Revista de Climatología

Vol. 20 (2020): 61-74 ISSN 1578-8768

Variability of Daily Precipitation on the Caribbean Coast of Costa Rica

Marvin E. Quesada Q.[1] and Peter Waylen[2]

[1]*Departamento de Ciencias Sociales, Universidad de Costa Rica, Sede San Ramón, Costa Rica. <marvin.quesada@ucr.ac.cr>*

[2]*Department of Geography, University of Florida, Gainesville, Florida, 32611-7315 United States of America. <prwaylen@ufl.edu>*

(Received: 23-Jun-2020. Published: 02-Oct-2020)

Abstract

This study analyzes daily rainfall to investigate its interannual variability at Limón, located in the Caribbean coast of Costa Rica. The station is the only one along the Caribbean coast with a large record (80 years) upon which to complete detailed analysis, however its general precipitation climatology is typical of the region. The Caribbean coast and its susceptibility to precipitation variability has been studied less extensively than the along the Pacific coast and populated regions of the Central Tectonic Depression, yet it supports nationally important agriculture. Seven variables related to the magnitude and frequency of daily rainfall each month are extracted: monthly totals, probability of a day with rain, mean size of daily measurable rains, probability of daily totals exceeding, 10 mm, 20 mm and 30 mm, and the maximum daily rainfall total. Unlike much of the rest of the country, the Warm phase of El Niño-Southern Oscillation brings increases in most of these variables during most of the year. Only during September through December, is this signal effaced or even reversed. The principal cause of these changes appears to be the intensification of the Caribbean Low-Level Jet (CLLJ) during Warm phase events, not ably during the boreal summer. This increases convergence and enhances orographic rainfall. However, the slight reversal of this pattern in the boreal winter, despite an enhanced CLLJ, implies a more complex relationship between ENSO and the outbreaks of cold air from North America, which are responsible for much of the rain at that time of year.

Key words: Daily precipitation, Limón, ENSO, climate variability, Caribbean Low-Level Jet.

Resumen

Este estudio analiza los datos diarios con el fin de investigar la variabilidad climática interannual de Limón, ubicado en la costa caribeña de Costa Rica. Sólo se utiliza una estación especialmente porque tiene un largo registro (80 años) y porque es difícil encontrar más estaciones cerca con esta calidad de registro. La costa caribeña de Costa Rica no se ha estudiado antes en detalle, especialmente teniendo en cuenta la variabilidad climática y el evento ENSO. A partir del análisis es posible visualizar que la Fase Cálida de ENSO predomina en la mayoría de los meses durante el registro del estudio. Por ejemplo, enero, febrero, gran parte de marzo, abril, mayo, junio, julio, agosto muestra más lluvia durante los eventos de El Niño. En contraste, septiembre, octubre, noviembre y diciembre muestran alguna mezcla entre la Fase Cálida y la Fría. En síntesis, se tiene que el evento de EL Niño tiene más precipitación (mm) por día y por mes en la costa Caribe. Esta investigación muestra un nuevo hallazgo, en el lado caribeño de Costa Rica no sólo difiere del sector Pacífico, sino que también su precipitación diaria es más alta durante El Niño y de alguna manera menor en ciertos meses durante el evento de La Niña.

Palabras clave: *Precipitaciones diarias, Limón, evento ENSO, variabilidad climática, climatología de precipitación.*

1. Introduction

Climate variability and global climate change will bring about environmental problems with severe consequences for the human well-being, and require timely investigation and planning (Alijani *et al.*, 2008; Gamble and Curtis, 2008; IPCC, 2014). Such impacts will be manifest in further extremes such as floods, droughts, and hurricanes. Central America is a region in which some of these extreme weather events and high interannual variability are already present and could provide insights into future conditions to ameliorate such changes, and reduce the scale ensuing potential disasters.

Precipitation is an important variable in understanding the impacts of climate change. Studies indicate that precipitation patterns in Central America will likely change, eaffecting the lives and livelihoods of millions of people (Sen and Balling, 2004; IPCC, 2014). Changes in the frequency and/or intensity of extreme climate events have deep effects on the environment and society. It is therefore crucial to analyze extreme events, particularly the monitoring, detection and attribution of changes in rainfall extremes at the daily time scale (Sohrabi *et al.*, 2013). The success of agriculture and many other human endeavors depends greatly on the vagaries of daily rainfall characteristics. In the absence of artificial impoundments or access to wells, a sequence of dry days at a particularly crucial time in the growing season can have devastating consequences. Likewise, excessive rains can cause soil erosion and the loss of seeds and young plants, while a sequence of wet days at the time of harvest can damage crops and prevent removal (Peterson *et al.*, 2002).

In seeking modern parallels to hypothesized future conditions, the National Institute of Meteorology (IMN) of Costa Rica, concluded that the climate conditions for 2080 would be very similar to those currently experienced during a strong El Niño episode. The El Niño-Southern Oscillation (ENSO) phenomenon is the principal cause of global interannual variability in climate. Both the Warm (El Niño) and Cold (La Niña) phases of ENSO exhibit considerable variability in strength and regional influence from event to event. The global impacts of ENSO extend to ecosystems, agriculture, and water resources, in both continental and marine habitats. For example, the strong El Niño of 2015 produced extensive droughts on the Pacific slope of Costa Rica, which devastated harvests. Meanwhile, extensive floods inundated the Caribbean cost. The phases of ENSO affects security, economies, and social stability (Glantz, 2001; McPhaden, 2006; Iizumi *et al.*, 2014; Barnard *et al.*, 2015; Mohaddes *et al.*, 2015), underscoring the present necessity to understand its impacts to better inform management of resources.

According to Santoso *et al.* (2017) extreme Cold phase (La Niña) events tend to be less studied, but their impacts can be equally dramatic. For instance, the 1998 event was associated with catastrophic flooding events that claimed thousands of lives in Bangladesh, Venezuela, and China (Ninno and Dorosh, 2001; Jonkman, 2005; Takahashi and Dewitte, 2016). Particularly worrisome is the fact that opposing phases often follow each other closely, compounding their individual impacts. Such swings in extreme phases have been projected to occur more frequently under greenhouse warming (Cai *et al.*, 2014)

There are several regional studies of trends and monthly variability, seasonal and interannual climate precipitation over Costa Rica. However, little work has focused on daily precipitation, related to extremes in relation to ENSO (Guillen-Oviedo *et al.*, 2020). Although small in geographic extent and population, Costa Rica occupies a key position between the two major ocean basins and Northern and South America. The alignment of its central mountainous spine, perpendicular to the northeast trades, and its position at the approximate average northward extension of the Inter-Tropical Convergence Zone (ITCZ), make it susceptible to changes in both the Atlantic and Pacific Oceans and can induce opposing extremes on either flank. Of the two coastal regions, the Pacific coast is more extensively studied, particularly the droughts associated with Warm phases of ENSO in the northwestern region of Guanacaste and the populated Central Tectonic Depression (e.g. Quesada-Hernández *et al.*, 2020; Sánchez-Gutiérrez *et al.*, 2020). The purpose of this study is to identify and quantify seasonal changes in daily rainfall characteristics at the interannual scale as a function of the phase of ENSO along the Caribbean flank of Costa Rica, as typified by the excellent long time record at Limón.

2. Methodology

2.1. Study Area

Limón is located on the extensive Caribbean coastal plain of Costa Rica several tenths of kilometers from the eastern margin of the Cordillera Talamanca. As such, it is very representative of the entire coastal plain, which broadens considerably to the north and supports extensive agricultural activity (figure 1). The coastal region possesses a tropical rainforest, or equatorial, climate, receiving precipitation throughout the year (figure 2), but particularly so when the northeast trade winds (Alisios) blow most strongly (May-August and November-January) (Poveda *et al.*, 2014). Embedded within the trade winds move fast flowing region of air at about, the Caribbean Low-Level Jet (CLLJ) (Wang, 2007; Martin and Schumacher, 2011; Hidalgo *et al.*, 2015). During the boreal winter, incursions of cold air (Nortes) from North America are associated precipitation and surface convergence (Shultz *et al.*, 1998). Both the Alisios and Nortes fluctuate to varying degree with the phases of ENSO (Waylen *et al.*, 1996, Poveda *et al.*, 2006) and it is therefore reasonable to hypothesize that this will be reflected in the daily rainfall characteristics, which have great local importance for agriculture and water resources planning.

Fig. 1: Costa Rica Caribbean Coast location.

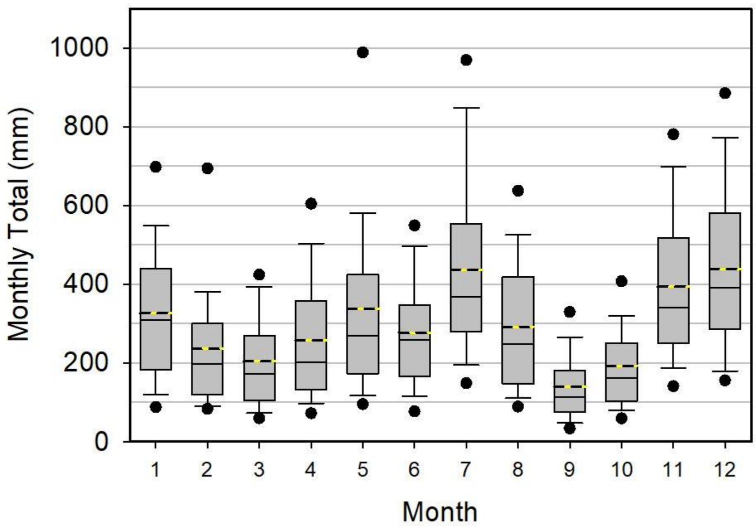

Fig. 2: Box and whisker plots of monthly precipitation totals at Limón 1949-2017. Dots represent the 5^{th} and 95^{th} percentiles, whiskers the 10^{th} and 90^{th}, and bounds of boxes the 25^{th} and 75^{th}. Solid horizontal lines within the box indicate the monthly median and the dashed line the mean.

2.2. Data and Methods

The Instituto Meteorológico Nacional of Costa Rica (IMN-CR) provided digitized daily records over the period 1949-2017 inclusive when daily observations are missing the entire month of record is ignored. The number of months of complete record range from 65 to 69 years. From each complete month of record, the following variables are extracted:

1. Monthy Precipitation Total
2. Mean Daily Precipitation
3. Probability of Wet (rainy) Day
4. Probability of Daily Total Greater Than 10 mm
5. Probability of Daily Total Greater Than 20 mm
6. Probability of Daily Total Greater Than 30 mm
7. Monthly Maximum Daily Precipitation

The second variable indicates the frequency with which the daily precipitation process occurs, and the third to sixth variables provide some indication of the magnitude of the process. The monthly total is a function of both the changing frequency and magnitude of events. Although monthly totals are more commonly used in the analysis of climatic data, partly because they are more widely available, changes in the frequency and magnitude of the process, which are both of practical importance can be lost.

Observations of these variables are subsequently categorized into one of three classes of ENSO phase based on the a priori classification of the Florida State University, Center for Ocean-Atmosphere Prediction Studies (COAPS). www.coaps.fsu.edu/jma. Monthly values of the Caribbean Low Level Jet Index (Wang, 2007) are downloaded from the International Research Institute for Climate and Society at Columbia University. https://iridl.ldeo.columbia.edu/maproom/ACToday/Colombia/CLLJI.html#tabs-2

F- and t-tests determine significant differences in the variances and means respectively of the variables under each phase of ENSO. Results from the comparison of variances determine the exact form of the t-test used. Both tests assume that the variables are normally distributed. Given the generally skewed nature of monthly rainfalls (total, mean, and maxima) and the bounded nature (0-1) of probabilities, this assumption is violated to varying degrees. Significance levels associated with the rejection, or otherwise, of the null hypothesis of no significant difference between the means (variances) of variables under combinations of pairs of ENSO phases is affected accordingly. The non-parametric hypergeometric probability distribution provides as a second quantitative measure of difference. For each variable, counts are kept of the number of observations falling below (above) the median. The probability, p(x), of the number of occurrences above/below median under the null hypothesis of no association between the phase of ENSO and the value of the variable is determined by the hypergeometric probability distribution is given as:

$$p(x) = \frac{\frac{k}{x}\,\frac{N-k}{n-x}}{\frac{N}{n}}$$

Where:
N = the overall population size (the number of monthly observations (65-69))
n= the sample size (the number of observations above/below median)
k = the number of observations with the desired characteristic (the number of monthly observations classified in each phase of ENSO)

3. Results

Application of the COAPS classification to the number of available complete monthly records yields the overall monthly counts and those in each ENSO category (table 1).

Table 1: Number of complete months of record in each month of historic record at Limón and the number falling into each phase of ENSO according to the COAPS classification, www.coaps.fsu.edu/jma

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total	65	69	68	68	69	69	68	68	68	68	66	68
Cold	15	16	16	16	16	16	16	16	16	16	14	16
Warm	16	17	16	17	17	17	17	16	16	16	16	16
Neutral	34	36	36	35	36	36	35	36	36	36	36	36

Simple average monthly values of each variable within each ENSO category are displayed as polar plots, to convey both intra-annual and interannual variability (figures 3-9).

As indicated in figure 2, Limón exhibits no marked dry season in figure 3. February-April and September-October experience least rainfall and seem to show little response to ENSO. However, periods of most rain, May to August, and to a lesser extent November to January, appear to be impacted, being wettest in the boreal summer months during Warm phases, and in the boreal winter month totals during Cold phases. July/August and November/December are the months when the CLLJ blows most strongly, particularly in Warm phase years.

Figure 4 plots the average daily rainfall depth during days of measurable rainfall. Days with zero rain are not included in the calculation. Mean daily rainfalls are about 10-12 mm from November through to May and there seems to be little influence of the phase of ENSO. However, during June-September, daily mean rainfalls are more variable-15 mm in September and as little as 5 mm in July. This is the period during which the phase of ENSO has the greatest impact. Mean daily totals are lowest during Warm phases.

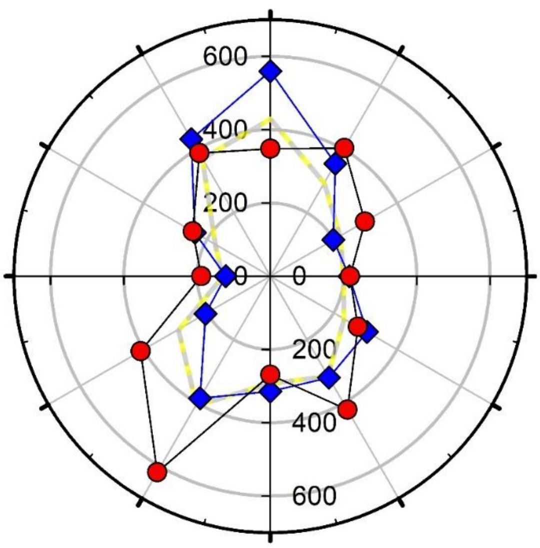

Fig. 3: Mean monthly rainfall totals (mm). Months proceed clockwise from January at the uppermost. The red symbols indicate mean during years of Warm phase ENSO, blue Cold phase, and grey dashed line, neutral.

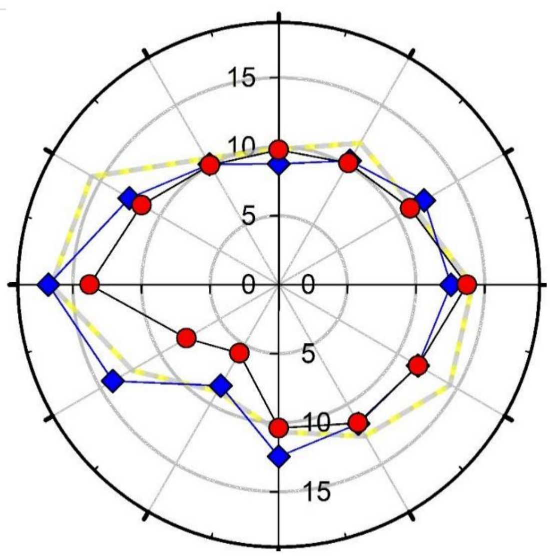

Fig. 4: As in figure 3 except for mean daily rainfall totals (mm).

At first sight, this seems at odds with the data displayed in figures 2 and 3, as the months with the lowest rainfall totals (particularly September) seem to have the highest mean daily totals. Also, in July/August when Warm phases are associated with the larger average total rainfalls, the mean daily rainfalls are lower in Warm phase. The reverse is true in December. However, the average daily rainfall size is only one factor governing the monthly total, others include the frequency of days with rain and the skewness of the daily rainfall values themselves.

The plot of the probability that any day will receive measurable rain (figure 5), resembles figures 2 and 3 more closely. For example, the chances of a day with rain in July lies between 70 to 80%. Even though the average size of those daily rainfalls is quite small (figure 4), their high frequency yields large monthly totals (figure 3). Again, Warm phase years produce daily rains more frequently in June through September, while Cold phase appears to increase the frequency of days with rain in November-December.

Examination of the single largest daily rainfall total in each month, or block maxima, might be considered to yield highly noisy results, however, figure 6 illustrates that the basic patterns of intra- and inter annual variability witnessed in the other variables are also present in this one. The times showing the greatest impact are July-August and November-December, but with a reversal of association with phases of ENSO.

Figures 3-9 plot measures of central tendency of the daily rainfall process (frequency or magnitude) by month and ENSO phase. Their interpretation is subjective and qualitative. The t-test and hypergeometric distribution provide more rigorous testing of these interpretations. As observed earlier, the variables under consideration fail to meet the assumption of normality. The empirical distributions of monthly maxima during the latter half of the year (figure 10), including the wettest months and those most impacted by ENSO, seem to be better represented as log-normal distribution as the data are positively skewed. The distribution of the probability of daily rainfall (figure 11) seems to follow a normal distribution even less than the daily maxima, primarily because of the bounded nature of the variable. All subsequent F- and t-tests are carried out at a significance level of 0.05, but the actual significance may be lower due to the violation of the distributional assumption.

Outcomes of the application of t-tests to the monthly mean values of the variables under various phases of ENSO are summarized in figure 12. The variables of the number of days of above 20 mm and 30 mm rainfall are excluded because of the large number of months return values of zero. Most tests ($>$90%) of variances failed to reject the null hypothesis of no significant difference between variances. For each variable/month, three pair-wise null hypotheses are tested between the means computed in each phase of ENSO: No significant difference between the mean in one phase and another phase-Neutral vs Warm, Cold vs Warm, and Cold vs. Neutral phases.

Figure 12 reinforces the notion that differences in daily rainfall characteristics between phases of ENSO are most marked during July-September, with means being greater in Warm phases than either neutral or Cold phases (figures 3-8). Likewise, the tests identify the change in relationship to ENSO phases during December, when Cold phases generally produce the larger means. Changes in monthly totals are most closely related to changes in the frequencies of wet days and days with totals above 10 mm, then its mean size (depth of rain).

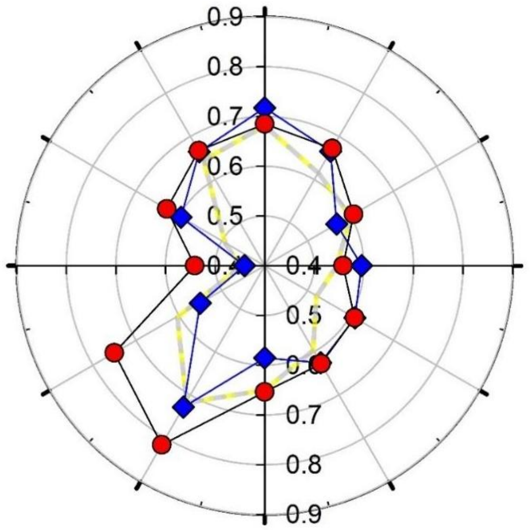

Fig. 5: As in figure 3 except for the monthly probability of a day with measurable rainfall.

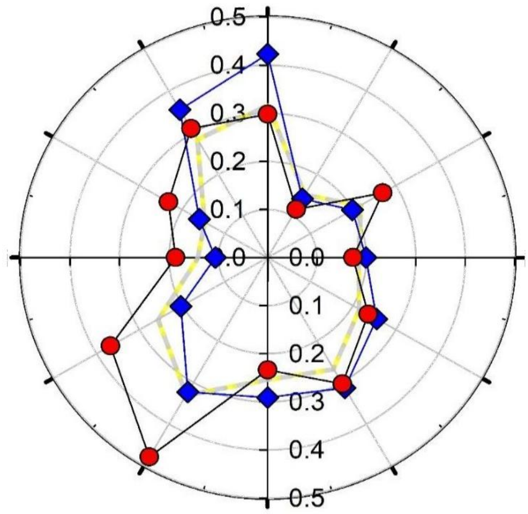

Fig. 6: As in figure 5 except for the probability of a daily rainfall total exceeding 10 mm.

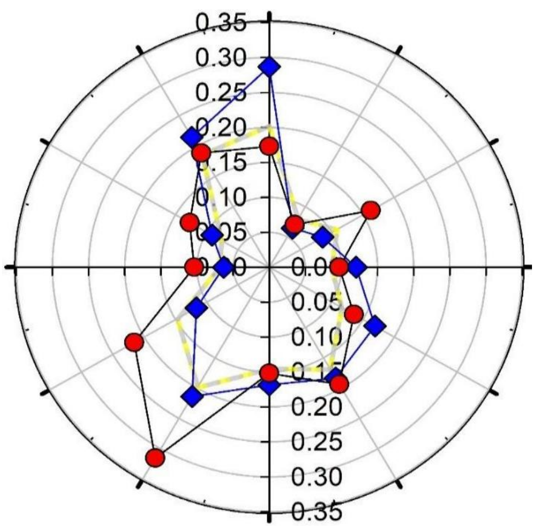

Fig. 7: As in figure 5 except for the probability of a daily rainfall total exceeding 20 mm.

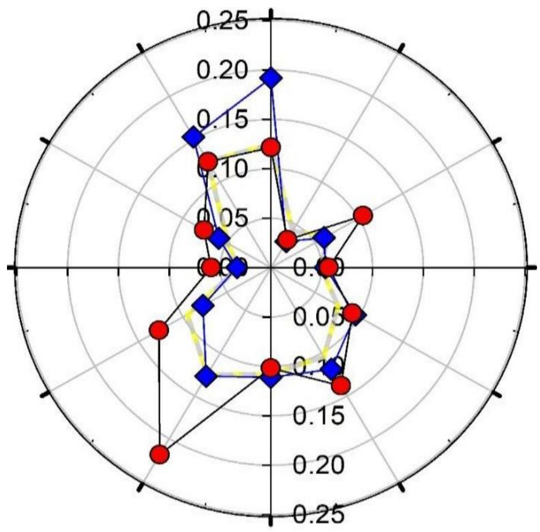

Fig. 8: As in figure 5 except for the probability of a daily rainfall total exceeding 30 mm.

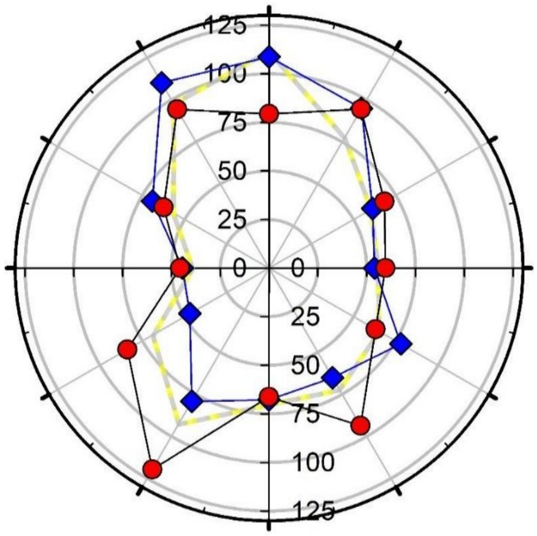

Fig. 9: As in figure 3 except for mean size of monthly maximum daily rainfall (mm).

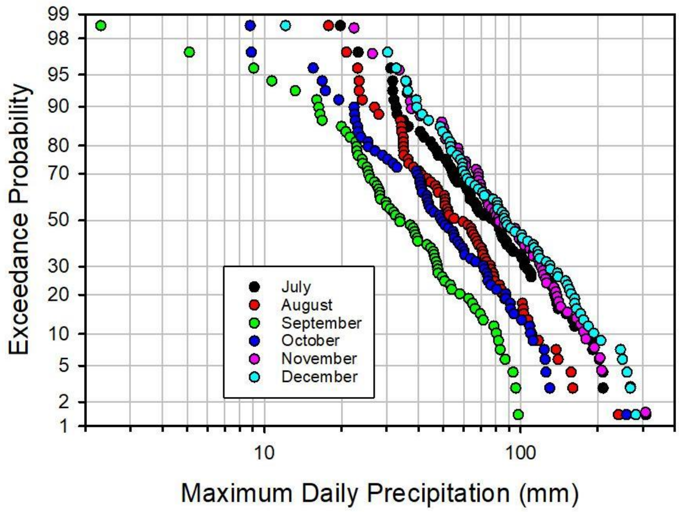

Fig. 10: Empirical plots of observed maximum daily precipitation (July-December).

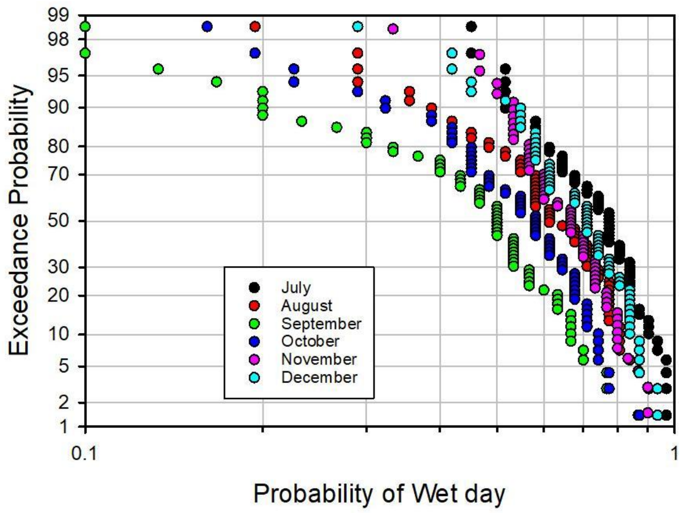

Fig. 11: Empirical plots of observed probability daily precipitation occurrence (July-December).

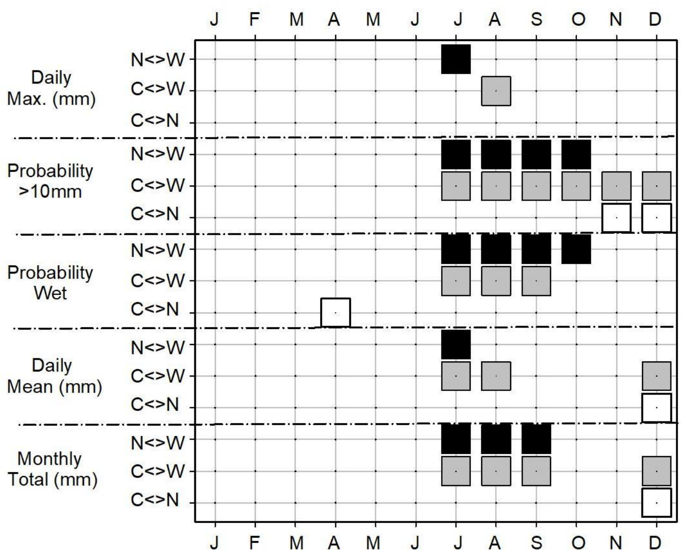

Fig. 12: Summary of the results of applying the t-test to differences in the means of variables (left axis) during Cold (C), Neutral (N) and Warm (W) phases of ENSO. Symbols indicate significantly different means at the 0.05 level. White squares show significant differences between Cold and Neutral phases, grey squares between Cold and Warm, and black squares Neutral and Warm.

The hypergeometric test, which has no limitation in terms of distributional assumptions, returns a very similar pattern of significant results in terms of when changes occur seasonally, the nature of the association with ENSO phase, and the variables that reflect that change most clearly (figure 13).

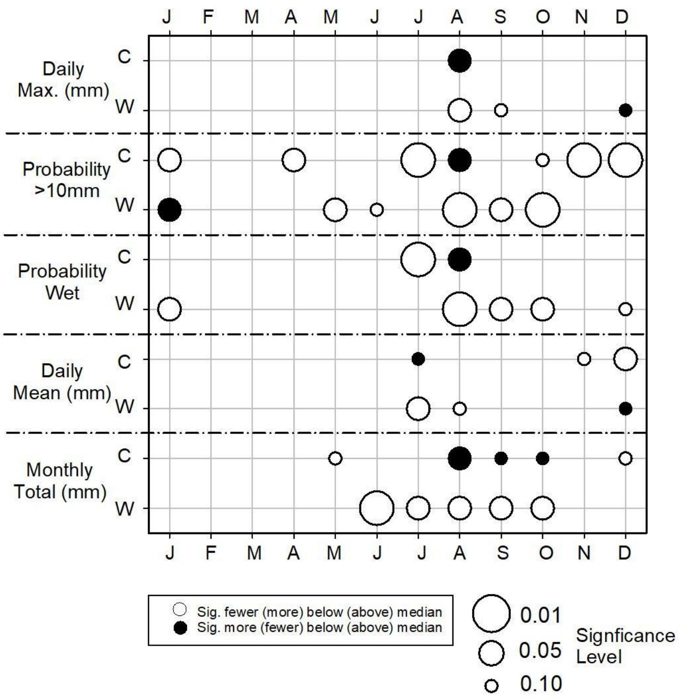

Fig. 13: Summary of application of the hypergeometric test to the numbers of occurrences above/below the medians of variables (left axis) during Cold (C), and Warm (W) phases on ENSO. Symbols indicate significantly more/fewer observations at three different significance levels. Empty symbols indicate fewer (more) below (above) the median, and filled symbols, more (fewer) below (above) it.

4. Discussion and conclusions

The analysis reveals that significant relationships exist between the characteristics of daily precipitation and ENSO at Limón on the Caribbean coast of Costa Rica. The positive association with the Warm phase of ENSO during June-September is particularly marked, while the reversal of association is seen briefly and not as strongly in December and perhaps surrounding months. The former finding is important as much of the Pacific slope of Costa Rica experiences droughts during the Warm phase. Thus, two agricultural hazards, flooding, and droughts, may impact the country simultaneously. Plots of the monthly precipitation totals, mean magnitudes and probabilities of days with precipitation (figures 14 and 15) clearly indicate that increased July monthly totals result from an increase in both the magnitude (horizontal marginal distribution) and frequency (vertical marginal) of daily precipitation during the Warm phase of ENSO. By contrast the increased precipitation totals in December during Cold phases seem to be brought about solely by increases in the mean magnitude (horizontal marginal) of the process rather than any change in frequency (vertical marginal).

The link between these two extremes is the Caribbean Low-Level Jet, which seasonally peaks in June-August and intensifies during Warm phases of ENSO. The stronger jet blows through the gap in the Central American cordillera along the line of the San Juan River marking the border between Costa Rica and Nicaragua. After accelerating through the gap, it emerges over the Pacific Ocean, forcing warm surface waters offshore and causing the upwelling of deeper cooler water in the Gulf of Papagayo, the "Costa Rica Dome". The surface cooling dampens the deep convection associated with the ITCZ over the eastern equatorial Pacific, thereby reducing precipitation along the Pacific versant in a "mid-summer drought", or locally, the "Veranillos de San Juan" or simply "Veranillos" (Magaña *et al.*, 1999, Karnauskas *et al.*, 2013). Usually a negative feedback loop initiates as the comparative absence of cloud permits greater insolation to reach the sea surface warming it again to the critical 29 °C sufficient to induce deep convection (Webster, 1994) and the Veranillos ends. However, during Warm phases of ENSO the strengthened CLLJ persists for longer, as do the drier conditions of the Veranillos. Meanwhile, on the Caribbean coast the combination of the surface divergence of the CLLJ and the topography of the Cordillera, serve to increase the moist conditions.

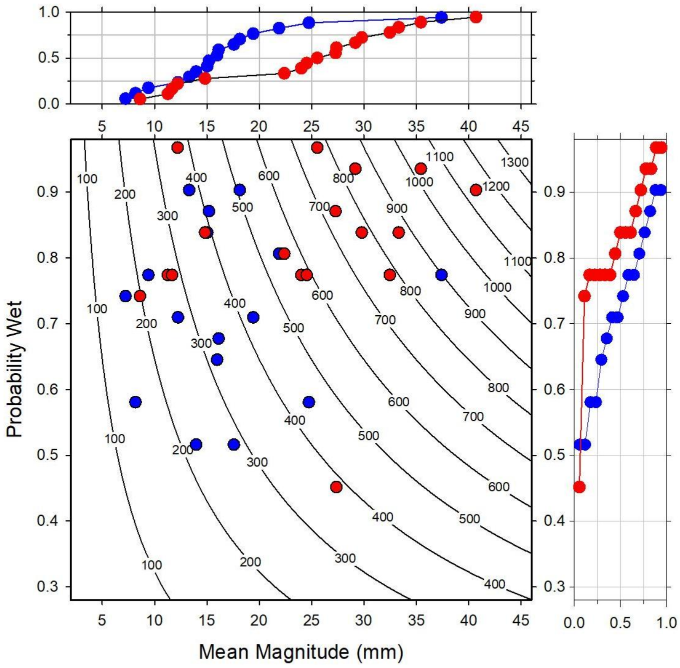

Fig. 14: The joint historic occurrences of mean magnitudes of daily precipitation and the probability, or relative frequency, of days with rain during July. The black isolines represent monthly rainfall totals. Blue and red symbols represent Cold and Warm phases of ENSO respectively. The smaller marginal graphs display the cumulative probabilities of the two marginal variables, probability of wet day (to the right) and mean magnitude (above), for the two phases of ENSO.

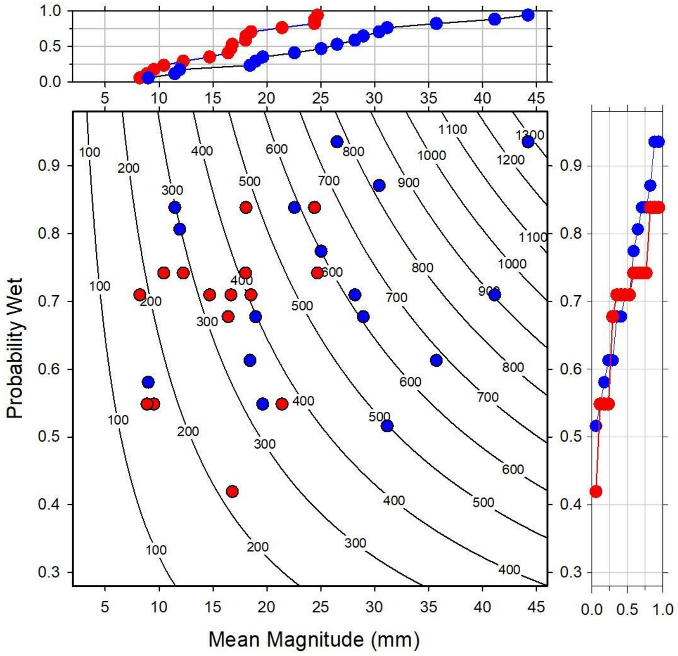

Fig. 15: As in figure 14 except for December.

The relationship between the CLLJ, indicated by the CLLJ Index (Wang, 2007), and monthly precipitation totals in July and December (figure 16) shows that the index is larger (stronger easterlies) in July during Warm phase years and produces higher totals. Not only is the monthly index generally lower in December than July (figure 17), but there is also little difference in the index between phases during the former. The noted increase in December totals during Cold phase ENSO, therefore, appears to be unrelated to the strength of the CLLJ (figure 18).

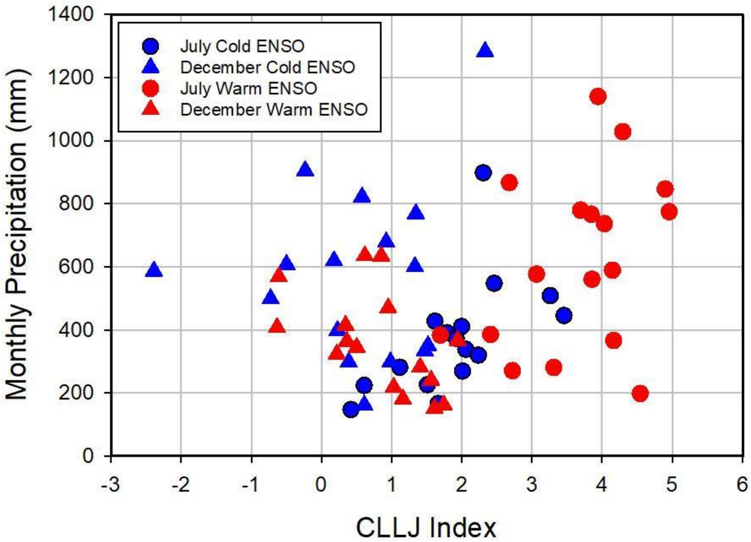

Fig. 16: Relationship between the CLLJ Index and monthly precipitation totals during July and December during opposing phases of ENSO.

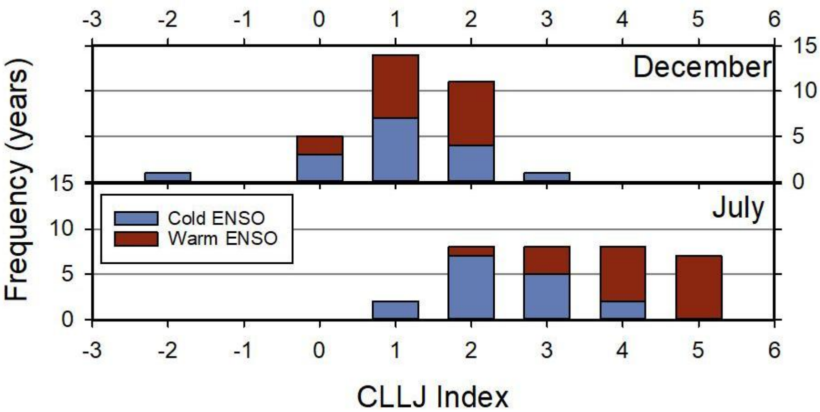

Fig. 17: Observed frequencies of monthly values of the CLLJ Index in December and July under opposing phases of ENSO.

A potential explanation may lie in the nature of the dominant precipitation process during the boreal winter (Muñoz *et al.*, 2008). It has long been recognized that the Caribbean coast of Costa Rica and neighboring states is most unusual amongst tropical locations in experiencing a slight precipitation maximum (figure 2) during the hemispheric winter (Portig, 1965), which is associated with the excursion of cold air masses and fronts from continental North America. This movement is encouraged by the meridional orientation of continental mountain chains and by the blocking effect of the Central American cordillera promoting southward penetration over the Gulf of Mexico and the Caribbean. Schultz *et al.* (1998) postulate a different generating mechanism for these "Los Nortes" earlier and later in the season. The statistical associations noted between daily rainfall characteristics are strong in December, only appear weekly in November and January and are completely absent during the later months of boreal winter.

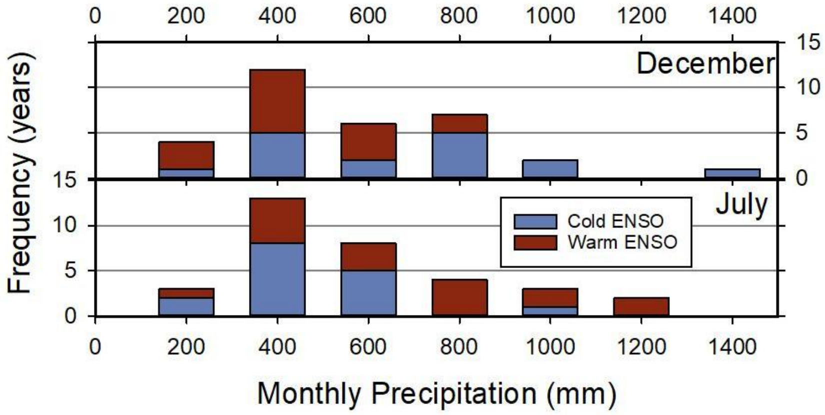

Fig. 18: As in figure 17 except for monthly precipitation totals.

This research sheds a little light on the climatic complexity of this region at both intra- and interannual scales as reflected in a meteorological variable of considerable practical importance to agriculturalists, water resources planners and emergency managers. Most prior research has focused on the droughts associated with the Warm phase of ENSO, particularly in "the dry sector" of Pacific Central America. These results indicate that interannual variability associated with the Warm phase of ENSO may produce both more frequent precipitation and larger daily totals during the months June-September when the CLLJ intensifies. The reversal of associations with ENSO and December precipitation appears to be unrelated directly to the CLLJ, but many involve connection to North America and the generation of cold surges of southward moving air.

5. References

Alijani B, O'Brien J and Yarnal B (2008): Spatial analysis of precipitation intensity and concentration in Iran. *Theoretical and Applied Climatology*, 94:107-124.

Barnard PL, Short AD, Harley MD, Splinter KD, Vitousek S, Turner IL, Allan J, Banno M, Bryan KR, Doria A and Hansen JE (2015): Coastal vulnerability across the Pacific dominated by El Nino/Southern Oscillation. *Nature Geoscience*, 8:801-807.

Cai W, Borlace S, Lengaigne M, Van Rensch P, Collins M, Vecchi G, Timmermann A, Santoso A, McPhaden MJ, Wu L and England MH (2014): Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature climate change*, 4:111-116.

Gamble DW and Curtis S (2008): Caribbean precipitation: review, model, and prospect. *Progress in Physical Geography*, 32:265-276.

Glantz MH (2001): *Current of Change: Impacts of El Nino and La Nina on Climate and Society*, 760 pp. Cambridge University Press, Cambridge, U.K.

Guillén-Oviedo HS, Cid-Serrano LR and Alfaro-Martínez EJ (2020): Comparación de parámetros de valor extremo de la distribución generalizada asociada a eventos de precipitación extrema en América Central. *Uniciencia*, 34:111-128.

Hidalgo HG, Durán-Quesada AM, Amador JA and Alfaro EJ (2015): The Caribbean low-level jet, the inter-tropical convergence zone and precipitation patterns in the intra-Americas sea: A proposed dynamical mechanism. *Geografiska Annaler: Series A, Physical Geography*, 97:41-59.

Iizumi T, Luo JJ, Challinor AJ, Sakurai G, Yokozawa M, Sakuma H, Brown ME and Yamagata T (2014): Impacts of El Niño Southern Oscillation on the global yields of major crops. *Nature communications*, 5:1-7.

IPCC (2014): Summary for policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed. CB Field *et al.* (Cambridge) (Cambridge University Press) (Cambridge, United Kingdom and New York, NY, USA) pp. 1-32.

Jonkman SN (2005): Global perspectives on loss of human life caused by floods. *Natural hazards*, 34:151-175.

Karnauskas KB, Seager R, Giannini A and Busalacchi AJ (2013): A simple mechanism for the climatological midsummer drought along the Pacific coast of Central America. *Atmósfera*, 26:261-281.

Magaña V, Amador JA and Medina S (1999): The midsummer drought over Mexico and Central America. *Journal of Climate*, 12:1577-1588.

Martin ER and Schumacher C (2011): The Caribbean low-level jet and its relationship with precipitation in IPCC AR4 models. *Journal of climate*, 24:5935-5950.

McPhaden M (2006): Genesis and Evolution of the 1997-98 El Niño. *Science*, 314:1740-1745.

Mohaddes K, Cashin P and Raissi M (2015): *Fair Weather or Foul? The Macroeconomic Effects of El Niño*. International Monetary Fund.

Muñoz E, Busalacchi AJ, Nigam S and Ruiz-Barradas A (2008): Winter and summer structure of the Caribbean low-level jet. *Journal of Climate*, 21:1260-1276.

Ninno CD and Dorosh PA (2001): Averting a food crisis: private imports and public targeted distribution in Bangladesh after the 1998 flood. *Agricultural Economics*, 25:337-346.

Peterson TC, Taylor MA, Demeritte R, Duncombe DL, Burton S, Thompson F, Porter A, Mercedes M, Villegas E, Semexant Fils R and Klein Tank A (2002): Recent changes in climate extremes in the Caribbean region. *Journal of Geophysical Research: Atmospheres*, 107(D21), 16 pp.

Portig WH (1965): Central American rainfall. *Geographical Review*, 55:68-90.

Poveda G, Waylen PR and Pulwarty RS (2006): Annual and inter-annual variability of the present climate in northern South America and southern Mesoamerica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 234:3-27.

Poveda G, Jaramillo L and Vallejo LF (2014): Seasonal precipitation patterns along pathways of South American low-level jets and aerial rivers. *Water Resources Research*, 50:98-118.

Quesada-Hernández LE, Hidalgo HG and Alfaro EJ (2020): Asociación entre algunos índices de sequía e impactos socio-productivos en el Pacífico Norte de Costa Rica. *Revista de Ciencias Ambientales*, 54:16-32.

Santoso A, McPhaden MJ and Cai W (2017): The defining characteristics of ENSO extremes and the strong 2015/2016 El Niño. *Reviews of Geophysics*, 55:1079-1129.

Sánchez-Gutiérrez R, Mena-Rivera L, Sánchez-Murillo R, Fonseca-Sánchez A and Madrigal-Solís H (2020): Hydrogeochemical baseline in a human-altered landscape of the central Pacific coast of Costa Rica. *Environmental Geochemistry and Health*, 42:2685-2701.

Sen Roy S and Balling Jr RC (2004): Trends in extreme daily precipitation indices in India. *International Journal of Climatology*, 24:457-466.

Sohrabi MM, Ryu JH and Alijani B (2013): Spatial and temporal analysis of climatic extremes in the mountainous regions of Iran. *International Journal of Climate Change: Impacts & Responses*, 4:19-36.

Schultz DM, Bracken WE and Bosart LF (1998): Planetary-and synoptic-scale signatures associated with Central American cold surges. *Monthly Weather Review*, 126:5-27.

Takahashi K and Dewitte B (2016): Strong and moderate nonlinear El Niño regimes. *Climate dynamics*, 46:1627-1645.

Wang C (2007): Variability of the Caribbean low-level jet and its relations to climate. *Climate Dynamics*, 29:411-422.

Webster PJ (1994): The role of hydrological processes in ocean-atmosphere interactions. *Reviews of Geophysics*, 32:427-476.

Waylen PR, Caviedes CN and Quesada ME (1996): Interannual variability of monthly precipitation in Costa Rica. *Journal of Climate*, 9:2606-2613.