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RESEARCH ARTICLE

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Precipitation regionalization, anomalies and drought occurrence in the Yucatan Peninsula, Mexico

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Abstract

Climate change projections have identified the Yucatan Peninsula as being vulnerable to increasing drought. Understanding spatial and temporal precipitation variability and drought occurrence are therefore important. Drought monitoring in Mexico has been carried out only relatively recently and often without considering the long-term variability in both droughts and precipitation. This research explores the spatio-temporal variability of precipitation and occurrence of droughts at a much finer spatial resolution and over a longer temporal period than previous studies. Using statistical (cluster analysis and standardized precipitation index) and geostatistical (kriging) techniques, maps of precipitation and droughts are generated for the period 1980–2011. These show that whilst many previous studies have regarded the Yucatan Peninsula as a homogenous region with respect to precipitation, there are actually four distinctive clusters of precipitation amount, showing climatic variability across the Peninsula. The analyses also show that droughts in the Peninsula are regionalised. Twelve-month Standardized Precipitation Indices (SPI), calculated for individual stations and for precipitation surfaces, reveal distinct patterns of spatial and temporal variability. SPI surfaces indicate the occurrence of major droughts in 1981, 1986–1987, 1994, 1996, 2003, 2004 and 2009, but these rarely affect the whole Yucatan Peninsula uniformly. Wetter years, such as 1983, 1984, 1988, 1992, 1995, 2002 and 2005 sometimes reflect the impact of individual extreme events, such as hurricane *Isidore* in 2002. Our results show that drought can be regionalised, thus enhancing the quality of information about droughts in the area and providing evidence and support for future drought mitigation and environmental protection. These methods could usefully be applied elsewhere.

KEYWORDS

droughts, extreme events, precipitation, Yucatan Peninsula

1 | INTRODUCTION

The most widely accepted climate change models indicate that subtropical and some tropical latitudes will experience a decrease in mean annual rainfall. In addition, extreme meteorological events (e.g., drought periods) are predicted to increase in frequency and intensity (Nicholls *et al.*, 2012; IPCC, 2013). Mexico, and in particular the Yucatan Peninsula, and Central America have been identified as areas that are particularly vulnerable to adverse climate change consequences (Orellana *et al.*, 2009; Christensen *et al.*, 2013). Projections suggest that precipitation will decrease and temperatures increase between 2 and 4°C by the end of the century (Magaña and Caetano, 2007; Magaña *et al.*, 2012; IPCC, 2013; Montero-Martínez *et al.*, 2013). A recent assessment of CMIP5 models (Colorado-Ruiz *et al.*, 2018), whilst confirming the broad patterns from CMIP3 models, has highlighted differences between northern and southern Mexico, with the largest decreases in summer rainfall (∼13%) likely to occur in southern Mexico, Central America and the Caribbean. Thus, it is valuable to create regional precipitation maps for areas, such as the Yucatan Peninsula, where recent climate variability and climate change projections are seen to be quite extreme.

Climate change effects and the increase in extreme weather events, combined with a growing population are likely to have adverse effects on society and ecosystems (Imbach *et al.*, 2012; Meyer and Jin, 2017; Schneider and Haller, 2017). The economic costs of extreme hydrometeorological events in Mexico have already increased from an annual average of $730 million pesos in the period 1980–1999 to $21,950 million for the period 2000–2012 (Diario Oficial de la Federación (DOF), 2013), due to both higher frequencies of these events and an increase of exposure (e.g., growing population). These changes are of great importance in emerging market economies where the economy and livelihoods depend to a significant extent directly on rainfall. Improved understanding of spatio-temporal variability in precipitation and in extreme meteorological events such as droughts, provides a vital basis for assessing the potential expression of future climate changes.

To understand temporal and spatial precipitation patterns, it is crucial to gather long-term, uninterrupted and spatially continuous precipitation data (Easterling, 2013); unfortunately, throughout Mexican history the collection of meteorological data has started and stopped as a result of political and economic problems in the country (CONAGUA, 2012). In the 1990s, however, climatological and precipitation maps for the whole of Mexico were developed for the National Atlas of Mexico (1990–1992) and by García (1998). These maps have been used as a baseline for many climatological and biodiversity studies (Arriaga *et al.*, 2004; Plasencia-Vázquez *et al.*, 2014; Ayram *et al.*, 2017; Suárez-Mota *et al.*, 2017). Recently, Cuervo-Robayo *et al.* (2014) created a long-term annual precipitation map for the period 1910–2009 using ANUSPLIN as an interpolation methodology. Even though the latter is relatively up to date (2009), mapping the whole country over a period of 90 years is challenging because of the limited number and distribution of rainfall gauges. At a regional level, these national maps can lose some of the finer detail that may help to understand more accurately how climatic variability is expressed. Analyses at scales suitable for regional studies are important since certain regions have particular vulnerabilities and geographies.

The Yucatan Peninsula of Mexico (Figure 1) is an area that has seen quite rapid population growth since the 1950s, with an annual growth rate of almost 4% from 1970 to 1995 (Eastmond *et al.*, 2000) and 2.9% from 1990 to 2015 (INEGI, 2018). Although Yucatan is the state with the largest population, the most rapid population growth has been occurring in Quintana Roo, especially since 1980. The Yucatan Peninsula has a population of approximately 4.7 million people and has a high proportion of indigenous people (46.9%), 43% in Campeche, 29% in Quintana Roo and 42% in Yucatan (CONEVAL, 2016); 72% are considered impoverished. These people are more vulnerable to a lack of precipitation because of their direct reliance on precipitation both for water supply and to support rain-fed agriculture. Rain-fed agriculture in this part of Mexico is one of the main economic activities and is closely linked to the rainfall patterns (dry-wet seasons) in the Peninsula (Ewell, 1984). Thus, changes in precipitation and in particular an increase in droughts would have important consequences for crop production (either subsistence or commercial) and therefore major implications for food security in the region (Estrada-Medina *et al.*, 2016). Droughts have long been a major concern in this area. The debate about the role of drought in the "collapse" of the Classic Maya culture about 900 CE has attracted attention for many years (Curtis *et al.*, 1996; Evans *et al.*, 2018).

A closer look at the literature on precipitation patterns in the Yucatan Peninsula reveals a number of gaps and shortcomings. In previous studies, precipitation in the peninsula has generally been analysed in the context of the whole country, or has sometimes been completely excluded from the country-wide analyses (Englehart and Douglas, 2002; Aguilar *et al.*, 2005; Bhattacharya and Chiang, 2014). In regionalizations based on precipitation, the Yucatan Peninsula is usually identified as a single unit, or linked to southern Mexico (Bravo Cabrera *et al.*, 2012). For instance, the Mexican drought monitoring programme (Programa Nacional contra la sequía) uses few

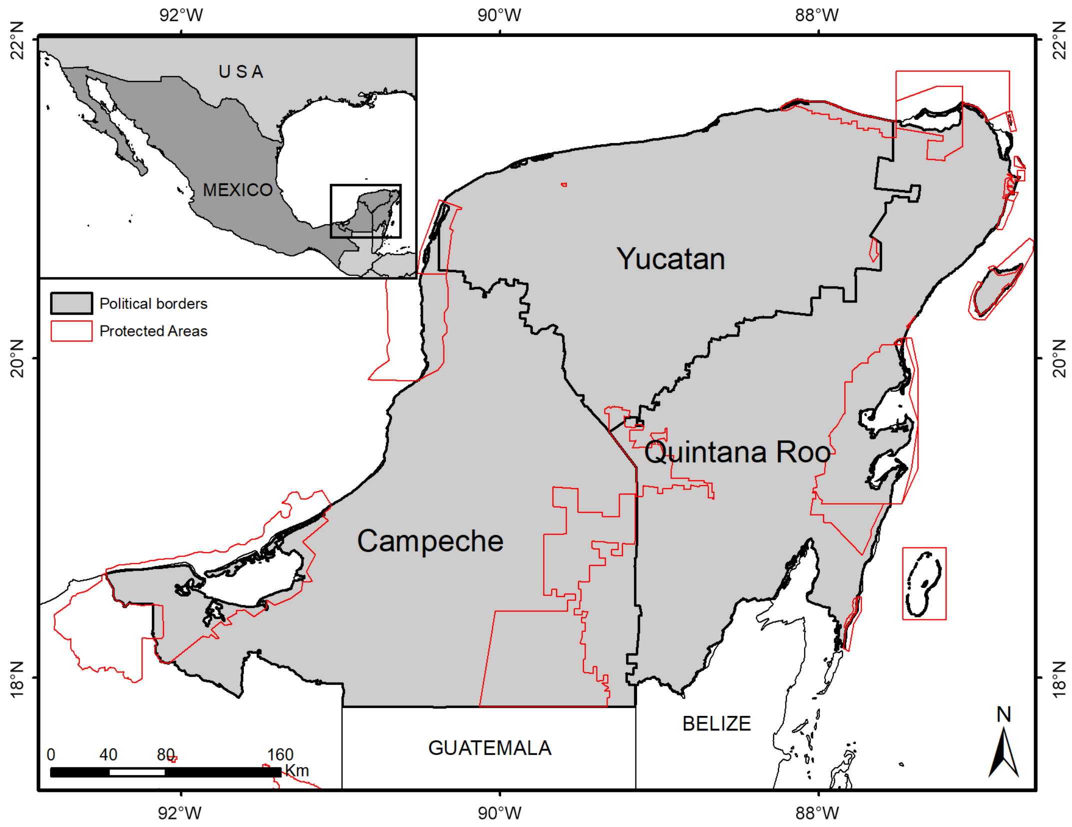

FIGURE 1 Location of the Yucatan Peninsula (21–17°N; 91–87°W) with the political divisions which includes the states of Yucatan, Campeche and Quintana Roo (Mexico) and the two adjacent countries (Guatemala and Belize). Red borders show the Natural Protected Areas within the Mexican Yucatan Peninsula. Locations of individual meteorological stations are shown in Figure 2 [Colour figure can be viewed at wileyonlinelibrary.com]

stations in the YP, almost all of them concentrated in Yucatan and Quintana Roo without almost none in Campeche. Thus, it is not surprising that the YP is recognized as a single unit (Lobato-Sánchez, 2016). Orellana *et al.* (2003) did map precipitation anomalies across the peninsula across two decades (1961–1970 to 1981–1990) noting a general trend to drier conditions over that period, but without any detailed spatial or temporal analysis. It is also significant that, as noted by Méndez and Magaña (2010), there is a "seesaw" structure in precipitation anomalies in Mexico and frequently, the Yucatan Peninsula does not experience droughts at the same time as the rest of the country (Núñez *et al.*, 2011; Fernández-Eguiarte *et al.*, 2018). This north–south dipole appears to have persisted over a range of timescales (Seager *et al.*, 2009). There is also some evidence of an uneven spatial distribution of droughts within the Yucatan Peninsula itself, both today (Márdero *et al.*, 2018) and in the past (Mendoza *et al.*, 2006), but there has been little work to explore the spatio-temporal patterns of droughts in the Yucatan Peninsula area specifically. This article aims to help fill this gap by studying spatio-temporal variability of precipitation and the occurrence of meteorological droughts during the period 1980–2011 in the Yucatan Peninsula, Mexico.

2 | MATERIAL AND METHODS

2.1 | Study area

The Yucatan Peninsula is located in southeast Mexico between 17°36′N to 21°36′N latitude and 86°43′W to 92°26′W longitude (Figure 1) dividing the Gulf of Mexico from the Caribbean Sea. This region comprises the Mexican states of Campeche, Yucatan and Quintana Roo, together with Belize and northern Guatemala. For this article, only the Mexican part of the peninsula is the focus. The Yucatan Peninsula, as it is now configured, arises from the Chicxulub impact (ca. 65 million years ago) and the emergence of the peninsula during the Eocene and Miocene (Vázquez-Domínguez and Arita, 2010). It is a unique and complex area due to the geomorphological, hydrological and edaphic features that have helped develop this region and its biota (Wilson, 1980).

The latitude of the Yucatan Peninsula, high insolation and its low elevation, gives rise to a truly tropical climate, with much of the peninsula falling into the Aw (warm subhumid) category of the Köppen classification, which is widely used in Mexico (García and García, 1973; Orellana *et al.*, 2003; Márdero *et al.*, 2012). In common with most of Mexico, it receives the majority of its rainfall in summer, here associated with the seasonal northerly location of the ITCZ, strengthening of the NE Trade winds and associated easterly waves, and strong convection over the western hemisphere warm pool (Amador *et al.*, 2006; Curtis, 2013). Warm sea surface temperatures in the Atlantic warm pool in the Gulf of Mexico/Caribbean also give rise to tropical cyclones (including hurricanes) in the late summer, that can bring significant amounts of precipitation (Boose *et al.*, 2003). In contrast, the winter is relatively dry as the subtropical Bermuda high expands southward and the ITCZ is displaced southwards, although cold fronts (*nortes*) originating over Canada do bring some winter and early spring precipitation following their transit over the relatively warm waters of the Gulf of Mexico. There is a clear gradient of precipitation across the Yucatan Peninsula, with a minimum in the NW (~300 mm), increasing towards the SE (~1,800 mm).

Interannual variability in climate across the Yucatan Peninsula is defined by precipitation, not temperature (which varies more diurnally than annually, annual average ~26°C). The impact of the mid-summer drought (a period of reduced precipitation within the main summer rainy season) appears to be modest in this part of Mexico (Magaña *et al.*, 1999; Perdigón-Morales *et al.*, 2018). Overall, the precipitation climate of the Yucatan Peninsula can appear quite distinctive from the rest of Mexico and does not easily fit in with the main regional clusters identified from analyses of meteorological records (Englehart and Douglas, 2002; Méndez and Magaña, 2010).

2.2 | Dataset

The Yucatan Peninsula has a total of 229 meteorological stations (during the period 1921–2015): 89 in the State of Yucatan, 59 in Quintana Roo and 81 in Campeche. Daily precipitation data for these stations were obtained from Mexico's National Meteorological Service (Servicio Meteorológico Nacional) for the period 1980–2011 inclusive. This time period was based on the data available at the time of this study for the area, no data for the Yucatan Peninsula as a whole were available after 2011 and in order to compile 30 years as proposed by the World Meteorological Organization (WMO), the time period started at 1980. Updated meteorological data are now available at https://smn.conagua.gob.mx/es/component/content/article?id=42.

Data preparation was not trivial due to the lack of uniform data—not all the rainfall records were complete and the data needed to be checked and cleaned prior to use—this was undertaken on the daily precipitation data for all 229 stations. The criteria for this process were

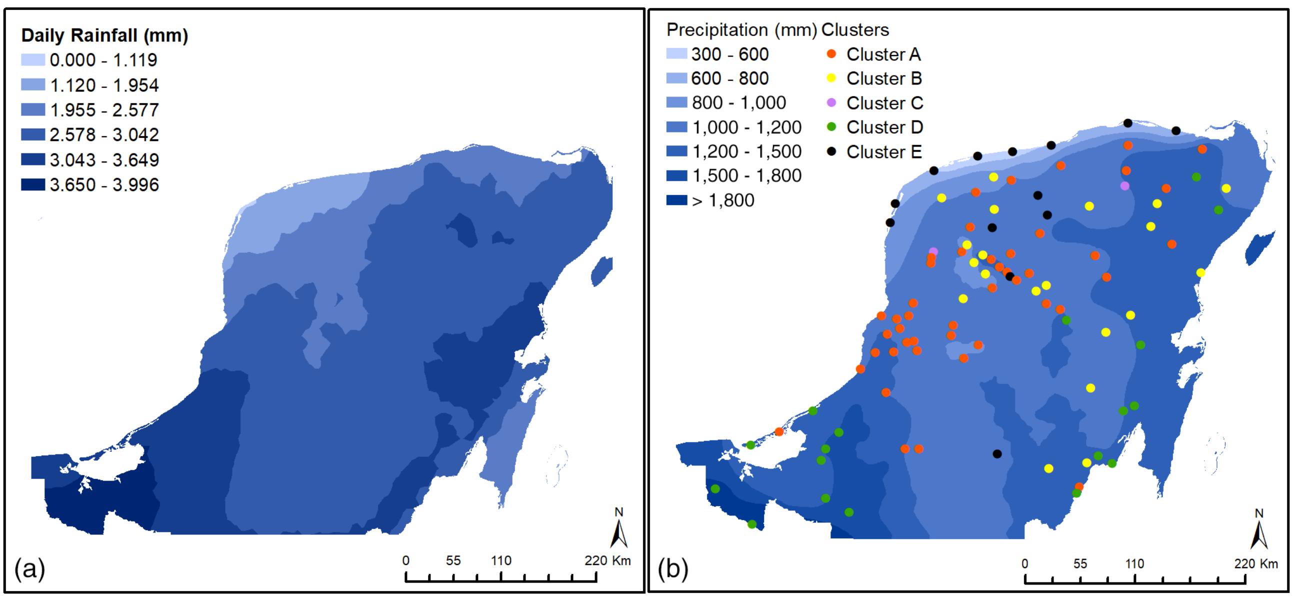

FIGURE 2 (a) Long-term daily precipitation average (1980–2011) map resulted from Kriging analysis; (b) spatial distribution of the clusters (A–E) resulting from the hierarchical cluster analysis on a map that represents the annual precipitation totals across the Yucatan Peninsula [Colour figure can be viewed at wileyonlinelibrary.com]

based on (a) the length of rainfall records and (b) the percentage of data for each station in the period from 1980 to 2011. According to WMO guidelines (WMO, 2017), a station was not considered if observations are missing for 11 or more days during a month or if observations were missing for a period of 5 or more consecutive days during the month. Following these guidelines, in this article a station was identified as "complete" when it had at least 70% (21 days in a month) of data. As a result of this process, 98 stations across the Yucatan Peninsula were included in the final analysis (see Figure 2b below). Monthly average precipitation time series were created from daily precipitation data following the same rule but on a monthly basis; this meant that a complete month must have had at least 70% data capture; the same procedure was applied for annual cumulative precipitation.

2.3 | Methods

2.3.1 | Spatio-temporal rainfall patterns

To understand the spatial regionalization of precipitation, and then its spatio-temporal patterns, a spatial interpolation of the station data was carried out using kriging, a geostatistical method that allows us to calculate the most probable value (precipitation in this case) in places where we do not have information and hence create a surface of precipitation (Goovaerts, 1997; Borrough and McDonnell, 1998). Kriging was used since it has been shown to provide reliable estimates of climatological variables and it performs best when it is used across homogeneous topographic surfaces (Marquínez *et al.*, 2003), which is the case for the Yucatan Peninsula; a predominantly flat area so that orographic effects are not likely to be significant. A long-term (30 year) annual average precipitation map was generated by kriging interpolation to provide a benchmark, then yearly maps using daily precipitation were created at 1.5 km spatial resolution for the same time period (1980–2011). The numbers of stations included in the analysis for each year are given in Table S1. Afterwards, kriging validation was performed using linear regressions between the krigged maps and remotely sensed data from The tropical rainfall measuring mission (TRMM) data (3B42 product). The 3B42 V7 product provides daily precipitation data from the very end of 1997 to the present at 0.25 x 0.25° latitude-longitude (30 m) spatial resolution (Huffman and Bolvin, 2013) and covers the YP. Due to the different spatial resolutions of the TRMM data and our krigged maps, it was necessary to resample and create reduced resolution krigged maps. These maps were converted into ASCII format to be compared with those from TRMM. Several studies have focused on understanding the performance of TRMM products (Kirstetter et al. 2013; Melo et al. 2015) and even with its limitations, it has been considered a good estimator especially in areas of low relief. We used the independent TRMM data for validation instead of doing cross-validation to make the most of the already rather limited data available for the YP.

2.3.2 | Regionalization by cluster analysis

A hierarchical cluster analysis was performed for the 98 stations across the Yucatan Peninsula that met the criteria for inclusion. Cluster analysis is an agglomerative multivariate statistical technique which repeatedly classifies datasets and/or reduces large amounts of data into subgroups or clusters creating a dendrogram where the different possible groups are visible and easy to manage (Olson, 1995; Bravo Cabrera *et al.*, 2012). This methodology does not need previous knowledge about the groups. We hypothesized that if a gradient of precipitation exists in the Yucatan Peninsula, differentiated clusters following this north–south, east–west precipitation gradient would arise from the analysis.

First of all, a dissimilarity matrix was created; then, each station was assigned to its own cluster, and next, based on the distance matrix, the two most similar objects were joined and this operation was repeated until a single cluster was created, including all objects (Murtagh and Legendre, 2011). Within this technique, there are different methods such as single linkage, complete linkage, average linkage, centroid method and Ward's method. In this case, since the dataset contained a large number of missing records, the complete linkage method was selected since it allows for missing data in the analysis. Concurrently, the distance matrix could be calculated by different methods, in this case we used the Euclidian distance, which is the arithmetic difference between two precipitation values. This method is the most straightforward and accepted to compute distances and it is useful to handle raw data (Murtagh and Legendre, 2011).

One of the advantages of using hierarchical clustering is that the number of clusters is defined by the user, the clusters' characteristics need to be analysed at every step and a decision made about when the number of clusters has an interpretable solution and homogenous groups. In order to assess the clusters quality (significance test), a silhouette width method was computed. This is a graphical display to help the cluster analysis interpretation and its goal is to show which objects fit strongly within their cluster, and which objects could belong to either one or other cluster (Rousseeuw, 1987).

2.3.3 | Monthly precipitation in clusters

In order to have a better understanding of the trends in precipitation across the Yucatan Peninsula, a monthly and yearly analysis of the clusters was carried out based on the average data per month per cluster. Bar charts were created to see the monthly distribution of precipitation. Mann-Kendall trend and Sen's slope test were used to see if any trend (positive or negative) in precipitation was present. Afterwards, matrix plots were generated in order to visualize and understand the seasonality for each cluster. Matrices are a powerful way to represent the amount of rain, and the dry/wet periods in a time series. It is also possible to see single extreme events such as hurricanes and they are good way to visualize the differences between clusters.

2.3.4 | Precipitation anomalies

Meteorological drought is defined by the magnitude (in relation to a baseline or average) of the lack or decrease of precipitation over a period of time (e.g., weekly, monthly, seasonal or annual; Orville, 1990; Hayes *et al.*, 2011). In this study, the SPI was used in order to detect such meteorological droughts since this index: (a) is accepted and recommended by the WMO; (b) it uses a rolling mean in its calculation and (c) is standardized, thus it controls for the different variances. It is also the most common and widely used index to monitor meteorological droughts. It was developed by Mckee *et al.* (1993) in order to determine, over different time scales (1, 3 and 9 months, etc.), when there is an abnormally dry period at a given time scale selected by the user. SPI is based on probabilities taking the monthly precipitation data as the unique input. The result of this index is a number for the given period of time that goes from −2 to 2, where values close to −2 are the periods when there is a water deficit, whilst values above zero represent more rain than the long term (the time scale given) precipitation. According to Mckee *et al.* (1993) and as recommended by the World Climate Programme (WCP) 30 years of monthly precipitation data need to be analysed to calculate the SPI.

In order to detect drought conditions in each cluster, the SPI was calculated for each cluster for 1, 3, 6, 9 and 12 months with the programme available in the National Drought Mitigation Center website (NDMC, 2015). Yearly anomaly maps with SPI 12-months results were created in order to be comparable with the precipitation maps.

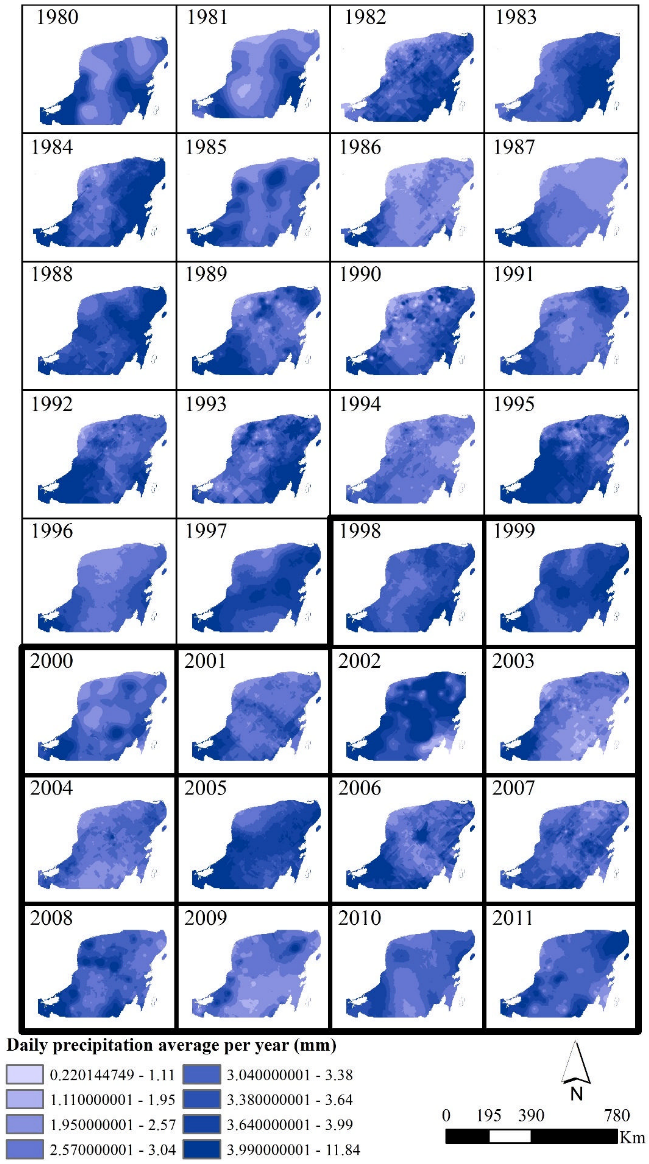

FIGURE 3 Maps (1980–2011) resulting from Kriging analysis. Each map represents the average daily precipitation for a given year in millimetres across the Yucatan Peninsula. Highlighted maps (1998–2011) were validated with TRMM data [Colour figure can be viewed at wileyonlinelibrary.com]

3 | RESULTS

3.1 | Spatio-temporal rainfall patterns

The long-term daily precipitation map (Figure 2a) shows the precipitation variability across the Yucatan Peninsula, with lowest values in the north and highest values in the southwest and southeast of the peninsula consistent with previous mapping exercises (e.g., Estrada-Medina *et al.*, 2016). Figure 2a also provides the point of comparison with the precipitation surfaces shown in Figure 3.

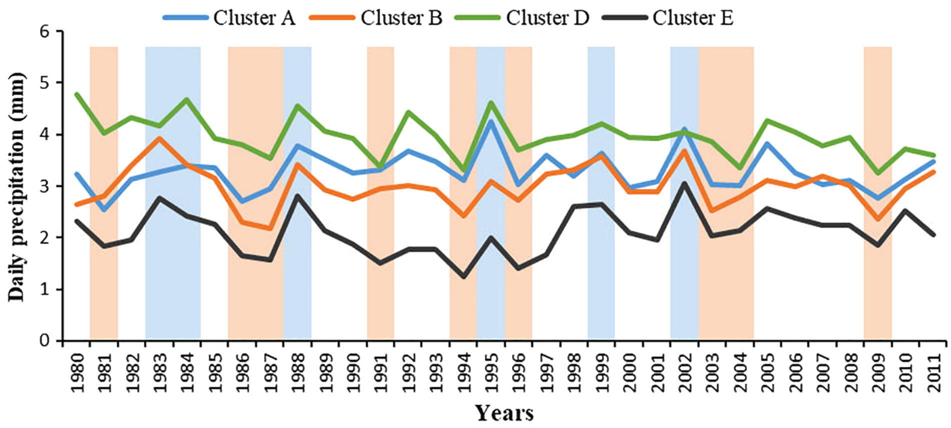

FIGURE 4 Cluster daily precipitation average (in mm) from 1980 to 2011. Each line represent the time series of each cluster. Orange bars indicate the dry years and blue bars the wet years for all clusters [Colour figure can be viewed at wileyonlinelibrary.com]

However, precipitation surfaces for each year for the period 1980–2011 (Figure 3) show that there is also variability in the pattern of precipitation across the Yucatan Peninsula between years. Although the broad N-S gradient is consistent, the spatial distribution of rainfall changes year by year. There are clearly some years (1981, 1986, 1987, 1994, 1996, 2003, 2004 and 2009) that are drier than others and some (1983, 1984, 1988, 1992, 1995, 2002 and 2005) that are wetter.

3.2 | Regionalization by cluster analysis

The hierarchical cluster analysis produced five clusters. Cluster spatial distribution is shown in Figure 2b and, as we hypothesised, the resulting groups follow the precipitation gradient across the Yucatan Peninsula. The spatial distribution shows that the clusters are spatially coherent, and that the two clusters with the highest significance values are those located in the north (E) and southeast and southwest (D) of the peninsula. The northern coast is dominated by one cluster (E) and as is shown in Figure 2b, is the driest part of the Peninsula. The central part of the Peninsula has three (A, B and C) fuzzy and overlapping clusters; Clusters A and B have the largest number of stations, whilst C is formed by only two stations (with lots of missing data) and is the cluster with the lowest value of significance. For this reason, from now on, cluster C will not be discussed. The overlapping clusters are in the most homogenous region in terms of precipitation values (Figure 2b) and this might be the reason why the clusters are similar. The locations with most rainfall fall within Cluster D, located in the southeast and southwest of the Yucatan Peninsula. Figure 4 shows average daily precipitation per year for each cluster and the variability within each cluster (standard deviation) is shown in Figure S1. The wettest cluster (D) is represented by the green line, where daily average precipitation exceeds that in all other clusters. Most of the stations of this cluster receive 1,200–1,800 mm precipitation per year. The driest cluster (E) is represented by the yellow line where most stations receive between 300 and 800 mm. The cluster analysis was useful to identify patterns in the data and confirmed the previously identified north–south rainfall gradient across the Yucatan Peninsula García, 1998). Other studies (Arbingast *et al.*, 1975; Bravo Cabrera *et al.*, 2012) have placed the three states of the peninsula within a single precipitation regime, whereas the analysis here shows more climatic variation across this area.

Mann Kendall trend and Sen's slope were computed for each cluster and it is notable that only the wettest (Cluster D) shows a significant negative trend (Z score = −2.45) suggesting that in the southern part of the Yucatan Peninsula precipitation has decreased over the period 1980–2011. Clusters in the centre and north, however, do not show any statistically significant trend, indicating that precipitation in these clusters has been relatively constant over this time period.

3.3 | Monthly precipitation in clusters

To represent and identifying seasonality (i.e., dry/wet months) from the monthly precipitation data, as well as to identify extreme events (i.e., abnormally dry or wet months) in each cluster we plotted matrices (Figure 5) of the monthly values for each year with the HydroTSM package (Zambrano-Bigiarini, 2012). Colours in these matrices represent the amount of rainfall in the given month and year. These plots make it easy to compare visually between months and years.

As might be expected all the matrices change colour from the dry season (red) to the wet season (yellow–blue), showing the basic seasonal pattern. Dry and wet periods in winter and summer respectively are very clear. The dry season is from November to May, when the rainfall starts increasing and the wet season is from June to

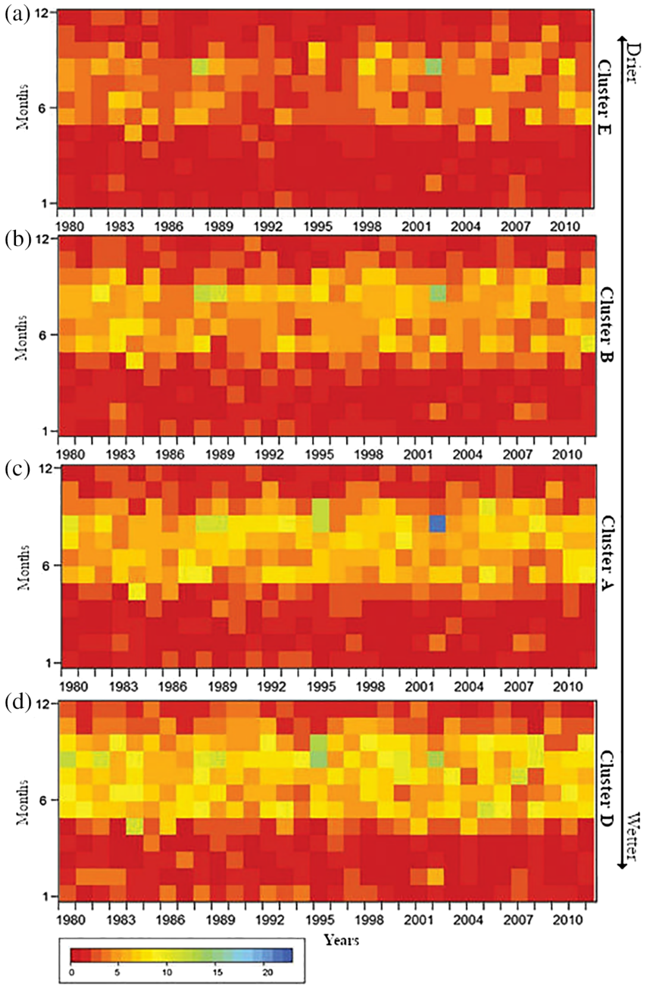

FIGURE 5 Matrix plots of daily average precipitation by month. *x*-axis represent the years (1980–2011) and *y*-axis are the months. (a) Cluster E; (b) Cluster B; (c) Cluster A; (d) Cluster D (from driest to wettest). Different colours represent the amount of precipitation in mm [Colour figure can be viewed at wileyonlinelibrary.com]

October. February and March are the driest months, whilst September is the wettest month across the Yucatan Peninsula. Despite this dry season, it should be noted that there are always rain events during the dry season across the study area and most of these events are related to cold fronts (*nortes* see above). In the same figure, there is some evidence of the midsummer drought (known as *canicula*) which occurs during July.

From these results, it is clear that the total amount of rain varies between clusters. Cluster E is the driest and it is marked by a predominance of red colour, whilst Cluster D is the wettest and has most rainfall events even during winter, in particular during November and December. This latter cluster is located in the southern part of the Yucatan Peninsula quite close to the wettest area in the whole of Mexico (Esparza, 2014). The importance of winter rain has been identified by Bravo Cabrera *et al.* (2012) who linked the Yucatan Peninsula with NW Mexico on this basis, even though the sources of this rainfall are different.

High amounts of rainfall in a given year and month can be seen in these matrices. The most extreme precipitation events are represented by the blue squares. Hurricanes and tropical storms are important events that hit the Yucatan Peninsula every year, mainly during September and October. Tropical storm activity was identified by Englehart and Douglas (2002) as one reason why meteorological sites in Yucatan and Campeche formed a subregional cluster in the context of Mexico as a whole. Some individual hurricanes can be identified in the matrices, for example, the highest amount of rainfall recorded for all clusters and almost for all individual stations was in September 2002, which was the month that hurricane *Isidore* (Category III), hit the Mexican coast. It resulted in a large amount of rainfall over 2 days and caused major social and economic impacts (the government declared a disaster area). Similarly, in 1988, the clusters show (Figures 4 and 5) an increase in rainfall amount reflecting hurricane *Gilbert* (Category V) and in 1995 with tropical storm named *Opal* (September) and hurricane *Roxanne* (October). There is little evidence in the results of the impact of the Category 5 hurricane *Dean* (2007), possibly because it weakened rapidly as it crossed the southern part of the Yucatan Peninsula and brought strong winds rather than high rainfall.

3.4 | Precipitation anomalies

3.4.1 | Drought detection in clusters

Results of SPI computations monthly, for each year, for each cluster are shown in Figure 6. Years (from 1980 to 2011) are on the *x*-axis and the *y*-axis represents the time scale (months). All clusters show a recurrence of Peninsula-wide dry periods (red/orange colours) in 1981, 1986–1987, 1994 (see also Figure 4) and 2009 and some wet years such as in 1983–1984 (blue/green colours).

It is worth noting that there are some years (e.g., 1995, 1996 and 2004) when the dry and wet periods are different between clusters and these differences are also reflected in the drought maps (Figure 7) where just certain areas of the Yucatan Peninsula were affected either by droughts (1996 and 2004) or wet periods (1995).

Different values of SPI between years indicate the spatial variability of droughts across the area. For example, as mentioned above, 2004 presents different values between clusters; in Cluster E (northern) conditions were wetter, whereas clusters D, B (southern and central) and

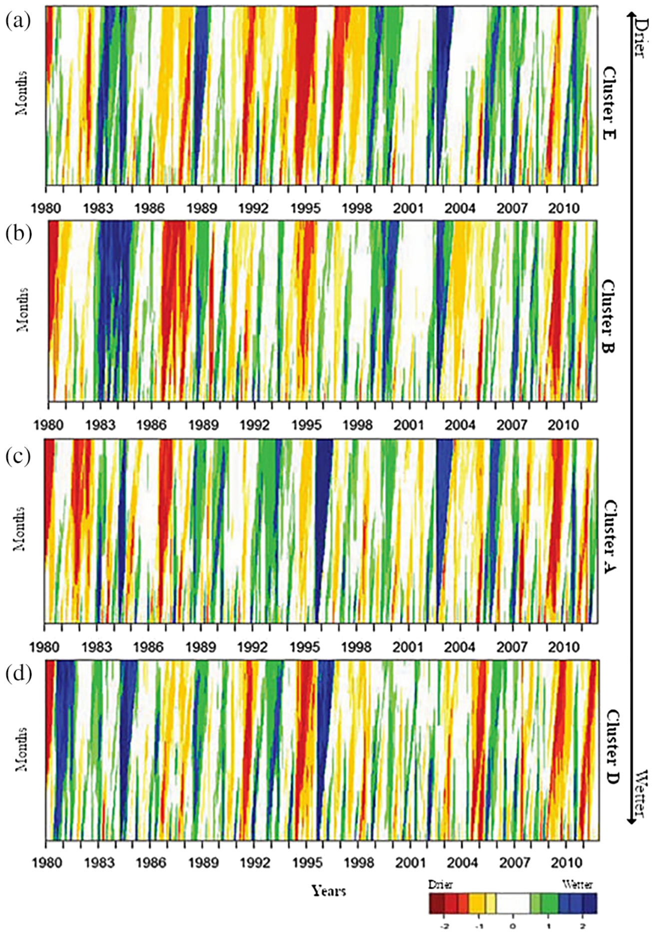

FIGURE 6 Standardized Precipitation Index (SPI) computed for each cluster at different time scales (1–12 months). Year from 1980 to 2011 on *x*-axis and *y*-axis represents the SPI time scale (months) from SPI-1 to SPI-12 for each cluster. (a) Cluster E; (b) Cluster B; (c) Cluster A; (d) Cluster D (from driest to wettest) [Colour figure can be viewed at wileyonlinelibrary.com]

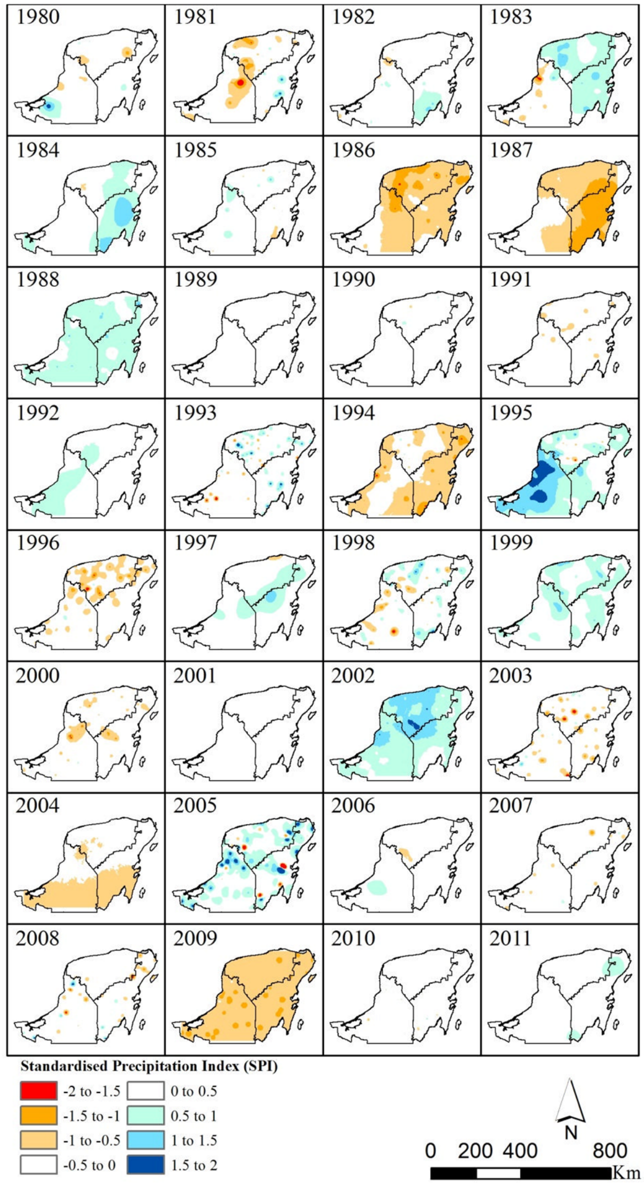

FIGURE 7 Maps showing the krigged annual SPI. Each map represents each year from 1980 to 2011. The scale is based on the North American Drought Monitor (NADM): (i) closer to −2: Low precipitation over 12 months; (ii) approximately 0: Normal precipitation over 12 months; (iii) closer to 2: Heavy precipitation over 12 months [Colour figure can be viewed at wileyonlinelibrary.com]

to a lesser extent A(central) experienced dry conditions. These findings are consistent with some patterns that can be seen in Figure 3 where the northern part of the Yucatan Peninsula seems to have normal conditions, whilst the southern part is drier.

3.4.2 | Spatio-temporal drought patterns

SPI 12-month time scale surfaces were created using the same technique as the precipitation dataset, showing the spatial and temporal variability of drought events for the period 1980–2011 (Figure 7).

Severe droughts occurred in 1981, 1986, 1987, 1994, 1996, 2004 and 2009. These findings are consistent with those resulting from the cluster analysis (Figure 6) and with the daily rainfall by cluster (Figure 4). The results are also consistent with some droughts reported in the literature. For instance, Giddings and Soto (2003) reported 1986 and 1987 as dry years in the central and north part of the study area, and Márdero *et al.* (2012) reported 1986 and 1994 as the years with largest negative anomalies during the period of 1953–2007; and 1987 with weaker negative anomalies. Diaz-Esterban and Raga (2018), focusing just on precipitation between May and October, identify 1997, 2003–2004 and 2009 as dry years. The drought analysis for 1982–2013 published by

CONAGUA (2014) shows that in the state of Yucatan the driest year was 1986 (22% below average), whereas in Campeche and Quintana Roo the driest year was 2009 (22.7 and 29.8% below average, respectively). These results are consistent with those presented in Figure 7. Wetter years (1983, 1984, 1988, 1992, 1995, 2002 and 2005) can be also identified in these maps. 1983 and 2005 were also identified as wetter than average years by Salas *et al*. (2014) and Diaz-Esterban and Raga (2018), respectively. Some extreme events are also reflected in these results, for example, hurricane *Isidore* in 2002 (see above).

CONAGUA through the Monitor de Sequías Multivariado en México (MoSeMM) has created drought surfaces for the whole Mexico (https://smn.cna.gob.mx/es/climatologia/monitor-de-sequia/monitor-de-sequia-en-mexico). Their methodology creates a multivariate drought index, using SPI, humidity and runoff data from MERRA-2. The results presented in our article are consistent with their findings both spatially and temporally. The driest years identified in our analysis (1986, 1987, 1994, 1996, 2004 and 2009) are also apparent in the CONAGUA results. The CONAGUA drought record by municipality (CONAGUA, 2018) also shows that all municipalities in the Yucatan Peninsula experienced droughts during 2009.

SPI kriging maps in combination with the analysis of precipitation variability and the cluster analysis give valuable information about the occurrence of droughts in the Yucatan Peninsula and indicate how these methodologies can improve the detection and monitoring of drought intensity and duration.

4 | DISCUSSION AND CONCLUSIONS

This research is a contribution towards a better understanding of the spatial and temporal variability of precipitation in the Yucatan Peninsula using rainfall records. According to the IPCC (2013), Mexico is particularly vulnerable to climate change and both precipitation and temperature are changing. Montero-Martínez *et al*. (2013) found a general decrease in precipitation projections across Mexico for this century, although the analysis of Colorado-Ruiz *et al*. (2018) indicates that there may be more spatial variability than suggested by this earlier study, with greater drying in the south. Together with the socio-economic conditions in the Yucatan Peninsula, this can have consequences for peoples' livelihoods and food security.

Although a precipitation gradient across the Yucatan Peninsula has been reported in the literature (García, 1998; Torrescano-Valle and Folan, 2015), we have analysed more recent data at spatial and temporal resolutions not previously seen. The combination of kriging and cluster analysis offered a more complete insight into precipitation variability. This is significant as regional studies are necessary to understand climatic changes and their impact on local scales. Despite the different amount of rainfall every year, as well as the uneven spatial distribution, only the south of the Yucatan Peninsula (Cluster D) presented a long-term negative trend in annual precipitation. Other clusters showed no systematic trends towards drier or wetter conditions during the period 1980–2011, at least in the overall total.

As described above, some years of distinct positive precipitation anomalies are clearly associated with the impacts of tropical cyclones crossing the peninsula. The relationship between storm intensity and precipitation is not straight forward however; storm *Opal* (1995) was only a weak depression when it made landfall, but it moved very slowly across the Yucatan Peninsula and produced prolonged rain, particularly in the SW (Campeche and Tabasco). Just few weeks after *Opal*, hurricane *Roxanne* struck the Yucatan Peninsula as Category 3, bringing large amounts of rain, for instance in Silvituc (centre of Campeche) up to 676 mm of rain was recorded. This is evident in the SPI map (Figure 7). Hurricane *Isidore* (2002, Category 3) was unusual as it made landfall on the north coast of the peninsula and then looped south, before turning north again. It brought heavy rain (>700 mm in places) across the north and centre of the peninsula. The extreme nature of precipitation associated with this event is apparent in both the matrix plots (Figure 5) and its spatial extent in the SPI maps (Figure 7). Category 5 Hurricane *Gilbert* (1988) crossed the northern part of the Yucatan Peninsula bringing the largest amounts of rain to the north coast (350 mm in the port of Progreso). In addition, the SPI and kriging maps show that 1984 was a particularly wet year, even though no extreme events were reported. CONAGUA (2016, 2017) reported 1984 as the wettest year for the whole of Mexico for the period from 1940 to 2016–2017.

With respect to the extremes of precipitation leading to a drought, the precipitation data were used in two ways to detect where and when droughts had occurred across the Yucatan Peninsula, during the period 1980–2011. Maps of SPI and precipitation anomalies showed that the years of 1981, 1986, 1987, 1994, 1996, 2003 and 2009 were those that could be described as having had a drought. Márdero *et al*. (2012) analysed precipitation in the southern part of the Yucatan Peninsula and also found that 1986, 1987 and 1994 were years with negative rainfall anomalies. 2009 was one of the driest years in the history of the Mexico (Esparza, 2014) and the second most damaging in terms of reported economic losses (>US$150 million). This drought affected most of Mexico, with Quintana Roo and Yucatan amongst the worst affected states and has been attributed to the moderate El Niño of 2009-10. The droughts identified here in 1986 and 1987 coincide with extended El Niño conditions between 1986 and 1988. An analysis of historic droughts in Southeastern Mexico by Mendoza *et al.* (2006) also shows a periodicity consistent with ENSO (3–7 years). The association of El Niño events with droughts in southern Mexico (including the Yucatan Peninsula) has been noted by Magaña *et al.* (2003) and Salas and Jones (2014), even though such events may actually increase winter (dry season) precipitation (Magaña *et al.*, 2003; Salas *et al.*, 2014). Diaz-Esterban and Raga (2018) report that El Niño events may increase the likelihood of weather regimes that are associated with below average precipitation across the Yucatan Peninsula and southern Mexico (whilst noting that other weather regimes seem unaffected by ENSO state). It is possible that positive SPI values shown in 1983 and 1997 (see Figure 7) were at least partly driven by the positive winter rainfall anomalies associated with major El Niño of 1982–1983 and 1997–1998 reported by Salas *et al.* (2014). There is, however, some evidence for dry conditions in 1998 particularly in the south and west of the peninsula (see Figures 6 and 7). García and Matías (2002) report a major drought across the Yucatan Peninsula in June 1998, with the loss of 5,000 ha of maize and pasture. Unlike the 2009 drought, our annual analysis shows little evidence of the 2011 Mexican drought which nationally was the worst in more than 70 years, although the municipal drought index (see above) does indicate that there were some months of drought in all municipalities of the Yucatan Peninsula during that year. The 2011 drought mainly affected northern Mexico. This may reflect the fact that 2011 saw the co-occurrence of strong La Niña conditions and positive AMO (Atlantic Multidecadal Oscillation), both of which tend to cause dry conditions in northern Mexico and wet conditions in southern Mexico and Central America (Méndez and Magaña, 2010), the dipole referred in Section 1.

Understanding precipitation variability is key in the study of climate change, as well as the detection and monitoring of droughts. The findings of this investigation complement those of earlier studies and this research provides a framework for the exploration of drought occurrence spatially and temporally. Here, we have focused on the Yucatan Peninsula, but this methodology could usefully be applied elsewhere. Moreover, with climate change being linked to change in precipitation (Villers-Ruiz and Trejo-Vázquez, 1997; Orellana *et al.*, 2009; IPCC, 2013), ongoing studies to understand the patterns of precipitation are particularly important in areas like the Yucatan Peninsula facing a combination of climatic, social and economic problems such as poverty and low levels of development. Droughts often occur at different times in different parts of the Yucatan Peninsula, highlighting the importance of higher spatial resolution analyses for this area. This spatial variability also has implications for the validity of climate projections from standard grid-size global climate models which generally perform rather poorly for Mexico (e.g., Pascale *et al.*, 2018).

Our work has illustrated the spatial and temporal complexity of precipitation and the distribution of droughts across the Yucatan Peninsula, a complexity that will probably continue into the future. Although we have focused here on the importance of understanding this variability in the context of recent and possible future change, this approach also offers some intriguing possibilities in improving our understanding of past climate-society interactions, here specifically associated with the Terminal Classic dry period (ca. 900 CE) and the associated widespread reorganization of Classic Maya culture. It highlights the need for a well distributed and reliable network of meteorological stations that can provide the long term, continuous records required for this sort of analysis and to detect patterns of change. As noted in Section 1, the history of the collection of meteorological data across Mexico has been problematic and our own study was hindered by the fact that data for the period after 2011 were not readily available for all states in our study region. Although beyond the scope of this research, a detailed consideration of the synoptic conditions, including the status of features such as ENSO/PDO and NAO/AMO that gave rise to the observed patterns would greatly enhance its value in terms of contributing to improved understanding of future climate scenarios. Diaz-Esterban and Raga (2018) have explored some of these relationships for the period 1997–2013, but taking the region as a whole. Given the similarities between southern Mexico (including the Yucatan Peninsula), Central America and at least parts of the Caribbean in terms of their responses to climatic forcings (e.g., Magaña *et al.*, 1999) our approach could usefully be extended to the wider region, although the availability of meteorological records would probably be a major constraint (Stephenson *et al.*, 2014) and the greater role of topography taken into account. Within the Yucatan Peninsula itself, our results do allow a more detailed assessment of the impacts of climatic variability over the period 1980–2011 which will be explored in a future paper. The complexity shown by this study could provide insights helpful to future drought mitigation (see

Magana, 2016) and is also likely to be indicative of the variability that will typify future climate change.

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REFERENCES

Aguilar, E., Peterson, T.C., Obando, P.R., Frutos, R., Retana, J.A., Solera, M., Soley, J., García, I.G., Araujo, R.M., Santos, A.R., Valle, V.E., Brunet, M., Aguilar, L., Álvarez, L., Bautista, M., Castañón, C., Herrera, L., Ruano, E., Sinay, J.J., Sánchez, E., Oviedo, G.I.H., Obed, F., Salgado, J.E., Vázquez, J.L., Baca, M., Gutiérrez, M., Centella, C., Espinosa, J., Martínez, D., Olmedo, B., Espinoza, C.E.O., Núñez, R., Haylock, M., Benavides, H. and Mayorga, R. (2005) Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *Journal of Geophysical Research: Atmospheres*, 110, D23. https://doi.org/10.1029/2005jd006119.

Amador, J.A., Alfaro, E.J., Lizano, O.G. and Magaña, V.O. (2006) Atmospheric forcing of the eastern tropical Pacific: a review. *Progress in Oceanography*, 69, 101–142. https://doi.org/10.1016/j.pocean.2006.03.007.

Arbingast, S.A., Holz, R.K., Gill, C.C. and Weiler, J.P. (1975) *Atlas of Mexico*, 2nd edition. Austin, TX: University of Texas.

Arriaga, L., Castellanos, A.E., Moreno, E. and Alarcón, J. (2004) Potential ecological distribution of alien invasivesSpecies and risk assessment: a case study of Buffel grass in arid regions of Mexico. *Conservation Biology*, 18, 1504–1514. https://doi.org/10.1111/j.1523-1739.2004.00166.x.

Ayram, C.A.C., Mendoza, M.E., Etter, A. and Salicrup, D.R.P. (2017) Anthropogenic impact on habitat connectivity: A multidimensional human footprint index evaluated in a highly biodiverse landscape of Mexico. *Ecological Indicators*, 72, 895–909. https://doi.org/10.1016/j.ecolind.2016.09.007.

Bhattacharya, T. and Chiang, J.C. (2014) Spatial variability and mechanisms underlying El Niño-induced droughts in Mexico. *Climate Dynamics*, 43, 3309–3326. https://doi.org/10.1007/s00382-014-2106-8.

Boose, E.R., Foster, D.R., Plotkin, A.B. and Hall, B. (2003) Geographical and historical variation in hurricanes across the Yucatan Peninsula. In: Gómez-Pompa, A., Allen, M.A., Fedick, S.L. and Jiménez-Osornio, J. (Eds.) *The Lowland Maya Area. Three millennia at the Human-Wildlife Interface*. New York: Haworth Press, pp. 495–516.

Borrough, P.A. and McDonnell, R.A. (1998) *Principles of Geographical Information Systems*. New York: Oxford University Press, p. 333.

Bravo Cabrera, J., Azpra Romero, E., Zarraluqui Such, V., Gay García, C. and Estrada Porrúa, F. (2012) Cluster analysis for validated climatology stations using precipitation in Mexico. *Atmósfera*, 25, 339–354 Available at: http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0187-62362012000400003&lng=es&nrm=iso.

Christensen, J.H., Krishna Kumar, K., Aldrian, E., An, S.-I., Cavalcanti, I.F.A., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, J., Lau, N.-C., Renwick, J., Stephenson, D.B., Xie, S.-P. and Zhou, T. (2013) Climate phenomena and their relevance for future regional climate change. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (Eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Colorado-Ruiz, G., Cavazos, T., Antonio Salinas, J., De Grau, P. and Ayala, R. (2018) Climate change projections from coupled model Intercomparison project phase 5 multi-model weighted ensembles for Mexico, the north American monsoon and the summer drought region. *International Journal of Climatology*, 38, 5699–5716. https://doi.org/10.1002/joc.5773.

CONAGUA. (2012) *Servicio Meteorológico Nacional: 135 años de historia en México*. México: Semarnat, p. 76.

CONAGUA. (2014) Programa de Medidas Preventivas y de Mitigación de la Sequía del Consejo de Cuenca Península de Yucatán (PMPMS-CCPY). In: *Comisión Nacional del Agua, Universidad Autónoma de Yucatán (UADY)*. México: Comision Nacional del Agua.

CONAGUA. (2016) Reporte del clima en México. Coordinación General del Servicio Meteorológico Nacional Gerencia de Meteorología y Climatología. Subgerencia de Pronóstico a Mediano y Largo Plazo. Reporte anual 2016. México.

CONAGUA. (2017) Reporte del clima en México. Coordinación General del Servicio Meteorológico Nacional Gerencia de Meteorología y Climatología. Subgerencia de Pronóstico a Mediano y Largo Plazo. Reporte anual 2017. México.

CONAGUA. (2018) *Monitor de Sequía en México*. Mexico: Datos y Recursos Available at: https://datos.gob.mx/busca/dataset/monitor-de-sequia-en-mexico.

CONEVAL. (2016) Evolución de la pobreza y pobreza extrema nacional y en entidades federativas, 2010, 2012, 2014 y 2016. Mexico: Consejo Nacional de Evaluación de la Política de Desarrollo Social. Informe anual. México.

Cuervo-Robayo, A.P., Téllez-Valdés, O., Gómez-Albores, M.A., Venegas-Barrera, C.S., Manjarrez, J. and Martínez-Meyer, E. (2014) An update of high-resolution monthly climate surfaces for Mexico. *International Journal of Climatology*, 34, 2427–2437.

Curtis, J.H., Hodell, D.A. and Brenner, M. (1996) Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. *Quaternary Research*, 46, 37–47.

Curtis, S. (2013) Daily precipitation distributions over the intra-Americas sea and their interannual variability. *Atmósfera*, 26 (2), 243–259.

de CD Melo, D., Xavier, A.C., Bianchi, T., Oliveira,P.T., Scanlon, B. R., Lucas, M.C. and Wendland, E. (2015) Performance evaluation of rainfall estimates by TRMM multi-satellite precipitation analysis 3B42V6 and V7 over Brazil. *Journal of Geophysical Research: Atmospheres*, 120(18), 9426–9436.

Diario Oficial de la Federación (DOF). (2013) Estrategia nacional de cambio climático (ENCC). Visión 10-20-40 Gobierno de la República Estrategia nacional de cambio climático Visión 10-20-40. In: *Diario Oficial de la Federación*. México: Gobierno de la Republica.

Diaz-Esterban, Y. and Raga, G.B. (2018) Weather regimes associated with summer rainfall variability over Southern Mexico. *International Journal of Climatology*, 38, 169–186.

Easterling, D.R. (2013) Global data sets for analysis of climate extremes. In: AghaKouchak, A., Easterling, D., Hsu, K., Schubert, S. and Sorooshian, S. (Eds.) *Extremes in a Changing Climate*. Dordrecht: Springer, pp. 347–361.

Eastmond, A., Garcia, A. and Cordoba, J. (2000) Recent population and education trends on the Yucatan peninsula. *Research Report-International Institute for Applied Systems Analysis IIASA RR*, 14, 54–72.

Englehart, P. and Douglas, A. (2002) Mexico's summer rainfall patterns: an analysis of regional modes and changes in their teleconnectivity. *Atmosfera*, 15, 147–164.

Esparza, M. (2014) La sequía y la escasez de agua en México: Situación actual y perspectivas futuras. *Secuencia*, 89, 193–219.

Estrada-Medina, H., Cobos-Gasca, V., Acosta-Rodríguez, J.L., Peña-Fierro, S., Castilla-Martínez, M., Castillo-Carrillo, C., Franco-Brito, S., López-Castillo, D., López-Díaz, M., Luna-Flores, W., Maldonado-Repetto, A., Álvarez-Rivera, O., Cámara-Romero, J. L., Morales-Guadarrama, A., Moreno-Arjona, A.M., Pérez-Niño, B., Rodríguez-Lara, P. and Zapata-Luna, R.L. (2016) La sequía de la península de Yucatan. *Tecnología y Ciencias del Agua*, 7(5), 151–165.

Evans, N.P., Bauska, T.K., Gázquez-Sánchez, F., Brenner, M., Curtis, J.H. and Hodell, D.A. (2018) Quantification of drought during the collapse of the classic Maya civilization. *Science*, 361 (6401), 498–501. https://doi.org/10.1126/science.aas9871.

Ewell, P.T. (1984) *Intensification of Peasant Agriculture in Yucatan*. Doctoral dissertation, Cornell University Ithaca, New York.

Fernández-Eguiarte, A., Zavala-Hidalgo, J. and Romero-Centeno, R. (2018) *Atlas climático digital de México*. Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México. Available at: http://uniatmos.atmosfera.unam.mx/

García, A.,.E. and García, E. (1973) *Modificaciones al sistema de clasificación climática de Köppen (para adaptarlo a las condiciones de la república mexicana)*. México: Instituto de Geografía, UNAM.

García, E. (1998) Precipitación total anual. CONABIO. Escala 1:1 000 000. México. Available at: http://www.conabio.gob.mx/informacion/metadata/gis/isoyt1mgw.xml?_httpcache=yes&_xsl=/db/metadata/xsl/fgdc_html.xsl&_indent=no

García, F.F.O. and Matías, L.G. (2002) *Sequías. Centro Nacional para la Prevención de Desastres (CENAPRED). Serie Fasciculos*, 1st edition. Mexico: Secretaría de Gobernación.

Giddings, L. and Soto, M. (2003) Rhythms of precipitation in the Yucatan Peninsula. In: Gómez-Pompa, A., Allen, M.F., Fedick, S.J. and Jiménez-Osornio, J. (Eds.) *The Lowland Maya Area*. New York: *Three millennia at the Human-Wildland interface*. Haworth Press, pp. 77–90.

Goovaerts, P. (1997) *Geostatistics for Natural Resources Evaluation*. New York: Oxford University Press.

Hayes, M., Svoboda, M., Wall, N. and Widhalm, M. (2011) The Lincoln declaration on drought indices: universal meteorological drought index recommended. *Bulletin of the American Meteorological Society*, 92, 485–488.

Huffman, G.J. and Bolvin, D.T. (2013) TRMM and other data precipitation data set documentation. Greenbelt, MD: NASA, 28 (2.3), 1.

Imbach, P., Molina, L., Locatelli, B., Roupsard, O., Mahé, G., Neilson, R., Corrales, L., Scholze, M. and Ciais, P. (2012) Modeling potential equilibrium states of vegetation and terrestrial water cycle of Mesoamerica under climate change scenarios. *Journal of Hydrometeorology*, 13, 665–680. https://doi.org/10.1175/JHM-D-11-023.1.

INEGI. (2018) Cuéntame. Available at: http://www.cuentame.inegi.org.mx. Viewed 16 October, 2018.

IPCC. (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Kirstetter, P.E., Hong, Y., Gourley, J.J., Schwaller, M., Petersen, W. and Zhang, J. (2013) Comparison of TRMM 2A25 products, version 6 and version 7, with NOAA/NSSLground radar-based National Mosaic QPE. *Journal of Hydrometeorology*, 14(2), 661–669.

Lobato-Sánchez, R. (2016) El monitor de la sequía en México. *Tecnología y Ciencias del Agua*, 7(5), 197–211.

Magana, V. (2016) Considerations for a research program on drought in Mexico. *Water Technology and Sciences*, 7(5), 115–133.

Magaña, V., Amador, J.A. and Medina, S. (1999) The midsummer drought over Mexico and Central America. *Journal of Climate*, 12, 1577–1588. https://doi.org/10.1175/1520-0442.

Magaña, V., Zermeño, D. and Neri, C. (2012) Climate change scenarios and potential impacts on water availability in northern Mexico. *Climate Research*, 51, 171–184.

Magaña, V.O. and Caetano, E. (2007) Pronóstico climático estacional regionalizado para la República Mexicana como elemento para la reducción de riesgo, para la identificación de opciones de adaptación al cambio climático y para la alimentación del sistema: cambio climático por estado y por sector. *Informe final, Número de proyecto: INE/A1–006/2007 (Final report. Project number: INE/A1–006/2007)*. Dirección General de Investigación sobre cambio climático, INE y Centro de Ciencias de la Atmósfera, UNAM: Mexico, DF, Mexico. Available at: http://www2.inecc.gob.mx/descargas/cclimatico/e2007o.pdf

Magaña, V.O., Vázquez, J.L., Pérez, J.L. and Pérez, J.B. (2003) Impact of El Niño on precipitation in Mexico. *Geofisica Internacional*, 42, 313–330.

Márdero, S., Nickl, E., Schmook, B., Schneider, L., Rogan, J., Christman, Z. and Lawrence, D. (2012) Sequías en el sur de la península de Yucatán: análisis de la variabilidad anual y estacional de la precipitación. *Investigaciones Geográficas, Boletin del Instituto de Georgafia*, 78, 19–33.

Márdero, S., Schmook, B., López-Martínez, J., Cicero, L., Radel, C. and Christman, Z. (2018) The uneven influence of climate trends and agricultural policies on maize production in the Yucatan Peninsula, Mexico. *Land*, 7, 80. https://doi.org/10.3390/land7030080.

Marquínez, J., Lastra, J. and García, P. (2003) Estimation models for precipitation in mountainous regions: the use of GIS and multivariate analysis. *Journal of Hydrology*, 270, 1–11. https://doi.org/10.1016/S0022-1694.

Mckee, T.B., Doesken, N.J. and Kleist, J. (1993) The relationship of drought frequency and duration to time scales. In: *Proceedings of the 8th Conference on Applied Climatology*, Vol. 18. Boston, MA: American Meteorological Society, pp. 179–183.

Méndez, M. and Magaña, V. (2010) Regional aspects of prolonged meteorological droughts over Mexico and Central America. *Journal of Climate*, 23, 1175–1188. https://doi.org/10.1175/2009JCLI3080.1.

Mendoza, B., Velasco, V. and Jáuregui, E. (2006) A study of historical droughts in southeastern Mexico. *Journal of Climate*, 19, 2916–2934. https://doi.org/10.1175/JCLI3726.1.

Meyer, J.D. and Jin, J. (2017) The response of future projections of the north American monsoon when combining dynamical downscaling and bias correction of CCSM4 output. *Climate Dynamics*, 49, 433–447. https://doi.org/10.1007/s00382-016-3352-8.

Montero-Martínez, M.J., Ojeda-Bustamante, W., Santana-Sepúlveda, J.S., Prieto-González, R. and Lobato-Sánchez, R. (2013) Sistema de consulta de proyecciones regionalizadas de cambio climático para México. *Tecnología y Ciencias del Agua*, 4, 113–128.

Murtagh, F. and Legendre, P. (2011) Ward's hierarchical clustering method: clustering criterion and agglomerative algorithm. *arXiv preprint arXiv:1111.6285*, 31(3), 274–295. https://doi.org/10.1007/s00357-014-9161-z.

NDMC. (2015) Program to Calculate Standardized Precipitation Index. Available at: http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx.

Nicholls, N., Seneviratne, S., Reichstein, M., Sorteberg, A., Vera, C. and Zhang, X. (2012) Changes in Climate Extremes and their Impacts on the 1 Natural Physical Environment 2. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge, London and New York, NY: IPCC.

Núñez, J.H., Verbist, K., Wallis, J.R., Schaefer, M.G., Morales, L. and Cornelis, W. (2011) Regional frequency analysis for mapping drought events in north-Central Chile. *Journal of Hydrology*, 405, 352–366. https://doi.org/10.1016/j.jhydrol.2011.05.035.

Olson, C.F. (1995) Parallel algorithms for hierarchical clustering. *Parallel Computing*, 21(8), 1313–1325.

Orellana R. E., Espadas, C., Conde, C., Gay, C. (2009) Atlas escenarios de cambio climático en la Península de Yucatán (No. CY/574.522209726 A8). Mérida: Centro de Investigación Científica de Yucatán (CICY), México.

Orellana, R.E., Islebe, G. and Espadas, C. (2003) Presente, pasado y futuro de los climas de la Península de Yucatan. In: Colunga-García Marín, A. and Larqué, S.P. (Eds.) *Naturaleza y Sociedad en el Área Maya: Pasado. Presente y Futuro*. Mexico City: Academia Mexicana de Ciencias and Centro de Investigación Científica de Yucatán, pp. 37–52.

Orville, H.D. (1990) AMS statement on meteorological drought. *Bulletin of the American Meteorological Society*, 71, 1021–1025.

Pascale, S., Kapnick, S.B., Bordoni, S. and Delworth, T.L. (2018) The influence of CO_2 forcing on north American monsoon moisture surges. *Journal of Climate*, 31, 7949–7968. https://doi.org/10.1175/JCLI-D-18-0007.1.

Perdigón-Morales, J., Romero-Centeno, R., Pérez, P.O. and Barrett, B.S. (2018) The midsummer drought in Mexico: perspectives on duration and intensity from the CHIRPS precipitation database. *International Journal of Climatology*, 38(5), 2174–2186. https://doi.org/10.1002/joc.5322.

Plasencia-Vázquez, A.H., Escalona-Segura, G. and Esparza-Olguín, L. G. (2014) Modelación de la distribución geográfica potencial de dos especies de psitácidos neotropicales utilizando variables climáticas y topográficas. *Acta Zoológica Mexicana*, 30, 471–490.

Rousseeuw, P.J. (1987) Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics*, 20, 53–65.

Salas, M.A., Cerda, M.E.H., Cruz, J.V., Romero, E.A. and Barrié, C.T.L. (2014) The influence of strong el Niño phases on the rainfall over the Yucatan Peninsula, Mexico. *Analele stiintifice ale Universitatii "Alexandru Ioan Cuza" din Iasi-seria Geografie*, 60, 15–28.

Salas, M.A. and Jones, P.D. (2014) The ENSO influence in the Mexican regional precipitation during the instrumental period. *Analele stiintifice ale Universitatii "Alexandru Ioan Cuza" din Iasi-seria Geografie*, 60, 29–65.

Schneider, L. and Haller, T. (2017) A region under threat? Climate change impacts, institutional change and response of local communities in coastal Yucatán. In: Filho, L. and Keenan, J. M. (Eds.) *Climate Change Adaptation in North America. Climate Change Management*. Cham: Springer., pp. 161–175. https://doi.org/10.1007/978-3-319-53742-9_16.

Seager, R., Ting, M., Davis, M., Cane, M., Naik, N., Nakamura, J., Li, C., Cook, E. and Stahle, D. (2009) Mexican drought: an observational modeling and tree ring study of variability and climate change. *Atmosfera*, 22(1), 1–31.

Stephenson, T.S., Vincent, L.A., Allen, T., Van Meerbeck, C.J., McLean, N., Peterson, P.C., Taylor, M.A., Aaron-Morrison, A.P., Auguste, T., Bernard, D., Boekhoudt, J.R., Blenman, R.C., Braithwaite, G.C., Brown, G., Butler, M., Cumberbatch, C.J.M., Etienne-Leblanc, S., Lake, D.E., Martin, D.E., McDonald, J.L., Ozoria Zaruela, M., Porter, A.O., Santana Ramirez, M., Tamar, G. A., Roberts, B.A., Sallons Mitro, S., Shaw, A., Spence, J.M., Winter, A. and Trotman, A.R. (2014) Changes in extreme temperature and precipitation in the Caribbean region, 1961-2010. *International Journal of Climatology*, 34(9), 2957–2971. https://doi.org/10.1002/joc.3889.

Suárez-Mota, M.E., Villaseñor, J.L. and López-Mata, L. (2017) Dominios climáticos de la Sierra Madre Oriental y su relación con la diversidad florística. *Revista Mexicana de Biodiversidad*, 88(1), 224–233.

Torrescano-Valle, N. and Folan, W.J. (2015) Physical settings, environmental history with an outlook on global change. In: Islebe, G.A., Calmé, S., León-Cortés, J.L. and Schmook, B. (Eds.) *Biodiversity and Conservation of the Yucatán Peninsula*. New York: Springer, pp. 9–37.

Vázquez-Domínguez, E. and Arita, H.T. (2010) The Yucatan Peninsula: biogeographical history 65 million years in the making. *Ecography*, 33(2), 212–219. https://doi.org/10.1111/j.1600-0587.2009.06293.x.

Villers-Ruiz, L. and Trejo-Vázquez, I. (1997) Assessment of the vulnerability of forest ecosystems to climate change in Mexico. *Climate Research*, 9(1–2), 87–93.

Wilson, E.M. (1980) *Physical Geography of the Yucatan Peninsula*. Tuscaloosa, AL: Yucatan: A world apart: University of Alabama Press, pp. 5–40.

World Meteorological Organization (WMO). (2017) *Guidelines on the Calculation of Climate Normals*. Geneva, Switzerland: World Meteorological Organization, p. 2017.

Zambrano-Bigiarini, M. (2012) HydroTSM: time series management, analysis and interpolation for hydrological modelling. *R package version*, 3, 3.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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