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ORIGINAL PAPER

Recent disruptions in the timing and intensity of precipitation in Calakmul, Mexico

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Abstract

This study addresses changes in the timing and intensity of precipitation from 1982 to 2016 from three meteorological stations around Calakmul, Mexico, a landscape balancing biodiversity conservation and smallholder agricultural production. Five methods were used to assess changes in precipitation: the Mann-Kendall test of annual and wet season trends; a fuzzy-logic approach to determine the onset of the rainy season; the Gini Index and Precipitation Concentration Index (PCI) to evaluate the temporal distribution of precipitation; Simple Precipitation Intensity Index (SDII) to evaluate precipitation intensity; and the Rainfall Anomaly Index (RAI) to identify the deficit or surplus of rainfall compared with the long-term mean. Overall, rainfall trends in Calakmul over this period indicate a slight increase, though results of the indices (Gini, SDII, PCI) all indicate that rainfall has become more intense and more unevenly distributed throughout the year. There was no significant trend in the onset date of rainfall or the RAI overall, though there were more pronounced crests and troughs from 2004 to 2016. Higher interannual variability and more pronounced rainfall anomalies, both positive and negative, suggest that rainfall in the Calakmul region has become more extreme. This research informs for management and livelihood strategies in the local region and offers insights for analyses of regional patterns of seasonal precipitation events in tropical landscapes worldwide.

1 Introduction

Recent changes to global and regional climates, exacerbated by anthropogenic activity, have accelerated global hydrological cycles, altering not only the overall magnitude of precipitation but also its seasonal distribution, interannual variability, intensity, frequency, and duration worldwide (Allan and Soden 2008; Easterling et al. 2000; Karl and Trenberth 2003; Trenberth et al. 2007; Zeng et al. 1999). In many regions, precipitation is the primary factor affecting water availability (Szwed 2018). Numerous Global CGCM-based studies (Coupled General Circulation Models) have indicated the potential for uneven impacts of future change on precipitation, with increases in many parts of the world and decreases in others (IPCC 2013; Kharin and Zwiers 2000, 2005; Osborn et al. 2016; Semenov and Bengtsson 2002; Voss et al. 2002). As local water resources depend not only on the quantity, but also on the frequency, intensity, and timing of precipitation, any changes in these characteristics may pose significant economic, ecological, and societal threats (Li et al. 2011; Qian et al. 2003; Zhang et al. 2009).

The agricultural sector is particularly vulnerable to changes in precipitation (Morton 2007; Parry and Carter 1989). Reliable predictions of precipitation play a crucial role in agricultural productivity (Adams et al. 1998; Kurukulasuriya and Rosenthal 2013; Rosenberg 1992), strongly influencing the ability to accommodate the world's growing food needs (Lal 2013; Risbey et al. 1999; Ziervogel and Ericksen 2010).

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With no major surface rivers and limited irrigation, agricultural activities in the Yucatan Peninsula Mexico are heavily dependent on the timing of the onset of the rainy season and prediction of the intensity and distribution of seasonal precipitation (García-Gil et al. 2002). In Calakmul, Campeche, the predominately small-scale, rain-fed agriculture, known as *milpa*,[1] has already been drastically affected by climatic stresses, including droughts and hurricanes, and further non-climatic stressors poses considerable stress on local farmers (Alayón-Gamboa and Ku-Vera 2011; Gurri-Garcia and Vallejo-Nieto 2007; Radel et al. 2012; Schmook et al. 2013; SIAP 2017).

Previous research by Mardero et al. (2014) addressed how farmers in Calakmul have modified their agricultural calendar, reducing the area under maize cultivation, and diversified economic activities due to the effects of increasing precipitation variability and droughts. The schedule of agricultural activities is largely dictated by rainfall, beginning with land preparation (including crop selection and planting) and culminating with harvest and transport to market (Conde-Álvarez and Saldaña-Zorrilla 2007; FAO 2009). Yields may suffer with either a late onset or early cessation of the growing season, or due to frequent dry spells or extreme precipitation events during the growing season (Mugalavai et al. 2008). While dry spells may limit agricultural productivity, changes in the intensity may also be reflected in soil structural parameters critical to crop growth (Allen et al. 2011).

While there has been considerable research on total annual and seasonal precipitation trends, relatively little research has addressed changes in the frequency, intensity, and timing of precipitation (Karl and Trenberth 2003; O'Gorman 2015; Pal et al. 2013; Sarhadi and Soulis 2017). Several methods used in this paper have been applied separately by researchers working in other regions. Konalapa and Mishra (2016) analyzed changes in the temporal variability of precipitation at both continental and global scales (from 1950 to 2005) due to anthropogenic activities, finding a decrease in rainfall uniformity as well as changes in quantity and intensity of annual precipitation. Valli et al. (2013) explored the Precipitation Concentration Index (PCI) (1981 to 2010) across various Agro-Climatic Zones of Andhra Pradesh, India, concluding that there have been significant changes in rainfall patterns especially during the 2000s. Li et al. (2011) used daily data to calculate the precipitation concentration index (PCI), precipitation concentration degree (PCD), and precipitation concentration period (PCP) in Xinjiang, China, showing that precipitation concentration is noticeably larger in places where both annual total precipitation and number of rainy days are lower, but also that most areas of Xinjiang are characterized by no significant trends of precipitation PCI. Using the Gini Index to measure the temporal distribution of daily precipitation worldwide from 1976 to 2000, Rajah et al. (2014) showed that East Asia, Central America, and Brazil exhibited a decrease in the number of both wet and light precipitation days, in contrast to the USA, southern South America, western Europe, and Australia, which all exhibited an increase in the number of both wet and light precipitation days.

In México, one of the few studies addressing changes in the distribution and intensity of precipitation, by Cavazos and Rivas (2004) on the variability of precipitation extremes in Tijuana, Baja California, from 1950 to 2000, found that the greatest recorded variability in precipitation extremes has happened since the mid-1970s. In the Yucatan Peninsula, Mardero et al. (2012) calculated precipitation trends from 1980 to 2010 in the southern Peninsula, showing that annual precipitation had decreased by 16%, while drought frequency had increased over the last 50 years across the Greater Calakmul Region. Martinez and Galindo-Leal (2002) demonstrated that mean precipitation in the Yucatan Peninsula declined from 1300 mm in the 1950s to 790 mm during the 1990s. Orellana et al. (2009) produced regional climate projections for the entire Peninsula, complementing the IPCC (2007, 2013) projections that this area will increasingly suffer from both extreme droughts and more extreme events, such as hurricanes, such as category-5 Dean in 2007 (Gurri-Garcia and Vallejo-Nieto 2007; Rogan et al. 2011). Further, the integration of farmers' empirical knowledge and quantitative assessments of impacts on subsistence agriculture suggest that patterns of rainfall are changing in timing and distribution (Mardero et al. 2018).

Understanding precipitation distribution and patterns in Calakmul is critical given the importance of water as a vital resource for both society and ecosystems. The municipality of Calakmul is home to the Calakmul Biosphere Reserve, the largest protected tropical forest in Mexico, covering 7231 km^2 (Fig. 1). Water availability determines the presence, abundance, distribution, and the survival of animal and plant species living in the Reserve (Carrillo-Reyna et al. 2015; Garza-López et al. 2018; Martínez 2016; Pérez-Cortéz et al. 2012). Water availability stored during rainy season in the few semi-permanent surface water bodies called *aguadas* (García-Gil et al. 2002) constrains the movements of several species, such as white-lipped peccaries (Reyna-Hurtado et al. 2009), Baird's tapir, and jaguar (O'Farrill et al. 2006) in the region. Aguadas are the main source of water supply for the native fauna of the Calakmul region during the dry season (Aranda 1990; Hernández-Huerta et al. 2000; Vaughan and Weis 1999) and the spatio-temporal variation of these water sources has an important effect on the activities and habits of many species

[1] The *milpa*, also called slash-and-burn farming system, is a complex combination of agricultural practices has enabled the cultivation of up to 87 crops, with rotation sequences that vary by cultural and agro-environmental context (Terán and Rasmussen 1994). This agricultural system consists in cutting, drying, and burning patches of woody vegetation to clear land for agricultural production (Ruthenberg 1980).

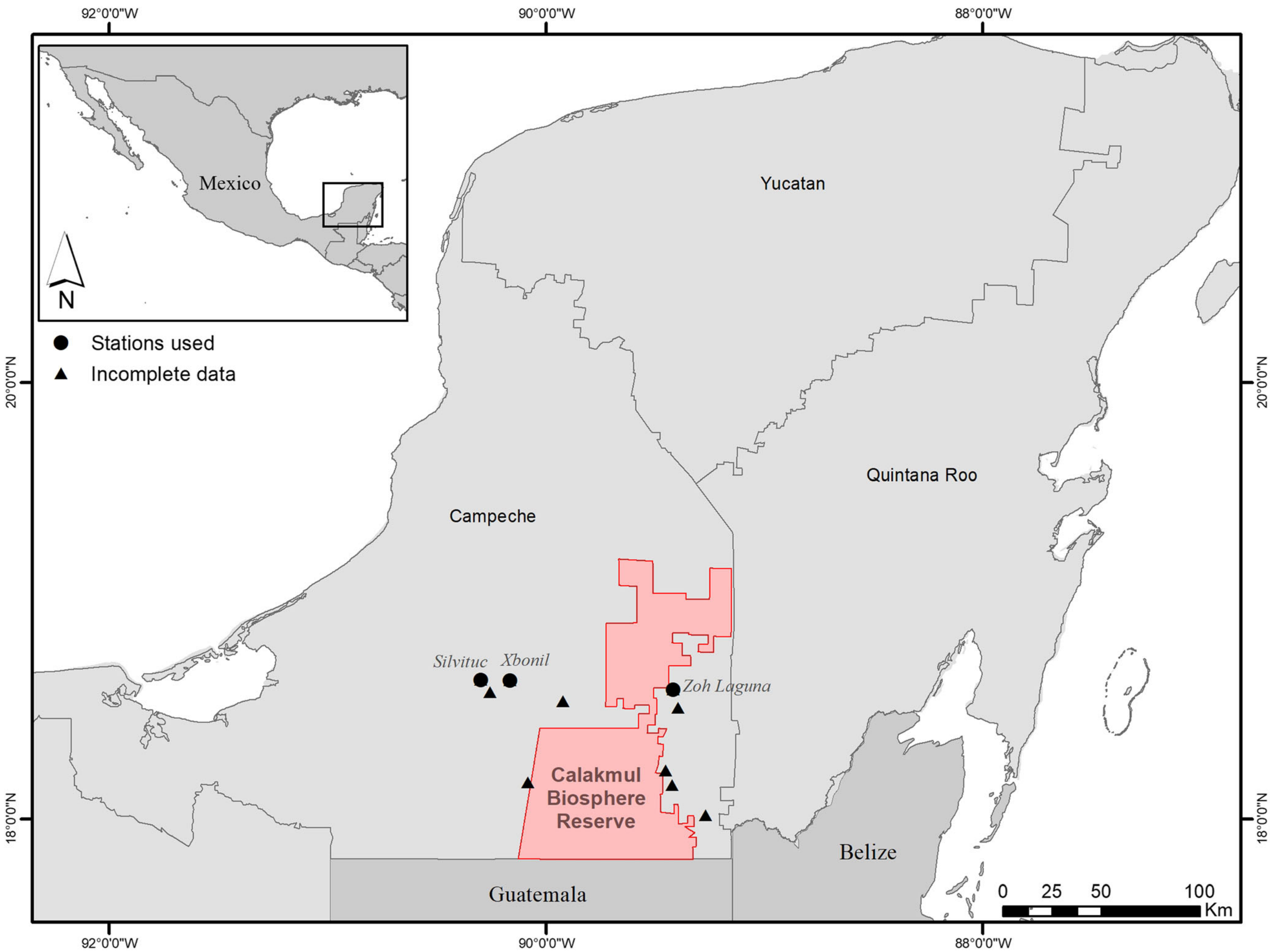

Fig. 1 Map of Calakmul with meteorological stations used in this study

(Chávez-Tovar 2010; García-Gil 2003; Naranjo and Bodmer 2002). If precipitation during the wet season does not replenish the *aguadas*, animals may broaden their migratory ranges to survive the dry season, increasing the risk of hunting or conflicts with rural communities.

By evaluating changes in the temporal distribution and intensity of rainfall from 1982 to 2016 in the municipality of Calakmul in the southern Yucatan Peninsula, Mexico, this study investigates both an overall decrease in regional precipitation (as indicated by previous research) and also whether changes in the onset of the wet season, the distribution and intensity of rainfall, and negative rainfall anomalies have become more frequent, through three hypotheses:

1) The intensity and distribution of total and wet season rainfall has changed from 1982 to 2016, independent of the total precipitation during this period.
2) The onset and duration of the wet season has changed during the period 1982–2016.
3) There is an increased frequency of anomalous rainfall events during the period 1982–2016.

2 Data and methods

2.1 Study area

The municipality of Calakmul covers 13,849 km^2 in southeastern Campeche, in the center of the Yucatan peninsula (Ibarra-Manríquez and Martínez-Ramos 2002).

Local physiography and vegetation around Calakmul are characteristic of the south-central Yucatán Peninsula (c.f., Lundell and Swallen 1934; Miranda 1958). Rolling hills of karstic upland (250 m.a.s.l.) are interspersed with low-lying areas, or *bajos*, covered mainly by medium and low semi-deciduous forest (Lundell and Swallen 1934; Miranda 1958). Soils vary physiographically, with shallow and relatively well-drained redzinas along hillsides and high ground, deep but poorly drained clays (vertisols) in the *bajos*, and extremely shallow and rocky lithosols on hill tops (Abizaid and Coomes 2004).

Annual average precipitation in the Yucatan Peninsula is highly variable, ranging from 900 mm in the northwest to 1400 mm in the southeast and is characterized by two main seasons: a dry season between November and April, followed by a wet season from May to October (Vidal-Zepeda 2005), with a mid-summer drought locally called *canícula* between the end on July and August. In addition, winter frontal systems originating in Canada, called Nortes, bring rain, wind, and cold air masses to the Gulf of Mexico (Márdero et al. 2012). The average annual temperature is 24–26 °C (Vester et al. 2007).

Mean annual precipitation across the three meteorological stations selected for this study varies from ~920 mm in Zoh Laguna to ~1300 mm in Silvituc (~100 km between these two stations). Silvituc station, the most humid, is situated near Laguna Silvituc, also called Noh Laguna, which may influence the surrounding microclimate, while the Zoh Laguna station does not have any significant water body nearby.

2.2 Data and preparation

While the Mexican National Climatological Database (CLICOM SYSTEM) lists 8 meteorological stations in the Municipality of Calakmul, only 2 have records that span at least 30 years (Zoh Laguna and Xbonil), reflecting one of the major challenges for climatological analysis in Mexico: the availability and reliability of precipitation data. Data spanning this period from another nearby station (Silvituc), in the neighboring municipality of Escárcega, was also used in this study (Fig. 1 and Table 1). Daily and monthly rainfall data for these stations from 1982 to 2016 were obtained from the Mexican National Water Commission (CONAGUA).

Data gaps were identified (see Table 1) and were filled by inverse distance weighting (IDW), using available data from the partial records of other stations within 50 km. This gap-filling process yielded a continuous and homogenous time series of precipitation data, with both daily and monthly precipitation data for each of the three stations for the entire study period, 1982 to 2016.

2.3 Statistical methods

This study included five types of analyses of precipitation: (a) calculation of precipitation onset and cessation; (b) annual and wet season trend analysis; (c) identification of rainfall anomalies; (d) calculation of analysis of temporal distribution; and (e) evaluation of intensity of rainfall events. A fuzzy-logic approach was used to determine rainy season onset. The Mann-Kendall trend test and the Sen's slope test were used to analyze annual and wet season trends over the study period. The Rainfall Anomaly Index (RAI) was used to address the deficit or surplus of rainfall relative to the average. The Gini Index and the Precipitation Concentration Index (PCI) were used to evaluate the temporal distribution of precipitation. Finally, the SDII (Simple Precipitation Intensity Index) was used to evaluate precipitation intensity.

2.3.1 Onset and cessation

Onset was defined as the first day of a 5-day period with a total rainfall of at least 20 mm of rainfall and at least two other wet days in this 5-day period (at least 1 mm of rainfall recorded), with no dry spell of seven or more consecutive days occurring in the subsequent 30 days (Dodd and Jolliffe 2001). Onset dates were calculated from Eq. (1), given by:

$$OD = D\frac{(20-F)}{R} \quad (1)$$

where OD is the onset date and D is the total number of days in the first month with effective rain (MER: the accumulated rainfall totals equal or exceeds 20 mm). F (mm) is the accumulated rainfall total of earlier months and R is the accumulated rainfall within the MER.

Precipitation onset and cessation for the entire period (i.e., long-term seasonality) were calculated following Marengo et al. (2001) and Liebmann et al. (2008), to create anomalous accumulation curves. This process yielded two values: the long-term annual precipitation mean and the long-term daily average for each day of the year. The daily average was subtracted by the annual mean daily average to produce a metric of the accumulated daily anomalies. The start of the season is the minimum value of the curve and the end of the season is the maximum value in the curve.

2.3.2 Trend analysis

The Mann-Kendall test is a statistical test widely used for trend analysis in climatic and hydrological time series (Mavromatis and Stathis 2011; Yue and Wang 2004). There are two advantages of using this test. First, it is a non-parametric test and does not require the data to be normally distributed. Second, the test has low sensitivity to abrupt breaks due to inhomogeneous time series (Tabari et al. 2011). Using the excel template application MAKESENS (Salmi et al. 2002), the Mann-Kendall test was conducted for each of the three stations, from 1982 to 2016, both annually and for the wet season (from May to October).

In addition to Mann-Kendall test, we also used the Sen's slope method. Sen's slope test was performed because even if the trend calculated through the Mann-Kendall test is no statistically significant (at 1%, 5%, or 10% level), there is still a trend which magnitude can be calculated (Salmi et al. 2002; Rahman et al. 2016).

2.3.3 Precipitation anomalies

The RAI, developed by Van Rooy (1965), was used to evaluate meteorological droughts (Keyantash and Dracup 2002). Rainfall anomalies were calculated and classified, both

Table 1 Geographical coordinates, elevation, annual mean precipitation, monthly precipitation, millimeters maximum in a day, date, years with more gaps in record (NAs) and percentage of NAs in those years in the three selected stations in the Calakmul area

Station and time series dates	Lat (N)	Lon (W)	Elevation (m.a.s.l.)	Annual mean precipitation (mm)	Monthly mean precipitation (mm)	Maximum precipitation (mm)/date	Years with gaps in record (% of NAs in that year)
Silvituc 1982–2016	18.6	− 90.3	75	1313	103.5	310 10 Oct 1995	1982,1988, 1989 (8%, 7%, 34%)
Xbonil 1982–2016	18.6	− 90.2	70	1114	84.8	170 10 March 2000	2007, 2009, 2012, 2014, 2016 (24%, 36%, 37%, 51%, 25%)
Zoh Laguna 1982–2016	18.6	− 89.4	265	921	67.7	152 8 Aug 2012	1982, 1985, 1987, 2014 (60%, 41%, 33%, 41%)

annually and for the wet season. Positive and negative RAI indices were computed using the mean of ten extremes for setting up a threshold for both positive and negative anomalies. The Index normalizes precipitation values against the long-term average (1982–2016), to place current conditions into a historical perspective. Rooy's classification is shown in Table 2.

2.3.4 Precipitation distribution

The Gini Index is a standard measure of inequality widely used to measure income inequality and, recently, in hydrology and climatology to evaluate how unevenly precipitation is distributed over a year (Ceriani and Verme 2012; Masaki et al. 2014). It ranges from 0 (which means that each of the 365 days of the year receives exactly de same amount of rainfall) to 1 (which indicates that all the yearly rainfall falls in 1 day) (Rajah et al. 2014).

Using the Inequality Measures Package in R (Cowell 2000), the Gini Index was calculated with four variations: annually and for the wet season alone, both for each year separately and for the entire time period. To estimate the Gini Index, daily precipitation is sorted by increasing amount, summed cumulatively, and converted to a percentage of total precipitation, forming a Lorenz curve to graphically illustrate inequality distribution (see Masaki et al. 2014).

Table 2 Rooy's classification of RAI

RAI	Class description
≥ 3.00	Extremely wet
2.00 to 2.99	Very wet
1.00 to 1.99	Moderately wet
0.50 to 0.99	Slightly wet
0.49 to − 0.49	Near normal
− 0.50 to − 0.99	Slightly dry
− 1.00 to − 1.99	Moderately dry
− 2.00 to − 2.99	Vey dry
≤ − 3.00	Extremely dry

To complement the precipitation distribution analysis, annual PCI was calculated (in R with the package precintcon, by Povoa and Nery 2016) to assess the precipitation concentration based on the variability of monthly precipitation (Sangüesa et al. 2018), complementing the Gini Index, which is based on daily precipitation data. PCI is a powerful indicator of the temporal distribution of precipitation, providing information on long-term total variability in the total amount of rainfall (Apaydin et al. 2006; De Luis et al. 2011; Michiels et al. 1992; Ngongondo et al. 2011). PCI categorizes precipitation distribution: values of less than 10 represent a uniform precipitation distribution (i.e., low precipitation concentration), values from 11 to 15 denote a moderate precipitation concentration, values from 16 to 20 denote irregular distribution, and values above 20 represent highly concentrated precipitation (De Luis et al. 2011; Oliver 1980).

2.3.5 Precipitation intensity

The SDII (Cooley and Chang 2017) is considered by the World Meteorological Organization as one of the best indicators for representing precipitation patterns, especially during the wet season. The SDII is the ratio of annual or seasonal total rainfall to the number of days during the year or season when rainfall occurred (rain day is defined as: daily rain ≥ 1 mm) (Keggenhoff et al. 2014), and it was used to determine the precipitation intensity of the rainy season and annually of each year of the data series.

3 Results

3.1 Rainy season onset and cessation

Results of the fuzzy-logic approach to determine the onset of the rainy season were calculated for each year, and for the entire 35-year period, for each station, an accumulation curve was also calculated to address the accumulated precipitation during the 365 days of the year. The precipitation curve increases in slope around day number 150 of each year, which corresponds to the end of May. Then, the curve drops approximately around day 300, in late October.

As illustrated in Table 3, rainy season dates in all stations start and end around the same time. The rainy season in Zoh Laguna starts in the second half of May, and in the other two stations by the end of May, with a maximum difference of 7 days between the stations. Cessation occurs by the end of October, or the first week of November at Silvituc. These results coincide with other studies (i.e., Orellana et al. 2009; Vidal-Zepeda 2005) and with local knowledge as reported by farmers (Mardero et al. 2014). For example, the agricultural calendar for the maize crop in the area usually starts in late May or June, coincident with precipitation onset.

Results of the trend tests indicate no significant trend of an advance or a delay in rainfall onset (Fig. 2). However, some changes over time can be observed. For example, the Silvituc station during the 1990s exhibited a delay in the rainfall onset, starting in August in half of the 10 years, then, during the 2000s, the onset went back to May/June. For Xbonil, during the late 1980s and early 1990s, there was a delay in the onset of rainfall, and for Zoh Laguna, a trend in the delay of rainfall onset was observed from 2005 to 2016, with several years in which the rainy season started after mid-July.

3.2 Long-term patterns and precipitation trends

Results of Mann-Kendall and Sen's slope test were performed for each year (entire year and wet season only) showed a small increase in precipitation at all stations, both annually and during the wet season (Fig. 2), but these results were not statistically significant. The three stations exhibit high interannual variability and exhibit similar patterns for some years.

The Mann-Kendall test for Silvituc demonstrated a positive, but not significant, trend (Z scores of 0.74 and 1.02, respectively). Sen's estimate shows a positive slope in the time series. Even though the results of the trend analysis are not statistically significant, it is notable that from 1994 to 2004, most of the residuals are negative, with positive residuals in the period from 2005 to 2016, both annually and during the wet season.

Similar to Silvituc, Xbonil, and Zoh Laguna show a non-significant, positive trend both annually and during the wet season (Z scores of 0.34 and 0.82; 0.23 and 0.85, respectively). In Xbonil, from 2000 to 2010, most of the residuals are negative, indicating drier years.

Table 3 Onset and cessation of the rainy season in the three stations, from 1982 to 2016

Station	Onset	Cessation
Silvituc	26 May	07 November
Xbonil	26 May	27 October
Zoh Laguna	19 May	23 October

Zoh Laguna showed a very dry period from 1985 to 2002; then, the precipitation recovered except for 2009 and 2015. During 2015, many local media reports (Chim 2017) called attention to the drought affecting agricultural activities and the wildlife inside of the Calakmul Biosphere Reserve.

Even with the lack of significant trends, the three stations did exhibit high interannual variability with similar patterns for some of the years. Years with the driest and wettest conditions vary from each station as shown in Table 4:

In general, the years with least rainfall at the three stations were 1986, 2004, and 2009; with 2009 the driest year during this period. The years with most rainfall were 1985, 1988, 1995, and 2013 (Fig. 3).

The lack of a significant trend further underscore the importance of analyzing the intensity and distribution of precipitation in order to investigate and understand the changes perceived in the area. Furthermore, variability in precipitation associated to both non-extreme and extreme events is of great importance due to its role in natural ecosystems and agricultural activities.

3.3 Rainfall Anomaly Index (RAI)

RAI was calculated for each of the three stations from 1982 to 2016. There are moderately wet years, years with normal precipitation, dry years, and very dry years distributed throughout the study period. Through this graphical analysis (Fig. 4), there is concurrency among all three stations for 1988–1990, 1995, 2005, 2006, 2010, and 2013 with positive anomalies, from moderately wet to extremely wet; and years of the mid-1980s, 2004, 2009, 2014, and 2015 showing moderately dry to extremely dry behavior.

The Mann-Kendall Test and the Sen's slope (Fig. 4) demonstrate an increase in positive rainfall anomalies for Silvituc and Zoh Laguna (Z value of 0.82 and 1.05, respectively) and an increase of negative anomalies at Xbonil (Z value of −1.56) especially after 2000, but these trends are not statistically significant.

3.4 Rainfall distribution and intensity

The Gini coefficient for daily data, for all the stations, over the 35-year period, is higher than 0.8, both annually and in the wet season, indicating highly concentrated precipitation in the study area (see Table 5). Annual Gini values are slightly higher than wet season values, reflecting the highly seasonal rainfall regime. Nevertheless, the Gini values for the wet season are still indicating that even wet season rainfall (May to October) is highly concentrated.

The most even rainfall distribution (lowest Gini values) even during the rainy season can be found at Silvituc and

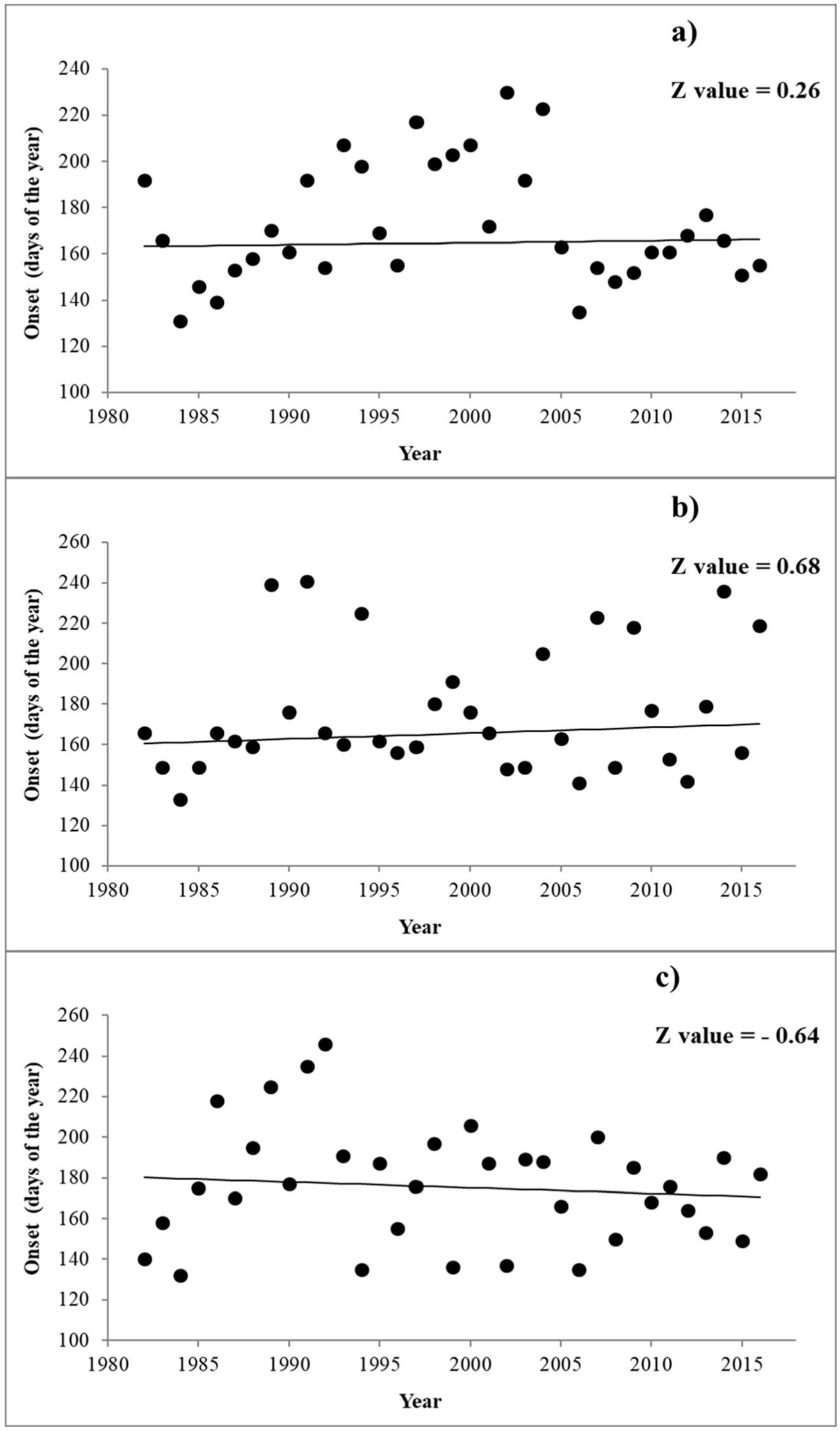

Fig. 2 Mann-Kendall Test and Sen's slope test for the precipitation onset of three stations: Silvituc (**a**), Zoh Laguna (**b**), and Xbonil (**c**), from 1982 to 2016

Xbonil, two stations on the western side of the study region. Zoh Laguna, the station to the east of the Calakmul Biosphere Reserve presents the most concentrated and unevenly distributed rains.

Precipitation intensity, as measured by SDII, exhibits a different pattern. The two western stations present higher values, indicating that the intensity of daily precipitation is higher there, and less intense closer to the reserve. Thus, during rainy season in Zoh Laguna precipitation is concentrated in a few very rainy days, as compared with Silvituc and Xbonil.

The values displayed in Table 5 represent the overall rainfall distribution and intensity during the 35-year study period. Figure 4 shows the annual and wet season trends for the Gini

Table 4 Wetter and drier years in the three stations

Station	Wetter years	Drier years
Silvituc	1985, 1995, 2006, 2013	1986–1987, 2000, 2003, 2004, 2015
Zoh Laguna	1985, 1988, 2001, 2002	1986, 1994, 2004, 2009
Xbonil	1985, 1988,1995	1983, 1986, 2004, 2009

Index for the three stations. There were statistically significant positive trends (99% confidence interval) for both, Silvituc and Xbonil, indicating an increasingly unevenly distributed (less uniform) precipitation over time. Unlike Zoh Laguna, which exhibits a positive, but not significant, trend (Z value 1.56).

Figure 5 shows that Zoh Laguna has a positive trend with a relatively high Mann-Kendall Z score of 1.42, indicating that the rainfall distribution has changed and being concentrated in some periods during the wet season. Xbonil displays the same tendency but with a lower Z score (1.16). In contrast, Silvituc shows that the Gini index has been stable over the time period studied.

Figure 6 shows the results of the Severity Index (SDII) for both annual and wet season precipitation. Each of the three stations presents a positive significant trend (Z scores > 1.96; 90% confidence), indicating that the intensity of daily precipitation has increased significantly. This suggests that rainfall has become more intense and concentrated.

To strengthen the analysis of precipitation distribution, in addition to the GINI index, the Precipitation Concentration Index (PCI) was calculated with monthly data, and PCI trends were calculated from 1982 to 2016 using the Mann-Kendall Test and Sen's slope. Most of PCI values in the Calakmul area range from 11 to 15 (moderate precipitation concentration) and from 16 to 20 (irregular distribution). There are also few years with a PCI higher than 20, indicating highly irregular precipitation distribution, especially from 2006 to 2016 and particularly at Xbonil.

The results showed no obvious trend for Silvituc and Zoh Laguna (Z values of 0.97 and 0.28 respectively), but Xbonil exhibited a significant positive trend with a 90% confidence interval (Z value of 2.76). However, there was a slight increase over time in PCI values, potentially indicating concentrated precipitation in some months, which may relate to the pronounced seasonal rainfall fluctuations in Calakmul.

Overall, all three stations display a significant increase in the intensity of precipitation, both annually and during the wet season. In addition, Xbonil station also showed a significant increase in precipitation concentration. These results together affirm that, even in the rainy season, precipitation is concentrated in shorter periods of time or in fewer events. Table 6 shows these results summarized by index.

4 Discussion

Any changes in precipitation patterns critically influence rainfed agriculture. Worldwide, scientists, academics, and decision makers have paid increased attention to the risks associated with climate change, including increased uncertainty regarding food production (Ewert et al. 2015; Reddy and Pachepsky 2000). As water availability is one of the most limiting constraints for crop production and food security, there is a critical need to understand the detail of precipitation patterns at a regional scale.

Investigations of changing precipitation patterns require at least 30 years of climate data, given temporal climate oscillations (Onyutha et al. 2016), especially in trend detection (Camberlin 2009; Di Baldassarre et al. 2011). In addition, trend results often depend not only on the length of the data record, but also on the specific time period selected for analyses. Previous research in the region by Martínez and Galindo-Leal (2002) found that precipitation in the Calakmul region declined from 1950 to 1990, and Mardero et al. (2012) also found an important precipitation decline at Zoh Laguna from 1973 to 2002. In many developing countries, the challenge of having access to a complete record of reliable data further complicates regional climate analysis and necessitates careful interpretation.

The overall rainfall trends in Calakmul indicate a slight, non-significant, increase during the study period, consistent with work in the Caribbean by Dore (2005), who also found an overall precipitation increase. However, this increase does not necessarily imply that the region has benefited from more precipitation. Rather, as others have noted (Chou et al. 2013; Karl and Trenberth 2003; Luo et al. 2007; Pal et al. 2013), analysis of rainfall intensity and distribution is necessary to understand its impacts. In Calakmul, the effects of increased rainfall variability and intensity in agriculture have contributed to the loss of food security in communities, thus aggravating poverty and modifying rural livelihoods.

Traditional knowledge from local farmers can provide further insights about climatic changes. Mardero et al. (2014, 2015) highlight that farmers in Calakmul have perceived substantial changes in the climate over the last three decades. Farmers report that temperatures are increasing and emphasize that now, "it is raining differently," indicating delayed onset of the rainy season and noting a few intense precipitation events and even flooding, followed by weeks without rain events.

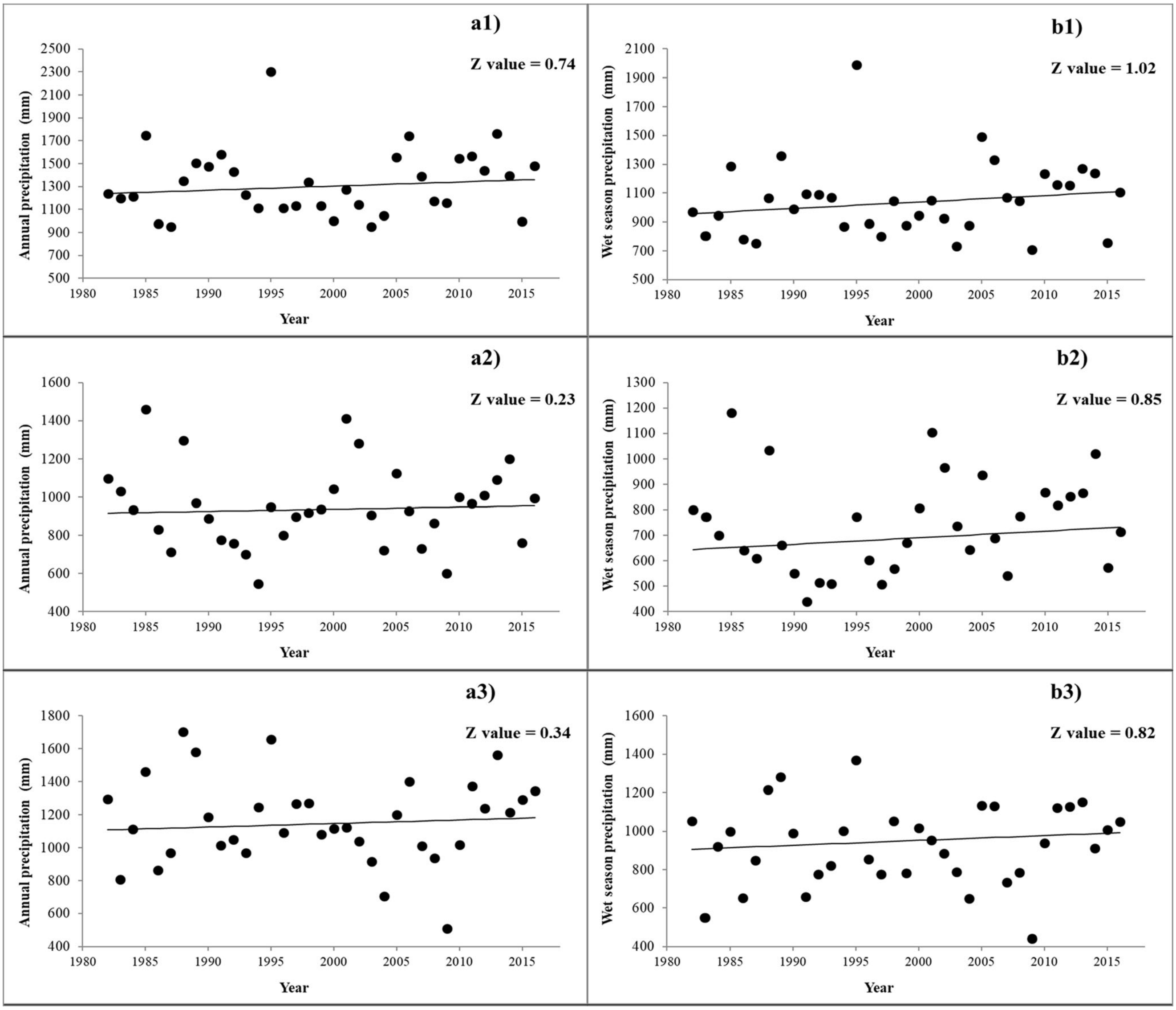

Fig. 3 Annual (**a**) and wet season (**b**) Mann-Kendall Test and Sen's slope test for the three stations: Silvituc (1), Zoh Laguna (2), and Xbonil (3) from 1982 to 2016

Predictable rainfall onset and cessation dates are critical to farmers in the Calakmul region, in order to decide which maize types to cultivate and when to plant. While the wet season in the Yucatán Peninsula is "traditionally" from May to October, results of this analysis indicate high interannual variability in the onset of the rainy season, starting in May in some years, and in late July or even as late as August in others. Similarly, years with great maize losses (such as 2004 and 2007) correspond to years in which the rainy season started later than usual.

These erratic patterns have caused substantial crop losses, especially in 2004 and 2007 when around 70% of the total maize surface was lost in Calakmul (INIFAP 2017). Mardero et al. (2012) found that years considered to be "severe drought years" were related to the agricultural losses and the desiccation of surface water bodies visited by many species of animals in the Reserve. The Yucatan Peninsula, including the Calakmul region, has a long history of droughts, which some scholars believe contributed to the collapse of Mayan civilization (Medina-Elizalde and Rohling 2012; Douglas et al. 2015).

The results of the indices (Gini, SDII, PCI) of the three stations in Calakmul consistently show similar trends in both an irregular precipitation distribution and also the increased intensity of rainfall events. These results suggest, as reported by the CEPAL (2015), IPCC (2013), and scholars like Bouroncle et al. (2017) and Dow and Downing (2016), that more extreme precipitation events are likely to happen in Central America, including the Mayan lowlands of Mexico.

The increased frequency of anomalous rainfall events was demonstrated through the RAI trend results. While RAI

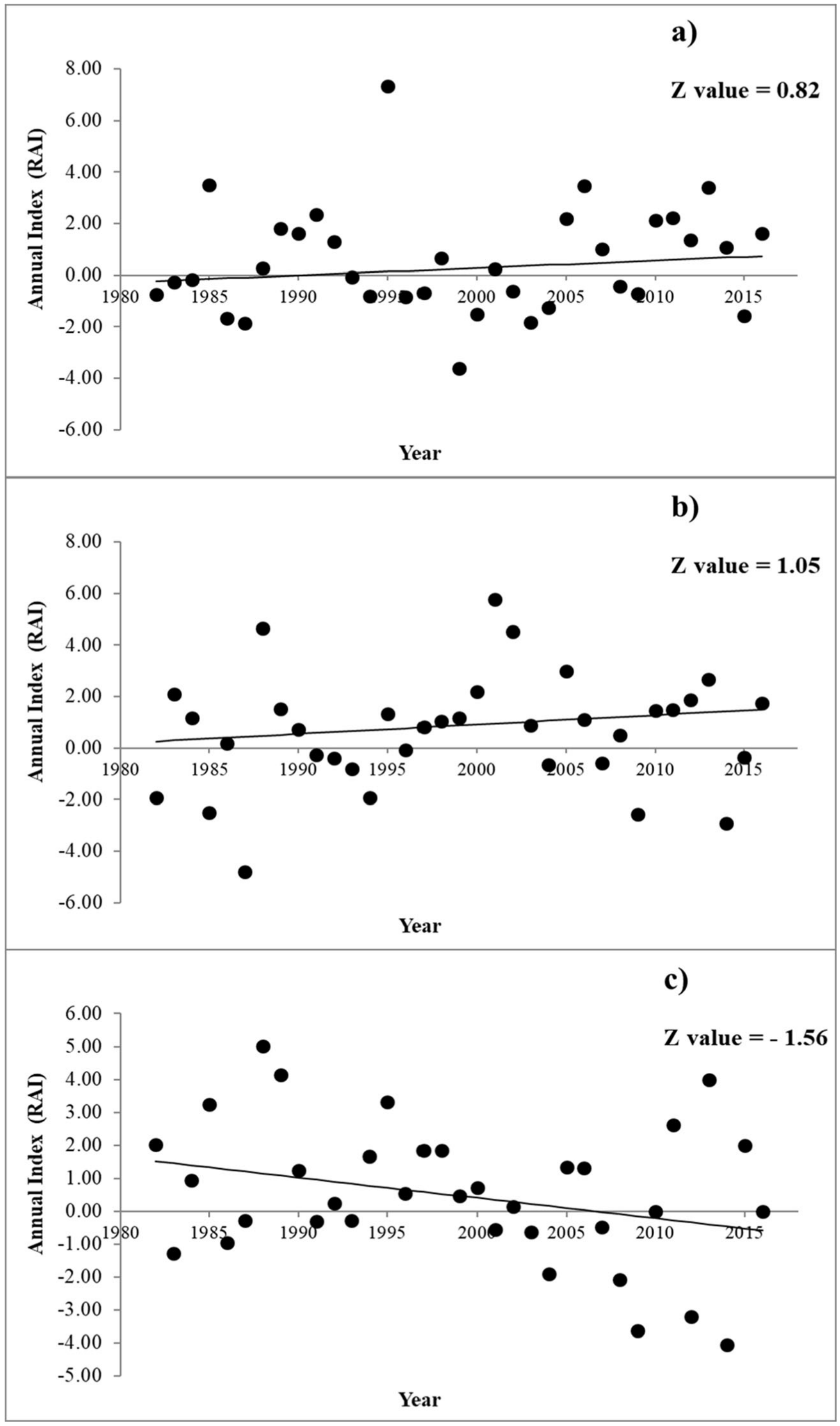

Fig. 4 Mann-Kendall Test and the Sen's slope applied for the annual RAI, for the three stations: Silvituc (**a**), Zoh Laguna (**b**), and Xbonil (**c**) 1982–2016

Table 5 Annual and wet season Gini Index and Intensity Index (SDII) for the wet season

Station	Gini annual	Gini wet season	SDII wet season
Silvituc	0.88	0.82	14.49
Xbonil	0.88	0.82	13.13
Zoh Laguna	0.87	0.83	11.99

analysis lacked a significant trend, it showed more pronounced crests and troughs over the last decade (2004–2016). This higher interannual variability and more pronounced rainfall anomalies (both positive and negative) suggest that the climate in Calakmul is becoming more extreme.

This increased variability in precipitation could be explained from a Global Climate Change perspective. There is

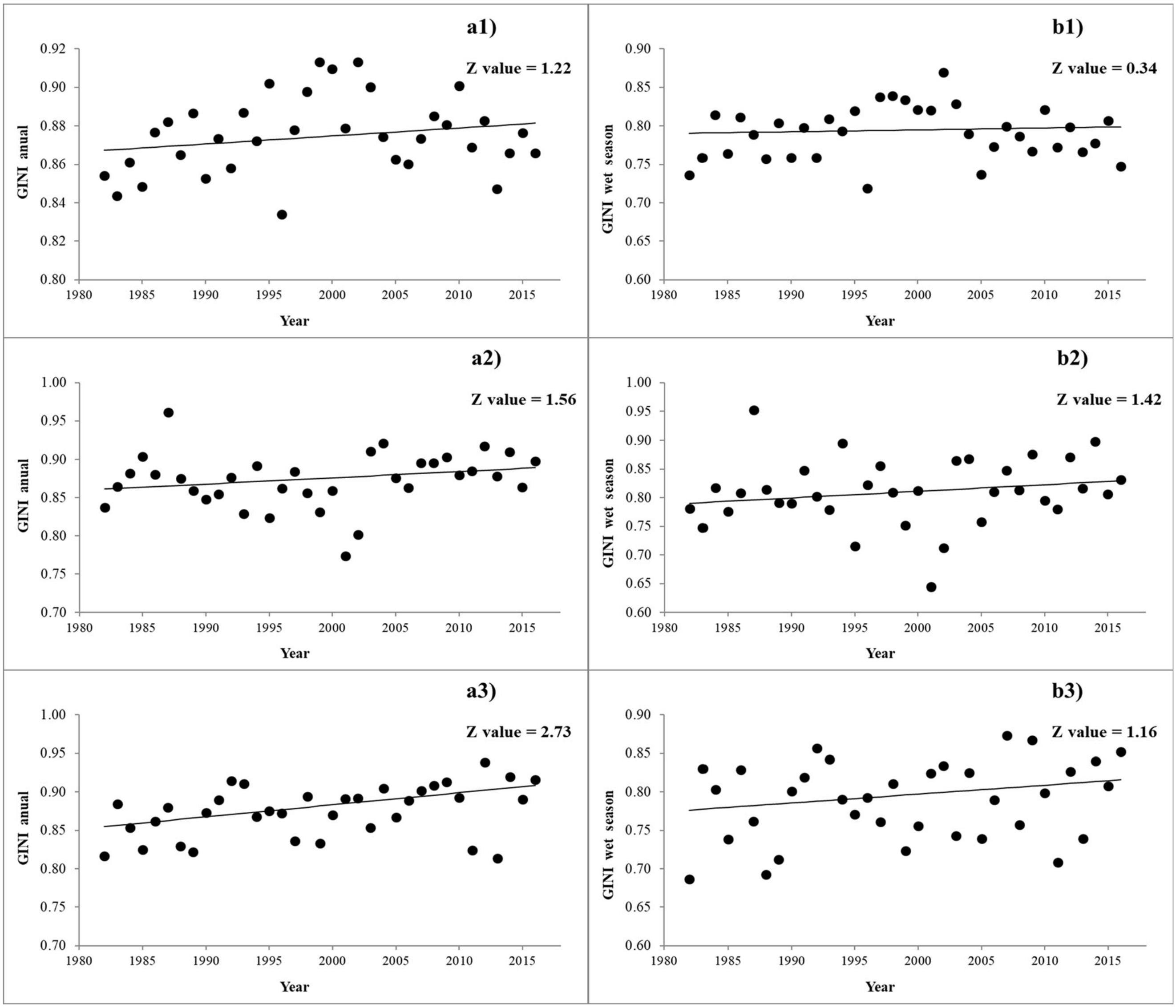

Fig. 5 Annual (**a**) and wet season (**b**) Mann-Kendall Test and Sen's slope test for the Gini Index of three stations: Silvituc (1), Zoh Laguna (2), and Xbonil (3), from 1982 to 2016

a direct influence of increased temperatures on precipitation, with greater evaporation and surface drying, thereby increasing the intensity and duration of droughts. However, the water holding capacity of the air increases by about 7% per 1 °C warming, leading to increased water vapor in the atmosphere. Hence, storms, whether individual thunderstorms, extra tropical rain, or tropical cyclones, fueled by increased moisture, may produce more intense precipitation events (Trenberth 2011). Temperatures in the Yucatan Peninsula are becoming more extreme, with higher temperatures events and for longer periods (Orellana et al. 2009; Mardero et al. 2018).

In the tropics and subtropics, precipitation patterns are dominated by fluctuations in sea surface temperatures, such as the El Niño-Southern Oscillation (ENSO), which have been shown to influence precipitation patterns in the Yucatan Peninsula and Calakmul (Neeti et al. 2012). Some years with strong negative anomalies in the area coincide with El Niño events, such as the moderate El Niño events of 1986–1987 and 2003–2004, and a very strong El Niño event in 2014–2015. Another major oscillation affecting the precipitation patterns in the Caribbean region is the Atlantic Multidecadal Oscillation (AMO), a pattern of climate variability which is detected as a fluctuation in sea surface temperatures over the Atlantic Ocean, between the equator and Greenland (Kerr 2000; Goly and Teegavarapu 2014).

Advances in climate behavior and prediction science have created significant potential to contribute to improved water resources management practices. Research on rainfall intensity and distribution is crucial both to create infrastructure to reduce risks associated with extreme flood events, and to

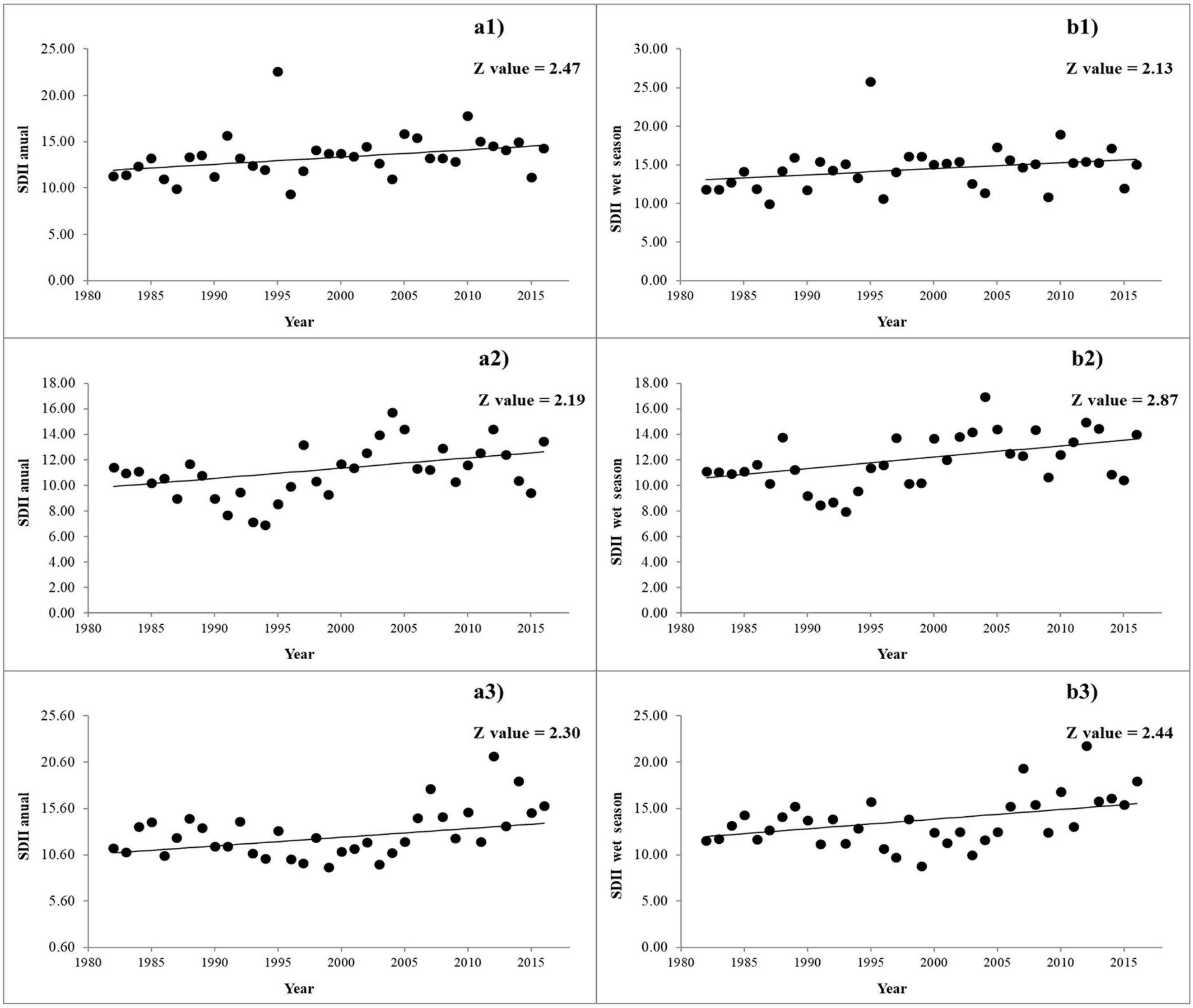

Fig. 6 Annual (**a**) and wet season (**b**) Mann-Kendall Test and Sen's slope for the Severity Index (SDII) of three stations: Silvituc (1), Zoh Laguna (2), and Xbonil (3), from 1982 to 2016

develop mechanisms to cope with the increasing drought events especially in economic sectors highly related to water availability such as agriculture. In Mexico, climate policy for the agricultural sector has focused on strategies boosting irrigation systems and the use of agricultural inputs such as modified seeds (more resistant to droughts), and farmers have been adapting their agricultural calendar to the changed rainfall patterns (Eakin 2005; Mardero et al. 2014). Researchers

Table 6 Trends of each Index from 1982 to 2016. Plus symbol indicates a positive trend; single asterisk and double asterisks indicate statistical significance at the 95 and 99% confidence interval, respectively

Station	General annual trend	Wet season general trend	Annual trend Gini	Wet season trend Gini	SDII annual	SDII wet season	PCI (annual)
Silvituc	+	+	+	+	+*	+*	+
Xbonil	+	+	+**	+	+*	+*	+**
Zoh Laguna	+	+	+	+	+*	+**	+

working in the Calakmul Reserve (Carrillo-Reyna et al. 2015; Martínez 2016; Pérez-Cortéz et al. 2012) have also called for increased information on precipitation patterns due to the importance of water availability in the aguadas and their role in wildlife distribution.

By addressing changes in the overall precipitation along with changes in the timing and intensity of rainfall events, this research contributes to agricultural management by contributing to the design of agricultural policies focused on farmers' adaptation to these new environmental conditions, and to conservation and management efforts, offering insights related to water availability and the characteristics and behavior of different animal and vegetable species, both for the Southern Yucatan and tropical landscapes worldwide.

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