

Researc<u>h Article</u>

# Impacts of Rainstorms during Austral Winter in Sao Paulo State, Brazil: A Case Study

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#### Abstract

September 2015 was an atypical austral winter rainy month. Rainstorms were observed in Sao Paulo State, Brazil (53°W-44°W; 20°S-25°S) with catastrophic consequences. In this paper the atmospheric conditions responsible for the rainstorms that occurred on 8<sup>th</sup> September 2015 in Sao Paulo State and their social and economic consequences were analyzed. The results showed that the rainstorms affected practically the entire Sao Paulo State causing floods and threw down trees, interrupting of the traffic on the streets and affecting the system of electric energy.

Rainstorms accompanied by high winds and strong divergence at 200 hPa and ascending motion were observed due to intense squall line moving over Sao Paulo State. Satellite and radar images showed strong convective activity and the heavier rainfall (around 90 mm) in the center-east sector at 20:45 UTC. Hourly data from meteorological stations showed that the wind gust and the precipitation were higher than 65 km h<sup>-1</sup> and 10 mm, respectively in almost the entire State. In Sao Paulo city, the rainfall was the highest for September in the last 20 years. The amount of precipitation was 3% higher than the amount expected for the entire September. Since each region of inundation in Sao Paulo city causes a daily damage higher than US\$ 263,000,00 a great economic harm must be expected.

A co-operative project between National Institute for Space Research (INPE) institution and Energisa Power Company is in progress aimed to mitigate the effects of adverse weather conditions as in the case of the rainstorm that occurred in 8<sup>th</sup> September 2015.

#### Keywords: Sao Paulo city; Rainstorms; Damages

# Introduction

Southeast Brazil (SEB) is characterized by strong annual variation of rainfall with rainstorms in austral summer and scanty rainfall in austral winter. This annual variation in rainfall is linked to the monsoon regime over South America [1-4]. Episodes of rainstorms with strong winds in this region may have drastic economical and social impacts because SEB is the most populous region and plays an important role in the economy of the country, being characterized by high industrial activity, agricultural productivity and hydroelectric generation. Some studies have been made to broach the occurrence of severe weather in SEB [5-8].

Although rainstorms and strong winds are concentrated mainly in austral summer, they could also be present during austral winter, the dry season. Very few references in the literature can be found on rainstorms in SEB during the austral winter months. Seluchi et al. [7] studied the mechanisms of rainstorms which occurred between 19 and 20 July 2004 in Serra do Mar, which is located in SEB and lies along the coastal region. This event represented one of the most extreme landslide events in the past 15 years in the region. They found that the persistence and configuration of the low–level circulation would play a more important role in the middle troposphere dynamics and the thermodynamic instability. Sias et al. [9] studied a convective event which occurred during winter 1989 in São Paulo city. In this work, they found that winter precipitation over 50 mm day<sup>-1</sup> occurred, on average, once in every ten years and it was mainly related to the passage of cold fronts.

Recently, although the austral winter months from June to August 2015 were very dry, during September 2015 many episodes of rainstorms and strong winds occurred in SEB, particularly over Sao Paulo State (53°W-44°W; 20°S-25°S), with harmful consequences. Sao Paulo State is the most populous and economically important state not only of the SEB, but of the entire Brazil. The capital Sao Paulo city, situated at 750 m of altitude, is the most populous and comprises an area of 1,521 km<sup>2</sup>. According to the climate classification Köppen-Trewartha (K-T) the type of climate is Cwa<sup>1</sup> (humid subtropical climate). Figure 1 shows the location of Sao Paulo State. According to the National Institute of Meteorology<sup>2</sup> (INMET) September of 2015 was the rainiest September since 1993. The record precipitation value in 1993 was 206.7 mm. September 2015 registered in Sao Paulo city the record of precipitation of 199.9 mm since 1993. The mean annual precipitation for Sao Paulo city is 78.8 mm.<sup>3</sup> In the present paper the atmospheric conditions responsible for the rainstorms that occurred in Sao Paulo State during 8<sup>th</sup> September 2015 and their consequences for the people, civil defense and electric energy distribution are analyzed.

# Data and Methodology

In order to analyze the destroying effects of the adverse meteorological conditions in many regions of Sao Paulo State information from news agencies is used. Satellite images are used to <sup>1</sup>https://pt.wikipedia.org/wiki/Classificação\_climática\_de\_Köppen-Geiger

<sup>2</sup>www.inmet.gov.br

<sup>3</sup>http://sao-paulo.estadao.com.br/noticias/geral,capital-paulista-registra-osetembro-mais-chuvoso-desde-1993,1770753

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identify the atmospheric conditions responsible for the intense rainfall associated with strong winds on 8th September 2015. Data of surface pressure, vertical velocity, divergence in high levels are used for analyzing the synoptic conditions during 8th September 2015. For this purpose 6 hourly gridded data from Climate Forecast System Reanalysis (GFS<sup>4</sup>) with 0.5° of horizontal resolution are used. For more details see information on-line<sup>5</sup>. The CAPE (Convective Available Potential Energy, Betts [10]) was calculated using data<sup>6</sup>. CAPE is effectively the positive buoyancy of an air parcel and it is an indicator of atmospheric instability, which makes it very valuable in predicting severe weather. High values of CAPE are indicative of high atmospheric instability. Radar images<sup>7</sup> are also used to verify the atmospheric instability in the region. In addition, data from meteorological stations of INMET in several cities in different regions of Sao Paulo State are used to analyze the hourly variation of wind gust, minimum pressure and precipitation. The rainfall data in each one of these cities come from rain gauges.

<sup>4</sup>http://nomads.ncdc.noaa.gov/data/gfsanl <sup>5</sup>http://nomads.ncdc.noaa.gov/data.php

<sup>6</sup>http://weather.uwyo.edu/upperair/sounding.html

<sup>7</sup>http://www.redemet.aer.mil.br/?i=produtos&p=radares-meteorologicos

The meteorological stations record wind gust, minimum pressure and precipitation.

# Results

# Synoptic conditions

The intensification of an area of low pressure located around Brazil, Bolivia and Paraguay together with a cold front passage from the South Region of Brazil to Sao Paulo and Rio de Janeiro States caused the development of several cumulonimbus clouds over the center-south of Brazil which provoked rainstorms (Figure 1). As one can see in Figure 2, at 06:00 UTC the low pressure region was located over Bolivia, Paraguay and Mato Grosso do Sul State (westward from Sao Paulo State) and moved from west to south at 12:00 UTC, 18:00 UTC and 00:00 UTC reaching Sao Paulo State. The strong and large squall line associated with the cold front over Sao Paulo State caused a high number and violent rainstorms in almost the entire state. Satellite images for 8<sup>th</sup> September show the strong activity during the afternoon in Sao Paulo State (Figure 1). Radar image at 20:00 UTC for Sao Roque<sup>8</sup>



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(near Sao Paulo city) shows the presence of rainstorms (around 90 mm) over the center-east of Sao Paulo State (Figure 3), in agreement with Figure 1c.

Strong divergence at upper levels associated with difluence (Figure 4) and intense ascending motion (Figure 5) due to the mesoscale convective cloud clusters were observed in the region. The displacement of the regions of strong divergence and intense vertical velocity (Figures 4 and 5) was in agreement with that of the sea level pressure as illustrated in Figure 2. As can be seen in Figure 4c-4d and Figure 5c-5d, areas of strong divergence and vertical velocity were present over Sao Paulo State at 18:00 UTC of 8<sup>th</sup> September and 00:00



Figure 2: Sea level pressure for: (a) 06:00 UTC (b) 12:00 UTC (c) 18:00 UTC 04:32 on  $8^{th}$  September and (d) 00:00 UTC on  $9^{th}$  September 2015. Units: hPa.



Figure 3: Radar image for  $8^{th}$  September 2015 at 20:00 UTC showing the rainstorm in the center-east region of Sao Paulo state. The number in the upper side of the legend correspond to dbz and those in the lower side correspond to precipitation.



**Figure 4:** The same as in Figure 2, but for the divergence at 200 hPa (s<sup>-1</sup>). Also shown are the wind vectors (m s<sup>-1</sup>) at 200 hPa. Units: m s<sup>-1</sup>.



UTC of 9<sup>th</sup> September. Figure 4b-4d also shows the presence of strong winds at 200 hPa in Sao Paulo State (around 25 m s<sup>-1</sup>, i.e., higher than 90 km h<sup>-1</sup>). This synoptic pattern is highly favorable for the occurrence of rainstorms and intense vertical movement that can intensify the winds close to the surface with harmful consequences as it happened in Sao Paulo State.

Due to the large number and the highly violent rainstorms a fantastic amount of atmospheric discharges were observed in Sao Paulo State. According to Atmospheric Electricity Group (ELAT) of the National Institute of Space Research (INPE), Brazil, 99,563

intracloud electric discharges and 31,929 cloud-to-ground discharges were observed during the 24 h of 8<sup>th</sup> September 2015 (Figure 6). The large number of lightning together wind strong winds and fall down trees were responsible for unroofing residences, interrupting of the traffic on the streets and electric system distribution and putting risks of life.

In order to know the hourly values of wind gust, minimum surface pressure and precipitation during 8<sup>th</sup> September 2015 in several cities in Sao Paulo State. Figures 7-10 were prepared. In Figure 7, some cities in different areas of Sao Paulo State that have INMET meteorological stations were chosen. Although in Campinas and Limeira there are no INMET meteorological stations their locations were inserted in this figure for use in the discussion of section 3b. In Figures 8-10 the hourly data of the wind gust, minima surface pressure and precipitation from 6<sup>th</sup> to 10<sup>th</sup> September 2015 in the cities of Figure 7 were showed. As can be noted, the stronger winds, the lower values of minima surface pressure and the heavier rainfall occurred during the 8<sup>th</sup> September 2015



Figure 6: Electric discharges during 24 hrs for  $8^{th}$  September 2015 observed in Sao Paulo state.

afternoon due to the presence of the strong squall line over Sao Paulo State. In general, wind gust was higher than 18 m s<sup>-1</sup> (approximately 65 km h<sup>-1</sup>) and in some regions the wind reached 25 m s<sup>-1</sup> (91 km h<sup>-1</sup>). The hourly precipitation matches approximately the minima surface pressure. The rainfall was in general higher than 10 mm in almost the entire state; in the northwest of the state it reached 30 mm.

#### Social and economic impacts

As show in Figure 1, on 8<sup>th</sup> September 2015 a strong and large squall line was present during afternoon over Sao Paulo State. During 24 h rainfall amounts up to 100 mm occurred in almost all the areas of the state. This severe weather condition affected practically the entire Sao Paulo State and many cities suffered the impacts of the adverse meteorological conditions.

The strong squall line moved from west to east over Sao Paulo State associated with a cold front (Figure 1). Using Python<sup>9</sup> a thermodynamic diagram was obtained where the CAPE value was calculated using radiosonde launched at 12:00 UTC in Campo Grande (Mato Grosso do Sul State, westward of Sao Paulo State). Campo Grande is the nearest location to Presidente Prudente (located in the west of the state, see Figure 7) with atmospheric sounding registers. The CAPE presented value higher than 1500 J kg<sup>-1</sup> showing atmospheric instability in the region (Figure 11). Unfortunately there were no more atmospheric soundings during the day in Campo Grande. However, taking into account that the CAPE presented high value already at 12:00 UTC it can be inferred that the atmospheric instability increased during the development of the observed mesoscale convective clusters in the squall line in the west of the Sao Paulo State.

At 16:45 UTC intense convective activity was observed over the west region of Sao Paulo State (Figure 1a). The impact on the cities located in this region was strongly destructive. Figure 12a illustrates the effect of the heavy rainfall and strong winds in the region of Presidente Prudente. Due to the rainstorm many places were flooded causing the floating of cars. Many trees fell down and the traffic of vehicles was affected<sup>10</sup>. At 18:45 UTC the strong convective activity moved to the <sup>a</sup>https://pypi.python.org/pypi/SkewT

<sup>10</sup>http://www.imparcial.com.br/site/forte-chuva-alaga-diversos-pontos-de-prudente-



Figure 7: Location of some cities in different regions of Sao Paulo State. All of them have meteorological stations of INMET, except Campinas and Limeira. Also are indicated the altitude of the cities.

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corresponds to the CAPE.



Figure 12: Damages due to the temporal of 8<sup>th</sup> September 2015 in Sao Paulo state: (a) Presidente Prudente, (b) Barra Bonita, (c) Campinas, (d) Limeira, (e) Piracicaba and (f) Sao Paulo.



central region of the state (Figure 1b). In Barra Bonita (Figure 7) many areas were flooded due to the intense rainfall and vehicles were dragged by the water current<sup>11</sup> (Figure 12b). Several problems occurred in the region of Campinas (Figure 7), an important city in the center-east region of Sao Paulo State. At least 736,000 people remained without electric energy due to strong wind and lightning associated to the rainstorm which damaged the electric distribution system<sup>12</sup>. Also the temporal caused much harm, such as floods and threw down trees. The wind reached 98.3 km h<sup>-1</sup> and the civil defense informed that 26 trees fell down. Figure 12c shows the onset of the rainstorm in Campinas<sup>13</sup>. Many other cities in the center-east sector of Sao Paulo State were affected by rainstorms. Figures 12d-12e illustrate, respectively, the onset of the temporal in Limeira<sup>14</sup> and the damage in Piracicaba, where cars were dragged by the water, trees were fallen down and there was cut of electric energy in many points of the city<sup>15</sup> (Figure 7).

At 20:45 UTC the strong convection was present in the east sector of Sao Paulo State (Figure 1c). Particularly in Sao Paulo city, the rainfall during 8<sup>th</sup> September 2015 was the highest during September in the last 20 years. The amount of precipitation (69.3 mm) was 3% higher than the amount expected for the entire September (67 mm). Around 21:30 UTC there were 29 regions with inundation, 5 of them were e-provoca-estragos.html

<sup>15</sup>http://g1.globo.com/sp/piracicaba-regiao/noticia/2015/09/chuva-de-20-minutos-alagaavenidas-e-arrasta-carro-no-centro-de-piracicaba.html impassable. The traffic was interrupted in many regions of the city, the metropolitan trains and some subway lines showed problems due to the strong rainfall. At 21:30 UTC Sao Paulo city<sup>16</sup> showed 184 km of traffic jam while in the average it is 70 km at 110 km h<sup>-1</sup>. The strongest rainfall occurred in the west region of Sao Paulo city (Figure 13). The accumulated precipitation from 23:00 UTC of 7<sup>th</sup> September 2015 to 23:00 UTC of 8<sup>th</sup> September 2015 in Butantan district was 97.8 mm. Wind gusts of 83 km h<sup>-1</sup> occurred in the region. Due to the temporal the distribution electric system suffered the worst damage during 2015 and at least 149 trees fell down in the city. Figure 12f illustrates the harm in Sao Paulo city<sup>17</sup>.

The metropolitan region of Sao Paulo, with 20 million of habitants, is the fourth urban agglomeration of the world. Each region of inundation in Sao Paulo city causes a daily damage with costs higher than US\$ 263,000,00 (one million of reais, a brazilian money). Since there are almost 749 regions of inundation the annual losses reach approximately US\$ 88.4 million (762 million of reais) [11]. The inundation contributes to reduce the city development and the people life quality. Direct losses are due to the interruption of economic activities in the areas affected by floods. In addition the floods have high repercussion affecting the daily traffic of the people inside and outside of the metropolitan region.

In the present study the rainstorms on 8<sup>th</sup> September 2015 in Sao Paulo State were considered. However, September 2015 was an atypical month where many rainstorms occurred not only in Sao Paulo State <sup>16</sup>http://sao-paulo.estadao.com.br/noticias/geral,chuva-em-sp-faz-corrego-transbordar-evento-derruba-arvores,1758465

<sup>&</sup>lt;sup>11</sup>http://noticias.bol.uol.com.br/ultimas-noticias/brasil/2015/09/30/enxurradacarrega-carros-e-motos-em-rua-principal-de-barra-bonita-sp.htm

<sup>&</sup>lt;sup>12</sup>http://www.cpfl.com.br/releases/Paginas/temporal89.aspx

<sup>&</sup>lt;sup>13</sup>http://g1.globo.com/sp/campinas-regiao/noticia/2015/09/temporal-deixa-274-mil-semenergia-em-3-cidades-da-regiao-de-campinas.html

<sup>&</sup>lt;sup>14</sup>http://g1.globo.com/sp/piracicaba-regiao/noticia/2015/09/imagem-mostra-mar-denuvens-no-ceu-de-limeira-e-vira-sucesso-na-web.html

<sup>&</sup>lt;sup>17</sup>http://sao-paulo.estadao.com.br/noticias/geral,capital-paulista-registra-o-setembro-maischuvoso-desde-1993,1770753

but also in the center-south of Brazil which deserves future studies.

#### Mitigation efforts to severe weather conditions

Extreme weather events like that in 8th September 2015 seem to be occurring more and more frequently, often with disastrous results. This is aggravated by the evidences reported in the AR4 and AR5 IPCC (Assessment Report 4 and 5 of the Intergovernamental Panel on Climate Change) which indicated that in the last decade extreme events such as tornadoes, heat waves and strong thunderstorms associated with rainstorms, windstorm and high incidence of lightning are occurring more frequently. In particular in Brazil the extreme events responsible for natural hazards have been occurring in almost all the regions, such for example those that occurred in September 2015, the Catarina cyclone [12,13] which left 33,000 people homeless in the State of Santa Catarina, the strong rainstorms which occurred in Angra dos Reis and many other regions of the State of Rio de Janeiro in 2010 which caused more than 200 regions of landscape and the death of more than 170 people, the rainstorms in the mountainous regions of Sao Paulo and Rio de Janeiro States in 2011 [14] which provoked the death of more than 900 people and destroyed thousands of homes, the thunderstorms that recently happened in November 2015 in the centersouth Brazil<sup>18</sup> and many others. Table 1 shows some of the extreme events occurring in Brazil and their consequences. Thus, there is need to mitigate the effects of the severe extreme events. Studies providing information of the atmospheric conditions in extreme situations are essential for the electric energy system security, national economy and the population comfort. In addition, it is necessary to have a system of analysis and meteorological management that allow: a) an ample access to meteorological data aggregating the network of meteorological, hydrological, radar and satellite data, b) to forecast locally the severe rainstorms at least 6 h ahead of time, c) to enable a warning scheme.

Recently, the project named "Management of the impact of climate severe events on the electric energy network" (In Portuguese, "Gestão dos impactos de eventos climáticos severos na rede elétrica") has been developed with the purposes above mentioned. It is a co-operative project between the National Institute for Space Research (INPE) and the Energisa power company. It is a interdisciplinary project with the participation of the ELAT/INPE Group which develops studies of thunderstorms and electrical discharges, the Center of Weather Prediction and Climate Studies (CPTEC/INPE) which run numerical weather prediction models and makes available several products of environmental monitoring for the society, the Division of Image Processing (DPI/INPE) which has been developed the TerraMA<sup>2</sup> Library that enables the generation of geo-processing application of spatial data in management systems.

The warning system is based on a platform that allow us to integrate in real time geoambiental data (atmospheric, climatological, hydrological, geotechnical) with maps of ambiental risks and vulnerabilities in order to give warning in several cases such as floods, dry weather, electric discharges, landscape among others. This platform is called TerraMA<sup>2</sup> – Monitoring, Analysis and Alert Plataform<sup>19</sup>. The TerraMA<sup>2</sup> needs essentially of data obtained from the geoambiental module and the mapping of the areas of risk. The geoambiental data provides information of weather, climate and other extreme events obtained from analysis of observational data and numerical weather predictions. The module that storages information about the risks and vulnerability associated to natural disasters takes into account geotechnical information obtained from local research institutes. The information associated with climate and hydrometeorological extremes are superposed to the mapping of the areas of potential risks. The intersection of all the information allows us the identification of potential risks which supplies the module of automatic analysis. The automatic analysis is converted in warnings which are sent to the agencies responsible to the prevention and mitigation. Besides to be useful for the power electric sector the results of the project can be applied to other sectors such as agriculture, civil defense, among others. The project just began and as the expected results are obtained future case studies will be showed in another paper. Studies such those in the present paper provides information of climate extremes which is useful to the project.

### Summary

In this paper the atmospheric conditions of the strong rainstorms which occurred in Sao Paulo State during 8th September 2015 and the social and economic damage were analyzed. This severe weather condition affected practically all the areas of the state and many cities suffered the impacts of the rainstorms. Intense rainfall associated with strong winds and lightning caused floods and threw down trees, turned street lamps out, unroofed residences, interrupted traffic on the streets, dropped conducting wires affecting the transmission and distribution of electric energy causing damage for the people. In the present study the harm effects of the rainstorms in various cities in different regions of Sao Paulo State were illustrated and discussed. Hourly data of wind gust, minima surface pressure and precipitation from 6<sup>th</sup> to 10th September 2015 in several cities of the state were plotted. It was observed that during 8th September the wind gust was in general higher than 18 m s<sup>-1</sup> (approximately 65 km h<sup>-1</sup>); in some regions the wind reached 25 m s<sup>-1</sup> (91 km h<sup>-1</sup>). The hourly precipitation matches approximately the minima surface pressure. The rainfall was in general higher than 10 mm in almost the entire state; in the northwest of the state it reached 30 mm.

<sup>18</sup>http://www.deolhonotempo.com.br/index.php/nacional/3412-tres-tornados-sao-registrados-num-so-dia-no-brasil

<sup>19</sup>www.dpi.inpe.br/terrama2

Extreme event	Consequences
Catarina cyclone in 2004	left 33,000 people homeless in the State of Santa Catarina
strong rainstorms in Angra dos Reis in 2010	caused more than 200 regions of landscape and the death of more than 170 people
rainstorms in the mountainous regions of Sao Paulo and Rio de Janeiro States in 2011	provoked the death of more than 900 people and destroyed thousands of homes
Rainstorms in Sao Paulo State in September 2015	caused floods and threw down trees, turned street lamps out, unroofed residences, interrupted traffic on the streets, dropped conducting wires affecting the transmission and distribution of electric energy producing damage for the people
thunderstorms that happened in November 2015 in the center- south Brazil	In Chapeco (State of Santa Catarina): entire buildings destroyed in few seconds due to strong winds; In Marechal Candido Rondon (State of Parana): the tornado destroyed part of the city and caused the death of 10 people

The storm over Sao Paulo State was due to a large and strong squall line moving from west to east in the region. Low pressure associated with strong divergence at high levels and ascending motion was observed. Satellite and radar images were used to illustrate the strong convective activity in the region, particularly at 20:00 UTC in the centereast sector (heavier rainfall around 90 mm). Due to the large number and the high violent rainstorms a fantastic amount of atmospheric discharges were observed. Data from ELAT/INPE indicated that 99,563 intracloud electric discharges and 31,929 cloud-to-ground discharges were observed during the 24 hrs of 8<sup>th</sup> September 2015.

Particularly in Sao Paulo city, the rainfall during  $8^{th}$  September 2015 was the highest registered for September in the last 20 years. The amount of precipitation (69.3 mm) was 3% higher than the amount expected for the entire September (67 mm). Each region of inundation in Sao Paulo city causes a daily damage higher than US\$ 263,000,00. Since the temporal of  $8^{th}$  September affected almost all the regions of the city a great economic harm must be expected.

A co-operative project between INPE institution and Energisa Power Company is in progress aimed to mitigate the effects of adverse weather conditions as in the case of the rainstorm during 8<sup>th</sup> September 2015. The project just began and it is expected that the results can help the electric energy system, the national economy and the population comfort.

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