

Spatial and temporal rainfall variability in the Caribbean coast of Costa Rica

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Abstract

Rainfall in the moist Tropical Caribbean region (MTCR) in Costa Rica occurs practically throughout the year, with the quarters June–August (JJA) and December–February (DJF) concentrating over 70% of annual rainfall. On the other hand, in March–April and September–October, it rains below 100mm per month. This seasonal rainfall behavior makes the region ideal for producing bananas (*Musa spp*) and pineapple (*Ananas comosus*) for export (10% and 8% of total exports in 2021, respectively). A national-scale study determined that agriculture in the MTCR is one of the most vulnerable sectors to climate changes. However, the climate in this region has been poorly studied so far. This research analyzed the spatial and temporal variability of annual, monthly, and seasonal (DJF, JJA, SO) rainfall in the MTCR and how they change in the study period based on quality-checked series of daily rainfall from 28 weather stations in two periods: 1985–2009 and 1997–2019. The results show that rainfall regimes in the region are variable in space and throughout the year, with peaks occurring close to the mountain range and minimum values close to the coast. Trends were statistically significant in the period 1985–2009 with a predominance of significant positive trends in DJF, and significant negative trends in SO. No significant trends (positive or negative) were observed in the period 1997–2019. JJA rainfall has uneven regional distribution and presents a positive and significant trend in the mountain region. This paper contributes to filling the knowledge gap in rainfall seasonality, variability, and trends in a region where banana and pineapple commercial plantations are fundamental to the country's economy thus providing information to decision-making in the agri-food sector to reduce the negative impacts of changing rainfall regimes.

1. Introduction

The moist Tropical Caribbean region (MTCR) in the Caribbean watershed of Costa Rica stretches over 23 130 km², i.e., almost half the national territory (51 179 km²). The country is strategically located between the Pacific Ocean and the Caribbean Sea (CS) in Central America. Large-scale processes that originate in those two water bodies have a major influence on the Central American climate.

In addition, the complex topography of the Central American isthmus interacts with the northeasterly trade winds that are associated with the North Atlantic anticyclone (Amador 1998). Such interaction induces spatial climate variations that may lead to opposite behaviors over the Pacific and the Caribbean watersheds (Quesada and Waylen 2020). The trade winds play an important role in the seasonal variability of climate variables (Alfaro 2002; Taylor and Alfaro 2005; Poveda et al. 2014).

The regional rainfall patterns in Central America are determined by trade winds that play a relevant role in the transport of moisture from the CS. There is also influence from low-level winds associated with the Caribbean Low-Level Jet (CLLJ) (Amador 2008) and from low-level winds from the Eastern Tropical Pacific (ETPac) in the west that are associated with the Chocó Jet (CJ) (Poveda and Mesa 2000). Their role in modulate rainfall patterns and their connectivity with large-scale features such as the Intertropical Convergence Zone (ITCZ) has been extensively studied (Cook and Vizy 2010; Durán-Quesada et al. 2017; Hidalgo et al. 2015).

Specific to Costa Rica, the rainfall in the Pacific watershed has bimodal behavior, with a well-defined dry season in the boreal winter (December–March), which in some areas extends to April, and a rainy season with two rainfall peaks, one in May–June and the other one (generally more intense) in September–October. Between the two rainfall peaks, a period of decreased rainfall occurs in July–August, which is called Mid-Summer Drought (MSD), and is locally known as *veranillo* or *canícula* (Amador 2008; Magaña et al. 1999; Maldonado et al. 2016). The spatial and temporal variability of the rainfall in this slope has been extensively studied (e.g., Alfaro and Hidalgo 2021; Maldonado et al. 2018; Quesada and Waylen 2013; Retana 2012). Mainly in the last decade, progress has been made in the analysis of extreme events (AlMutairi et al. 2019; Quesada-Hernández et al. 2020; Quesada-Montano et al. 2019).

On the other hand, the Caribbean watershed has no defined dry season. The rainfall does not vary much between January and the middle of October. This period accounts for approximately 60% of the annual total in this region. From mid-October onwards there is a marked increase in rainfall accumulation of between 400 and 600 mm per month (Taylor and Alfaro 2005). This annual cycle presents a spatial variation from warm subhumid with low rainfall in the northwest of the region to excessively wet and cold climate in the mountain area (Pérez-Briceño et al. 2017). Although the region lacks a defined dry season there are two periods of significant rainfall decrease in March–April and in September–October (Alfaro 2002; Alfaro and Hidalgo 2021; Sáenz and Amador 2016).

The Caribbean watershed has a growing industrial and port activity, likewise recreation activities. It is one of the main tourist destinations in the country, due to its landscapes and the natural beauty of its beaches and reefs (Piedra-Castro et al. 2021). In the other hand, supports extensive agricultural activity (Quesada and Waylen 2020). The climate features acting on the Caribbean coastal plain give rise to ideal conditions for the production of bananas (*Musa spp.*) and pineapple (*Ananas comosus*). Both are the main export crops of Costa Rica and represent 39% and 31%, respectively of the agri-food sector export, or 10% and 8% of total exported goods (PROCOMER 2021). However, according to Bouroncle et al. (2015), the agri-food sector in this region is the most vulnerable economic sector to climate changes.

The temporal rainfall variability has not been studied in detail on the Caribbean slope. The literature includes works such as that of Quesada and Waylen (2020), which analyse the daily rainfall series from individual station and long record (Limón and 1949–2017); or Alfaro (2002), in his study of Central America, includes few meteorological stations located in the CS for at least 20 years (1950–1994).

The climate variability creates conditions that may exceed the adaptive capacity of the activities that depend on it, which can lead to social vulnerability and economic losses. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change mentions that human-induced climate change is already affecting many weather and climate phenomena, mainly extremes. These include an increase in the frequency and intensity of extreme precipitation events (excesses/deficits) (IPCC 2021).

In the study region, the spatial behaviour and temporal variability of precipitation in recent decades is unknown. To address this issue, the objective of this research is to analyse the spatial and temporal variability of annual, monthly, and seasonal (DJF, JJA, and SO) rainfall, and how they change in the study

period. The interest in these seasons lies in the fact that they are critical periods for pineapples and banana crops (Serrano et al 2018; Soto 2014).

2. Data And Methodology

2.1. Observational data

This paper examined daily rainfall series from initially 40 weather stations covering the longest period from 1943 to 2019 (Fig. 1). Data were provided by the National Weather Institute (IMN, by its Spanish acronym) of Costa Rica and the Costa Rican Electricity Institute (ICE, by its Spanish acronym). Quality and consistency controls made it possible to identify gaps in the time series of some weather stations, as well as inconsistent (negative) values and outliers. We removed negative values and checked the validity of outliers by analyzing daily and monthly data from nearby stations and information from monthly meteorological IMN newsletters. Finally, after determining the number of missing data in each series, we excluded from the study the stations with 10–15% missing data, according to the criteria set by the World Meteorological Organization (WMO 2003).

Table 1 shows the period, location, and altitude above sea level of the 28 weather stations included in the study (Fig. 1). The longest period common to 24 stations is 1985–2009. Four stations are located in areas of pineapple or bananas cultivation and have uninterrupted observations from 1997 to 2019. Specific statistical analysis of these four stations was performed and compared to nearby stations in the 1985–2009 records. Since no particular issues were observed, the data were included in the climatological analysis of the study area.

Table 1
Name, location, altitude, and record periods of the weather stations analyzed

Station name	Latitude (°N)	Longitude (°W)	Altitude (masl)	Period
Hacienda El Carmen	10.20	-83.48	15	1972–2013
La Mola	10.34	-83.67	70	1980–2010
La Lola	10.09	-83.39	40	1949–2013
La Montura	10.11	-83.97	1146	1985–2010
Siquirres	10.11	-83.50	68	1985–2018
Guayabo	9.97	-83.69	1003	1985–2017
Limón	9.96	-83.03	5	1943–2019
Hitoy Cerere	9.68	-83.02	100	1982–2019
Puerto Vargas	9.73	-82.82	11	1977–2015
Pacuare	9.82	-83.52	798	1985–2018
Pacuar	9.92	-83.56	721	1985–2018
Sixaola Day	9.53	-82.64	10	1985–2019
San Jorge	10.72	-84.67	55	1980–2009
San Miguel	10.32	-84.18	500	1960–2010
Quebrada Azul	10.40	-84.47	83	1962–2019
La Selva	10.43	-84.00	40	1971–2019
San Vicente	10.29	-84.38	1640	1973–2019
Pital	10.46	-84.28	150	1974–2010
Santa Clara	10.36	-84.51	170	1984–2018
Piedades Sur	10.12	-84.54	1020	1984–2017
Zarcero	10.19	-84.40	1736	1950–2019
Bajos del Toro	10.21	-84.30	1449	1985–2018
Presa Sangregado	10.48	-84.76	547	1985–2018
Cantagallo*	10.50	-83.67	20	1996–2019
Upala*	10.88	-85.07	60	1997–2019
Comando Los Chiles*	11.03	-84.71	40	1995–2019

*Stations located in priority areas for banana and pineapple cultivation.

Station name	Latitude (°N)	Longitude (°W)	Altitude (masl)	Period
Coopevega*	10.72	-84.40	100	1996–2019
El Bum	10.66	-84.00	59	1985–2018
*Stations located in priority areas for banana and pineapple cultivation.				

2.2. Methodology

This study analyzed annual, monthly, and seasonal (DJF, JJA, SO) high-quality rainfall data from 28 weather stations. The climatological analysis was based on the mean, median, standard deviation, and the 25th and 75th percentiles of the rainfall series. In addition, we determined the contribution of seasonal rainfall to annual totals. The spatial analysis was made with the spline with barriers interpolation method. This minimum curvature method makes it possible to analyze information from regions with natural barriers (orography, lakes, and rivers) or surface discontinuities (Briggs 1974; Wolny et al. 2017).

A non-parametric Mann-Kendall test (Siegel 1956) was used to analyze the temporal variability, with a statistical significance of 90, 95, and 99%. The test was performed on series without data gaps in the two periods of analysis: fifteen stations in 1985–2009, and five stations in 1997–2019. Finally, trends were examined in the percentage of seasonal rainfall (DJF, JJA, SO) contribution to annual rainfall.

3. Results

3.1. Annual and monthly rainfall climatology

We first analyzed the spatial distribution of annual and monthly rainfall in the MTCR in Costa Rica (Fig. 2 and Fig. 3, respectively). The total mean annual rainfall in the region is around 4 000 mm, with amounts ranging from 1 750 to 7 300 mm approximately. Geographically, the greatest amounts (above 7 000 mm) fall in the part of the mountain that separates the Caribbean and Pacific watersheds, following a southwest–northeast line that coincides with the plains located close to the CS coast (Fig. 2). The lowest annual rainfalls, about 2 000 mm and less occur in the north close to the border with Nicaragua and the southeast of the study area. The uneven distribution of annual rainfall in the region observed here agrees with that found by Pérez-Briceño et al. (2017) for the period 1960–2011.

The mean annual rainfall cycle in the MTCR presents monthly and spatial variations. Rainfall peaks in June–August and in November–December, mainly in the northeast and southwest of the region, with a characteristic strip appearing in December that connects the northeast of the Caribbean coastline with the mountain range in the southwest. Although more intense, this spatial pattern is also observed in July (more intense), and in August (less intense). The characteristics of the rainfall cycle of July and August are related to the MSD (Magaña et al. 1999), which results in relatively low precipitation over the Pacific watershed and intense rainfall in the Caribbean watershed in both months (Hidalgo et al. 2015).

On the other hand, rainfall amounts decrease towards the west of the study area in the first part of the year (January–April), with rains below 100 mm per month, mainly in March and April. Another less pronounced drop occurs in September–October along the Caribbean coast following a mountain–coast gradient, where rainfall amounts plummet from the mountain range towards the northeastern Caribbean coast, with a difference of 500 mm between both points (Fig. 3). These results are in agreement with those of Alfaro (2002) for the period 1950–1994, Amador et al. (2013) for 1960–2011, and Maldonado et al. (2021) for 1976–2015, who identified that it rains over the Caribbean watershed in all the months of the year, with two peaks, one in July and the other one in November –the latter being wetter than the former– and two troughs in March–April and September–October.

A spatial behavior similar to that of the annual rainfall cycle is observed in January and February, with peaks on the mountain range (mainly in the southwest) and minimum values in both the northwest extreme at the border with Nicaragua and the southeast extreme of the region (Fig. 2).

3.2. Seasonal rainfall climatology

Given the importance of seasonal rainfall variability to pineapple and banana crops, a detailed analysis was made of rainfall in the periods JJA, SO, and DJF. Quarter JJA has a spatial distribution similar to that of the climatology of annual rainfall in the MTCR, with peaks above 2 000 mm in one part of the mountain range and minima in the northwest and the southeast of the region. A change in the rainfall regime is observed in SO when the smallest amounts follow the Caribbean coastline, and the peaks occur in the mountain area, close to the border with the Pacific watershed in the southwest. In DJF, the greatest amounts occur along the Caribbean coast and in some areas in the southwest, close to the Pacific watershed (Fig. 4, top). Based on this, a shift in the spatial distribution of rainfall is seen in JJA and DJF, with both quarters presenting maximum values over the coast and in sectors of the mountain area, while in SO minimum values occur along the coastline and maximum values over the mountain range.

In addition to the analysis of –annual, monthly, and seasonal– regional rainfall behavior, we analyzed the contribution of seasonal rainfall to annual totals (Fig. 4, bottom). In general, spatial changes are observed according to the time of the year. In JJA, the contributions close to and over 40% concentrate in the north of the study region. It is worth highlighting that from 30% to over 40% of the MTCR rainfall occurs in JJA. On the other hand, around 20–30% of the annual rainfall occurs in DJF. A mountain area in the southwest, close to the border with the Pacific watershed explains up to 10% of annual rainfall. This situation reverts in SO when the coastal area accounts for less than 15% of annual rainfall while contributions in the mountain range are above 35% (Fig. 4, bottom). This is evidence that approximately 70% of the region's precipitation is concentrated between the JJA and DJF quarters.

Piedades Sur station, located in the extreme southwest of the MTCR, in the mountain range, presents opposite behavior to the rest of the domain, as it concentrates 40% of the annual rainfall in SO, and less than 10% in DJF. Such behavior might be explained by its closeness to the Pacific watershed, as its annual cycle is similar to that of the Pacific (Maldonado et al. 2021).

These results are in agreement with those obtained by Sáenz and Amador (2016) in their study of 20 stations in the period 2006–2011, and with those of Villalobos and Rojas (2016), who found that JJA accounts for the greatest concentration of annual rainfall –38%– followed by DJF –32.5%– in the period 1941–2016.

In addition, we analyzed the spatial distribution of minimum (25th percentile) and maximum (75th percentile) rainfall (Fig. 5). The information provided by percentile 25 is of major importance mainly at the stations located in banana and pineapple crop areas (see crop location in Fig. 1), given that rainfall below 100 mm per month has negative impacts on banana crops, according to Robinson and Galán-Sauco (2010). Such rainfall values were observed in February (north Caribbean region), March (south Caribbean region), and September, when they extended over the entire Caribbean coast (results not shown).

Pineapple crops do not have such water requirements and they can develop with monthly rains of up to 50 mm (Pérez and Garbati 2004). Nevertheless, the first four months of the year (January–April) are the most critical for pineapple, when rainfall in percentile 25 in each of those months ranges from 20 to 100 mm per month. The northeastern and northwestern regions are identified as the most affected, particularly from February through April.

Following with the analysis of percentile 25, seasonally (Fig. 5 top), JJA presents rainfall amounts between 800 mm and 1 000 mm over almost the entire region, which would potentially have no impact on crops in terms of minimum water requirements. SO presents amounts below 400 mm in the border strip with Nicaragua and the plains near the Caribbean coast where bananas are grown. Values even below 200 mm can be observed in Punta Castilla in the north extreme of the Caribbean coast, on the border with Nicaragua. In DJF, it rains less than 400 mm, and even less than 200 mm over a small strip in the northeastern region, where pineapple crops are located.

On the other hand, the areas with larger rainfall amounts corresponding to the 75th percentile (Fig. 5, bottom) are located in the center of the MTCR, with south-to-north latitudinal distribution, and the greatest rainfalls (above 2 000 mm) concentrating in the south over the mountain area during JJA. The amounts in this period ranging from 1 600 to 2 200 mm can be harmful to both crops –bananas and pineapple– which are mostly located in the northern plains, from the foothills of the mountain range to the border with Nicaragua. This situation repeats in DJF, though with less rain (between 1 400 and 2 000 mm) and the spatial distribution displaced to the east of the domain, closer to the Caribbean coast.

3.3. Trend analysis

Annual and monthly rainfall trends were analyzed for each period (Fig. 6 and Fig. 7) and in the three selected seasons (JJA, DJF, and SO). In general, the annual trends (Fig. 6) are statistically significant at some stations in the period 1985–2009 (circles in Fig. 6); the greatest significance (99%) was observed at the stations located over the mountain range. In contrast, trends were not significant at the five stations in the period 1997–2019 (triangles in Fig. 6).

The analysis of the spatial behavior of monthly rainfall trends (Fig. 7) showed an interesting heterogeneous behavior both in space and time. For instance, although with opposite signs, September and November stand out for their high significance in the period 1985–2009 (Fig. 7). In September, negative trends prevail in the Caribbean coast, while in November trends are positive and significant (99%) at most stations. Indeed, a decreasing –although not significant– trend is observed in rainfall from August through October, mainly over the plains of the north and south Caribbean regions. September stands out with significant trends in the north Caribbean region. The situation reverts in November, when significant positive trends are observed at all the stations, except for the one located in the northwestern region. This pattern lasts until February.

Significant positive trends concentrate over the mountain range in April and May; in June, a sign switch is seen at the stations of the North Caribbean region, although the trend is not significant. The situation in July is different with all the stations presenting increasing –non-significant– trends, except for two of them located in the plains of the eastern and the northwestern regions, respectively.

The period 1997–2019 presents few signals with significant trends. The months with significant positive trends are May, July, and September all at different stations (triangles in Fig. 7).

We analyzed the trends for the three seasons and found that the first period (1985–2009) (circles, Fig. 8, top) presents a dominance of positive trends in JJA and DJF. Most of the trends in DJF are significant. The opposite behavior is observed in SO when significant negative trends predominate. In addition, the trend behavior stands out in JJA, which presents negative, though non-significant trends at some stations, mainly near the Caribbean coast. In the second period (1997–2019) (triangles, Fig. 8, top), negative trends dominate in the three seasons although they are not significant.

JJA trends in the 1985–2009 period are positive and significant only at a couple of stations near the mountain area, while negative, though non-significant trends are observed in the Caribbean plains (below 200 m asl) close to the coastal area. During this quarter, the behavior of June and August rainfall plays a major role in the north Caribbean region, where stations present negative trends, which switch sign in July (Fig. 7).

A dominance is seen of intense negative trends near the coast, mainly in the north during SO in the period 1985–2009 (Fig. 8, top). In the mountain area, trends are positive at some stations in the south and the southwest and negative in the southeast, however, none of them is significant. Values are significant mainly at stations close to the coast, and significance decreases towards the mountains. The five stations located in the Caribbean watershed have significant values at the 99, 95, and 90% levels. Only one station in the west has a significant trend at 90%. The comparison with the results of Fig. 7 reveals that both September and October present negative trends, mainly in the north and south Caribbean regions. These trends are predominantly significant over the former region in September.

Next, the DJF quarter in the period 1985–2009 shows a categorical change in the rainfall trend, which becomes positive and significant at most of the stations, particularly in the northeastern, north, and south

Caribbean regions. More marked trends stand out in the mountain range as well as in the plains of the north Caribbean region. Only two stations present no statistical significance in DJF, one in the north of the study region and the other one in the south (Fig. 8, top). The comparison of the result with the trends of individual months (Fig. 7) shows that each one presents positive trends at practically all studied stations, being January the most significant.

Given the importance of these seasons for banana and pineapple crops, we analyzed the trends of the contributions of each season to total annual rainfall (Fig. 8, bottom). It is worth noticing that although total annual rainfall presents a positive trend, the trend of the contributions of seasons JJA and SO to the annual trend is negative and significant in most of the stations (mainly in SO). On the other hand, DJF presents positive trends with significant values in the mountain area. Trend behavior in the period 1997–2019 is uneven and not significant in any season.

These results can be connected to the path of the trade winds within the domain, mainly in DJF, with positive significant trends near the coast and in the mountain area. The trade winds are more intense in DJF and weaken in May; then they become stronger in July and weaken again in October (Alfaro 2002). These winds contribute moisture to the windward watershed and have a major influence on the climate of the region (Amador et al. 2013).

The negative trend found for JJA, when the trade winds are stronger and cause a rainfall peak, according to the annual cycle of the region (Hidalgo 2021; Hidalgo et al. 2015; Maldonado et al. 2021) suggests the need for a more detailed analysis of this quarter and especially of July to verify whether rainfall maxima are decreasing along the years.

An interesting fact is that in the most recent twenty-three-year period (1997–2019) rainfall trends are not significant. In the north of the country, close to the border with Nicaragua, trends are negative in SO and DJF, and positive in JJA. At the stations close to the Caribbean coast and the Panama border, trends are positive, though not significant in the three seasons analyzed.

4. Discussion And Conclusions

This study was aimed at improving the understanding of the spatial and temporal variability of rainfall in the Costa Rican MTCR (Moist Tropical Caribbean Region). Contrarily to the Pacific watershed, meteorological information in this region is scarce and there are few studies available. After data quality control, an analysis was made of daily rainfall series in two overlapping periods: one of twenty-five years (1985–2009) and the other one of twenty-three years (1997–2019), at 28 sites located throughout the Caribbean watershed of Costa Rica.

The analysis revealed rainfall regimes are variable both in time and space throughout the year in the very moist MTCR, where the mean annual total is around 4000 mm. Although rainfall decreases in some months, it rapidly recovers in the following months. The spatial distribution of the annual rainfall cycle

repeats in January and February, with peaks (between 500 and 600 mm) in the mountain range in the southwest and minimum values in the northwest at the border with Nicaragua (less than 100 mm).

Minimum rainfall values occur in the west (mainly in the northwestern region) during the first four months of the year (January–April), being March the month with the lowest rainfall in the entire region (with values below 100 mm and not exceeding 400 mm). In the last two months of the year (November–December) peaks between 500 mm and above 700 mm per month and minimum values larger than 200 mm are observed in the east, over the coastal plains (particularly the north Caribbean region). In July and December, a southwest–northeast strip develops with abundant monthly rainfall (between 500 and 700 mm) that connects the mountain range with the north of the Caribbean coast. This rainfall strip is more intense and extensive in July.

Rainfall amounts in the seasons analyzed are quite different throughout the region, which is vital for pineapple and banana crops. The JJA quarter concentrates the greatest amounts and SO, the lowest. The spatial distribution of rainfall in JJA presents maximum values in the mountain range (above 2 200 mm) and a range of 600–2 400 mm over the entire MTCR. A mountain range–coast gradient is observed in SO, when contours have clear southwest–northeast direction, with peaks over the mountains (1 200 mm) and a gradual decrease towards the Caribbean coast (between 200 and 400 mm). Rainfall spatial behavior in DJF is similar to that of JJA, although with smaller amounts that range from 200 mm in the northeastern region to 1 800 mm over the mountain range in the southeast.

The results highlight the contrast between rainfall regimes in the Pacific and Caribbean watersheds of Costa Rica, whose annual cycles have opposite behavior. On the one hand, the MSD in July–August causes low rainfall amounts in the Pacific (Magaña et al. 1999; Hidalgo et al. 2015; Maldonado et al. 2021), on the other hand, rainfall peaks occur in the Caribbean during those months. In addition, the Pacific rainfall regime presents the most intense peak during SO (Maldonado et al. 2021), while a decrease is seen in the Caribbean during those two months.

Regarding the spatial behavior of the 25th and 75th percentiles, specific areas are observed where rainfall is likely to have minimum or maximum values, respectively and in turn, negative impacts on crop development. In general, JJA presents the greatest values; SO, the lowest; and an uneven behavior is seen in DJF (peaks in the east and over the coast in the north and south Caribbean regions; and minimum values in the north of the northwestern region).

In the 25th percentile, minimum values (between 800 and 1 000 mm) are observed over the northern and Caribbean plains in JJA, and maxima (from 1 600 to 2 000 mm) are seen in the southeast over the mountain range. SO has the lowest rainfall amounts in the north of the Caribbean coast (below 200 mm) –which could affect banana crops negatively–; the highest values reach 1 200 mm in the mountain area. During DJF, minimum values (about 400 and less than 200 mm) concentrate in the northeastern region and the peaks (from 1 200 to 1 400 mm) over the mountain range in the southeast.

Percentile 75 indicates that maximum values occur in JJA, over the entire region with a range from 1 000 to 2 600 mm. The lowest values in JJA are found in the northeastern region (between 1 000 and 1 400 mm). Maximum values occur along the strip that connects the mountain range with the border with Nicaragua. The strip has a south–north direction with peaks of 2 600 mm over the mountains and minimum values of 1 600 mm in the north, which could affect pineapple crops in the region. In SO, the smallest amounts (below 400 mm) concentrate on the Caribbean coast (in the areas of banana crops) and the highest, in the mountains (1 600 mm). During DJF, maximum values (between 1 600 and 2 000 mm) stretch in the southeast–northeast direction (mountains–north Caribbean coast), which could affect banana and pineapple crops in the north Caribbean region.

Annual trends are positive over the entire MTCR, which means increasing rainfall, especially along the mountain range and over the coastal plains of the north Caribbean region. However, the monthly behavior is quite uneven. A decreasing pattern is observed from August to October. The most outstanding results are the rainfall reductions (negative significant trends) in September, particularly in the coastal plains of the north Caribbean region. Although the trend in August and October is slight and not significant at all the stations, we note its relevance to crop growth. We also note the need for further studies of this downward trend. The period is followed by increased rainfall (positive significant trends) over the entire MTCR in November. Rainfall behavior in the remaining months is uneven. An interesting fact is that positive and negative (annual, monthly, and seasonal) trends were not significant in the past twenty-three years (1997–2019).

Seasonal trends, in general, present uneven behavior. In JJA, trends are positive over the mountain area and negative over the plains – although they are significant only in the mountains. SO trends are negative and significant at the stations located in the coastal plains of the north and south Caribbean regions. In DJF, trends are positive and significant over the entire MTCR.

The trends in the percentage contribution of seasonal rainfall to the annual cycle show decreasing amounts in JJA and SO, which are significant in the plains of the northeastern and north Caribbean regions during JJA and over the entire MTCR during SO. This means that decreasing trends are observed in both seasons. As a consequence, there are five consecutive months (June through October) when the rainfall contribution to the annual cycle is decreasing, the most evident period being SO. On the contrary, the contribution of DJF to the annual cycle would be increasing, particularly in the northeastern region and at some stations in the north and south Caribbean regions.

These findings imply an alert for fruit farmers, mainly in SO, since rainfall during these two months is between 200 and 300 mm over the entire Caribbean coast. In addition, percentile 25 shows rainfall amounts below 200 mm over the northernmost part of the north Caribbean region. And even more, the trend for SO is negative and significant over the plains of the north and south Caribbean regions and the trend of the SO rainfall percentage contribution to the annual cycle is also negative and significant in the entire MTCR.

The described situation might have negative impacts on the crops cultivated in the north and south Caribbean regions. Bananas are cultivated in both regions and require a minimum rainfall of 100 mm per month (Robinson and Galán-Saúco 2010) distributed evenly throughout the year. Lower amounts of rain cause the growth of leaves to slow and stop (Galán-Saúco and Robinson 2013). A continued and abundant water supply provides bananas with the optimal conditions for their shallow root system and their large evergreen leaves (Salvación 2020). On the other hand, pineapple crops are located in the north Caribbean region and require at least 50 mm of rainfall per month to thrive (Pérez and Garbati 2004). The effects of atmospheric water deficit on pineapple are reduced growth, longer growing cycle, and reduced fruit weight (Jiménez 1999).

This is the reason for climate monitoring for pineapple and banana crops in Costa Rica, which begins yearly in September and continues until May of the following year. The most critical months are SO because of possible water deficit and DJF for water excess, as the latter period accounts for an average of 32.5% of annual rainfall (Sáenz and Amador 2016; Villalobos and Rojas 2016). Since DJF is between two low-rainfall periods –SO and March–April of the following year– it is of major importance to rainfall distribution. Reduced rainfall in this quarter could have negative impacts on the crops given that it is followed by a low-rainfall period.

The results obtained support the need for more detailed and specific studies of the changes in rainfall regimes, using fixed thresholds for critical crop periods to help plan and optimize production. Such research is important as a baseline for further studies and input to decision-making in the agri-export sector of the MTCR, aimed at minimizing the negative impacts of extreme rainfall events.

We here provide an overall view of rainfall behavior and distribution, aimed at filling knowledge gaps in the MTCR. Understanding such variability is important for agricultural planning in the region, particularly pineapple and banana plantations –the most important export products– which are mostly produced in the MTCR. Moreover, this study provides up-to-date information for future studies focusing on more detailed analyses of the variables and physical circulation mechanisms affecting the spatial and temporal distribution of rainfall. In summary, this is a contribution to improving the understanding of meteorological processes in the Costa Rican Caribbean.

Declarations

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Author contributions: RO: Conceptualization, methodology, collected the data, prepared figures, analyzed the results, wrote the main manuscript text. OP: Conceptualization, methodology, wrote the main manuscript text and supervision. All authors read and approved the final manuscript.

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Figures

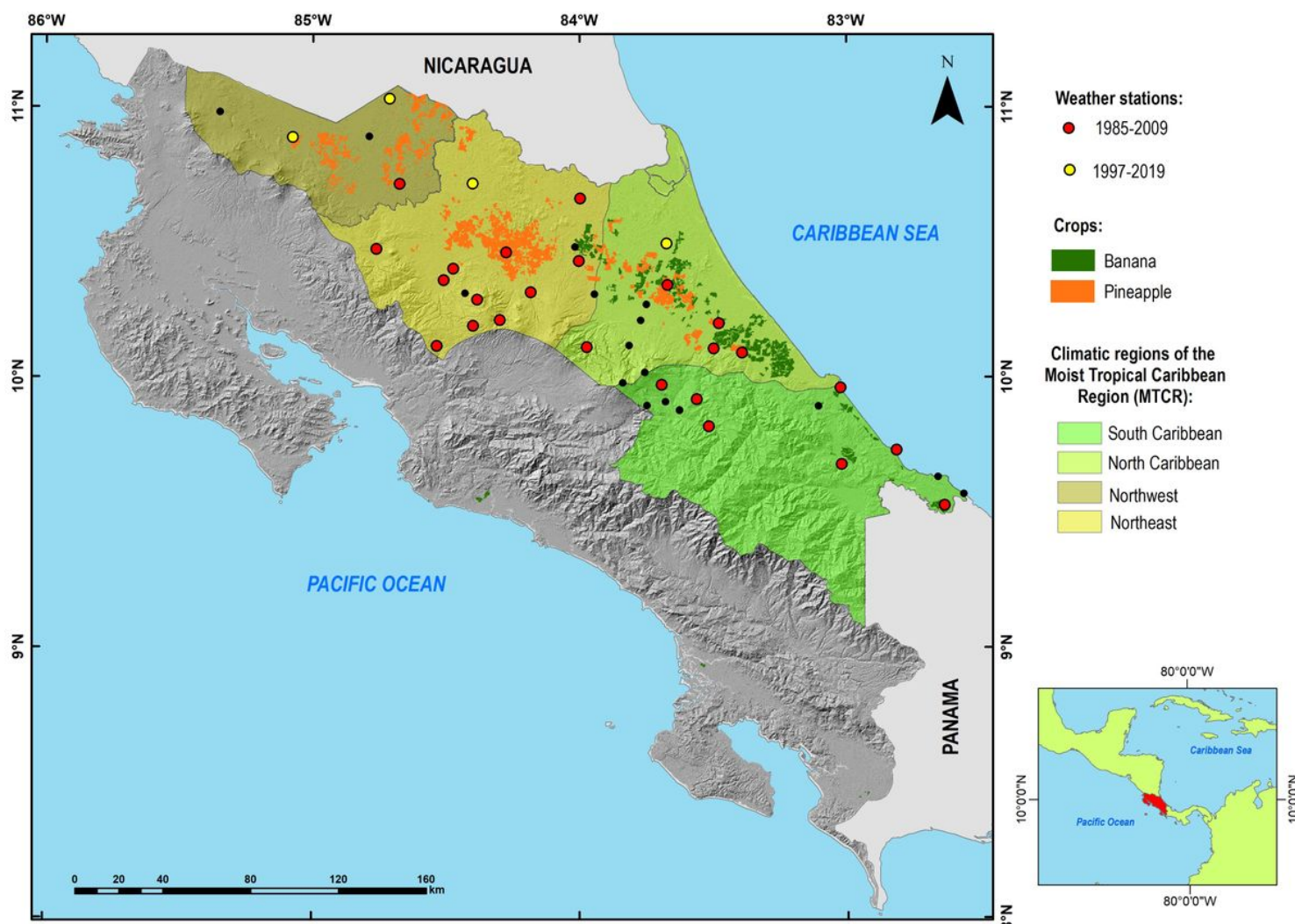


Figure 1

Location of the weather stations analyzed: red circles (period 1985–2009), yellow circles (period 1997–2019), and black circles (stations presenting over 10 % of missing data).

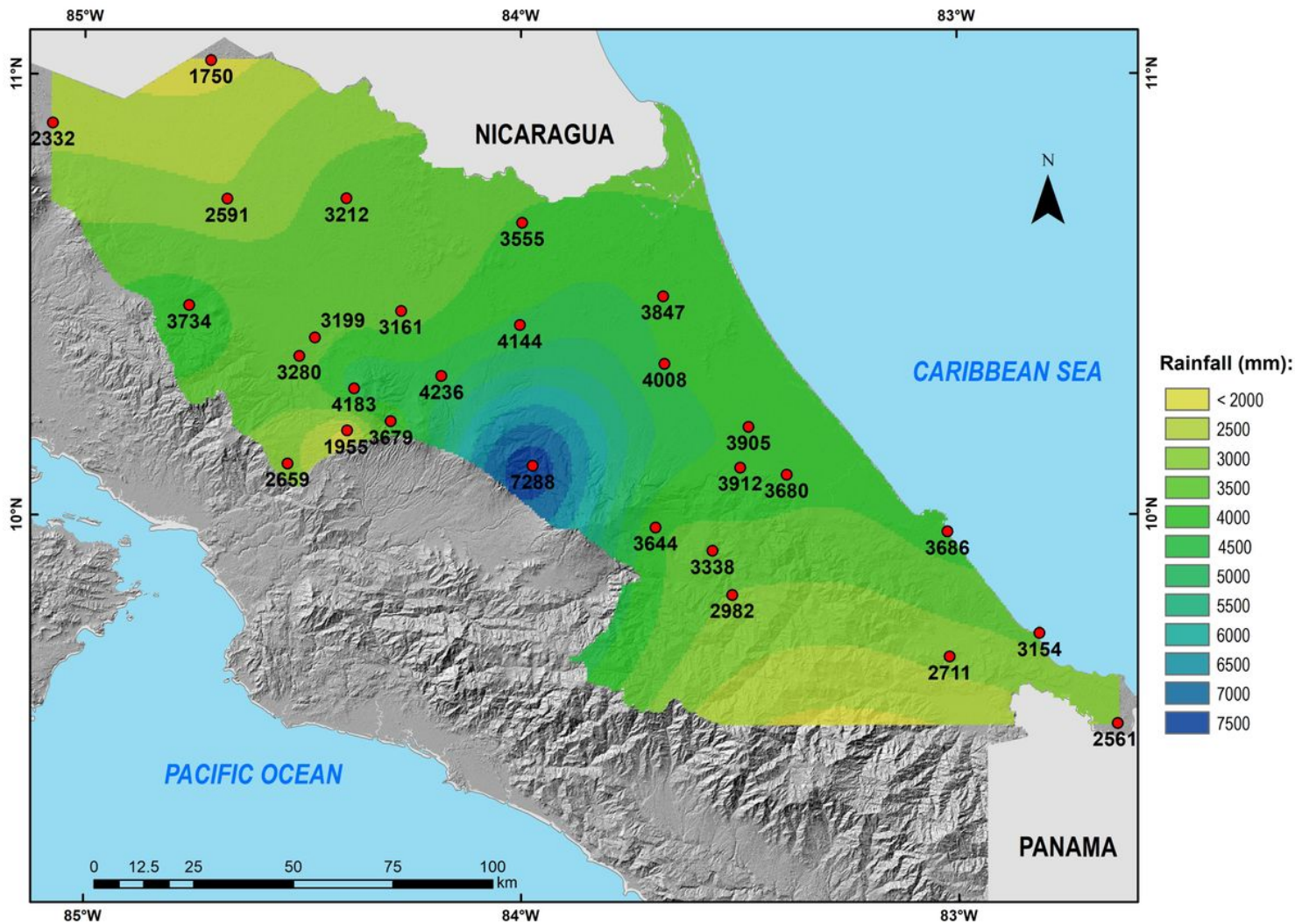


Figure 2

Annual average rainfall (mm) in the MTCR, Costa Rica.

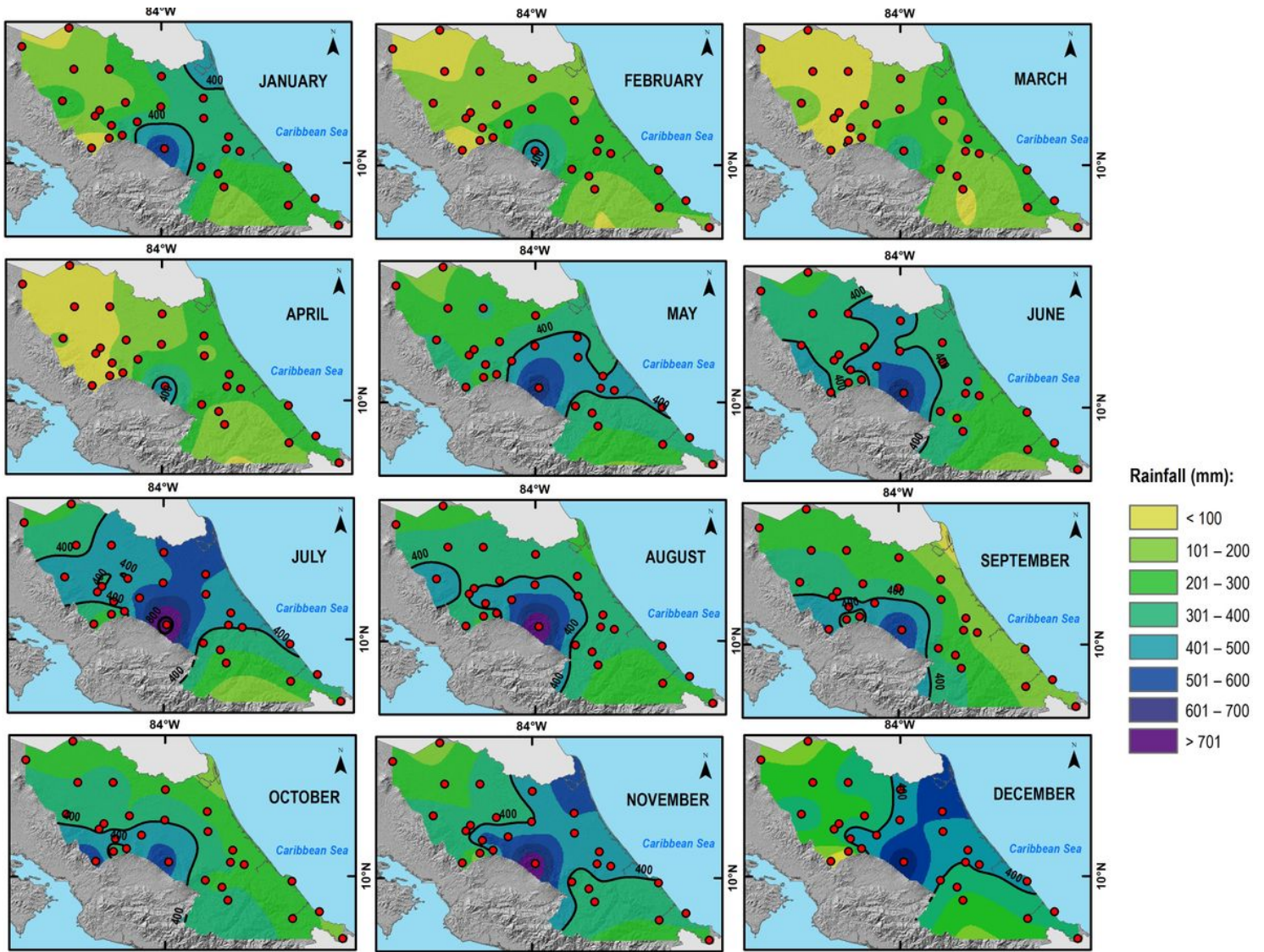


Figure 3

Total monthly rainfall (mm) in the MTCR, Costa Rica: The black line indicates the 400 mm contour.

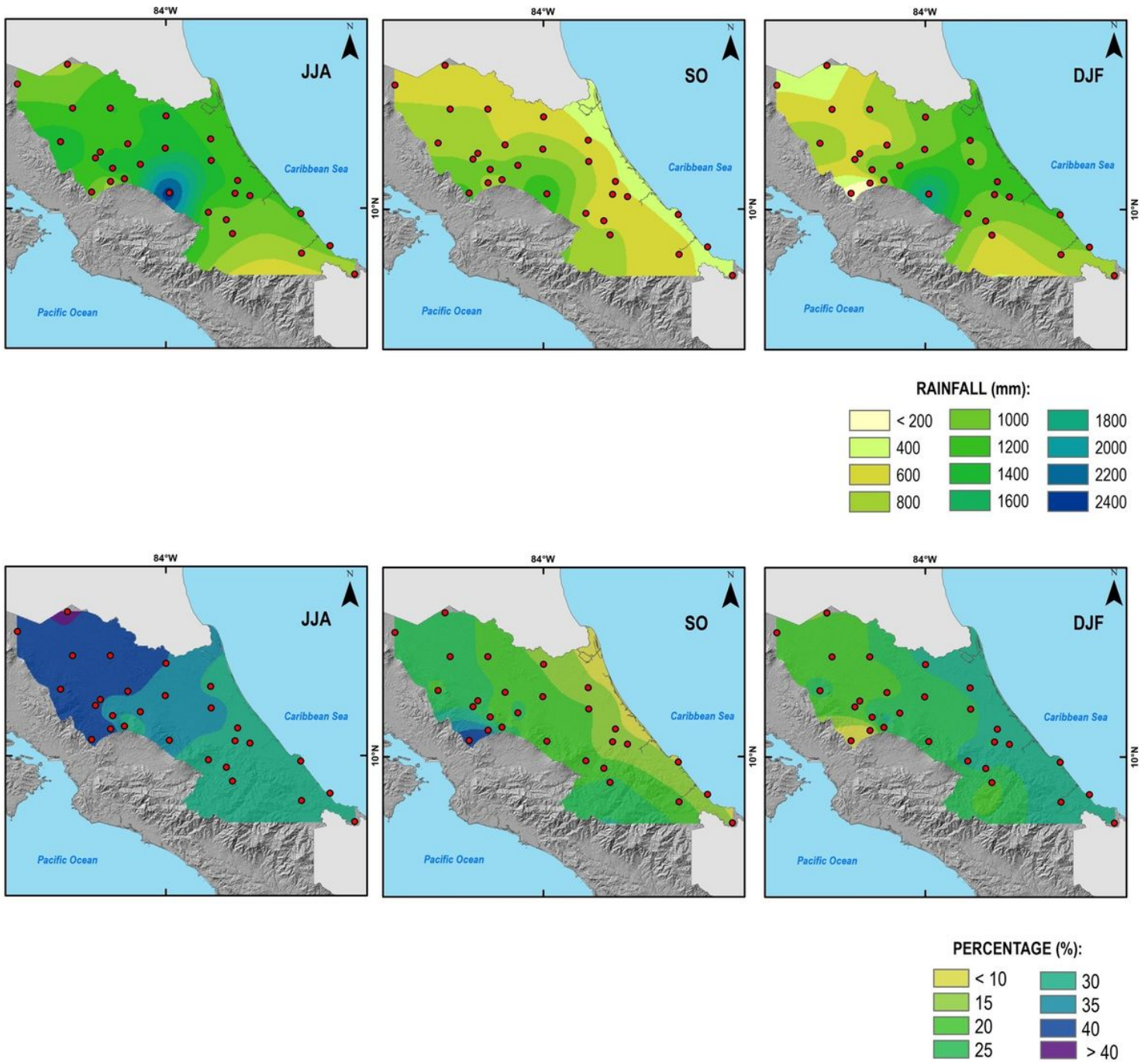


Figure 4

Total seasonal rainfall (mm) in JJA, SO, and DJF (top); and contribution of each season to total annual rainfall in the MTCR, Costa Rica (bottom).

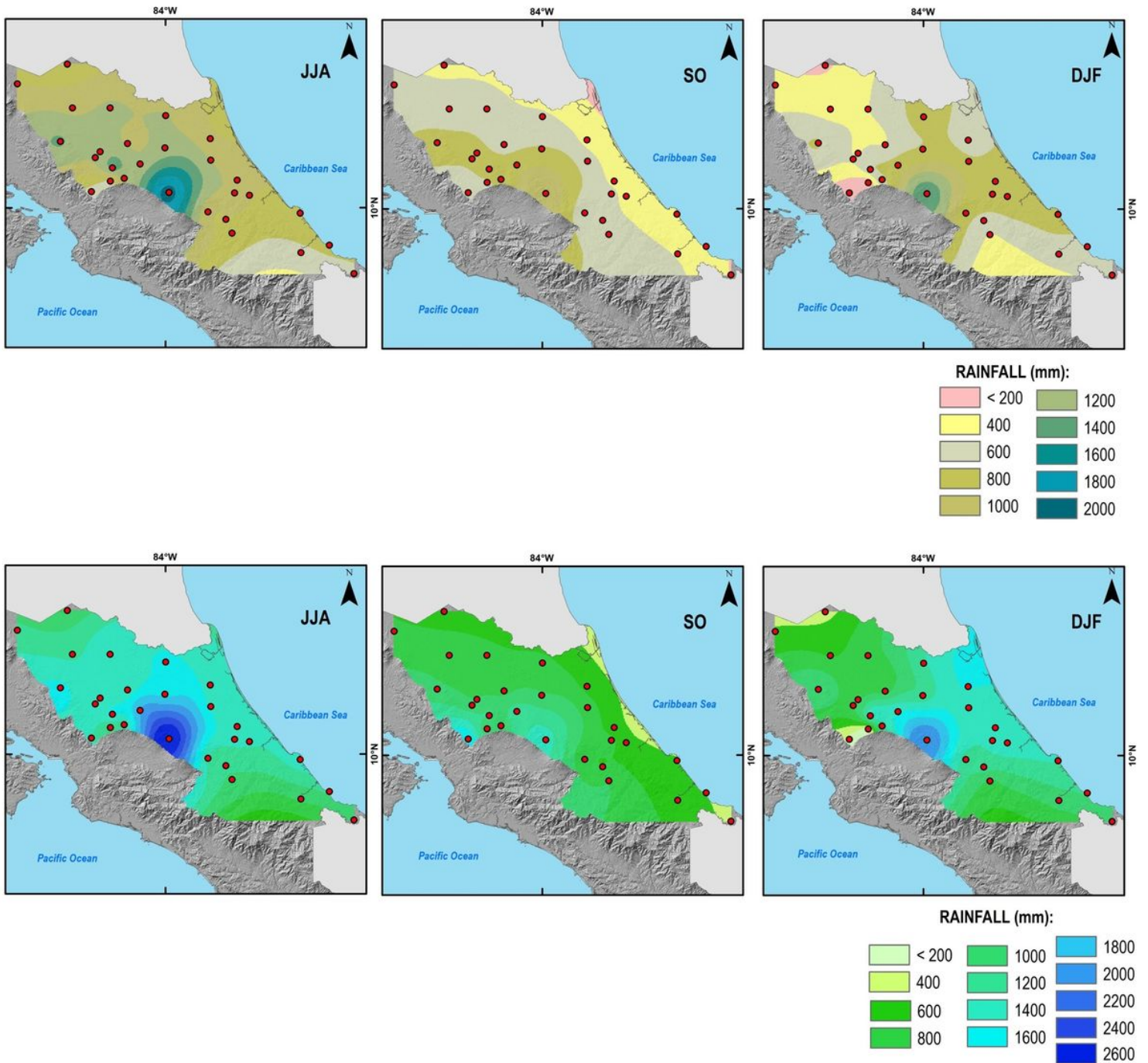


Figure 5

Mean percentiles 25th (top) and 75th (bottom) of seasonal rainfall (JJA, SO, and DJF) over the MTCR, Costa Rica.

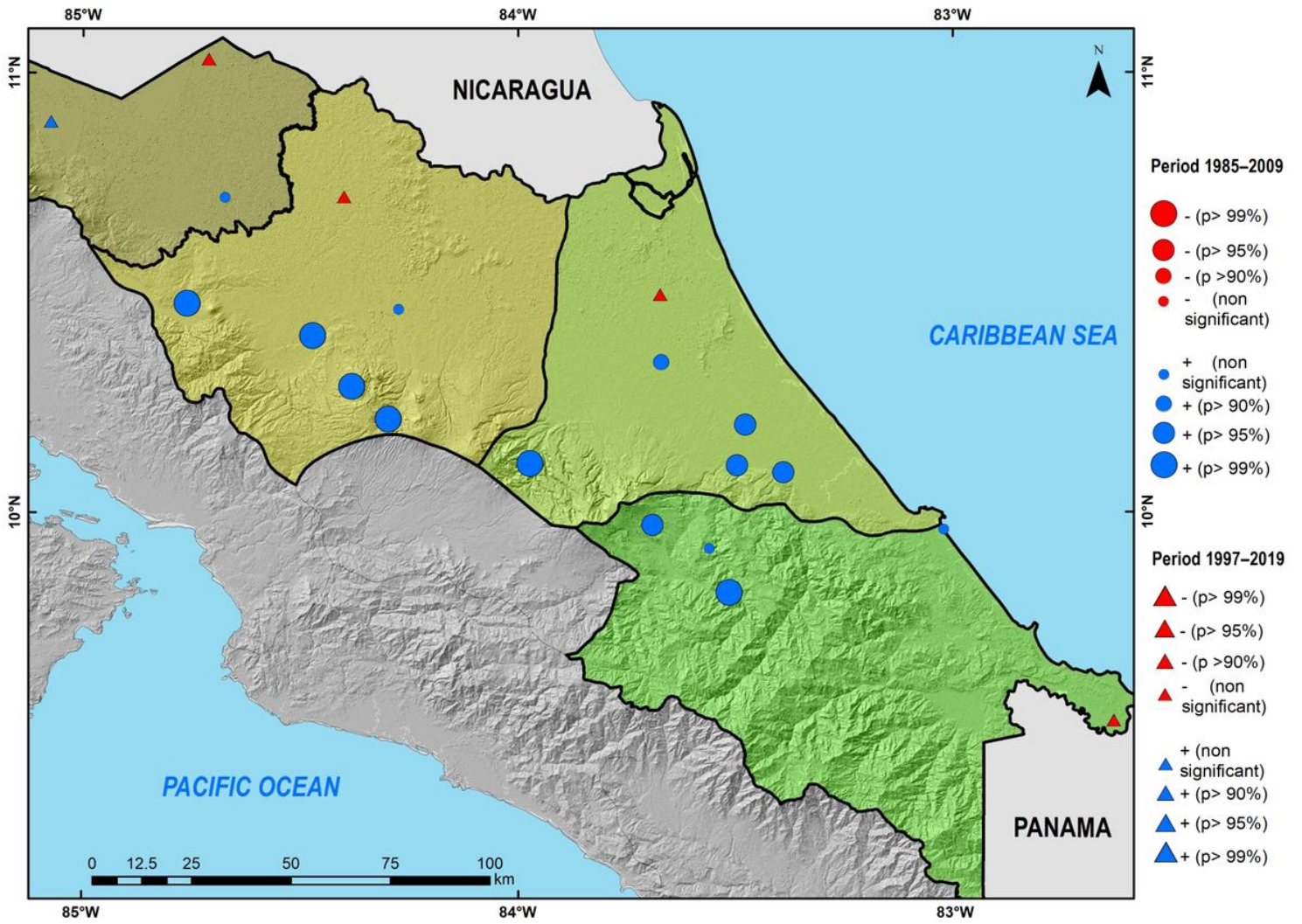


Figure 6

Annual rainfall trend in the MTCR, Costa Rica. Circles (period 1985–2009), triangles (period 1997–2019).

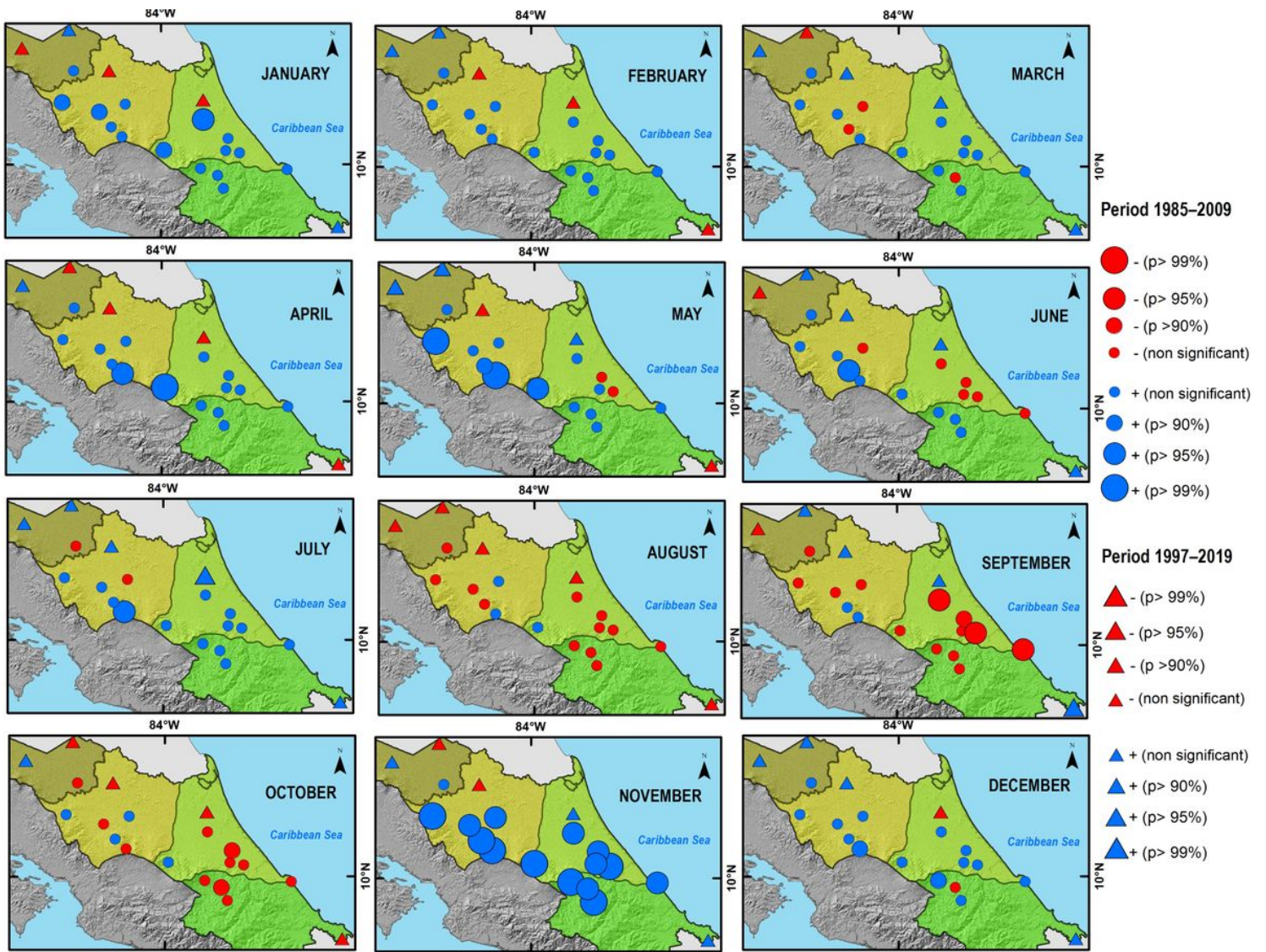


Figure 7

Monthly rainfall trend in the MTCR, Costa Rica.

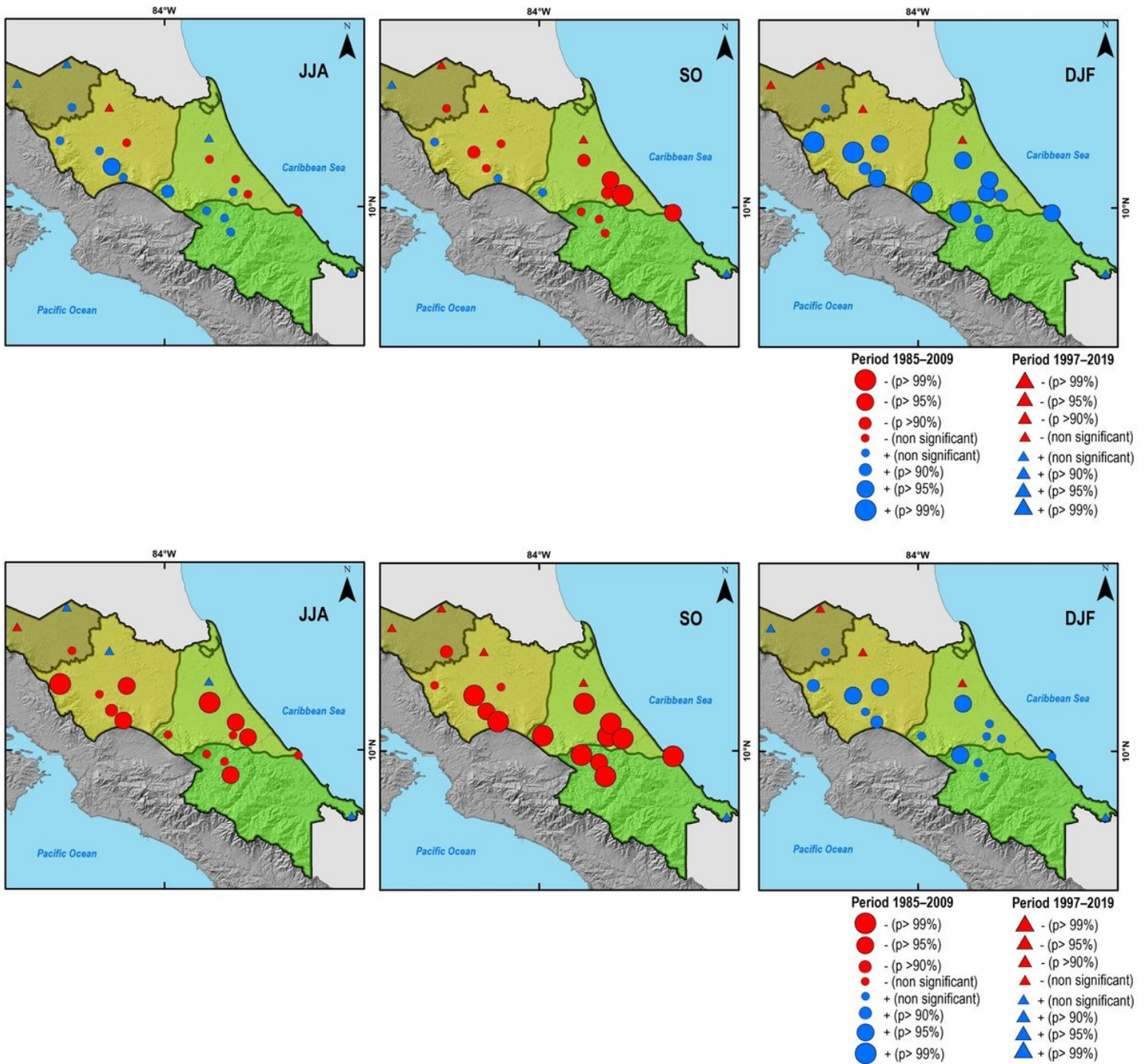


Figure 8

Seasonal rainfall trend in JJA, SO, and DEF (top); and sign of the trend of seasonal contribution to total annual rainfall in the MTCR, Costa Rica (bottom).