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Analysis of Concentration and Seasonality of Precipitation in Recife - Pernambuco, Brazil

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ABSTRACT

This study investigates the variability of precipitation distribution and rainfall seasonality regime in Recife-PE, Brazil, using the Precipitation concentration index (PCI) and Seasonality indices (SI). PCI was calculated on annual (PCI_a), seasonal (PCI_s), and supra-seasonal (PCI_{ss}) scales for the period 1962-2020. Rainfall seasonality regime classification was performed using the individual seasonality index $(\overline{SI_i})$, the general seasonality index (SI), and the replicability index (RI). The PCI_a time series revealed precipitation distribution ranging from moderate (79.66% of the years) and irregular, with mean value of $\overline{PCI_a} \approx 13.58$. Seasonality analysis indicated a mean rainfall regime classified as rather seasonal with a short drier season $(\overline{SI} \approx 0.56)$, and a high degree of replicability $(RI = 0.85)$, characterized by maximum rainfall concentrated in a few months and limited interannual variability in SI_i values. Trend analysis using the Mann-Kendall test and Sen's slope estimator showed no significant trends in the time series of PCI and SI_i, except for spring (PCI_s), which exhibited a significant negative trend. A Spearman correlation analysis between SI_i and PCI_a yielded a strong positive correlation ($\rho = 0.86$), reinforcing the link between precipitation concentration and seasonality structure.

Keywords: Seasonality index; Precipitation concentration index; Recife; Brazil

Introduction

Northeastern Brazil (NEB) exhibits pronounced spatiotemporal variability in rainfall, directly affecting agriculture, water resources, urban infrastructure, human health, and the vegetation structure of local biomes (Marengo et al., 2022; de Medeiros et al., 2022; da Silva et al., 2021; de Oliveira Souza et al., 2018). Rainfall in NEB is highly seasonal, with the peak of the rainy season typically occurring between February and April, primarily driven by the influence of the Atlantic Intertropical Convergence Zone (ITCZ) and the South American Monsoon System (SAMS). Superimposed on this seasonal cycle is pronounced interannual variability, marked by episodes of excessive rainfall and severe droughts. These fluctuations are closely linked to large-scale ocean–atmosphere phenomena, particularly the El Niño–Southern Oscillation (ENSO). Generally, the negative phase of ENSO (La Niña) is associated with above-average rainfall in NEB, while the positive

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phase (El Niño) tends to suppress precipitation, often resulting in prolonged and severe droughts across the region (Hänsel et al., 2016).

Rainfall is highest along the coastal and forested zones (*Mata Atlântica*), making urban centers in these areas especially vulnerable to extreme precipitation events. Such events frequently result in flash floods, infrastructure disruption, increased incidence of waterborne diseases, and, in severe cases, loss of human life (Rodrigues et al., 2021).

Recife, the capital of the state of Pernambuco in Northeastern Brazil (NEB), is a coastal city that exemplifies the region's vulnerability to hydrometeorological extremes. Characterized by a humid tropical climate, Recife receives high annual rainfalls, concentrated mainly during the austral autumn and winter months (March to August), followed by a markedly drier season (Coutinho et al., 2016). This uneven distribution contributes to natural disasters such as floods and landslides (Nóbrega et al., 2023; Marengo et al., 2023), posing significant challenges for urban infrastructure, public health, and water resource management.

Several studies have addressed the impacts of rainfall variability in Recife. Pereira et al. (2025) investigated slope stability in the Nova Descoberta neighborhood using a geological-geotechnical planialtimetric model that incorporated extreme rainfall events and anthropogenic pressures. Their findings revealed that rainfall infiltration significantly compromised slope stability, while the use of plastic tarps failed to meet safety standards. Oliveira et al. (2014) analyzed water quality in the Apipucos Reservoir, located in Recife's western zone, and reported elevated concentrations of cyanobacteria during the dry season, indicating seasonal stress on aquatic ecosystems. Borges et al. (2024) examined the relationship between precipitation and confirmed dengue cases, identifying a direct correlation: the highest incidence occurred during the rainy season, with a marked decline during the dry months.

Given these diverse impacts, it is essential to investigate the temporal variability of precipitation, particularly its seasonality and concentration throughout the year. Understanding these patterns is critical for developing effective mitigation strategies and enhancing urban resilience in Recife's rapidly evolving socio-environmental landscape.

Two indices are widely recognized for their effectiveness in characterizing precipitation distribution and provide complementary insights: the Seasonality Index (SI) and the Precipitation Concentration Index (PCI). The SI quantifies the degree to which rainfall is concentrated in specific months, capturing the seasonal dynamics of precipitation regimes (Walsh & Lawler, 1981). In contrast, the PCI measures the irregularity of monthly rainfall distribution throughout the year, highlighting temporal concentration and potential extremes (Oliver, 1980). Together, these indices provide a robust framework for evaluating rainfall patterns and their implications for flood risk, drought vulnerability, and climate adaptation planning.

Both SI and PCI have been applied in diverse climatological contexts, including the assessment of rainfall concentration in river basins (Yang et al., 2020; Sa'adi et al., 2023), validation of general circulation models (Doyle, 2020), and evaluation of climate change impacts on precipitation regimes (Stosic et al., 2024).

Despite Recife's well-documented vulnerability to hydrometeorological extremes, no studies have systematically assessed rainfall seasonality and concentration using long-term datasets and standardized indices. Recently, PCI and SI were analyzed across the entire state of Pernambuco. The results showed that, compared to other regions, the Recife Metropolitan Area exhibited the lowest PCI values (indicating moderately seasonal distribution) (Silva et al., 2022) and the lowest SI values, classifying the rainfall regime as moderately seasonal, with a short dry season (da Silva Araújo et al., 2023).

The present study aims to fill a literature gap by analyzing the temporal patterns of SI and PCI in Recife using historical rainfall records. Specifically, we seek to: (i) characterize the seasonal structure of rainfall; (ii) identify trends and anomalies in rainfall concentration and seasonality; and (iii) discuss the implications for urban planning and climate adaptation in Recife.

Materials and Methods

Study area and data

Recife, the capital of Pernambuco state, is located on the eastern coast of Northeastern Brazil (NEB), near 8°S latitude and 34°W longitude (Fig. 1). It is one of the most densely populated urban centers in NEB, with over 1.5 million inhabitants. Geographically, Recife is a coastal city, about 2.5–5 m above sea level, in a region comprised of the Atlantic Rainforest Biome (Marengo et al., 2023).

The climate is humid tropical (Köppen classification: Am), characterized by high temperatures and relative humidity throughout the year, with a rainy season from March to August. Average annual precipitation is between 1,800 and 2,300 mm, with rainfall concentrated in a few months, contributing to frequent urban flooding and drainage challenges. The city's climatology is influenced by multiple atmospheric systems, including the Intertropical Convergence Zone (ITCZ), Easterly Wave Disturbances (EWD), High-Level Cyclonic Vortices (HLCV), and the South Atlantic Subtropical High (SASH), as well as ocean–atmosphere interactions such as ENSO and the Atlantic SST gradient (Borges et al., 2024).

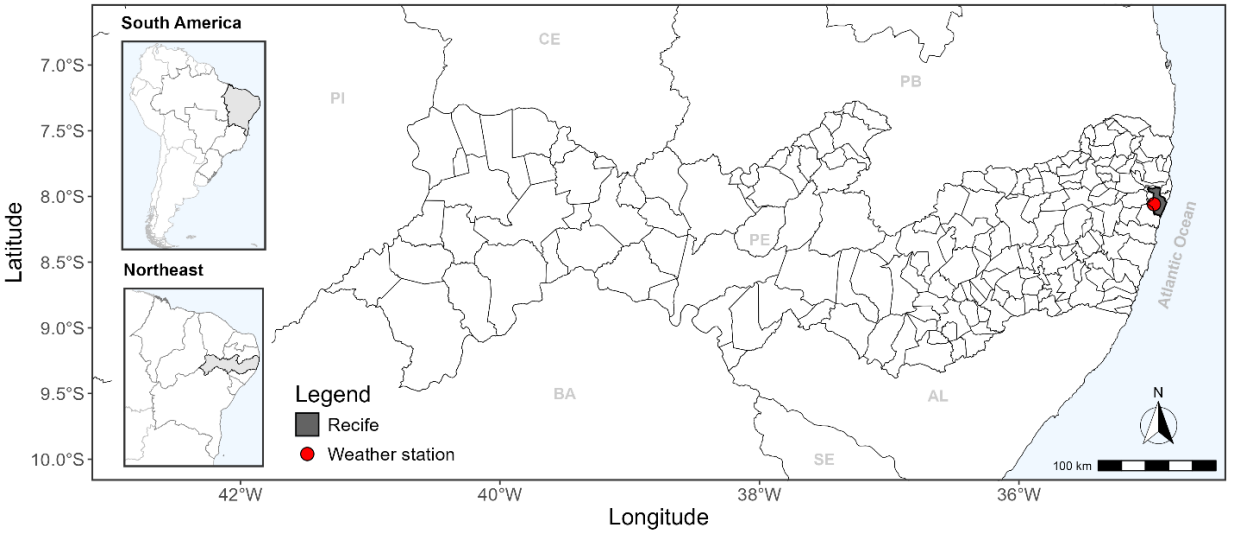

Figure 1. Map of Brazil showing the location of Pernambuco State and the Recife weather station.

The data used in this study consist of monthly accumulated precipitation records from the Curado weather station in Recife (latitude: 8.03°S, longitude: 34.55°W; altitude: 7 m), spanning the period from July 1961 to December 2020. These records were obtained from the National Water Agency (Agência Nacional de Águas – ANA, 2025).

Methods

Precipitation Concentration Index

The Precipitation Concentration Index (PCI), introduced by Oliver (1980) quantifies the degree to which annual precipitation is distributed over 12 months of the year. It is defined as:

$$PCI_a = \left[\left(\sum_{i=1}^{12} p_i^2\right) \Big/ \left(\sum_{i=1}^{12} p_i\right)^2\right] \times 100,$$

where p_i represents the monthly precipitation in month i. When applied to the full annual dataset, it results in one time series representing annual PCI values. Theoretically, PCI values range from 8.33 (indicating uniform monthly precipitation) to 100 (indicating that all annual precipitation occurs in a single month).

PCI can also be calculated for each season of year using:

$$PCI_s = \left[\left(\sum_{i=1}^{3} p_i^2\right) \Big/ \left(\sum_{i=1}^{3} p_i\right)^2\right] \times 25,$$

which produces four time series, one for each season: summer (Dec - Jan - Feb), autumn (Mar - Apr - May), winter (Jun - Jul - Aug) and spring (Sep - Oct - Nov). The theoretical range for seasonal PCI values is 8.33 to 25, with higher value indicating that total precipitation occurs within a single month of the season.

Additionally, PCI can be calculated on a supra-seasonal scale, distinguishing between wet and dry periods (De Luis et al., 2011):

$$PCI_{ss} = \left[\left(\sum_{i=1}^{6} p_i^2\right) \Big/ \left(\sum_{i=1}^{6} p_i\right)^2\right] \times 50$$

which produces two time series, one for the wet season (March to August) and another for the dry season (September to February). Theoretical values range from 8.33 to 50. The higher value is obtained when total precipitation occurs within a single month of the season.

The classification of rainfall regime based on PCI values is presented in Table 1.

Table 1. Classification of the precipitation distribution based on Precipitation Concentration Index values (Oliver, 1980).

Precipitation distribution	Class	PCI
Uniform	I	[8.33, 10]
Moderate	II	(10, 15]
Irregular	III	(15, 20]
Strongly irregular	IV	(20, PCI_{MAX}*]

*Maximum possible values of PCI are equal to 100 (for PCI_a), 25 (for PCI_s), 50 (for PCI_{ss}).

Seasonality index

To assess rainfall seasonality and its interannual variability, three complementary indices are used: the general seasonality index *(denoted as $\overline{SI}$)* , the individual seasonality index *(SI_i)*, and the replicability index *(RI)*. Their definitions and interpretations are outlined below, following the methodology of (Walsh & Lawler, 1981).

The general seasonality index $\overline{SI}$ quantifies the average deviation of monthly precipitation from a uniform distribution over the entire study period. It is defined as:

$$\overline{SI} = \frac{1}{\overline{P}} \sum_{n=1}^{12} \left| \overline{p_n} - \frac{\overline{P}}{12} \right|,$$

where $\overline{p_n} = \frac{1}{N}\sum_{i=1}^{N} p_{in}$ is the mean precipitation in month n over N years, $\overline{P} = \frac{1}{N}\sum_{i=1}^{N} P_i$, is the mean annual precipitation, p_{in} is the precipitation in month n of year i and P_i is the total annual precipitation in year i. Theoretically $\overline{SI}$ ranges from 0 (uniform monthly distribution) to approximately 1.83 (total annual precipitation occurs in a single month). The classification of rainfall regime based on $\overline{SI}$ is presented in Table 2.

Individual seasonality index SI_i is defined as

$$SI_i = \frac{1}{P_i} \sum_{n=1}^{12} \left| p_{in} - \frac{P_i}{12} \right|,$$

where p_{in} is the precipitation amount in month n and year i and $P_i = \sum_{n=1}^{12} p_{in}$ the total precipitation in year $i = 1,...,N$ (N is the number of years of the analyzed period). This index is designed to assess the variability of the rainfall regime year-to-year. The values of SI_i vary from zero (when the same amount of monthly precipitation p_{in} occurs in each month) to 1.83 (when total annual precipitation occurs in a single month).

Mean individual seasonality index $\overline{SI_i}$ is obtained by averaging the values of SI_i over the analyzed period:

$$\overline{SI_i} = \frac{1}{N} \sum_{i=1}^{N} SI_i,$$

Table 2. Rainfall regimes classification based on $\overline{SI}$ classes (Walsh & Lawler, 1981).

Rainfall regime	Class	SI
Very equitable	I	≤ 0.19
Equitable with a definite wetter season	II	(0.19, 0.39]
Rather seasonal with a short drier season	III	(0.39, 0.59]
Seasonal	IV	(0.59, 0.79]
Markedly seasonal with a long drier season	V	(0.79, 0.99]
Most rain in a maximum 3 months or less	VI	(0.99, 1.19]
Extreme seasonality, almost all rain in 1-2 months	VII	> 1.19

where N is the number of years of the considered period and SI_i is the individual seasonality index of year i.

Replicability Index RI is defined as the ratio between the general seasonality index and the mean individual seasonality index:

$$RI = \frac{\overline{SI}}{\overline{SI_i}}$$

This index quantifies the degree of variability in rainfall regimes over time. The averages $\overline{p_n}$ and $\overline{P}$ used to calculate $\overline{SI}$, smooth out interannual fluctuations in monthly precipitation, thereby underestimating year-to-year seasonality. As a result, $\overline{SI} \leq \overline{SI_i}$, if the mean precipitation regime were identical each year, with consistent months of maximum and minimum rainfall, then $RI = 1$, indicating perfect replicability ($\overline{SI} = \overline{SI_i}$). In practice, a high RI implies that the month of maximum rainfall is concentrated within a narrow temporal window, reflecting a highly replicable rainfall regime. Conversely, a low RI suggests that the peak rainfall month varies widely across years, indicating low replicability in seasonal patterns (Walsh & Lawler, 1981; Livada & Asimakopoulos, 2005).

The modified Mann-Kendall (MMK) test

In this study we applied the Mann-Kendall test modified by effective sample size (MMK), as proposed by Yue & Wang (2004), to detect trends in serially correlated hydrological series. Compared to the classical Mann–Kendall (MK) test (Kendall, 1975; Mann, 1945), the MMK approach effectively reduces bias introduced by autocorrelations, while preserving the original MK test's robustness, non-parametric and distribution-free properties. A detailed description of the MMK procedure is provided in (Stosic et al., 2024), and all the calculations were performed using open-source software tools (Patakamuri & O'Brien, 2021; R Core Team, 2023).

Results and Discussion

Seasonal analysis

Figure 2 shows the annual precipitation values alongside the long-term mean. Periods of below-average rainfall are evident during major drought episodes in NEB, in 1979–1981, 1982–1983, 1992–1993, 1997–1998, 2010, and 2012–2016 (Marengo et al., 2017). In contrast, above-average precipitation observed in 2000 and 2011 coincides with La Niña events, which are typically associated with increased rainfall in the region (CPTEC/INPE, 2025).

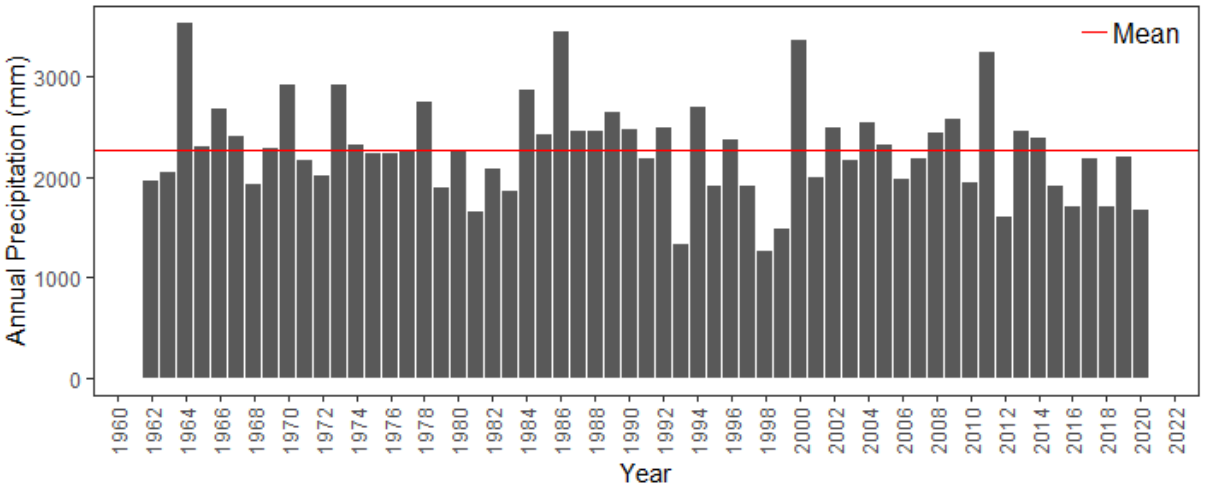

Figure 2. Annual precipitation totals for the period January 1962 to December 2020. The long-term mean of 2,270.9 mm is indicated by the red line.

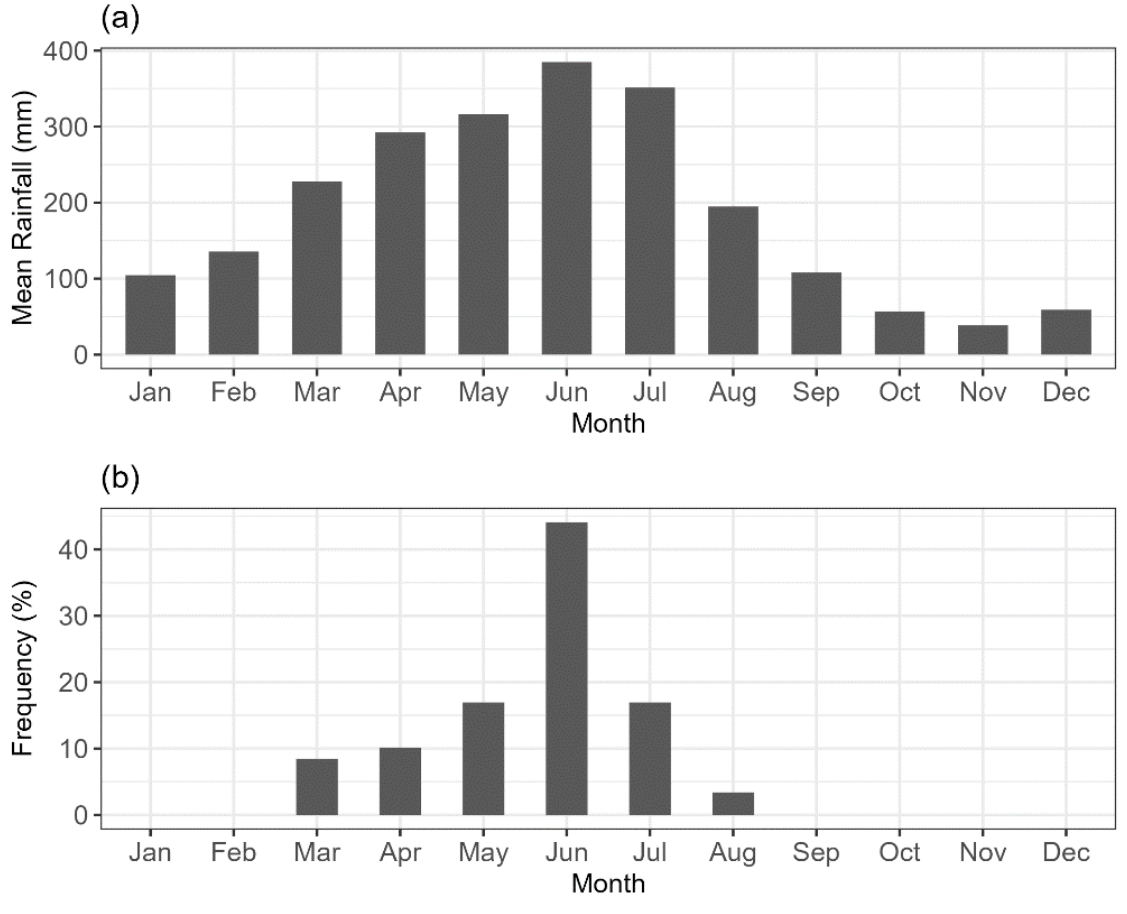

Figure 3. (a) Mean monthly precipitation for the period from 1962 to 2020, (b) Percentage frequency of the month with maximum rainfall between 1962 and 2020.

The mean monthly precipitation and the percentage frequency of the month with maximum precipitation are presented in Figure 3.

Figure 3a shows that the wet season extends from March to August, corresponding to the six months with the highest mean monthly precipitation. During this period, an average of approximately 1,769 mm is accumulated, representing about 78% of the annual mean (2,270.9 mm). The trimester October–November–December, on the other hand, exhibited the lowest mean rainfall, with only about 154 mm accumulated. The wettest period is further confirmed in Figure 3b, which indicates that, from 1962 to 2020, the months of maximum rainfall occurred exclusively between March and August, with the highest frequency in June (over 40% of all years).

Precipitation concentration index

Figures 4–6 show the time series of the Precipitation Concentration Index (PCI) at three temporal scales for 1962–2020: annual (Fig. 4), seasonal (Fig. 5), and supra-seasonal (Fig. 6). In each graph, dashed lines indicate the four PCI classification categories defined in Table 1: uniform (I), moderate (II), irregular (III), and strongly irregular (IV) precipitation distribution.

Annual scale

Figure 4 shows the results of the Precipitation Concentration Index on an annual scale *(PCI_a)* for the period 1962–2020. The precipitation distribution is predominantly classified as moderate (Class II), with a mean value of approximately $\overline{PCI_a} \approx 13.58$, although occasional irregular events are observed. The most irregular precipitation distribution, indicated by the highest annual PCI value (PCI_a= 17.78, Class III), occurred in 2005, when severe drought occurred in the Northeast region (Marengo et al., 2017). The three consecutive years 2015, 2016, and 2017, with irregular precipitation distribution, belong to the period of the multiyear drought (2011–2017) in the Northeast, which was the most extreme in decades (Cunha et al., 2019).

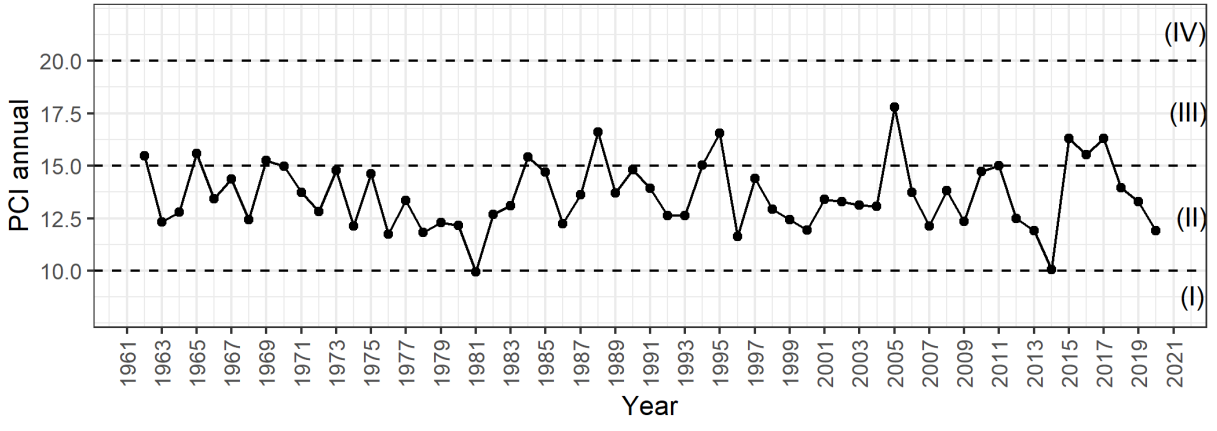

Figure 4. Time series of the precipitation concentration index on annual scale *(PCI_a)* for the period between 1962 and 2020. Dashed lines delimit the classes of the precipitation distribution (I: uniform, II: moderate, III: irregular, IV: strongly irregular) as defined in Table 1.

Seasonal scale

Figure 5 presents the seasonal time series of the Precipitation Concentration Index *(PCI_s)*. In summer (Figure 5a), for most of the period, precipitation had a moderate distribution (Class II). Irregular distribution (Class III) occurred in only five years: 1962, 1965, 1980, 2006, and 2009, with the highest PCI_s value recorded in 1965 (PCI_s = 18.3). The remaining years mainly fell into the uniform distribution category (Class I), with the lowest PCI_s value of 8.4 in 2015.

Between 2012 and 2020, the range of PCI_s values narrowed significantly, from a minimum of 8.41 in 2015 to a maximum of 10.62 in 2013, indicating a marked reduction in variability. This pattern suggests that, after 2011, the summer season maintained a relatively stable and regular precipitation regime, trending towards or remaining within the uniform distribution class.

Figures 5b and 5c show the seasonal PCI time series for autumn and winter, respectively. Both seasons exhibit similar behavior, with precipitation distributions mainly falling between uniform (Class I) and moderate (Class II). The highest PCI_s value for autumn was recorded in 2005 (PCI_s = 12.9), while for winter it occurred in 1965 (PCI_s = 12.7), both identified as drought years in NEB (Marengo et al., 2017). A notably stable period is observed in the autumn PCI_s series from 1976 to 1981, characterized by consistently uniform precipitation distribution and a narrow range of PCI_s values. These results are expected, as the period from March to August, which overlaps with the autumn and winter seasons in Recife, corresponds to the region's wet season, thereby contributing to a more evenly distributed rainfall pattern.

Figure 5d presents the PCI time series for the spring season. The values of PCI_s indicate precipitation distributions ranging between uniform (Class I) and irregular (Class III), with a predominance of years classified as moderate (Class II). Notably, clusters of similar PCI_s values are observed during 1985–1987, 1997–1999, and 2004–2006, suggesting periods of relative stability in rainfall distribution. From 2001 to 2020, the precipitation regime remained consistently within Class I and Class II, indicating a sustained trend toward uniform to moderately distributed rainfall during spring in the latter part of the study period.

Supra-seasonal scale

Figure 6 presents the time series of the Precipitation Concentration Index on a supra-seasonal scale (PCI_{ss})

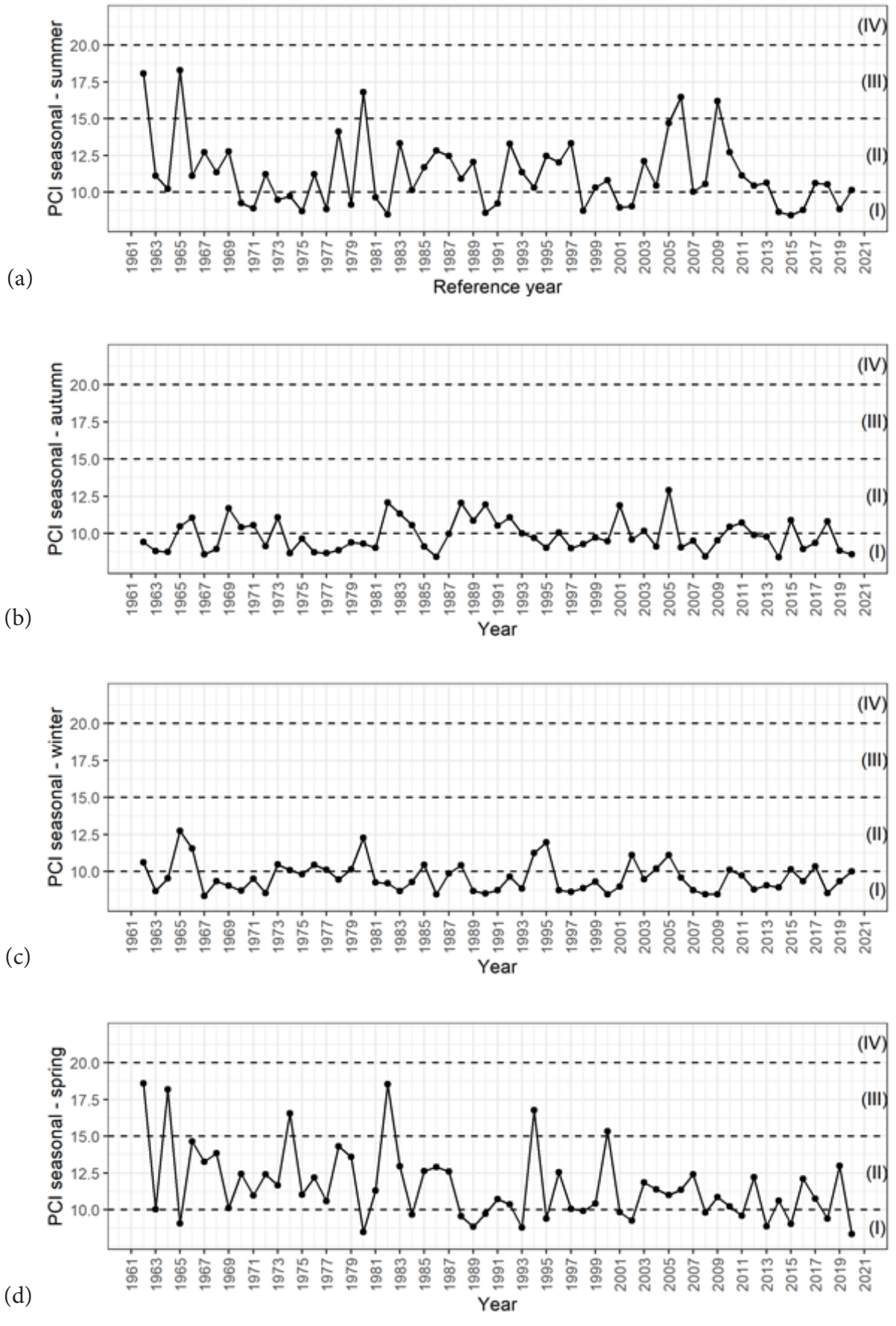

Figure 5. Time series of the precipitation concentration index on a seasonal scale (PCI_s) for the period between 1962 and 2020: (a) summer (Dec - Jan - Feb), (b) autumn (Mar - Apr - May), (c) winter (Jun - Jul - Aug), (d) spring (Sep - Oct - Nov). Dashed lines indicate the thresholds between the precipitation distribution classes (I: uniform, II: moderate, III: irregular, and IV: strongly irregular) as defined in Table 1.

for the period 1962–2020. The supra-seasonal classification distinguishes the wet season (March to August) from the dry season (September to February). The results reveal a clear separation between the two regimes, with blue dots representing the wet season and red dots the dry season.

During the wet season, precipitation concentration generally ranged between uniform (Class I) and moderate (Class II). The lowest PCI_{ss} value (8.5) was recorded in 2008, coinciding with a La Niña episode, which typically brings increased rainfall to Northeastern Brazil (NEB) (CPTEC/INPE, 2025).

In contrast, the dry season showed a more variable precipitation distribution, predominantly within the moderate category (Class II). Uniform distribution (Class I) was observed in only three years: 1981 (PCI_{ss}= 9.26), 1990 ($PCIss$ = 8.80), and 2014 (PCI_{ss} = 8.83). Notably, 2009 stands out with a strongly irregular distribution (Class IV), marked by the highest $PCIss$ value of 21.68, indicating a highly concentrated and uneven rainfall pattern during that dry season, which could be related to the El Niño episode in 2009–2010 (CPTEC/INPE, 2025).

Table 3 shows the percentage of years classified in each PCI distribution class across different temporal scales for 1962–2020. Notably, no years showed a strongly irregular precipitation distribution (Class IV), except for one year (1.69%) during the dry season. Similarly, irregular distribution (Class III) was absent in the wet season, autumn, and winter, indicating a predominance of moderate (Class II) and uniform (Class I) rainfall patterns across these scales.

The highest percentage of years with moderate precipitation distribution (Class II) was observed on the annual scale and during the dry season, both at 79.66%. In contrast, the lowest percentage of moderate distribution occurred in winter (32.20%), when precipitation was predominantly uniform (Class I) in 67.8% of the years, representing the highest frequency of uniform distribution across all scales. Conversely, the annual scale showed the lowest frequency of uniform distribution, with only one year (1.69%) classified as Class I.

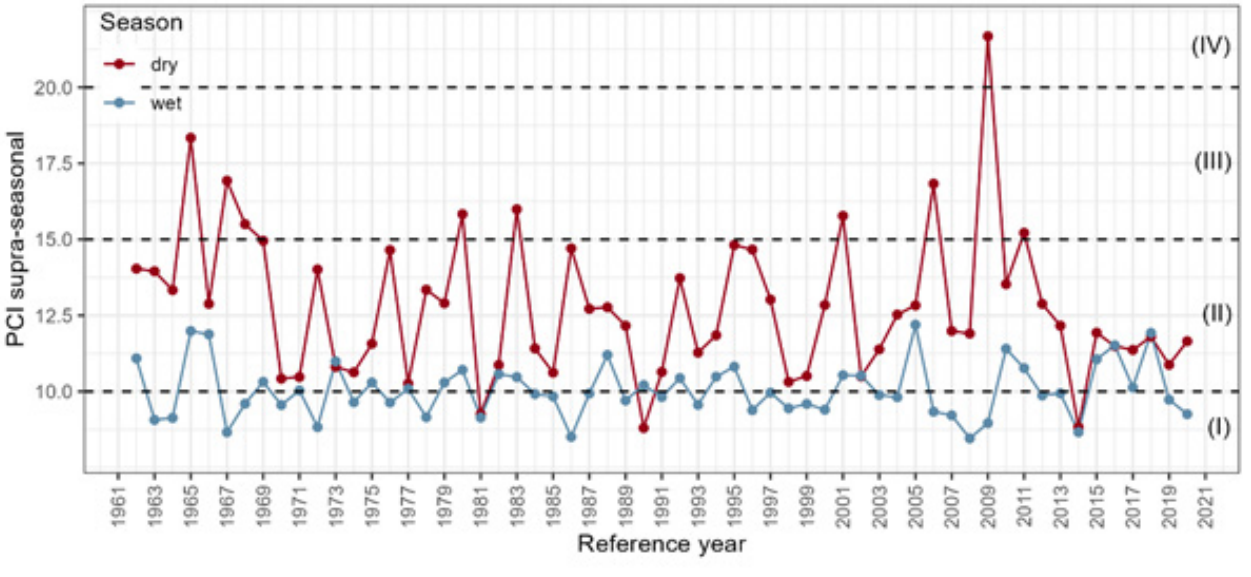

Figure 6. Time series of the Precipitation Concentration Index on a supra-seasonal scale (PCI_{ss}). Dashed lines indicate the thresholds between the precipitation distribution classes (I: uniform, II: moderate, III: irregular, and IV: strongly irregular), as defined in Table 1.

To investigate potential trends and their magnitudes in the PCI time series at annual (Fig. 4), seasonal (Fig. 5), and supra-seasonal (Fig. 6) scales, the Mann-Kendall test and Sen's slope estimator were applied. The results are summarized in Table 4. Based on the p-value (pv), no statistically significant trends were detected, except for the spring season, which exhibited a significance level below 1%. The negative sign of Q_{med} (or Z) indicates a downward trend, with a Sen's slope magnitude of $Q_{med} = 0.0466$.

Spring corresponds to the dry season in Recife, and this negative trend suggests a gradual shift towards a more uniform rainfall distribution, potentially indicating a reduced risk of drought events during this period.

Table 3. Percentage of years in each class of precipitation distribution according to the Precipitation concentration index (PCI) on annual (PCI_a, Fig.4), seasonal (PCI_s, Fig.5), and supra-seasonal (PCI_{ss}, Fig.6) scales.

Class of precipitation distribution (based on PCI)	Annual (%)	Seasonal (%)				Supra-seasonal (%)	
		Summer (Dec-Feb)	Autumn (Mar-May)	Winter (Jun-Aug)	Spring (Sep-Nov)	Dry (Sep-Feb)	Wet (Mar-Aug)
I – Uniform	1.69	30.51	61.02	67.8	28.81	5.08	55.93
II – Moderate	79.66	61.02	38.98	32.2	61.02	79.66	44.07
III – Irregular	18.64	8.47	0	0	10.17	13.56	0
IV – Strongly irregular	0	0	0	0	0	1.69	0

Table 4. Results of the Mann-Kendall test (significance level α = 5%) and Sen's slope estimator applied to the Precipitation Concentration Index (PCI) time series on annual (PCI_a; Fig. 4), seasonal (PCI_s; Fig. 5) and supra-seasonal (PCI_{ss}; Fig. 6) scales.

Timescale	Mann-Kendall test			Sen's slope
	p-value (*pv*)	*Z*	Trend test	Q_{med}
Annual PCI_a	0.9583	-0.0523	Negative non-significant	-0.001
Seasonal PCI_s				
Summer (Dec - Feb)	0.2189	-1.2294	Negative non-significant	-0.0169
Autumn (Mar - May)	0.9896	0.0131	Positive non-significant	6.83E-05
Winter (Jun - Aug)	0.4403	-0.7717	Negative non-significant	-0.0057
Spring (Sep - Nov)	0.0042	-2.8643	Negative significant	-0.0466
Supra-seasonal PCI_{ss}				
Dry season (Sep - Feb)	0.1779	-1.3471	Negative non-significant	-0.0255
Wet season (Mar - Aug)	0.824	0.2223	Positive non-significant	0.0021

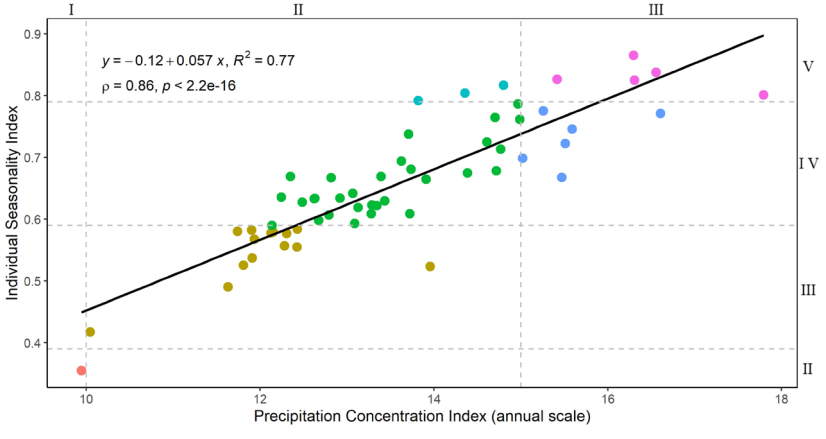

Figure 8. Scatter diagram of the individual seasonality index (SI_i) plotted against the annual Precipitation Concentration Index (PCI_a), including the linear regression line (black). Each color represents a distinct pair of corresponding rainfall regime classes (based on SI_i) and precipitation distribution classes (based on PCI_a) that occurred simultaneously in the same year.

Seasonality index

Figure 7 presents the time series of the individual seasonality index SI_i with dashed lines marking the thresholds between rainfall regime classes as defined in Table 2. The results indicate year-to-year variability mainly between Class III (rather seasonal with a short drier season) and Class V (markedly seasonal with a long drier season). Of the 59 years analyzed, 36 years (61.02%) fell into Class IV (seasonal), 14 years (23.73%) into Class III, and 8 years (13.56%) into Class V, resulting in an average $\overline{SI_i} \approx 0.66$, which corresponds to Class IV. An exception occurred in 1981, when the SI_i value of 0.35 placed the year in Class II, indicating a more equable rainfall regime with a definite wetter season.

The general seasonality index ($\overline{SI} \approx 0.56$) indicates that the mean rainfall regime in Recife over the entire period (1962–2020) was fairly seasonal with a short dry season, corresponding to Class III, but close to the threshold between Classes III and IV. As previously noted, it is expected that $\overline{SI_i} > \overline{SI}$, since the formulation of the general index tends to smooth interannual variability, thereby underestimating year-to-year seasonality.

The Mann-Kendall test applied to the SI_i time series (Fig. 7) revealed no statistically significant trend *(pv ~ 0.92)* at the α = 5% significance level. This result indicates that the annual rainfall regime in Recife continues to oscillate between Class III (rather seasonal with a short drier season) and Class V (markedly seasonal with a long drier season), with the mean $\overline{SI_i}$ falling within Class IV (seasonal).

The replicability index (*RI*), calculated as the ratio $\overline{SI}/\overline{SI_i}$ yielded *RI* = 0.85, suggesting a highly replicable rainfall regime (Livada & Asimakopoulos, 2005). This interpretation is supported by two key observations: i) the percentage frequency of the month with maximum rainfall (Fig. 3b) shows that, on average, peak precipitation is concentrated in a few months, most notably in June; ii) the year-to-year variability in SI_i values is relatively narrow, with fluctuations primarily between Classes III and IV.

Together, these findings, along with the high RI value, indicate that the mean rainfall regime in Recife shows a high degree of replicability, characterized by consistent seasonal patterns and limited interannual variability.

Figure 8 shows the scatter diagram of the individual seasonality index (SI_i) as a function of the annual Precipitation Concentration Index (PCI_a). Dashed lines delineate the classes of annual rainfall regimes (based on SI_i values, shown on the right) and precipitation distribution classes (based on PCI_a values, shown at the top). Color coding distinguishes between the different classes.

The diagram reveals a clear linear relationship between SI_i and PCI_a indicating that SI_i increases proportionally with PCI_a. This implies that a uniform precipitation distribution (low PCI_a) corresponds to a very equable rainfall regime (Class I), while a strongly irregular precipitation distribution (high PCI_a) is associated with extreme seasonality (Class VII), where most rainfall is concentrated in only one or two months. The Spearman correlation analysis confirms this relationship, yielding a correlation coefficient of ρ = 0.86, which indicates a strong positive association between the two indices.

Implications for urban planning and climate adaptation

The results of this study provide new information about the precipitation regime of Recife and have direct implications for urban resilience and climate adaptation strategies. The rainfall regime was characterized as rather seasonal with a short dry season and exhibited a high degree of replicability (RI = 0.85), indicating that the temporal distribution of precipitation is relatively stable from year to year. This behavior is consistent with the climatological characteristics of the eastern coast of northeastern Brazil (ENEB) where rainfall is strongly influenced by large-scale atmospheric systems and ocean–atmosphere interactions. Among the main atmospheric systems related to rainfall seasonality in ENEB are the Upper-Tropospheric Cyclonic Vortices – UTCV, Intertropical Convergence Zone - ITCZ), Cold Fronts and Easterly Wave Disturbances – EWD (Lyra et al., 2024).

The predominance of moderate precipitation concentration at the annual scale and the lower concentration of rainfall during autumn and winter agree with previous studies which have reported a marked wet season from March to August (Coutinho et al., 2016). The absence of significant long-term trends in most PCI and SI series suggests that the overall rainfall regime in Recife remained relatively stable during the study period. However, the significant negative trend detected in spring PCI indicates a gradual reduction in precipitation concentration during this season, which may reflect subtle changes in intra-annual rainfall distribution. The absence of statistically significant trend in annual PCI and SI in Recife was also found in recent studies (Silva et al., 2022; da Silva Araújo et al., 2023).

From a practical perspective, these findings support several adaptation measures. First, stormwater drainage systems and urban flood-control infrastructure should be designed and maintained considering the concentration of rainfall during peak months, particularly June, when flood risks are greatest. Second, water storage and supply systems can be designed according to replicable and relatively predictable seasonal rainfall regime, ensuring water capture during wet months and adequate reserves during drier periods. Third, the observed changes in spring precipitation concentration suggest the need for adaptive planning in sectors de-

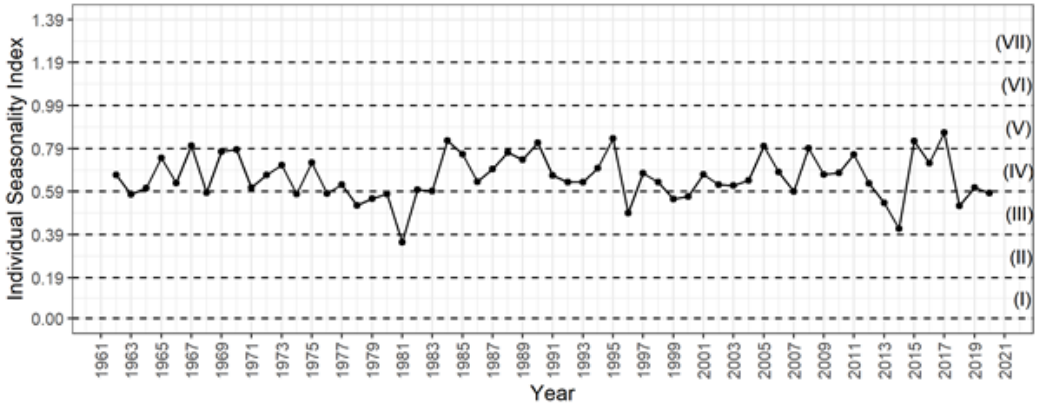

Figure 7. Time series of the individual seasonality index SI_i. Dashed lines represent the thresholds separating rainfall regime classes (I – VII), as defined in Table 2.

pendent on seasonal rainfall, including agriculture and water-resource management.

The methodology adopted in this study offers several advantages. The combined use of PCI, SI, and RI provides a comprehensive assessment of precipitation distribution, seasonality, and temporal consistency. In addition, the Mann–Kendall test and Sen's slope estimator are robust non-parametric techniques that are widely used for detecting climatic trends because they are less sensitive to outliers and do not require normally distributed data. The application of these complementary indices enabled a detailed characterization of Recife's rainfall regime across multiple temporal scales.

Nevertheless, some limitations should be acknowledged. The analysis was based on precipitation records from a single location, which may not fully capture spatial variability across the metropolitan region of Recife. Future studies could integrate spatial datasets, climate-model projections, and the influence of large-scale climate drivers such as the El Niño–Southern Oscillation (ENSO) and Atlantic sea-surface temperature variability.

Overall, the results demonstrate that while Recife's precipitation regime remains relatively stable, ongoing monitoring is necessary to detect emerging changes in rainfall seasonality and concentration that could affect urban infrastructure, water security, and climate adaptation planning.

Conclusions

This study investigated precipitation variability in Recife, Pernambuco, Brazil, from July 1961 to December 2020, focusing on precipitation distribution and seasonality. Monthly precipitation data were analyzed using the Precipitation Concentration Index (PCI) at annual, seasonal, and supra-seasonal scales, together with the Seasonality Index (SI) and the Replicability Index (RI). Temporal trends were assessed using the Mann–Kendall test and Sen's slope estimator, while the relationship between precipitation concentration and seasonality was evaluated through Spearman correlation analysis.

The results showed that precipitation distribution at the annual scale was predominantly moderate (79.66% of the years) with a mean annual PCI of approximately 13.58. Rainfall regime ranged from rather seasonal with a short dry season to markedly seasonal with a long dry season, with seasonal conditions prevailing in 61.02% of the years. The high RI value (0.85) indicated strong interannual consistency in rainfall seasonality, demonstrating that Recife's precipitation regime is relatively predictable. The highest variability in precipitation concentration was observed during the dry season and in summer and spring, whereas autumn and winter generally exhibited more uniform precipitation distribution. Trend analysis revealed no significant changes in both precipitation indices, except for a significant negative trend in spring PCI, suggesting a gradual decrease in precipitation concentration during that season. The strong positive correlation between annual PCI and SI confirmed the close relationship between rainfall concentration and seasonality.

The methodology employed in this study proved effective for characterizing rainfall variability and seasonality across multiple temporal scales. The combined application of PCI, SI, RI, and non-parametric trend analysis provided a robust framework for understanding precipitation dynamics and identifying potential changes in rainfall behavior relevant to climate adaptation and water-resource management.

The findings contribute directly to several United Nations Sustainable Development Goals (SDGs) (United Nations, 2015). In particular, they support SDG 6 (Clean water and sanitation) by providing information that can improve water-resource planning, storage strategies, and sustainable water management. The results also contribute to SDG 11 (Sustainable cities and communities) by supporting the design of resilient urban drainage systems and flood-risk reduction measures. Furthermore, the study contributes to SDG 13 (Climate action) by enhancing the understanding of rainfall variability and seasonality, thereby supporting

evidence-based climate adaptation and resilience planning. Consequently, the research provides valuable scientific information for policymakers, urban planners, and water managers seeking to strengthen climate resilience and sustainable development in Recife and other tropical coastal cities.

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