of squall lines generated by the coastal sea breeze. Meisner and Arkin (1987) using geostationary satellite data show the importance of the sea breeze in the cloud cover, local maximum, diurnal variance near coastal regions. Garreaud and Wallace (1997) suggest that the maximum cloud cover in the central Amazonian diurnal cycle is related to the reactivation of the landward propagating coastal squall lines.

Garstang et al. (1994) classified the convective system during ABLE-2B as: coastal occurring systems – squall lines with lengths of up to 3500 km; basin occurring systems – meso to synoptic scale systems ranging in area from 1000 to 100000 km^2 and local occurring systems – smaller convective systems with an area smaller than 1000 km^2. Cohen et al. (1995) point out that the squall line activity and its relation with the sea breeze is important for the total precipitation over the rainforest of central Amazonia.

Horel et al. (1989) and Hastenrath (1997) describe the annual cycle of the convective activity over Amazonia using outgoing longwave radiation and numerical weather analyses. They describe the seasonal migration of convective activity in the South American continent and the associated upper troposphere general circulation.

Williams et al. (2002) show that, in the south of Amazonia, large convective available potential energy (CAPE) values are mainly found during the dry to wet transition season rather than during the wet one. They suggest that the transition season has more intense convection than the wet season. Durieux et al. (2003), using three pairs of deforested and forested areas at a climate model grid scale, compare changes in land cover with changes in cloudiness. They found significant changes in cloud cover pattern over deforested areas at the seasonal and diurnal time scales. During the dry season they observed more shallow cumulus clouds in the early afternoon and less convective clouds at night and in the early morning over deforested areas, while during the wet season, convection is stronger in the early night over deforested areas.

The aim of the present study is to give an integrated description of the diurnal and seasonal variability of total and convective cloud cover over Amazonia, as well as their relationships with the atmospheric thermodynamics and the vegetation types. Using long climatological datasets over four selected regions, a robust climatology of the surface and atmospheric parameters is presented. The impact of the different vegetation types and the large scale forcing in the convective variability at seasonal and diurnal time scales is discussed.

Section 2 describes the data used and Section 3 presents the results describing the diurnal and seasonal fluctuations of the cloud cover, thermodynamic variables, surface observations and vegetation index. Section 4 summarizes the main results.

2. Data

The positions of the radiosonde and surface stations used in this study is shown in Fig. 1. This figure also shows the vegetation map of Brazil (adapted from IBGE/IBDF, 1988) at the scale of 1:5,000,000. It has been categorised here into five main classes: dense and open rainforest,

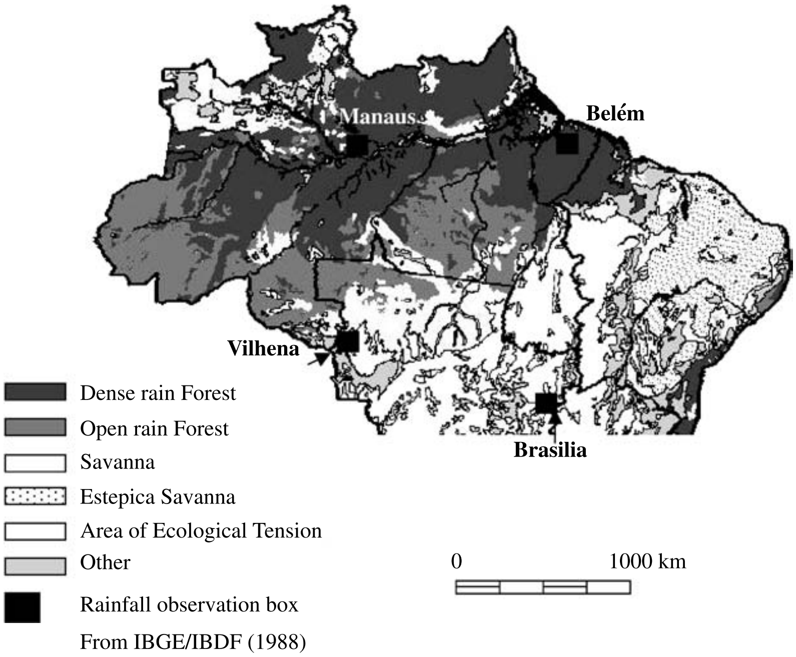


Fig. 1. Brazilian dominant vegetation types (adapted from Instituto Brasileiro de Geografia e Estatística) and location of the sites used in the study. The squares represent the regions used for NDVI and rainfall analyses

savanna, estepica savanna, and areas of ecological tension. The difference between open and dense rainforest is that open rainforest has less biodiversity than the dense rainforest, its canopy is lower and the tree density is less. Manaus station (03.15° S–59.98° W) is located in a region typical of continental dense rainforest. Belém station (01.38° S–48.48° W) is also located in dense rainforest; however it is on the coast and is strongly influenced by the Atlantic Ocean. The estepica savanna characteristic of the semi-arid northeast of Brazil is not studied here. Vilhena station (12.73° S–60.13° W) is in a region classified as an area of ecological tension. The areas of ecological tension correspond to the contacts between two or more vegetation types, here forest and savanna. This area is also in a highly deforested region, along the so-called arc of deforestation. The savanna composed of medium to tall plants is characteristic of the central Brazil region and is also the vegetation type that replaces the forest after deforestation. Brasília station (15.87° S–47.93° W) has been selected because this region is representative of savanna. However, although Brasília is close to the edge of the hydrological Amazon Basin it is located outside the humid tropical zone generally associated with Amazonia. One must therefore be careful when comparing Brasília with the other Amazonian sites because the large scale forcing is different from that in the equatorial region.

2.1 Radiosonde, surface observations and rainfall data

The radiosonde and surface observation data were obtained from the Brazilian Air Force meteorological stations of Belém, Manaus, Brasília and Vilhena. The data are in digital form, archived in a relational database prepared by the Centro Técnico Aeroespacial. After being digitised the data were quality controlled, following the standard WMO recommendations, using several reasonability tests, which include limit check, internal consistency, physical, horizontal, vertical, and time consistency (Filippov, 1968; Abbot, 1986). The surface observation used in this study is the present weather, i.e. a subjective report of the main phenomena taking place in the vicinity of the weather station at the time of the surface observation. This observation ranges from 0 (nothing to inform) to 9 (hail). The rain observation, hereafter called a rain event, and lightning, thunder and hail, hereafter referred to as a thunderstorm event, were used in this study.

The radiosoundings used in the analysis were those released at 12:00 UTC (i.e. 09:00 LST for Brasília and Belém and 08:00 LST for Manaus and Vilhena), over the period from 1968 to 1990. The surface observations were collected each hour from 1968 to 1991 for Manaus, from 1968 to 1990 for Belém, from 1968 to 1980 and from 1984 to 1987 for Brasília and from 1971 to 1990 for Vilhena. Manaus, Belém and Brasília operated 24 hours/day but Vilhena, at this time, only from 06:00 to 17:00 LST.

Monthly rainfall data were provided by the Agência Nacional de Energia Eléctrica. The rainfall data have been quality controlled and have been homogenised by the method described by Hiez et al. (1992). Climatic values are computed here for the period 1977–1999 (see Ronchail et al., 2002 for a detailed description). In order to estimate rainfall at a spatial scale consistent with the other datasets (see also Section 2.2), raingauge data have been averaged over an area of 128 km × 128 km centred on each site. The number of available raingauges is 5 for Belém, 4 for Manaus and Vilhena and 3 for Brasília.

2.2 Satellite data

Different parameters derived from satellite data have been used. This work combines data with different spatial resolutions which are difficult to overlay spatially. For example, radiosounding and surface observations are a local measurement but the World Meteorological Organization considers them to be representative of a 250 km and 150 km radius respectively. Of course this definition is subjective and qualitative, as it is very difficult to determine the spatial coverage of a radiosonde flight, mainly due to height-spatial scale dependence. The surface observation is also a local measurement but the weather observation used in this study is representative of the observer's field of view. Thus, the option taken in this work was to use the data as temporal series of parameters nearly at the same spatial scale of about 128 km, ranging from the surface observation (of spatial scale around 40 km) to ISCCP data of 280 km.

2.2.1 Cloud cover and high cloud fraction

The time series of cloud cover and high cloud fraction were obtained from the International Satellite Cloud Climatology Project (ISCCP). The ISCCP is an effort to reduce, calibrate and uniformly format geostationary weather satellite data for climate studies. The gridded cloud product, called the C1 dataset, consists of a set of cloud statistics derived from satellite measured radiance, compiled every 3 hours on an equal-area grid at a spatial resolution of 280 km (Schiffer and Rossow, 1983). The cloud cover, available directly from the ISCCP dataset, is based on a cloud classification and a radiative transfer calculation. The high cloud fraction is obtained from the corrected cloud top pressure. It is calculated as the ratio between the number of cloudy pixels with top pressure lower than 310 hPa and the total number of pixels in the grid. This pressure level was defined to select the high cloud cover as a proxy for the clouds related to the convective activity. This dataset was used for the period from July 1983 to December 1993.

2.2.2 Normalized Difference Vegetation Index (NDVI)

The remote sensing dataset used in this study is a 15-day composite NDVI dataset covering the period from July 1981 to December 1999. It is provided by the Global Inventory Monitoring and Modelling Studies (GIMMS) Group at National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC). The NDVI is calculated as the normalised difference of corrected reflectance of the near infrared and visible channels using AVHRR GAC (Global Area Coverage, 4 km resolution) data from Channels 1 and 2 onboard the NOAA satellite series (NOAA 7, 9, 11 and 14). The spatial resolution is resampled to 8 × 8 km pixel. The NDVI GIMMS dataset takes into account, the improvement of the navigation (Rosborough et al., 1994), and the calibration of visible and NIR channels (Vermote and Kaufman, 1995), improved by the method of sensor degradation correction of Los (1998). This dataset is corrected for the effects of stratospheric aerosol, resulting from volcanic eruptions, by the method developed by Vermote and El Saleous (1994).

For each pixel, monthly data have been calculated by taking the maximum NDVI value of the two 15-day composites of every month. An additional quality control was applied to the NDVI dataset to filter out some persistent, unrealistic values (Dessay et al., 2003). A spatial scale of 128 km × 128 km has been chosen, as a compromise between large-scale atmospheric features measured by radiosonde and cloud data and homogeneous neighbouring vegetation as depicted by NDVI data. Therefore the vegetation variations at each site are estimated as the average of 16 × 16 NDVI pixels centred on the radiosonde station.

2.2.3 Synoptic convective perturbations

Using ISCCP C1 data with a spatial resolution of 280 km it is not possible to observe individual mesoscale convective clouds. Rather one can use these data to identify the areas where large amounts of organised convective clouds concentrate, such as cold fronts, persistent parts of the ITCZ (Inter Tropical Convergence Zone), large squall lines or cloud clusters associated with synoptic scale disturbances. These areas are here identified as ISCCP grid cells with a mean brightness temperature of 260 K or less. Indeed this condition can be fulfilled if there are some very high cloud tops in the grid cell (localized deep convection), or if there is a large amount of moderately high cloud tops (large scale disturbance). In both cases the area is considered as convectively active. The contiguous grid cells identified as convectively active define clusters that are then tracked over successive 3-hourly data with the method developed by Machado et al. (1998). The temperature threshold is close to the threshold of 258 K used by Hodges and Thorncroft (1997) to track synoptic perturbation from smoothed ISCCP B2 data at 150 km resolution.

3. Results

3.1 The seasonal cycle of rainfall, cloudiness and vegetation

Considering that there is a good relationship between precipitation and high cloud cover at a monthly scale in Amazonia and the sparse rainfall network in Amazonia, the high cloud cover was used to define the dry and wet seasons. The driest month was computed as the month of minimum high cloud cover. As a first step the rainy (dry) season was defined as the months when high cloud fraction is larger (smaller) than the average plus (minus) half the standard deviation. This definition, that does not include the absolute value makes it difficult to compare the dry season over different regions. Thus an additional criterion was introduced: the high cloud cover of a dry month should be smaller than 10%. This threshold was ajusted by comparison with the dry season charts from the Brazilian Institute of Geography and Statistics (IBGE) made using rainfall data and the dry season defined as by Gaussen and Bagnouls (1953). Our definition leads to a description of the dry season duration close to the IBGE estimate; the benefit is that the high cloud cover approach is simple and objective, and covers the full region avoiding extrapolations that may be spurious in the case of a few raingauge measurements. A lag up to one month can be observed between precipitation and high cloud cover in some places. Marengo et al. (2001) define the onset and end of the rainy season as the pentad in which rainfall exceeds (falls below) a given threshold; Kousky (1988) using pentad of Outgoing Longwave Radiation (OLR) data, presents another definition that qualitatively agrees with the Marengo et al. (2001) results. The descriptions of dry or wet seasons derived from these definitions agree reasonably well with the results obtained in this study.

The dry season duration and the driest month were computed to describe the spatial distribution of the seasonal cycle of convective activity over Amazonia. Figure 2(a) shows that July is the driest month for most of Brazil except for the north where it is in August or September. As the extreme north of Brazil is in the Northern Hemisphere, it is not surprising that the driest month is January in the region of the Roraima state. This pattern is well related to the seasonal movement of maximum solar irradiance, which drives the position of the ITCZ, the monsoon circulations and the position of the subtropical high pressures (Hasternrath, 1997). The importance of the interaction between the tropics and middle latitudes in the convective activity in Brazil is shown by Garreaud (2000), and Paegle and Mo (1997). The interaction between cold fronts and Amazonian convection forming the SACZ (South Atlantic Convergence Zone) and the northward and southward propagation of convection in Brazil is well established by Siqueira and Machado (2003). Regardless of

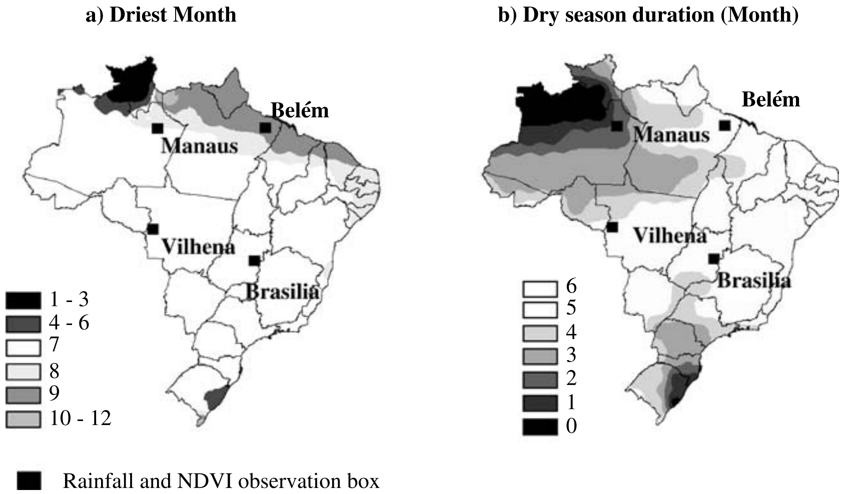


Fig. 2. **a**) Driest month (month of minimum high cloud cover) and **b**) dry season duration defined using high cloud cover

these complexities, the huge region in Brazil with the same seasonal phase as shown in Fig. 2(a) suggests that an integrated circulation between the tropics and middle latitudes is the main mechanism that drives the seasonal variations in the atmospheric circulation.

The dry season duration presents a different regional pattern. The northwest and south of Brazil have significant high cloud fraction occurrences throughout the year, leading to reduced dry season. The dry season duration is 2 months or less for the centre of Amazonia and 3 to 4 months for the south of Amazonia, Acre, some regions of Rondônia, the south of Pará and the northwest of Mato Grosso. The pattern in Fig. 2(b) shows the path of seasonal convective migration of the convective activity, as described by Horel et al. (1989). The northwest of Brazil is located in the middle of the two extreme positions of the path of seasonal migration of the convective activity and has almost no dry season. In the south of Brazil there is almost no dry season due to the cold front activity throughout the year (Siqueira and Machado, 2003). In the region dominated by the rainforest (see Fig. 1) the dry season duration is less than 4 months, with the exception of west–northwest Amazonia where the dry season duration is as large as over the regions covered by savanna. Whilst the vegetation cover may affect characteristics of convection, no conclusion can be presented at this stage because the data available do not allow the impact of the vegetation cover to be separated from the large scale atmospheric forcing.

The seasonal variations of cloud cover and high cloud fraction over tropical Brazil (not shown) present two distinct patterns. The cloudiness over the northwest tropics has a small amplitude and two maxima: the main one in April and a secondary one in October. This secondary maximum decreases from northwest to northeast Amazonia. In southeast Amazonia the cloudiness has larger seasonal amplitudes and a well-defined maximum around February. The seasonal amplitude increases from southwest to southeast Amazonia, as also shown by Fisch and Nobre (1998) using rainfall data.

The following analysis will focus on the four sites presented in the previous section. Figure 3 shows the seasonal variation of the total cloud cover and high cloud fraction for Belém, Manaus, Vilhena and Brasília. On average, Belém has 73% cloud cover during the rainy season and 30% during the dry season, Manaus has a smaller amplitude varying between 76% and 42%. The increased seasonal variations for the deforested region (Vilhena), even more pronounced for the savanna (Brasília), is mainly due to the decrease of high cloud coverage during the dry season. It is interesting to note that the maximum cloud cover is quite similar during the rainy season for the four sites. In general, the high cloud fraction, parameter related to the convective activity, varies in a similar way to the cloud cover. During the dry season the cloud cover in Manaus and Belém has a larger proportion of convective clouds (15–25%) than Vilhena and Brasília (5% or less). However, during the

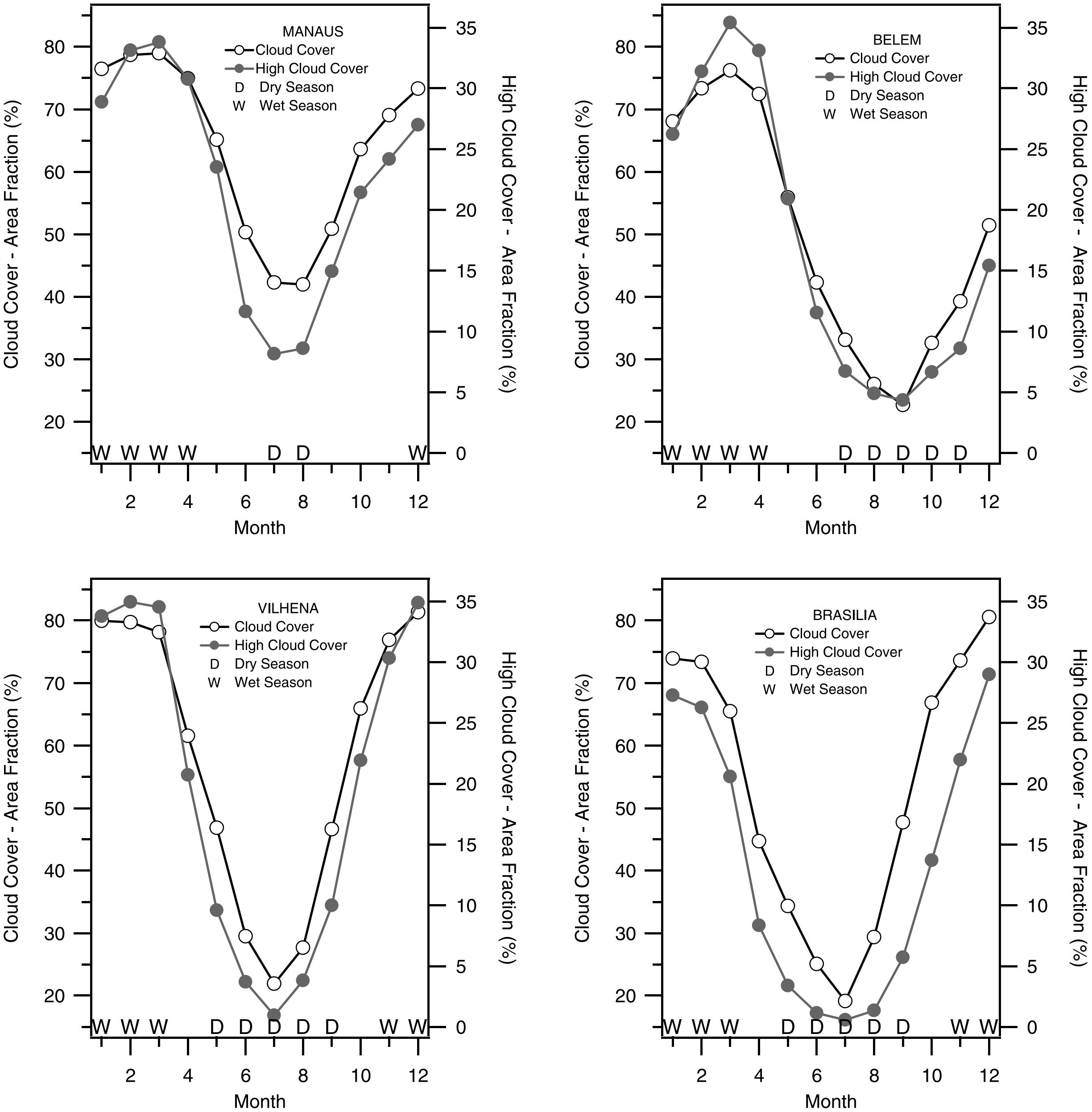


Fig. 3. Seasonal variation of the cloud cover and high cloud cover fraction for a region of 2.5° × 2.5° centred in Belém, Brasília, Manaus and Vilhena. W indicates wet season and D indicates dry season as defined using high cloud cover

rainy season the differences between the sites are small with a similar proportion of around 35–45%. Vourlitis et al. (2002) show that the seasonal latent heat fluxes for the tropical transitional forest were more comparable to tropical savanna than to rainforest, which is consistent with the result that the cloud cover in Vilhena presents a sharp dry season.

The seasonal cycle of precipitation is displayed in Fig. 4. As already mentioned the precipitation is generally very well correlated with the high cloud fraction (see Fig. 3). However the minimum of precipitation in Manaus and Belém occurs about one month later than the high cloud cover minimum, probably due to the increase in local convection that generate less organised and extended cloud structures. Figure 4 also shows the seasonal NDVI variations. NDVI composites in the equatorial regions can be affected by persistent cloudiness during the monsoon, which results in smaller NDVI values. This is probably true during the wet season from January to April,

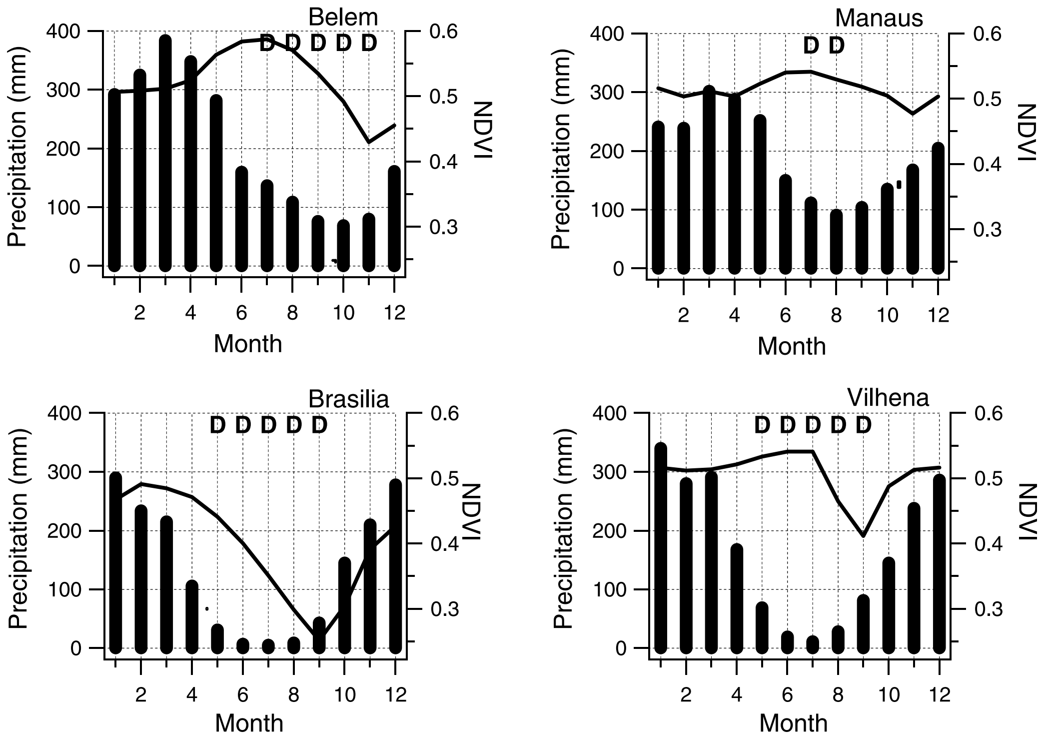


Fig. 4. Seasonal variation of the Normalized Difference Vegetation Index (NDVI) and rainfall for Belém, Manaus, Brasília and Vilhena. D indicates dry season as defined using high cloud cover

however the NDVI variations observed during the rest of the year over Belém and Manaus cannot be explained by cloud contamination alone. For all sites the time between the onset of the rainy season and the precipitation maximum is shorter than the time between the end of the rainy season and the precipitation minimum. Marengo et al. (2001) studying the onset and end of the rainy season in Amazonia also report this feature. Precipitation in Belém varies from 390 to 80 mm per month, in Manaus from 300 to 95 mm per month, in Vilhena from 340 to 15 mm per month and in Brasília from 295 to 5 mm per month. The precipitation during the rainy season differs among the sites by around 30%, whereas during the dry season it varies by about 150%. This result shows again that the larger differences among the sites take place during the dry season. The maximum rainfall value in Brasília differs from the others sites (maximum is 100 mm per month less than Belém) which is probably related to the different large scale forcing in Amazonia and central Brazil. Fisch et al. (2004) show significant differences between pasture and forest during the dry season. Pasture areas have higher, hotter and dryer convective boundary layers than forested areas. However, no significant differences were found during the wet season. This result is in agreement with the seasonal cloud cover and precipitation differences between forested and deforested sites presented in this work, since those convective boundary layer features during the dry season over pastures sites can increase the inhibition of the convective processes.

There is very little seasonal variation of the vegetation for continental rainforest (in Manaus the NDVI variation is around 0.06 only), but it is larger for the savanna (0.28 for Brasília). In the area of deforestation around Vilhena, NDVI has a seasonal amplitude of around 0.15; the rainforest site of Belém has a similar amplitude, maybe because part of the region analysed is composed of agricultural areas, but also because the dry season is more marked than in Manaus. Again, the larger differences between the sites occur during the dry season. For all sites, the maximum vegetation stress occurs between the end of the dry season and the beginning of the wet season and the maximum chlorophyl activity occurs when average precipitation decreases, between the end of the wet season and the beginning of the dry season. There is a slow decrease of the NDVI until the maximum vegetation stress occurs, this is then followed by a fast increase. The maximum NDVI during the wet to dry season occurs about three months after the maximum precipitation for the rainforest. In Brasília (savanna) this lag is smaller. In Vilhena, the NDVI maintains nearly the same value between the dates of maximum and minimum precipitation then decreases abruptly, presenting a typical rainforest behaviour during the rainy season and savanna behaviour during the dry season.

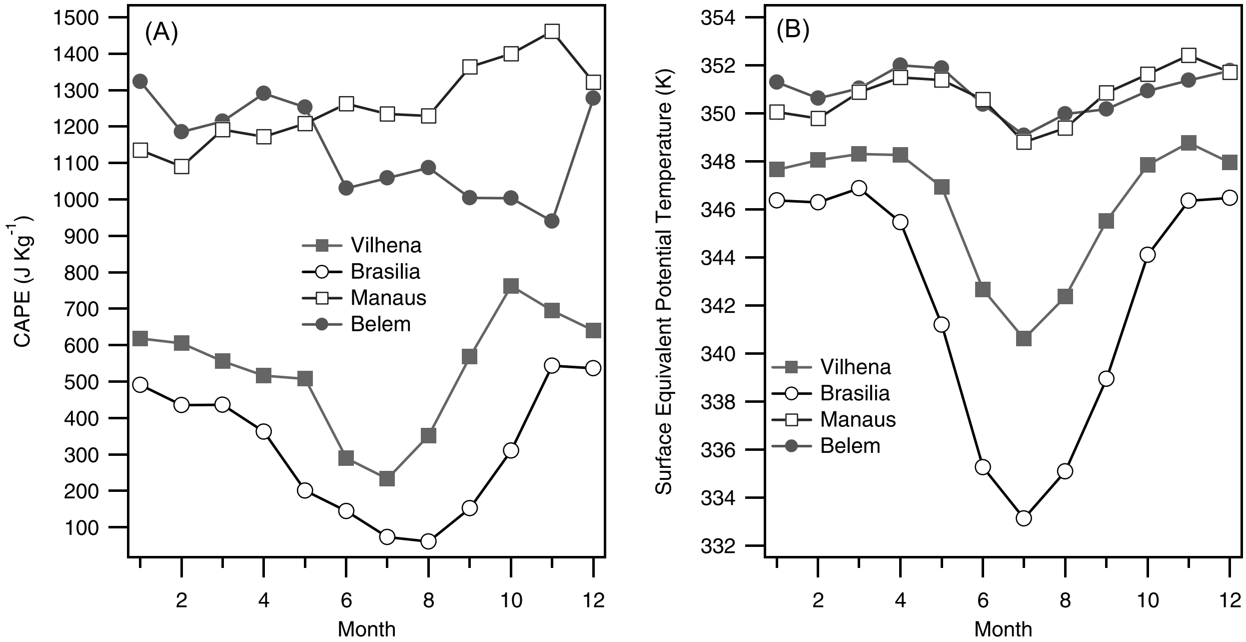
A noticeable difference among the sites is the time lag between the beginning of precipitation decrease and the time of NDVI minimum. During the rainy season the NDVI has similar values for all sites, but during the dry to wet season the differences are very large. For the savanna vegetation, which is more dependent on the precipitation than the forest, the vegetation starts to stress as soon as precipitation decreases, in contrast the forest takes a longer time to become stressed. The strong seasonal amplitude over the savanna sites, mainly explained by the sharp vegetation stress, is probably related to the vegetation physiology as well as the smaller amount of precipitation during the dry season, which is mainly related to the difference of large scale forcing between the equatorial and central Brazil regions – as has already been mentioned in discussion of the precipitation observations.

3.2 The seasonal variation of atmospheric thermodynamics

The seasonal variations of the thermodynamic variables were studied using the climatological radiosonde dataset for the four sites. Figure 5a and b present the seasonal variation of the convective available potential energy (CAPE) and the surface equivalent potential temperature (θ_e) respectively. Measurements of temperature and humidity at the surface were used to estimate CAPE. CAPE was computed using the 08:00 or 09:00 LST radiosoundings and therefore the moment of maximum CAPE value is not captured. The WETAMC/LBA experiment data show that CAPE starts to increase systematically at 08:00 LST, reaching the maximum value at 14:00 LST. In general CAPE and surface θ_e have the same seasonal variation showing that the surface humidity and temperature (hence the surface moist static energy) are well associated with the atmosphere lapse rate. Two different patterns appear, one for the Manaus/Belém stations, typical of the rainforest vegetation sites and close to the equator, and another for the Vilhena/Brasília stations representing the deforested-savanna vegetation sites and far from the humid equatorial zone. Manaus and Belém have weak seasonal variations and large CAPE and θ_e values, around $1200\,\mathrm{J\,kg^{-1}}$ and 350 K. Vilhena and Brasília have smaller CAPE around $500\,\mathrm{J\,kg^{-1}}$ and θ_e around 342 K and large seasonal amplitude. The small CAPE seasonal variation over the rainforest/ equatorial sites (about $300\,\mathrm{J\,kg^{-1}}$) contrasts with the large variations of seasonal convective activity (see Figs. 3 and 4).

In general, for the Vilhena, Manaus and Brasília stations, the maximum CAPE value occurs during the transition season between dry to wet season and in the beginning of the wet season. After the beginning of the wet season the CAPE value slowly decreases until the driest month (for Manaus, CAPE remains nearly unchanged during the wet season). The same behaviours are observed for Belém, i.e. an increase in CAPE value during the beginning of wet season and a slow decrease during the wet season, but CAPE increases again at the end of wet season. This is probably due to the high frequency of squall lines during this period (Cohen et al., 1989). Due to the large amount of convective clouds during the rainy season the atmospheric lapse rate is likely to nearly reach the saturated adiabatic, decreasing CAPE value. The upward flux of water vapour in convective cells moistens the middle and upper troposphere while the downdrafts cool the air near the surface; this is one of the principal means by which convection stabilises its environment (Emanuel, 1994). Williams et al. (2002) also show larger occurrences of high CAPE values during the dry to wet season than during the wet season. They found the distributions of mean CAPE values are nearly the same, but the very large values happen more frequently during the transition season than during the wet season.

Figure 5c shows the seasonal variation of the average maximum lapse rate in the layer between



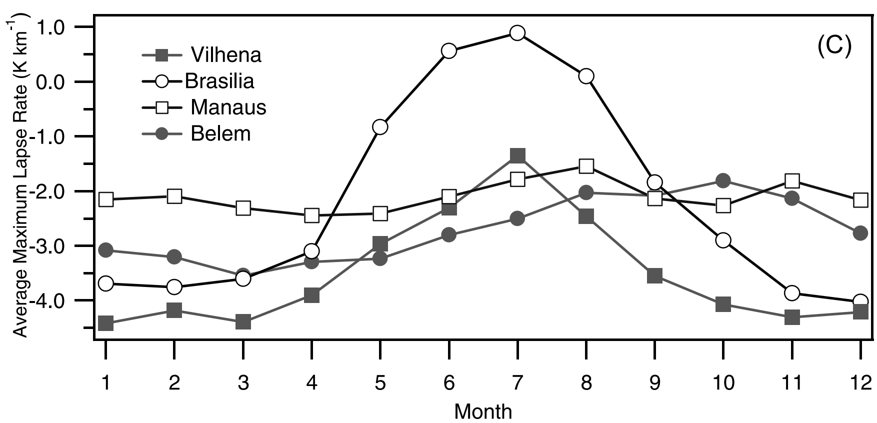
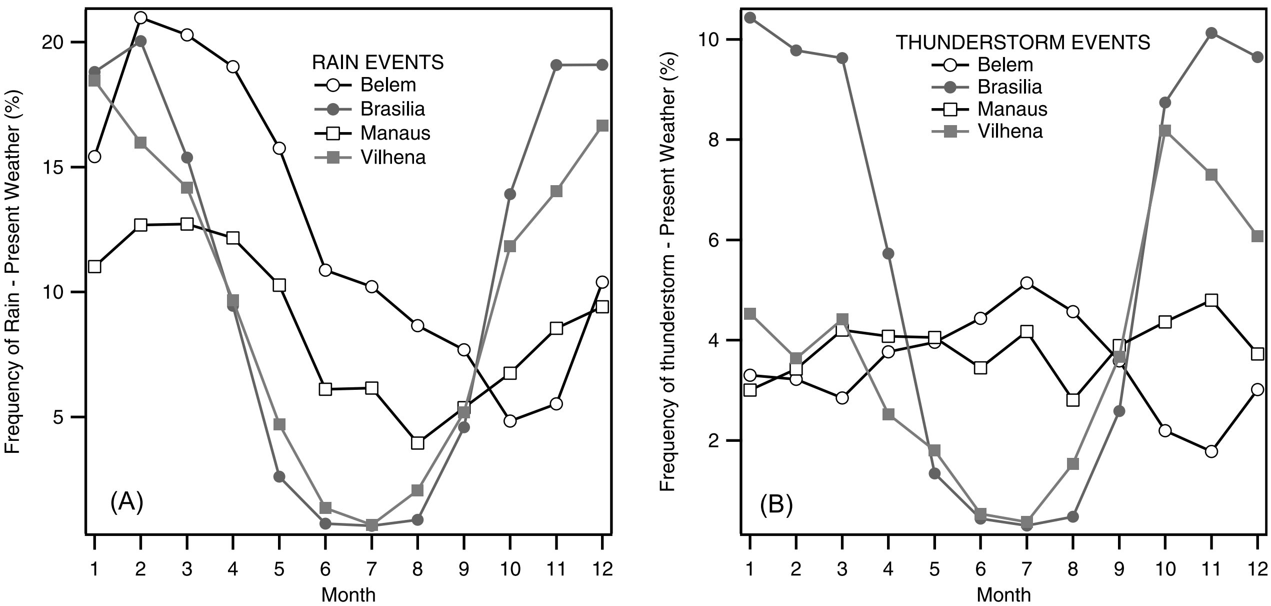


Fig. 5. Seasonal variation of convective available potential energy (CAPE), surface equivalent potential temperature (θ_e), and average maximum lapse rate for Belém, Brasília, Manaus and Vilhena

500 m and 4500 m height, which gives an indication of the intensity of the subsidence temperature inversion. This layer was chosen to avoid surface inversion and upper levels inversion (4500 is close to the average 0 °C level); the majority of subsidence inversion occurs within this layer (for example, the average height of minimum lapse rate is 1800 m in Belém). The Brasília site clearly shows different behaviour to the other three sites. The average maximum lapse rate, during the dry season, is about $+1\,°\mathrm{C\,km^{-1}}$ and during 60% of the time (figure not shown) there is a strong convective inhibition (lapse rate higher than $0\,°\mathrm{C\,km^{-1}}$), which is explained by the large scale forcing. For Vilhena, the maximum lapse rate also presents a significant seasonal variation, even if smaller than for Brasília. For the two other sites the seasonal variation is weak. The results show that for the two equatorial rainforest sites there are large seasonal variations of cloud cover and small seasonal variations in the CAPE, equivalent potential temperature and lapse rate magnitude. In other words, small changes in large-scale circulation or in surface conditions can result in large changes in the cloud cover of the equatorial rainforest region. It can be interpreted as large sensitivity of climate to small variations in the large scale forcing over this region.

Figure 6 presents: (a) the seasonal variation of the frequency of rain events, (b) the number of thunderstorm (lightning, thunder and hail)



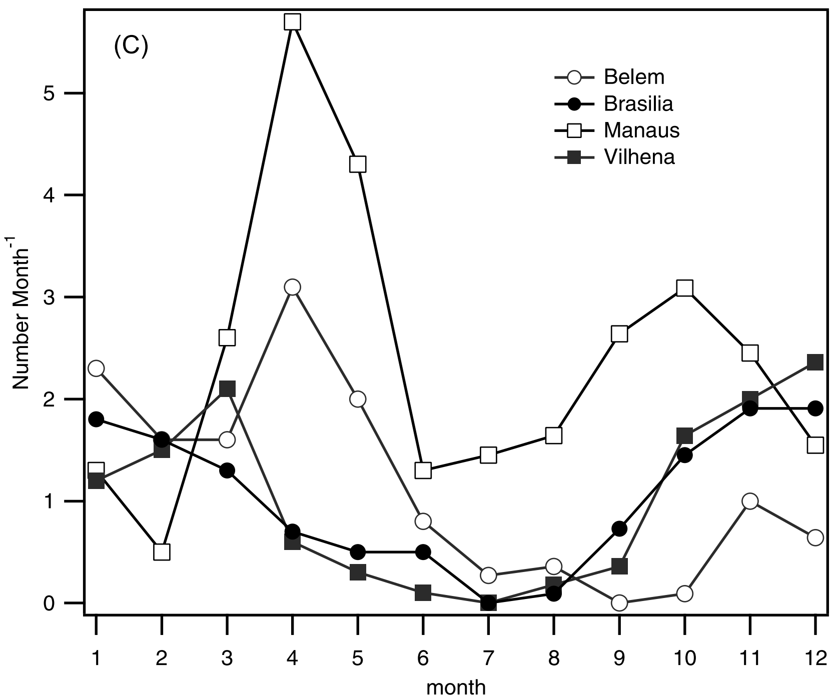


Fig. 6. Seasonal variation of rain (**A**) and thunderstorm (**B**) events observed by surface observer. Number of synoptic convective perturbations (**C**) from satellite data for a region of $10° \times 10°$ centred on Manaus, Belém, Vilhena and Brasília

events, and (c) the number of synoptic organized convective systems, for the four sites. The rain event observation agrees very well with the seasonal cycle of precipitation and cloud cover as shown in Figs. 3 and 4. During the rainy season, there is a rain event about 20% of the time, except for Manaus where the frequency of occurrence is about 13% only. The thunderstorm frequency shows nearly the same number of events during the pre-wet season and the wet season. Belém presents the maximum frequency of thunderstorm at the end of the wet season and during the transition season from wet to dry that corresponds to the period of intense squall line activity. Besides these, the seasonal variation is small for both sites of rainforest. The most notable feature is the high frequency of thunderstorm events in Brasília when compared with the rainforest sites, as well as the strong variations during the year. The thunderstorms in Brasília occur 10% of the time during the transition season and wet season; only Vilhena has a comparable number of events during the pre-wet season. Note that Vilhena weather reports do not include observations from 18:00 LST to 05:00 LST and thus the number could be higher than that presented in Fig. 6, because there is presumably a large occurrence of thunderstorms during the evening (see the large number of rain events at 17:00 LST in Fig. 8). As the rain event number is larger during the wet season than during the transition between the dry and wet season and the frequency of thunderstorms is larger, or nearly the same, during the transition and wet seasons, then the rain events are more intense during the transition season or beginning of the wet season than when the wet season is established. Also, Williams et al. (2002) show that the lightning record is characterized by a semi-annual component, with maxima in both transition periods. Fu and Li (2004) suggests that the transition from dry to wet season in southern Amazonia is mainly initiated by increases of surface latent heat flux and local precipitation; these fluxes rapidly increase CAPE, consequently providing favourable conditions for increased rainfall even before the large-scale circulation has changed. These different atmospheric forcings between the transition season and the regular wet season can explain the more intense thunderstorms found during the transition season.

The frequency of organized synoptic convective events (Fig. 6c) is highest during the end of the wet season with a secondary peak during the start of the wet season, for Manaus, Belém and Vilhena. Brasília presents a single maximum of organized synoptic convective events during the beginning of the wet season. These events in the southern part of Amazonia are related to the penetration of cold fronts and the SACZ formation; Marengo (2004) discuss the importance of extra tropical perturbation in the precipitation regime in southern Amazonia. In northern Amazonia these events are mainly due to the monsoon circulation that increase the ITCZ activity over Amazonia and to the squall lines (here detected by their signature at synoptic scale) which originate near the coast and propagate into central Amazonia (Cohen et al., 1995). Manaus has the largest number of events per month, around 6 during March and 3 during October, presumably because this region is influenced by both types of synoptic perturbations (Fisch and Nobre, 1998). Belém has more rain events and less organized large-scale perturbations than Manaus. It means that the sea breeze effects, which are mainly due to local convection, dominate the convective activity in Belém, whereas in Manaus the synoptic events have stronger impact on the total number of rain events.

The more intense rain events during the transition season can be related to the maxima CAPE values found during the dry to wet season. During the rainy season the atmosphere is close to the saturated adiabatic lapse rate because there is strong convective activity. During the dry to wet season, the subsidence temperature inversion decreases and CAPE increases and reaches the maximum value, because of the increase of surface temperature and the supply of moisture provided by the monsoon circulation. Fu et al. (1999) showed that before the beginning of the rainy season there is a systematic build-up of planetary boundary layer moisture. Only in some places can the temperature inversion be broken and a large convective activity develop, fed by the nearby regions that are not developing convective activity. By reason of a smaller number of convective cells, there is less “competition” of surface moisture convergence to feed the cumulonimbus during the dry to wet season than during the rainy season, which can explain the larger convective intensity.

Another possible explanation for the more intense rain events during the transition season is related to the cloud condensation nuclei (CCN) concentration. CCN measurements in Amazonia during the wet season, show very low values more typical of maritime clouds than most continental sites (Roberts et al., 2001). During the WETAMC/LBA experiment two regimes of low tropospheric wind were observed. Rickenbach et al. (2002) show that convection oscillates between a more stratiform behaviour, associated with less lightning, lower cloud tops and low ice water content during the western wind regime and more isolated clouds, with a large frequency of lightning, large ice liquid water content and higher cloud tops during the

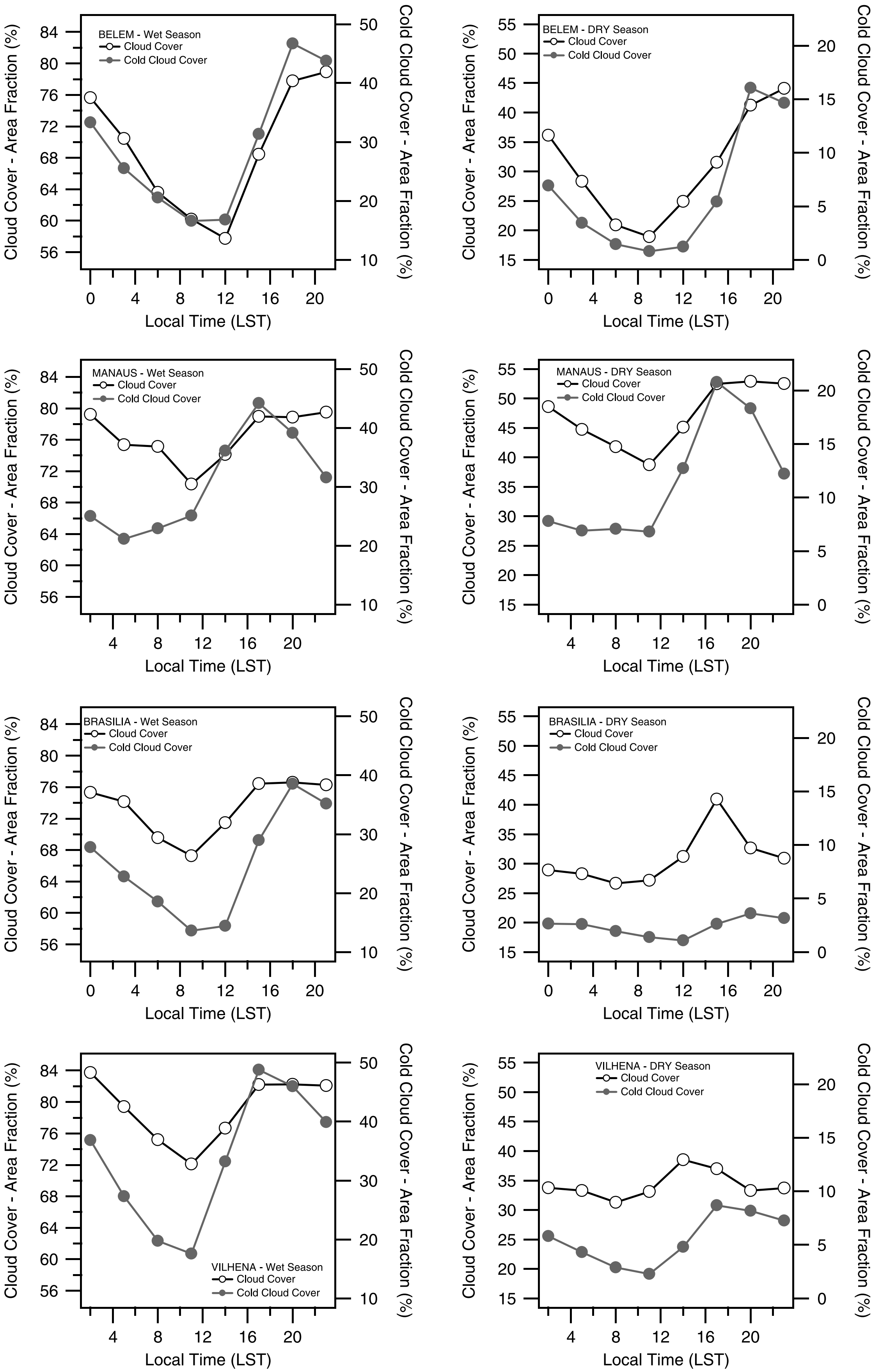


Fig. 7. Diurnal variation of cloud cover and high cloud fraction for the dry and wet seasons for a region of 2.5° × 2.5° centred on Belém, Brasília, Manaus and Vilhena

easterly regime. Williams et al. (2002) shows that an easterly wind regime has higher CCN concentration than a westerly wind regime. These results suggest that CCN can have an important impact on cloud convection intensity. During the dry to wet period the atmosphere has larger CCN concentration than during the wet season when the CCN have already been washed out.

3.3 The diurnal cycle

Figure 7 shows the diurnal cycle of cloud cover and high cloud fraction for the dry and wet seasons for the four sites studied. The high cloud fraction presents nearly the same diurnal phase for the wet and dry seasons for all sites studied. It is at a minimum during the morning and a maximum at the end of the afternoon. The main difference between the dry and the wet seasons is in the range of variation: during the wet season it varies generally from 15 to 45% and during the dry season from 0% to 20%.

During the wet season Manaus, Vilhena, Brasília and Belém have the maximum of high cloud cover at nearly the same time; Belém has a much stronger diurnal variation of convective clouds than any other site. This is consistent with the importance of the sea breeze effect in the convection in this region, as inferred from the high frequency of local rain events and the low frequency of synoptic convective events (see Section 3.2). With the exception of Belém, during the wet season the convective cloud cover varies out of phase with the total cloud cover. The maximum cloud cover occurs later during the night around 02:00 LST. Machado et al. (2002) showed that the maximum rainfall takes place at the time of the maximum initiation of the convective systems observed by satellite and radar. At the time of maximum diurnal cycle of precipitation the majority of the convective systems and rain cells are small sized and present the maximum increasing area fraction rate. The night maximum of cloud cover is an important factor in the atmosphere energy budget because it reduces the outgoing long wave radiation and increases the greenhouse effect.

During the dry season for the two rainforest sites the diurnal variations are similar as in the wet season, showing the cloud cover maximum at night, some hours after the high cloud fraction maximum. For the two other sites the picture is very different, showing the cloud cover maximum in the afternoon, before the high cloud fraction maximum. During the dry season there is more rainfall over the rainforest equatorial sites than over the savanna sites. Also, rainforest areas have larger soil moisture availability than areas with typical vegetation of pasture or savanna

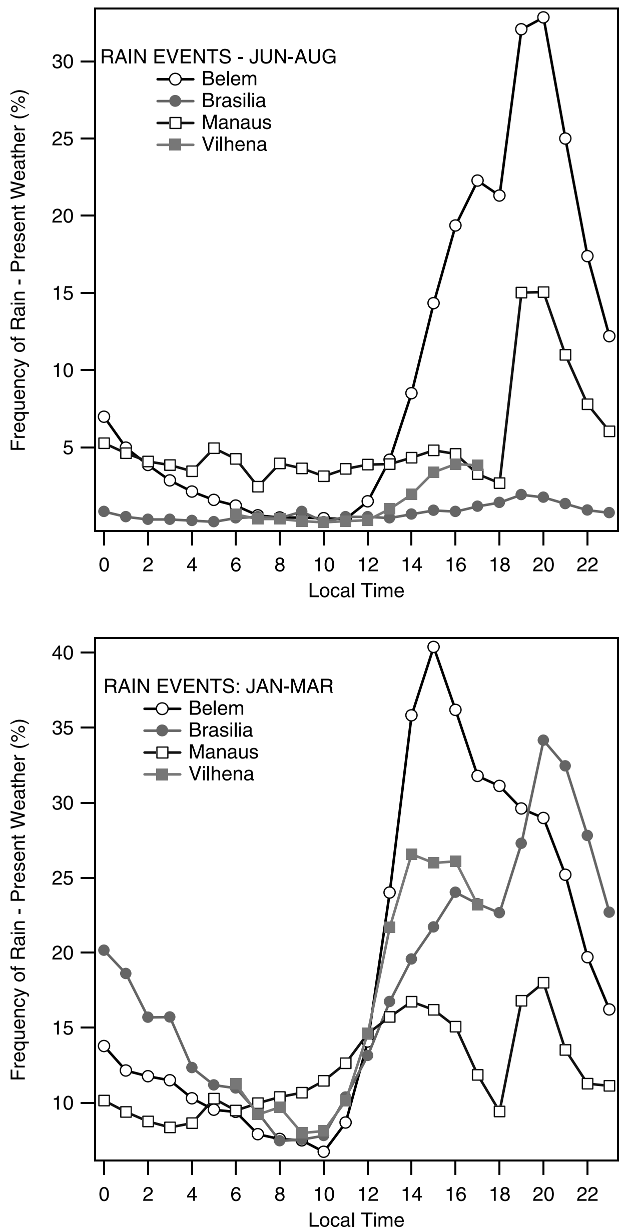


Fig. 8. Diurnal variation of rain events obtained from surface observations for January to March (wet season) and June to August (dry season)

(rainforest has deeper roots than pasture/savanna) and therefore higher transpiration rates (Hodnett et al., 1996). Both reasons can explain differences in low level cloud formation.

Machado et al. (2002) show that high and convective cloud covers reach their maxima some hours after the maximum rainfall. Figure 8 presents the diurnal cycle of the rain events for January to March (wet months) and for June to August (dry months). The rain events during the wet months, show two maxima around 14:00 LST and 20:00 LST. For Brasília the night maximum is more important. Vilhena has observations only until 17:00 LST and a possible secondary maximum cannot be indentified. For Belém the number of rain events is large during the whole afternoon with a maximum in the beginning of the afternoon and a relatively small contribution of the 20:00 LST peak. For Manaus both maxima are important. During the dry season only, Manaus and Belém have a significant number of rain events peaking at 19:00–20:00 LST. It seems that non-forest sites during the wet months, or forest sites during the dry months, need a longer time to develop convective activity. However, it is very difficult to separate the large scale forcing (depending on the geographical location) from the vegetation effect (rainforest or savanna). Durieux et al. (2003) show that changes in cloud cover over deforested areas are not significant for interannual variation, rather they are for the seasonal and diurnal distributions. They also show that during the dry season, observations show more low-level clouds in early afternoon and less convection at night and in early morning over deforested areas whereas during the wet season, convective cloudiness is enhanced in the early night over deforested areas.

4. Conclusion

The seasonal and diurnal cycles of convection in tropical South America have been documented using a climatological dataset of more than 25 years of daily radiosoundings and surface observations combined with a climatological satellite dataset. The combination of conventional data with processed satellite data has allowed us to describe and understand the behaviours of the seasonal and diurnal cycles over regions having different vegetation types and different large scale forcing.

July is the driest month for the majority of South America. The dry season duration shows two minima, one over west Amazonia, associated with the monsoon circulation and persistent convection and another in the south of Brazil associated with the penetration of cold fronts.

The rainforest sites, Manaus and Belém, have smaller seasonal amplitudes than the sites within the deforested arc of southern Amazonia (Vilhena) and savanna (Brasília). Although seasonal amplitudes of cloud cover, high cloud fraction and precipitation are smaller for Manaus than for the other sites, there is still a clear seasonal cycle whereas vegetation index and thermodynamic variables have a very weak seasonal cycle. Equatorial/rainforest sites show significant seasonal cycles in precipitation and cloud cover, linked to small seasonal changes in CAPE and subsidence temperature inversion. This feature shows how sensitive the Amazonia tropical atmosphere can be to climate change.

During the rainy season the differences among the sites are quite small; larger differences appear during the dry season. This is observed for all variables, either related to precipitation, cloud cover, vegetation stress or thermodynamics. The period from the dry to wet season and beginning of the wet season has, for nearly all sites, the largest CAPE values. The number of rain events is larger during the rainy season, however the number of thunderstorms is larger during the dry to wet season and the beginning of the wet season, in other words the rain events are more intense during the beginning of the wet season than when it is well established. During the rainy season the atmosphere is close to the saturated adiabatic lapse rate because of the large area covered by convective clouds. During the dry to wet season and beginning of the wet season, the subsidence temperature inversion decreases and CAPE increases reaching the maximum value, probably because of the increase in the surface temperature and moisture (equivalent potential temperature). Only in some places can the temperature inversion be broken to allow a strong convective activity to develop, fed by the neighbouring regions that do not develop convective activity.

The synoptic scale convective cloud organization, mainly associated with the SACZ and Amazonian squall lines is an important feature in central Amazonia. The savanna and deforested regions have a larger frequency of thunderstorm than the rainforest sites. Belém has more local convection than Manaus, which can be explained by the convection enhanced by sea breeze effects.

The high cloud fraction, closely associated with the convective clouds, presents nearly the same diurnal phase for the wet and dry season for all regions. A high cloud minimum in the morning is followed by a fast increase in the early afternoon, reaching a maximum at the end of the afternoon. The main difference between the dry and the wet season is the range of variation: during the wet season it varies, in general, from 15 to 45% and during the dry season from 0 to 20%.

The maximum total cloud cover, during the wet season, is during the night. During the dry season the diurnal variations are smaller but similar for Manaus and Belém. For non-forest sites, the maximum occurs before the time of maximum high cloud fraction. During the dry season, the regions covered by forest appear to have enough capability to store latent energy in the atmosphere-biosphere, which is not the case for the regions with vegetation typical of deforestation and savanna. Besides, rainforest/equatorial sites have larger amount of rainfall during the dry season than the savanna sites.

The majority of the rain events during the wet season occur around 14:00 LST in Belém, Manaus has a secondary maximum around 20:00 LST and Brasília has the majority of rain events at this time. During the dry season only Manaus and Belém have significant peaks of rain events, in the evening.

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