Characterization of precipitation and frequency of rainy days in the municipality of Botucatu – São Paulo – Brazil

Jose Rafael Franco
jose_rafael.franco@hotmail.com

São Paulo State University (UNESP), FCA, Botucatu
Victor Crespo de Oliveira
São Paulo State University (UNESP), FCA, Botucatu
Alexandre Dal Pai
São Paulo State University (UNESP), FCA, Botucatu
Valéria Cristina Rodrigues Sarnighausen
São Paulo State University (UNESP), FCA, Botucatu
Sérgio Augusto Rodrigues
São Paulo State University (UNESP), FCA, Botucatu
Firmo Souza Campos
São Paulo State University (UNESP), FCA, Botucatu
Enzo Dal Pai
São Paulo State University (UNESP), FCA, Botucatu

Research Article

Keywords: Rainy years, Dry years, Accumulated precipitation, Rainfall regime

Posted Date: April 19th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4238333/v1

Additional Declarations: No competing interests reported.

Abstract

Knowledge of the rainfall regime is vital information for agricultural and environmental activities. Rainfall is a component of the hydrological cycle, in which liquid water uses energy from the environment to change its phase to the gaseous phase. The cooling of this water vapor causes condensation and subsequent precipitation. Mean precipitation values, distribution during the year, variation between years, and maximum and minimum values are useful parameters for rural and urban planning. This study aimed to characterize the rainfall regime in the municipality of Botucatu through the assessment of precipitation and frequency of rainy days, considering the history of 52 years. The mean local precipitation during the period of analysis was 1,525.53 ± 284.71 mm. The rainiest month is January, with 284.92 ± 123.87 mm, which is also one of the months with the highest variability. August is the month with the lowest rainfall volume, reaching 40.40 ± 43.72 mm. The highest rainfall volume was observed in 1983, with 2,278 mm accumulated and 147 days of rain. In 1984, the lowest rainfall volume was observed, reaching 964 mm, and only 82 days of rain. The mean number of annual rainy days is 107 ± 14 days. In terms of the frequency of rainy days, 50% of the years in the analyzed history had 12 days or more of rainfall in January, February, March, November, and December. The remaining 50% of the years had up to two days of rain in July and up to 4 days in June.

Introduction

Knowledge of the rainfall regime is useful for planning agricultural and environmental activities. Rainfall, or precipitation, is a component of the hydrological cycle, in which liquid water in the environment uses energy from the medium to change phase and evaporate. The cooling of this water vapor causes condensation and subsequent precipitation. Rainfall regime quantification is important for managing water resources, considering mean, maximum, and minimum values and distribution during the year, in addition to the variation between years (Sant’anna 1999; INMET 2009).

The importance of knowing the local rainfall regime goes beyond scientific or academic knowledge, acting directly in the daily life of society and contributing to urban and rural development through predictions of the most adverse behaviors involving the climate (Sant'anna 1999; Mendes & Zukowski 2019).

Generally, rainfall analysis is performed by analyzing the precipitation volume in millimeters. It allows the distinction between maximum, mean, minimum, and accumulated precipitation values, allowing climate analysis on droughts, rainy years, and groundwater recharge, among others (ANA, 2021). Furthermore, the number of rainy days can be analyzed when evaluating rainfall. In this modality, the precipitation volume is not the focus but rather the number of rainy days in a certain period. This analysis allows us to identify the number of days without rain in a period, on average, knowledge that is vitally important in agricultural operations, such as planting and harvesting (Araujo et al. 2011; Ataíde et al. 2012).

According to Pezzopane et al. (1995) and Diniz (2013), the temporal distribution of rainfall in a location can be a limiting factor for agricultural activities. Irrigation systems allow to carry out cultivation in times of low rainfall, but they are still a high-cost method in Brazil. According to Irrigation Atlas (ANA, 2021), Brazil totaled 8.2 million hectares (Mha) equipped for irrigation in 2019, of which 2.9 Mha with fertigation from reused water and 5.3 Mha with irrigation from spring water.

Agricultural planning can be improved with knowledge of the rainfall regime. A high accumulated rainfall volume and/or a high number of rainy days can restrict the use of agricultural machinery in carrying out agricultural activities (Assad 1992; Pezzopane et al. 1995; Back 2006). Decision-making from soil tillage and planting to harvesting is linked to soil moisture in the layers to be worked, which depends on the rainfall regime (Fernandes et al. 2000; Dallacort et al. 2011).

The sizing of agricultural machinery depends on the frequency of precipitation, as higher rainfall regimes reduce the period available for machines to work in the field (Mialhe 1974; Pezzopane et al. 1995; Estrada 2015; Shaheb et al. 2021). The number of agricultural machines to be purchased depends on their daily work capacity and the period available for desired operation, which, in turn, depends on the number of days without rainfall. An undersized fleet can lead to operational difficulties within a few years. On the other hand, an oversized fleet can guarantee successful operation every year, but part of these machines will be unused in some years, representing higher maintenance costs.

According to Silva et al. (2010), the major problem in characterizing the climate of the most diverse regions of Brazil is the difficulty in obtaining data either due to the lack of equipment and flaws in records or the lack of data series for long periods, which makes these characterization procedures difficult. The lack of rainfall data makes it difficult to model and understand precipitation patterns and their spatial and temporal variations, which are directly related to the most diverse sectors of the economy, with an impact on fishing, navigation, and mainly agriculture, standing out irrigation, which has not yet been explored to its greatest potential in Brazil (Ruezzene et al. 2021). Thus, understanding the patterns resulting from precipitation is of paramount importance for the planning and operation of these sectors (Soares et al. 2016), consisting of important tools that contribute to agricultural planning, standing out studies at the local level (Pezzopane et al. 1995; Mendes & Zukowski 2019).

Therefore, this study aims to characterize the rainfall regime in the municipality of Botucatu – São Paulo, using a 52-year climatological series. The monthly and annual rainfall volume and the occurrence of rainy days in each month were studied to identify and quantify trends in more or less rainy seasons so that useful information can be provided to aid agricultural planning for producers in the region.

Material and method

Location and climate

The study was conducted using data from the Weather Station of the Department of Rural Engineering and Socioeconomics of the School of Agricultural Sciences of the São Paulo State University (UNESP) in Botucatu, São Paulo, Brazil (22°54' S, 48°27' W, and mean altitude of 786 m). The municipality of Botucatu (Fig. 1) has approximately 149 thousand inhabitants and is located in a territorial area of 1,482.6 km^2, with the Cerrado and Atlantic Forest biomes (IBGE 2022). The municipality is located close to two large dams (Barra Bonita and Jurumirim) approximately 221 km from the Atlantic Ocean (Rossi et al. 2018). According to Franco et al. (2023), the Botucatu climate is classified as Aw, with hot, rainy summers and cold, dry winters, with well-defined seasons. However, this climate was considered as Cwa in previous classifications by other authors (Rossi et al. 2018).

The work developed by the authors Franco et al. (2023) presents the values of air temperature and relative humidity considering the period from 1991 to 2020 in the municipality of Botucatu. The hottest months occur in the summer, with a mean temperature of 23.80°C in February. The maximum mean relative humidity of 75.76% occurs in January, as well as the maximum monthly accumulated precipitation of 310.37 mm. The lowest values occur in the winter, with a minimum mean temperature (18.28°C) in July, minimum mean relative humidity (61.86%) in June, and minimum monthly accumulated precipitation (38.76 mm) in August. The annual accumulated precipitation is approximately 1,500 mm, with precipitation occurring, on average, on 107 days of the year (Franco et al. 2023).

Instruments and measurements

Daily values (data from 1 day of rain read at 9 am) of precipitation between 1971 and 2022, totaling 52 years, were used to conduct the study. The data were measured by a TB4 Rain Gage Campbell Scientific, INC rain gauge of the automatic weather station (Fig. 2a) in the period from 2015 to 2022. Before this period, the data were measured by a Ville de Paris conventional rain gauge (Fig. 2b). Franco et al. (2022) compared measurements from the same automatic and conventional rain gauges for the municipality of Botucatu, which allowed the creation of a unified database from 1971 to 2022.

Source: The authors (2023)

The data were obtained on a daily scale using the unit of millimeters (mm), equivalent to liters per square meter (L/m^2). The number of rainy days was also obtained. For this analysis, days with precipitation higher than or equal to 1 mm were considered rainy days (INMET 2022a).

Calculations of arithmetic mean, variance, and standard deviation, accumulated precipitation values in the periods, relative deviations, coefficients of variation of the distribution, frequency of occurrences, and related plots were used to characterize the data. Student's t-test was used to compare means and Tukey's test was used for multiple comparisons.

Descriptive statistics and calculations were prepared using a Microsoft Excel® spreadsheet. The number of rainy days was analyzed in annual (variation between years), monthly (variation between months), and 10-day intervals (variation within each month), as well as its frequency of occurrence.

Results and discussion

Annual precipitation

Figure 3 shows the values of annual accumulated precipitation (PA_A) and the number of annual rainy days (NRD_A), considering the years that make up the historical series from 1971 to 2022. Knowledge of the accumulated volumes and the number of rainy days helps in interpreting the intensity and seasonality of occurrences. Years considered rainy have a large annual accumulated volume or a high number of rainy days compared to the other analyzed years. Importantly, the analyzed 52-year historical series is sufficient for all local climatological trends to have been recorded in the municipality.

The municipality of Botucatu is located in the center of the State of São Paulo. In this region, there is a strong predominance of continentality in the winter periods, resulting in low relative humidity values and low amounts of rain in this period. Although the data are valid for the municipality of Botucatu, its rainfall regime does not differ significantly from several neighboring locations that have a continentality effect at the same time. Therefore, the values for a large part of the west of the State of São Paulo, with a rainfall regime similar to that of Botucatu, are expected to be close to those presented in this study, validating this research for coverage higher than the municipality of Botucatu.

Source: The authors (2023)

The mean PA_A value was 1,525.53 ± 284.71 mm, considering all years of the historical series (Fig. 3a). The highest PA_A value occurred in 1983, reaching 2,278.33 mm (49.35% above the annual mean), and the lowest value was recorded in 1984, reaching 964.84 mm (36.75% below the annual mean). Importantly, the years 1971, 1973, 1984, 1994, 2008, 2014, and 2021 showed PA_A records below the mean standard deviation value (284.71 mm). These 7 years can be classified as dry years (13.46% of the total number of years), considering the accumulated volume criterion. On the other hand, 10 years of the historical series (1972, 1976, 1982, 1983, 1991, 2009, 2011, 2012, 2015, and 2016) presented PA_A records above the mean standard deviation (19.23% of the total years), being considered as rainy years. In total, 17 years were out of the limit established by the mean standard deviation, which is equivalent to 32.69% of the total evaluated.

Figure 3b shows the NRD_A for each year in the series. The mean NRD_A value in the series was 107 ± 14 days of rain (29.31% of the year). The highest NRD_A value recorded was 147 days in 1983, that is, it rained on 40.27% of the days of the year. Importantly, the year 1983 also showed the largest record of PA_A. On the other hand, the year 2021 presented the lowest NRD_A, totaling only 80 days of rain in the year (21.91% of the days in 2021 rained). In this case, the year with the lowest NRD_A record did not coincide with the year with the lowest PA_A, which was 1984. However, 2021 and 1984 presented similar values (82 days of rain in 1984).

Moreover, 7 years (1975, 1984, 2014, 2018, 2019, 2020, and 2021) showed NRD_A lower than the lower limit of the mean standard deviation, which represents 13.46% of the total years evaluated. The criterion of rainy days in a year shows that the mentioned 7 years could be categorized as dry years. On the other hand, considering the same criterion, we found that 8 years (1972, 1976, 1982, 1983, 1990, 1993, 2009, and 2015) could be considered rainy years, as these years (15.38% of the total assessed) presented NRD_A higher than the mean standard deviation value. In total, 15 years were out of the limit established by the mean standard deviation regarding NRD_A, equivalent to 28.84% of the years evaluated.

Regarding the dry or rainy year classification criteria, the two criteria (PA_A and NRD_A) presented equal results in the number of dry years and different results in the number of rainy years, that is, some years are not the same and do not match. The number of years categorized as dry years was 7 years in both criteria. The total number of years classified as rainy years was 10 and 8 years, according to the PA_A and NRD_A criteria, respectively. This difference occurs because the values of PA_A and NRD_A vary significantly, being directly related to the intensity values and temporal distribution of rainfall. Thus, the historical series shows years with low NRD_A values, but with high PA_A values, and the opposite is also verified.

In 2016, for example, it rained on 99 days (below the annual mean value and close to the lower limit of the mean standard deviation), but PA_A was 1917 mm (above the upper limit of the mean standard deviation). This behavior was similar to that found in 2020, which had only 87 days of rain (below the lower limit of the mean standard deviation) and a PA_A of 1431 mm (close to the annual average value). The opposite situation was observed in 1993, during which the NRD_A value was 124 days (above the upper limit of the mean standard deviation) and PA_A was 1550 mm (close to the annual mean value).

The PA_A criterion apparently tends to present a higher number of values out of the standard deviation for the municipality of Botucatu. Therefore, this criterion tends to present a higher number of extreme occurrences for studies on extreme events, such as years of drought or years of heavy rain.

Figure 4 shows the relative deviation (%) of PA_A and NRD_A values relative to the mean for the 52-year period. Importantly, positive values of relative deviation indicate that the PA_A or NRD_A value of a given year was higher than the mean of the historical series, and the higher this value, the higher the deviation from the mean. This applies to negative relative deviation values, that is, higher negative values indicate a higher distance from the mean value of the historical series. Furthermore, relative deviation values close to zero indicate no difference between the evaluated variable and the mean of the historical series.

This analysis shows that the largest relative deviation in PA_A values occurred in 1983 when values of 49.35% were recorded. It shows that 1983 was an atypical year, presenting the highest volume of rain of the years considered in the historical series. On the other hand, the smallest relative deviation of PA_A values was observed in 1984, being – 36.75% lower than the annual mean value, leading to the conclusion that this year had the lowest volume of rain than the other years in the historical series.

The evaluation of the relative deviation for NRD_A (Fig. 4) showed that the highest value also occurred in 1983 (36.79%). In other words, NRD_A exceeded the annual mean of the historical series by 36.79% in 1983, showing the highest NRD_A. On the other hand, the year 2021 presented the lowest relative deviation value (– 25.55%) in the historical series, that is, the NRD_A was 25.55% lower in 2021 compared to the annual mean value.

Considering the behavior of the relative deviations of the PA_A and NRD_A variables (Fig. 4), the values showed agreement in some years but discrepancies in others. In general, the years in which the values of the relative deviation of the PA_A and NRD_A variables were closer (1975, 1982, and 2021, for example) presented a behavior of the volume and temporal distribution of rain similar to the mean values of the historical series.

Figure 4 shows that the years with positive relative deviation values, in which the PA_A value was higher than NRD_A, presented more intense rainfall, as observed in 1972, 1976, 1982, 1983, 1982, 1991, 2009, 2012, and 2015, for example. In contrast, years that presented a value of a positive relative deviation of PA_A lower than that of NRD_A indicate a higher temporal distribution of rainfall, as observed in 1993, 1998, and 2004.

Regarding the negative relative deviation values (Fig. 4), years with PA_A relative deviation values higher (in absolute values) than NRD_A presented low precipitation volume relative to the historical mean but with a better temporal distribution of rainfall, as observed in 1971, 1973, and 2006. On the other hand, years that presented lower PA_A relative deviation values (in absolute values) than those of NRD_A may have presented a higher intensity of rainfall, such as the years 1978, 1985, and 2020.

The pattern of rain characteristics presented in recent years (2018 to 2022) shown in Fig. 4 draws attention. The relative deviation values of PA_A and NRD_A were negative for these years, indicating years with low volume and temporal distribution of rainfall. Similar but milder characteristics were also observed between 2002 and 2008. This behavior observed in recent years indicates a possible change in the characteristics of the rainfall regime in Botucatu.

One way to explain the results is to establish a relationship with El Niño and La Niña events. El Niño and La Niña events are climate events observed over the waters of the Pacific Ocean, around the equator. They consist of periodic events that cause changes in meteorological patterns at a global level (Cunha et al. 2011; Medeiros et al. 2016; Rodrigues et al. 2017). Figure 5 shows the El Niño and La Niña values from the Oceanic Nino Index (ONI) between 1971 and 2022, obtained through NOAA (National Oceanic and Atmospheric Administration). Ocean temperature values 1.5°C above average represent strong El Niño events, while temperature values 1.5°C below average represent strong La Niña events (Nery & Siqueira 2019).

Seven periods of strong or severe El Niño (1972, 1983, 1986, 1991, 1997, 2009, and 2015) and La Niña events (1973, 1975, 1988, 1998, 1999, 2007 and 2010) could be observed in the period between 1971 and 2020. According to Minuzzi et al. (2006), the El Niño events considered the strongest of the 20th century occurred between the years

1982/83 and 1997/98. Marcuzzo & Romeiro (2013) analyzed data from 1977 to 2006 and observed that the most intense La Niña event occurred in 1988. In this study, the researchers did not evaluate the 1973 event.

Five out of the seven years of severe El Niño events coincided with the wettest years of the series in Botucatu (1972, 1983, 1991, 2009, and 2015) and two (1986 and 1997) did not coincide. The PA_A value in 1986 (Fig. 3a) was close to the mean of the historical series, but the recorded NRD_A was above the mean of the historical series (close to the upper limit). On the contrary, the PA_A value in 1997 (Fig. 3a) was above the mean of the historical series, whereas the NRD_A value was close to the mean value of the historical series.

This result may infer that the El Niño event tends to change the rainfall pattern in Botucatu, causing higher PA_A and NRD_A values. In general terms, a higher water abundance in the municipality of Botucatu is observed in years when the El Niño phenomenon occurs.

The seven strong La Niña events that occurred in the series led to lower PA_A and NRD_A values in Botucatu. In 1973, the PA_A was below the lower limit of the standard deviation (Fig. 3a) and NRD_A was close to the mean of the historical series (Fig. 3b), being considered a drought year. PA_A and NRD_A were below the mean of the historical series in 1975, 1998, 1999, 2007, and 2010. Moreover, lower PA_A and NRD_A values were observed in the periods of 2020 and 2021, when the La Niña phenomenon was not severe but occurred for a long period. Given this evidence, the occurrence of the La Niña phenomenon is related to periods of higher water scarcity in the municipality of Botucatu.

Cunha et al. (2011), Medeiros et al. (2016), and Rodrigues et al. (2017) also verified a relationship between water abundance/scarcity and the El Niño/La Niña phenomena. These researchers concluded that some extreme rainy or drought events can be explained and correlated by severe El Niño/La Niña events. However, not all extreme events are related to periods of El Niño/La Niña.

Tables 1 and 2 and Fig. 6 show the histograms of frequency distribution for the annual accumulated precipitation volumes (PA_A) and the number of rainy days in a year (NRD_A), grouped into seven classes ($\sim\sqrt{N}$ – N: number of years). Most years are in the central classes (Fig. 6) and the distribution of frequencies resembles the normal distribution (a symmetrical bell-shaped curve). In this sense, this behavior is expected when it comes to observing natural events, such as rain, being characterized by a smaller number of observations the further away from the mean of the data (Dallacort et al. 2011; Santos et al. 2020).

Table 1
Frequency distributions of annual accumulated precipitation (PA_A) grouped into classes and respective probabilities of non-exceedance.

Class	Range (mm)	Median (mm)	Absolute frequency (number of years)	Relative frequency	Accumulated non-exceedance probability
1	963–1,152	1.058	3	0.0566	0.0566
2	1,152–1,339	1.245	13	0.2453	0.3019
3	1,339–1,527	1.433	14	0.2642	0.5660
4	1,527–1,715	1.621	9	0.1698	0.7358
5	1,715–1,902	1.808	4	0.0755	0.8113
6	1,902–2,090	1.996	8	0.1509	0.9623
7	2,090–2,278	2.184	1	0.0189	0.9811

Table 2
Frequency distributions of number of annual rainy days (NRD_A) grouped into classes with respective probabilities of non-exceedance.

Class	Range (mm)	Median (mm)	Absolute frequency (number of years)	Relative frequency	Accumulated non-exceedance probability
1	79–89	84	4	0.0755	0.0755
2	90–99	95	13	0.2453	0.3208
3	100–109	105	13	0.2453	0.5660
4	110–119	115	11	0.2075	0.7736
5	120–129	125	7	0.1321	0.9057
6	130–139	135	3	0.0566	0.9623
7	140–149	145	1	0.0189	0.9811

Figure 6a shows that class 3 presented the highest frequency (14 observations), with PA_A between 1,339 and 1,527 mm (close to the mean of the 52-year periods). The second highest frequency occurred in class 2 (1,152 to 1,339 mm), in which 13 observations were observed. Classes 1 (963 to 1,152 mm), 5 (1,715 to 1,902 mm), and 7 (2,090 to 2,278 mm) presented the lowest frequencies (3, 4, and 1, respectively), representing classes further away from the mean of the historical series.

The probability of non-exceedance shows that class 1 presented a value of 5.66%, indicating a 5.66% probability of occurring a year with PA_A up to 1,152 mm. Furthermore, the probability of a year having a PA_A lower than 2,278 mm is 98.11% or a 1.89% chance of observing a year with precipitation higher than this value.

Concerning NRD_A (Fig. 6b), classes 2 and 3 had a higher number of observations, 13 in each, totaling 50% of the evaluated years. These classes encompass years that had 90 to 119 days of rain, an interval that covers the mean NRD_A value of the historical series, which is 107 ± 14 days. The third highest frequency was observed in class 4 (11 observations) and the other classes comprised approximately 28.8% of the evaluated years. Thus, the number of observations in classes 1, 5, 6, and 7 was 4, 7, 3, and 1, respectively.

Based on the probability of non-exceedance (Fig. 7b), the chance of a year with an NRD_A lower than 79 (lower limit of class 1) is 7.55%. On the other hand, the chance of NRD_A being lower than 149 (upper limit of class 7) is 98.11% or a 1.89% chance of observing a year with days of rain higher than this value.

The histograms in Figs. 6a and 7b have similarities but are not identical. The values of class 6 in Fig. 6a were higher than those of class 5, which caused slight distortion compared to the normal curve. This behavior is related to the incidence of extreme rainfall, that is, when there are large volumes of precipitation in one day. The histogram referring to NRD_A shows that the behavior of this variable was closer to the normal distribution.

Importantly, the differences observed between the two plots may be directly associated with the rainfall intensity. More intense rainfall is associated with higher PA_A values, which causes an increase in observations in classes with higher limits (Fig. 6a). However, NRD_A is not influenced by this event, considering that the intensity of the rainfall is not computed for recording NRD_A, that is, it is only considered whether or not there was rain with a volume greater than 1 mm.

Brússolo et al. (2020) found similar PA_A values in the municipality of Assis – SP, as well as Santos et al. (2020) for 16 municipalities located in the central portion of the State of São Paulo. The values identified for the municipality of Botucatu are within expectations considering the local climate. The continentality climate factor prevails for much of the year in this city, located in the countryside of the State of São Paulo, far from large natural bodies of water such as the sea (Rossi et al. 2018). Rainfall is generally higher in volume compared to evapotranspiration, but this rainfall is poorly distributed. Large volumes of rainfall in the summer and low rainfall in the winter are generally observed.

Monthly precipitation

Figure 7 shows the monthly mean and standard deviation of the monthly accumulated precipitation values (PA_M) and the number of monthly rainy days (NRD_M), considering the historical series from 1971 to 2022, which totaled 52 years of measurements.

Higher PA_M and NRD_M are observed in the summer months. In January, PA_M was 284.82 ± 123.87 mm and NRD_M was 17 ± 4 days. In February, PA_M reached 204 ± 95.69 mm and NRD_M was 13 ± 4. In December, rainfall totaled 212.06 mm ± 74.98 mm and NRD_M reached 14 ± 3 days.

The months with the lowest PA_M occurred in the winter, with June showing MA_P of 59.14 ± 58.93 mm and NRD_M of 5 ± 4 days. July showed a reduction in the volume of precipitation, with PA_M of 42.40 ± 43.57 mm and NRD_M of 4 ± 3 days. Finally, August had the lowest records, with MA_P reaching 40.48 ± 40.72 mm and NRD_M 4 ± 3 days. This month can be considered the driest of the year.

This seasonal behavior is typical of the region of this study (Santos et al. 2020; Brússolo et al. 2020). The large volumes of rain in the summer are responsible for recharging the water table, which, consequently, guarantees flow to the rivers during dry periods. Winter periods show a predominance of droughts (low rainfall), limiting agricultural activity and significantly increasing the risk of fires and the need for irrigation (Giacomeli et al. 2022; Carvalho et al. 2023).

Importantly, the information shown in Fig. 7 is important when sizing agricultural fleets. For instance, October has a historical mean of 9 days with rain or 22 days without rain, which means that, on average, this month has 22 days favorable for working in the field with machinery. However, years with just 3 days of rain (28 days without rain) or with up to 16 days of rain (only 15 days without rain) may occur given the variations between years. The probability of occurrence of these two scenarios is approximately 1.9% (calculated based on the frequency of occurrence in 52 years).

Table 3 shows NRD_M distribution values per month, with their respective standard deviations. January tends to have a higher number of rainy days, with approximately half of the days of the month (53.57%) presenting rain. This information is important for the agricultural sector, as days with rain can limit the movement of agricultural machinery in the field. According to Beutler et al. (2009), Jimenez et al. (2021) and Shaheb et al. (2021), agricultural machinery traffic on wet soils can increase soil compaction, which can affect negatively plant growth and crop productivity.

Table 3
Descriptive summary of the frequency of the number of monthly rainy days (NRD_M) in the period from 1971 to 2022.

Month	Mean ± SD	Med [Min-Max]	CV	Rainy days (%)
January	16.5 ± 4.0	16.5 [9–24]	0.24	53.23
February	13.4 ± 4.3	13.5 [6–23]	0.32	48.21
March	11.7 ± 3.4	12.0 [5–20]	0.29	38.71
April	5.9 ± 2.7	6.0 [1–12]	0.47	20.00
May	6.0 ± 3.3	6.0 [0–16]	0.55	19.35
June	4.9 ± 3.5	5.0 [0–14]	0.72	16.67
July	3.6 ± 2.8	3.0 [0–15]	0.78	9.68
August	3.9 ± 2.8	4.0 [0–10]	0.73	12.90
September	7.2 ± 3.7	7.0 [0–16]	0.52	23.33
October	9.2 ± 3.2	9.0 [3–16]	0.35	29.03
November	10.5 ± 3.1	10.5 [5–19]	0.29	35.00
December	14.5 ± 3.4	14.0 [7–24]	0.24	45.16

SD = standard deviation, Med = median, Min = minimum, Max = maximum and CV = coefficient of variation.

Table 3 shows that the lowest values of the coefficient of variation occurred in the summer, indicating less temporal variability in this season. Winter months show higher variability in rainy days during the study period. Winter rains have lower volumes, lower intensities, and fewer days of rain (Varejão 2006; Mendonça & Oliveira 2017).

July and August presented the lowest mean number of rainy days, with a mean of 4 days with rain. These months have no major restrictions on mechanized agricultural operations (soil tillage and harvesting), but the low rainfall volume restricts some agricultural activities that require rain to be carried out, such as planting and liming (Botta et al. 2022). Importantly, the volume of rain increases in October and November, intensifying agricultural activity in the harvest and soil tillage for the next growing season. These months had a mean of 30% more days of rain (between 7 and 9 days), which requires good planning for the correct handling of the machinery during this period.

Figure 8 shows the histograms of the number of rainy days in each month (NRD_M). The distribution of this number in the summer months shows a different behavior than in the winter months. In the summer, rainfall volumes are higher, and this is reflected in the number of rainy days, as indicated by the more asymmetrical histograms to the left. January had 12 or more days of rain in 44 years of the historical series (84.6% of the years), a situation that led to severe restrictions on the movement of agricultural machinery. Moreover, 11 years had more than 20 days of rain in January (21.15% of the historical series), with 1983 having 24 days of rain (80% of the days of the month).

The NRD_M frequency distribution in January showed 98% of years with 10 or more days of rain. Consequently, the class in which 50% of the accumulated frequency was observed was the class with 12 days or more of rain, which indicates that half of the evaluated years had 12 or more rainy days in January. This median value (50%) is often used in the planning, acquisition, and operation of agricultural machinery. Although the time window for field machinery operations after rain also depends on the type of local soil and its drainage speed, knowledge of the number of rainy days allows better planning/forecasting in the number of hours worked or to work in the field with machines and tractors (Pezzopane et al. 1995; INMET 2021).

The prior planning of many agricultural activities, such as the application of pesticides, harvesting, and soil tillage, is costly, involving labor, jobs, and appropriate machinery. The risk of these activities being hampered by rain is high, as rainfall with more than 5 mm interferes with soil tillage operations, such as plowing (Pezzopane et al. 1995).

February and December presented a similar behavior to January, showing 50% of the years with 12 days or more of rain, with December showing this number in 84.61% of the historical series, while February presented six or more rainy days in 99.11% of the years. The large number of days of rain at this time of year (summer) is explained by the climate. The sun declines towards the southern hemisphere, radiating a higher amount of energy compared to winter. This energy is used in latent processes of water evaporation, providing the formation of convective systems and, consequently, rain. Convective systems are large summer rains, with the formation of storms, causing thunder and lightning (Back et al. 2020).

These convective systems lose strength from March and April onwards and rain only begins to occur when cold fronts arrive. Cold fronts come from the southern regions of the globe to the Southern Hemisphere and enter Brazil through Argentina, continuing through the Southern region until reaching the state of São Paulo. These frontal rains are predominant until the return of the hot summer period (close to November). In this winter period when rainfall is frontal, the volume, intensity, and frequency of rain depend on the number of cold fronts and their properties. There are years when dozens of cold fronts enter each season, providing a large number of days of rain. There are years in which few cold fronts advance over South America, providing years with fewer days of rain. There are still larger cold fronts (called “strong” cold fronts) and smaller magnitude cold fronts (“weak”). Strong cold fronts can cause rain lasting more than 24 hours. Weak cold fronts are more common although they cause fewer days of rain (INMET 2022b).

April showed frequencies more distributed between the classes of rainy days, resulting in a median value of 6 days, that is, 50% of the years in this month had 6 days or more with rain. The number of days of rain reduces in May and June compared to previous months. In June, 50% of the years in the historical series had around 4 days or less of rain.

The situation is similar in July and August. However, the median value in July and August is 2 days of rain, that is, 50% of the years in the historical series had up to two days of rain in these months. It means that, at most, 2 to 3 days of rain are expected in July. However, August presented more than 10 days of rain in some years. It occurs in years with a higher number of cold fronts when the season begins in May-June and lasts until July-August, but they may occur later in some years (August-September).

Ten-day period precipitation

Table 4 shows the ten-day values for each month with mean values for the number of decennial rainy days (NRD_D). In this methodology, the third ten-day period (D3) of each month will not necessarily have 10 days. Thus, D3 was 11 days for January, March, May, July, August, October, and December. D3 was 10 days for April, June, September, and November and 8 days for February. This difference in days in the values shown in Table 4 was considered in the calculation.

Table 4
Comparison of the number of decennia rainy days (NRD_D) occurring in three periods of the month (~ 10 days) with the mean monthly value.

Month	D1	D2	D3	Mean of the month
January	5.7	5.3	5.6	16.5 ^{A}
February	4.8	4.9	4.4	14.2 ^{B}
March	4.2	4.0	3.6	11.8 ^{C}
April	2.1^{ab}	2.3^{a}	1.5^{b}	5.9 ^{GH}
May	1.8	1.9	2.3	6.0 ^{FG}
June	1.9	1.5	1.5	4.9 ^{GHI}
July	1.1	1.2	1.4	3.6 ^{I}
August	1.1	1.4	1.5	3.9 ^{GH}
September	2.2	2.3	2.8	7.3 ^{EF}
October	3.0	2.9	3.3	9.3 ^{DE}
November	3.3	3.4	3.8	10.5 ^{CD}
December	4.2 ^{b}	4.7 ^{ab}	5.6 ^{a}	14.5 ^{AB}

* Different lowercase letters in the row and uppercase letters in the columns indicate a significant difference by the Tukey test at a 5% significance.

** D1 – first 10-day period of the month; D2 – second 10-day period of the month; D3 – third 10-day period of the month.

The 10-day period values were processed aiming to obtain differences in NRD_D (number of 10-day period rains) within a month. The three 10-day periods of each month were subjected to the Tukey test at a 5% significance level. April and December were the only months in which the three periods showed significant differences. The 2nd 10-day period (D2) of April presented a higher NRD_D, while the third 10-day period (D3) had a lower number of days of rain than the rest of the month. The third 10-day period (D3) of December presented a higher NRD_D, while the first 10-day period (D1) presented a lower NRD_D. The other months showed no significant difference between the three 10-day periods, demonstrating a more homogeneous distribution of rainfall throughout the month.

The comparison of days of rain between months showed a large variation. January presented the highest number of days of rain in the series, followed by December. July presented the fewest days of rain. The Tukey test shows the behavior of changing the rainfall regime: from the rainy season to the dry season and from the dry season to the rainy season.

The change to the rainy season (September to November) showed a gradual increase in the number of days of rain each month: November had no significant difference from October and October had no significant difference from September. September and August differed but in neighboring classes (letters F and G). The period of change to dry (March to May) had a more abrupt reduction in the number of days of rain. A change from class C to class G occurred from March to April. It demonstrates that the decrease in NRD_D at the end of the rainy season occurs more abruptly.

Conclusions

The analysis of the historical series allowed the evaluation of the rainfall behavior and revealed significant variation in precipitation patterns over time in Botucatu-SP. The PA_A and NRD_A values had disagreements in some years, indicating that these parameters are not necessarily correlated, and these differences may be associated with the intensity and temporal distribution of rainfall.

The climate phenomena El Niño and La Niña presented influences on the Botucatu rainfall regime. Overall, the PA_A and NRD_A values were higher when El Niño occurred, indicating years of higher water availability. In contrast, the incidence of La Niña was related to periods of lower volumes and days of rain, implying years with higher water scarcity.

The evaluation of the historical series on a monthly scale allowed the identification of the seasonal standard of rainfall over the months of the year, which significantly influences agricultural activities. Thus, the rainfall regime characterization in the municipality of Botucatu showed that PA_M and NRD_M were higher during the summer, while this behavior is inverse in the winter when the lower PA_M and NRD_M values are recorded.

Also, the rainfall regime had less temporal variability in the summer months, contrasting with higher variability in the winter months. Notably, July and August stood out by presenting the lower means of days of rain, contributing to a lower NRD_M but demanding precautions regarding the conduct of agricultural activities during this period.

Regarding the evaluation of 10-day periods, the rainfall regime in most months was distributed evenly over the days, i.e., no large difference was observed in the rainfall volume and NRD_D at the beginning, middle, and end of the month. The comparison between the months of the year was important, evidencing the seasonality of volume and days of rain.

In general, the application of the information presented and discussed in this paper can improve and substantiate agricultural management, reduce financial and operational risks, and contribute to the most sustainable development of agribusiness in the region of Botucatu-SP.

Declarations

Acknowledgments The authors thank the Coordination for the Improvement of Higher Education Personnel (CAPES) for granting the scholarship and the Graduate Program in Agricultural Engineering at the School of Agronomic Sciences (UNESP) of Botucatu (SP) – Brazil. To all the meteorological observers who worked day by day throughout these years and made it possible to perform this research.

Funding The authors would like to thank the research scholarship provided by CAPES (Finance Code 001) and the resources made available by UNESP through the Prope N° 02/2024.

Author contributions Data colletion, processing, data curation and validation: J.R.F, V.C.O, E.D.P, S.A.R; Conceptualization, methodology, validation, formal analysis: J.R.F, V.C.O, E.D.P, S.A.R, A.D.P; Original draft: J.R.F, V.C.O, E.D.P, S.A.R, V.C.R.S, F.S.C; Funding: J.R.F, V.C.O, F.S.C, A.D.P; All authors were involved in writing, reviewing, and editing

Data availability The datasets generated and analyzed in this study are not publicly available due to the utilization of a comprehensive dataset spanning 52 years, which is also being employed in other ongoing research projects. Premature release of this dataset could compromise the integrity and outcomes of these concurrent studies.

Compliance with ethical standards

Conflict of interest the authors declare that they have no conflict of interest.

Ethics approval This article does not contain any studies with human or animal participants performed by any of the authors.

Consent to participate All authors have read and agreed to the published version of the article.

Conflict of interest The authors declare no competing interests.

References

1. ANA - Agência Nacional de Águas e Saneamento Básico (2021) Atlas irrigação: uso da água na agricultura irrigada. https://portal1.snirh.gov.br/ana/apps/storymaps/stories/a874e62f27544c6a986da1702a911c6b. Accessed 12 February 2023
2. Araujo CF, Dias MDS, Guimarães PTG, Alcântara EM (2011) Capacidade de suporte de carga e umidade crítica de um Latossolo induzida por diferentes manejos. Rev Bras Ci Solo 35:115–131. https://doi.org/10.1590/S0100-06832011000100011
3. Assad ED (1992) Estimativas das precipitações máximas prováveis, com duração de 24 horas e de 30 minutos. Pesq Agropec Bra 27:677–686
4. Ataíde LT, Caramori PH, Silva RW, Silva DAB, Souza JRP (2012) The probability of potentially useful work days during the year in Londrina. Semina 33:2215–2226. https://doi.org/10.5433/1679-0359.2012v33n6p2215
5. Back ÁJ, Sônego M, Pereira J (2020) Indices de concentração de chuvas da região sul do Brasil. Rev Bras Clim 27:114–126. http://dx.doi.org/10.5380/abclima.v27i0.65466
6. Back ÁJ (2006) Relações intensidade-duração-frequência de chuvas intensas de Chapecó, Estado de Santa Catarina. Agronomy 28:575–581
7. Beutler AN, Centurion JF, Mengatto LH, Alves JB, Wagner GPC (2009) Impacto do tráfego de máquinas na qualidade física do solo e produtividade de milho em. Argissolo Agron 31:359–364. https://doi.org/10.1590/S1807-86212009000200025

8. Botta GF, Nardon GF, Guirado R (2022) Soil sustainability: Analysis of the soil compaction under heavy agricultural machinery traffic in extensive crops. Agronomy 12:282–294. https://doi.org/10.3390/agronomy12020282
9. Brússolo RG, Santos BC, Vecchia FSA (2020) Caracterização das chuvas no município deassis (SP) no recorte temporal de 1991 a *2016.* Geog Op Temp. 6:79–92
10. Carvalho DFD, Teles GD, Cruz ESD, Valença DDC, Medici LO (2023) Yield response factor (Ky) and initial growth in black pepper in a tropical environment. Sci Agri 80:e20220171–e20220182. https://doi.org/10.1590/1678-992X-2022-0171
11. Cunha GR, Pires JLF, Dalmago GA, Santi A, Pasinato A, Silva AAG, Rosa C (2011) El Niño/La Niña-Oscilação Sul e seus impactos na agricultura brasileira: fatos, especulações e aplicações. Rev Plan Dir 3:1–5
12. Dallacort R, Martins JA, Inoue MH, Freitas PSLD, Coletti AJ (2011) Distribuição das chuvas no município de Tangará da Serra, médio norte do Estado de Mato Grosso. Brasil Agron 33:193–200. https://doi.org/10.4025/actasciagron.v33i2.5838
13. Diniz JMT (2013) Variabilidade da precipitação e do número de dias com chuvas de duas cidades distintas da Paraíba. HOLOS 3:171–180
14. Estrada JS, Shlosser JF, Farias MS, Santos GO, Rüdell IYP (2015) Metodologia para estimar o número de dias trabalháveis com máquinas agrícolas. Rev Ceres 62:414–419. https://doi.org/10.1590/0034-737X201562040011
15. Fernandes HC, Souza AP, Vitória EL (2000) Determinação do número de dias potencialmente úteis parta o trabalho com máquinas florestais. Rev Arv 24:269–274
16. Franco JR, Dal Pai E, Calça MVC, Raniero MR, Dal Pai A, Sarnighausen VCR, Román RMS (2023) Update of climatological normal and köppen climate classification for the municipality of Botucatu-SP. Irriga 28:77–92. http://dx.doi.org/10.15809/irriga.2023v28n1p77-92
17. Franco JR, Ranieiro MR, Calça MVC, Rodrigues SA, Pai AD, Pai ED (2022) Análise Comparativa Entre Medidas Meteorológicas da Estação Convencional e Automática da Fazenda Lageado no Município de Botucatu, São Paulo, Brasil. Rev Bras Meteo 37:223–232. http://dx.doi.org/10.1590/0102-77863720033
18. Giacomeli R, Carlesso R, Petry MT, Chechi L, Beutler NA, Fulaneti FS, Ferrazza CM (2022) Improving irrigation, crop, and soil management for sustainable soybean production in Southern Brazilian lowlands. Sci Agri 79:1–15. https://doi.org/10.1590/1678-992X-2021-0115
19. IBGE - Instituto Brasileiro de Geografia e Estatística (2022) Cidades: IBGE. https://cidades.ibge.gov.br/brasil/sp/botucatu/panorama. Accessed 02 August 2022
20. INMET - Instituto Nacional de Meteorologia (2009) Agrometeorologia dos Cultivos. Brasília – DF. https://www.embrapa.br/documents/1355291/37056285/Bases+climatol%C3%B3gicas_Accessed 12 September 2023
21. G.R.CUNHA_Livro_Agrometeorologia + dos + cultivos.pdf/13d616f5-cbd1-7261-b157-351eaa31188d?version = 1.0. Accessed 01 October 2023
22. INMET - Instituto Nacional de Meteorologia (2021) A importância da previsão de tempo específica para seu plantio. https://portal.inmet.gov.br/noticias/a-import%C3%A2ncia-da-previs%C3%A3o-de-tempo-espec%C3%ADfica-para-seu-plantio. Accessed 15 October 2023
23. INMET - Instituto Nacional de Meteorologia (2022a) Normais Climatológicas do Brasil 1991. https://portal.inmet.gov.br/uploads/normais/NORMAISCLIMATOLOGICAS.pdf. Accessed 28 September 2023
24. INMET - Instituto Nacional de Meteorologia (2022b) O que é e como se forma uma Frente fria? https://portal.inmet.gov.br/noticias/o-que-%C3%A9-e-como-se-forma-uma-frente-fria#:~:text=Durante%20seu%20deslocamento%2C%20essa%20massa,e%20seco%20aparece%20em%20seguida. Accessed 23 September 2023

25. Jimenez KJ, Rolim MM, Gomes IF, Lima RP, Berrío LA, Ortiz PF (2021) Numerical analysis applied to the study of soil stress and compaction due to mechanised sugarcane harvest. Soil Tillage Res 206:104847–104899. https://doi.org/10.1016/j.still.2020.104847
26. Marcuzzo FFN, Romero V (2013) Influência do El Niño e La Niña na precipitação máxima diária do estado de Goiás. Rev Bra Met 28:429–440. https://doi.org/10.1590/S0102-77862013000400009
27. Medeiros RM, Brito JIB, Silva VMA, Melo VS, Costa FA (2016) El Niño/La Niña e sua influência no número de dias com chuva em Bom Jesus – Piauí, Brasil. Rev Ver Agroeco Desenv Sust 11:16–23. http://dx.doi.org/10.18378/rvads.v11i2.3993
28. Mendes AT, Zukowski JC (2020) Caracterização do Regime Pluviométrico do Município de Araguaína–TO. R Bra Met 34:449–458. http://dx.doi.org/10.1590/0102-7786344056
29. Mendonça F, Oliveira IM (2017) Climatologia: noções básicas e climas do Brasil. Oficina de textos, São Paulo
30. Mialhe LG (1974) Manualde mecanização agrícola. Agronômica Ceres, São Paulo
31. Nery JT, Siqueira B (2020) Índice de Anomalia de Chuva aplicado ao estudo das precipitações no Estado do Paraná. Rev Bras Clim 27:772–788. http://dx.doi.org/10.5380/abclima.v27i0.65691
32. NOAA - National Oceanic and Atmospheric Administration (2023) Cold & Warm Episodes by Season. https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php
33. Pezzopane JEM, Sentelhas PZ, Ortolani AA, Moraes ADC (1995) Caracterização da chuva horária em três locais do Estado de São Paulo: um subsídio ao planejamento de operações agrícolas de campo. Sci Agri 52:70–77. https://doi.org/10.1590/S0103-90161995000100013
34. Rodrigues L, Souza WM, Costa VS, Pereira MLT (2017) Influência dos eventos de El Niño e La Niña no regime de precipitação do Agreste de Pernambuco (Influence of El Niño and La Niña events on rainfall of Agreste Pernambuco). Rev Bras Geo Fis 10:1995–2009
35. Rossi TJ, Escobedo JF, Santos CM, Rossi LR, Silva MBP, Dal Pai E (2018) Global, diffuse and direct solar radiation of the infrared spectrum in Botucatu/SP/Brazil. Renew Sust Ener Rev 82:448–459. https://doi.org/10.1016/j.rser.2017.09.030
36. Ruezzene CB, Miranda RB, Tech ARB (2021) Preenchimento de falhas em dados de precipitaçãoatravés de métodos tradicionais e por inteligênciaartificial. Rev Bras Clim 29:179204. https://ojs.ufgd.edu.br/index.php/rbclima/article/view/15184
37. Sant'Anna JLSA (1999) Avaliação das mudanças no regime das chuvas do Estado de São Paulo durante um século (1888–1993). Technology 21:915–921. https://doi.org/10.4025/actascitechnol.v21i0.3163
38. Santos BC, Fontão PAB, Souza PH (2020) O efeito do relevo nas chuvas na porção central do Estado de São Paulo em anos padrão extremos. Revdo Dep d Geo 40:132–147. https://doi.org/10.11606/rdg.v40i0.172973
39. Shaheb MR, Venkatesh R, Shearer SA (2021) A review on the effect of soil compaction and its management for sustainable crop production. J Biosys Eng 3:1–23. https://doi.org/10.1007/s42853-021-00117-7
40. Silva PCG, Moura MSB, Kiill LHP, Brito LDL, Pereira LA, Sá IB, Guimarães C (2010) Caracterização do Semiárido brasileiro: fatores naturais e humanos. Embrapa Semiárido, Pelotas
41. Soares ASD, Paz ARD, Piccilli DGA (2016) Avaliação das estimativas de chuva do satélite TRMM no Estado da Paraíba. Rev Bra Rec Hidr 21:288–299. https://doi.org/10.21168/rbrh.v21n2.p288-299
42. Varejão MA (2006) Meteorlogia e Climatologia Digital. Version 2, Recife

Figures

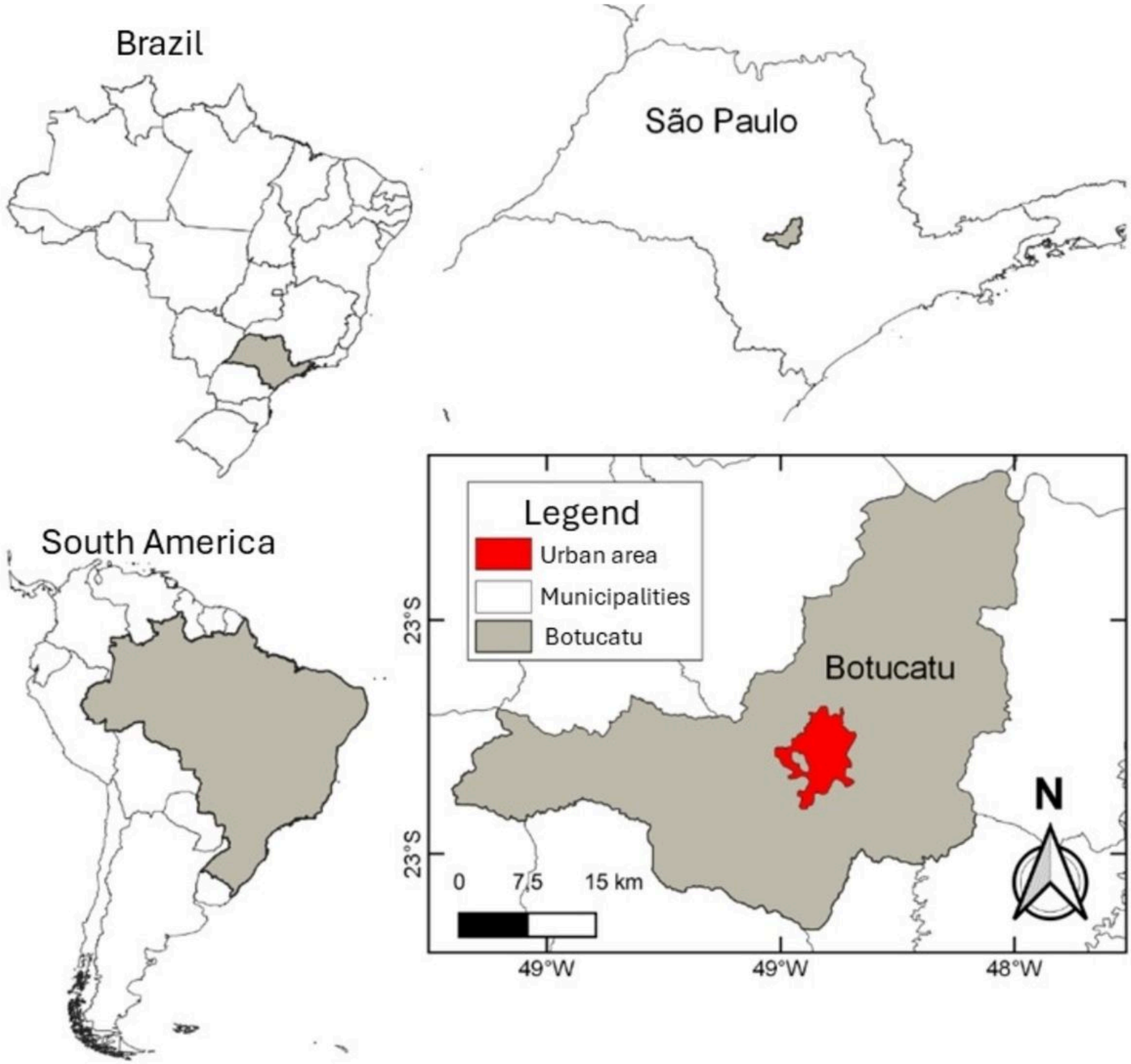

Figure 1

Municipality of Botucatu – São Paulo – Brazil.

Figure 2

Rain gauge at Fazenda Lageado (Botucatu – SP – Brazil) weather station (**a**) Automatic; (**b**) conventional.

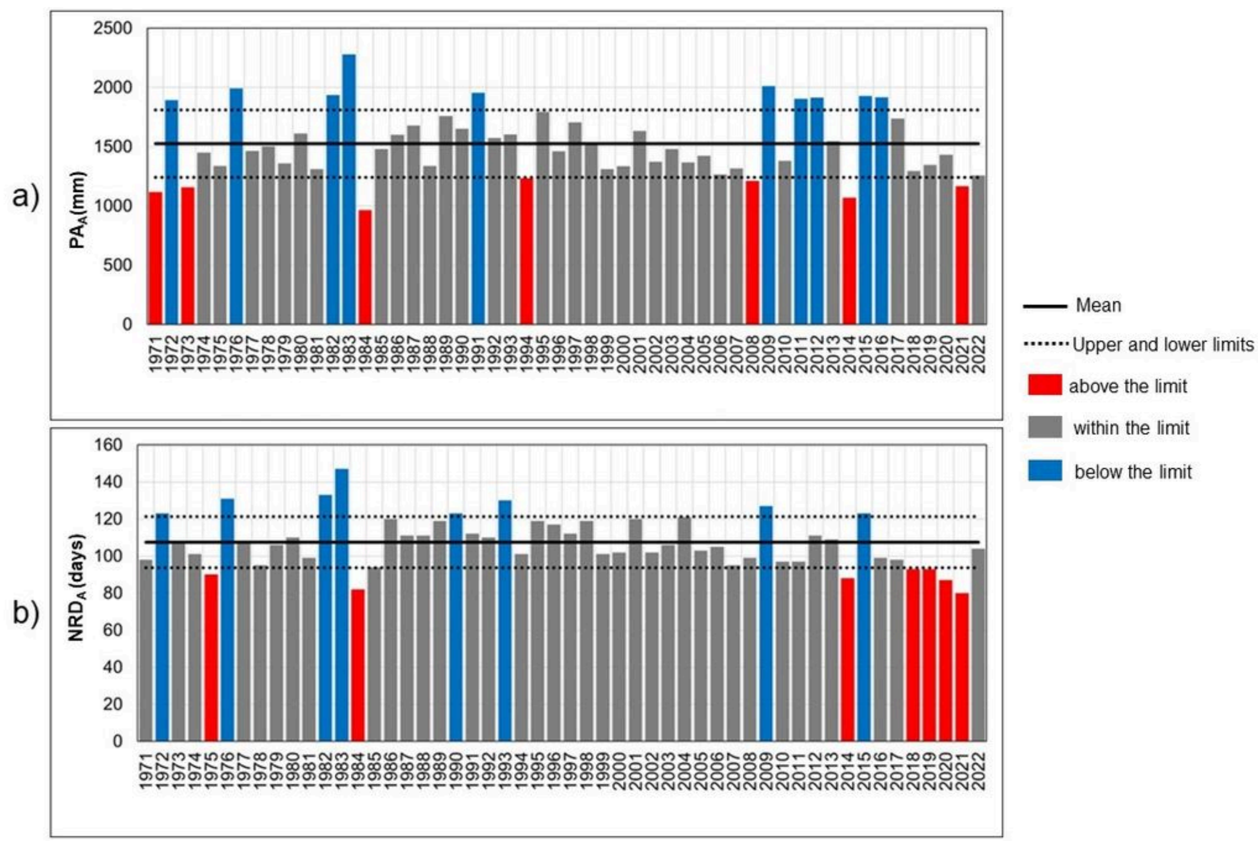

Figure 3

52-year historical series (1971 to 2022) in the municipality of Botucatu for the values of **(a)** annual accumulated precipitation (PA_A); (**b**) number of annual rainy days (NRD_A).

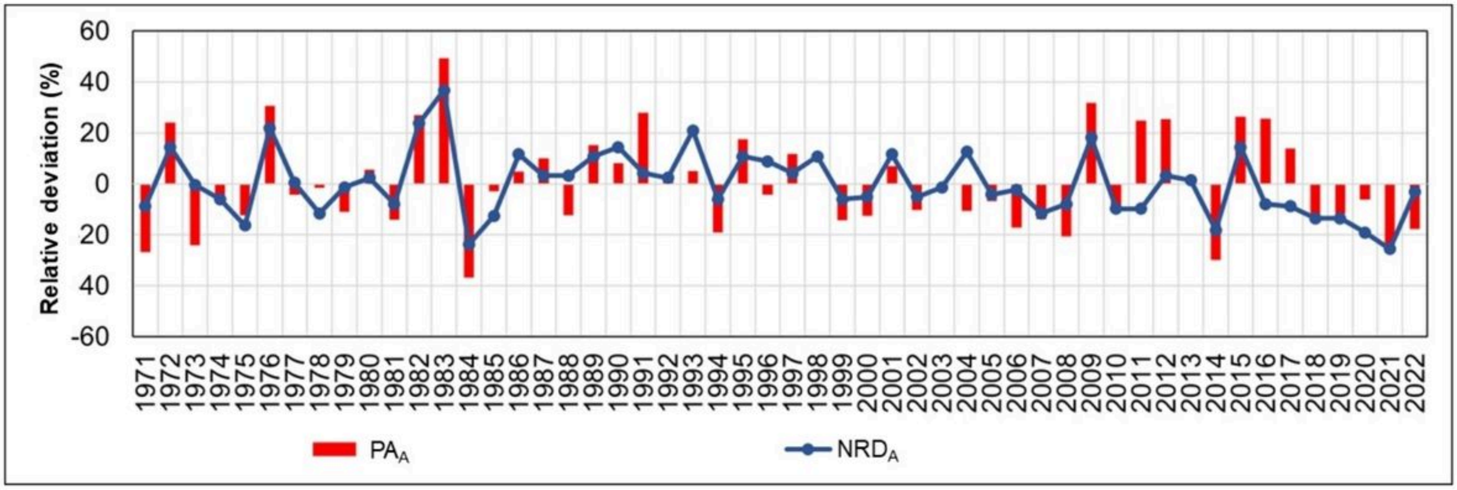

Figure 4

Relative deviation of the 52-year historical series (1971 to 2022) in the municipality of Botucatu for the values of (**a**) annual accumulated precipitation (PA_A); (**b**) number of annual rainy days (NRD_A).

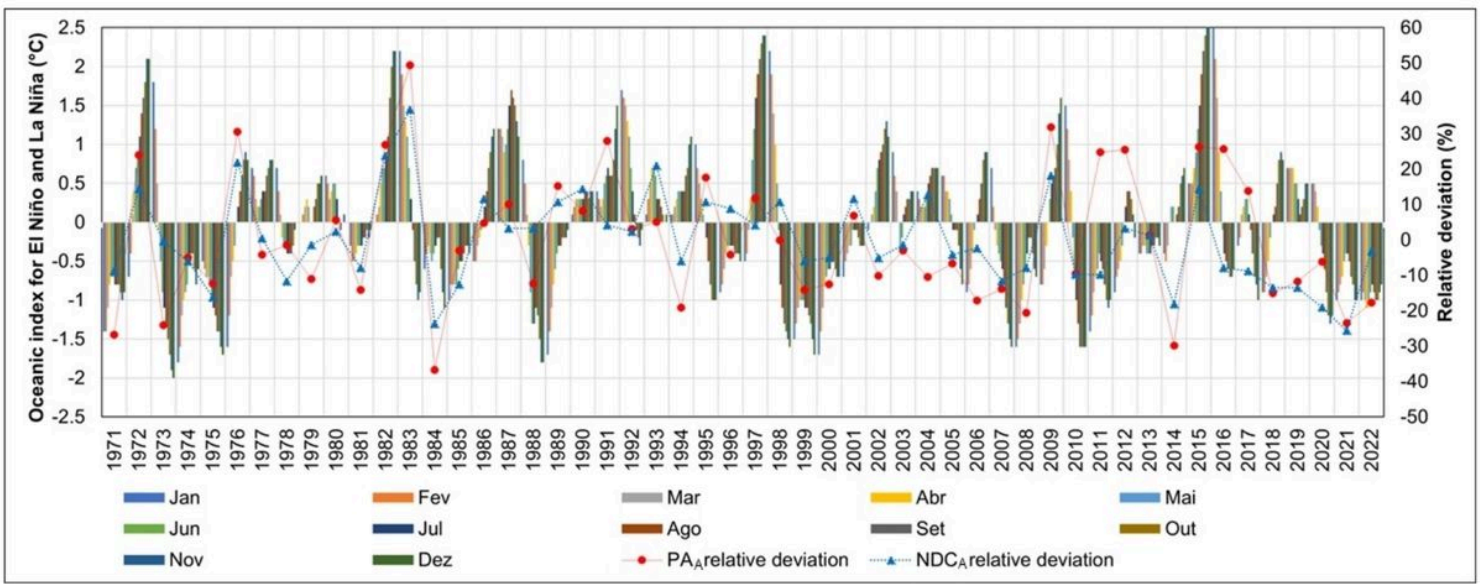

Figure 5

Oceanic index for the El Niño and La Niña phenomenon for the period between 1971 and 2022.

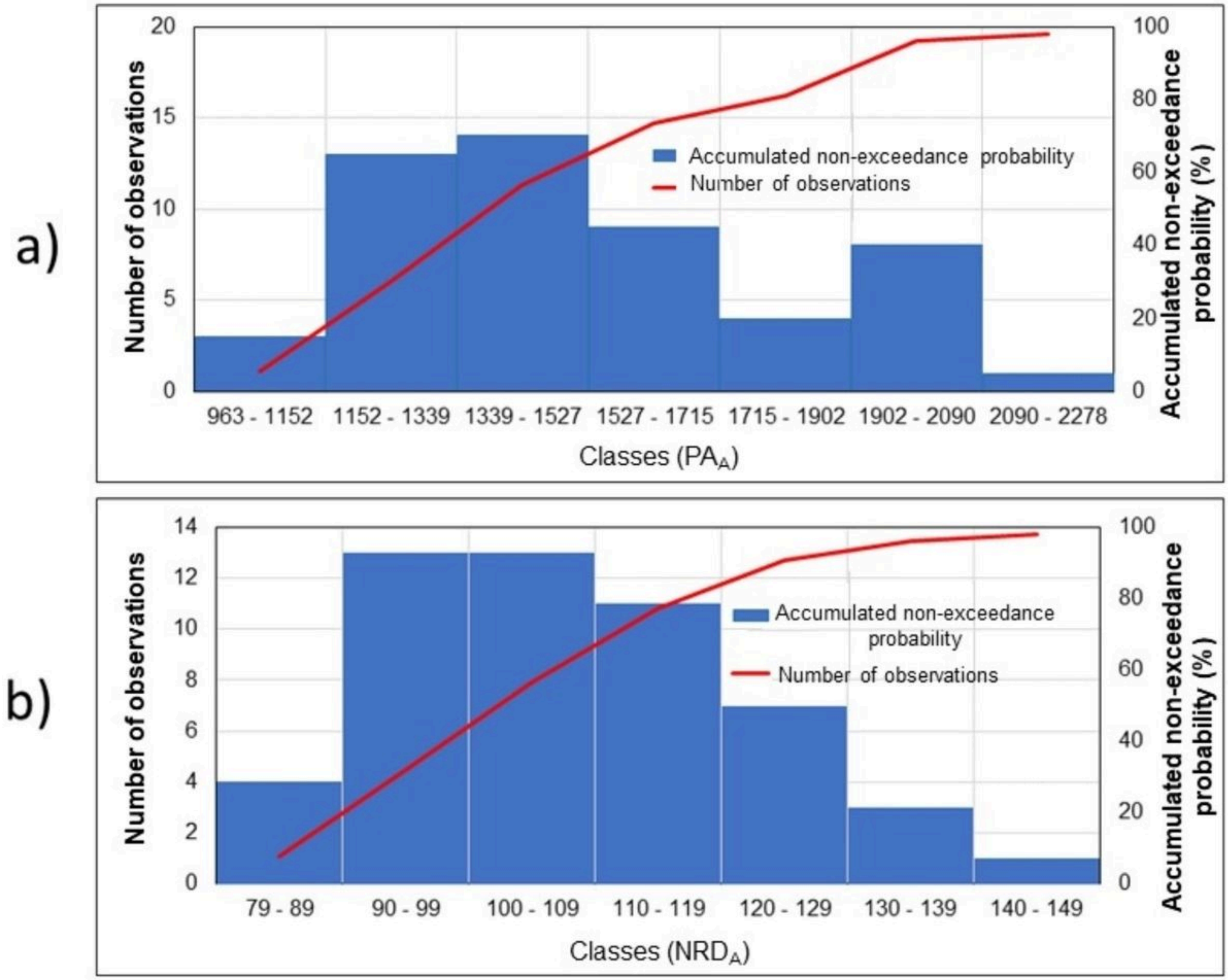

Figure 6

Histogram and accumulated probability of the (**a**) annual accumulated precipitation (PA_A); (**b**) number of annual rainy days (NRD_A).

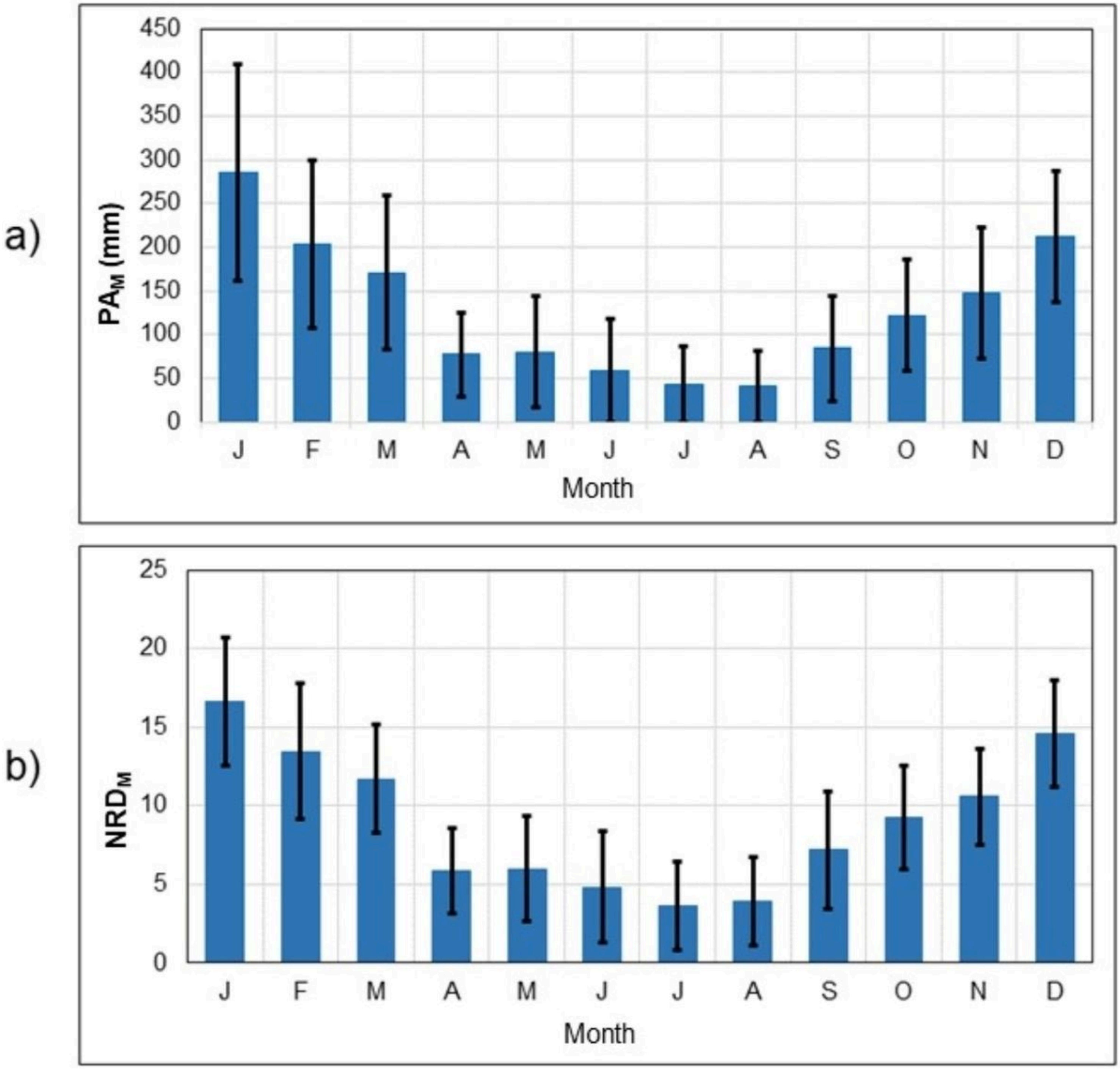

Figure 7

Precipitation from 1971 to 2022 for the municipality of Botucatu – SP – Brazil (**a**) monthly accumulated precipitation (PA_M); (**b**) number of monthly rainy days (NRD_M).

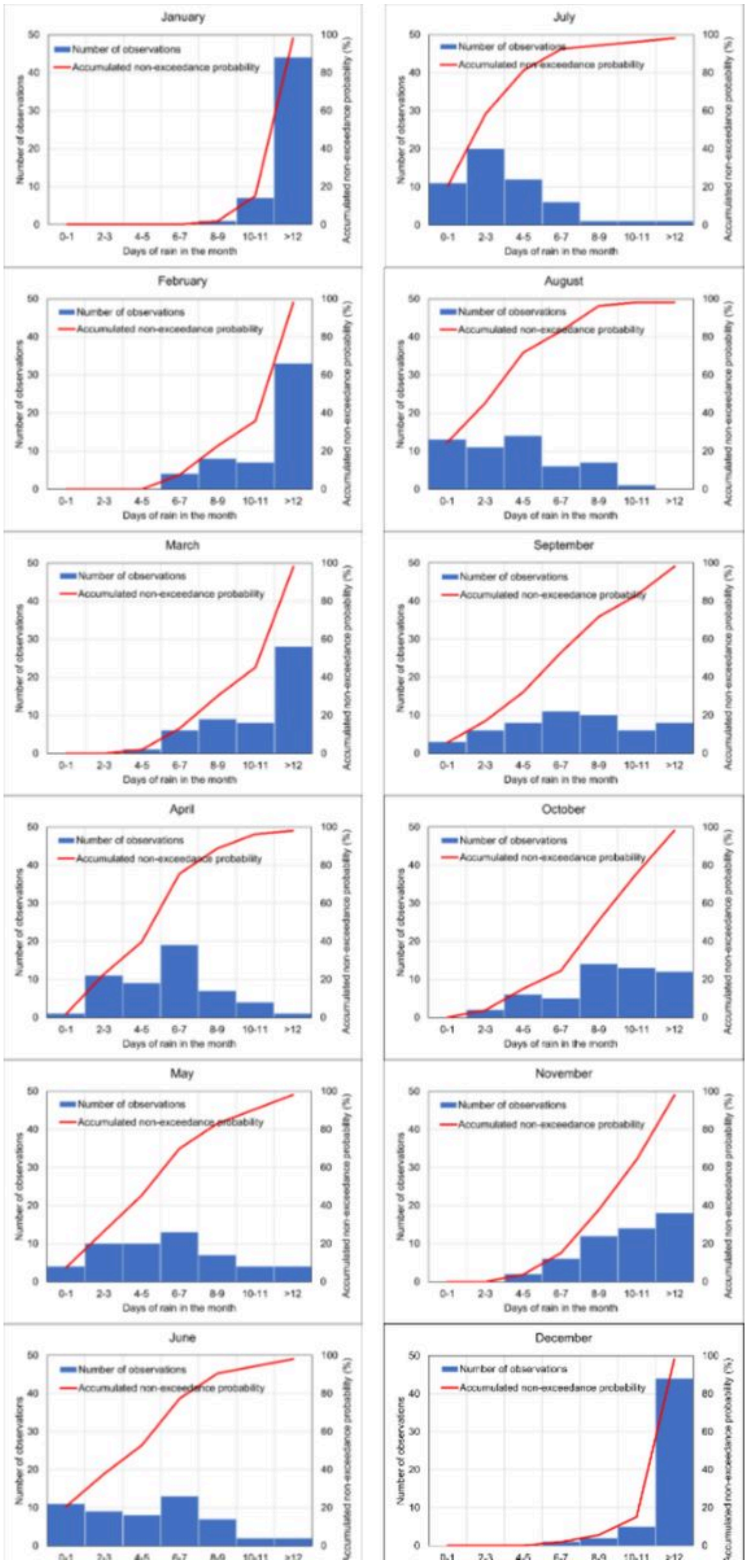

Figure 8

Histograms of frequency and relative accumulated frequency of the number of monthly rainy days (NRD_M), from 1971 to 2022 (52 years).