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LIGHTNING AND PRECIPITATION PRODUCED BY SEVERE WEATHER SYSTEMS OVER BELÉM, BRAZIL

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ABSTRACT

CG Lightning flashes events monitored by a LDN of the Amazon Protection System, which included 12 LPATS IV VAISALA sensors distributed over eastern Amazonia, were analyzed during four severe rainstorm occurrences in Belem-PA-Brazil, in the 2006-2007 period. These selected case studies referred to rainfall events, which produced more than 25 mm/hour, or more than 40 mm/ 2 hours of precipitation rate totals, registered by a tipping bucket automatic high-resolution rain gauge, located at 1° 47' 53'' S and 48° 30' 16" W. Centered at this location, a 30 ,10 and 5 km radius circles were drawn by means of a geographic information system, and the data from lightning occurrences within this larger area, were set apart for analysis. During these severe storms the CG lightning events, occurred almost randomly over the surrounding defined circle, previously covered by mesoscale convective systems, for all cases studied. This work also showed that the interaction between large-scale and mesoscale weather conditions have a major influence on the intensity of the storms studied cases. In addition to the enhancement of the lightning and precipitation rates, the electric activity within the larger circles can precede the rainfall at central point of the areas
Keywords: Lightning, Storms, Amazonia.

RESUMO: RELÂMPAGO E PRECIPITAÇÃO PRODUZIDOS POR SISTEMAS DE TEMPO SEVERO EM BELÉM, BRASIL

Eventos de raios nuvem-solo registrados pela rede de detecção do SIPAM, integrada por 12 sensores VAISALA LPATS IV, distribuídos no leste da Amazônia, foram analisados durante 4 tempestades com ocorrência de precipitação intensa em Belém-PA-Brasil, em 2006-2007. Esses casos selecionados, correspondem a eventos de chuva com mais de 25 mm/hora ou 40 mm/ 2 horas, de precipitação registrada por um pluviômetro instalado em 1° 47' 53'' and 48° 30' 16" O. Com centro nessa localização, um círculos de 30, 10 e 5 km de raio foram traçados através de um sistema de informação geográfica e os dados de eventos de raios nessas áreas foram separados para analise. Durante essas tempestades, os eventos de raios ocorreram de maneira quase aleatória, sobre a área maior que já havia sido previamente coberta por sistemas convectivos de mesoescala, em todos os casos. Esse trabalho também mostrou a grande influencia dos sistemas de larga escala nas condições de tempo que levaram às tempestades severas estudadas. Adicionalmente, foi observado que, quando existe interação entre sistemas de larga e meso escalas, tanto a precipitação como o numero de relâmpagos aumentaram significativamente e a atividade elétrica nos círculos maiores pode anteceder a chuva no ponto central.
Palavras-chave: raios, tempestades severas, Amazônia.

1. INTRODUCTION

Severe weather has been a permanent concern to people, considering its potential to cause loss of lives, damage to property, and regarding other environmental concerns, all over the world (Ortega et al., 2009; Kohn, et al., 2011; Qie et al., 2009; Dimitrova et al., 2009;Pucik et al., 2011). Intense rainfall and lightning storm occurrences are associated to strong convection and meteorological systems in large and mesoscales, which enhance them following the daily solar heating pulses (Feng et al.,2009; Mastrangelo et al., 2011; Sátori et al., 2009; Matsudo and Salio, 2011; Mattos and Machado, 2011; Curic et al., 2009).

The events of rainfall and lightning storms naturally depend on the local climate, land and ocean surface characteristics. Their forecasts are of critical importance when they occur over populated or urban regions as is the case of Belém, whose metropolitan area has over 2.5 million inhabitants.

In Brazil several studies have been made on this topic (Farias et al., 2009; Rodriguez et al., 2010; Machado et al., 2009; Almeida et al.,2011; Davidson et al., 2012; Silva Dias, 2007). In the especial case of the Brazilian Amazon Region these studies are scarce, and the present work is supposed to contribute to the understanding of the peculiarities of the regional weather, when intense storms occur. It deals with four severe storms occurrences with the objective to find out the climatic context and the characteristics of the meteorological systems which produced them, as well as, the time and space relationships between precipitation and lightning.

The severe weather storms in Belém should be studied taking into account the regional climatic characteristics. For instance, El Niño events in the Pacific Ocean appear to decrease the total rainfall in the eastern Amazon, while during La Niña periods one observes positive anomalies of precipitation (Cutrim et al., 2000). These authors determined a high correlation between the anomalies of sea surface temperatures (SST) of the Pacific and Tropical Atlantic oceans, with the duration of the rainy season in this Region. The occurrence of a positive SST anomaly in the Equatorial Pacific favors a short rainy season in the Amazon. However, when a positive anomaly occurs in the Tropical South Atlantic, a long rainy season is observed in the same region.

The convection in the Amazon region is an important mechanism for heating of the tropical atmosphere and its variations, in terms of intensity and position, play a key role in determining the weather and climate of this region. Waliser and Gautier (1993) showed the importance of the Intertropical Convergence Zone (ITCZ) in the definition and analysis of the terrestrial climate on a global scale. Molion (1993) studied the macro and mesoscale circulations that act in the Amazon and the dynamic processes that organize and promote the precipitation in that area. The dynamic mechanisms that produce precipitation in the Amazon were also described by Vianello and Alves (1991). According to these authors they result from the combination of the predominant role played by the ITCZ, the squall lines, the penetration of frontal systems, the source of water vapor represented by the Amazon forest and the role of the Andes. On the other hand, the occurrence of mesoscale systems such as squall lines, may be responsible for up to 45% of the precipitation in the eastern Amazon Region (Cohen et al., 1989).

In addition to the above mentioned meteorological phenomena, the Amazonian climate variability is significantly influenced by the intra-seasonal large scale phenomenon called the South Atlantic Convergence Zone (SACZ) (Kodama, 1992; Quadro, 1994; Nogues-Paegle and Mo, 1997; Liebmann et al., 1999). This extensive cloudiness band produces large increments of precipitation over southeastern Brazil and central and western Amazonia, during the summer months of the southern hemisphere. Frequently, parts of this system drift northward, resulting in increased rainfall over eastern Amazonia. It is common during these episodes the occurrence of a coupling of the SACZ with the ITCZ, in association with systems such as the Bolivian High and cyclonic vortices at high levels, which can cause widespread rainfall and lightning storms over much of eastern Amazonia (Gan and Kousky, 1986; Souza and Ambrizzi, 2003).

The squall lines (SL) formed on the Atlantic coast of the Amazon are responsible for a large part of the rain formation near the coast, as well as, in central Amazonia. These lines are characterized by having large clusters of cumulonimbus clouds and are formed along the coast due to the sea breeze circulation. The development of a cumulonimbus cloud is associated with the presence of warm, moist and unstable air, and usually produce local storms with high incidence of lightning, strong winds, sudden temperature changes, and occasionally tornados (Vianello and Alves, 1991). In addition to these characteristics, Gandú (2004) suggested that the proximity to the ocean and large rivers, creates areas with specific spatial and temporal variability of precipitation. The mesoscale circulation associated with the sea breeze is an example of very active structured convective systems whose squall lines propagation over the continent, is responsible for a significant portion of the precipitation in this region (Cohen et al., 1995)

Observational studies have shown a relation between the thermodynamic conditions of the atmosphere and precipitation, i.e., the rainfall rate varies with the change of the Convective Available Potential Energy (CAPE) (Zawadzki and Ro, 1978; Zhang and Chou, 1999; Groenemeijer et al., 2011; Mota and Nobre, 2006; Tavares, 2008; Pawar et al., 2012). Nevertheless, other factors such as wind shear and relative humidity are also important for the formation of precipitation (Yao and Del gênio, 1999), showing that high CAPE value is a necessary but not sufficient condition for the formation of deep convection and electrified cumulonimbus clouds which may produce lightning.

In the Amazon, lightning was first studied based on thunder data recorded by meteorological observers at weather surface stations (Serra, 1997; Nechet, 1994). These studies showed that this region has one of the highest keraunic indices in the world, usually greater than 140 thunder days per year. This was expected due the frequent formation of cumulonimbus clouds over the region, which has high rainfall (above 2500 mm/year) in its east and west sub-regions (Souza and Ambrizzi, 2003).

Recent studies made with precipitation estimates and lightning detections made through sensors on board of the Tropical Rainfall Monitoring Mission (TRMM) satellite, by Teixeira et al. (2008; 2009) and Ribeiro et al. (2009a,b) have shown that higher lightning production is associated frequently to mesoscale meteorological systems with cloud tops ice crystals, over eastern Amazonia. These systems also produce intense rainfall in all sub areas of this region.

Another study by Almeida *et al.* (2007) conducted an analysis of the characteristics of lightning and rainfall during five storms observed in Belém. In this more localized study, the maxima lightning occurrence rates observed, preceded the maxima rainfall rates measured at the center of the lightning detection area, by at least 20 minutes. Additionally, Ribeiro *et al.* (2008) examned the relationship between lightning and rainfall in the wettest months (February and March) and one dry bimester (July and August) of the year 2007, in Belém. Their results also showed that the frequency of lightning strikes per hour reached their maxima always preceding the corresponding maximum precipitation over this area. In general, it was observed that the rainfall peak delay after the lightning occurrence rate peak was about 45 minutes on the average. This seems to indicate that the lightning occurrence rate may be used to warn about imminent heavy rain, in this area (Ribeiro et al., 2008). The possibility to use this parameter as a short term predictor to severe storms, in the near future, provided stimulus for the detailed analysis of four severe storms events observed simultaneously by the Amazonian Protection System – Lightning Detection Network (SIPAM – LDN), digital pluviometers and satellite images, presented in this work. All these new storms selected produced both intense rainfall and a large number of lightning events around the metropolitan area, surrounding Belem. The cloud-to-ground occurrence rate within the time frame of the rainfall observations were made by local institutions, through a joint effort which will be described further on, in this work.

2. MATERIALS AND METHODS

2.1 Area of study - location and characteristics

The study area (Figure 1) was defined within a circle of 30 km radius, covering the metropolitan area of Belém,

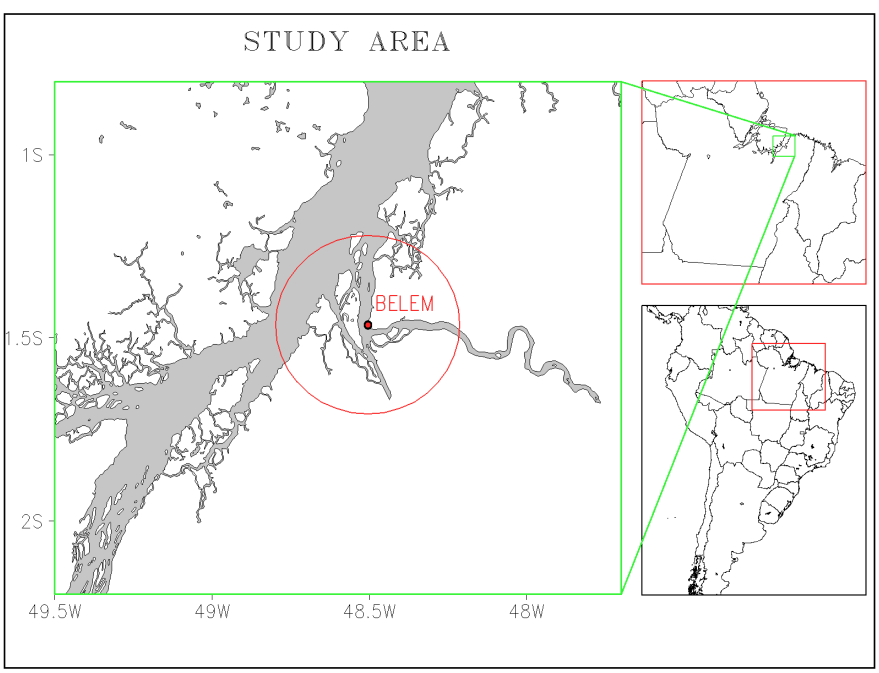

Figure 1 – Area of study with close up image of the 30 km circle drawn through the Arc GrADS 2.0 software, surrounding the metropolitan area of the city of Belém.

plus close water surfaces. It was centered at the Brazilian 4th Naval District Headquarters weather station, with geographical coordinates 1º 47' 53" S and 48º 30' 16" W, where is installed the main high time resolution rainfall gauge, used for data collection.

Belem is located at the confluence of the Guamá River with the Guajará Bay, about 150 km away from the Atlantic Ocean, along the southern shore of the mouth of the Amazon River. The level of its surrounding water masses is significantly determined by tides, which during the trimester March to May, may exceed the 2.5 m amplitude. This period coincides with part of the local rainy season, when the precipitation is strongly influenced by the inter-annual variability of the atmospheric general circulation, accumulating most of its nearly 3,000 mm annual average total (Figueroa and Nobre, 1990). The rainy period in Belem is largely modulated by the drift of the Inter Tropical Convergence Zone (ITCZ) over this equatorial latitude (Ferreira, 1996), frequently producing severe lightning and rain storms, from January to May. The combined simultaneous effect of the high tides with severe rainfall, is the overflow of the drainage channels of the city, resulting in serious traffic jams and economic losses to its population. At present, no real time flood warning system is available to mitigate these situations, through the local Civil Defense and communications media. This work represents an attempt to contribute to the development of a low cost intense rainfall warning method, based on the knowledge of the relationship between the lightning frequency of occurrences and the associated rainfall, during severe storm events, in Belém.

The main socio-economic impacts associated with rain storms and lightning are related to the overflow of channels and rivers, flooding of roads and houses. For the analysis of socioeconomic impacts were selected events of severe storms with material losses as reported through the local news media, such as roads and homes flooded in several neighborhoods, and slow traffic on the main access route to the city. In especial, the four stormy days selected for study caused consequences and impacts according to the local news media, as we can be seen in Table 1.

The newspaper "Diario do Para" published on December 12, 2007 printed the headline "Storm: City is again facing chaos". This newspaper edition described the impossibility of traffic on some streets, traffic accidents and also the situation whereby three cars that were swept away by the flash flooding waters.

On January 10, 2007 the newspaper "Diário do Pará" and "O Liberal" brought headlines about the heavy rain occurrence on the day before. They displayed the headlines: "Thunderstorms are back and causing disorders" and "Flooding worsens quality of life", respectively.

The floods caused by the rainfall on February 14, 2007, caused much inconvenience to the population in the affected areas as described in an article published in the issue of February15, 2007 of the newspaper "O Liberal" where the headline read: "One hour of rain overflows the city". It took about an hour of rain to flood the periphery and the center of Belém. There was flooding in 6 neighborhoods. The water invaded houses, shops and offices. The traffic was jammed for several hours."

On March 3, 2007 the newspapers reported several traffic jams and traffic accidents occurred due to heavy rain that fell on the city in about 30 minutes on the previous day. The fire department also registered 10 instances of landslides an fallen tree and several car accidents.

2.2 Lightning data

The individual lightning flash occurrences data used in this study were collected by the Amazon Protection System

Table 1 - Four days with severe storm events and headlines published on the following day to the event as well as the social impacts caused by these events.

Day	Rainfall (mm)	Summary of published news	Impacts
Dec. 11, 2006	65.2	"Intense Storm Made City to Face Chaos Again"	Flash floods, traffic jams and car accidents, etc.
Jan. 09, 2007	35.0	"Flooding Worsens Quality of Life"	Floods, traffic jams and car accidents, etc.
Feb. 14, 2007	59.4	"One Hour of Rain Floods the City"	Houses and shops flooded in six neighborhoods.
Mar. 02, 2007	53.4	"Rain Floods Almirante and Duque Avenues	Floods, traffic jams and car accidents, landslides and fallen tree, etc.

lightning detection network (SIPAM-LDN), which included 12 sensors LPATS IV, manufactured by Vaisala. These data were registered in the international format ASCii Lightning Universal Format (UALF) on a stable platform UNIX®, computing solutions from LF signals. Their times of arrival are inputted as raw data from various sensors of the system. Detection solutions were processed by a software at a central station (CP 8000) of the network, installed in Belem. The lightning locations are sent directly to display devices in real time, including an analysis of the network performance; and/or stored on files for several applications.

The Microsoft Office EXCEL 2007 was used to process the charts displaying the behavior of lightning versus rainfall during the periods of the storms.

Figure 2 shows the layout of the LPATS-IV sensors, located over four Brazilian states in the eastern Amazon Region. Six sensor sites are in the Para (PA) state, four in the Maranhão (MA) state, one in Mato Grosso (MT) state and one single sensor in the Tocantins state. Except for two sensors located further east (São Luís and Barra do Corda, both in Maranhão), the SIPAM- LDN spatial distribution shows a nearly axial configuration with northward extremes in Breves and Belém, and the southern extremes located in São Félix do Araguaia, in Mato Grosso, and Natividade, in Tocantins.

This LDN received maintenance at the end of 2006, so that in 2007 it was operating with one of its best detection efficiency levels. Its performance was degrading during subsequent years and it is presently out of operation.

2.3 Precipitation data

The analysis of the severe storms days was made using data from a high time resolution pluviometer, operated by the Mineral Resources Research Company (CPRM) in Belem.

Belém has an extensive drainage network formed by rivers and channels, many of the latter with paved embankments and silted beds. In addition to these conditions, the influence of the tide, which can block the natural flow of some of these rivers and canals, is an extra factor that can cause overflow of the natural drainage network. Thus, high rates of precipitation, especially when they occur simultaneously with the high tide, greatly increase the risk of urban flooding. According to Santos (2010), rainfall rates exceeding 12 mm / h represent imminent risk of flooding to some urban watersheds of Belém.

These case studies referred to rainfall events, which produced more than 25 mm/hour or more than 40 mm/two hours, of precipitation totals, registered by a tipping bucket automatic pluviometer located at 1° 47’ 53’’ S and 48° 30’ 16” W. This pluviometer time resolution was five minutes or 0.2 mm rainfall accumulation, whichever occurred first. To draw the figures, the rainfall data were totaled at 15 minutes intervals.

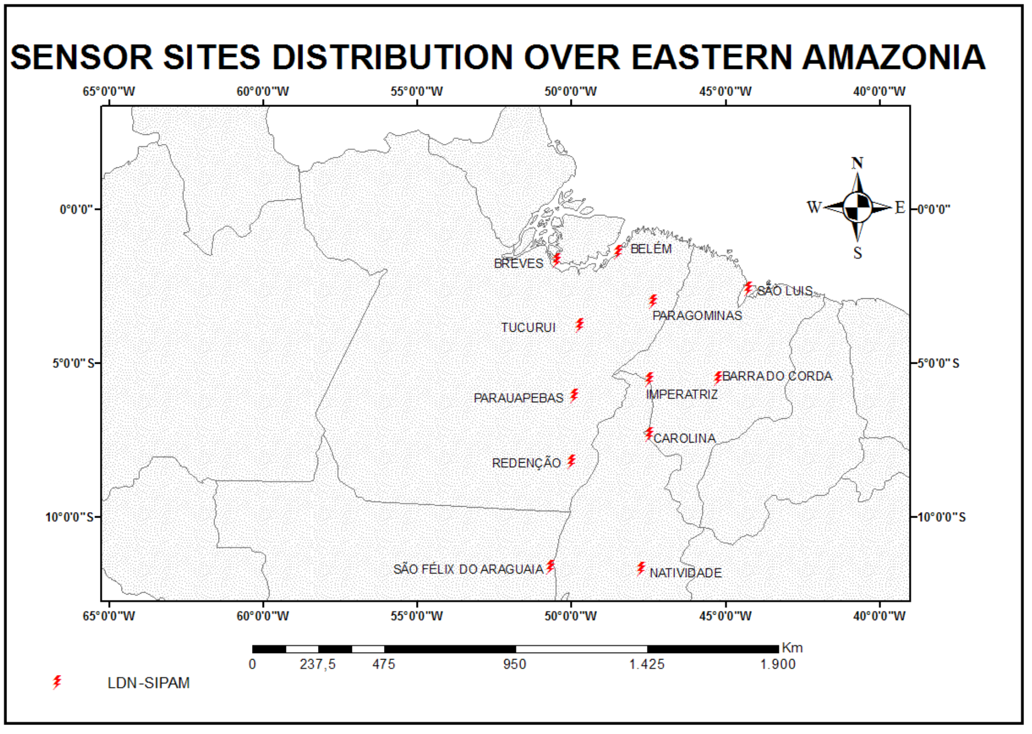

Figure 2– Geographical location of the 12 LPATS - IV Vaisala sensor stations which integrate the SIPAM - LDN.

Table 2 –Lightning and rainfall data from four severe storms observed around Belém.

Day	Rainfall (mm)	Number of Sensor 4	5	6	Total Number of Flashes
		Flashes Detected			
11/12/2006	65.2	183	489	27	699
09/01/2007	35.0	83	85	11	119
14/02/2007	59.4	68	46	20	62
02/03/2007	53.4	25	6		31

2.4 Analysis of the atmospheric data

The synoptic conditions, i.e., the weather systems that influenced the storm events were characterized using data available at the National Center for Environmental Prediction - NCEP, with the following variables: outgoing longwave radiation (LWR), low and high wind levels, air temperature and relative humidity. The daily LWR data were derived from polar-orbiting weather satellites (Liebmann and Smith, 1996), covering the period from 1974 to the present. This variable is arranged in a regular global grid with a resolution of 2.5º latitude by 2.5º longitude, having been used to characterize the convective activity associated with tropical weather phenomena, whereas the threshold for deep convection was considered to be around 240 Wm^{-2}, as described in Zhang (1993) and Lau et al. (1997).

Daily averages of the zonal and meridian components of wind, air temperature and relative humidity were obtained from the NCEP reanalysis. These data are generated through a consistent data assimilation system used in its global circulation model (GCM) with a resolution of the NCEP T62L28 (approximately 210 km in latitude versus longitude and 28 vertical levels), according to Kalnay et al. (1996). The analysis of horizontal wind allowed the evaluation of active synoptic systems. The wind data, together with the air temperature and relative humidity were used to calculate the moisture convergence for the area of study.

3. RESULTS AND DISCUSSION

3.1 Lightning characteristics from four selected events of severe storms

Table 2 presents data from four storm events that occurred in Belém. From the displayed physical characteristics of the observed flashes, it is evident that the day of strongest electrical activity was 11 December 2006, with 699 lightning flashes and 65.2 mm of rain. The day with fewer lightning events among the selected four, occurred on March 02, 2007 with only 31 events lightning. It is also observed that all events studied were detected at least by four sensors.

3.2 Case 1: severe strom occurence on december 11, 2006

3.2.1 Meteorological analysis

Figure 3 shows the sequence of images captured through the infrared channel of the GOES- 12 satellite at 2045 UTC,

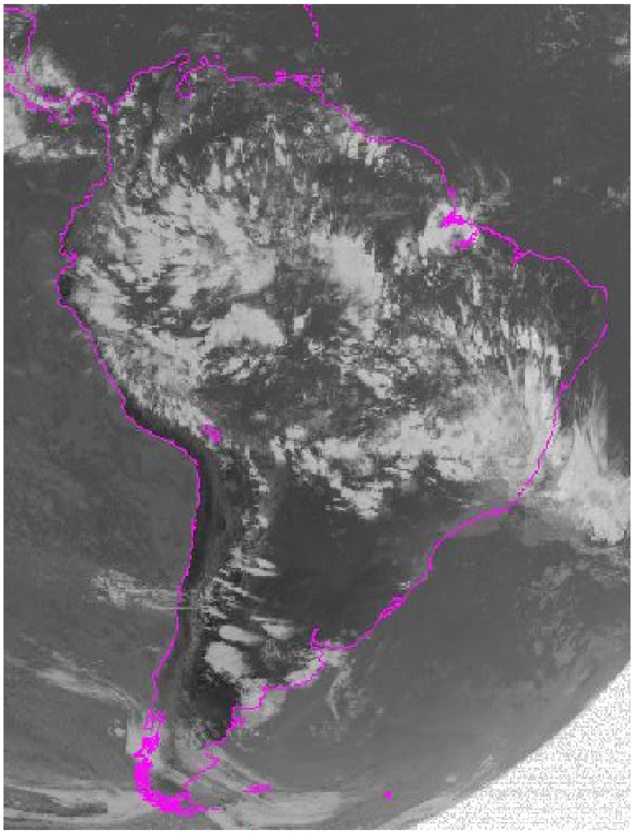

Figure 3 - GOES-12 satellite infrared channel image on December 11, 2006 at 20:45 UTC showing the presence of deep convective systems near the region of Belém.
Source: National Oceanic and Atmospheric Administration (NOAA).

which allows us to identify the formation of a convective cluster between the region of Belém and the Marajó Island in the evening of December 11, 2006.

The low values of LWR indicate deep convection (Lau et al., 1997) associated with vertically well developed cloudiness, which favors the formation of cumulonimbus clouds and thunderstorms. In Figure 4b one may see a band of convective clouds predominantly oriented NW / SE, featuring the South Atlantic Convergence Zone (SACZ), organized from over the state of Amazonas towards southeastern Brazil. This storm, represented as CASE 1, resulted from the projection of a branch of the SACZ over the area of interest.

The interaction between phenomena of different scales, in this case the SACZ and the sea breeze along the northeastern Pará Atlantic coast, resulted in the convergence of moisture and wind direction observed on Figure 4c, acted simultaneously for the formation of a squall line that caused this severe storm in Belém, during December 11, 2006, together with a large number of lightning and high rainfall volume (Figure 4a).

3.2.2 Local weather conditions.

According to weather reports regularly released by operational staff stationed at the Belém International Airport (SBBE), known as METAR code (Meteorological Aerodrome Report), there were four important moments during this storm, as described below in Table 3.

At 1600 UTC on December 11, 2006, the predominant wind was from northeast, with an intensity of 6 knots. The air temperature increased, reaching 31 ºC. At that moment, there were already some cumulus towers and a large high cloud layer, probably of cirrostratus, characterizing the approaching of the top of a cumulonimbus.

Immediately after 1700 UTC, light rain occurred, thus contributing to a reduction of 3 °C on the near surface air temperature. The proximity of a cumulonimbus system caused variations on the wind direction, which changed towards the southeast.

The first thunderstorm at the station (SBBE) was recorded at 2019 UTC. At that time the intense rainfall reduced the horizontal visibility to about 500 meters. Near 2200 UTC, the thunder registers ceased at the station (SBBE), but the rainfall remained light and continuous, as usually happens during the dissipation stage of a cumulonimbus

3.2.3 Space and time distributions of lightning and rainfall on December 11, 2006.

The Figure 5a shows the time distribution of the number of lightning CG flashes and precipitation, which occurred on December 11, 2006 in Belem. It appears that most of the electrical activity considering the events within the larger circle area occurred at 1900 UTC, with 101 events in 15 minutes. It was also noted that in the interval of 1900 to 2100 UTC, 636 CG events were detected, i.e., an average of 70 events every 15 minutes.

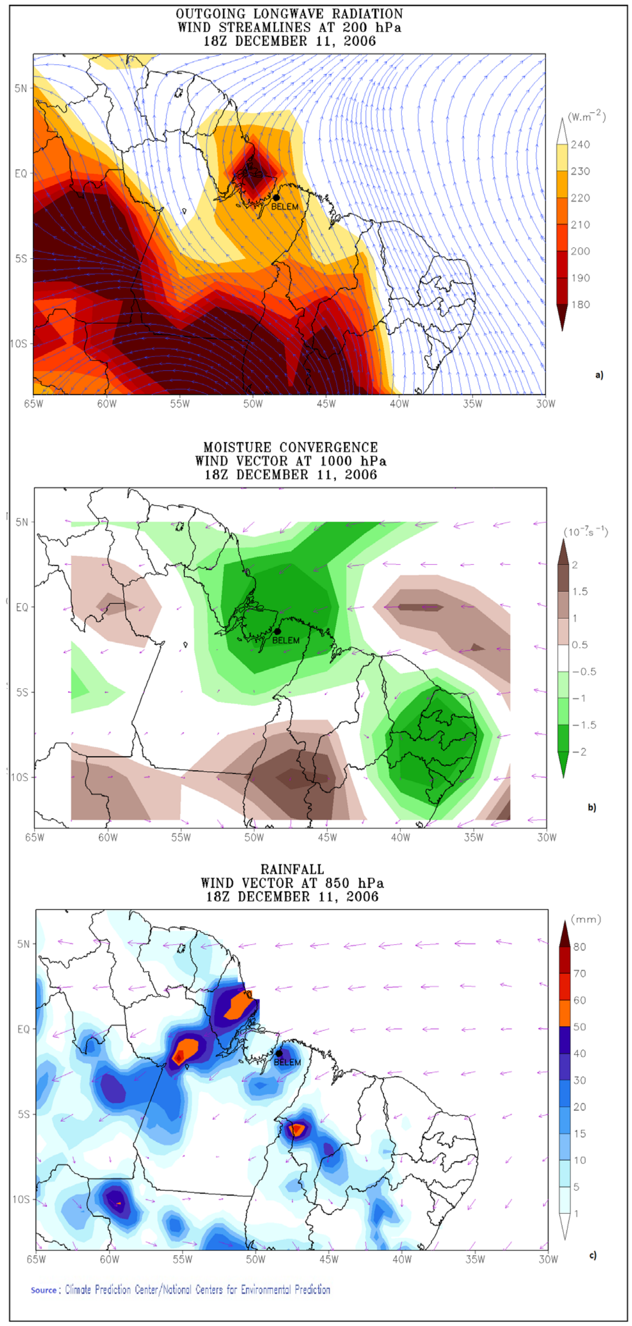

Figure 4 - (a) Outgoing longwave radiation -OLWR (W.m-2) ; (b) Moisture convergence and winds at 1000 hPa (m s-1) , Winds at 850 hPa (m s-1) and (c) Precipitation on Dec,11/2006.
Source: Climate Prediction Center/National Center for Environmental Prediction.

Table 3– Sequency of METAR code registers from the airport station in Belém on December11,2006. Source: http://www.redemet.aer.mil.br.

METAR	SBBE 111400Z 10005KT 9999 BKN020 33/25 Q1012=
METAR	SBBE 111500Z 05002KT 9999 BKN020 33/25 Q1012=
METAR	SBBE 111600Z 04006KT 9999 SCT020 FEW025TCU BKN300 31/24 Q1011=
METAR	SBBE 111700Z 16004KT 9999 -RA SCT020 SCT100 BKN300 28/25 Q1010=
METAR	SBBE 111800Z 08003KT 9999 4500N -SHRA SCT010 FEW025TCU BKN100 30/25 Q1009=
SPECI	SBBE 111816Z 03003KT 3500 -TSRA SCT010 FEW025CB BKN100 28/25 Q1009=
METAR	SBBE 111900Z 35003KT 3000 -TSRA SCT010 FEW025CB OVC100 27/25 Q1008=
METAR	SBBE 112000Z 20001KT 3000 -TSRA BKN008 FEW025CB OVC100 26/24 Q1009=
SPECI	SBBE 112019Z 10004KT 0500 R06/0400 +TSRA BKN005 FEW025CB OVC100 26/25 Q1010=
SPECI	SBBE 112033Z 06005KT 0500 R06/0400 +TSRA BKN003 FEW025CB OVC100 25/24 Q1010=
METAR	SBBE 112100Z 34002KT 1500 R06/P2000 -TSRA BKN005 FEW025CB OVC100 25/23 Q1009=
SPECI	SBBE 112126Z 30003KT 5000 -TSRA SCT010 FEW025CB OVC100 25/23 Q1009=
METAR	SBBE 112200Z 30002KT 9999 -RA SCT015 OVC100 26/24 Q1009 RETS=
METAR	SBBE 112300Z 20002KT 9999 -RA SCT015 OVC100 26/25 Q1010=

Analyzing the temporal behavior of lightning with respect to total rainfall, one could verify that there were several rainfall events throughout the day. The hourly totals went up to 14.6 mm between 1700 and 2000 UTC, but their daily maximum was reached at 2100 UTC with 41.8 mm of rain. Considering the time at which the lightning rate peaks, one observes that as the lightning incidence area is drawn to smaller radius of 10 and 5 km, the lightning rate delay with respect to the time of the rainfall peak , tends to vanish.

The space distribution of the hourly lightning flashes on December 11, 2006 (Figure 5b), shows two bands of lightning occurrences over the northwest and northeast of the area around 1900 UTC. Later on, the events seem to converge towards the urban area of Belém, placed at the center of the area of study.

3.3 Case 2: severe storm occurence on January 09, 2007

3.3.1 Meteorological analysis

The Figure 6 exhibits the highlighted infrared channel image from GOES-12 satellite on January 09, 2007, at 1800 UTC. It shows the presence of deep convective systems near the Belém area, with clouds whose temperature at their tops reached -70 ºC. This condition led to the development of cumulonimbus clouds with intense electrical activity. One may notice also a coupling of the ITCZ with the HLCV on the Brazilian Northeast favoring the occurrence of heavy rainfall over the states of Maranhão, Amazonas and Pará, due to the strong divergence at high levels of the atmosphere.

The active weather systems in the region on this day were: the ITCZ, with shaft around 2 ° C, entered between the states of Maranhão and Piauí , and coastal instability lines from the State of Ceará to Pará. The low level circulation had winds blowing from the ocean to the continent, bringing more moisture (Figure 7a), while in the upper troposphere, prevailing winds circled the continent to the ocean (Figure 7b). The change of the wind vector at high levels of the atmosphere provided the wind shear, which contributed to the formation of intense storms and high volumes of rainfall, especially in the region of Belém (Figure 7c).

3.3.2 Local weather conditions.

According to METAR weather reports regularly released with observations made at the surface meteorological station of the Belém International Airport (SBBE), there were three important phases of the storm, as described below in Table 4.

There were strong indications, before noon, of high atmospheric instability on January 09, 2007. This day was characterized by high air temperatures, whose maximum reached 34 °C at 1500 UTC (12:00 Local Time), when the first cumulus towers appeared. At this time the predominant winds from northeast were weak, but they began to intensify, so that their speed reached 14 knots when the cumulonimbus clouds approached this station. Around 1700 UTC a light rain started, accompanied by thunder, restricting the visibility to 4 km in the eastern sector. Shortly thereafter, at 1710 UTC there was intensification of precipitation, with heavy rain, thunder, and the horizontal visibility was reduced to 1 km. At about 1740 UTC, the rainfall diminished its intensity to moderate and light; and finally stopped at 1900 UTC. There was again formation of cumulonimbus clouds at night which produced lightning but no rain, around the weather station.

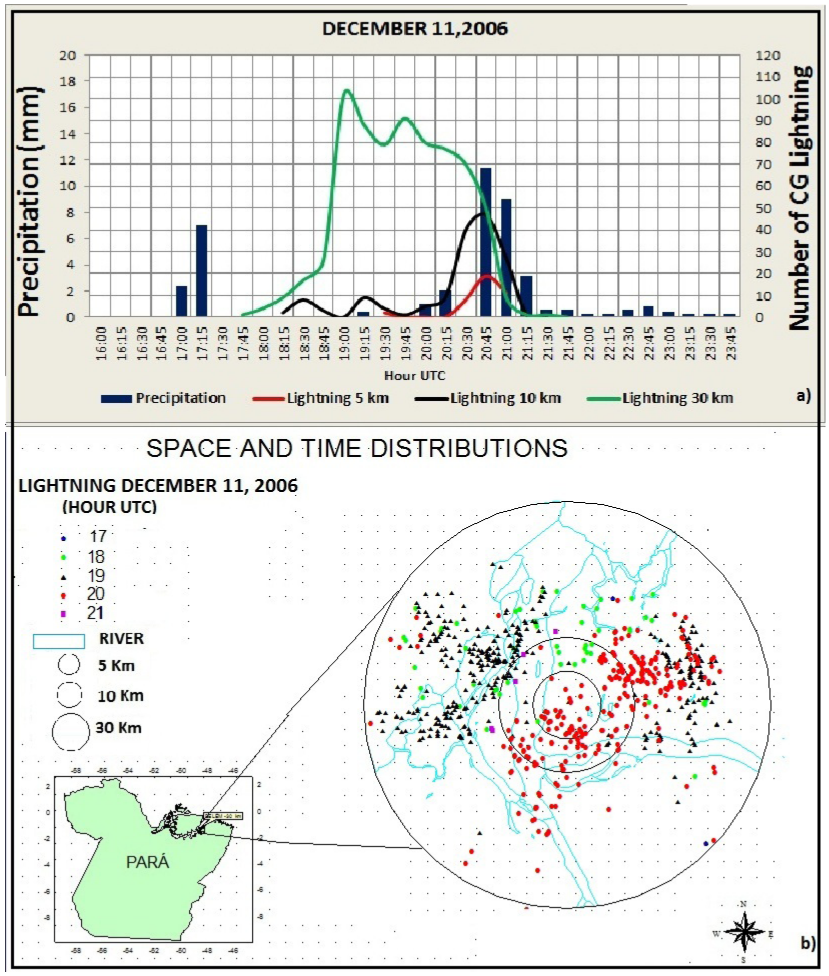

Figure 5 - (a) Time relationship between lightning and rainfall. (b) - Space distributions of the hourly lightning occurrences around Belém, on December 11, 2006.

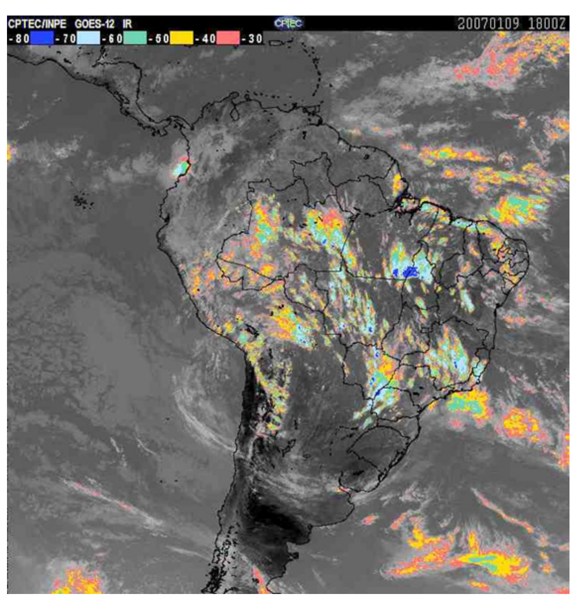

Figure 6 - Infrared channel Image from GOES-12 satellite on January 09, 2007 at 18:00 UTC showing the presence of deep convective systems near the region of Belém, where one can observe clouds whose temperature at their tops reached -70 °C.Source: CPTEC/INPE.

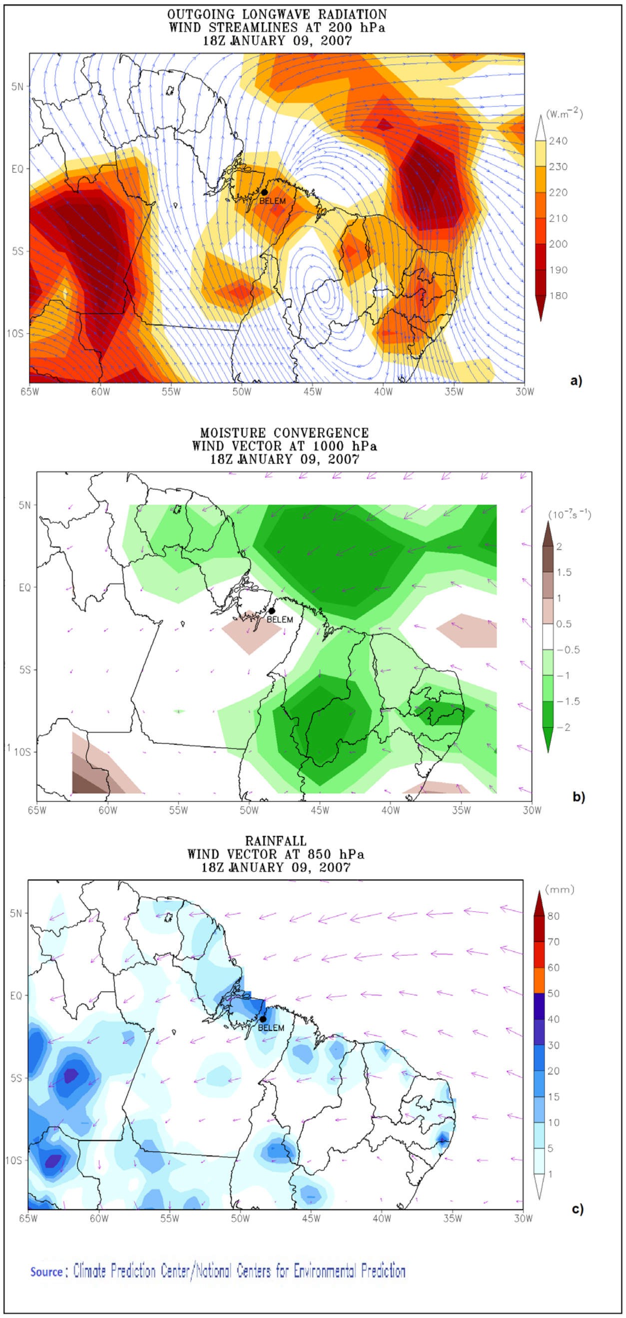

Figure 7 - (a) Outgoing longwave radiation -OLWR (W.m-2) and (b) Moisture convergence and winds at 1000 hPa (m s-1) , (c) Winds at 850 hPa (m s-1) and Precipitation; on January 09, 2007.
Source: Climate Prediction Center/National Centers for Environmental Prediction

3.3.3 Space and time distributions of lightning and rainfall on January 09, 2007.

Figure 8b shows the time distribution of lightning during January 09, 2007. It can be observed that the electrical activity peak within the 30 km circle, occurred at 1700 UTC, probably caused by large convective activity associated to the Bolivian High circulation and to episodes of a Cyclonic Vortex on the Brazilian Northeast which produced cloudiness on its edge, plus rain and lightning on the northeast of the State of Pará. The electrical activity on that day began at 1600 UTC, and the Figure 8b shows that it drifted from east to west.

The hourly distribution of the number of lightning, presented its largest incidence activity at 1700 UTC, with 34 flashes, while precipitation had its highest rainfall rate occurring at 1730 UTC with 20.6 mm/15 minutes. The rainfall rate per 15 minutes dropped to 11.4 mm at 1745 UTC, and almost vanished at 1830 UTC.

In this particular case, Figure 8a indicates that the lightning peak rate of occurrences preceded the rainfall rate peak, for about 30 minutes within the 30 km circle, 15 minutes for the 10 km circle and no time gap was observed between these parameters for the inner 5 km circle. This confirms the radial dependence of the time delay between the lightning and rainfall peal rates, already observed in the previous case study.

3.4 Case 3: severe storm occurence on February 14, 2007

3.4.1 Meteorological analysis

The Figure 9 shows an image of the GOES-12 infrared channel, where is evident the presence of cloud systems as part of the large scale South Atlantic Convergence Zone (SACZ) and the Intertropical Convergence Zone (ITCZ) which were moderately active on the center and northern ares of the state of Para on February 14, 2007, at 1730 UTC. The interaction between these two systems contributed to a large electrical activity resulting in 134 lightning events in Belém and a total of 59.4 mm of rainfall.

Figure 10a shows the atmospheric circulation at low levels over northern Brazil and rainfall on February 14, 2007. It displays the confluence of winds and mass convergence at low levels, associated with the ITCZ, especially in the region of the Tropical Atlantic. These movements favor the transport of moisture and increased convection over northern South America, with evidence of the interaction between the Intertropical Convergence Zone (ITCZ) associated with sea breezes, thus favoring the formation of Squall Lines (SL). The favorable position of cyclonic vortices at high levels contributed to the heavy rainfall and large electrical activity in some localities in the northeast and eastern Pará, justifying the total of 59.4 mm rainfall registered in Belém on February 14, 2007.

Table 4–Sequency of METAR code registers from the airport station in Belém on January 09, 2007. Source: http://www.redemet.aer.mil.br

METAR	SBBE	091500Z 05004KT 9999 BKN030 FEW030TCU 34/25 Q1011=
METAR	SBBE	091600Z 35006KT 9999 BKN030 FEW030TCU 32/26 Q1010=
METAR	SBBE	091700Z 36010KT 9999 4000E -TSRA SCT005 BKN020 FEW023CB BKN100 31/26 Q1009=
SPECI	SBBE	091710Z 07014KT 1000 R06/1000 +TSRA BKN005 BKN017 FEW023CB BKN100 28/24 Q1010=
SPECI	SBBE	091740Z 10003KT 1500 R06/1300 TSRA OVC005 //////CB 26/25 Q1010=
METAR	SBBE	091800Z 03002KT 5000 -TSRA SCT006 BKN023 FEW023CB BKN070 26/25 Q1009=
SPECI	SBBE	091810Z 36002KT 9999 -RA SCT017 FEW023TCU BKN070 BKN300 27/25 Q1008 RETS=
METAR	SBBE	091900Z 36003KT 9999 SCT017 FEW023TCU BKN070 BKN300 27/25 Q1008 RETS=
METAR	SBBE	092000Z 05004KT 9999 SCT015 BKN070 BKN300 28/26 Q1007=
METAR	SBBE	092100Z 04003KT 9999 SCT015 BKN100 BKN300 29/26 Q1008=
METAR	SBBE	092200Z 03003KT 9999 VCTS FEW017 FEW023CB BKN100 BKN300 28/26 Q1009=
METAR	SBBE	092300Z 02002KT 9999 VCTS FEW017 FEW023CB BKN100 BKN300 28/26 Q1009=

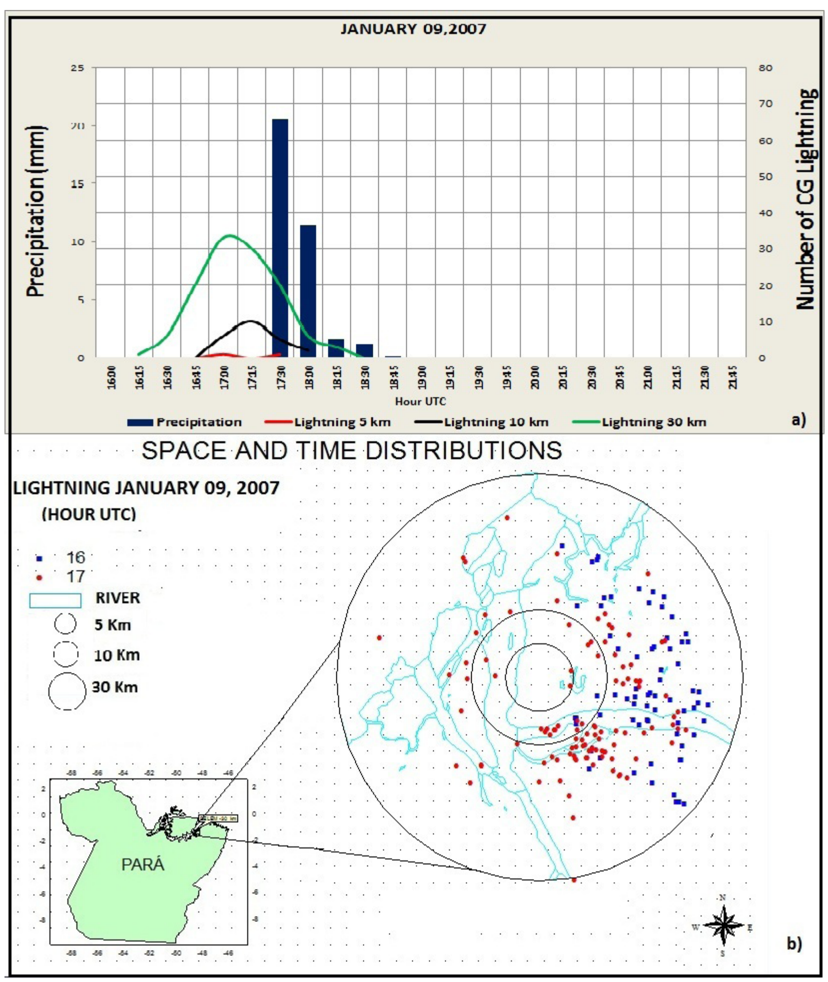

Figure 8 - (a) Time relationship between lightning and rainfall. (b) - Space distributions of the hourly lightning occurrences around Belém.

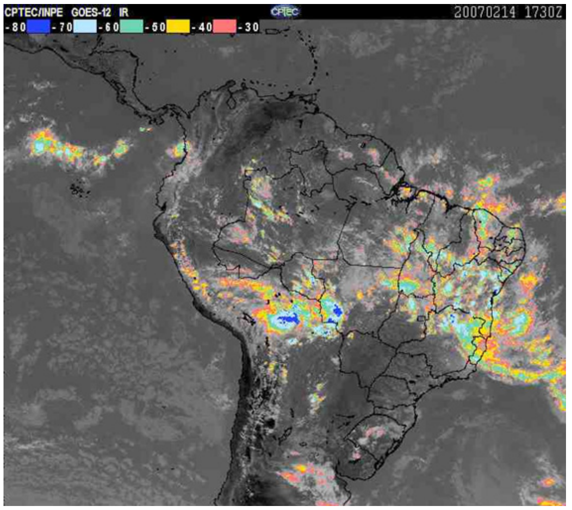

Figure 9 - Image from the GOES-12 satellite infrared channel on February 14, 2007 at 17:30 UTC showing the presence of deep convective systems near the region of Belém, where one may observed clouds whose temperature reached -50 °C at their tops.
Source: CPTEC/INPE

Figure 10b shows both, the Longwave Radiation (LWR) and winds at high levels of the atmosphere (200 hPa) indicating the presence of a frontal system on the northern part of the state of Bahia fed by moisture from the Amazon that contributed to the total rainfall above average in the states of Tocantins and most of Pará. The contribution of the Intertropical Convergence Zone (ITCZ) associated with the formation of Squall Lines (SL) and the favorable position of the high levels cyclonic vortices resulted on severe rainfall in some localities in the northeast and east of the state of Pará. It should be mentioned also that, the center of the Bolivian High was observed at the approximate position of 20 ºS, 72 ºW, near its climatological normal position. The interaction of all these systems must be taken into consideration in future forecasts analysis of severe weather conditions for the studied area.

3.4.2 Local weather conditions

According to the time observations made at the international airport of Belém, on February14, 2007, the day dawned partly cloudy turning to cloudy, still early in the morning. This situation contributed to the maximum temperature below 31 °C (Table 5). Beginning at 1500 UTC, towers of cumulus, and cumulonimbus appeared and evolved during the whole afternoon. The incoming winds were predominantly from the northeast direction and had weak intensity. A thunderstorm with moderate rain was recorded at 1800 UTC, with visibility restricted to 1km in the east sector and 4 km in the other sectors. The rain persisted throughout the night, but the storm ceased at 1920 UTC.

3.4.3 Space and time distributions of lightning and rainfall on February 14, 2007.

Figure 11a presents the temporal distribution of the lightning during February 14, 2007. It can be observed that the greater electrical activity occurred at 1700 UTC, coming from east to west, probably caused by the interaction of various systems that were active on the east and south of Pará.

The rainfall data from the 4th ND station were analyzed on that day revealing that the rainfall rate in Belém reached 41 mm in 30 minutes, with maximum rainfall occurring at 1830 UTC, with 21 mm in 15 minutes. It was also observed that the occurrence peak of lightning preceded the maximum precipitation rate by about 45 minutes within the 30 km circle, and about 30 minutes for both 10 and 5 km circles, in this case.

3.5 Case 4: severe storm occurence on March 02, 2007

3.5.1 Meteorological analysis

The Figure 12 exhibits the infrared channel image from the GOES-12 satellite at 1745 UTC, on March 2, 2007. The display of the cloudiness associated with the Intertropical Convergence Zone (ITCZ) shows that its band lays almost on the equator, with strong mass convergence there, favoring rainfall over northern Brazil. One may observe the interaction of the ITCZ with the HLCV over northeastern Brazil and a frontal system in the South of Brazil, activating the cloudiness in northeastern Pará. This combination of factors, produced heavy rainfall in the city of Belém, Pará, where 53.4 mm of rainfall were registered on that day.

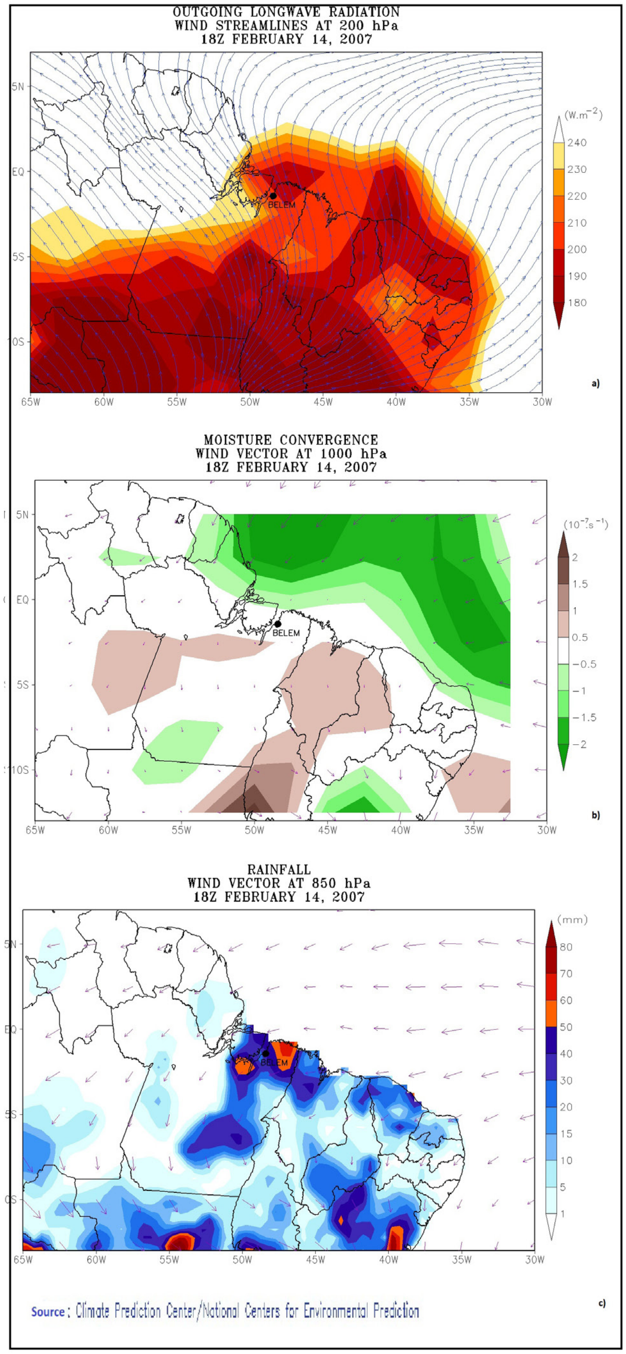

Figure 10 - (a) Outgoing longwave radiation –OLWR- (W.m-2) and (b) Moisture convergence and winds at 1000 hPa (m s-1) , (c) Winds at 850 hPa (m s-1) and Precipitation during February 14, 2007. **Source:** Climate Prediction Center/National Center for Environmental Prediction.

The wind field at low levels, was predominantly from the south below the equator, and from the east above the equator. This is consistent with the presence of the ITCZ and its influence on the region, as shown by the strong moisture convergence (Figure 13a). The low values of longwave radiation, especially near Belém where they reached less than 200 W / m² (Figure 13b) reinforce the prevailing conditions of strong atmospheric instability. The scenario in large and mesoscale had been completely favorable to the formation of deep convective clouds that originated storms with large rainfall accumulation levels, as shown in Figure 13c.

3.5.2 Local weather conditions.

On March 2, 2007 the skies were cloudy since early afternoon and the air temperature was around 33 °C. From 1700 UTC on, a moderate intensity rain began, restricting the horizontal visibility to 2 km in the northeast sector, from where the storm approached Belém. Cumulus clouds towers appeared in the early afternoon and evolved into cumulonimbus, producing thunderstorms after 1740 UTC, with moderate rain . This situation restricted visibility even more, to about 1500 meters. After 2100 UTC the rain reduced its intensity, keeping an intermittent character until 2100 UTC, when the lightning ceased. Strangely, at that time still there were no well-developed convective clouds of the cumulus tower type. Nevertheless, at 1800 UTC a localized system cloud produced strong gusts of wind and 46.4 mm of rainfall register in 15 minutes (Table 6).

3.5.3. Space and time distributions of lightning and rainfall on March 02, 2007

Figure 14b shows the time distributions of the CG lightning occurrences and rainfall during March 2, 2007. One can observe that the increased electrical activity occurred at 1700 UTC, probably caused by the interaction of several systems that were active on the east and southern areas of Pará. These systems can be better visualized in the satellite image (Figure 12). Still regarding this time distribution it was observed that the lightning occurrence rate peaked at 1730 UTC within the 30 km circle, that is, about 30 minutes before the maximum precipitation which occurred at 1800 UTC (Figure 14a). Such time gap was just a few minutes when the 10 km circle was considered and no lightning flashes were detected within the inner 5 km circle around that time.

4. CONCLUSIONS

Four severe weather storm occurrences near the city of Belém, PA, Brazil were analyzed, with respect to the lightning and rainfall, produced by them. Different space and time evolutions of the storms were identified in association with especial configurations of the main climatic and meteorological systems which produce intense convection over the selected study area of metropolitan Belém and its surroundings. Some specific meteorological features such as the SACZ, the ITCZ,

Table 5 – Sequency of METAR code registers from the airport station in Belém on February 14, 2007. Source: http://www.redemet.aer.mil.br

METAR	SBBE 141400Z 34003KT 9999 BKN017 30/26 Q1012=
METAR	SBBE 141500Z 35003KT 9999 BKN017 FEW023TCU 31/26 Q1012=
METAR	SBBE 141600Z 35005KT 9999 BKN017 FEW023TCU 31/26 Q1011=
METAR	SBBE 141700Z 35006KT 9999 VCSH SCT017 FEW023TCU SCT100 31/25 Q1009=
METAR	SBBE 141800Z 07007KT 4000 1000E R06/1200 TSRA SCT017 FEWO20CB BKN100 29/25 Q1009=
METAR	SBBE 141900Z 05004KT 4000 -TSRA SCT012 SCT017 FEW020CB BKN100 27/26 Q1009=
SPECI	SBBE 141920Z 03002KT 9999 -RA SCT012 SCT017 BKN100 27/25 Q1009 RETS=
METAR	SBBE 142000Z 04002KT 9999 -RA SCT012 SCT017 BKN100 27/25 Q1008 RETS=
METAR	SBBE 142100Z 03002KT 9999 -RA SCT012 SCT017 BKN100 27/25 Q1009=
METAR	SBBE 142200Z 01002KT 9999 -RA SCT012 BKN100 OVC300 28/26 Q1009=
METAR	SBBE 142300Z 04002KT 9999 SCT012 BKN100 OVC300 27/26 Q1010=

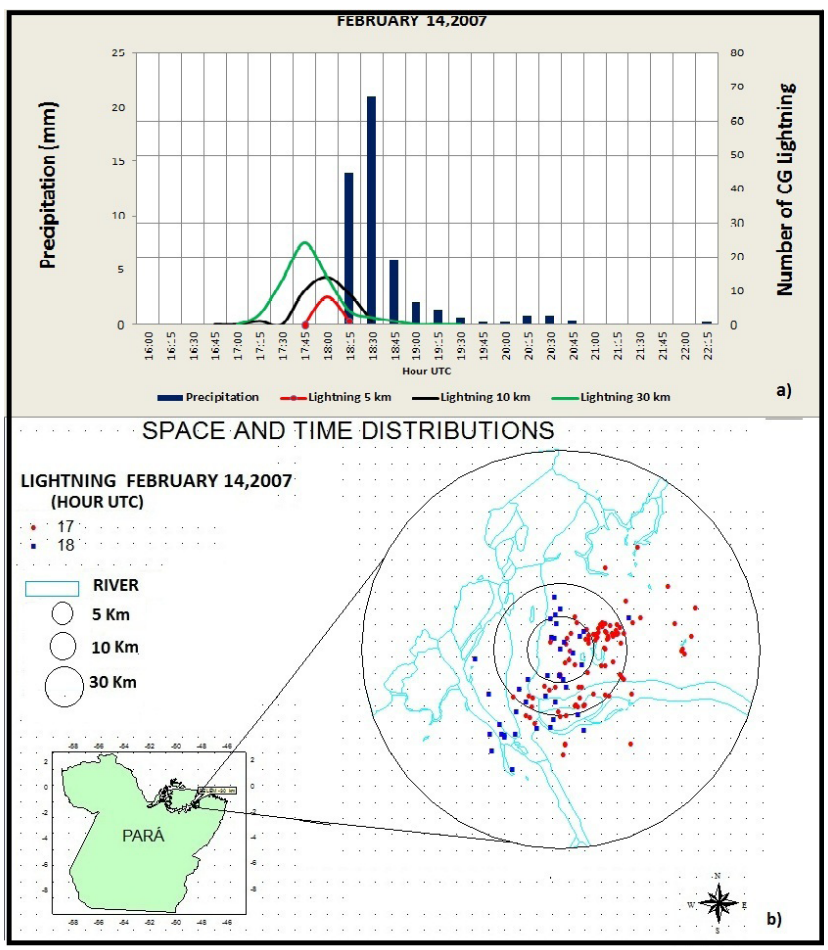

Figure 11 - (a) Time distribution and relationship between lightning occurrences and rainfall. (b) - Space distributions of the hourly lightning occurrences around Belém.

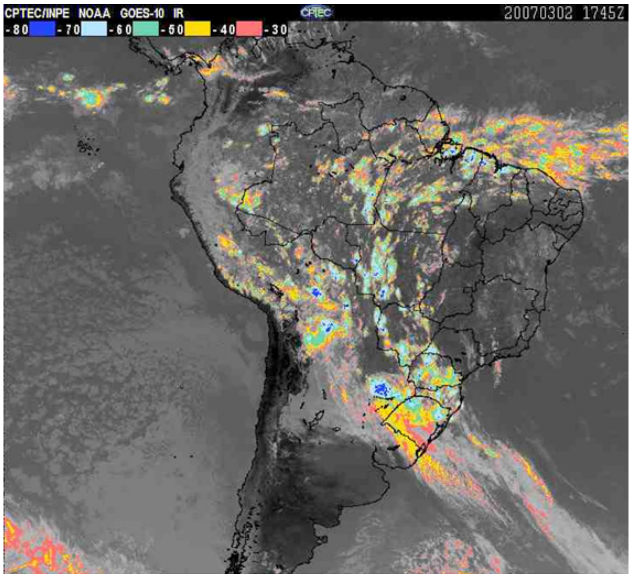

Figure 12 - Image from the infrared channel of the GOES-12 satellite on March 02, 2007 at 17:45 UTC, showing the presence of deep convective systems near the region of Belém, where it can be observed clouds whose temperature reached -80 °C at their tops.
Source: CPTEC/INPE

the Bolivian High, the Northeastern Brazilian Trough, and breeze circulations, may be useful as prognosticators of intense convection and lightning plus rainfall severe storms in the area, many hours in advance of these occurrences. One of the findings of this study was that even though most severe weather in Belém come from thunderclouds drifting from northeast propped by the prevailing winds, lightning and the associated events appear to occur in a more or less random way in space, meaning that, when lightning starts to occur, the storm clouds are already covering almost all the 30 km circular area. Under these circumstances and in the now casting time scale, this work determined for all cases studied that the lightning occurrence rate tends to peak before the observed maximum precipitation occurs at the center of the lightning monitored area. However, this time delay depends someway on the radii of the circles around the reference pluviometer placed at their center. For the central area of 5 km radius in the cases studied this time gap tends to vanish. Therefore, a compromise radial distance of lightning monitoring should be established, if one desires to use lightning occurrence data to warn about imminent severe rainfall at a given point location, in this area of study.

Finally we wish to conclude that a combination of satellite and surface real time meteorological variables monitoring systems may provide useful information about severe weather storms in this area, and this research may contribute for future forecasts, seeking to mitigate the described storm losses to the local population.

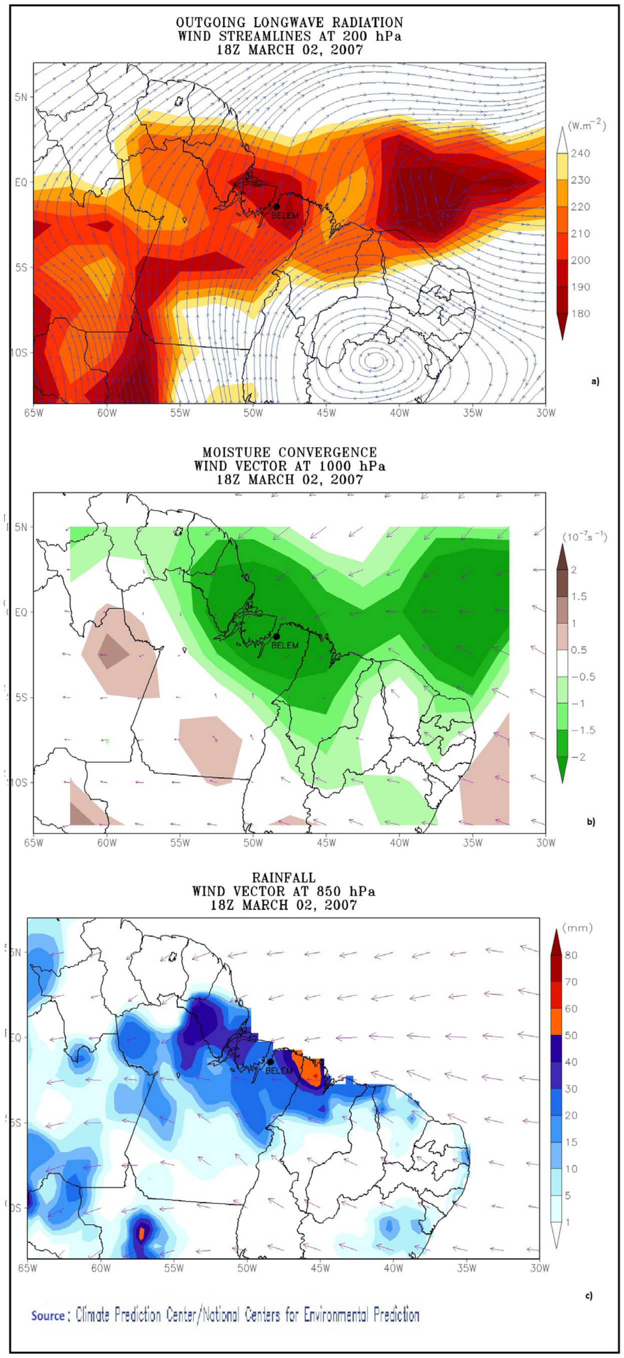

Figure 13 - (a) Outgoing longwave radiation – OLWR - (W.m-2) and (b) Moisture convergence and winds at 1000 hPa (m s-1) , (c) Winds at 850 hPa (m s-1) and Precipitation; during March 02, 2007.
Source: Climate Prediction Center/National Center for Environmental Prediction.

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Table 6 - Sequency of METAR code registers from the airport station in Belém on March 02, 2007. Source: http://www.redemet.aer.mil.br

METAR	SBBE 021500Z 18003KT 9999 BKN020 33/25 Q1010=
METAR	SBBE 021600Z 09003KT 9999 FEW010 BKN020 33/25 Q1008=
METAR	SBBE 021700Z 35008KT 9999 2000NE RA BKN004 FEW025TCU 30/25 Q1007=
SPECI	SBBE 021740Z 12008KT 1500 TSRA BKN003 FEW025CB 27/26 Q1008=
METAR	SBBE 021800Z 08004KT 3000 -TSRA BKN002 FEW025CB 26/25 Q1007=
SPECI	SBBE 021830Z 07004KT 9999 TS BKN015 FEW030CB BKN100 26/25 Q1007=
METAR	SBBE 021900Z 06007KT 9999 3000NE -TSRA BKN005 FEW030CB BKN100 27/25 Q1008=
METAR	SBBE 022000Z 10002KT 9999 -TSRA BKN010 FEW030CB BKN100 26/25 Q1008=
METAR	SBBE 022100Z 09003KT 9999 SCT015 FEW025TCU BKN100 26/25 Q1008 RETS=
METAR	SBBE 022200Z 10003KT 9999 SCT015 BKN100 BKN300 26/25 Q1009=
METAR	SBBE 022300Z 08002KT 9999 SCT017 BKN100 BKN300 26/25 Q1010=

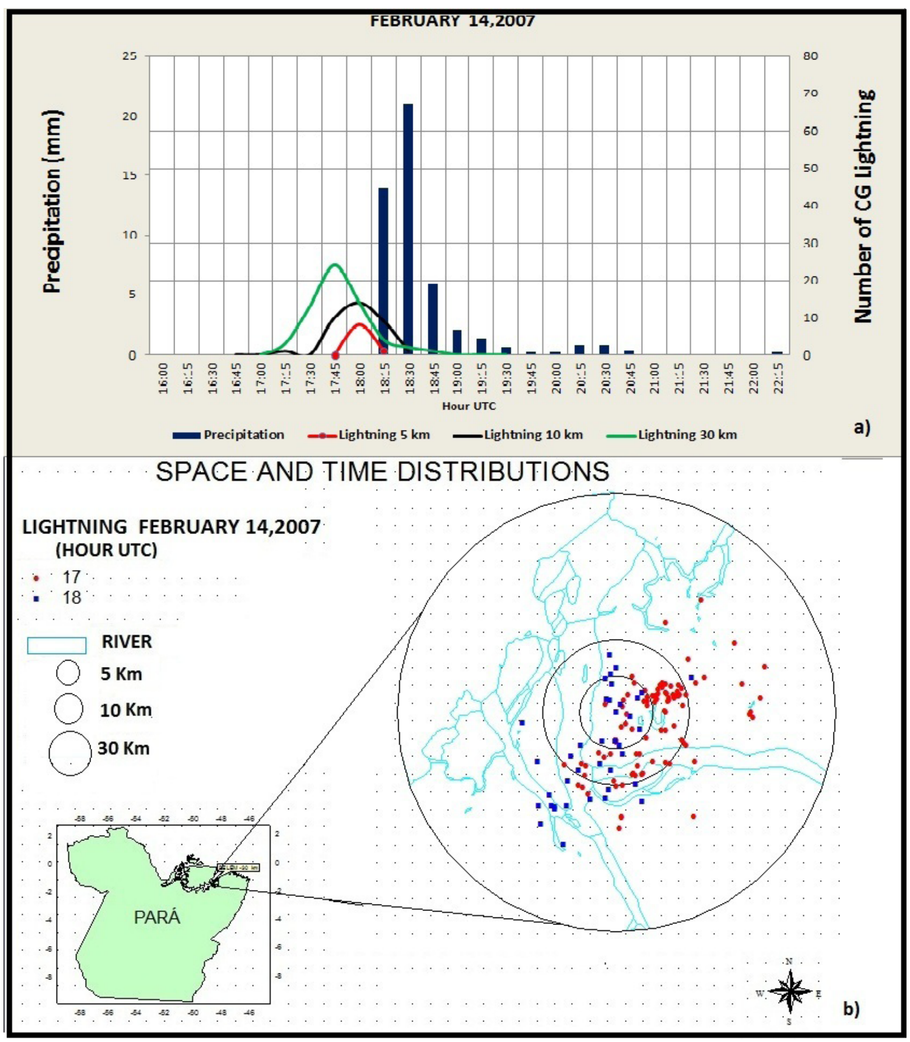

Figure 14 - (a) Time relationship between lightning and rainfall. (b) - Space distributions of the hourly lightning occurrences around Belém.

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