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Artigo

Analyses of Shallow Convection over the Amazon Coastal Region Using Satellite Images, Data Observations and Modeling

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Abstract

The Belem region of the state of Para, which is located in northern of Brazil and part of the Amazon biome is characterized by high temperatures, strong convection, unstable air conditions and high humidity favoring the formation of convective clouds. Shallow convection and deep convection are among the main components of the local energy balance**.** Typically a deep convection over the continents is preceded by a shallow convection. An analysis of the performance of the Jet Propulsion Laboratory / National Aeronautics and Space Administration (JPL/NASA) model of shallow convection parameterization in a framework of the single column model (SCM), in relation to the cluster of cumulus clouds formed in the coastal region of the Amazon forest due to squall lines, is provided. To achieve this purpose enhanced satellite images and infrared images from channels 2 and 4 from the GOES-12 satellite, and data obtained by the "**C**loud processes of t**H**e main precipitation systems in Brazil: A contrib**U**tion to cloud resol**V**ing modeling and to the GPM (Glob**A**l Precipitation Measurement)" - CHUVA - campaign, during the month of June of 2011, were used. During that period, clusters of cumulus clouds penetrated the interior of the Amazon, causing heavy rains. Results demonstrated that the parameterizations performed well in the case where only a core of clouds was observed, such as at 18:00h on 14 June. This period of the day also presents the smallest bias and root mean square error (rmse) values for the relative humidity. For the potential temperature the smallest value of bias is at 12:00h on June 7th (0.18 K), the largest one is on June 11th (-2.32 K) and the rmse ranges from 0.59 to 2.99 K.

Keywords: convective parameterizations, Single Column Model (SCM), CHUVA experiments, infrared images.

Análise da Convecção Rasa sobre a Região Costeira Amazônica Usando Imagens de Satélite, Dados Observacionais e Modelagem

Resumo

A região de Belém, no estado do Pará, localizada na região norte do Brasil e parte do bioma da Amazônia, é caracterizada por altas temperaturas, forte convecção, alta umidade e instabilidade atmosférica, favorecendo a formação de nuvens convectivas. As convecções rasa e profunda estão entre os componentes principais do balanço de energia local. A convecção profunda sobre os continentes é tipicamente precedida pela convecção rasa. Uma análise do desempenho das parametrizações para convecção rasa do Modelo de Coluna Única (MCU) do Laboratório de Propulsão à Jato / Administração Nacional Aeronáutica e Espacial (sigla em inglês JPL/NASA) em relação ao aglomerado de nuvens cúmulus formado na região costeira da Amazônia devido às linhas de instabilidade foi realizada. Para alcançar este propósito foram usadas imagens classificadas e dos canais infravermelhos 2 e 4 do satélite GOES-12 e dados obtidos na campanha CHUVA "**C**loud processes of t**H**e main precipitation systems in Brazil: A contrib**U**tion to cloud resol**V**ing modeling and to the GPM (Glob**A**l Precipitation Measurement)", durante o mês de junho de 2011. Durante aquele período, aglomerados de nuvens cúmulus penetram o interior da Amazônia, causando chuvas fortes. Resultados demonstraram que as parametrizações apresentaram bom desempenho para o caso onde somente um núcleo de nuvens

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foi observado, tal como o ocorrido em 14 de junho às 18:00h. Este período do dia apresentou os menores valores de viés e erro médio quadrático (EMQ) para a umidade relativa do ar. Para a temperatura potencial, o menor valor de viés foi às 12:00h do dia 7 de junho (0,18 K), o maior valor foi em 11 de junho (-2,32 K) e o EMQ variou de 0,59 à 2,99 K.

Palavras-chave: parametrizações convectivas, Modelo de Coluna Única (MCU), campanha CHUVA, imagens infravermelhas.

1. Introduction

The largest forest of the world, the Amazon, presents an interesting and very complex system-mixing forests, various topographies, sites of deforestation, cities, and regions close and far from the coast, which influence the climatology of the region (Garstang *et al.*, 1990 and 1994; Greco *et al.*, 1990 and 1994; Cohen *et al.*, 1995; Fu *et al.*, 1999; Petersen *et al.*, 2002 and 2006). Greco *et al.* (1990) classify the Amazon convection in three systems: Coast Occurring Systems (COS), Basin Occurring Systems (BOS) and Locally Occurring Systems (LOS) (see Adams *et al.*, 2009 for a review). This study was focused in the region of Belem which is considered the rainiest region in the eastern Amazon with precipitation around 2000 mm/year (Figueroa and Nobre, 1990) and is localized approximately 120 km from Atlantic Ocean.

The Belem region in Brazil is characterized by high temperatures, strong convection, unstable atmospheric conditions and high humidity, favoring the formation of convective clouds. High temperatures are associated with high intensity of incident solar radiation, although most of the energy is converted into latent heat of evaporation and the remainder converted into sensible heat. The strong convection, instability and high humidity favor the formation of convective clouds, giving rise to a high incidence of rainfall in the form of showers, mainly in the afternoon, a situation characteristic of a type of continental rain system (Nechet, 1997), also found by Negri *et al.* (2000) whose article about the 10 years of climatology of Amazonian rainfall shows a persistent local rainfall maximum at 18:00 LST on the northern coast of South America, which due to interactions between sea-breeze and the squall line formation moved inland at 21:00 LST. According to Nechet (1997) frequent formation of cumulonimbus clouds over Belem also favors the occurrence of various types of thunderstorms, the occurrence of which average around 165 days annually. Campos *et al.* (2014) describe the socioeconomic impacts of the extreme precipitation in Belem and linked years with the El Niño phenomena with the smaller instances of precipitation and the La Niña phenomena with the larger instances (Cutrim *et al.*, 2000; Ribeiro *et al.*, 2014). Shallow convection (no precipitation, following the traditional division of convective parameterization) and deep convection (precipitation) are among the main components of the local energy balance (Adams *et al.*, 2009; Tavares and Mota, 2012).

The main mechanisms that explain the rainfall patterns within the context of global scale are the result of combining the predominant role of the Intertropical Convergence Zone (ITCZ), which is characterized by weak winds and intense rainfall (Vianello and Alves, 1991; Moura and Vitorino, 2012) resulting from the convergence of the trade winds from the northeast and southeast, the sea breezes, the penetration of frontal systems from the south of the continent and the vapor source represented by the vegetation of the region. In 2015, Ferreira *et al.* (2015) employed Empirical Orthogonal Functions (EOF) to study the ocean atmosphere patterns over the Atlantic Ocean to identify the impacts of the ITCZ on the spatial distribution of rainfall in the eastern Amazon, the ITCZ again was confirmed as the main rainfall producing system in that region, while Gille and Da Mota (2014) in their thermodynamic study determined the ITCZ as the source of dynamic forcing in the rainy season and, in the dry season, the squall line is the source of dynamic forcing. Within the more local context, it can be said that rainfall in Belem is the result of the following scenarios (Vianello and Alves, 1991):

i) December to May (Tavares and Mota, 2012; Figueroa and Nobre, 1990), rainiest season, rainfall is caused by the ITCZ and by the effects of mesoscale such as the squall lines formed in the Atlantic coast of Guyana and Para which propagate westward as a line of cumulonimbus clouds. These lines originate in association with the sea breezes and form in the afternoon.

ii) from June to August, during the end of the rainy season, the rain being caused by local effects, such as land and sea breezes and by easterly waves encountering currents of trade winds, usually from the southeast. These waves are phenomena that form in the field of atmospheric pressure over the trade winds in the tropical zone of the globe, moving from east to west. According to Garstang *et al.* (1994) and Cohen *et al.* (1995) the end of the wet season, in June, also present the maximum squall line frequency. In the preliminary analyses of the CHUVA project presented in Machado *et al.* (2014), an interesting multi-scale nature feature of the squall lines was noted. Successively smaller scale propagating rainfall cell lines were noted surrounded by the large cloud deck. Cohen *et al.* (1995) described the squall lines formed along the coast and sea breeze front, propagating inland over the Amazonian rainforest. In addition, Machado *et al.* (2014) noticed several of the squall lines initiated at the semi-arid region of the east of Belem and along the boundary of the rainforest.

iii) during the September to November dry season, the precipitation is usually caused by mesoscale phenomena.

An simplified definition of Belem's season is proposed by Figueroa and Nobre (1990), Marengo *et al.* (2001), and De Souza and Ambrizzi (2002) who define Belem's seasons as rainy (December to May) and less rainy (June to November). According to Marengo and Hastenrath (1993) large-scale climate phenomena such as the Southern Oscillation and the Interhemispheric Thermal Gradient also cause variability in the duration and intensity of the rainy season in the Amazon. A review describing the systems that act on the South American continent including the more relevant atmospheric systems responsible for the rainfall in the Amazon region can be found at Cohen *et al.* (2009).

For decades, relating the local nature of convection and its interaction with the atmosphere on a large scale has been one of the main challenges of the assessment of tropical meteorology of the Amazon region (Adams *et al.*, 2009). Although the centers of Brazilian meteorology show generally good accuracy in predicting the weather through the use of Atmospheric General Circulation Models (AGCMs) or Regional Forecast Models (see Chou and Nobre (2015) and also Nobre *et al.* (2013) for the complete evaluation of these models) they still experience some difficulty in prediction in the Amazon, considered a peculiar region, with complex interactions and various convective regimes where those models do not have an accurate parameterization to represent the atmospheric mechanisms that cause precipitation over that region (Moraes *et al.*, 2013; Bechtold *et al.*, 2004). Convection parameterization relates unresolved convective properties and its associated transport to the resolved large scale. Lin *et al.* (2000), Yang and Slingo (2001), Cavalcanti *et al.* (2002), and Adams *et al.* (2009 and 2015), call attention to the problem of the convective parameterizations (see Kain (2004), Arakawa (2004) and Lopez (2007) for a review of convective parameterizations) used in large-scale models and the difficulties in simulating the effects of convective processes in all tropical regions, particularly in representing the diurnal cycle.

Despite shallow cumulus clouds receiving less attention in numerical models (Souza *et al.*, 2009), they play an important role in maintaining the structure of the earth-atmosphere system, resulting in various mechanisms of retro-feed as found in Stull (1985). Typically a deep convection over the continents is preceded by a shallow convection. Shallow convection and boundary layer processes precondition the atmosphere for a deep convection. This transition is a key element for an accurate representation of the diurnal cycle of precipitation (Khairoutdinov and Randall, 2003; Grabowski *et al.*, 2006 and Souza *et al.*, 2009). The absence of interaction processes between shallow convection and radiation causes the surface energy balance of the surface to be overestimated in models (Adams *et al.*, 2009).

Souza *et al.* (2009) studying the effect of shallow convection in the diurnal cycle of the surface energy balance of the Amazon, implemented the BRAMS (Brazilian developments on the Regional Atmospheric Modeling System) and showed a good agreement between the interaction of shallow convection and radiation at noon and early afternoon and a qualitative deficiency of the model to represent these flows during the morning portion of the diurnal cycle. Lopes *et al.* (2012) used the BRAMS model to investigate the relationship between soil moisture and cloud cover in the shallow cumulus energy balance of the Amazon, finding interactions among shallow convection and radiation. Chagnon *et al.* (2004) reported a significant climatic shift in shallow cloudiness patterns associated with deforestation in the Amazon in 2004, using shallow cumulus cloud maps derived from geostationary satellite imager data, obtained from GOES-8.

With the foregoing background, the primary goal of this article is to analyze the performance of the Jet Propulsion Laboratory / NASA (JPL/NASA) model of shallow convection parameterization in the framework of the single column model (SCM) (Suselj *et al.*, 2012; 2013) for the Amazon coastal region and, as a secondary objective, the generation of the profiles by the SCM of turbulent fluxes in order to increase the formal literature data available on the Amazon coastal region. This will be done after validation between the observational data and the parameterizations, and several steps will be necessary:

i) Due to the known complexity of simulation of the Amazon region, we started from a synoptic analysis of classification of images obtained from GOES-12 satellite, which provided the essential information to select the days which were more significant for the study because of the presence of shallow cumulus clouds;
ii) Study and analysis of the observational data available from the "Cloud processes of tHe main precipitation systems in Brazil: A contribUtion to cloud resolVing modeling and to the GPM (GlobAl Precipitation Measurement)" - CHUVA - campaign in the region of Belem, Brazil, that would match with selected days from the satellite images and that would fit the exigencies for initial conditions for the SCM model;
iii) Implementation of the SCM and feed with the CHUVA campaign data for the selected days.

The next topic will detail the methodology used as well as the region of study.

2. Material and Methods

The methodology is composed of four parts: the study region, satellite images, observational data, and model description.

2.1. The study region

Belem is the capital of Para state, which is located in northern Brazil, 2,146 kilometers from Brasilia with an area of about 1,059.458 km^2, a population of 1,393,399 in 2010, and an estimated population in 2016 of 1,446,042 inhabitants (the most densely populated region of the north part of Brazil 1,315.26 inh/km^2) (IBGE, 2010), with 26% of the area of the Brazilian Amazon and having 49% of its natural attractions, according to the Organization of American States (Organização dos Estados Americanos - OEA). Figure 1 shows a demarcation of Amazon and the location of the city of Belem.

The Belem region is situated on the banks of Guajará Bay, at the confluence with the Rio Guamá, approximately 120 km from Atlantic Ocean, with an area of 719 km^2, and an average elevation of 12 m. Its main physiographic characteristic is numerous small bodies of water, known regionally as holes and creeks, which associated with low latitude, influence the region to a hot and humid climatic environment (Bastos *et al.*, 2002).

2.2. Satellite data

For this study data were used from GOES-12 satellite available at the Satellite Division and Environmental Systems (Divisão de Satélites e Sistemas Ambientais - DSA) from the Center for Weather Forecasting and Climate Studies (Centro de Previsão do Tempo e Estudos Climáticos - CPTEC) at the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais - INPE) of Brazil. The Geostationary Operational Environmental Satellite (GOES) is positioned over the Equator at a height of 35,800 km. The objective of GOES is to monitor the severe weather conditions such as hurricanes and storms. The GOES-12 is at 60° of west longitude and it is dedicated to the monitoring of South America and adjacent oceans providing images every 15 min. For the enhancement of the scenes during the daytime, the factorial analysis shows that of 10 data sets obtained from the five channels of the GOES satellite (reflectance in channel 1 and temperature of brightness in the other channels, plus their textures), only four of them (those associated to channels 1 and 4) provide non-redundant minimal information about a given pixel (Ceballos e Bottino, 1998).

Figure 1 - Frontier of the Brazilian Amazonian biome and location of the most representative cities of Para state, Belem and Santarem.

A method was developed to enhance targets on GOES-8 images, based on using three variables: reflectance (channel 1), temperature of brightness (channel 4), and their textures (local variance). The principle of this method is to classify each pixel according with the smallest Euclidean distance to a set of reference decentroides in a multidimensional space. The method is iterative, so that the centroids are defined by successive processes of classification until a stability criterion is reached (Bottino *et al.*, 2004). Based on this method, the enhanced infrared satellite images of clouds used in this article were obtained from the GOES-12 satellite.

The images derived from the products of cloud image enhancement from CPTEC/INPE were used to analyze the period of June 07th, 10th, 11th, 14th, and 15th of 2011 corresponding to the same period of the CHUVA campaign in Belem. The enhanced images from the GOES-12 satellite at 12:00 UTC showing the cloud cover over Brazil were analyzed for the days and times when the presence of shallow cumulus clouds was significant. Moreover, GOES-12 Satellite images in the infrared channels 2 and 4 from Brazil and the Para state were used for analysis of the active systems for the same period in June in the local hours of 00:00, 06:00, 12:00 and 18:00.

2.3. Observational data

The data used to evaluate the SCM are obtained from the CHUVA project. The CHUVA project was created to describe the cloud processes of the main precipitating system in Brazil and give support to the GPM constellation program which launched the GPM Core Observatory on February 27th, 2014 at 1:37 pm EST from launch pad 1 of the Space Center of Tanegashima, Japan (GPM, 2014).

This project is carrying out field experiments at seven sites to investigate the different precipitation patterns in Brazil. More details about the CHUVA project can be found at Machado (2014). Experiments conducted around the city of Belem were chosen for this paper. The CHUVA campaign was conducted in June 2011 representing the end of the wet season period. The measurements started on June 1th and were completed on June 30th. This region is characterized by formation of squall lines in the coastal part of the continent causing large clusters of cumulonimbus clouds. According to the information available at CHUVA project webpage (CHUVA, 2011), these clusters of cumulus clouds penetrate the interior of the Amazon, causing heavy rains during that time of year. These rains, though critical to the climate of the Amazon rainforest, cause recurrent serious flood damage to the towns and cities in the region. Therefore it is useful for the General Circulations Model (GCM) be enhanced to realistically predict these types of events by improved accuracy of the parameterizations.

2.3.1. Equipment description

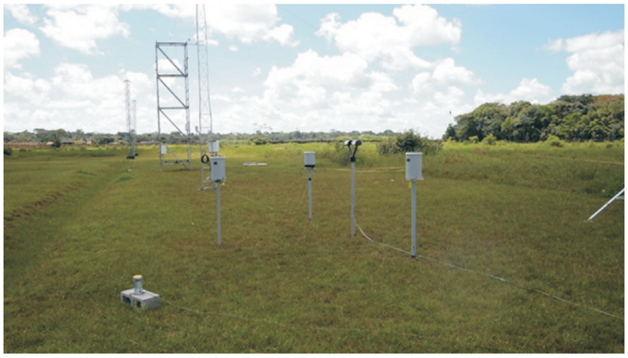
Micro radar data was used in the analysis of height of clouds. Surface flux data was utilized for the analysis of temperature, winds (3D), humidity, momentum, sensible and latent heat fluxes and time series of the fluxes; the radiossonde data provided the wind profiles, temperature and humidity for analysis of the atmospheric boundary layer profiles.

The micro radar and the surface data were measured at the site of Outeiros (01°16’03” S - 48°25’56” W). The radiosondes were released from the airport (1°22’45” S, 48°28’35” W) which is located at 21 km distance from the Outeiros site. Figure 2 shows the infrastructure in both sites.

The equipment has the following configuration:

- Micro Rain Radar - Vertical pointing micro Doppler rain radar Keplel - 24.1 GHz, Instantaneous or average droplet spectral profile, reflectivity and rain rate, vertical pointing, every 10 seconds.
- Surface station - 3D Sonic Anemometer (Scientific) and Li-COR IRGA from Campbell with a sample tax of 20 Hz and the flux were calculated online.
- Radiosondes - Digicora III (RS 92) from Vaisala.

a) Outeiro site



b) Airport site

Figure 2 - Equipment at the experimental Outeiro (a) and Airport (b) sites. (Source: CHUVA, 2011).

2.4. Model description

To understand how well the shallow convection may be represented by the atmospheric models, the idealized single-column-model (SCM) has been used to simulate the development of the boundary layer for selected days. The SCM used here is fully described in Suselj *et al.* (2012, 2013). In short, the SCM solves the equations for moist conserved variables (liquid water potential temperature, θ_L; and total water mixing ratio q_t) and horizontal wind components (u and v). Atmospheric turbulence and convection are assumed to be subgrid scale processes and are parameterized with a unified eddy-diffusivity/mass-flux (EDMF) scheme. In the EDMF framework, turbulent fluxes are written as a sum of eddy-diffusivity contribution and a mass-flux contribution as:

$$\overline{w'\varphi'} = -K_m \frac{\partial \overline{\varphi}}{\partial z} + \sum_{i=1}^{I} a_i w_i (\varphi_i - \overline{\varphi}) \qquad (1)$$

where $\varphi = \{\theta_L, q_t, u, v\}$.

The first term of the Eq. (1) denotes the eddy-diffusivity part of the turbulent flux. The eddy-diffusivity coefficient (K_m) is a function of the turbulent-kinetic-energy, for which a prognostic equation is solved. The second term on the right hand side of Eq. (1) denotes the mass flux contribution. The mass flux part of the parameterization model steady state laterally entraining convective thermals**.** In Eq. (1) w_i, a_i and φ_i are the vertical velocity, relative area and the value of the moist conserved variable or wind component in the i-th thermal. The thermals can be either dry (with no condensed water) or moist (containing condensed water). To obtain the properties of the thermals, a set of steady state equations for each of the thermals is solved. The key component of the mass-flux model is the treatment of entrainment. In this model, the entrainment is parameterized as a discrete stochastic event, which eventually allows for the realistic representation of turbulent fluxes in cumulus-dominated boundary layer.

The initial conditions for SCM are the profiles of potential temperature, relative humidity and the components of the wind speed taken at 00 UTC from the CHUVA campaign measurements. We initialize the model early in the morning before the onset of the convection to allow the convection to form in the model. The model is forced with a time**-** varying surface latent, sensible and momentum fluxes, also obtained from the measurements. We do not force the model with a horizontal advection of moist conserved variables, since those data is not readily available. As a result of this, the model’s free tropospheric values might drift from the measurements. However, the boundary layer properties do not seem to be highly influenced by the advection. The wind speed is relaxed toward the initial values with a relaxation time of 2 h.

3. Result and Discussions

The days of June 07th, 10th, 11th, 14th and 15th, with strong presence of cumulus clouds over the north of the country and daytime data without the presence of rain were selected by color enhanced infrared satellite images of cloud cover type under Brazil (Fig. 3) aiming to represent the shallow convection. Their synoptic characteristics were analyzed and explained hereafter separately for each day followed by the validation of the parameterization and the turbulent fluxes generated for the SCM results to vertical resolution.

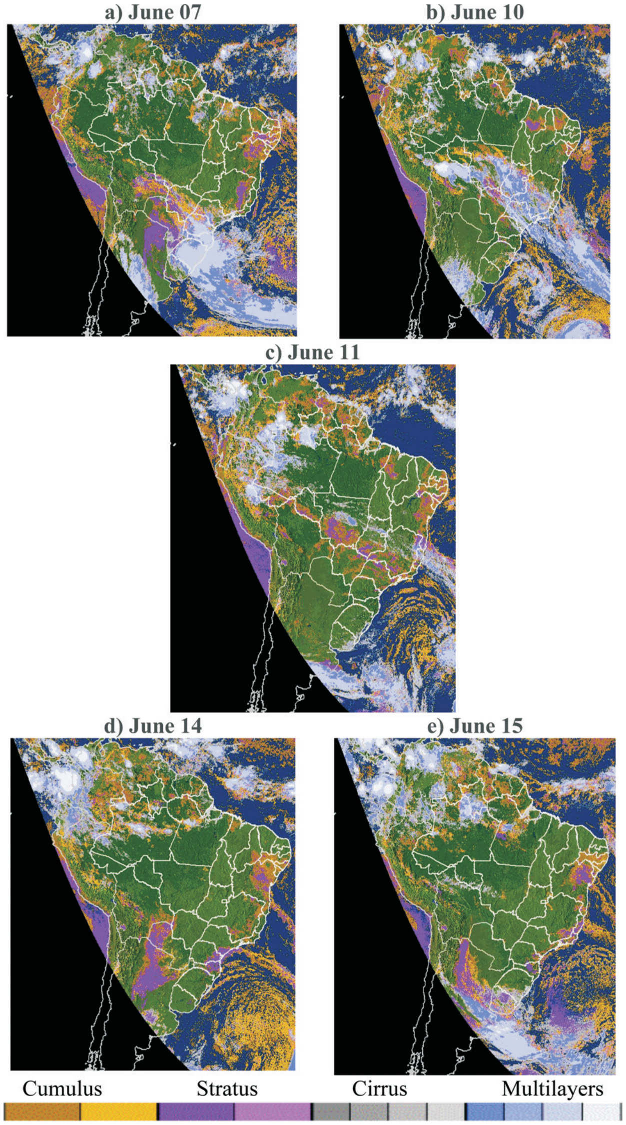


Figure 3 - Enhanced infrared satellite images from the GOES-12 satellite at 12:00 UTC showing the cloud cover over Brazil on June 07th, 10th, 11th, 14th, and 15th of 2011. (Source: DSA - INPE).

The satellite images of June 07th (Fig. 3a) show some cumulus and stratus cloud cover holdover at 12:00 h over the north and center of the Para state. Figure 4 presents detail of infrared satellite images at different hours of the day, where some cumulus clouds are visible toward the northern and coastal areas of the Para state moving southward at the beginning of the day (00:00-06:00 local time). At 18:00 h it is possible to see many convective cores and the formation of the squall lines. The propagation of squall lines to the interior of the continent can be noted. The CHUVA's report (CHUVA, 2011) registered convection around 20:00 h at Belem city (Outeiros site) and after 21:00 h, convection for almost all the Amazonian State; the Intertropical Convergence Zone (ITCZ) was in the north of Brazil, and the south and southeast regions of Brazil were covered by an extra-tropical cyclone. According to Machado (2014) on that day, more than twenty rain events crossed the experimental region; the rain rate at the 99th percentile (corresponding to 1380 J kg^{-1}) was 122 mm h^{-1}. The CAPE was also very high and a cloud top of approximately 13 km at 22:00 UTC was found.

Like the day before, June 10th (Figs. 4a-b) started with clouds over the north of the state and close to the coast. At noon (Fig. 3b) the cloud cover of Para shows some cumulus and stratus clouds over the northern inland area but the coast is clear. At 18:00 h (Fig. 4d), the presence of many convective cores in the north and along the coast was noticed. According to CHUVA's report (CHUVA, 2011), at 21:00 h local convection was noted under the entire Para state. It was an extra-tropical cyclone under the Brazilian southeast region (Fig.4a-d) that influenced the amazon south region. Also the presence of easterly waves arriving in the east coast of Brazilian northeast was noted.

At June 11th the systems on the Para state seem to be associated with the local convection that was formed in the coast. The ITCZ was in the north. In the satellite images (Fig. 4a-d) we can see clouds in the north and close to the ocean during the entire morning. The cloud cover at noon (Fig. 3c) shows the predominance of cumulus clouds over the north of the state. According to CHUVA's report (CHUVA, 2011) in that day the squall lines were formed in the Maranhão coast until Amapa, not showing in the satellite images.

On June 14th the satellite images showed that the day started with more clouds at the coast and convective cores in the north and center of the Para state; at noon we have a predominance of cover of the cumulus and multilayer clouds over the northern inland area; at 18:00 local time the formation of convective cores began, perhaps because of the interaction between the sea breeze circulation and ITCZ. It is noted (Fig. 4d) that the squall line system was formed at the Para coast and followed toward the continent. Note that there are well formed convective cores at 6:00 and 18:00 h.

At 00:00 GMT on June 15th (Fig. 4a) the dissipation of the convective system in the northeast of Para can be

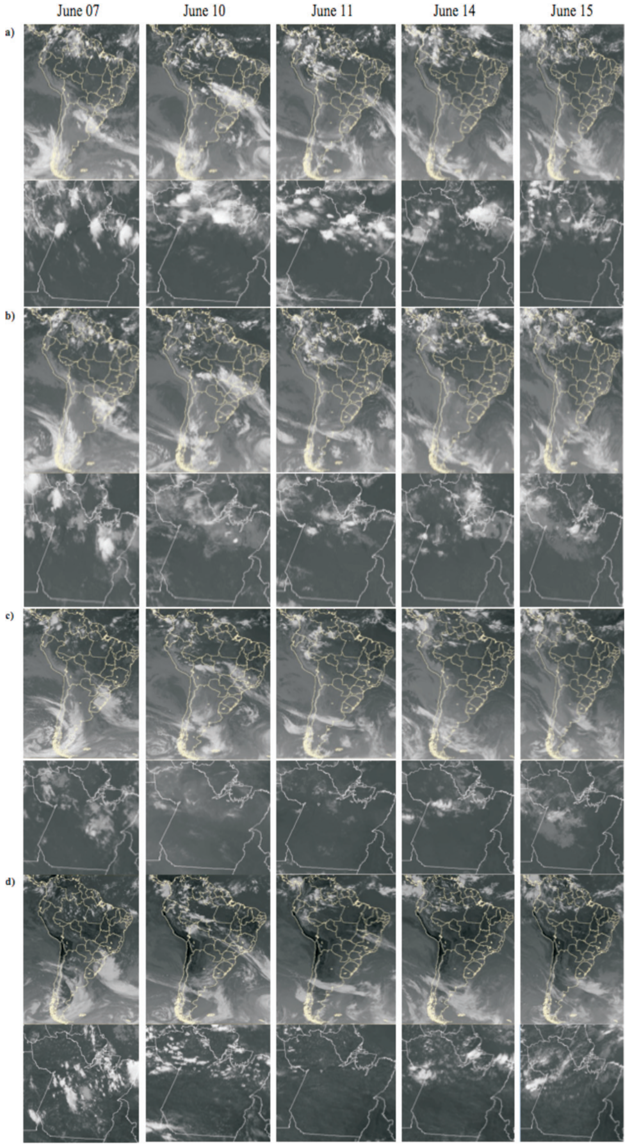


Figure 4 - GOES-12 satellite infrared image from Brazil (channel 2) and Para state (channel 4) at (a) 00:00, (b) 06:00, (c) 12:00 and (d) 18:00 local time on June 07th, 10th, 11th, 14th, and 15th of 2011. (Source: DSA - INPE).

noted, causing weak and isolated rains; instability areas at the western Amazon are starting to be formed. At noon notice the predominance of cumulus cloud cover in the northern of the Para state (Fig.3e). At 18:00, the presence of shallow and stratiform clouds along the northern part of the state is noted. According to CHUVA's report (CHUVA, 2011) the ITCZ was in its position further north and at 21:00h the convective cell was in the mature and dissipation phase.

Figure 5 shows the comparison between the observational data and the SCM for the potential temperature and Fig. 6 shows the relative humidity comparison between the SCM and the observational data for the selected days. Table 1 shows the bias (the difference between the simulated and observed values) and the root mean square error (rmse) for the potential temperature and relative humidity profiles. Notice that for the potential temperature the smallest value is at 12:00 h on June 7th (0.18 K) and the biggest one is at June 11th (-2.32 K) and the rmse ranges from 0.59 to 2.99 K. For Relative Humidity Table 1 shows a substantial difference on the relative humidity between the days with the bias ranging from 3.06% to 16.11% and rmse ranging from 8.08% to 24.14%. Gochis *et al.* (2001) in his study about the sensitivity of the modeled North American monsoon to convective parameterization showed significant differences between mean biases, at the 95% level, of the modeled and observed temperature, specific humidity and equivalent potential temperature at seven stations.

At June 7th (Fig. 5a), although the negative potential temperature bias at 18:00 was shown as -0.67 K (Table 1), the profile was represented very well. The potential temperature for the day June 10th (Fig. 5b) shows a good comparison between the SCM and observational data, also despite of the negative potential temperature bias at noon (Table 1) but the relative humidity (Fig.6b) shows only a similar tendency between the observational data and the model in the first few meters of height. June 11th shows a negative bias during noon of -2.32 K (Table 1), but at 18:00 h the potential temperature showed a very good accord between the observational and model data (Fig. 5c). This might be due to the presence of clouds on that day without any precipitation. The tendency of relative humidity agreed somewhat better on this day than on the days before; the model seems to have coherency until 1300 m of height (Fig. 6c). At June 14th note that the relative humidity at 18:00 (Fig. 6d) is generally similar between the observational and model data until approximately 1300 m. This period of the day also presents the smallest bias and rmse values for the relative humidity (Table 1). The potential temperature (Fig. 5d) shows a good agreement also, especially at 18:00 h. June 15th showed a good agreement of potential temperature at 12:00 h (Fig. 5e); at this time we note clouds (Fig. 4c) towards the interior of the state and no tendency was shown for the relative humidity at the same time (Fig. 6e). At least there is tendency at 18:00 h (Fig. 6e), but with an rmse of 18.50% in the relative humidity, shown in Table 1.

The observational hourly turbulent flows data (Figs. 7, 8 and 9) was used as input to analyze the vertical motions of energy in the atmosphere through the both latent and sensible heat generated by the SCM in the vertical resolution of the turbulent flows at 6:00, 12:00 and 18:00 local time of the days June 7th, 10th, 11th, 14th and 15th (Fig. 10). It is noteworthy that the number of studies related exclusively with turbulent flows of the atmosphere eastward from the Amazon is still limited in the formal literature, making a comparison between the results inadequate. However, citations about the articles and their results in the neighboring regions of Belem will be shown.

The surface friction velocity (u_*) cycle (Fig. 7) present significant values until 13:00 h for all days; af-

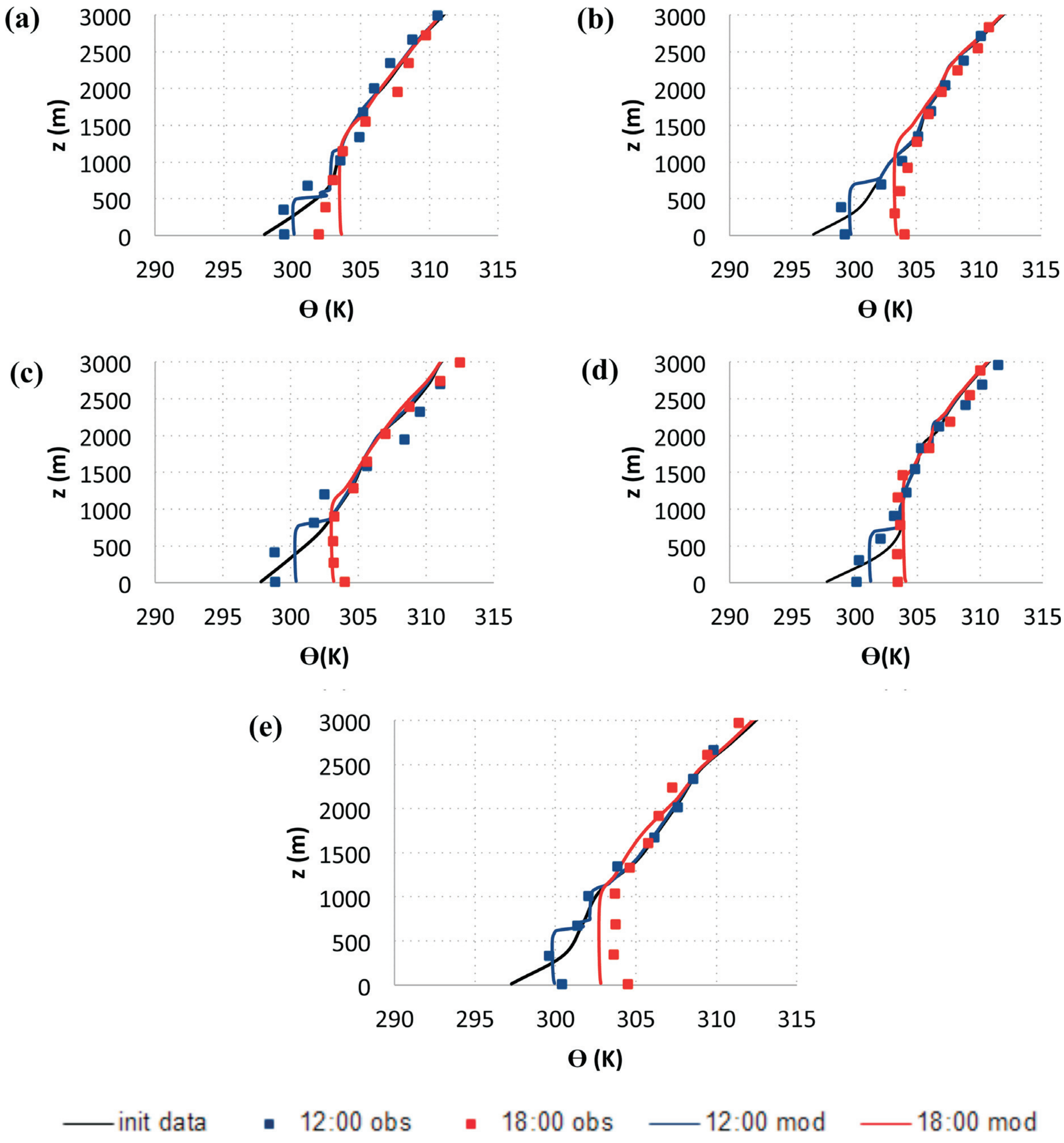


Figure 5 - Potential temperature for June 7th (a), June 10th (b), June 11th (c), June 14th (d) and June 15th (e). The initial data in black solid line, dashed line for the observational data, blue at 12:00 and red at 18:00. Colored solid lines for model results in blue 12:00 and red 18:00 local time.

Table 1 - Bias and Rmse statistics for the potential temperature profiles of June 07th, 10th, 11th, 14th and 15th at 12:00 and 18:00 h.

	Potential temperature (θ)				Relative humidity			
	Bias (K)	Rmse (K)	Bias (K)	Rmse (K)	Bias (%)	Rmse (%)	Bias (%)	Rmse (%)
Days	12:00		18:00		12:00		18:00	
June 7th	0.18	0.70	-0.67	1.16	10.63	16.39	12.48	15.46
June 10th	-0.64	0.99	1.29	2.22	11.60	14.16	14.82	15.90
June 11th	-2.32	2.99	0.68	0.93	14.65	24.14	16.11	21.68
June 14th	0.78	1.23	0.64	0.94	11.04	19.04	5.56	8.08
June 15th	0.41	0.59	1.41	2.29	3.06	11.31	11.82	18.50

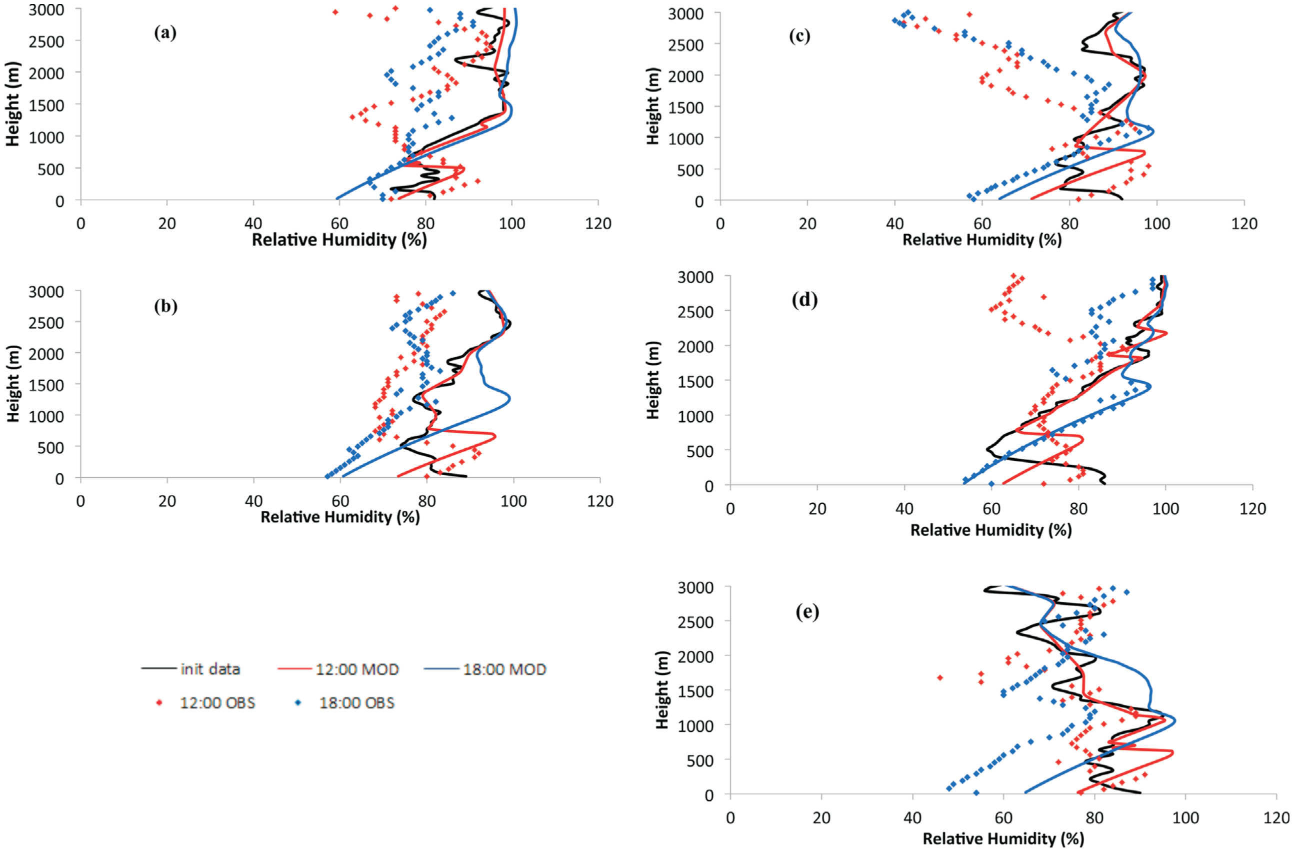


Figure 6 - Relative humidity for June 7th (a), June 10th (b), June 11th (c), June 14th (d) and June 15th (e). The initial data in black solid line, dashed lines for the observational data, red at 12:00 and blue at 18:00. Colored solid lines for model results in red 12:00 and blue 18:00 local time.

ter that, there are disparities between 13:00 and 16:00 h on June 7th and 14th, and between 14:00 and 16:00 h on June 10th, where the values increase to 0.5 ms^{-1}. Roballo, 2007, analyzed values of u_* at the Maranhão coast of Brazil during the dry and rain periods of 1995-1999 year, finding values between 0.48 and 0.38 for the June month according with 3.3 m movement in the zero plane d.

Figures 8 and 9 shows the Latent (LE) and sensible Heat Fluxes (H) for the days June 7th, 10th, 11th, 14th and 15th. Note that the biggest values at 12:00 h for LE are between 300 and 400 W m^{-2} and the H is between 80 and 200 W m^{-2}. June 7th presents the smallest mean of LE with its maximum value around 300 W m^{-2} at noon. At 14:00 and 16:00 h on June 10th, negative peaks of LE are shown and June 15th presents a peak value at 20:00h. Studies per-

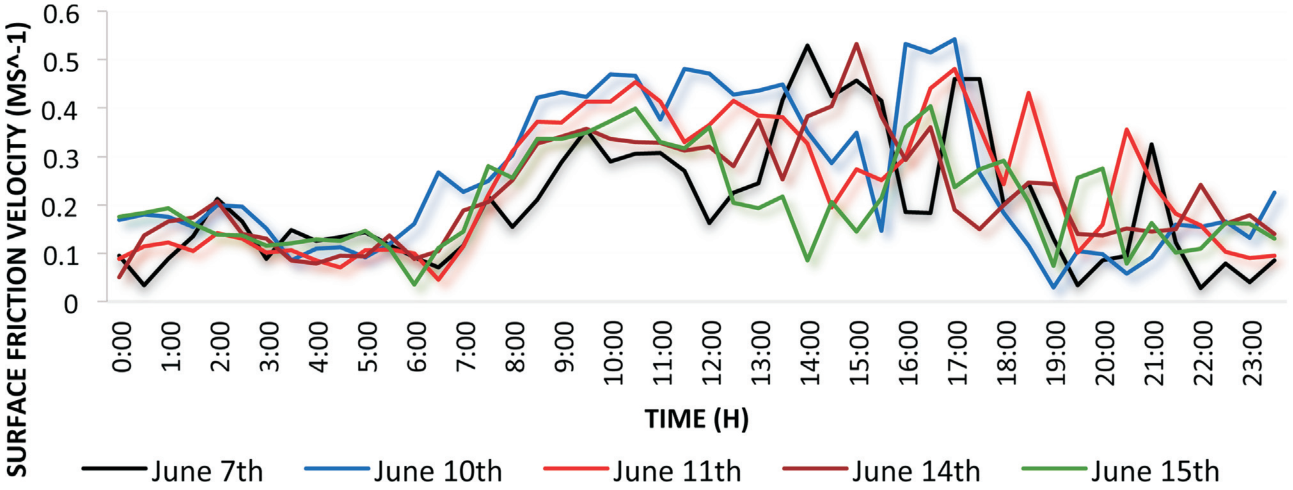


Figure 7 - Surface friction velocity cycle for the CHUVA experiment on June 7th, 10th, 11th, 14th and 15th.

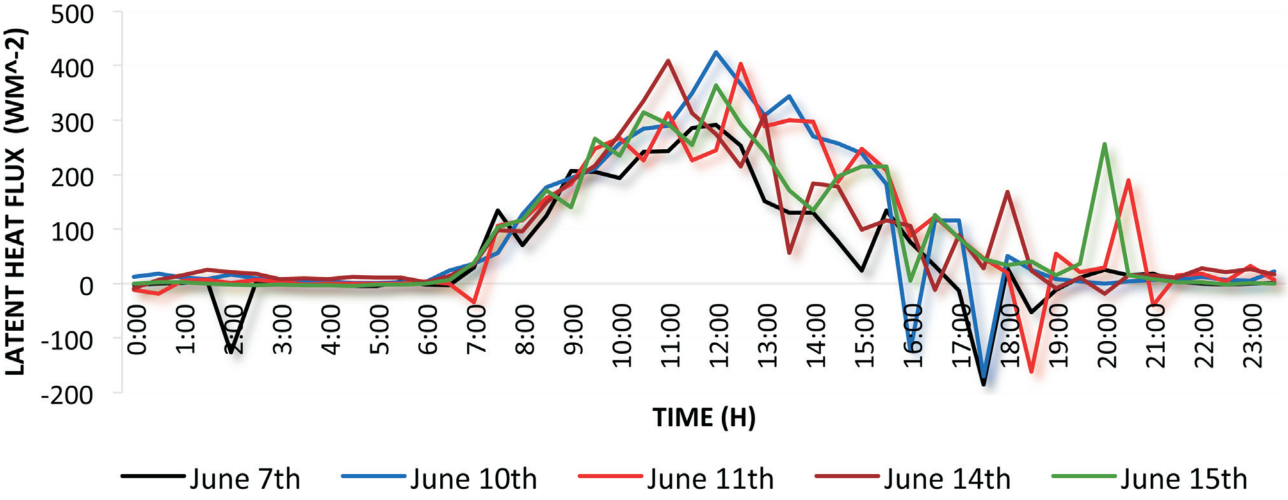


Figure 8 - Latent heat fluxes cycle for the CHUVA experiment on June 7th, 10th, 11th, 14th and 15th.

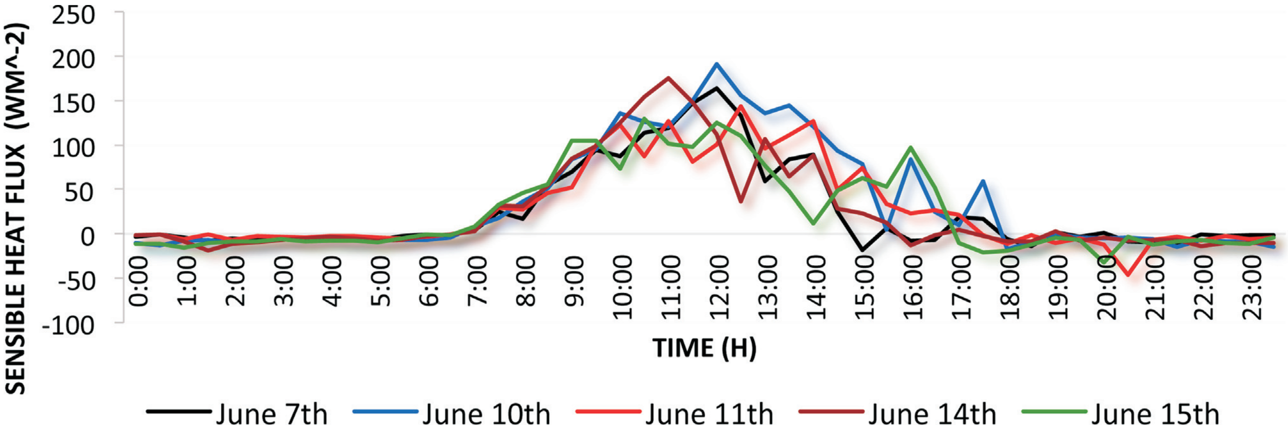


Figure 9 - Sensible heat fluxes cycle for the CHUVA experiment on June 7th, 10th, 11th, 14th and 15th.

formed during rain periods in the Caxiuana forest (Belem region) for Souza Filho (2002) present the values of 307.7 W m^{-2} (LE) and 105.4 W m^{-2} (H); in periods of less rain the values were 431.62 W m^{-2} (LE) and 162.9 W m^{-2} (H) at 12:00 h. Da Rocha *et al.* (2004) in his study about the seasonality of water and heat fluxes over a tropical forest in the eastern Amazon, made in the Tapajós National Forest, 83 km from Santarém, state of Pará, which analyses were divided into 15 July to 14 December as the dry season and the remaining period as the wet season for the year of 2000-2001, found the values of LE for the wet season around 300 W m^{-2} (LE) and 80 W m^{-2} (H) and for the dry season around 350 W m^{-2} (LE) and 100 W m^{-2} (H) at 12:00h. Souza *et al.* (2009) in their studies about shallow convection and radiation in the diurnal cycle using the BRAMS (Brazilian developments on the Regional Atmospheric Modelling System) and validating with Rondonia site experiments in the month of February found values around 100 W m^{-2} (H) and about 340 W m^{-2} (LE) at noon for the west wind regime and around 180 W m^{-2} (H) and 320 W m^{-2} for the east wind regime in the case of the interaction between the radiation and the shallow convection.

Figure10 shows the vertical turbulent fluxes obtained by the SCM for 6:00, 12:00 and 18:00 h of at June 7th, 10th, 11th, 14th and 15th. We note that the largest profiles of LE and H occur at June7th going until 3500m. June 10th presents values of H higher than 350 W m^{-2}. June 14th, which showed the smallest % of bias and rmse related with the relative humidity at 18:00 (Table 1), as illustrated in Fig. 10, peaks close to 2000 m at 18:00 h where the value of LE goes to approximately -10 W m^{-2} and H to approximately 60 W m^{-2}.

4. Conclusions

To keep the work consistent, a synoptic study using satellite images was carried out to identify the optimal days and physical conditions to obtain better approximations for the results of the SCM and the CHUVA data campaign. It was noted that the potential temperature was overall predicted very well by the model. Regarding relative humidity,

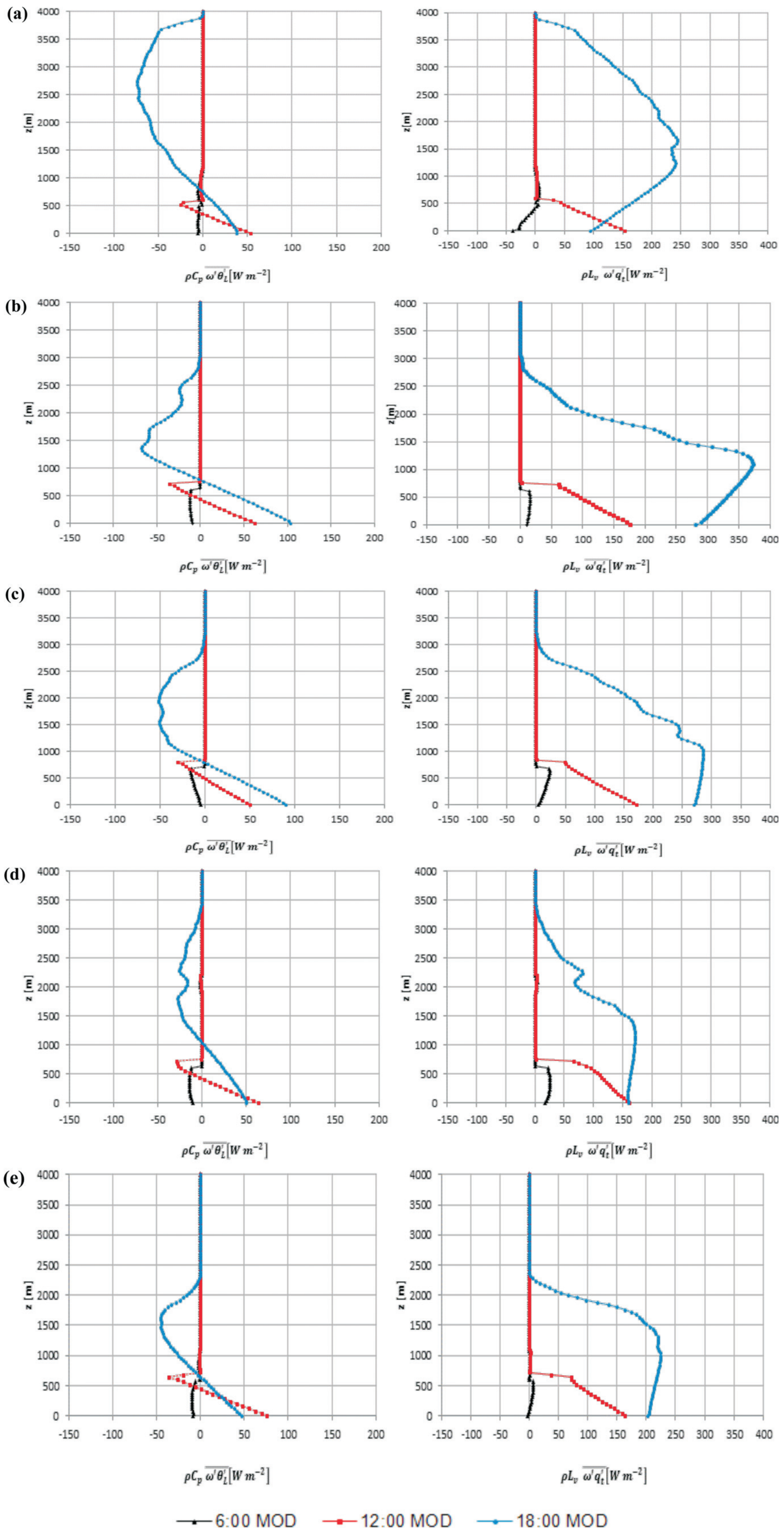


Figure 10 - Turbulent fluxes generated from the SCM at 6:00, 12:00 and 18:00 local time on June 7th(a), June 10th (b), June 11th (c), June 14th (d) and June 15th (e).

the model follows a tendency in the first meters of height and in some cases such as on June 14th at 18:00 h, when the core of clouds was very consistent under Belem, the agreement between the model and the observational data are reasonably good. For a day such as June 11th at 18:00 h the model was also quite precise in the modeling of the relative humidity; on this day clouds were present without any precipitation.

It is important to note that the SCM used in this article assumes horizontal homogeneity and cannot simulate sea-breeze conditions. Another factor to be considered is that the horizontal advection of moist conserved variables were not forced into the model, causing a drift of the model's predictions for the free tropospheric values from the actual measurements. The general profile of potential temperature structure was reproduced well, although negative potential temperature bias is identified for two days at noon and for one day in the afternoon (18:00 h). Considering that June is the end of the rainy station in Belem, it was noticed that the Latent (LE) and sensible Heat Fluxes (H) generated by the SCM agreed with the values available in the literature from the observational studies made in the Caxiuana forest in the Belem region and the Tapajós National Forest in the Pará state.

This initial study about the Jet Propulsion Laboratory / NASA model of shallow convection parameterization in a framework of the single column model for the Amazon coastal region demonstrated a good starting point but much more still needs to be done for that particular region. The work of parameterization of the Amazon region in all of its complexity, in addition to the problem of tropical convection parameterization generally, remains a challenge. It is a consensus among the experts that more attention needs to be given to convective parameterizations and that shallow convection parameterization plays a key role in the accuracy of global models, because it affects vertical structures. However, the number of studies focused solely on convective parameterization in large-scale models in the Amazon, also is quite limited in the formal literature. There are even fewer publications available regarding the areas east of the Amazon, restricting opportunities for meaningful comparisons.

These analyses were our first step in parameterization of the model of the Amazon region. Future studies in different regions of the Amazon are being planned to test the accuracy and sensibility of the SCM model in different scenarios.

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References

ADAMS, D.K.; SOUZA, E.P.; COSTA, A.R. Convecção úmida na Amazônia: Implicações para a modelagem numérica. **Revista Brasileira de Meteorologia**, v. 24, n. 2, p. 168-178, 2009.

ADAMS, D.K.; FERNANDES, R.M.S.; HOLUB, K.L.; GUTMAN, S.I.; BARBOSA, H.M.J. *et al.* The Amazon Dense GNSS Meteorological Network: A New Approach for Examining Water Vapor and Deep Convection Interactions in the Tropics. **Bulletin of the American Meteorological Society**, v. 96, p. 2151-2165, 2015.

ARAKAWA, A. The Cumulus Parameterization Problem: Past, Present, and Future. **Journal of Climate**, v. 17, n. 13, p. 2493-2525, 2004.

BASTOS, T.X.; PACHECO, N.A.; NECHET, D.; ABREU SÁ, T.D. Aspectos Climaticos de Belém nos Ultimos Cem Anos, EMBRAPA, Empresa Brasileira de Pesquisa Agropecuária, Pesquisa Agroflorestal da Amazônia Oriental, Ministerio da Agricultura, Pecuaria e Abastecimento, 31 p., ISSN 1517-2201, Fevereiro, 2002.

BECHTOLD, P.; CHABOUREAU, J.P.; BALJAARS, A.; BETTS, A.K.; KöHLER, M.; *et al.* The Simulation of the Diurnal Cycle of Convective Precipitation over Land in a Global Model. **Quarterly Journal of the Royal Meteorological Society**, v. 130, p. 3119-3137, 2004.

BOTTINO, M.J.; CEBALLOS, J.C.; LIMA, W.F.A. Classificação de Nuvens em Imagens Multiespectrais GOES-8 na Região Amazônica: Comparação com Radiossondagens. Third LBA Scientific conference, 2004, **Anais...** Brasília, Brasil.

CAMPOS, T.L.O.B.; MOTA, M.A.S.; SANTOS, S.R.Q. Eventos Extremos de Precipitação em Belém-PA: Uma Revisão de Notícias Históricas de Jornais. **Revista Ambiente & Água**, v. 10, n.1, p. 182-194, 2015.

CAVALCANTI, I.F.A.; MARENGO, J.A.; SATYAMURTY, P.; NOBRE, C.A.; TROSNIKOV, I.; *et al.* Global Climatological Features in a Simulation Using the CPTEC-COLA AGCM. **Journal of Climate**, v. 15, n. 21, p. 2965-2988, 2002.

CEBALLOS, J.C.; BOTTINO, M.J. Classificação Automática de Cenas: Uma Análise da Informação Mínima Contida em Imagens GOES-8 Multiespectrais. X Congresso Brasileiro de Meteorologia, 1998, **Anais...** Brasília, Brasil (COMPACT DISK ART. MS98032).

CHAGNON, F.J.F.; BRAS, R.L.; WANG, J. Climatic Shift in Patterns of Shallow Clouds over the Amazon. **Geophysical Research Letters**, v.31, Issue 24, L24212, 2004.

CHOU, S.C.; NOBRE, P. Avaliação de Modelos Globais e Regionais Climáticos. In: AMBRIZZI, T.; ARAUJO, M. **Base Científica das Mudanças Climáticas**. Rio de Janeiro: COPPE, v. 1, p. 278-319, 2015.

COHEN, J.C.P.; DIAS, M.A.F.S; NOBRE, C.A. Environmental Conditions Associated with Amazonian Squall Lines: A Case Study. **Monthly Weather Review**, v. 123, Issue 11, p. 3163-3174, 1995.

COHEN, J.C.P.; CAVALCANTI, I.F.A.; BRAGA, R.H.M. Linhas de instabilidade na costa N-NE da América do Sul. In.

CAVALCANTI, I.F.A.; FERREIRA, N.J.; SILVA, M.G.A.J.; DIAS, M.A.F.S. (Orgs.). **Tempo e Clima no Brasil**. São Paulo: Oficina de Texto. p. 75-92, 2009.

CUTRIM, E.M.; MOLION, L.C.B.; NECHET, D.: Chuvas na Amazônia durante o século XX, XI CONGRESSO BRASILEIRO DE METEOROLOGIA, 2000, **Anais...** Rio de Janeiro, Brasil.

DA ROCHA, H.R.; GOULDEN, M.L.; MILLER, S.D.; MENTON, M.C.; PINTO, L.D.V.O.; *et al.* Seasonality of Water and Heat Fluxes over a Tropical Forest in Eastern Amazonia, **Ecological Applications***,* v. 14, p. 22-32, 2004.

DE SOUZA, E.B.; AMBRIZZI, T. ENSO Impacts on the South American Rainfall during 1980s: Hadley and Walker circulation. **Atmósfera**, v. 15, n. 2, p. 105-120, 2002.

FERREIRA, D.B.S.; DE SOUZA, E.B.; MORAES, B.C.; MEIRA FILHO, L.G. Spatial and Temporal Variability of Rainfall in Eastern Amazon during the Rainy Season, **The Scientific World Journal**, v. 2015, p. 1-9, 2015.

FIGUEROA, S.N.; NOBRE, C.A. Precipitations Distribution over Central and Western Tropical South America. **Climanálise - Boletim de Monitoramento e Análise Climática**, v. 5, n. 6, p. 36-45, 1990.

FU, R.; ZHU, B.; DICKINSON, R. How do Atmosphere and Land Surface Influence Seasonal Changes of Convection in the Tropical Amazon. **Journal of Climate**, v. 12, p. 1306-1321, 1999.

GARSTANG, M.; GRECO, S.; SCALA, J.; SWAP, R.; ULANSKI, S.; *et al.* The Amazon Boundary Layer Experiment (ABLE 2B): A Meteorological Perspective. **Bulletin of the American Meteorological Society**, v. 71, p. 19-32, 1990.

GARSTANG, M.; MASSIE Jr., H.L.; HALVERSON, J.; GRECO, S.; SCALA, J. Amazon Coastal Squall Lines. Part I: Structure and Kinematics. **Monthly Weather Review**, v. 122, p. 608-622, 1994.

GILLE, F.S.S.; MOTA, M.A.S. Importância das Condições Termodinâmicas nos Eventos Extremos de Precipitação na Cidade de Belém e Região Metropolitana. **Revista Brasileira de Meteorologia**, v. 29, n. esp., p. 73-82, 2014.

GOCHIS, D.J.; SHUTTLEWORTH, W.J.; YANG, Z.L. Sensitivity of the Modeled North American Monsoon Regional Climate to Convective Parameterization. **Monthly Weather Review**, v. 130, p. 1282-1298, 2001.

GRABOWSKI, W.W.; BECHTOLD, P.; CHENG, A.; FORBES, R.; HALLIWELL,C.; *et al.* Daytime Convective Development over Land: A model Intercomparison based on LBA Observations. **Quarterly Journal of the Royal Meteorological Society**, v. 132, p. 317-344, 2006.

GRECO, S.; SWAP, R.; GARSTANG, M.; ULANSKI, S.; SHIPHAM, M.; *et al.* Rainfall and Surface Kinematic Conditions over Central Amazonia During ABLE 2B. **Journal of the Geophysical Research**, v. 95, p. 17001-17014, 1990.

GRECO, S.; SCALA, J.; HALVERSON, J.; MASSIE, H.L.; TAO, W.K.; *et al.* Amazon Coastal Squall Lines. Part II: Heat and Moisture Transports. **Monthly Weather Review**, v. 122, p. 623-635, 1994.

KAIN, J.S. The Kain-Fritsch Convective Parameterization: An Update. **Journal of Applied Meteorology**, v. 43, p. 170-181, 2004.

KHAIROUTDINOV, M.F.; RANDALL, D.A. Cloud Resolving Modeling of the ARM Summer 1997 IOP: Model Formulation, Results, Uncertainties, and Sensitivities. **Journal of the Atmospheric Sciences**, v. 60, p. 607-625, 2003.

LIN, X.; RANDALL, D.A.; FOWLER, L.D. Diurnal Variability of the Hydrological Cycle and Radiative Fluxes: Comparisons between Observations and a GCM. **Journal of Climate**, v. 13, p. 4159-4179, 2000.

LOPES, Z.F.; DE SOUZA, E.P.; GALVÍNCIO, J.D. Estudo Numérico da Interação entre Convecção Rasa e Radiação com ênfase no Ciclo Diurno do Balanço de Energia à Superfície: Comparação entre duas Simulações. **Revista de Geografia (UFPE)**, v. 29, n. 1, p. 193-208, 2012.

LOPEZ, P. Cloud and Precipitation Parameterizations in Modeling and Variational Data Assimilation: A Review. **Journal of the Atmospheric Sciences**, v. 64, p. 3766-3784, 2007.

MACHADO, L.A.T.; DIAS, M.A.F.S.; MORALES, C.; FISCH, G.; VILA, D.; *et al.* The CHUVA Project - How does Convection vary across Brazil? **Bulletin of the American Meteorological Society**, v.95, p. 1365-1380, 2014.

MARENGO, J.A.; HASTENRATH, S. Case Studies of Extreme Climatic Events in the Amazon Basin. **Journal of Climate**, v. 6, p. 617-627, 1993.

MARENGO J.A.; LIEBMANN, B.; KOUSKY, V.E.; FILIZOLA, N.P.; WAINER, I.C. Onset and End of the Rainy Season in Brazilian Amazon Basin. **Journal of Climate**, v. 14, p. 833-852, 2001.

MORAES, B.C.; FERREIRA, D.B.S.; FILHO, L.G.M.; OLIVEIRA, J.V.; SOUZA, E.B.; *et al.* Comparative Skill of Numerical Weather Forecasts in Eastern Amazonia. **Atmospheric and Climate Sciences**, v. 3, p. 355-363, 2013.

MOURA, M.N.; VITORINO, M.I. Variabilidade da Precipitação em Tempo e Espaço associada à Zona de Convergência Intertropical. **Revista Brasileira de Meteorologia**, v. 27, n. 4, p. 475 - 483, 2012.

NECHET, D. Variabilidade Diurna de Precipitação em Belém-PA: Aplicação em Planejamentos a Médio e Longo Prazo. **Boletim Climatológico dos Anais do II Simpósio Brasileiro de Climatologia Geográfica**. Presidente Prudente, SP, v. 2, n. 3, p. 223-227, 1997.

NEGRI, A.J.; ANAGNOSTOU, E.N.; ADLER, R.F. A 10-yr Climatology of Amazonian Rainfall Derived from Passive Microwave Satellite Observations. **Journal of Applied Meteorology**, v. 39, p. 42-56, 2000.

NOBRE, P.; SIQUEIRA, L.S.P.; ALMEIDA, R.A.F.; MALAGUTTI, M.; GIAROLLA, E.; *et al.* Climate Simulation and Change in the Brazilian Climate Model. **Journal of Climate**, v. 26, p. 6716-6732. 2013.

PETERSEN, W.A.; NESBITT, S.W.; BLAKESLEE, R.J.; CIFELLI, R.; HEIN, P.; *et al.* TRMM Observations of Intraseasonal Variability in Convective Regimes over the Amazon. **Journal of Climate**, v. 15, p. 1278-1294, 2002.

PETERSEN, W.A.; FU, R.; CHEN, M.; BLAKESLEE, R. Intraseasonal Forcing of Convection and Lightning Activity in the Southern Amazon as a Function of Cross-Equatorial Flow. **Journal of Climate**, v. 19, p. 3180-3196, 2006.

RIBEIRO, W.M.N.; SOUZA, J.R.S.; LOPES, M.N.G.; CAMARA, R.K.C.; ROCHA, E.J.P.; *et al.* Lightning and Precipitation Produced by Severe Weather Systems over Belém, Brazil. **Revista Brasileira de Meteorologia**, v. 29, n. esp., p. 41-59, 2014.

ROBALLO, S. T. **Estudo do Escoamento Atmosférico na CLA, através de Medidas em Torre Anemométrica e em Túnel de Vento**. Dissertação de Mestrado em Meteorologia, Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, 2007.

SOUZA, E.P.; LOPES, Z.F.; ARAUJO, T.L. Estudo numérico da interação entre convecção rasa e radiação com ênfase no ciclo diurno do balance de energia a superfície na Amazônia. **Revista Brasileira de Meteorologia**, v. 24, n. 2, p. 158-167, 2009.

SOUZA FILHO, J.D.C. **Variação Sazonal dos Componentes do Balanço de Radiação e Energia sobre a floresta de Caxiuanã**. Tese de Doutorado em Meteorologia, Universidade Federal de Viçosa, Viçosa, 2002.

STULL, R.B. A Fair-Weather Cumulus Cloud Classification Scheme for Mixed-Layer Studies. **Journal of Climate and Applied Meteorology**, v. 24, p. 49-56, 1985.

SUŠELJ, K.; TEIXEIRA, J.; MATHEOU, G. Eddy Diffusivity/Mass Flux and Shallow Cumulus Boundary Layer: An Updraft PDF Multiple Mass Flux Scheme. **Journal of Atmospheric Sciences**, v. 69, p. 1513-1533, 2012.

SUŠELJ, K.; TEIXEIRA, J.; CHUNG, D. A Unified Model for Moist Convective Boundary Layers Based on a Stochastic Eddy-Diffusivity/Mass-Flux Parameterization. **Journal of Atmospheric Sciences**, v. 70, p. 1929-1953, 2013.

TAVARES, J.P.N.; MOTA, M.A.S. Condições termodinâmicas de eventos de precipitação extrema em Belém - PA durante estação chuvosa. **Revista Brasileira de Meteorologia**, v. 27, n. 2, p. 207-218, 2012.

VIANELLO, R.L.; ALVES, A.R. **Meteorologia básica e Aplicações**. Viçosa (MG): Imprensa Universitária, 449 p., 1991.

YANG, G.Y.; SLINGO, J. The Diurnal Cycle in the Tropics. **Monthly Weather Review**, v. 129, p. 784-801, 2001.

Internet Resources

CHUVA Project, 2011. Campanha de Belém. Available at: http://chuvaproject.cptec.inpe.br/portal/belem/br/index.html. Accessed August 28, 2014.

DSA, Divisão de Satélites e Sistemas Ambientais, Centro de Previsão do Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais. Available at: http://satelite.cptec.inpe.br/informacao/orbitas.jsp. Accessed March 19, 2016.

GPM, Global Precipitation Measurement, National Aeronautics and Space Administration, Goddard Space Flight Center, 2014. Available at: http://pmm.nasa.gov/node/243. Accessed March 19, 2016.

IBGE, Instituto Brasileiro de Geografia e Estatística, Censo Demográfico 2010. Available at: http://cidades.ibge.gov.br/xtras/perfil.php?lang=&codmun = 150140&search=para belem.Accessed March 19, 2016.