

Extreme Rainfall Events in the Southwest of Rio Grande do Sul (Brazil) and Its Association with the Sandization Process

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Abstract

Part of the sandization process in southwestern Rio Grande do Sul (Brazil) originates from daily torrential rains. However, it is believed that climate changes have been provoking more frequent and more intense rains in the region, a phenomenon which can change the dynamic of erosion/transport/sedimentation natural processes. The objective of this work is to identify the behavior of daily rainfall extreme events (in terms of their frequency, return time, tendency and genesis), relating them to both climatic change issue and enhancement of erosive processes. We have used daily rainfall data from meteorology stations of Brazilian National Water Agency (ANA) for the period between 1928 and 2017 and the percentile 99 was used to identify daily rainfall extreme value (71.5 mm). The upper values were categorized and their absolute and relative frequencies as well as their return time were identified. The temporal tendency of these events was evaluated by the Mann-Kendall test, considering the 90 years of the series. The results showed that there was a significant increase in heavy rainfall events in November and December in the last two decades and that the return time for these events decreased throughout the time. Synoptic analyses from GOES 13 satellite infrared imagery and from ECMWF/ERA/Interim reanalysis data allowed concluding that such intense rainfall events originated themselves from the transport of moisture from the Amazon by Low-Level Jets, which promoted the formation of Mesoscale Convective Complex, with large volumes of rain in the study region. Thus, the recurrence of these events in the southwest of Rio Grande do Sul may in-

tensify these sandization processes, since they arise from the association between natural morphosculptural dynamics and agricultural practices, generating environmental problems for the region.

Keywords

Climate Change, Sandization, Mesoscale Convective Complexes, Low-Level Jets, Statistical Tests

1. Introduction

Discussions on the occurrence of global climate change and its repercussions at regional and local levels have been a constant theme in scientific debates in recent decades. Problems related to planetary temperature rising, that are associated with the greenhouse gas emissions and the increase of extreme weather events (storms, extreme rainfall, prolonged droughts, heat/cold waves, for example) have guided work produced by several researchers around the world [1]-[11].

At the extreme events issue, [12] defined them as anomalies in relation to climatology, in time scales that can vary from days to millennia. For the authors, the increase in the occurrence of extreme short-term events in recent years has attracted the attention of climatologists. Climate projections proposed by the Intergovernmental Panel on Climate Change (IPCC), in its 5th Report (AR5), published in 2014 [13], has indicated an increment in frequency and intensity of heavy rainfall, heat and cold waves, dry periods, etc. (extreme events).

In southern Brazil (Paraná, Santa Catarina and Rio Grande do Sul states), the formation of rain is associated with several weather systems: frontal systems, cyclones and cold fronts, Mesoscale Convective Complexes (MCC), average-level cyclones (inverted comma-shape) and atmospheric blocking systems, in addition to the indirect actions of the South Atlantic Convergence Zone (SACZ) [14].

In Rio Grande do Sul state (RS), the occurrence of disasters (floods, windstorms, intensive rains, hails, overflows, inundations and landslides), which are associated to extreme meteorological conditions, was studied by [15]. During the months of October, November and December from the year 2003, the MCC were responsible for 90 incidents registered by the Civil Defense of the state, which reached about 16,500 people and caused 11 deaths throughout the state.

In the southwest of Rio Grande do Sul there are grassland areas (from the Pampa biome) that have sandy and uncovered soils, which are known locally as sand stretches (*areais* in portuguese). These *areais* are formed by the “reworking of little or non-consolidated sand deposits, that promotes in these areas many difficulties to vegetation fixation, due to sediment mobility by the action of water and wind”—a process called sandization [16] [17]. When these spaces are exposed to irregular and sometimes intensive rain—a regional hydroclimatic dy-

namic, it triggers some morphosculptural processes which forms ravines and gullies [18] [19].

So, considering the climatic changing evidences, especially those associated to the occurrence of extreme events, and that intense rains in the region (extreme rains) are responsible for much of the morphosculptural dynamics (sandization) in southwestern Rio Grande do Sul, the purpose of this work is to analyze a long series of rainfall data, identifying the daily rainfall extremes, its frequency, its return time, its temporal tendency and the synoptic mechanisms which are responsible for the genesis of these events.

2. Material and Methods

2.1. Daily Rainfall Data

For this paper, there were used daily rainfall data from Brazilian National Water Agency (ANA) rainfall stations network, that are available through the National Water Resources Information System (SNIRH) (<http://www.snirh.gov.br/HIDROWEB>). The information was selected from ANA's stations in Alegrete municipality (**Figure 1**), which encompass the ecosystem of *areais*.

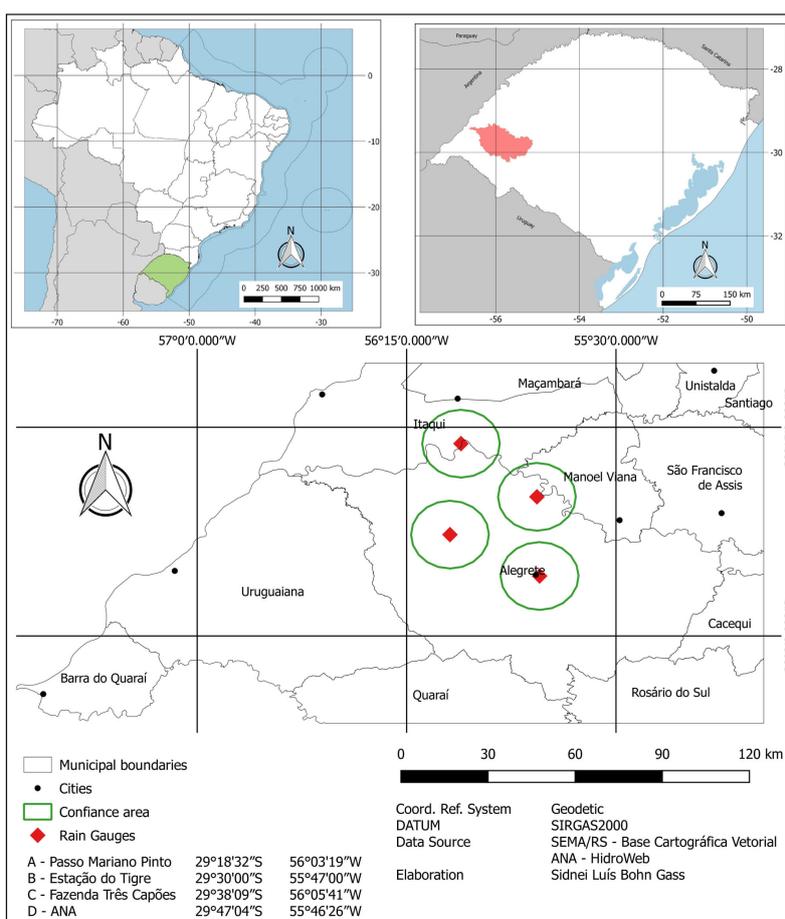


Figure 1. Location of the rainfall stations used in the city of Alegrete (RS).

In order to achieve continuous and homogeneous data, it was tried to maintain the pluviometry stations of Alegrete (which belongs to INMET/ANA) as the main data sources, since they offered the largest set of continuous daily data. The information from other stations were used to fill gaps in main data sources.

After applying statistical techniques to verify the homogeneity and consistency of the rainfall stations data—Determination Coefficient (R^2), Pearson Correlation (r), Double Mass Analysis, Mean Relative Error, Mean Absolute Error and Root Mean Square Error—the time sequence 1928-2017 was obtained.

2.2. Analysis Techniques

1) *Extreme rainfall events, Frequency and Return Time*

The definition of extreme value for daily rainfall in the study area was obtained by using Expert Team of Climate Change Detection Indices (ETCCDI) recommendation, which uses the percentile 99 (R99) in the identification of extreme events.

After setting up the extreme value index, there were identified and categorized the daily pluviometry volumes which were higher than percentile 99 value through their frequency and relative frequency values (Equation (1)), being estimated also their time of return (Equation (2)).

$$Rf = \frac{n_i}{\sum_i n_i} \quad (1)$$

The relative frequency (Rf) is the occurrence number of the event (n_i), in relation to the total number of elements in the series ($\sum_i n_i$), which means that the amount of each rainfall extreme event from Alegrete data came from the whole 90 years of the series (1928-2017).

The Return Time (RT) for each extreme precipitation event was defined as the inverse of probability [20].

$$RT = \frac{1}{Rf} \quad (2)$$

2) *Extreme rainfall events tendency*

The evaluation of extreme events tendency was made by applying the Mann-Kendall Test (MK). The MK consists of a non-parametric test, recommended by World Meteorological Organization (WMO) to identify climate tendencies over long time series [3] [6] [21].

In this test we have adopted the hypothesis of stability for the time series (H_0), in which the values must be independent, and the distribution of their probability must remain the same.

The signal of MK statistic indicates whether the tendency is increasing ($MK > 0$) or decreasing ($MK < 0$). At a significance level of 95% ($\alpha = 0.05$), H_0 should be rejected whenever the MK value is $-1.96 < MK < +1.96$.

3) *Genesis of extreme events: satellite image and synoptic analysis*

From the dates of occurrence of extreme rainfall events, it was identified its genesis by using winds, moisture flow and accumulated precipitation informa-

tion, which were obtained through data from European Center for Medium-Range Weather Forecasts (ECMWF), from ERA/Interim reanalysis data (<https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-dataset/era-interim>), as well as from Geostationary Operational Environmental Satellite (GOES) 13 infrared images, that were provided by the Center for Weather Forecasting and Climate Studies, from Brazilian National Institute for Space Research (CPTEC/INPE) (<http://satelite.cptec.inpe.br/home/index.jsp>).

3. Results and Discussion

1) Frequencies and Return Time of Extreme Events

From the application of percentile 99 to the precipitation data, the volume of daily rainfalls of 71.5 mm were considered as episodes of extreme precipitation events. However, as shown in **Figure 3**, such events were very common over the 90 years of the study. Thus, we chose to categorize the daily rainfall events between 71.5 mm (percentile 99 value) and the maximum value during the review period (183.9 mm), extracting frequency, relative frequency and return time variables, *cf.* **Table 1**.

It is found that daily rainfall events between 71.5 mm and 80 mm can be repeated at least twice a year. Meanwhile, events between 80 - 90 mm, 90 - 100 mm and 100 - 110 mm, equally intense, can return (statistically) in up to two years. Incidentally, torrential daily rainfall characterizes themselves as common in the study area.

Thus, considering that sandization processes (**Figure 2**) have hydroclimatic phenomena (intensive rains, erosive processes—erosion, transport and deposition—and fluvial dynamics) as part of its genesis, intense daily rain events connected to these processes are part of the regional climate dynamics.

Defined by [18] as **hydrological summer**, the period from September to November is characterized by heavy rains, which are responsible for direct surface

Table 1. Statistical frequency, relative frequency and return time of rainfall events for algrete series (1928-2017).

Daily rainfall events	Frequency (events)	Relative Frequency (%)	Return Time (years)
71.5 to 80 mm	104	1.1678	0.9 (every 10 months)
80 to 90 mm	66	0.7411	1.3 (every 16 months)
90 to 100 mm	52	0.5839	1.7 (every 21 months)
100 to 110 mm	37	0.4155	2
110 to 120 mm	16	0.1797	6
120 to 130 mm	23	0.2583	4
130 to 140 mm	8	0.0898	11
140 to 150 mm	5	0.0561	18
150 to 160 mm	7	0.0786	13
160 to 170 mm	1	0.0112	90
170 to 180 mm	2	0.0225	45
>180 mm	2	0.0225	45



(a)



(b)

Figure 2. (a) Overview of *Cerro da Esquina* sand stretches (*areais*), in the municipality of São Francisco de Assis (RS). On (b), a view inside a ravine, which is formed by surface runoff processes, due to recurrent torrential rains. Source: Sidnei L. Bohn Gass (2013).

runoff and rapid recharge of aquifers in the region. These same hydrological characteristics are also observed between the months of April and June, interspersing long periods of droughts and intense rainfall episodes.

Thus, from this perspective, rainfall events of greater magnitude (over 150 mm) also deserve more attention; not only because of its return time, but also because the dates of their occurrence. Throughout the series, five events exceeding 150 mm happened in the months of May, two events in April and one event occurred in November, December, February, March and June (**Figure 3**).

It is verified that the return time for rainfall events between 150 mm and 160 mm was estimated in 13 years. Information related to the seven events throughout the series (**Figure 3**) shows occurrences in the years 1936, 1947, 1961, 1975, two events in the 1990s (1992 and 1993) and the last on held in 2014.

Only one event in the range of 160 mm to 170 mm had occurred throughout the series, in the year 1974, generating a return time of 90 years.

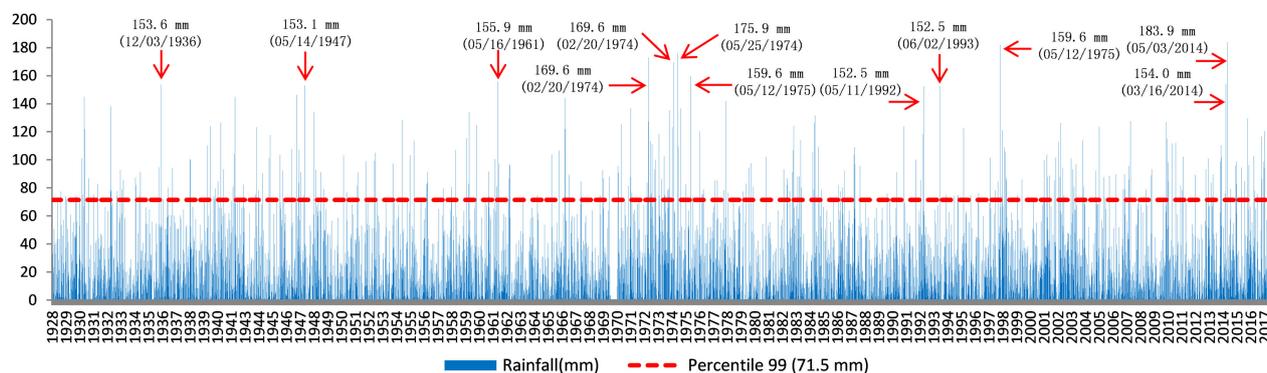


Figure 3. Daily rainfall for Alegrete series (1928-2017).

The return time statistics for rainfall events between 170 mm and 180 mm were 45 years. Both occurrences were recorded between April 1972 and May 1974, that is, over two years in the period of study, which was marked by high daily rainfall volumes, as seen in **Figure 3**.

On the other hand, even though the statistic of return time for greater than 180 mm events has also indicated a 45-year interval between one event and another, the period between the first occurrence (November/1997) and the last one (May/2014) was only 17 years. During this period (Nov./1997-May/2014), it has occurred at least 17 rainfall events greater than 100 mm, demonstrating an increase in the frequency of rainfall days above the percentile value for the series (71.5 mm). In all, between November 1997 and the end of the series (December 2017) there were 83 events that were considered extreme. Thus, seeing the number of extreme rainfall days in the last 21 years, we started to assess the tendency in the number of these events throughout the series.

2) Tendency for extreme events

The number of days with intense rainfall events (over 80 mm) was submitted to MK evaluation, which considered as significant the tendency ($MK = 2.23$) during the 90 years of the series (**Figure 4**).

This dataset shows an increase in the number of over-80 mm rainfall days from 1997.

This same significant increase in the number of over-80 mm rainfall days was also observed for the months of November ($MK = 2.28$) and December ($MK = 2.00$)—Spring/Summer months (**Figure 5**). It is verified that an increase above this value occurred to both the frequency and the number of rainfall days.

On the other hand, in April and May (during the autumn) (**Figure 6**), the tendency of these events was not considered significant by the MK assessment. However, events of this nature (greater than 80 mm) occur relatively frequently in autumn months.

3) Extreme rain events in the southwest of Rio Grande do Sul and its relationship with LLJ and MCC

The increase in the amount of intense rainfall events observed in the months of November and December can be associated with the performance of the

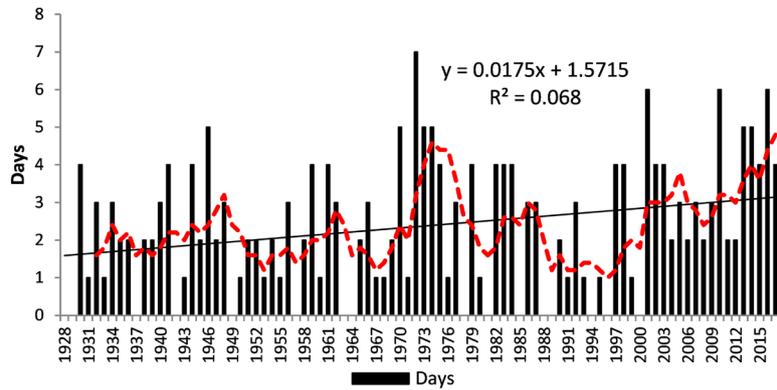


Figure 4. Annual number of over-80mm rainfall days, with its linear tendency line and its five-year moving average tendency line (red line).

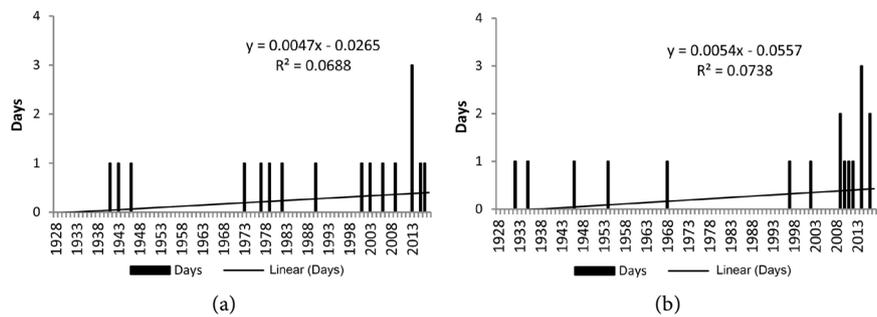


Figure 5. Number of over-80 mm rainfall days in the months of (a) November and (b) December.

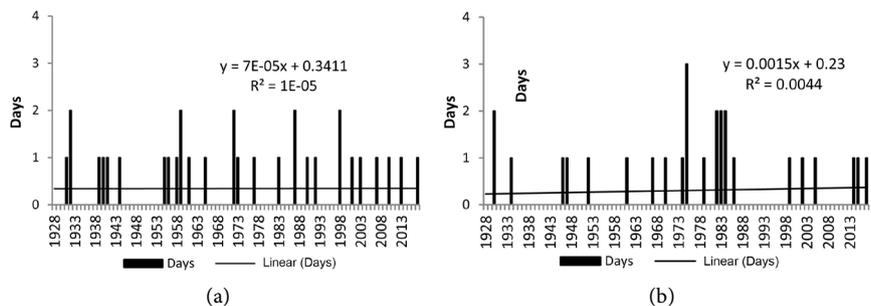


Figure 6. Number of over-80 mm rainfall days in (a) April and (b) May.

Mesoscale Convective Complexes (MCC). According to [15], the MCCs are formed on part of southern Brazil during spring, summer and autumn months, been responsible for the occurrence of strong storms, with gusty winds and highly concentrated rainfall. Such systems are formed and developed very fast (up to 12 h), usually during the night.

Figure 7(a) shows GOES 13 satellite pictures and atmospheric condition maps from South America, referring to an extreme event, which has occurred on May 03, 2014. It can be seen, highlighted, the MCC, in which the accumulated daily rainfall was 183.9 mm. The map on **Figure 7(b)** shows the vapor water flow that was carried by the winds at 700 hPa (LLJ), which were responsible for

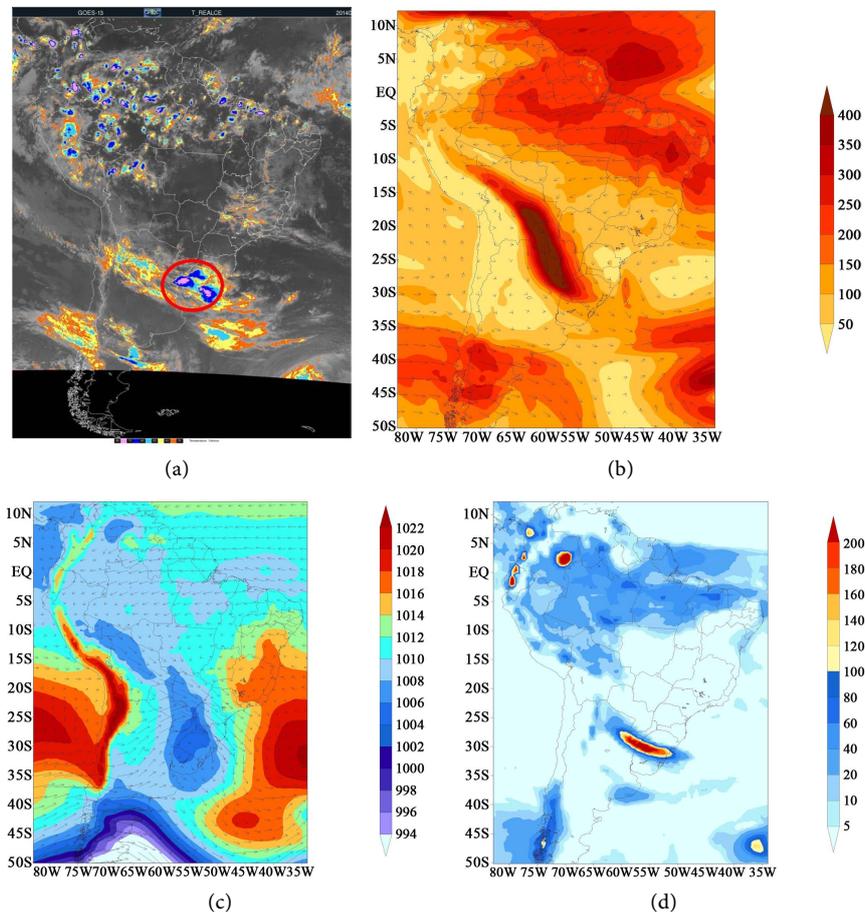


Figure 7. Representations of the extreme event occurred on May 03, 2014, in which the rainfall recorded in 24 hours was 183.9 mm. The (a) shows a GOES 13 satellite image (in infrared, with enhanced temperatures), demonstrating the occurrence of MCC over Rio Grande do Sul state. In (b) there is the map of the vertically integrated water vapor flow ($\text{kg}\cdot\text{m}^{-1}/\text{s}^{-1}$) over South America, measured by ERA-Interim (ECMWF) reanalysis. The (c) shows a horizontal wind field at 700 hPa, indicating the action of LLJ at the east of the Andes, by using ERA-Interim (ECMWF) data reanalysis. The (d) brings the cumulative precipitation of that day over South America ($\text{mm}\cdot\text{day}^{-1}$), considering the ERA-Interim (ECMWF) reanalysis method.

the formation of high rainfall. In **Figure 7(c)** it is possible to observe the atmospheric flow of LLJ at 700 hPa and its pressure levels, as well as **Figure 7(d)** brings the accumulated daily precipitation values.

In this event, which represents the highest daily rainfall recorded in the analyzed series, it is possible to verify the LLJs' interactions. These winds come from the Amazon region and they carry high flows of water vapor, assisting in the development of MCC formation and the high daily rainfall value.

It is believed that the increase in MCC frequency in the southwest of Rio Grande do Sul (as well as in Prata river basin) is due to changes in the moisture transport, which comes from Amazon region [15] [22]. The Amazon space receives horizontal flows of moisture through the action of trade winds, which comes from the Atlantic, forming the Intertropical Convergence Zone (ITCZ),

and vertical flows of moisture from the interaction of evapotranspiration/precipitation processes in the vegetation area.

Considering that the mean rainfall recycling in Amazonian environment is 22% [23], the remaining moisture for rainfall originates from Atlantic Ocean, by the action of the trade winds [22]. Isotopic analysis (using O¹⁸) done by [24] show that about 44% of the water vapor that enters in Amazon region through these winds goes out from Amazon basin to conditioning the rainfall in other regions of South America [25].

This moisture transport is made by low-flowing winds (between 850 and 700 hPa)—LLJ, which, conditioned by the Andean topography, intensify the rains in the Prata basin and in the southeast of South America. The intensification of both frequency and speed of these winds in spring/summer/autumn increases the occurrence of extreme rainfall events in the Prata basin region and in the southeast of South America [26].

Finally, for [27], the increase in global temperatures observed in the second half of the 20th century contributed to the intensification of the western and southern Amazonian moisture fluxes through the LLJs, increasing the frequency of intense rainfall events in the Prata basin. So, it is possible to relate the increase of the frequency of extreme precipitation events in the study area to the increment of LLJ from Amazon region, which promoted the formation of a larger number of MCC phenomena.

4. Conclusions

The reconstruction of a long time series of daily rainfall data and the application of a statistics set (percentile 99, absolute frequency, relative frequency and return time) over that data allowed identifying extreme rainfall events for the southwestern region of Rio Grande do Sul. Daily rainfall data have shown much higher pluviometry events than the value considered as extreme. In addition, the phenomenon of extreme rainfall has been repeated more frequently and more intensively over the last 20 years of the series.

The assessment of the tendency for the increasing on heavy rain days in November and December suggests that such events have become more frequent in recent years and it is considered significant for changes in weather behavior—a possible evidence of climate changing.

The origin of these intense rains can be attributed to the formation of large convective systems (MCCs). They are formed by the atmospheric runoff and the low level moisture transport originated in the Amazon region; as ongoing climate changes (the Amazon deforestation, the increment of the amount of aerosols, the heating of atmosphere and oceans, etc.) intensify, it is believed that LLJs tend to become more intense, carrying more moisture and promoting MCC in greater quantity and magnitude.

More intense and more frequent extreme rainfall events in the *areais* region, in the southwestern portion of Rio Grande do Sul, intensified the natural processes of morfoescultural dynamics, enhancing geomorphological processes

such as erosion, transport and deposition of sandy material and expanding an environmental problem for the region of study, mainly due to its agricultural tradition of extensive livestock and temporary crops. In this way, the present work tried, beyond to identify the origin of these extreme rainfall events in the region of Rio Grande do Sul, to demonstrate an example of a systemic connection between the effects of global climate change on both regional and local scale.

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Conflicts of Interest

The authors declare no conflicts of interest.

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