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The midsummer drought in Mexico: perspectives on duration and intensity from the CHIRPS precipitation database

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ABSTRACT: In many regions of Mexico, precipitation occurs in a very well defined annual cycle, with peaks in May–June and September–October and a relative minimum in the middle. This minimum in the middle of the rainy season is known as the midsummer drought (MSD) and impacts agriculture and industry. However, in Mexico there are large areas with either sparse meteorological station coverage or where time series of historical observations have many missing data, which make it difficult to study and analyse the precipitation variability at different scales of space and time. Therefore, the most important objective of this study is to evaluate the performance of the recently available Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) product in estimating the duration and intensity of the MSD in Mexico, taking advantage of its very fine spatial resolution (0.05°) and continuous coverage to improve on current understanding of the MSD. In order to achieve this, MSD duration and intensity are calculated from the CHIRPS data and then compared to gauge data for the 1981–2010 period. In addition, two new indices for estimating the intensity of the MSD are defined, and these new indices provide complementary information to that obtained with more traditional methods. Results show that CHIRPS overestimates (underestimates) precipitation in Mexico during summer and autumn (winter and spring) seasons by up to 30%. Most importantly, by using CHIRPS and the two new indices proposed, the most detailed spatial representation ever of the MSD in Mexico has been obtained through the elimination of spatial and temporal coverage gaps.

KEY WORDS midsummer drought; precipitation in Mexico; CHIRPS database

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1. Introduction

In Mexico, like in other places in the world, precipitation affects a large number of activities, such as agriculture, industry, and power generation (Englehart and Douglas, 2000; Arreguín Cortés *et al.*, 2011; Fuchs and Wolff, 2011; CNA, 2014; Rogé *et al.*, 2014). It is therefore essential to know, as precisely as possible, the spatial distribution of precipitation and its variability across different temporal scales. It is also critical to have climatological information on the onset and duration of the rainy season, in order to take better advantage of available water resources.

Precipitation in Mexico shows high spatial and temporal variability (Englehart and Douglas, 2002; Giddings *et al.*, 2005; Seager *et al.*, 2009). In much of the country, the greatest amount of precipitation occurs during the summer months. Mosiño and García (1966, 1974), pioneers in documenting the behaviour of rainfall in Mexico, roughly define the most important climatological characteristics of precipitation in Mexico as follows: a rainy season of monsoon type in most of the country; a region of Mediterranean climate over northwestern Baja California Peninsula, with a rainy season during winter; and a dry climate in the northern half of the country.

During the summer months, surface, middle- and upper-troposphere wind circulation over northwestern Mexico presents a monsoon pattern, the so-called North American monsoon system, which causes transport of water vapour from both the Gulf of California and the Gulf of Mexico and produces deep convection and intense precipitation over northwestern and western Mexico (Adams and Comrie, 1997; Higgins *et al.*, 2003). Over central and southern Mexico, and extending into Central America (CA), a very well defined annual cycle of precipitation occurs, with peaks in May–June and September–October and a relative minimum in the middle of the rainy season. This relative minimum in precipitation is known as the midsummer drought (MSD) (Mosiño and García, 1966; Hastenrath, 1967; Magaña *et al.*, 1999; Amador *et al.*, 2006; Gamble *et al.*, 2008). During this relatively dry period, precipitation is reduced by up to 40% (Curtis, 2002; Small *et al.*, 2007) and constitutes a clear signal of the bimodal nature of the summer precipitation over the tropical Americas (Herrera *et al.*, 2015, and references therein). This phenomenon is colloquially known as ‘canícula’ in some regions where it is experienced.

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There have been several studies focused on explaining the physical forcing mechanisms, both local and large scale, of the MSD in Mexico, CA, and the Caribbean region. Among these forcing mechanisms are seasonal changes in sea surface temperature, incoming solar radiation, and low-level winds (Magaña *et al.*, 1999); variability of the position and strength of the North Atlantic subtropical high-pressure system and related wind anomalies (e.g. Hastenrath, 1967; Giannini *et al.*, 2000; Mapes *et al.*, 2005; Romero-Centeno *et al.*, 2007; Small *et al.*, 2007; Gamble *et al.*, 2008); intensification of the Caribbean low-level jet and associated direct circulations (e.g. Magaña and Caetano, 2005; Herrera *et al.*, 2015; Moron *et al.*, 2016); vertical wind shear and increase in atmospheric particle concentrations coming from the Saharan dust in the Caribbean basin (Angeles *et al.*, 2010); and insolation variability associated with the biannual crossing of the solar declination (Karnauskas *et al.*, 2013).

Despite these studies on physical mechanisms, relatively fewer studies have focused on the climatological characterization of the MSD in Mexico. Defining regions where the MSD occurs, both in terms of its duration and intensity, remains a critically important task due, among other things, to the impact of MSD on rain-fed crop yields in many locations where agricultural activities play a key role in the local economy (e.g. Pereyra Díaz *et al.*, 1994; Peralta-Hernández *et al.*, 2008). Mosiño and García (1966) (MG66 henceforth) studied the spatial and temporal distribution of the MSD using monthly mean precipitation data from 1900 climatological stations operated by the National Weather Service of Mexico (SMN, by its Spanish acronym) and created a 'relative drought' (RD) index to quantify its intensity. They found areas with MSD distributed over a wide latitudinal range, covering a large portion of the country, although they noted more stations with MSD in the south and east of Mexico. More recently, Reyna-Trujillo *et al.* (2007) (RT07 henceforth) also used the observed data from the SMN to analyse the distribution of MSD in Mexico. They analysed the information from 527 stations for the period 1980–2000 using a modified RD index, obtaining similar results to those of MG66.

Other authors have analysed the spatial and temporal variability of the MSD by using other kinds of data. For example, Magaña *et al.* (1999) analysed the distribution of fortnightly accumulated precipitation data over Mexico, CA, and the Caribbean based on weather station observations and satellite estimates over the ocean for the period 1979–1993. They observed that the signal of the MSD stretched from northeastern Mexico to CA, being more clearly defined over southwestern Mexico, CA, and the eastern Pacific warm pool. Sánchez-Santillán and Garduño-López (2005) studied the behaviour of the MSD in Mexico City (located in the highlands of central Mexico) for the period 1878–2004. These authors found that the MSD was of intermittent character, being registered in 59% of the analysed years. Martínez-Jiménez (2013) used daily precipitation data from the ERA-Interim reanalysis in a 0.7° resolution grid for the period 1979–2010 and defined the MSD region where its signal was stronger, locating it between 10°–20°N and 103°–88°W. Similarly, García (2015) investigated the spatial and temporal distribution of the MSD using precipitation data from the Climate Forecast System Reanalysis with a resolution of 0.5° for the period 1979–2010 and determined that the region affected by MSD was bounded between 10°–25°N and 105°–80°W. Both Martínez-Jiménez (2013) and García (2015) assumed that the MSD occurs during July and August.

Small *et al.* (2007), using the Tropical Rainfall Measuring Mission 3B43 precipitation product and the Climate Prediction Center Merged Analysis of Precipitation data, estimated the amplitude and spatial extent of the MSD by subtracting the rainfall climatological mean of June and September from that of July and August, i.e. from the difference between the average precipitation of the driest and wettest summer months. They found the MSD to be approximately bounded by 10°–20°N and 100°–85°W, being similar to the MSD regions identified in Martínez-Jiménez (2013) and García (2015). Using an algorithm to determine the global distribution of the existence and strength of the MSD, Karnauskas *et al.* (2013) estimated its intensity by calculating the difference between the mean of the two rainfall maxima and the relative minimum from several monthly gridded climatological data sets. They found a MSD signal in land places all around the globe, with one of the more outstanding regions being that of Mexico and CA, due to its spatial scale and coherence (their figures 3 and 4). Particularly for Mexico, the region they identified with MSD is very similar to that of MG66 and resembles that of Curtis (2002) who identified MSD using the second-order harmonic in pentad precipitation data from the Global Precipitation Climatology Project.

The variability of precipitation in many places of the world is strongly linked not only to global-scale atmospheric disturbances but also with disturbances of the climate system at regional or local scale. In Mexico, the precipitation pattern is very closely linked to its complex topography and has a high degree of spatial and temporal variability owing to this topography (e.g. Wallén, 1955; García, 1965; Englehart and Douglas, 2002; Vidal, 2005). Thus, it is very important to have high-quality and high-resolution databases for studies that aim to better understand and characterize rain in Mexico. In this sense, the newly released Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS; Funk *et al.*, 2015) database could be a good option because, among other aspects, it contains precipitation information in a quasi-global grid with very high spatial (0.05° lat-lon) and temporal (daily, pentad, and monthly) resolutions. CHIRPS is constructed from satellite observations, providing information for broad regions where there are scarce, incomplete, or even absent observations from meteorological stations. Estimates of precipitation based on satellite observations do have several limitations, particularly because satellite sensors do not directly detect precipitation but estimate it using one or several proxy variables (Wu *et al.*, 2012; Toté *et al.*, 2015; Paredes-Trejo *et al.*, 2016). However, this relatively new database has shown good performance in several regions of the world (e.g. López-Carr *et al.*, 2015; Duan *et al.*, 2016; Katsanos *et al.*, 2016; Verdin *et al.*, 2016) although it has not yet been analysed for Mexico.

Therefore, the objectives of this work are (1) to analyse the ability of CHIRPS to reproduce known rainfall patterns in Mexico, specifically the MSD as identified by others using surface stations, satellite observations, and reanalysis data and (2) to use CHIRPS to better define regions of the country where the MSD occurs, by taking into account its duration and intensity. A direct benefit of this study is an evaluation of the quality of CHIRPS precipitation estimates as compared with the observational data of the SMN climatological stations, in order to recommend it as a new database with high spatial resolution for other studies of precipitation in Mexico. The remainder of the article is organized as follows. Section 2 describes the databases used in this study and explains the methodology applied in the analysis. Section 3 presents the results, and Section 4 includes the discussion and conclusions of this study.

2. Data and methodology

Observational data sets are generally the most reliable sources of information for precipitation events. However, observational data sets sometimes have missing data, and furthermore it is not always possible to have adequate spatial coverage, especially in regions with complex topography such as Mexico. Both of these challenges apply to the observational stations of the SMN network. Therefore, it would be very useful and desirable to have a precipitation database whose performance has been evaluated in the region and to have the confidence to use it, at least, in analyses of climatological nature.

CHIRPS is a product developed by the US Geological Survey Earth Resources Observation and Science Center, in association with the Santa Barbara Climate Hazards Group at the University of California. CHIRPS contains precipitation data in a quasi-global grid [(50°S, 50°N), (180°E, 180°W)] with a very high spatial resolution ($0.05 \times 0.05°$). It has over 35 years of data, spanning from 1981 to the present. Both satellite infrared observations and surface stations data are combined by means of a novel 'smart interpolation' algorithm (Funk *et al.*, 2015). The CHIRPS database contains several temporal series of precipitation (daily, pentad, and monthly), available at each grid point. In a validation analysis, Funk *et al.* (2015) calculated bias, mean, absolute error and correlation coefficient between CHIRPS and the Global Precipitation Climatology Center data set (GPCC; Becker *et al.*, 2013), which was taken as baseline. The average absolute errors with respect to GPCC show that the performance of CHIRPS in the quasi-global, Africa, and United States domains is high, thus giving confidence to use the data set in other regions.

Because of its recent creation, CHIRPS has been used in several studies that take advantage of its high temporal and spatial resolution. For instance, Verdin *et al.* (2016) examined CA, Colombia, and northwestern Venezuela and concluded that the combination of observational data and satellite estimates implemented in CHIRPS offers a precipitation product sufficiently robust to predict hydrologic hazards in those regions. Paredes-Trejo *et al.* (2016) came to a similar conclusion by evaluating CHIRPS's ability to detect precipitation events and to estimate rainfall amounts in Venezuela. Their results for the period 1981–2007 showed that CHIRPS overestimated (underestimated) lowest (highest) rain values, even though overall it performed well on most of the calculated metrics.

In Mexico, as stated in the former section, the MSD has been previously analysed by means of station observations, satellite estimates, and reanalysis data. In this study, both the ability of CHIRPS to represent precipitation in Mexico and its ability to capture the MSD were evaluated. For that, the CHIRPS monthly precipitation series, along with historical records of the SMN climatological stations, were analysed. The SMN historical records used were released on January 2016 and processed by the Informatics Unit for the Atmospheric and Environmental Sciences (UNIATMOS; Fernández-Eguiarte *et al.*, 2016) of the Centro de Ciencias de la Atmósfera at the Universidad Nacional Autónoma de México. In both the SMN and CHIRPS data sets, monthly accumulated precipitation (mm month^{-1}) for the 1981–2010 period was analysed. Because the length of the records varies from one station to another, only stations with observations available for a period of at least 15 years were considered, resulting in 2150 stations available for the analysis (Figure 1(a)). Furthermore, monthly accumulated precipitation for each year was calculated only for those months that had at least a 90% of the records available, and the monthly climatologies for the 1981–2010 period were calculated considering only those 2150 stations.

In spite of the relatively high number of stations considered, some regions (particularly in the north and southeast of Mexico) still have sparse station coverage (Figure 1(a)). Furthermore, in recent years, observational data availability from SMN stations have decreased, and this impacts the use of SMN stations to compare with CHIRPS. It also impacts CHIRPS itself, as the number of stations in Mexico that CHIRPS includes in its products decreased from a maximum of nearly 3000 stations in 1983, to nearly 2300 stations in 2007, to only 900 stations from 2009 forwards (CHIRPS, 2017). The SMN data were used to (1) define Mexican regions where MSD occurs, (2) determine its intensity and duration, and (3) compare with CHIRPS. In order to compare climatologies, monthly values of accumulated precipitation from the CHIRPS grid, spanning the area between 14°–33°N and 118°–86°W, were interpolated to the geographical coordinates of each SMN station (Figure 1(a)), by means of a linear interpolation. To determine the duration of the MSD, the criteria proposed by MG66 were employed. The duration of the MSD at each SMN station and each CHIRPS grid point was defined by the number of consecutive months during the rainy season (May–October), which presents

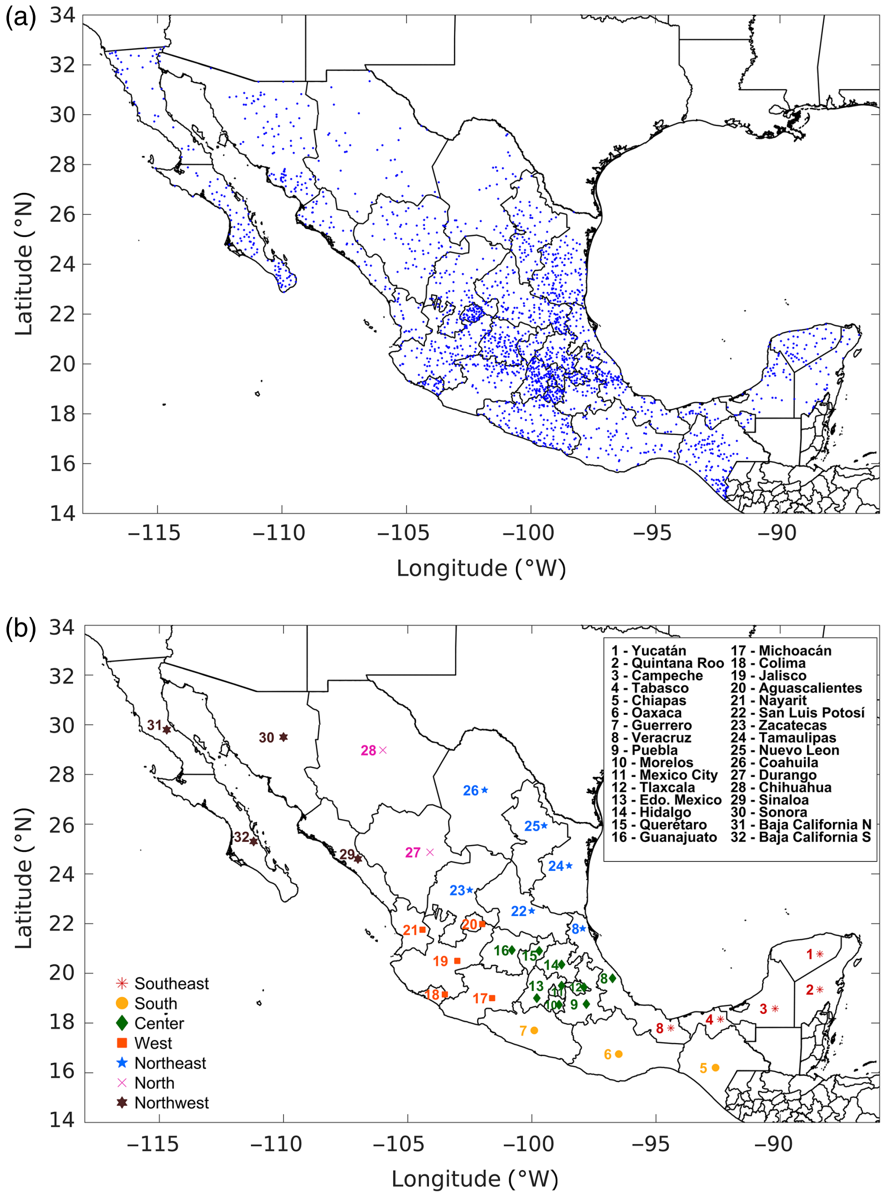

Figure 1. (a) Location of the 2150 climatological stations of the SMN used in this study. (b) Political division of Mexico, composed of 32 federal entities. [Colour figure can be viewed at wileyonlinelibrary.com].

a decrease in mean monthly accumulated precipitation with respect to the 2 months of maximum precipitation that bound them. In this way, four cases of duration of the MSD were established in this study and were carried out so separately for the two data sets (SMN and CHIRPS). In the first two cases, the MSD has a duration of only 1 month and occurs in either July (Figures 2(a) and (b)) or August (Figures 2(c) and (d)). Those two 1-month MSDs are further stratified by the adjacent month with highest precipitation. As an illustration, for MSD in July, cases with June precipitation higher than August (Figure 2(a)) were separated from cases with August precipitation higher than June (Figure 2(b)). August was treated similarly (Figures 2(c) and (d)). In the third case, the MSD has a duration of 2 months, in July and August (Figure 2(e)), in which precipitation in each of these 2 months is lower than precipitation of June and September, and precipitation in May is lower than in June. In the fourth case, the MSD has a duration of 3 months, from June to August (Figure 2(f)), meaning that precipitation in each of these 3 months is lower than precipitation in May and September.

In addition to the duration calculation, three indexes were computed in order to determine the intensity of the MSD in Mexico. First, we replicated the methodology of MG66, which quantifies the intensity in terms of rain deficits by means of the ‘RD’ index. RD computes the quotient between the representative area of the deficit (the blue shaded regions in Figure 2) and the total accumulated precipitation from May to October, which is expressed as a percentage. The MSD is considered weak when $\mathrm{RD} < 10\%$, moderate when $10\% \le \mathrm{RD} < 16\%$, and strong when $\mathrm{RD} \ge 16\%$. However, due to the procedure

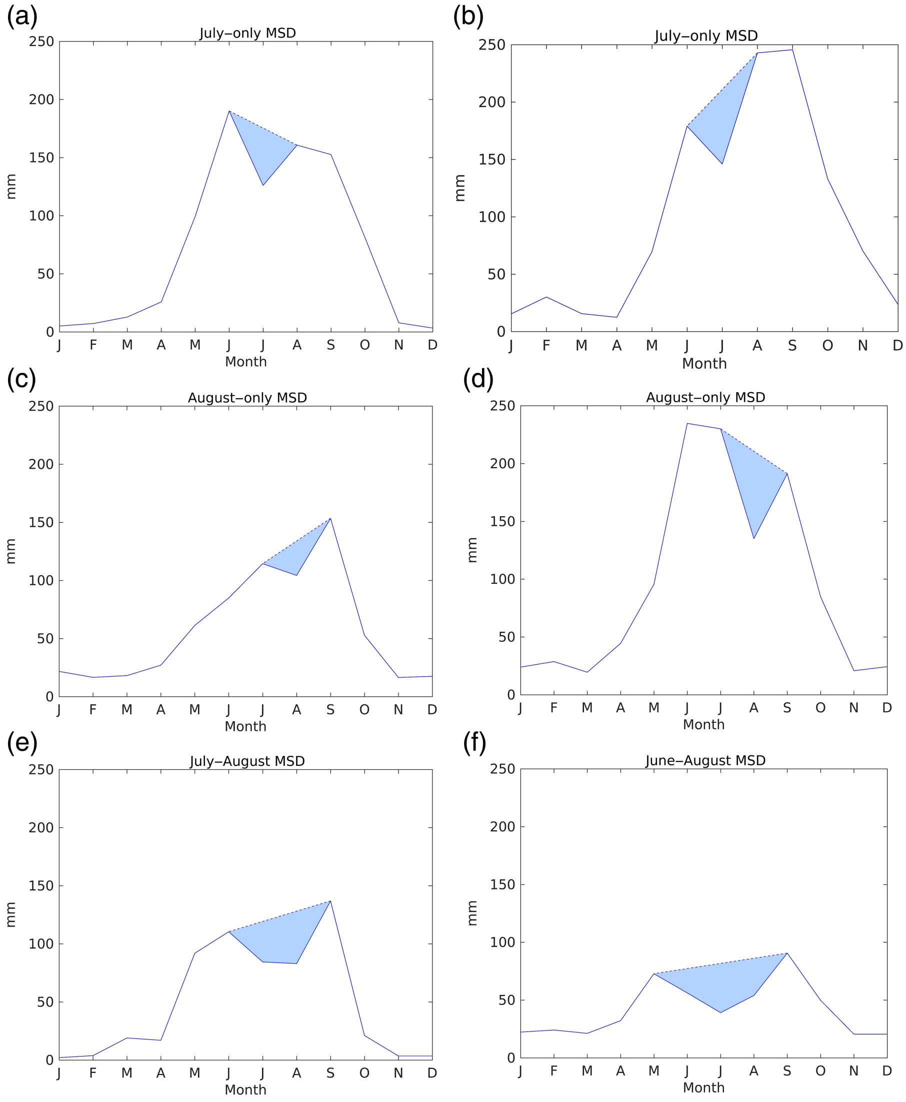

Figure 2. Example plots of each of the four duration cases of the MSD: July-only (a, b); August-only (c, d); July and August (e); and June–August (f). Shaded areas represent the polygons used to estimate the MSD strength by the RD index. [Colour figure can be viewed at wileyonlinelibrary.com].

used to calculate the RD index (i.e. using the representative area of the deficit indicated in Figure 2), the length of the MSD could influence the estimation of its intensity. For instance, the RD index could identify a June–August MSD as strong even when there is not a remarkable deficit of precipitation in these months. With this weakness of the RD index in mind, two new indexes are proposed here to estimate the MSD intensity in distinct regions of Mexico. These two additional indices, calculated from the CHIRPS gridded precipitation values, complement the information provided by the RD index and are one way in which the high-resolution CHIRPS database is used to extend our understanding of the MSD.

The first of these two new indices is calculated as the percentage of precipitation diminished during the MSD month (or, for cases in which the MSD lasts for more than 1 month, the month with least accumulated precipitation), with respect to the accumulated precipitation of the month of relative maximum. This index is called the ‘percent diminished’ (PD) index ($\frac{\text{precip}_{\text{max}}-\text{precip}_{\text{min}}}{\text{precip}_{\text{max}}} \times 100$). Strong and moderate MSD events were defined from the 90th and 50th percentiles, respectively, of the PD index frequency distribution. These percentiles are commonly used for this purpose (e.g. Ordoñez *et al.*, 2012; Barrett and Esquivel, 2013; Takahashi and Dewitte, 2016). The 50th percentile value was 18.0% and the 90th percentile value was 38.1%. Therefore, the thresholds for the PD index were established as follows: if $0\% < \text{PD} \leq 18\%$, the MSD is considered weak; if $18\% < \text{PD} \leq 38\%$, it is considered moderate; and if $\text{PD} > 38\%$, it is considered strong. These thresholds agree with the work of Curtis (2002) and Small *et al.* (2007), in which the decrease in precipitation during the MSD was estimated up to 40%.

The second of these two new indices is calculated as the percentage of precipitation accumulated during the month (or months) of the MSD with respect to the total accumulated precipitation from May to October. This index is

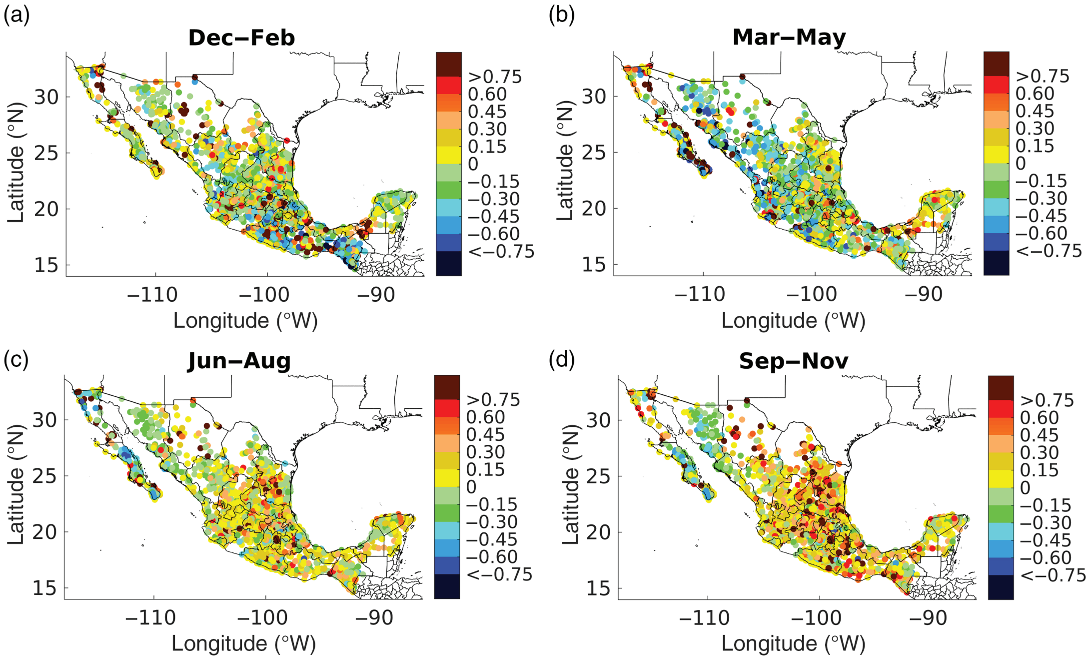

Figure 3. Relative differences of the seasonal accumulated precipitation between $\mathrm{CHIRPS}_{\mathrm{SMN}}$ values and SMN stations observations values for (a) winter (December–February), (b) spring (March–May), (c) summer (June–August), and (d) autumn (September–November). The period considered was 1981–2010. Locations where $\mathrm{CHIRPS}_{\mathrm{SMN}}$ overestimates (underestimates) SMN observations are coloured yellow to red (green to blue).

called the 'percent accumulated' (PA) index. The thresholds of the PA index were established in a similar way as the limits of the PD index. The strong and moderate MSD events were defined from the 10th and 50th percentiles, respectively, of the PA index frequency distribution, taking into account the duration of the MSD. For a 1-month duration MSD, the intensity ranges of the PA index were defined as follows: if $\mathrm{PA} \geq 17\%$, the MSD is considered weak; if $13\% < \mathrm{PA} < 17\%$, it is moderate; and if $\mathrm{PA} \leq 13\%$, it is strong. For a 2-month-long MSD (July and August), the ranges were if $\mathrm{PA} \geq 32\%$, the MSD is weak; if $25\% < \mathrm{PA} < 32\%$, is moderate; and if $\mathrm{PA} \leq 25\%$, then it is strong. Finally, for an MSD taking place from June to August, the ranges were if $\mathrm{PA} \geq 42\%$, the MSD is considered weak; if $38\% < \mathrm{PA} < 42\%$, it is moderate; and if $\mathrm{PA} \leq 38\%$, it is strong.

Finally, the magnitude of the inter-annual variability of MSD intensity in Mexico was analysed using the standard deviation of the three intensity indices. To calculate the standard deviation across the 30-year period, each yearly index was converted to a category. A value of 0 was assigned for cases of MSD absence (because the absence of the MSD is also an important component of its variability), 1 for cases of weak, 2 for moderate, and 3 for strong MSD. Then, the standard deviation was calculated from those values.

3. Results

3.1. Climatology of monthly rainfall over Mexico

In order to establish how accurately the CHIRPS data represent the spatio-temporal variability of monthly precipitation over Mexico, the relative differences between the climatological values of accumulated precipitation from SMN observations and the CHIRPS values interpolated to the SMN geographical coordinates (hereafter $\mathrm{CHIRPS}_{\mathrm{SMN}}$) were calculated $[(\mathrm{CHIRPS}_{\mathrm{SMN}} - \mathrm{SMN})/\mathrm{SMN}]$. These relative differences, at the seasonal time scale, are depicted in Figure 3. The relative differences are coloured according to their sign, to highlight regions where $\mathrm{CHIRPS}_{\mathrm{SMN}}$ overestimates SMN (yellowish and reddish) and where $\mathrm{CHIRPS}_{\mathrm{SMN}}$ underestimates SMN observations (greenish and bluish). In general, $\mathrm{CHIRPS}_{\mathrm{SMN}}$ mainly overestimates precipitation in Mexico during summer and autumn (June–November) and underestimates precipitation during winter and spring (December–May). It is important to highlight that most of the points show values of relative differences in the range of ±0.30 (less than 30% difference) over the course of the year and that the percentage of points with the smallest differences is highest during the months when MSD is typically found (June–August; Table 1). Greater differences are observed mainly over the south of Mexico during winter (Figure 3(a)), over the northwestern part during spring (Figure 3(b)), and along the eastern part during autumn (Figure 3(d)). Some of the largest differences are located over regions of complex terrain. The relative magnitudes of differences between $\mathrm{CHIRPS}_{\mathrm{SMN}}$ and SMN are similar to those found by Funk *et al.* (2015), Paredes-Trejo *et al.* (2016), and Verdin *et al.* (2016). Those authors concluded that differences and biases of this magnitude do not prevent the data from capturing important local precipitation features. We reached a similar conclusion that the CHIRPS data represent precipitation in Mexico sufficiently well to proceed to use them in analysis of the MSD.

Table 1. Percentage of sites where $\mathrm{CHIRPS_{SMN}}$ overestimates (OV) or underestimates (UN) the observation at the corresponding SMN station, according to season.

Range	Dec–Feb		Mar–May		Jun–Aug		Sep–Nov	
	OV	UN	OV	UN	OV	UN	OV	UN
0 to ±0.15	**18.2**	**22.6**	**15.9**	**19.7**	**26.6**	**23.5**	**21.3**	**14.0**
±0.15 to ±0.30	**9.6**	**16.4**	**10.7**	**18.4**	**18.4**	**9.3**	**20.8**	**8.0**
±0.30 to ±0.45	6.4	10.3	5.7	12.1	9.6	3.8	14.1	3.2
±0.45 to ±0.60	3.6	5.3	3.8	6.2	4.1	0.8	8.5	1.0
±0.60 to ±0.75	2.3	1.8	2.0	2.6	1.9	0.2	5.1	0.1
±0.75 to ±1	2.6	0.9	2.0	0.9	1.7	0	3.7	0

Percentages are divided according to relative difference range. Percentages of these sites exceed 60% in the first two ranges for all seasons, as is indicated in bold.

Table 2. Percentage of stations (or grid point) showing July-only, August-only, July–August, and June–August MSD according to the SMN observations, CHIRPS values interpolated to SMN stations ($\mathrm{CHIRPS_{SMN}}$), and CHIRPS data set.

Duration	SMN	$\mathrm{CHIRPS_{SMN}}$	CHIRPS
July	29.40	22.60	28.08
August	40.09	29.12	23.85
July–August	28.17	46.84	43.52
June–August	2.34	1.44	4.55

3.2. Duration of the MSD in Mexico

A MSD signal was identified in 42% (898) of the 2150 analysed SMN stations: 29.4% of them showed MSD only in July, 40.1% only in August, 28.2% in July–August, and 2.3% in June–August (Table 2). The spatial distribution of the MSD signal over Mexico, as seen in the SMN stations and colour-coded by duration, is shown in Figure 4. From this, it is clear that the MSD occurs mainly in the southern half and eastern part of Mexico, including the Yucatan Peninsula. This pattern is similar to that previously identified by MG66 and RT07, but a noticeable difference is observed in a wide area in the central northern region of the country (in the states of Chihuahua and Durango, Figure 1(b)), where MG66 and RT07 indicated the occurrence of MSD (from the interpolation of 1900 and 527 stations, respectively) and we do not. The MSD region here identified from $\mathrm{CHIRPS_{SMN}}$ extends more to the north compared to the regions defined by Small *et al.* (2007), Martínez-Jiménez (2013), and García (2015), and resembles very well those mapped in Curtis (2002) and Karnauskas *et al.* (2013).

The MSD that occurs only in July is found primarily in stations located to the south and southeast of Mexico, but it is also present in some stations of the northeast and of the central region (Figure 4). The MSD that occurs only in August is found mainly in the central region and the southern part of the northeastern region of Mexico. The 2-month-long (July–August) MSD presents a very similar distribution to the pattern shown by the MSD that occurs in July although the former is present in a slightly lower number of stations. Both, the July-only and July–August, are the predominant cases of MSD over southern and southeastern Mexico. Finally, the 3-month-long (June–August) MSD is only found over extreme northeastern Mexico, implying that there the rainy season begins in May. This may be due to moisture transport from the western Gulf of Mexico associated with the prevailing and relatively intense southeasterly winds during that month (Romero-Centeno *et al.*, 2007, figure 2(e)). The identification of geographical regions of the different MSD cases (i.e. the months with MSD) represents one of the important extensions this current work makes to our understanding of the spatial and temporal distribution of MSD.

$\mathrm{CHIRPS_{SMN}}$ reproduces the spatial pattern of the MSD region quite well (not shown) when compared to the spatial pattern seen in the SMN stations (Figure 4) although more points with MSD were detected in $\mathrm{CHIRPS_{SMN}}$ (49 *vs* 42%). Further insight into the differences between $\mathrm{CHIRPS_{SMN}}$ and SNM was gained by comparing each case of MSD duration (Table 2). $\mathrm{CHIRPS_{SMN}}$ does not completely identify the July-only MSD case over southern and some regions of northeastern Mexico. The main differences for the August-only MSD case are located over northeastern Mexico and the Yucatan Peninsula, where either $\mathrm{CHIRPS_{SMN}}$ does not identify the occurrence of the phenomenon or it identifies a different case of MSD. Also, $\mathrm{CHIRPS_{SMN}}$ identifies a higher number of points with August-only MSD over southern Mexico. In general, it seems that $\mathrm{CHIRPS_{SMN}}$ shifts the August-only MSD cases to the south compared with SMN observations alone. In the case of the 2-month long (July–August) MSD, $\mathrm{CHIRPS_{SMN}}$ identifies approximately the same regions as those obtained with observations, but it finds this type of MSD at more locations (Table 2). Finally, $\mathrm{CHIRPS_{SMN}}$ and SMN are quite similar in representing the 3-month-long MSD although $\mathrm{CHIRPS_{SMN}}$ identifies fewer points with this characteristic (Table 2). An interesting difference between $\mathrm{CHIRPS_{SMN}}$ and SMN is found in San Luis Potosi (Figure 1(b)), an important agricultural state in central Mexico, where $\mathrm{CHIRPS_{SMN}}$ detects a more complicated pattern in the occurrence of the MSD. $\mathrm{CHIRPS_{SMN}}$ identifies three different cases of MSD duration in this region: July-only in the western part of the state, August-only in the eastern part, and July–August in the rest of the state. However, the SMN stations show the August-only type of MSD in nearly the whole state.

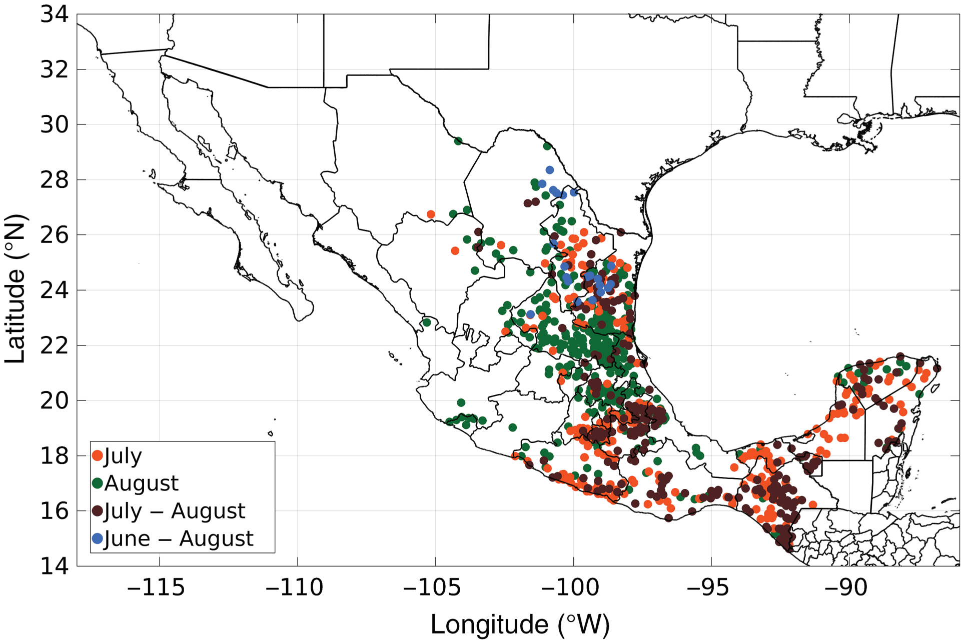

Figure 4. Duration of the MSD in Mexico as detected by SMN observations. Colour legend is shown in the lower left corner.

3.3. Intensity of the MSD in Mexico

The RD index calculated from SMN station data shows that MSD is weak at 86% of the stations; moderate at 10% of the stations, and strong at 4% of the stations. The SMN stations with a weak MSD are found throughout the entire region where MSD occurs in Mexico, while moderate MSD is found mostly in the centre and south of the territory (Figure 5). The few stations that show a strong MSD are mainly in northeastern Mexico, with some isolated points in the centre and southern end of the country (Figure 5).

The spatial pattern of the strength of the MSD obtained from $\text{CHIRPS}_{\text{SMN}}$ (not shown) corresponds very well with that obtained from the SMN stations (Figure 5) although some important differences can be seen mainly towards the north of the country. Stations with weak MSD are similarly located by $\text{CHIRPS}_{\text{SMN}}$, with a few exceptions. The $\text{CHIRPS}_{\text{SMN}}$ points with strong MSD are mainly found in the northeast part of Mexico, like the SMN stations, but they are more numerous, and a few appear in the south. Similarly, $\text{CHIRPS}_{\text{SMN}}$ identifies a larger number of sites with moderate-intensity MSD, in both the northeast and south parts of Mexico, than SMN.

In Table 3, the percentage of points with weak, moderate, and strong MSD is given for both the SMN stations and the $\text{CHIRPS}_{\text{SMN}}$ data set, for each case of duration of the phenomenon. Both SMN and $\text{CHIRPS}_{\text{SMN}}$ indicate that the MSD that has a duration of 1 month, either July or August, has mainly weak intensity, with no 1-month-long MSD points registering strong intensity. Additionally, both data sets indicate that nearly all of the moderate and strong MSD occur across either 2 or 3 months. The 2-month MSD is still mostly of weak intensity for both data sets although $\text{CHIRPS}_{\text{SMN}}$ identifies fewer points with this characteristic compared to SMN stations (60 *vs* 45%) and more points with moderate and strong MSD. In contrast, the 3-month MSD (June–August) has only moderate and strong intensity, the latter being predominant in this case. Compared to SMN stations, $\text{CHIRPS}_{\text{SMN}}$ identifies fewer points with moderate MSD and more points with strong MSD for the 3-month MSD case.

3.4. Duration and intensity of the MSD in CHIRPS

Based on the relative agreement between the SMN observations and $\text{CHIRPS}_{\text{SMN}}$ (Tables 2 and 3), we conclude that CHIRPS captures, in an acceptable manner, the duration and intensity of the MSD in Mexico. The spatial patterns of duration and intensity of the MSD, presented in the following subsections, are thus based on the entire CHIRPS data set for all of Mexico (instead of $\text{CHIRPS}_{\text{SMN}}$). The result is that CHIRPS provides a more detailed representation of the MSD phenomenon than can be obtained from SMN stations, which are often sparsely sited or with incomplete records.

3.4.1. Duration of the MSD

CHIRPS detected occurrence of MSD in regions where the SMN stations were sparse, including the north of Coahuila (July-only MSD and June–August MSD), the central south of Veracruz (August-only MSD), and northeast of Oaxaca and Chiapas (mainly July–August MSD) (Figure 6 and see Figure 1(b) for locations). Unlike MG66 and RT07, CHIRPS does not identify the presence of MSD in the central part of Chihuahua but shows some regions with MSD in August in the eastern part of Chihuahua and northeastern Durango (Figure 6). It should be noted that we do not have detailed information on the stations that were used by MG66 and RT07 to determine their MSD regions.

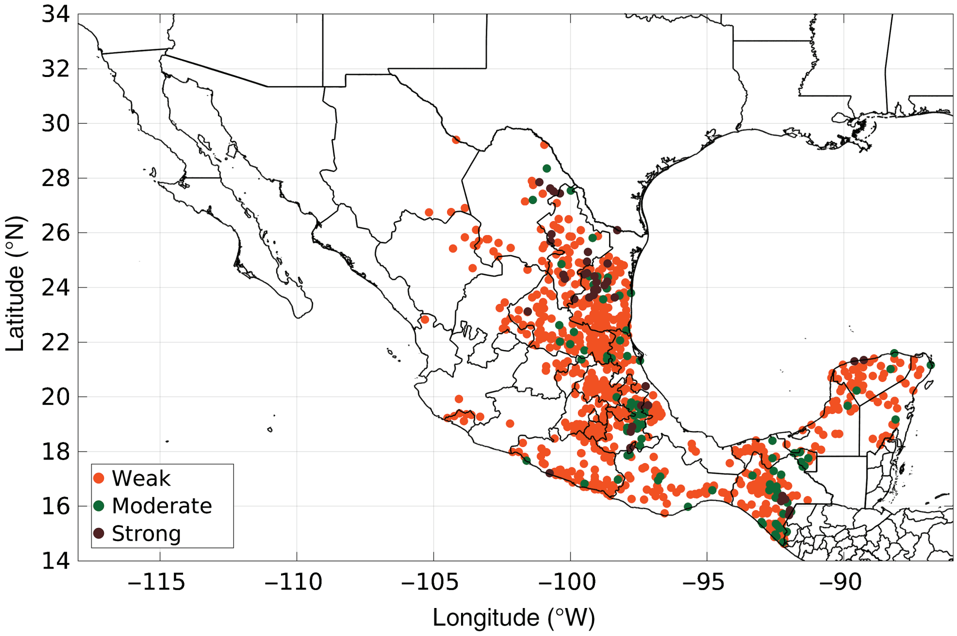

Figure 5. Intensity of the MSD in Mexico as detected by SMN observations. Colour legend is shown in the lower left corner.

Table 3. Percentage of stations showing weak, moderate, or strong MSD according to the SMN observations and CHIRPS values interpolated to SMN stations ($\mathrm{CHIRPS}_{\mathrm{SMN}}$), stratified by MSD duration.

Intensity duration	Weak		Moderate		Strong	
	SMN	$\mathrm{CHIRPS}_{\mathrm{SMN}}$	SMN	$\mathrm{CHIRPS}_{\mathrm{SMN}}$	SMN	$\mathrm{CHIRPS}_{\mathrm{SMN}}$
July	100	98.7	0	1.3	0	0
August	97.8	99.3	2.2	0.7	0	0
July–August	60.1	45	31.6	36.4	8.3	18.6
June–August	0	0	14.3	6.7	85.7	93.3

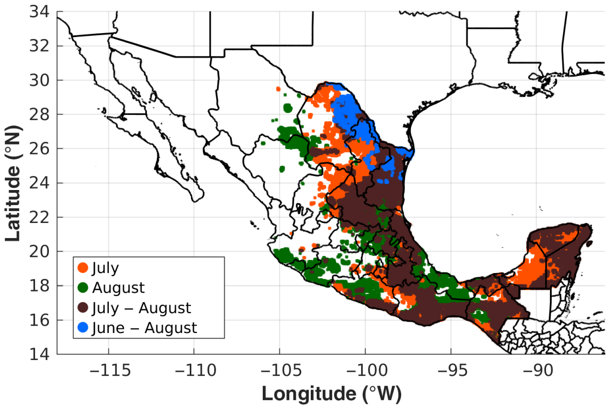

Figure 6. Spatial pattern of the duration of the MSD in Mexico according to the entire high-resolution CHIRPS data set for the period 1981–2010.

3.4.2. *Intensity of the MSD using three indices*

The spatial patterns of the intensity of the MSD obtained from the RD, PD, and PA indices, all calculated from the CHIRPS grid, are presented in Figure 7. The patterns obtained using the RD (Figure 7(a)) and PD (Figure 7(b)) indices are very similar although the regions of strong MSD obtained with RD cover slightly more area than those obtained with the PD index. The PA index (Figure 7(c)), however, identifies strong MSD in only the extreme northeast and southeast of Mexico. In general, all the three intensity indices signal more intense MSD primarily in the northeast of Mexico.

In some regions of the northeastern states of Mexico, even though the RD index indicates the occurrence of strong MSD, the PD index indicates moderate MSD. In these regions, the MSD exhibits its longest duration (Figure 6), which could influence the RD index to register a strong MSD while the PD index registers only moderate. In these cases, the PA index agrees with the PD index that the ratio between the accumulated precipitation during the MSD months and the accumulated precipitation during the entire rainy season (May–October) does not indicate strong MSD.

The MSD intensities obtained from the PA index (Figure 7(c)) differ from those obtained with the RD (Figure 7(a)) and PD (Figure 7(b)) indices as follows: with the PA index, weak MSD is present throughout nearly all of Mexico where MSD occurs, and moderate intensity MSD is mainly found along the states bordering the Gulf of Mexico and the Yucatan Peninsula, while RD and PD indices also show moderate MSD in some regions of central and southern Mexico.

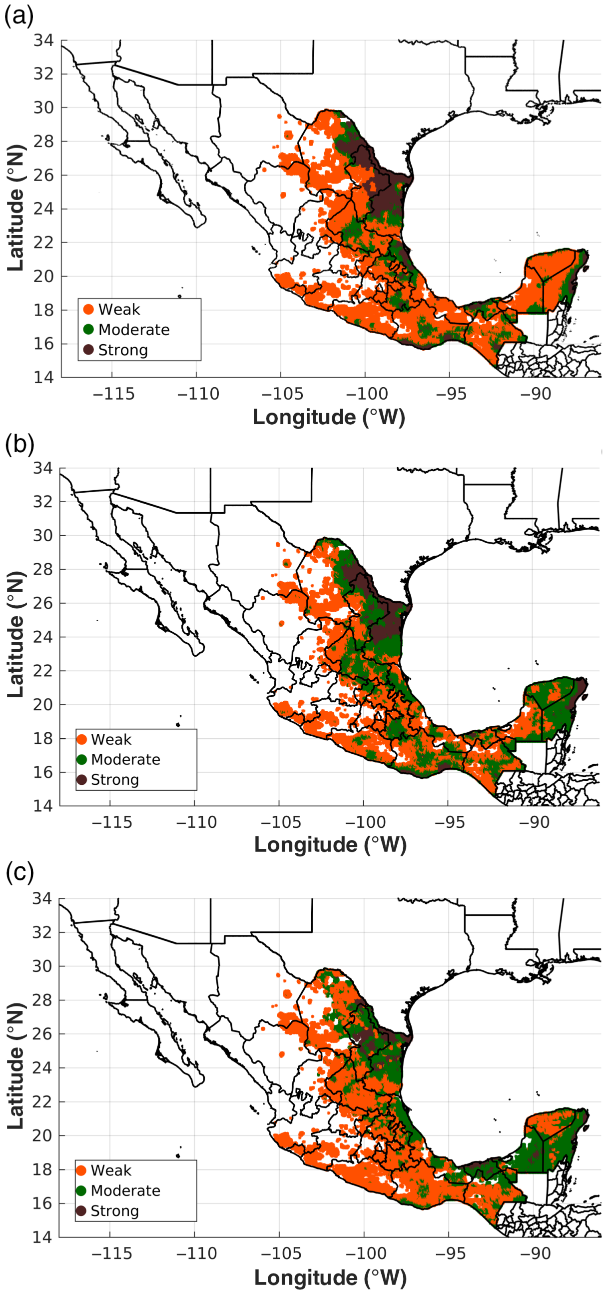

Figure 7. Intensity of the MSD in Mexico calculated from three different indices according to the high-resolution CHIRPS data set: (a) RD index, (b) PD index, and (c) PA index.

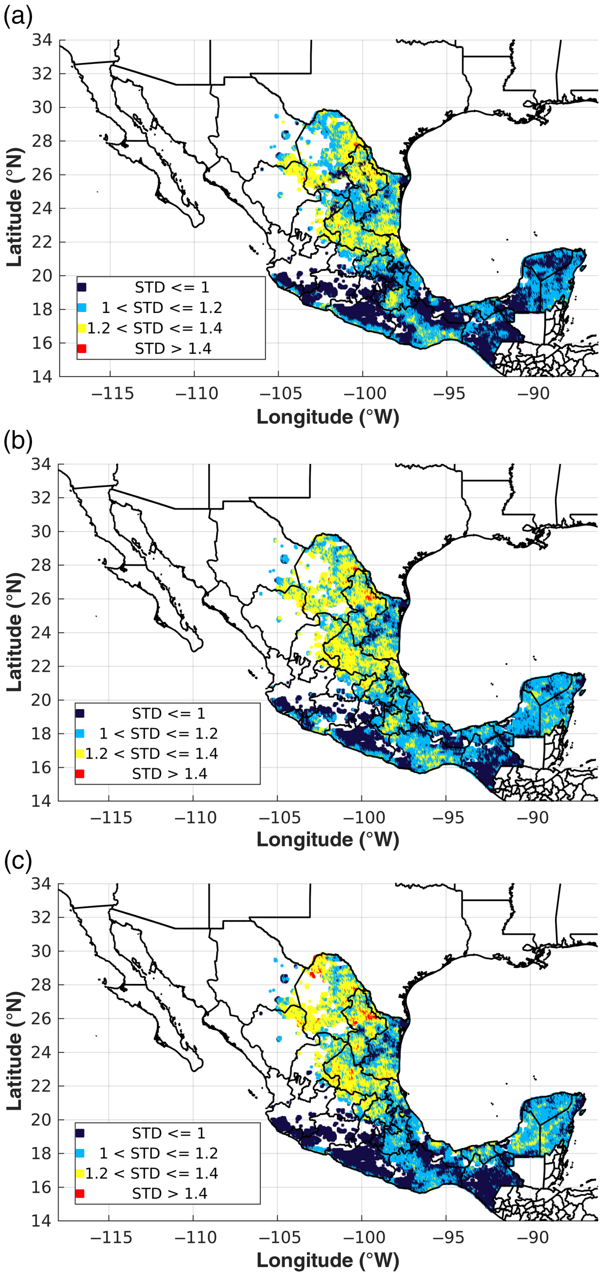

Figure 8. Spatial pattern of the standard deviation of the (a) RD index, (b) PD index, and (c) PA index, for the period 1981–2010.

3.4.3. Magnitude of the inter-annual variability of the MSD

The standard deviation of the RD, PD, and PA indices shows that the magnitude of the inter-annual variability of MSD intensity increases towards the northeast of the country, and it is higher in those regions where MSD presents the longest duration and greatest intensity (Figure 8). Furthermore, San Luis Potosi (Figure 1(b)) also shows high inter-annual variability, where CHIRPS detected a more complicated pattern in the occurrence of the MSD compared with SMN observations (Section 3.2). In some isolated regions of southern and southeastern Mexico, high standard deviation values are also obtained. The RD index presents the lowest variability, while the PA index presents the highest. This spatial representation of the inter-annual variability magnitude of the MSD intensity is another contribution this article makes to our understanding of the MSD in Mexico.

4. Discussion and conclusions

The very high spatial and temporal resolution of CHIRPS makes it a useful database for a wide range of studies, particularly for Mexico where there are large areas with little coverage of stations or where time series of historical observations have many missing data. In this study, the performance of the CHIRPS database to reproduce the observed precipitation climatology in Mexico was evaluated, with emphasis on the MSD, as it is a main feature of the annual cycle of rainfall in many regions of the country.

The presence of MSD was identified in 42% of the 2150 observing stations analysed, and MSD was located mainly in the southern half and eastern part of the Mexican territory (Figure 4). Delineation of the affected areas according to the duration, intensity, and variability of the MSD is of considerable importance, particularly from the agricultural point of view, because the MSD alters crops planting and harvesting strategies in the regions where it occurs. Similar to previous studies, four cases of MSD duration were identified: 1 month, which may be in July or August; 2 months (July and August), and 3 months (from June to August), with the August-only MSD being the most common (Figure 4). Only 2.3% of the stations where MSD occurs presented a duration of 3 months, and they were confined to the northeastern region of the country. In general, the July cases are located to the east of the August cases which is consistent with a westwards migration of the MSD (Figure 6).

In this work, possible physical mechanisms supporting the observed MSD duration pattern (e.g. a clear zonal gradient of the MSD and the apparent lack of a meridional gradient) were not explicitly explored. However, the results obtained here show a complex spatial structure, suggestive of influences from both local topography (which might explain some of the mesoscale variability) and large-scale forcing (which might explain more of the synoptic-scale variability).

Analysis of the intensity of the MSD, estimated using a RD index calculated from SMN stations, showed that MSD has mostly weak intensity. However, even in those areas with weak MSD, the standard deviation of the intensity indices shows that years with moderate and even strong MSD can occur. The most intense MSD occurs mainly in the northeastern part of the country (Figure 5), where it has a longer duration and the accumulated precipitation is lower than observed in southern Mexico. Even there, inter-annual variability suggests that MSD is not uniformly moderate or strong.

The CHIRPS data, interpolated to the geographical points of the SMN climatological stations, confirm that CHIRPS is acceptable in reproducing the climatological values of the monthly precipitation accumulations in Mexico (Figure 3) and, particularly, the MSD. In general, CHIRPS captured the characteristics of the spatial pattern of the MSD, both in terms of its duration and intensity. Thus, the entire high-resolution ($0.05 \times 0.05°$) database was then analysed. In performing so, CHIRPS provided a more detailed spatial representation of the MSD in Mexico than has ever been obtained before, allowing analysis of the MSD behaviour in those regions where there is a lack of station coverage or stations with incomplete records. In this sense, new sites with MSD were identified, located mainly to the north and southeast of Mexico, where the low density of SMN observing stations prevented the identification of its signal (Figures 1(a), 4, and 6).

The complex spatial structure of the MSD in CHIRPS includes some small and isolated regions, mainly in the northern region of the country (Figures 6 and 7). SMN climatological stations show the same features, with stations located very close to each other presenting differences in the pattern of the seasonal cycle of precipitation. This complex regional variability was seen in both SMN and CHIRPS. Nevertheless, the most common cases of MSD are captured by the CHIRPS data.

Spatial patterns of the MSD strength in Mexico were obtained by three indices calculated with the CHIRPS data: one existing index, the RD index, and two new indices designed to improve our knowledge on the MSD, PD and PA indices. The patterns obtained with the RD and PD indices were very similar to each other, while the PA index showed fewer sites with moderate and strong MSD. By calculating the PA index, novel features on the MSD strength were obtained, particularly in regions where the accumulated precipitation during the MSD is very low compared to the accumulated total of the summer months.

Because the RD index estimates the intensity of the MSD by calculating the area of the polygon that is formed according to the duration of the event, it implicitly considers the duration of the MSD to define its intensity. This was considered as a potential weakness in the original index; namely, the RD can indicate a strong MSD in cases when in fact there was not an important decrease in the amount of precipitation in the month (or months) of MSD. If, however, information on the relative decrease in precipitation during the month (or months) of MSD is more useful, then the PD index is likely the better choice. Nevertheless, the RD and PD indices generally give similar MSD results, especially when the decline in summer mid-season precipitation is not very large. The concepts of ‘PD’ and ‘PA’ presented here can thus be applied also to study the MSD in other tropical and subtropical regions where the phenomenon occurs. Furthermore, although not considered for this study, because MSD is shown to be a very complex phenomenon (as seen in the spatial patterns presented in Figures 6 and 7), a multivariate MSD index, perhaps based on convection, circulation, or atmospheric pressure fields, could produce an even more accurate depiction of the MSD.

Finally, it is important to clarify that the objective of this study was not to investigate the possible physical causes of the MSD, but to analyse and redefine its duration and intensity distribution over the Mexican territory using the newly available, high-resolution CHIRPS database. However, our results can be considered consistent with some of the mechanisms that have been related to the occurrence and development of this phenomenon. For example, the westwards migration of the MSD, particularly in the central region of Mexico (~18°–24°N), could be related to the intensification and westwards expansion of the North Atlantic subtropical high (NASH) during midsummer (e.g. Curtis and Gamble, 2008). The occurrence of the MSD in regions of southern Mexico could be also associated with the intensification of the winds over the Gulf of

Tehuantepec, which causes a displacement of the convergence and convection areas over the eastern Pacific and a cooling of the sea surface temperature in that region (Romero-Centeno *et al.*, 2007). Furthermore, the decrease in tropical storm activity in the eastern Pacific during midsummer (e.g. Curtis, 2002; Inoue *et al.*, 2002; Small *et al.*, 2007) is likely an important factor influencing the occurrence of the MSD, not only in coastal regions of the Mexican Pacific but also inland. Also, direct atmospheric circulations related with the intensification of the Caribbean low-level jet (CLLJ) could favour subsidence and divergence over the Yucatan Peninsula and adjacent areas (Curtis and Gamble, 2008; Whyte *et al.*, 2008). Finally, as previously mentioned, the precipitation maximum observed in May over the northeastern part of Mexico could be associated to moisture transport from the western Gulf of Mexico (Section 3.2), which may be interacting with other processes, such as the extension of the NASH and the strengthening of the CLLJ, and jointly determine the decrease in precipitation during the 3-month period of June–July–August.

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