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Statistical Variability of Severe Rainfall Events in Southeastern Brazil

Variabilidade Estatística dos Eventos Severos de Chuva no Sudeste do Brasil

Angélica Nardo Caseri[1]; Carlos Frederico Angelis[1]; Vinícius Banda Sperling[1] & Etienne Leblois[2]

[1]Cemaden, Estrada Dr. Altino Bondensan 500, Eugênio de Melo, 12247-016, São José dos Campos, SP, Brasil
[2]INRAE Lyon-Grenoble Auvergne-Rhône-Alpes, RiverLy Research Unit,
5 rue de la Doua – CS 20244, 69625 Villeurbanne Cedex, França
E-mails: angelica.caseri@gmail.com; carlos.angelis@cemaden.gov.br; vinicius.sperling@cemaden.gov.br; etienne.leblois@inrae.fr
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Abstract

Extreme rainfall events are one of the natural phenomena that cause more damages. These events are known to be well localized, especially in tropical and subtropical climate regions such as southeastern Brazil. These events have high heterogeneity and the evolution of rain cells changes is quick, the forecast and knowledge of these extreme rainfall events still represent a challenge for the scientific community, such as the spatial variability of rainfall. For this, data from the weather radar installed in Campinas city were used, which generates new radar images every 10 minutes, and data from twenty-nine rain gauges located in the region. For this, 16 rainfall events were selected, located in the region of Campinas/SP, southeast of Brazil, a region that has already recorded many events. For this study, rain and intermittent zones were analyzed separately. This study helps to understand the main statistical characteristics of severe events, mainly located in the region of Campinas. In addition, the information extracted and the analyzes carried out in this study can be used as input data for models that generate possible rainfall scenarios, ensembles, such as, methods based on geostatistics or machine learning.

Keywords: *Extreme events; statistical analysis; spatio-temporal variability*

Resumo

Eventos extremos de chuva são um dos fenômenos naturais que causam mais danos. Esses eventos são bem localizados, especialmente em regiões de clima tropical e subtropical, como o sudeste do Brasil. Esses eventos têm alta heterogeneidade e a evolução das mudanças das células de chuva é rápida, a previsão e o conhecimento desses eventos extremos ainda representam um desafio para a comunidade científica, como a variabilidade espacial da chuva. Este trabalho tem como objetivo estudar a variabilidade espaço-temporal das chuvas, bem como suas principais características estatísticas, como a média e o desvio padrão da intensidade dos eventos chuvosos. Para isso, foram utilizados dados do radar meteorológico instalado na cidade de Campinas, o qual gera novas imagens de radar de 10 em 10 minutos, e dados de vinte-nove pluviômetros localizados na região. Para este estudo, a chuva e as zonas intermitentes foram analisadas separadamente. Este estudo auxilia na compreensão das principais características estatísticas de eventos severos, principalmente localizados na região de Campinas. Além disso, as informações extraídas e as análises realizadas neste estudo podem ser utilizadas como dados de entrada de modelos de geração de cenários possíveis de precipitação, como por exemplo métodos baseados em geoestatística ou em aprendizagem de máquinas.

Palavras-chave: *Eventos extremos; análise estatística; variabilidade espaço-temporal*

1 Introduction

Every year, floods generated by extreme rainfall events cause high socioeconomic damages. The magnitude and frequency of these events are expected to increase with the global warming due to the intensification of greenhouse gases (Mal *et al*., 2018). The results of the study confirm the increase in water vapor that leads to more extreme rainfall events, thus raising the risk of flooding (Rajeevan *et al*., 2008; Mukherjee *et al*., 2018). According to Marengo *et al.* (2013) in the São Paulo region, the total and intensity of severe rainfall events increased. Marengo *et al.* (2013) found that in the region of São Paulo the total and intensity of severe rain events increased since mid-1930. These events can generate floods and may have a strong impact on human activities, especially in urban areas, as metropolitan region of Campinas/SP; where values-at-risk also increase along the development of the economy, independently of the evolution of climate hazard (Ootegem *et al*., 2018). The spatio-temporal scale of these rainfall events is a challenge for numerical weather forecasting models. Flash floods are particularly dangerous because of their sudden and difficult to predict (Jonkman & Vrijling, 2008). Flash floods most often result from extreme rainfall events occurring over areas (or catchment areas) that, given local hydrometeorological features, are prone to this specific natural hazard (Borga *et al*., 2010).

In Europe, more than 550 extreme flood events were identified in the period 1946-2007 (Bastone *et al*., 2011). According to Nunes (2011) 413 floods were registered in South America in the period 1904-2011. According to Sprissler (2011), in 2010, economic losses summed to $ 950 million. According to the author, it is estimated that, between 2010 and 2030, such losses can increase between 33 million to 43 million, this is mainly due to climate change and the growth of urban areas. Brazil is among the ten countries most affected by floods in the world (Guha-Sapir *et al*., 2016). These severe events have high spatial and temporal variability, and thus the prediction of these events is an important challenge for the scientific community (Machado *et al*., 2014; Caseri *et al*., 2016).

Descriptors of spatial and temporal variabilities of these severe rainfall events can help in management of water resources and the prevention of damages caused by water-related disasters such as floods. Studying these statistical characteristics may contribute to the understanding and detection these events (Bonta, 2001; Rysman *et al*., 2016). Especially in the perception of the structure and behavior of the rain cells and how they evolve in time and space.

Many studies have already been done to analyze the different characteristics of extreme rains. Rodríguez-Solà *et al.* (2017) investigated the temporal variability of extreme events from the intensity-duration-frequency (IDF). Jung *et al.* (2017) studied the temporal structure of extreme rainfall in South Korea based on a block bootstrap to detect changes in temporal structure.

As examples of research that carried out post-event analysis to understand its main characteristics can be cited, can be cited, Doswell *et al.* (1996), Hlavčová *et al.* (2016), Saint-Martin *et al.* (2016), Amponsah *et al.* (2018). Doswell (1996) presents a study of severe convective rainfall events in order to identify the main ingredients needed to occur these events and causes flash flood. The mainly features considered were: the rainfall intensity, the duration, direction and speed of the event and the size of the system that caused the event. Hlavčová (2016) characterize and identify flood and runoff peaks, addressing post-flood analysis. Saint-Martin (2016) present a post-event study which analyzes the damage caused by these events, creating the DamaGIS database. Finally, Amponsah (2018) were interested in studying flash flood events in the Mediterranean region. The aim of this research was creating a base comprising 49 severe rainfall events that occurred in France, Israel, Italy, Romania, Germany and Slovenia.

In Brazil, several studies have been conducted in order to understand the climate change and the increasing frequency and intensity of severe rainfall events. These works were carried mainly in the metropolitan region of São Paulo, this region has an important historical of severe rainfall events (Silva Dias *et al*., 2012). These studies show that urban areas have a great impact on the hydrometeorological behavior of the watersheds (Lima *et al*., 2018).

This article aims to deeply understand the statistical characteristics of severe rainfall events. This research analyzes severe rainfall events considering the statistical characteristics of the intermittent zones separately from the rainy zones using geostatistical techniques (based on the analysis of variograms, for example) and combining information from radar and pluviometer data. This can be considered as one of the main differences of this research in relation to the majority of scientific studies that analyze historical rain events. Thus, helping to understand how these regions can interact and correlate with each other. And what are the key behaviors that can be noticed in the case of storm events. The Campinas region (state of São Paulo) was used as study area. Many extreme events have already been detected in this region, such as the event of June 5, 2016 (Pereira Filho *et al*., 2019; Rehbein *et al*., 2018).

This paper presents the following sections: Section 2 is a presentation of the data and study area that was applied the methodology, as well as the selected storm events for this study. Section 3 describes the method used to analyze the main statistical characteristics of the events. Section 4 shows the results found using the methodology developed in this paper, considering the selected storm events. Lastly, section 5 completes the paper contributing to the conclusions reached and suggestions for future work.

2 Data and Study Area

2.1 Location

The study area considered here is in the region of Campinas/SP (state of São Paulo) within a 60 km radius of the Exploratory Science Museum – UNICAMP (State University of Campinas). The study area was limited by the area covered by the radar, data used in this study. The period considered is this study is November 2016 to May 2017. Within Brazil the region of Campinas is noticeable for its high economic development. The main economic activities in this region are: crops such as sugarcane, orange, pasture, in the primary sector; and agribusiness, which predominates in the secondary sector (Government of the state of São Paulo, 2016). Numerous flood events were recorded in urban areas, responsible for various property damages evicting hundreds of residentes (Sprissler, 2011). For example, the floods occurred on March 24, 2016 and June 7, 2016 caused at least 19 deaths (Folha de São Paulo, 2016).

Recently, in the city of Campinas, the INPE (National Institute for Space Research) and CPTEC (Center for Weather Forecast and Climate Studies) research institute, in partnership with the Center for Meteorological and Climate Research Applied to Agriculture (CEPAGRI), in the scope of the The São Paulo Research Foundation (FAPESP) SOS-CHUVA project, installed a X-Band dual polarization weather radar (more details about X-Band radar in Diss *et al*., 2009) near the premises of the Exploratory Museum of Science – UNICAMP, aiming to improve the knowledge related to the spatial variability of the rainfall, the predictability and the severity of rainfall events.

2.2 Data

The dataset used in this study was made available by the weather radar installed in in the Exploratory Museum of Sciences in UNICAMP, Campinas-SP. The dual-polarized X-Band weather radar provides data every 10 minutes, the pixels are square with 200 m side (ie 25 pixels per km²). The total radar coverage area is 150km.For this study, the radar reflectivity data was already converted into rainfall millimeters. The precipitation rate was estimated from reflectivity through empirical relationships of the form Z = ARb, where A and b are coefficients related to the size and distribution of the spectrum of drops in the clouds. These and are determined using statistical methods (for more details SOS-CHUVA, 2015).

These measures are continuous, spatially and temporally. Besides the weather radar data, the data from 29 automatic rain gauges of the National Centre for Monitoring and Early Warnings of Natural Disasters (Cemaden) located in the studied region were also used. Figure 1 shows the location of the weather radar and the rain gauges.

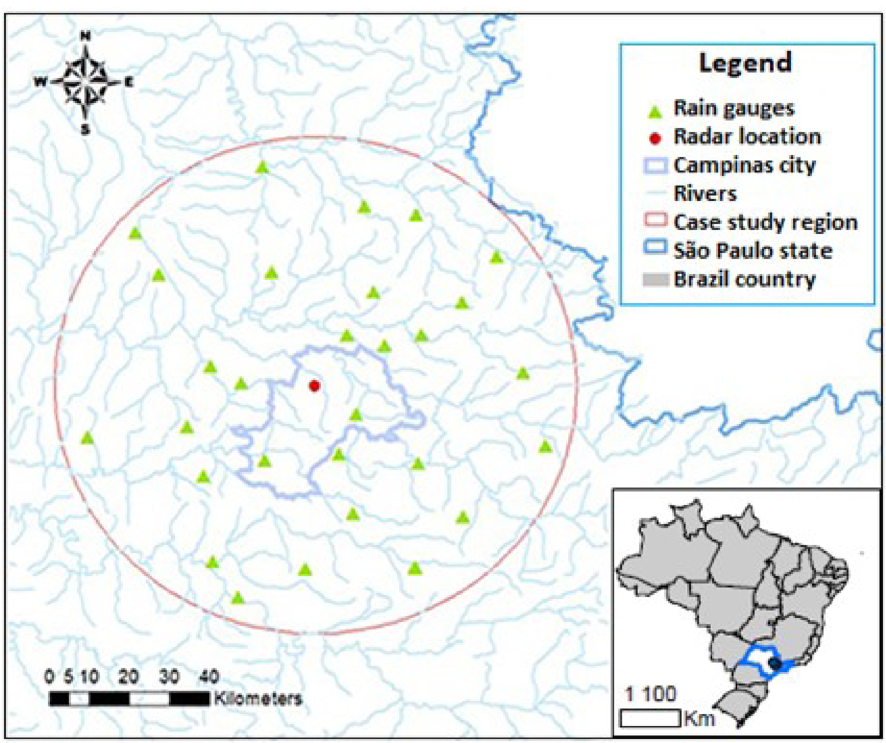

Figure 1 Study area (Campinas region), X-band weather radar location (red point) installed in the region during the study period of this article and rain gauges used in this study (green triangles).

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2.3 Anaysis of Events

For this study, considering the period from November 2016 to May 2017, rainfall events were selected from the historical series of the radar data installed in Campinas (presented in the previous section). These events were selected as follows:

1. An event starts, in the study area, when the hourly radar accumulated rainfall exceeds the threshold of 5 mm/h with the minimum area of 5 pixels (25 km²).
2. The event ends when hourly rainfall rate data is accumulated drop below the threshold of 5 mm/h.
3. For each event thus defined, accumulated rainfall are calculated in each pixel.
4. The events selected are those with the highest cumulative pixel count, but also those involving minimum half the study area

Considering these criteria and the study area, 15 rain events were identified. The selected 15 rainfall events correspond to a total of 202 hours of rain. Table 1 shows the start and end dates, duration, and maximum radar accumulations at a given pixel of each selected event. We observe that the duration of events varies between 5 hours (event # 6) and 20 hours (event # 1 and 10). Figure 2 shows an example of rainfall event evolution (selected event #14, Table 1) considering radar measurements. The event lasted 18 hours and had a maximum height of 191 mm.

3 Method

In order to analyze the extreme events presented in this study we considered the following characteristics of each event:

- The probability of distribution and the spatio-temporal structure of non-zero rain (PNN).
- The spatio-temporal structure of the rain/no-rain intermittence (which corresponds to the determination of rainy areas and areas where there is no rain).
- The displacement of rainfall fields, i.e., the mean of the velocity of displacement of clouds.

In this work, we considered the spatio-temporal variogram with an exponential model to be able to estimate the parameters related to the structure of the rainfall field (the rainy zones and the intermittency, the intermittent is a field of 0,no rain, and 1, rain, which defines the rainy zones). The variogram illustrates the spatial and temporal correlation of the sampling points as a function of the distance between points (Isaaks & Srivastava, 1989). The exponential model is characterized by a plateau reached asymptotically. In this model, the correlation distance is defined as the point where the variogram reaches 95% of its plateau (Mälicke *et al*., 2018). In summary, the characteristics studied here are (Caseri *et al*., 2016):

- **Three parameters characterize the intermittency:** the percentage of the region (radar area considered in this paper, 60km radius) that has zero rain zones (Pz), the distance (LInd) and the correlation time (TInd) of the intermittence zones, defined by the spatio-temporal variogram model considering intermittency field. All of these parameters are calculated considering all the time steps of the rainfall event. These parameters were calculated for each rainfall event selected in this paper.
- **Four parameters define the non-zero rainy zone:** the non-zero rain correlation distance (LPNN) and time (TPNN), which are defined by the spatio-temporal variogram model of non-zero rainfall; the average (mPNN) of the non-zero rain and the standard deviation (sPNN) of the non-zero rain.
- **Two parameters to characterize the displacemenet of rain cells:** the speed (U) and the direction (D) of the wind. Both are estimated based on the monitoring of correlated rainfall fields, where the displacement of consecutive fields is deduced through the spatio-temporal autocorrelation of the rainfall radar observation. In this role, speed (U) is represented in m/s and direction (D), in geographic degrees (0 ° = north, 90 ° = east, 180 ° = south, 270 ° = west; more details Leblois & Creutin, 2013, Creutin *et al.,* 2015). In this study, we considered the Lagrangian method, these characteristics concern individualized rain cells (in this case, it follows a particular cell and observes how its characteristics vary over time). In this study a rain cell is characterized by the most important rain zone of the event considering a threshold (in this study 5mm/h) and the total area that the rain zones cover.

The radar data were used to estimate the parameters related to the rain structure (Pz, TInd, LInd, LPNN, TPNN) and tracking the trajectory of the rain cells (U and D). The data from rain gauges are used to estimate the parameters that represent the rain field distribution function (mPNN and sPNN). The data of rain gauges and radar were used in this way, mainly, due to the characteristics of these data. Compared to rain gauges, radars provide better information on the spatial and temporal variability of rain (Fukao & Hamazu, 2014). On the other hand, rain gauges provide direct measurement of rain, they are occasionally more accurate than radar data. For better analysis of selected

Event (ID)	Event start date (year/month/day hour)	Duration (hours)	Maximum accumulation pixel from the given radar data (mm)
1	2016/11/23 06:30	20	169
2	2016/11/26 15:30	8	149
3	2016/11/27 13:30	15	150
4	2016/11/28 15:30	17	183
5	2016/12/03 14:30	9	117
6	2017/02/18 00:30	5	113
7	2017/02/24 15:30	11	172
8	2017/02/25 10:30	13	83
9	2017/02/26 13:30	11	144
10	2017/03/02 11:00	20	168
11	2017/04/21 16:30	11	212
12	2017/05/05 02:00	15	291
13	2017/05/18 13:00	12	282
14	2017/05/19 02:00	17	191
15	2017/05/21 12:30	18	139

Table 1 shows the start dates, duration, and maximum radar accumulations at a given pixel of each selected event.

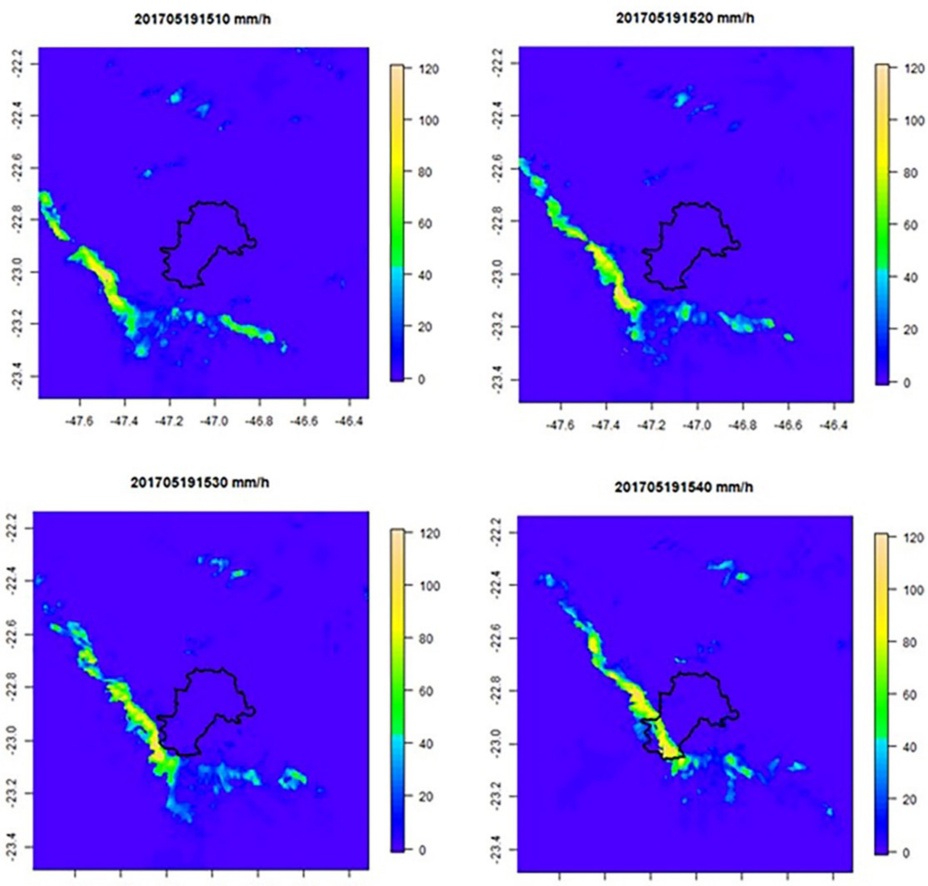

Figure 2 Example of rainfall event evolution selected for this paper, Event # 14(2017/05/19 2h – 2017/05/19 18h). The images show rainfall rates estimated by radar for a line of convective storms approaching to Campinas city (black line on the map), the images show a 40min event Evolution, the duration of the event was 18h.

rainfall events, measurements made by these two data sources can be combined in order to best take advantage of each type of measurement.

4 Results

The spatio-temporal correlation of intermittency is estimated between 7-51 km in space (LInd) and between 0.7-3.2 hours in time (TInd). The spatio-temporal correlation of non-zero rain zone is estimated between 4-35 km in space (LPNN) and between 0.5-5.5 hours in time (TPNN). The average percentage of zero rain (Pz) varies between 38% and 91%. That is the area of zero rain zones, considering all the time steps of each event, varies between 38% to 91%. This shows that some of the selected events are well located, affecting only one area of the entire study region. Considering the events selected here, the rains come mostly from the west. The mean (mPNN) and standard deviation (sPNN) of non-zero rainfall range from 2 to 4.6 mm/h and 1.4 to 9 mm/h, respectively. Through these results it can be seen that the sPNN, in some selected rainfall events, are higher than the mPNN, such as event 2. Thus, it is noted that in some cases the sPNN values are high. On the other hand, the mPNN values can be considered low, as it is lower than the threshold (5 mm/h) considered to selection the rainfall events used in this paper.

Figure 3 shows a radar chart (also known as spider chart) for each rainfall event. In these are presented the

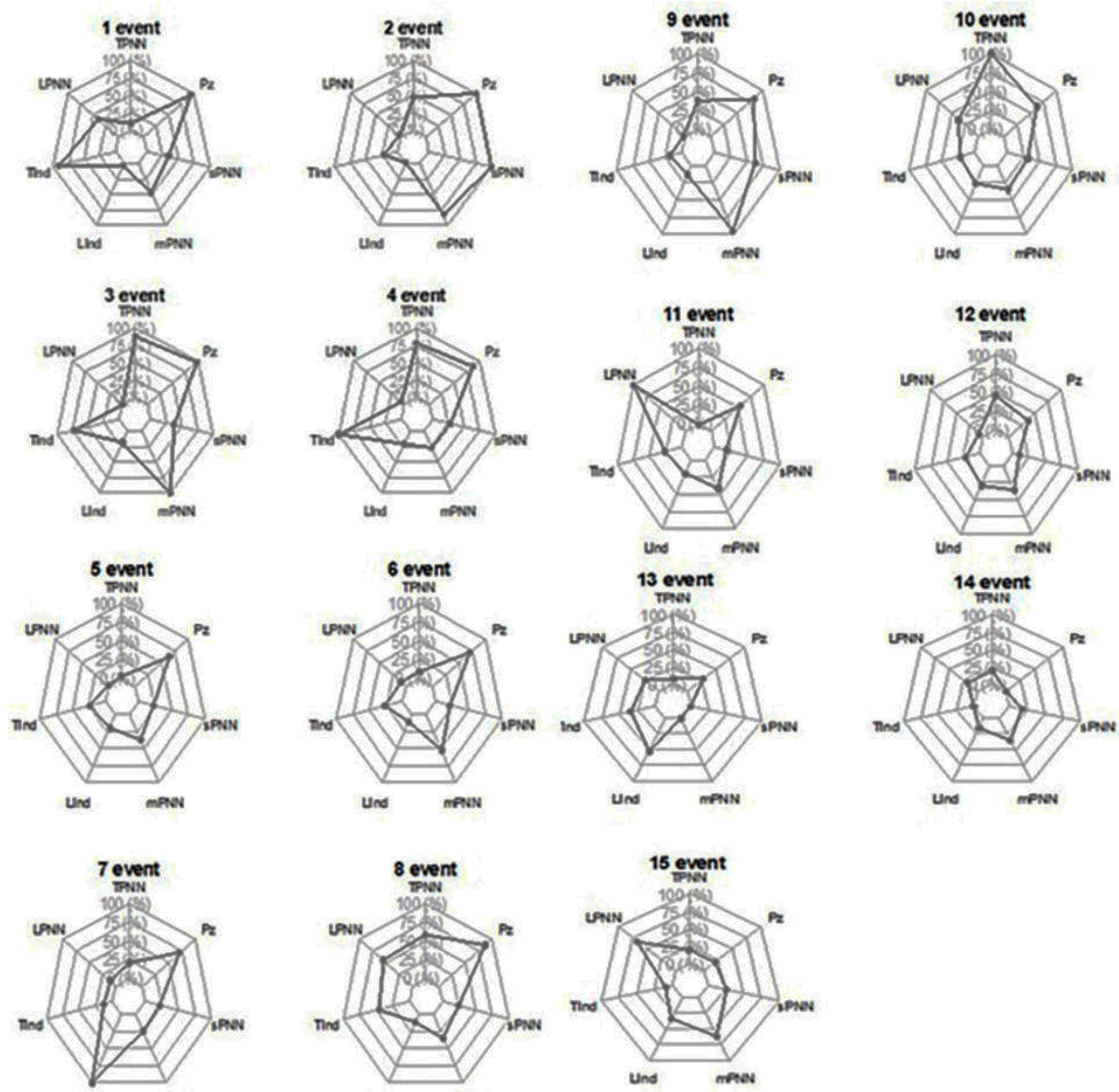

Figure 3 Summary of the parameters studied by event presented from radar-type graphs. The values of each parameter were converted into percentages, with 0% being the minimum value and 100% the maximum value identified for each parameter considering all selected rainfall events.

statistical characteristics found for each rainfall event. The radar charts were generated considering the maximum and minimum values found for each parameters (Pz, mPNN, sPNN etc.) taking into account all the rainfall events selected in this paper, with the minimum value representing 0% and the maximum representing 100%. This type of graph is suitable for presenting multivariate data. The figure 3 presents a summary of the variables studied for each event as radar-type graphs. After analysis of the main characteristics of extreme rainfall events in Campinas region, we can observe that most of the events selected in this study have the following characteristics:

- Low spatio-temporal correlation of the rainfall and intermittency zones (for this, it was used weather radar data);
- High standard deviation value considering non-zero rain zones (remembering, as already mentioned here, the standard deviation was calculated considering data from rain gauges selected in this paper);
- High Pz paremeter value (percentage of zero rain). This can represent that the majority of the region during a rainfall event (considering the events selected in this paper) is covered by a zero rain zone. Thus, in these cases, the rain zones are well located, covering only a small portion of the region (these characteristics were identified considering the data from the weather radar).

It is important to remember that in Figure 3, the parameters are represented by percentages which represent the minimum and maximum values of each parameter. For example, in the case of the parameter Pz, 100% in Figure 3 represents 91% (the maximum Pz value observed considering the selected rainfall events), this can be observed in events 1, 2 and 3.

We can consider that the events with the least spatio-temporal correlation are the most difficult to predict. One reason is due to the high variance of the rainfall fields, considering first the spatial correlation, even taking into account the same time step of the rainfall event, it can be observed that the rainfall intensities can have a high variability even in points that are spatially close. In addition, in relation to the temporal correlation, it is noted that the current state of the precipitating structure system has a weak effect on the future evolution of the system.

Considering the results observed, the 5, 13, 14 and 15 rainfall events can be considered one of the most difficult to predict, in relation to the others events selected here. This may be due the characteristics identified, as low spatio-temporal correlation and high standard deviation and high.

The results suggest that the severe rainfall events presented in this research, generally, have characteristics that can represent the high dynamics of rain zone and zero rain zones. This can be noticed, mainly, by the fact that they present a short spatial-temporal correlation. The analysis in this study shows that the events studied change rapidly, having often high variability. This can be observed, mainly, when the start of the event characteristics is compared with the time of the peak of rain.

This is due to the complexity of the atmospheric system, and, due the high variability of the types of weather systems that operate in the region (i.e., convective cells, MCS, squall lines, ZCAS, cold fronts, among others). The severe rainfall events, are often formed by convective systems, which in turn, are characterized by a high spatial-temporal variability of the rainfall (Loriaux *et al*., 2013; Terranova & Gariano, 2014).

5 Conclusion

The study of the past and the characteristics of extreme events has high importance for the short and long-term predictions, as well the development of tools for monitoring future events. The objective of this paper is to study the main characteristics of extreme rainfall events to improve our understanding of and their main features.

The analysis performed shows that the spatio-temporal correlations of the intermittent zones and the rain zones react differently, i.e., an event may have high correlation in the zone of intermittence and low correlation in the rain zone and vice-versa. It is also verified that extreme events of storm have low temporal-spatial correlation, high variability and are well located (isolated convective cells). This may make forecasting difficult, as forecasting methods depend on past data to predict the evolution of these events. These characteristics identified in this study allow us to know in more depth the extreme events of a region.

Therefore, which can aid in decision-making of forecasting, for the development of a satisfactory forecasting method, for post-event studies and for the elaboration of mitigating measures. The analysis of the characteristics of extreme events showed that for the prevention of these extremes events a method is needed that captures quickly the evolution of the event that is to come, taking into account information about the physics of these systems at different stages of the storm life cycle.

Besides the study of the statistical characteristics of the rain, and their more-or-less predictable dependence to the general state of the atmosphere, it would be interesting to study the spatial and temporal characteristics of the flow of these events. It would also be important to deepen the study of the physical characteristics of the rainfall by associating the space-time variability with the life cycle phases of the cloud. Likewise, as a perspective of this work, these characteristics of the events will be used for the development of a short-term forecasting system for extreme events based on the geostatistical method of turning bands, TBM (Mantoglou & Wilson, 1982). At this stage the SAMPO-TBM software will be used. This software is based on the TBM method to generate possible rain fields considering statistical characteristics of the extreme event considered. This rain simulator was developed in Irstea Lyon (Leblois & Creutin, 2013) and has been used in other studies, as: Ramos (2002); Renard *et al*. (2011); Folha de São Paulo (2016); Caseri *et al.* (2016).

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