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Comparative analysis of indices of extreme rainfall events: Variations and trends from southern México

A. R. PERALTA-HERNÁNDEZ
Centro de Ciencias Agropecuarias, Universidad Autónoma de Aguascalientes
Jesús María, Aguascalientes, México.
Corresponding author; e-mail: arperal@correo.uaa.mx

R. C. BALLING, Jr.
School of Geographical Sciences, Arizona State University, Tempe, AZ, USA

L. R. BARBA-MARTÍNEZ
Centro de Ciencias Agropecuarias, Universidad Autónoma de Aguascalientes
Jesús María, Aguascalientes, México.

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RESUMEN

Estudios en décadas pasadas en muchas partes del mundo han mostrado un aumento general en eventos de precipitación extrema, aunque la mayoría de esos estudios han sido enfocados a estaciones terrestres ubicadas en latitudes medias y altas, particularmente en el hemisferio norte. Muchas áreas tropicales y subtropicales no han sido analizadas debido en parte a la falta de datos, o porque las series de datos no son continuas para evaluaciones de tendencias de largo plazo en eventos extremos. Sin embargo, en esta investigación, reunimos registros de precipitación diaria de 142 estaciones climatológicas en el sureste de México en el periodo de 1960-2004, y se calcularon 23 indicadores anuales diferentes de eventos de precipitación extrema que han sido ampliamente usados en la literatura especializada. Empleando sólo 44 de las estaciones iniciales con los registros más completos, utilizamos varios procedimientos estadísticos tanto univariados como multivariados para investigar el significado esencial en la tendencia al incremento de eventos extremos. Encontramos que las variaciones en eventos extremos estuvieron relacionadas significativamente a El Niño-Oscilación del Sur y a la Oscilación Decadal del Pacífico (ODP), con los eventos extremos ocurriendo más frecuentemente durante períodos de La Niña y durante la fase positiva de la ODP.

ABSTRACT

Studies from throughout much of the world have shown a general increase in extreme precipitation events over the past few decades, although most of these studies have focused on mid-to-high latitude land-based locations, particularly in the Northern Hemisphere. Many tropical and subtropical areas have not been analyzed due in part to non-existent or non-continuous data required for assessments of longer-term trends in extreme events. However, in this investigation, we assembled daily precipitation records for 142 stations in southern México over the period 1960-2004 and calculated 23 different annual indicators of extreme precipitation events that have been widely used in the professional literature. Ultimately using 44 of these stations with the most complete records, we used various univariate and multivariate statistical procedures to uncover the underlying significant upward trend in the occurrence of extreme events. Furthermore, we found that the variations in extreme events were significantly related to El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), with extreme events tending to occur more frequently during La Niña periods and during the positive phase of the PDO.

Keywords: Extreme rainfall, southern México, El Niño-Southern Oscillation, Pacific Decadal Oscillation.

1. Introduction

The recent scientific assessment of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2007) acknowledges throughout that there is increasing concern that extreme precipitation events may be changing in frequency and intensity as a result of human influences on climate. The conceptual basis for changes in precipitation has been detailed by Allen and Ingram (2002), among many others, and numerical climate models consistently predict an increase in extreme rainfall events in many parts of the world given the continued buildup of greenhouse gases (IPCC, 2007). In simplest terms, warming of the planet increases evapotranspiration rates, a warmer atmosphere has the ability to hold more water, the higher moisture levels and temperatures tend to destabilize the atmosphere, and changes then occur in the type, amount, frequency, intensity, and duration of precipitation.

While the theoretical basis for expecting an increase in extreme precipitation is well-developed, many climatologists have examined records from throughout the world in an attempt to identify trends in extreme rainfall events. Based largely on Alexander *et al*. (2006), the IPCC (2007) reports that extreme precipitation events have increased by approximately 0.21% per decade over the last half century. However, despite literally dozens of articles on trends in precipitation extremes from many parts of the world, four important points are made by the IPCC (2007) and many others. First, the results are far from spatially coherent, with vastly different results from one study area to the next. Second, the identification of changes in extreme rainfall is highly dependent on analytical procedures used to define such events and those used to detect any changes in the extreme events. Third, by the very nature of extreme events, they are rare and require relatively long-term, homogeneous records for robust detection of changes or trends. Fourth, most of studies have been conducted in the mid-to-high latitudes of the Northern Hemisphere, and as noted by the IPCC (2007), "It is still difficult to draw a consistent picture of changes in the tropics and the subtropics, where many areas are not analyzed and data are not readily available."

In this investigation, we turn our interest to southern México where studies of trends in extreme precipitation have been limited. Easterling *et al*. (2000) compiled trends in extreme precipitation for many regions around the globe, and they indicated that an increase in extreme precipitation had occurred in southern México over the past half century. However, the details regarding the station network, indices to describe extreme rainfall, and analytical procedures were not detailed in their overview article. Magaña *et al*. (2003) examined extreme precipitation events in central México and noted "The number of severe storms (more than 20 mm h^{-1} of rainfall) in the México City basin has increased in recent decades", but they believed that the increase was due to the urban heat island effect. Other authors have suggested that extreme precipitation in southern México could be impacted by SOI (Cavazos and Hastenrath, 1990) and PDO (Pavía *et al*., 2006).

An examination of trends in extreme precipitation would be particularly valuable in southern México because a) to date, most studies have been conducted in mid-to-high latitude regions, b) Southern México is an area periodically impacted by catastrophic floods, and c) much of the rainfall in the region comes during the hurricane season when heavy precipitation events are common. Thus, the objective of this investigation is to analyze variations and trends in various extreme rainfall indices computed from a network of stations in southern México.

Any review of the recent literature will reveal a large number of indices used to represent temporal and/or spatial variations in extreme precipitation events (IPCC, 2007). Many scientists have used measures of extreme frequency that count the number of events each year above fixed threshold values (e.g., events > 100 mm per day) or above thresholds determined by the precipitation climatology at individual stations (e.g., events > 95th percentile). Others have focused on extreme intensity levels with choices ranging from the largest one-day event to the mean of the events in the 95th percentile to the annual total divided by the number of rain days. Other popular choices involve quantifying the proportion of annual precipitation coming from extreme events (e.g., total from events in the 95th percentile/annual total). In some cases, it can be surprisingly difficult to determine exactly how the researcher operationalized various definitions of extreme events. Furthermore, it is not clear how these various indices of extreme rainfall events are related to one another, and how the selection of the indices influences the resulting temporal or spatial variations.

Evaluation of extreme rainfall indices in southern México will not only show how the indices are interrelated, their variations and trends could reveal potentially important patterns in the hydroclimate of an area with an agricultural economy closely tied to climate conditions.

2. Study area

The study area is located in southern México (Fig. 1) and is bounded to the north by the states of Jalisco, Guanajuato, Hidalgo, Querétaro, and central Veracruz, by the Gulf of México and the Caribbean Sea on the east, by the Pacific Ocean on the southwest, and by Guatemala and Belize on the southeast. The Isthmus of Tehuantepec in our study area is where the Atlantic and Pacific Oceans are at their closest distance in Central America. The Trans-Mexican Volcanic Belt extends 900 km from west to east across central-southern México and delimits the region physiographically on the north. The main factors governing southern México's climate are the low latitude of this region, the presence of both oceans off México's southern coasts, and the irregular topography of these major sierras. The elevation varies from sea level to 5,745 m at the snow- and glacier-covered peak of El Pico de Orizaba (19°02'N, 97°26'W); the average elevation is approximately 550 m.

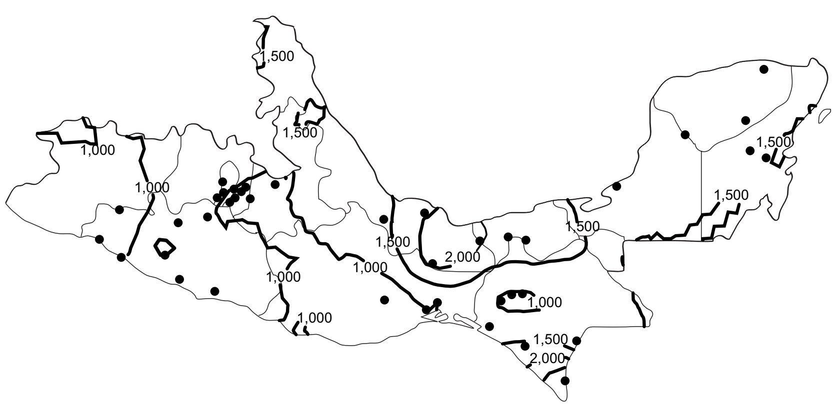

Fig. 1. Kriged surface of mean annual precipitation (mm) in southern México based on the 44 stations used in the analyses.

In general, much of our study area is comprised of the tropical savanna type of climate, although the tropical rainforest climate type appears in coastal areas of the Gulf of México (Peel *et al.*, 2007). A small steppe climate region appears on the northwestern coast of the Yucatán Peninsula, and steppe and even desert types appear in the central Balsas valley in the mountainous eastern portion of Oaxaca.

The economy of the region consists of subsistence agriculture (corn, rice and beans are popular crops), commercial agriculture featuring cacao, coffee, banana, orange trees, sugar cane, peanuts, mango, watermelon, and other cash crops, and commercial lumbering of pine, mahogany, cedar, and oak trees. Lumbering also meets the energy needs of the indigenous inhabitants for fuel wood and charcoal to be sold in local markets (Ochoa and González, 2000). The study region's population is roughly 49 million people, and the population is growing.

3. Daily precipitation data

Historical daily precipitation data are available from 1960 to 2004 for hundreds of weather stations within 12 states in southern México. The data were obtained from the ERIC III (Extractor Rápido de Información Climática) file from the Instituto Mexicano de Tecnología del Agua (IMTA). Prior to creating the daily databases, individual station data time series were evaluated for potential irregularities through time; weather stations with 30% or more of missing daily data were eliminated. In addition, stations with gaps of three or more years in between series were also discarded as were stations with clearly erroneous precipitation values. Then, from the daily data we created the annualized data with the criteria that an individual year would be considered missing if more than 10% of the daily data were missing in a given year throughout the 1960-2004 study period (Fig. 1.) In the end, we were left with 44 stations located throughout southern México with elevations averaging 551 m, ranging from 1 to 2,850 m. We calculated the nearest-neighbor statistic for the network and found the value to be 1.41 which indicates a highly statistically significantly ($p < 0.01$) dispersed distribution of the stations (Clark and Evans, 1954). Our network of stations averaged 1,237 mm of precipitation each year with a spatial range from 533 to 3,174 mm per year (Fig. 1). When averaged across the study area, the mean annual precipitation shows considerable variability from year to year with a range from 980 mm in 1994 to 1,534 mm in 1981. There is a slight upward trend in the precipitation totals of 2 mm per year, but the trend is not statistically significant ($p = 0.12$).

4. Indices of extreme precipitation

We carefully examined the methods used to quantify extreme rainfall events in many recent articles and found dozens of often redundant indices that generally fall into three broad categories:

4.1 Frequency indicators

For each year and station, we determined the number of days with rainfall ≥ 0.1, 1.0, 2.0, 10.0, 25.4, and 100 mm. We also determined the threshold (mm day^{-1}) for the 1-year return interval for 1-year events and used that value to determine the number of events in each year. Similarly, we determined the threshold for the 95th and 99th percentiles based on the data for all years and used those values to determine two other frequency measures. Finally, we identified the longest consecutive rain day streak for each year and station.

4.2 Intensity indicators

All of the intensity measures are in the units of rainfall amount per unit time; these include total annual rainfall that was adjusted for missing days by multiplying each year's value by N/(N – m) where N is the number of days in a year and m is the number of missing values in that year. We conducted all analyses with and without this adjustment and found virtually no change in our final results. Other indices include the largest 1-day total, the largest 3-day total, the amount of the 4th largest event of the year, the average of the largest 5% of all events in the year, the mean of events above the 95th percentile threshold, the mean of events above the 99th percentile threshold, and the annual total divided by the number of rain days.

4.3 Extreme percent

The final four indices involved dividing the annual total of the four largest events, the total of the largest 5% of events, the total of events above the 95th percentile threshold, and the total of events above the 99th percentile threshold by the annual total precipitation.

Basically, for each station and each year, we generated 23 different indicators of extreme precipitation activity all based on indices found commonly throughout the literature on the subject. We suspected these indices would be highly correlated through time at any station, and while each index undoubtedly has its strengths and weaknesses, we planned to extract the temporal variance structure underlying the 23 different indices.

5. Analyses and results

5.1 Characterization of extreme rainfall indices

For each of the 44 stations, we produced a matrix of 45 rows, one for each year from 1960 to 2004, and 23 columns, one for each of our extreme rainfall event indices. The 45 × 23 matrix has one row for each year from 1960 to 2004 and 23 columns containing the mean z-score averaged across the network of stations; there are no missing data in the matrix. The goal in constructing the matrix was to capture the temporal variance in each of the 23 extreme precipitation indices averaged across the station network. We converted each column at each station into z-scores, and we averaged the z-scores for each row and column across the entire network. This procedure minimized the effect of missing data and produced a southern-México-wide 45 × 23 matrix of mean z-scores representing temporal variance in each of the 23 extreme precipitation indices (Table I).

We conducted a principal components analysis on the resulting 45 × 23 matrix to determine the underlying temporal variance structure in the extreme rainfall indices. Our unrotated and rotated solutions were similar and showed four basic dimensions in our dataset (each with an eigenvalue ≥1.00). The loadings (Table I) revealed a first component that explained 41.3% of the variance in the southern-México-wide matrix with absolute highest loadings (≥0.90) on the largest one-day total rainfall, the mean of all events falling into the 99th percentile, the percentage of annual total from the 99th percentile, and the frequency of daily events >100 mm. This first component summarizes temporal variance in the largest of the extreme events, and as seen in Figure 2, the component scores show a statistically significant ($p = 0.02$) increase over the 1960-2004 period with a step-like jump in the early 1970s.

The second component explained 33.4% of the variance in the composite matrix and had high positive loadings on the frequency of 0.1, 1, and 2 mm events and appeared to characterize variance in the frequency of small rainfall events. Trend analysis revealed no significant ($p = 0.63$) trend in that dimension in the precipitation data. However, the third component, explaining 8.6% of the total variance, had a strong upward trend ($p = 0.00$) with highest loadings on the two variables related to the mean of events in the 95th percentile. The component seemed related to the occurrence of moderately large precipitation events and as seen in Figure 3, the scores show an increase largely occurring in the early-to-mid 1970s. Finally, the fourth component explains 6.5% of all variance with the highest loading (0.88) on the frequency of one year return interval events; no significant trend ($p = 0.18$) appeared in the component scores.

Table I. Components loadings and diagnostics for 23 extreme rainfall indices for 44 stations in southern México.

Variable	Component 1	Component 2	Component 3	Component 4	Communality
Frequency measures (days year $^{-1}$):					
Frequency > 0.1 mm		0.94			0.91
Frequency > 1 mm		0.95			0.92
Frequency > 2 mm		0.95			0.94
Frequency > 10 mm		0.89			0.94
Frequency > 25.4 mm		0.71			0.95
Frequency > 100 mm	0.90				0.84
Frequency > 1 yr return interval				0.88	0.88
Frequency > 95th percentile	0.71				0.91
Frequency > 99th percentile	0.75				0.92
Largest consecutive rain days	0.88				0.86
Intensity measures (mm time $^{-1}$):					
Total annual		0.81			0.99
Largest one day	0.95				0.93
Largest 3-day	0.86				0.83
4th largest event					0.86
Mean of 4 largest events					0.67
Mean of largest 5%	0.85				0.80
Mean of events in 95th percentile			0.93		0.96
Mean of 99th percentile events	0.93				0.90
Total annual/total rain days	0.80				0.87
Percent of annual total:					
Total of 4 largest/total annual		–0.82			0.90
Total of largest 5% /total annual		–0.95			0.94
Total of events in 95th%tile/total annual			0.98		0.99
Total of events in 99th%tile/total annual	0.92				0.93
Eigenvalue	9.48	7.69	1.98	1.49	
Portion of variance explained	0.41	0.33	0.09	0.06	
Cumulative explained variance	0.41	0.74	0.83	0.90	

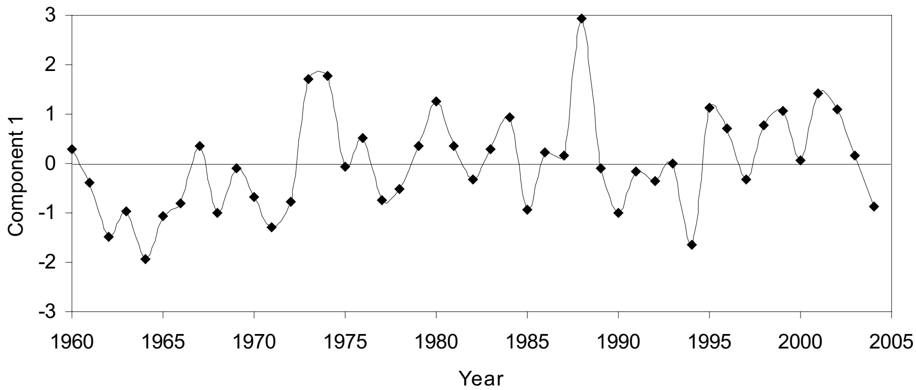

Fig. 2. Time series plot of standardized scores for the component related to the largest of the extreme events over the period 1960-2004.

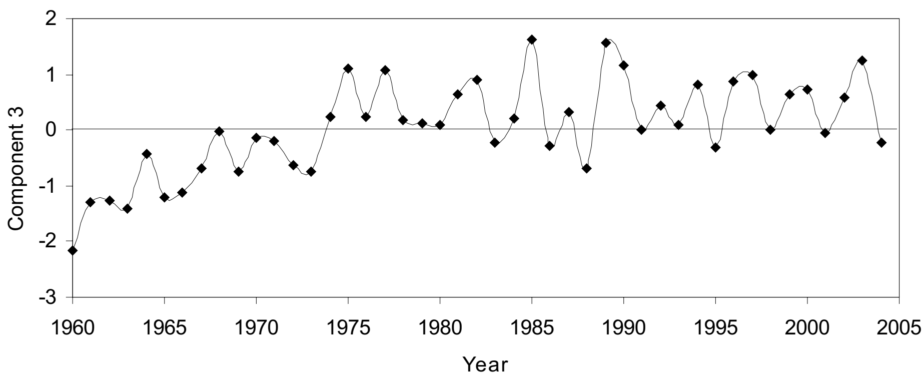

Fig. 3. Time series plot of standardized scores for the component related to the moderately large extreme events over the period 1960-2004.

5.2 Explaining variance in extreme rainfall

We assembled three different variables that could explain temporal variance in extreme rainfall variations and trends in our study area. The Southern Oscillation Index (SOI) is based on the difference between standardized sea level pressures at Tahiti and Darwin, with the resultant time series of differences then being standardized. Large negative values indicate periods of El Niño while large positive values indicate periods of La Niña. While the SOI is determined by atmospheric circulation, we used a second indicator of ENSO based on sea surface temperatures (SST). Trenberth (1997) determined that the El Niño 3.4 SST (5°N-5°S, 120°-170°W) are particularly good indicators of ENSO, and accordingly, we selected the annual SST anomalies for that region for the period 1960-2004. Many others have suggested a link with ENSO (e.g., Ropelewsky and Halpert, 1986, 1987; Reyes and Mejía-Trejo, 1991; Douglas and Englehart, 1998; Englehart and Douglas, 2002), and we selected two different variables to characterize ENSO over the same time period as well.

The Pacific Decadal Oscillation (PDO) characterizes low frequency changes in the North Pacific Ocean with a period of approximately 50 years. The PDO index is the leading principal component or eigenvector of the mean monthly SST in the Pacific Ocean north of 20°N (Mantua *et al*., 1997).

Positive values of the index refer to above normal SST along the west coast of North America and along the equator and below normal SST in the central and western North Pacific around 45°N. During the past century, there have been only two complete cycles of the PDO (Mantua and Hare, 2002). Cool phases of the PDO have persisted from 1890 to 1924 and from 1947 to 1976, while warm phases persisted from 1925 to 1946 and from 1977 through at least the late 1990s. While several researchers (Hare and Mantua, 2000; Schwing and Moore, 2000) have shown there may have been a phase change at the completion of the 1997-98 El Niño, the current phase of the PDO is uncertain as the index has displayed greater interannual variability than usual in recent years. Whether or not 1999 represents the beginning of a multidecadal cool phase will not be known for some time.

We used multiple regression analysis to link variance in the component scores of the four eigenvectors to the annual values of SOI, SST at Niño 3.4, and the PDO. No statistically significant linkage could be established between the predictors and the scores for components 2, 3, and 4. However, the SOI and PDO explained 31.7% of the variance in the scores for the first component (related to the largest of the extreme events), and the equation took the form "Comp One = 0.08 + 0.84 SOI + 0.72 PDO", where both partial regression coefficients for SOI and PDO are significant at the $p < 0.01$ level of confidence (SOI and PDO share 29% variance over the 45 year time period). The results show that largest extreme events are more likely to occur during La Niña period with cool water off the equatorial coast of South America, but also during times with above normal SST along the west coast of North America and below normal SST in the central and western North Pacific around 45°N. The t values for the partial regression coefficients are 3.95 and 3.81 for SOI and PDO respectively, and indicate a near equal influence of these two variables on the occurrence of large, extreme events.

6. Conclusions

We used daily precipitation records for 44 stations in southern México with relatively complete records over the period 1960-2004 and computed 23 different annual extreme rainfall indices that have been used recently in the literature. We found four underlying components in the data explaining 90% of the variance in the composite matrix of extreme rainfall indices. The first and third components appeared related to the largest and the moderate extreme events and both showed a significant upward trend over the 1960-2004 period, although most of the increase occurred early in the record. Most extreme events appeared to occur more frequently during the positive phase of both SOI (La Niña) and PDO. Our results are also in agreement with those from Rogers (1988), Cavazos and Hastenrath (1990), and Englehart and Douglas (2002), who found that precipitation is related to the high index phase of the SOI in southern México. Our results are generally consistent with presentations by Alexander *et al*. (2006) and the IPCC (2007), and suggest that extreme precipitation events have increased in frequency and intensity over the past half century.

Our research appears to contribute in two areas. First, we show that researchers dealing with the issue of changes in extreme precipitation events must be very clear in defining and explaining the indices they use in their works. As shown in this study, indices of extreme rainfall that might be expected to be highly correlated through time or space may in fact be completely uncorrelated. This leads to the possibility of remarkably different conclusions from the analysis of the same set of basic measurements. Researchers dealing with extreme precipitation analyses should be encouraged to indicate how sensitive their results are to the choices they have made in defining extreme events. Secondly, to date, analyses of extreme events in southern México have been limited. In this study we provide further evidence that extreme events tend to occur more frequently during the positive phase of SOI and PDO events, and these extreme events have increased over the past four decades. Finally, these results from the practical viewpoint can help to deal with extreme rainfall events in southern México, since a large part of this area is devoted to rain-fed agricultural activities.

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