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Spacial distribution of rain types in Pernambuco with the usage of Remote Sensing

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Abstract

This study aims to identify the rate of convective and stratiform rain in the state of Pernambuco (Brazil), with data collected by the satellite TRMM. For the research, 12 points in different cities were chosen to work with the data of the algorithm 3A25, with a spatial resolution of 0,5°x0,5° from January 1st, 1998 to June 30th, 2011. After the analysis of the rates, variations of the rates according with the spatial localization of the points were identified. The higher convective rain rate was in Cabo de Santo Agostinho (3,32) and the lower rate was situated in Santa Cruz (2,22). Regarding stratiforms rain, the rates varied according to their special localization. The points which presented the highest rates were the closest to the coastline – Cabo de Santo Agostinho (1,19); Bezerros (0,92); Belo Jardim (0,83). The points that showed the lowest averages are the ones far from the littoral - Parnamirim (0,74); Santa Filomena (0,69); Santa Cruz (0,83).

Keywords: types of precipitation, stratiform, convective, remote sensor

1. Introduction

Water as a major agent of environmental balance is fundamental for life and indispensable to various human activities (Nóbrega, 2008). Therefore, one of the main natural sources of water is rainfall, making studies related to the formation of rains and temporal and spatial variability, as well as an effective daily monitoring to make better use of water and prevention of natural disasters related to rainfall extremely important.

The formation processes of rain on a large scale are linked to the radiation balance and the energy cycle of the atmosphere over the globe. Based on this assumption, the validation of the rain is essential for studies that seek to identify how weather elements act in the formation of geographical landscape. However, there are various difficulties to achieve a "true value" of rain due to its pronounced spatial and temporal variability (Park et al., 2007).

This variability was approached by Collischonn (2006), stating that although rainfall can be considered the variable of the hydrological cycle that has the highest spatial variability, its spatial representation depends on the rainfall stations, which makes this rather limited representation. Although the World Meteorological Organization (WMO) suggest that data from a synoptic weather station represents a distance of 150 km away from the stations, some climatic factors are not taken into account in this representation, for the relief, the soil cover, the altitude and the distance from the sea may vary in distances shorter than 150 km.

By obtaining the precipitation of a watershed by more traditional procedures (rain gauge and pluviographs), for example, information from rain gauges are punctual, and may extend the occurred rainfall at a certain point for a whole watershed. (Nóbrega et al., 2008).

In his statement Biazeto (2007) says that "the assimilation of estimated rainfall data via satellite has been used as an effective tool for correcting errors generated by the parameterization of precipitation unresolved by forecasting models".

The usage of remote sensing in precipitation estimation has shown to be an interesting alternative to counteract such problems. In the last three decades, advances in remote sensing in the context of environmental satellites have been observed, increasing the amount of information available, including precipitation estimates. With better results in the estimates, the products have migrated from research to operational products, being distributed by actors of hydrometeorology (Collischonn et al., 2007; Nóbrega et al., 2008).

Given the above, the objective of this study is to analyze the vertical structure of precipitation systems through precipitation radar data (PR) to diagnose the spatial and temporal variability of the types of rainfall occurring in the state of Pernambuco.

1.1. Theoretical Background

Historical overview of the TRMM satellite

The satellite Tropical Rainfall Measuring Mission (TRMM) was created through a partnership between NASA and the Japan Aerospace Exploration Agency (JAXA). It was released on November 27, 1997, with the specific objective of monitoring and studying the precipitation in the tropics, and of identifying how it influences the climate on global climate. The polar lower orbit of the satellite (initially 350km, 403km since 2001), along with the translational short period (91 minutes) enables high temporal and spatial resolution imaging.

The satellite data information comprises a core that enables the estimation of the rainfall on a global scale, and the estimates can be created from one only sensor, although the use of more sensors can increase the coverage accuracy and the data resolution.

Altogether there are five sensors on board the satellite: the *Visible Infrared Radiometer* (VIRS), *TRMM Microwave Imager* (TMI), *Precipitation Radar* (PR), L*ightning Imaging Sensor* (LIS) and the *Clouds and the Earth's Radiant Energy System* (CERES). The VIRS is a passive cross band scanning radiometer with five channels centered on wavelengths (0.63) (1.6) (3.75) (10.8) and 12 µm, providing high resolution observations of cloud covers, the temperature of the cloud top and its type (NASA, 2015).

The TMI is a passive microwave radiometer that provides information about the integrated content of the rainfall column, liquid water in the cloud, rain intensity and type of precipitation (convective and stratiform).

The PR was the first radar designed specifically for monitoring rainfall to operate from space. Despite the small data history and suffering from the same uncertainty for the estimation of rainfall as do land-based radar, the sensor has issued an incredible amount of detailed information of the rain structure (Kummerow et al., 2000).

The sensor provides the intensity of rain with horizontal resolution of 4.3 km at nadir and vertical resolution of the Earth's surface from 250m to 20 km altitude. Furthermore, the data contains information of the type based on vertical rain patterns. Thus, it allows precipitation measuring in three-dimensional shape, layer thickness and precipitation that reaches the surface. Its spatial resolution allows it to capture convective systems exceeding 16 km², and due to the low temporal resolution it is suggested that convective systems perform sampling of long duration (Yoshida, 2009).

The LIS is a passive optical sensor that detects and locates lightning events in oxygen range (0.777) micrometers. Teixera (2010) utilized the sensor for the verification of patterns of the lightning in the North of Brazil correlating with the Mesoscale Convective System (MCS).

Data from the CERES instrument can be used to study the energy exchanged between the Sun, the atmosphere and the Earth's surface. However, the sensor only worked from January 1998 to March 2000, therefore, registration of data available is quite short (NASA, 2015).

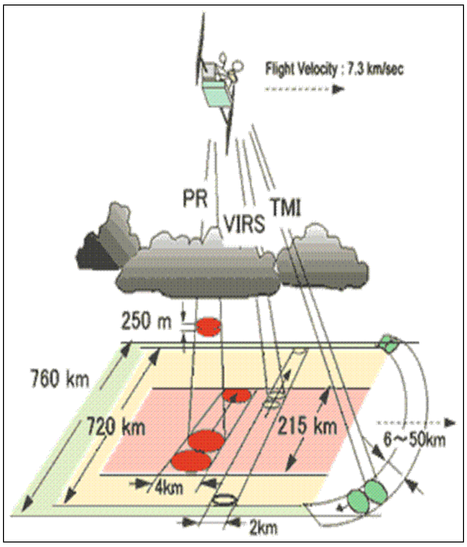

Figure 1 - TRMM satellite's instruments and the reception area of each sensor. Source: http://trmm.chpc.utah.edu/, 2014.

To estimate the precipitation, the TRMM satellite combines passive microwave data (HQ - High Quality Microwave Estimates) with infrared data (VAR - Variable Rate Rain IR Estimates) (Biazeto, 2007).

It is worth noting that studies have been conducted to analyze precipitation measurements for a given region, comparing surface data and weather radar data, and even integration between surface and satellite data (Nóbrega et al., 2008).

Several results related to validating the use of TRMM in estimating rainfall were found, such as the analysis by Collischonn (2006), who found relative errors in 9% for the annual cumulative rainfall compared by surface data. The results were in accordance with the ones found by Nóbrega et al. (2008) in which he compared TRMM data with the "Climate Prediction Center" (CPC), as well as the meteorological stations of the Sub-Basin of western Amazonia.

Some studies identified the relation between the types of the rain and the accuracy of the estimates, Duan et al. (2015) and Shrestha et al. (2015) analyzed the accuracy of the dates of the TRMM and the influence of the characteristics of the rain (quantity and intensity) included the elevations of the surface.

Ochoa et al. (2014) verified that the formation of the rain and the localization of the estimates can contributed for a variation of the accuracy.

Furthermore, Romatschke and House (2011) verified the strong land–sea contrasts and extreme topography of the region determine broad aspects of the rainfall pattern much as they do during the monsoon. In the East Asian, Fu et al. (2003) described the patterns of the rains and the distribution of the differences behind the observed and estimates dates.

Algorithm 3A25

A number of products is produced from the combination of TMI and PR sensors. The existence of various products from this combination is due to the fact that each one of them has its advantages and disadvantages.

The algorithm 3A25 is one of the products resulting from this combination. It offers various types of data, each of those being represented by a variable. The dataset of this product provides monthly average rates of rainfall on the surface, vertical profile of rain, convective and stratiform precipitation fraction and other related parameters.

Altogether, there are 121 variables that differ from each other in how the raw data is processed. As an example, there is the variable *surfRainConvMean2*, which provides the average rates of convective precipitation (mm / hr) on the surface with a resolution of 0.5 ° x0,5 °.

The PR emits a pulse of energy and, upon returning, it is proportional to the diameter of the drop illuminated by the sensor to the sixth power. The rain is characterized as stratiform or convective from that data. If the PR detects a bright band near the freezing level in the atmosphere, the rain profile is categorized as stratiform. If any value in the radar reflectivity of the beam exceeds the predetermined value of 39 dBZ, the rain profile is reported as convective (Fu et al., 2006).

Classification of rain types

Distinct reflectivity patterns obtained by precipitation radars have been associated with two main types of precipitation: convective and stratiform. Convective precipitation is characterized by its high altitude, steep vertical development, strong horizontal gradient of reflectivity and considerable variations in time and space (Leary and Houze Jr, 1978). Precipitation defined as "continuous" or stratiform has lower vertical speed in relation to convective rainfall, being characterized for covering large areas and for a more uniform distribution of levels of reflectivity.

From the point of view of vertical wind speed, there are equations that differentiate these two types of rain through this parameter. The following condition is necessary for stratiform rain formation:

$$[W] << [V_t]$$

in which w is the vertical speed of the wind and Vt is the terminal speed of the snow particles (~ 1-3 ms-1). In this condition, ice particles in the upper regions should precipitate, for they cannot stand or be carried up by vertical movements as they grow (Albrecht & Dias, 2014).

In tropical cloud systems, the stratiform precipitation is usually associated with intense and deep convection systems and not as a separate phenomenon (Figure 2).

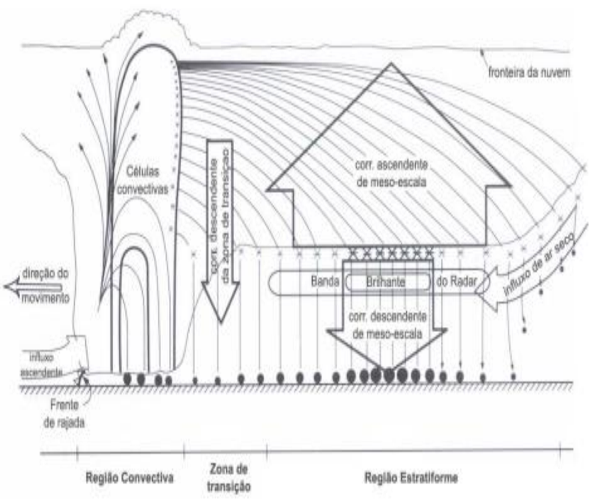

Figure 2 - Conceptual model of the trajectory of convective and stratiform precipitation and its average vertical movements. Asterisks represent hydrometeors and the filled circles represent the intensity of precipitation. Source: Albrecht and Dias (2014).

The precipitation of convective origin is associated with the cumulonimbus type of cloud and with it the presence of storms with lightning, hail, gusty winds and even tornadoes (Cotton, 2010 *apud* Segalin, 2012, p. 31).

Convective rains, for being quite intense, have significant impacts on society resulting in flooding and landslide, causing countless inconveniences. One of these convective rain events, which took place on June 7th and 8th, 2006, was caused by a cumulus conglomerate in a convective system of mesoscale, causing a fatal electric shock and commercial losses for up to 70% of the city of Olinda, Pernambuco (Agência Brasil, 2016).

In stratiform precipitation, the air movements are usually in horizontal direction, and this dynamics is particularly characteristic to some atmospheric events, such as sea breezes. They are often associated with a smaller amount of rainfall and therefore with much lower intensities than precipitation from convective sources.

Figure 3 - *Cumulonimbus* cloud, typical of convective precipitation. Source: spaceplace.nasa.gov, 2014.

It is worth noting that the types of rains do not happen in isolation, but in some cases simultaneously.

2. Materials and methods

2.1 Study area and data

For the study, 12 points were chosen from different cities in a longitudinal section in the state of Pernambuco (Figure 4), whose geographical grid is bounded by geographical coordinates -7 ° -10 ° latitude and -35 ° to -42 ° longitude.

After reviewing the rates described in points, maps of the average of precipitation rates were generated for the whole state. These maps were produced from the interpolation of satellite data through the GrADS software.

The cities selected according to the longitudinal section are in Figure 10 and Table 1 in accordance with the observed points.

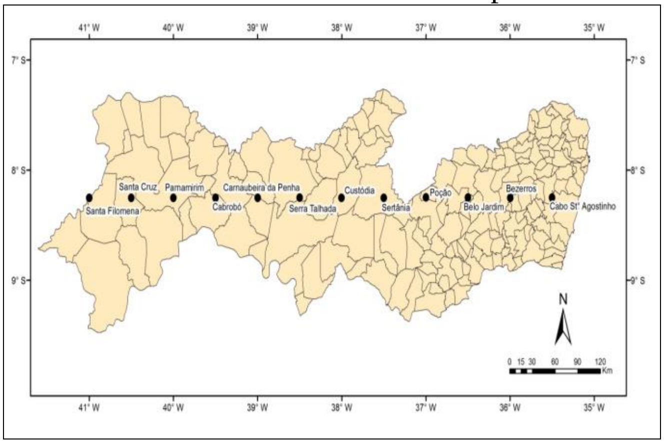

Figure 4 - Location of the cities used for the study of the types of precipitation. Source: IBGE (2010). Adapted by Rafael Anjos, 2014.

Table 1 - Selected cities and the coordinates of the points of the TRMM satellite data.

Cities	**Longitude**	**Latitude**
Cabo de Santo Agostinho	-35,25	-8,25
Bezerros	-35,75	-8,25
Belo Jardim	-36,25	-8,25
Poção	-36,75	-8,25
Sertânia	-37,25	-8,25
Custódia	-37,75	-8,25
Serra Talhada	-38,25	-8,25
Carnaubeira da Penha	-38,75	-8,25
Cabrobó	-39,25	-8,25
Parnamirim	-39,75	-8,25
Santa Cruz	-40,25	-8,25
Santa Filomena	-40,75	-8,25

2.2 Atmospheric systems active in Pernambuco

Rainfall in the state of Pernambuco has a standard behavior in its spatial distribution. Generally, the greater the distance from the coast, the lower the average precipitation is. It is noted that along the coast, average rainfall may vary from 1.800 mm to 2.000 mm, whereas in the countryside average values range from 400 to 600 mm (Figure 5). The main weather systems which inhibit or cause rains in Pernambuco state will be described below.

1- The Intertropical Convergence Zone (ITCZ) is characterized by cloud band in the equatorial belt, formed by the confluence of the trade winds from the northern and southern hemisphere. Its area is predominantly marked by low pressures, high temperatures and intense convective activity.
2- A cold front is characterized by the confluence of cold air masses with warm air masses. Its occurrence is given to tropical latitudes, being a rare occurrence on a large scale in the Northeast of Brazil. Nimer (1989) states that in the spring, these currents, which are generally originated in southern Brazil, cannot reach the south of Bahia. This fact changes in the winter season, when it may reach the coast of Pernambuco.
3- The Upper Tropospheric Cyclonic Vortex (UTCV) is formed in the Atlantic Ocean between the months of November to March. Its movement is from east to west. The lifetime of this system lasts around 7 days.
4- Instability lines are the cumulus cloud lines that form from the large amount of incoming solar radiation, causing a convective activity of the air. It usually occurs in the end of the afternoon and early evening.
5- Mesoscale Convective Complexes are clusters of clouds that form from the influence of climatic factors and conditions such as pressure, temperature and relief, causing intense and short rains. There are more of these in the spring and summer seasons.
6- Eastern Waves are formed in the atmospheric pressure field, suffering influence of the trade winds. Its performance can extend from the Reconcavo Baiano to the coast of Rio Grande do Norte, rarely reaching the coast of Ceará. It predominates in the autumn and winter seasons.
7- Sea breeze and land breeze are the result of the thermal gradient and pressure between land and sea surfaces. Rainfall from these systems are very brief.

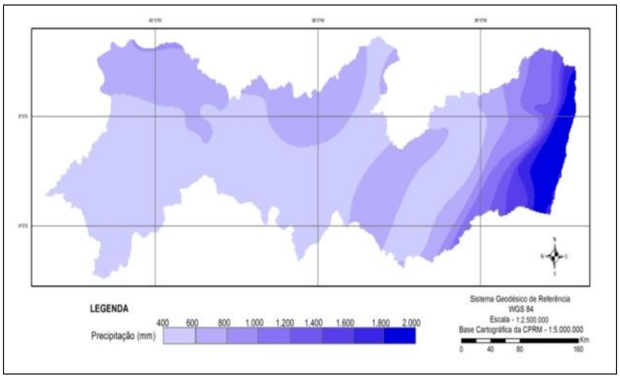

Figure 5 - Annual rainfall average rates in Pernambuco. Source: CPRM (2010). Adapted by Anjos (2014).

2.3 Temperature in Pernambuco

The average temperatures in Pernambuco vary according to important climatic factors, such as relief and sea breezes. The lowest average rates are registered in the massif of Garanhuns, in the north of the dry region of Pernambuco, near the city of Brejo da Madre de Deus and close to the city of Triunfo. The highest averages predominate in the mesoregions of Sertão do São Francisco and Sertão Pernambucano, although in the areas of Zona da Mata and Metropolitan Recife the temperatures vary between 25 and 26 °C (Figure 6).

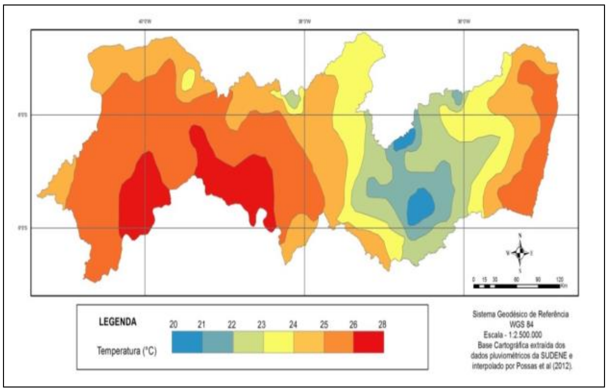

Figure 6 - Annual temperature rates in Pernambuco. Source: SUDENE (2010). Adapted by Anjos (2014).

Is worth mentioning that the northeastern semi-arid region is characterized by high average temperatures, further aggravating the consequences of drought - as this region has low levels of rainfall. This will influence the rainwater collection methods, which will have to prioritize the closed vessels such as tankers, to prevent the water to evaporate more easily.

Temperatures can influence the air dynamics and consequently the rains formation processes. Due to the dependence on convective activities, convective rains tend to form where the temperatures are higher, as is the case of the Intertropical Convergence Zone (ITCZ), where convective rainfall is quite common.

2.4 TRMM Rainfall Data

For the implementation of work, 3A25 algorithm data were used. They are a standard product derived from the precipitation sensor (PS) of the TRMM with spatial resolution of 0.5 ° x 0.5 ° in the period from January 1st 1998 to June 30th 2011.

To generate the data, the satellite passes three times a day with duration of each observation point of ~ 90 seconds, thereby providing the precipitation rates during this short sampling period. That is, the amount of rainfall is shown by time interval, by estimates that are presented in millimeters per minute (mm / hr).

The variable data of the algorithm were e.surfRainConvMean2 and e.surfRainStratMean2, which are the averages of convective and stratiform precipitation rates between the surface and 2 km height

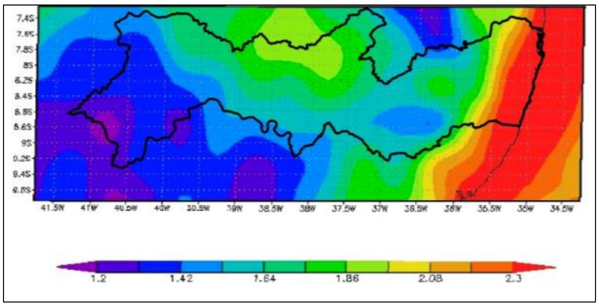

Figure 7 - Average precipitation rate close to the surface from January 1998 to June 2011 in the state of Pernambuco. Source: NASA (2012). Adapted by Anjos (2014).

2.5 Methodologies used in the analysis of TRMM data

The entire study was divided into two types of analysis: an analysis of rates in a longitudinal section and an observation of the maps with interpolated rates for the entire state of Pernambuco.

Thus, for each point the averages of convective and stratiform precipitation rates and stratiform were collected in the period described above. The aim of this type of analysis would be a study of the influence of the effects of sea breeze on both types of rain and the identification of other factors that are related.

The preparation of maps aimed at better representation of the spatial distribution of the types of rains across the state. The observation of other maps (temperature, rainfall and altitude) aimed at identifying the possible relations with the dynamics of convective and stratiform rain.

3. Results and discussion

3.1 Diagnosis of the average of the types of rain in Pernambuco 1998-2011

By analyzing convective and stratiform precipitation rates, several characteristics were analyzed according to the surveyed points. By correlating the geographical position of the points with the predominant types of rain and their intensity rates, it was observed that they possess spatial variation (Table 1).

Table 1 – Averages of convective and stratiform rates in the period of Jan/98 to Jun / 11 and rainfall, and the average of the precipitation in ascending order of length of points.

City	Convective Average (mm/hr)	Stratiform Average (mm/hr)	Precipitation Normals (mm)
Cabo de Stº Agostinho	3,32	1,19	2.301
Bezerros	2,66	0,92	603
Belo Jardim	2,49	0,83	708
Poção	2,59	0,79	762
Sertânia	2,81	0,79	575,3
Custódia	2,99	0,78	800
Serra Talhada	2,93	0,8	657
Carnaubeira da Penha	3,11	0,82	579
Cabrobó	2,43	0,75	490
Parnamirim	2,49	0,74	580
Santa Cruz	2,22	0,59	589
Santa Filomena	2,55	0,69	580

By analyzing convective rainfall rates of all points (Figure 8 and Table 2), the point which showed the highest rates was the one inserted in the city of Cabo de Santo Agostinho, whereas the lowest point was located in the city of Santa Cruz.

This variation can be explained by the fact that rainfall normals are the lowest in the last point, resulting in a smaller convective index than the one in the point located in the city of Cabo, where the average annual rainfall is also determined by the high rates of convective and stratiform precipitation.

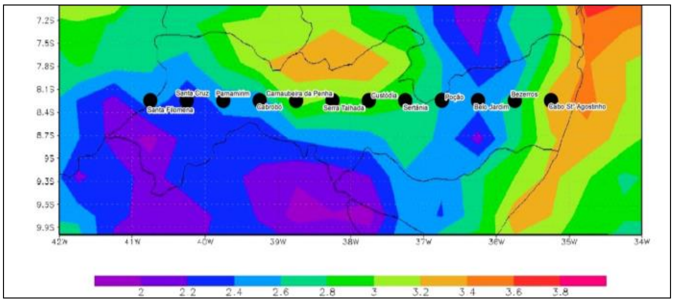

Figure 8 - Average intensity of accumulated convective precipitation Jan/98 to Jun/11 in Pernambuco. analyzed. Source: NASA (2012). Adapted by Anjos (2014).

Table 2 – Average intensity of convective and stratiform precipitation Jan/98 to Jun/11 in Pernambuco. (Convective rates are in descending order).

City	Convective Average (mm/hr)	Stratiform Average (mm/hr)
Cabo de Stº Agostinho	3,32	1,19
Carnaubeira da Penha	3,11	0,82
Custódia	2,99	0,78
Serra Talhada	2,93	0,8
Sertânia	2,81	0,79
Bezerros	2,66	0,92
Poção	2,59	0,79
Santa Filomena	2,55	0,69
Belo Jardim	2,49	0,83
Parnamirim	2,49	0,74
Cabrobó	2,43	0,75
Santa Cruz	2,22	0,59

However, in some points it was observed that convective and stratiform precipitation rates are correlated not only by the amount of annual rainfall. As it can be seen, the point located in Carnaubeira da Penha, although the average annual rainfall is 579 mm (UFCG, 2013), has the 2nd largest convective precipitation rate of the studied points. The same happens with the points of Serra Talhada and Sertânia (4th and 5th respectively) with higher rates than the city of Poção, which has higher annual rainfall averages.

It is important to note that close to these points, in the northern part of Pernambuco outback, there is an activity of convective centers being heavily influenced by the Intertropical Convergence Zone (ITCZ), bringing more intense convective rains. In addition to these factors, the relief of the region (Figure 9) can contribute to forced convection, depending on the dynamics of the winds.

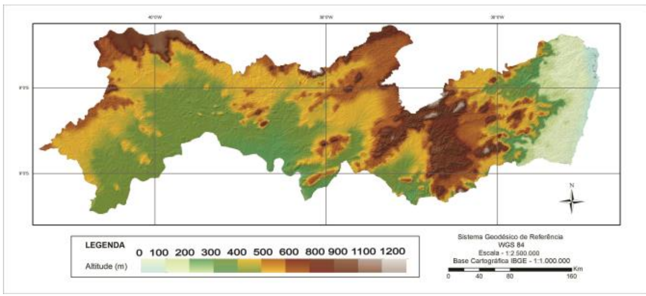

Figure 9 - Altitude levels in Pernambuco. Source: IBGE (2010). Adapted by Anjos (2014).

Another point to consider is the low convective activity in the highest areas of the Borborema Plateau (eastern part of the state), even though the windward region of the plateau gets higher rates of convective and stratiform precipitation.

Regarding the stratiform precipitation rates, the rates vary spatially according to their spatial location (Table 3 and Figure 10).

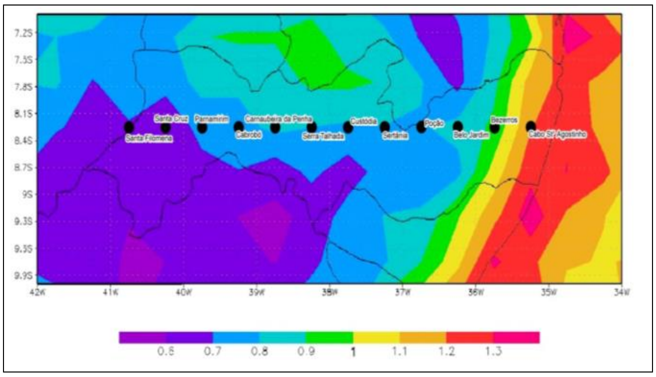

Figure 10 - Accumulated stratiform precipitation intensity from Jan/98 to Jun/11 in Pernambuco. Source: NASA, 2012. Adapted by Anjos (2014).

The areas that showed highest rates were those that were located closer to the coast of Cabo de Santo Agostinho, Bezerros and Belo Jardim (1.19); (0.92) and (0.83), respectively. The points that presented the lowest rates were located farther from ocean, as the cities of Parnamirim, Santa Filomena and Santa Cruz presenting (0.74); (0.69) and (0.59) respectively.

Table 3 – Stratiform and convective precipitation intensity averages from Jan/98 to Jun/11 (Stratiform in descending order).

City	Stratiform Average (mm/hr)	Convective Average (mm/hr)
Cabo de Stº Agostinho	1,19	3,32
Bezerros	0,92	2,66
Belo Jardim	0,83	2,49
Carnaubeira da Penha	0,82	3,11
Serra Talhada	0,8	2,93
Sertânia	0,79	2,81
Poção	0,79	2,59
Custódia	0,78	2,99
Cabrobó	0,75	**2,43**
Parnamirim	0,74	2,49
Santa Filomena	0,69	2,55
Santa Cruz	0,59	2,22

Source: NASA, UFCG (2014). Adapted by Anjos (2014).

It is remarkable that the role of the relief may be one of factors which block the flow of air to the countryside of the state, since the Borborema Plateau, due to its high levels of height, forms an orographic barrier which hinder the horizontal movement of the air to areas more distant from the coastline, thus reducing the intensity of stratiform rain. It is important to highlight that, due to the fact that stratiform rains are related to sea breeze, they tend to decrease in intensity as they move away from the coast, as the moisture coming from the ocean is limited in scope, making the rates in the mesoregions of Sertão do São Francisco and Sertão Pernambucano the smallest of the state. One of the main weather systems operating in the coast of Pernambuco and which are characterized by occasioning stratiform rains are the sea breezes.

Based on this assumption, as it is noticeable in Figure 11, it is possible to infer that although convective rainfall rates do not have a direct relationship with increasing longitude, stratiform rains rates gradually diminish as the points are located farther from the coast.

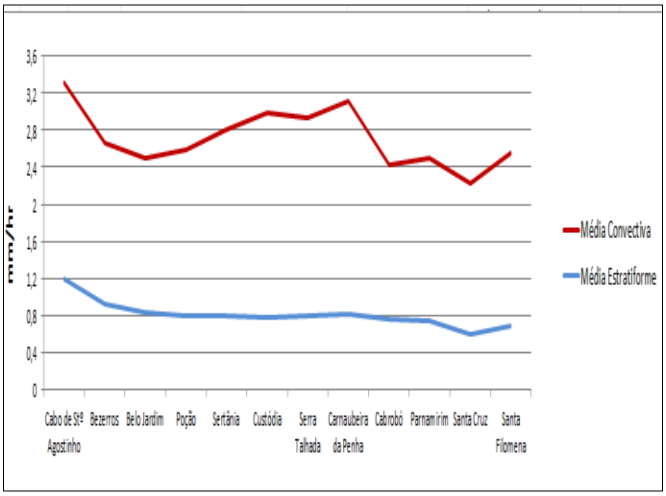

Figure 11 - Intensity of convective and stratiform rainfall averages during the period of Jan/98 to Jun/11 in ascending order of longitude. Source: NASA (2012). Adapted Anjos (2014).

The reduction in the intensity of types of stratiform rain with increasing longitude had been one of the hypotheses for the best accuracy of cumulative rainfall estimates from TRMM in cities more distant from Pernambuco's coast. This suggests that the satellite is more adequate to quantify precipitation when its source is convective and in greater proportions than the stratiform rains, since the rain formed by convection has larger droplets and more intense precipitation.

Others hypotheses are discussed, Gomes (2010) affirmed that the homogeneity of meteorological systems could allow the decrease of the difference behind the observed dates and the estimates.

4. Conclusions

Given the above, it is possible to conclude that the types of rainfall vary according to the geographic location of points. However, the factors that influence this variation are different for each type of rain analyzed.

The convective rainfall rates did not obtain a spatial distribution pattern, presenting high rates in the countryside of the state. Regarding the stratiform rainfall, it was observed that it tends to lessen its intensity as the points move away from the coast, implying that some climatic factors, such as sea breeze and relief, may be responsible for this variation.

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