Water Practice & Technology

 Water Practice & Technology Vol 18 No 2, 304 doi: 10.2166/wpt.2023.015

Influence of the AMO and its modulation of the ENSO effects on summer precipitation in Mexican coastal regions

Uxmal Rodríguez Morales [a,*], Benito Corona Vásquez [a], Ricardo Prieto González [b] and Polioptro Martínez Austria [a]

[a] Department of Civil and Enviromental Engineering, Universidad de las Américas Puebla, Ex Hacienda Sta. Catarina Mártir S/N, San Andrés Cholula, Puebla C.P. 72810, Mexico
[b] National Meteorological Service, Av. Observatorio 192, Colonia Observatorio, Alcaldía Miguel Hidalgo, Ciudad de México C.P.1860, Mexico
*Corresponding author. E-mail: uxmal.rodriguezms@udlap.mx

URM, 0000-0003-3963-0926; BCV, 0000-0003-0538-2741; PMA, 0000-0002-9565-1708

ABSTRACT

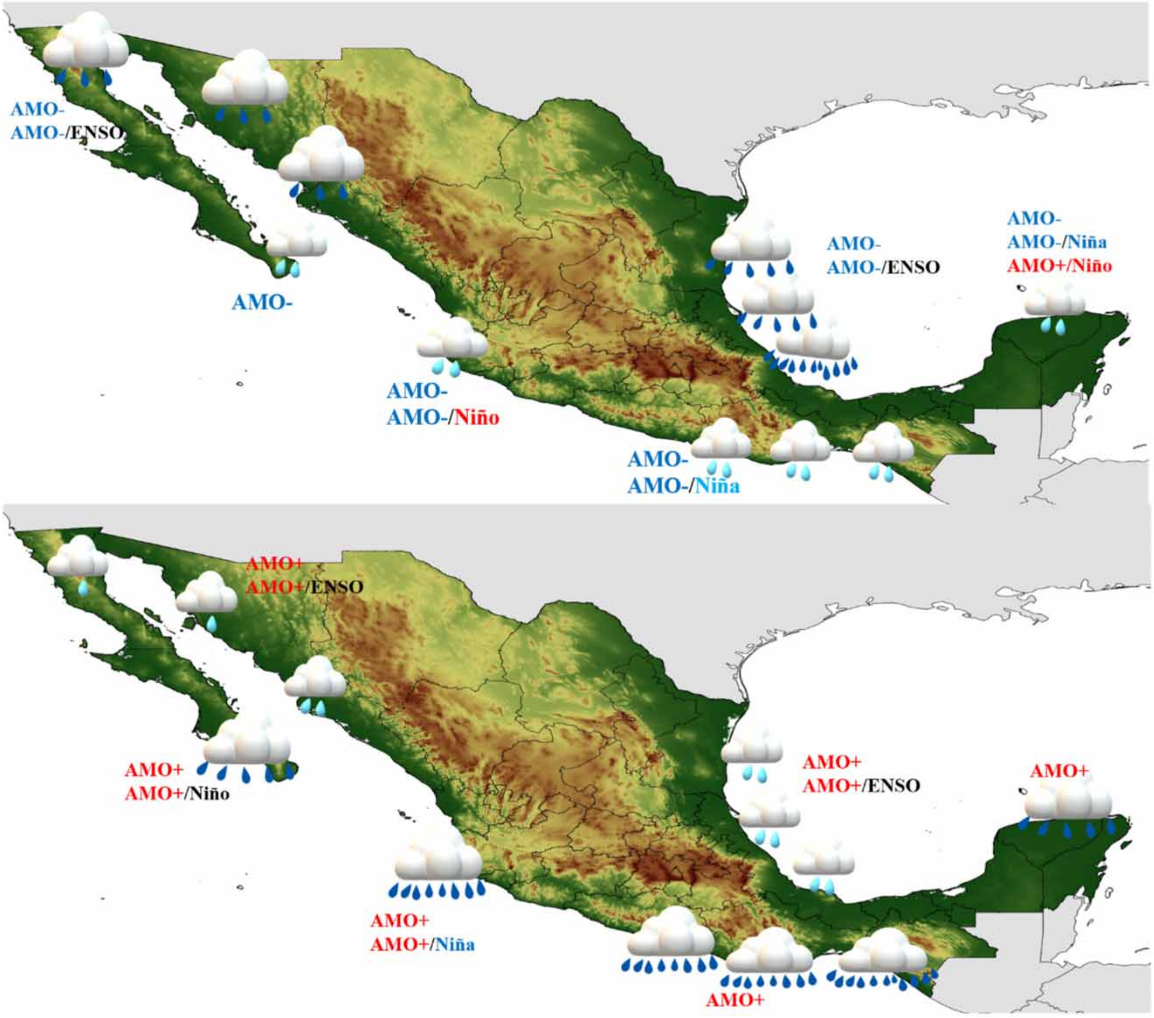
Due to its geographical location and interaction with the two largest oceans, Mexico's climate is strongly influenced by various climatic oscillations. Therefore, association studies between climatic indices and Mexico's climate have scientific and practical importance. Teleconnection patterns have been reported between summer precipitation and various climate oscillations. For the AMO, results are not totally coincident, and modulation of ENSO effects has not been explored. Correlation analyses between AMO and ONI 3.4 with summer precipitation (June–September) at individual 203 weather stations in Mexican coastal zones were carried out, and average precipitation was compared according to AMO phases and their combinations with ENSO events. With AMO + , it tends to rain more in northern Yucatan Peninsula, from Chiapas to Jalisco, and in the southern California Peninsula; with AMO− in Tamaulipas, Sonora and northern California Peninsula. AMO modulates ENSO effects; ONI correlations pattern strengthens with AMO+. El Niño summers are less dry with AMO− on Atlantic coast, Sonora and northern California Peninsula; on Pacific coast, alternating bands are observed. With AMO − , La Niña summers tend to be wetter toward south with AMO+ and toward north with AMO−. These changes can be related to variations in the surface and low-level wind regimes previously reported in literature.

Key words: AMO, ENSO modulation, Mexico, summer precipitation, teleconnections

HIGHLIGHTS

- There is a tendency for greater precipitation northward, associated with negative AMO and southward with positive AMO on both coasts.
- Summers with El Niño tend to be less dry with cold AMO on the Atlantic coast; but on the Pacific coast, alternating bands are observed.
- Summers with La Niña tend to be wetter southward during warm AMO and northwards with cold AMO on both coasts.

GRAPHICAL ABSTRACT



INTRODUCTION

Due to its geographical position and complex teleconnection mechanisms, Mexico is susceptible to the influence of conditions and modes of climate variability from both the Pacific and Atlantic Oceans. The influences of the El Niño Southern Oscillation (ENSO) (Bhattacharya & Chiang 2014; Alvarez-Olguin & Escalante-Sandoval 2017; Bravo-Cabrera *et al.* 2017) and the Atlantic Multidecadal Oscillation (AMO) (Curtis 2008; Alvarez-Olguin & Escalante-Sandoval 2017; Azuz-Adeath *et al.* 2019) have been reported among others. In Figure 1, location of Mexico, the states and the geographical features hereinafter mentioned can be seen.

The ENSO phenomenon has a great influence on climate variability because it is one of the oscillations with the lowest frequency (between 3 and 8 years) and its effects can be felt on a global scale. The name ENSO refers to variations in the equatorial Pacific in surface and subsurface ocean temperatures, atmospheric pressure gradients and Walker circulation. In general, during warm ENSO or El Niño events, the surface temperature of the South American equatorial Pacific increases and the trade winds decrease in strength; during cold ENSO or La Niña events, the surface temperature of the same area decreases and the trade wind pattern strengthens. Several indices are used to characterize this oscillation, including the MEI (Multivariate El Niño Index) and the ONI (Oceanic El Niño Index). In the case of the ONI 3.4 index when its value is equal or higher than 0.5 during 3 months, or more, it is considered an El Niño or warm event or positive phase. If ONI 3.4 is equal to −0.5 or lower for 3 months, or more, it is considered a La Niña or cold event or negative phase (Fang & Xie 2020).

ENSO effects on precipitation in Mexico have been the most studied among the oceanic and atmospheric indices, and this seems to be the oscillation with the greatest influence on the interannual variations of precipitation, due to its lower frequency (Bhattacharya & Chiang 2014). Although the resulting temporal and spatial patterns

Figure 1 | Mexican territory. In this map, the geographical location and orography of Mexico can be seen. Also, costal states and some important geographical features used in the text are indicated.

vary depending on precipitation data processing, either with values of individual stations or averaged by regions, they can be generalized as follows: during the dry season (November–April) positive correlations are observed in the great majority of the territory between the MEI and the average daily precipitation for individual stations (Bravo-Cabrera *et al.* 2017); also with the average accumulated precipitation by regions significant positive correlations are obtained for the winter (December–February) (Alvarez-Olguin & Escalante-Sandoval 2017). This means that, in general, precipitation tends to decrease during the coldest months during La Niña episodes and the opposite during El Niño events.

During the wet season (May–October) there is a north–south pattern with negative correlations south of the 22 N parallel and positive correlations in the northwestern region of Mexico between the average daily precipitation and the MEI index for individual stations (Bravo-Cabrera *et al.* 2017); for the average accumulated precipitation in the summer (June–August) by region, significant negative correlations are obtained in the Pacific region from Chiapas to Jalisco (Alvarez-Olguin & Escalante-Sandoval 2017). It is an increase in precipitation in the northwest and a decrease toward the south when El Niño events occur and the opposite with La Niña episodes. Beyond these general considerations found in the literature, the influence of ENSO is actually much more complex, temporally and spatially, since it varies intra-seasonally and differs from the development and decaying phases of the El Niño event (Bhattacharya & Chiang 2014).

The AMO is another mode of ocean variability but of lower frequency. This describes variations in sea surface temperature (SST) in the North Atlantic between 0° and 70° north of the Atlantic Ocean (Enfield *et al.* 2001). A positive AMO index indicates a warmer SST while a negative value indicates a colder SST. The first case is simply called positive or warm phase or AMO + ; in the same way, the second condition is called a negative or cold phase or AMO−. So far, a neutral condition has not been formally considered for the AMO as for the ENSO. This oscillation can remain on average for around 40 years approximately in one phase. The AMO has a global influence, as significant correlations have been found with temperature and precipitation in regions of

Europe, Africa, Asia and the Americas (Chen & Xu 2020; Yang *et al.* 2020). These effects can be associated with changes in the location and strength of the large centers of high pressure in the northern hemisphere, the direction and strength of the northern trade winds and changes in variations in the position of the Intertropical Convergence Zone (ITCZ) (Moreno-Chamarro *et al.* 2020; Yang *et al.* 2020).

For Mexico, several studies have reported the association of the AMO with precipitation, although for some of the studied areas, the results are contradictory. The long-standing periods of the AMO in a condition have been linked with droughts occurrence (Méndez & Magaña 2010). The most important positive correlations are obtained with accumulated precipitation in the summer (June–August) and autumn (September–November) periods. The former is located in the Yucatan peninsula and the Pacific coast from Chiapas to Guerrero, and the latter occurs in the north-central region as well as in the northern and southeastern areas of the Baja California peninsula. The main negative correlations are observed in northern Veracruz and southern Tamaulipas during winter (December–February) as well as in spring (March–May), when the same occurs for the north-central region (Alvarez-Olguin & Escalante-Sandoval 2017).

For the August–October season, negative correlations are observed between the AMO and average daily mean precipitation, mainly in the northeastern region of the Yucatan peninsula and northwestern Mexico, including the northern Baja California peninsula. This means a decrease in mean daily precipitation during these 3 months when the AMO is in a positive phase. A positive relationship is observed in some regions of south-central Mexico, but not in the southern region of the Pacific coast (Curtis 2008).

Regarding the correlation between the annual precipitation and AMO, positive and significant values were obtained for the Atlantic coast states of Campeche and Veracruz while negative values were reported for the states of Tamaulipas and Yucatan. On the Pacific coast, the positive and significant correlations are located from Chiapas to Colima and in Baja California; the negative ones are from Jalisco to Sonora (Azuz-Adeath *et al.* 2019). Some differences in results among the last three aforementioned works can be seen, especially in the northern part of the Yucatan Peninsula and the southern Pacific regions. These contradictions are probably due to the different methods used to average and filter the time series, the differences in the way of grouping the precipitation data, either in gridded reanalysis databases, averaging data from meteorological stations grouped by homogeneous regions of precipitation or by states and the months included in each study. An analysis of the influence of the AMO at the level of individual stations in Mexico had not been performed yet.

Climate oscillations are quasi-periodic and have different average periods, which generates several scenarios according to the combinations between their different phases. Among these modes of variability, there can also be dependence and modulation relationships as reported for the ENSO and AMO (Gong *et al.* 2020). ENSO events have a much higher frequency than AMO phases, so El Niño or La Niña events can occur in either two phases of the AMO, thus it can modulate ENSO effects.

In South America, ENSO effects are enhanced when the Atlantic is in the opposite phase (Niña/AMO+ or Niño/AMO− and diminished when the contrary occurs (Kayano & Capistrano 2014). In the USA, for AMO+, in the eastern part of the Mississippi River Basin, precipitation shows an increase in significant negative correlations with the ONI 3.4, but a decrease in significant positive correlations in the Southeastern coast when compared with AMO− (Enfield *et al.* 2001). It is logical to assume that if the AMO modulates ENSO effects on precipitation in both North and South America, it also does so in Mexico. Recently, it has been reported that a below-average decrease in SST in the Tropical North Atlantic (TNA) and Atlantic El Niño region increases the drought conditions generated by El Niño events in Central America and Mexico during the summer (Singh *et al.* 2021). The amount of these effects have not yet been explored in the country at the level of single meteorological stations or associated with the general average situation of the entire North Atlantic Ocean.

Correlations between precipitation and indexes and later association with climatic processes allow us to establish teleconnection patterns. These patterns are used to make simple precipitation change estimations linked to climatic variability. Hence, contradictory results, despite that they could have different interpretations, lead to contradictory estimations, even if they are qualitative ones. Given that there are some contradictions regarding the effect of the AMO on precipitation in some coastal regions and states of Mexico when analyzing data in grids or group, it is necessary to explore this effect in coastal regions, but through the analysis of summer precipitation reported by individual meteorological stations. Another issue making these evaluations more difficult, is that a slower climatic oscillation modulates the correlation pattern of faster ones. It is the case of the AMO and ENSO, as previously mentioned. These effects have not been explored in Mexico; so doing will increase the power of summer rain estimations because at least two very important interacting modes of climatic variations are included. These data analyses are expected to improve water management local strategies on the basis of these environmental conditions. Therefore, the aim of this research is to analyze the influence of the AMO and its modulation of ENSO effects on summer precipitation in coastal regions of Mexico while evaluating data from individual meteorological stations.

METHODS

Monthly accumulated precipitation values were obtained from the official database of Mexico's National Meteorological System (SMN). Stations were included in the study if they were located in or near coastal areas, at less than 700 m above sea level and had records of at least 30 years between 1950 and 2016, the analyzed period. The main variables employed for calculations were accumulated summer precipitation and precipitation mean regarding the index phase for every meteorological station; for the two used indexes were average summer value and oscillation phase.

The accumulated summer precipitation was considered as the sum of the monthly accumulated precipitation from June to September, the season with the highest rainfall in most of the country (Bravo Cabrera *et al.* 2010). Millimeters values of every summer were transformed to percentages with respect to the historical mean for every station within the period analyzed; this series was later used for correlation. Precipitation mean for the index phase was calculated as the average of all accumulated summer precipitation corresponding to the considered phases, positive or warm and negative or cold. These two series were expressed in percentage and millimeters; the first ones are used for the description of results but are not shown in figures; the second ones are for calculating average precipitation differences between index phases.

The average summer values of each index were calculated with monthly values from June to September, also in the same period. These series were used for correlation calculations. If the value was greater than zero, the AMO was considered to be in the positive (+) or warm phase; if lower, then in the negative (–) or cold phase. For the classification of ENSO phases, the classical criterion was modified (Trenberth 1997). A Niño summer was considered when the average of the 4 months was greater than 0.5 or the monthly value met this criterion for at least 2 months out of fourth considered; a Niña summer if the average was lower than −0.5 or 2 months met this criterion. The climate indices data were obtained from the official NOAA website:

- AMO (https://www.esrl.noaa.gov/psd/data/correlation/amon.us.data)
- ONI3.4 (https://www.esrl.noaa.gov/psd/data/correlation/oni.data)

In order to analyze the association between the AMO and summer rain, Pearson's correlation coefficients between each station's accumulated summer precipitation and average AMO value were calculated. Besides, differences between the precipitation mean of the two AMO phases were calculated in millimeters and both means were compared with the independent Student's *t*-test. For examining whether the AMO has an influence on the ENSO effect, the series of cumulative precipitations of every station was divided into two groups regarding AMO phases, positive and negative. Pearson correlations between average ONI3.4 and the two aforementioned summer rain groups were calculated. From the accumulated precipitation series the values corresponding to Niño summers were selected and divided according to AMO phases; so, differences between the precipitation mean of Niño/AMO− and Niño/AMO+ were calculated, and means were compared also with independent Student's *t*-test The same procedure was done for Niña summers. Both applied statistical tests are considered as classical ones and widely used in teleconnections studies as in Curtis (2008) and Bravo-Cabrera *et al.* (2017).

Correlation coefficients and mean differences were considered significant at a 95% confidence level. In the figures, they are also indicated for a level lower than 95%, but higher than 90%. These cases are considered to be close to significance. In some works, the correlations between precipitation and climatic indices and differences between means of precipitation are considered significant at 90% confidence (Enfield *et al.* 2001; Curtis 2008). Minitab16 software was used for the statistical analysis and ArcGIS 10.8.1 for the figures.

RESULTS

The study included 203 meteorological stations; 61 are located on the Atlantic coast and 142 are located on the Pacific side. They cover most of Mexico's coastal regions although at some fringes, suitable meteorological stations were not found. On the Atlantic coast, average accumulated summer precipitation ranged from 317.1 to 2,040.5 mm. The lowest accumulated precipitation values, in the order of 300–400 mm, were registered in the north of the Yucatan peninsula and north of Tamaulipas; the highest precipitation records are located in the south of Veracruz, where all the points of the east coast considered in the study that exceeds 1,000 mm are concentrated. These precipitation ranges correspond to a percentage of the annual precipitation that varies between 36.9 and 82.5%. Just 1 out of 61 stations, shows an accumulated summer precipitation lower than 40%.

The 142 stations chosen from the west coast showed greater variability, summer rainfall ranges from 4.9 to 2,173.9 mm. From Chiapas to the center of Sinaloa, all included stations presented values greater than 500 mm; only two locations in Chiapas reached accumulations greater than 2,000 mm. From the center of Sinaloa to Sonora and the Baja California peninsula, all stations displayed rainfall records lower than 500 mm. The stations with the lowest precipitations are located in the north and west of the Baja California peninsula, where all accumulations below 25 mm are concentrated. Percentages of annual precipitation are likewise variable. From Chiapas to the center of Sonora, in the south and southeastern areas of the Baja California Peninsula summer rainfall represents more than 50% of the annual precipitation and it can reach 86.6%. Northern Sonora and the other peninsular regions exhibit values smaller than 40% and as low as 0.3%. Locations whose summer precipitation accounts for less than 10% of the annual accumulated rainfall are consistently located on the northwestern side.

Correlations between the percentage of accumulated summer precipitation and average AMO are shown in Figure 2. On both coasts, a south–north pattern can be clearly noted, where positive correlations predominate toward the south and negative correlations to the north. On the Atlantic coast, two zones can be distinguished where the correlation coefficients obtained with the most extreme and significant values or close to significance are grouped: in the north of the Yucatan peninsula and from the north of Veracruz to Tamaulipas. In the former, positive correlation coefficients predominate and their values range between 0.28 and 0.52; in the second, negative correlations predominate and vary from −0.28 to −0.40.

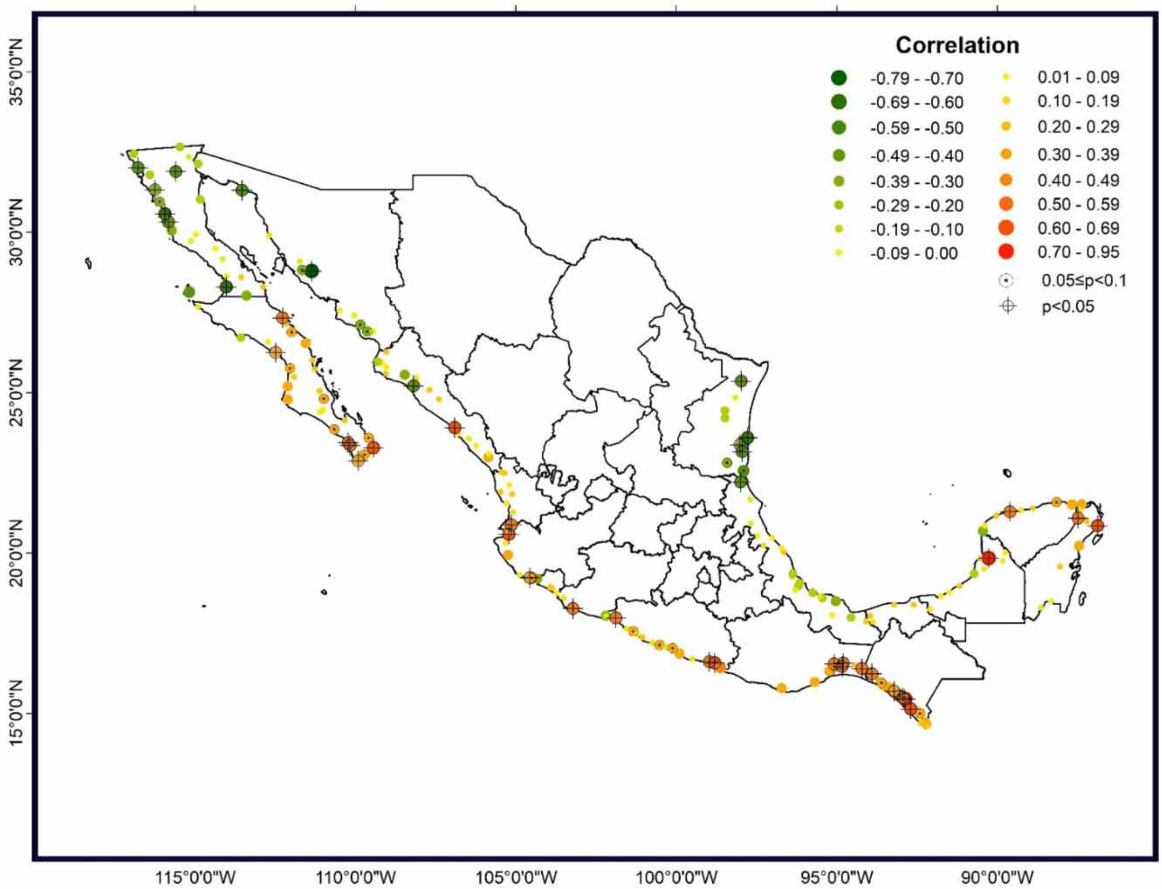


Figure 2 | Correlation between accumulated summer precipitation and average AMO index. The values of the correlation coefficients are represented by a combination of size and color as indicated in the legend.

On the Pacific coast, positive correlations were obtained mainly from Chiapas to central Sinaloa and in the south of the Baja California peninsula. Significant or close coefficients range between 0.21 and 0.5. As shown in Figure 2, there is a greater concentration of stations with significant and higher coefficients from the coast of Chiapas to the south of Guerrero. In northern Sinaloa, Sonora and the northwestern region of the Baja California peninsula, locations with negative correlations predominate, with significant or close values ranging between −0.25 and −0.54.

The correlation pattern described above indicates that, in general, at locations with relevant positive coefficients, it tends to rain more during the AMO+ phase; on the contrary, those with remarkable negative correlations with AMO−. This can be seen more clearly in Figure 3; it shows the difference between precipitation means when the AMO is in the negative phase minus the mean for the positive phase. Thus, when the difference is positive it indicates that precipitation is higher in the negative phase of the oscillation and lower in the positive phase; when it is negative it indicates the opposite. The value of the differences is expressed in millimeters as shown in Figure 3.

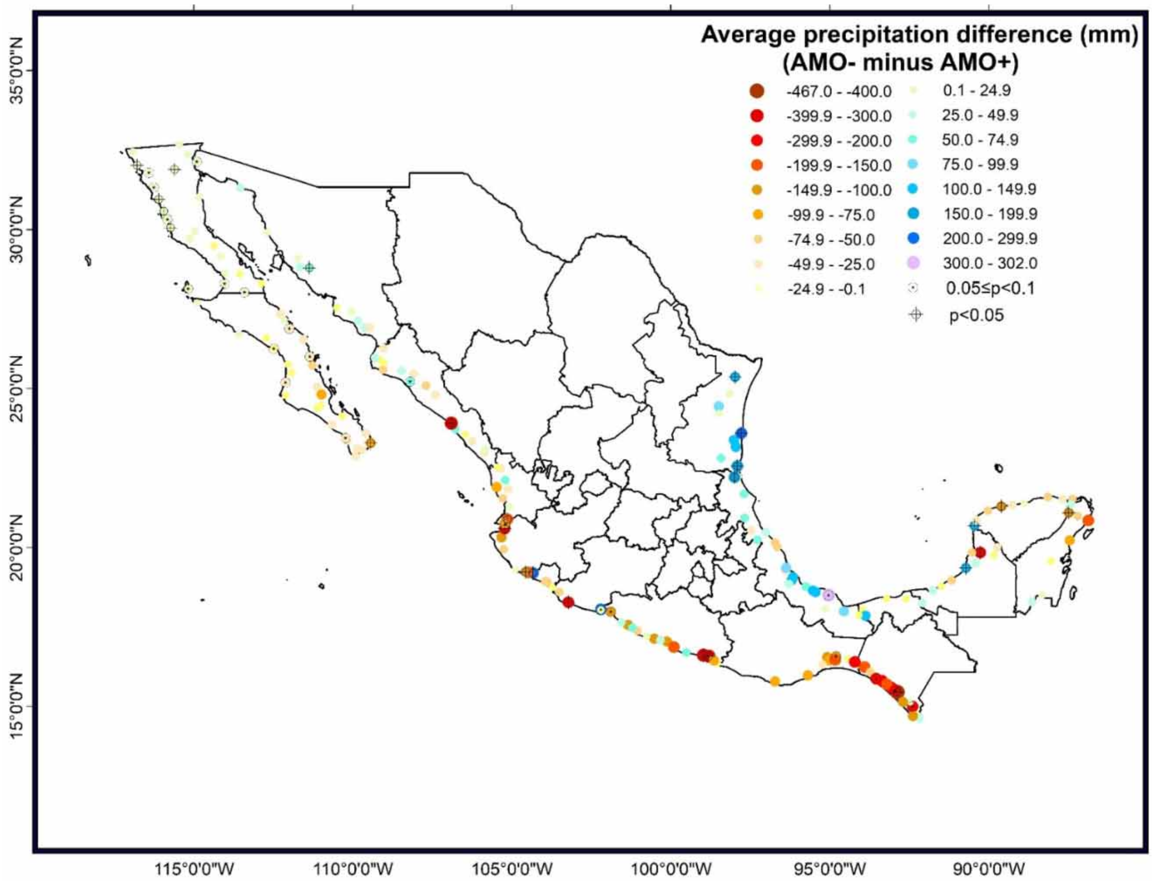


Figure 3 | Difference between precipitation means during the AMO phases (negative phase – positive phase) expressed in mm. The values of the differences are represented by a combination of size and color as indicated in the legend.

In the northern region of the Yucatan peninsula, it tends to rain more during the warm phase of the AMO, although there are a few stations with significant differences. For these, on average, precipitation can be higher between 18 and 33%; it means from 114 to 239 mm more accumulated summer precipitation, when the AMO is in the warm phase if compared with the cold one. A few points with significant differences, but with opposite behavior are observed on the west coast of the Yucatan Peninsula. From southern Veracruz to the northern, greater precipitation tends to occur during AMO – , although these positive differences are greater toward northern Veracruz and Tamaulipas. Here, the significant values range between 24 and 47%, which correspond to 146–247 mm more accumulated precipitation in individual stations during the summer, on average, when the AMO is in the cold phase.

On the Pacific coast, from Chiapas to southern Sinaloa, negative mean differences predominate, pointing to higher summer rainfall with AMO+. Significant and closer differences indicate between 104 and 467 mm more summer precipitation (between 11 and 33%) during warm AMO. Within this zone, the region between Chiapas and southern Guerrero has the highest concentration of stations with higher and significant differences.

A similar behavior is observed in the south of the Baja California peninsula. Here, localities with important differences accumulate, on average, summer precipitation between 33 and 76% higher (23–79 mm) in warm AMO. In the northern regions of Sonora and the northern half of the Baja California peninsula, the opposite occurs. Herein, differences indicate higher rainfall from 61 to 150% (5 and 79 mm) in summer with cold AMO. Since this is the region with the lowest precipitation records, these high percentages are not equivalent to high accumulated values. A qualitative general summary of these results is shown in Table 1.

Table 1 | AMO main effects and its ENSO modulation

General effect on summer rainfall and scenario	Coastal region and observations
Above average with AMO +	Atlantic cost: N Yucatan Peninsula Pacific coast: Chiapas to S Sinaloa, S Baja California Peninsula
Above average with AMO −	Atlantic coast: Veracruz to Tamaulipas Pacific coast: N Sinaloa, Sonora, N Baja California Peninsula
More rain with Niño/AMO− than Niño/AMO +	Atlantic coast: N Tamaulipas, S Veracruz, SW and NE Yucatan Peninsula (around average or more)/NW Yucatan Peninsula, central Veracruz to central Tamaulipas (less dry) Pacific coast: South Chiapas, Guerrero to S Michoacan (less dry) / Sonora, N Baja California Peninsula (above average)
More rain with Niño/AMO+ than Niño/AMO −	Pacific coast: N Chiapas to S Guerrero, N Jalisco to S Sinaloa (less dry)/Center and SW Peninsula Baja California (above average)
More rain with Niña/AMO− than Niña/AMO +	Atlantic coast: N Veracruz to Tamaulipas, central Veracruz, (some points below average with AMO−) Pacific coast: Sonora, N Baja California Peninsula (less dry but in central Sonora above average with AMO−)
More rain with Niña/AMO+ than Niña/AMO −	Atlantic coast: N and E Yucatan Peninsula (below average with AMO−) Pacific coast: Chiapas to N Nayarit (mainly wetter)/SE extreme Baja California Peninsula (above average with AMO+)

Note: These results are given in a qualitative form to help overall comprehension but for more specific details main text should be consulted.

As shown in Figure 4, the general correlation pattern between precipitation and ENSO are modified by the AMO. During the warm phase, correlations are reinforced, increasing absolute values and the geographic extent of stations with significant or closer coefficients. This indicates that there is a tendency to intensify the effects of ENSO events during an AMO positive phase. On the Atlantic coast, negative correlations are extended and strengthened. The same occurs on the Pacific coast from Chiapas to central Sinaloa. In the region of the northern coast of Sonora and the Baja California peninsula, positive correlations are reinforced. In general, these variations of correlations pattern show an increase in ENSO effects during warm AMO. This modulation can be better observed in Figures 5 and 6 where the differences between summer precipitation means are represented, according to AMO phases for summers classified as Niño or Niña, respectively.

During the 1950–2016 period, 15 summers were classified as Niño; 9 of them occurred during a positive AMO and 6 during a negative AMO. In general, summer precipitation in coastal areas tends to decrease below average during warm ENSO events, with the exception of the northwestern region (northern Sinaloa, Sonora and the Baja California peninsula). Bands with larger extension and most precipitation decreasing are located from the center of Veracruz to the center of Tamaulipas, on the east coast, and from Chiapas to the south of Sinaloa on the west coast. Precipitation reduction can reach up to 42% below average on the Atlantic coast and 36% on the Pacific coast (data not shown in figures).

The effect of El Niño events is modulated by the phase of AMO. Figure 5 shows the difference between accumulated precipitations expressed in millimeters, for Niño summers for both AMO phases. The meaning of negative values is the same as explained above in Figure 3. A more homogeneous pattern arises on the east coast. On this side, when the Atlantic SST is colder, summers with El Niño events show higher precipitation when compared with warmer Atlantic SST. Although the number of meteorological stations with significant differences is low as depicted in Figure 5, when El Niño events occur during AMO − , summer rainfall can exceed, on average, between 146 and 402 mm, compared with the same events but during AMO+. Hence,

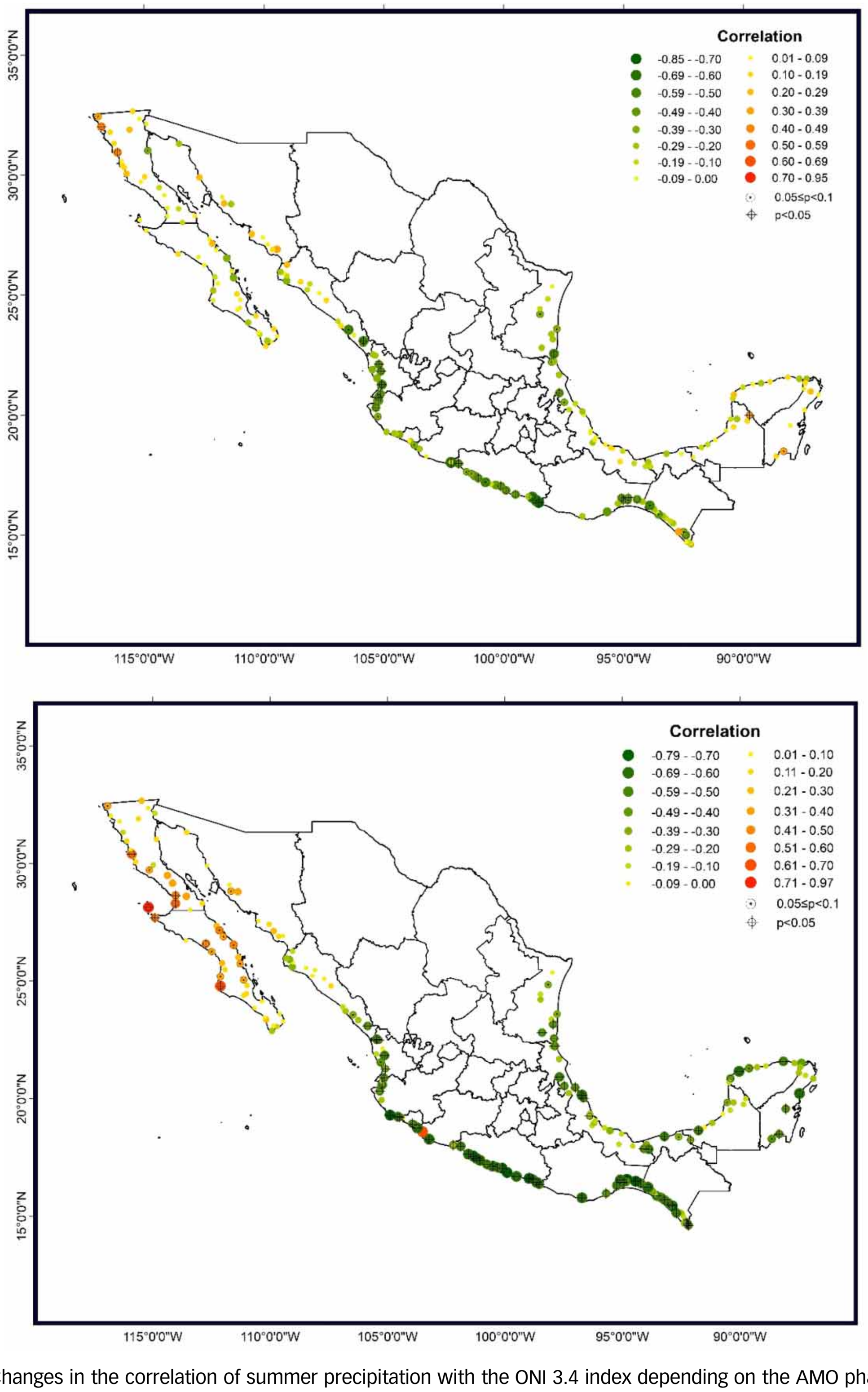


Figure 4 | Changes in the correlation of summer precipitation with the ONI 3.4 index depending on the AMO phases. Results for the cold and warm phases are plotted in the upper and lower panels, respectively. The values of the differences are represented by a combination of size and color as indicated in the legend.

summer rainfall reduction associated with El Niño tends to be lower with cold AMO, or in another way, less dry summers or even reach positive values like in northern Tamaulipas, south-central Veracruz, west and northeast of Yucatan peninsula precipitation. Some locations, mainly in the northern Yucatan Peninsula, display an opposite modulation regarding AMO.

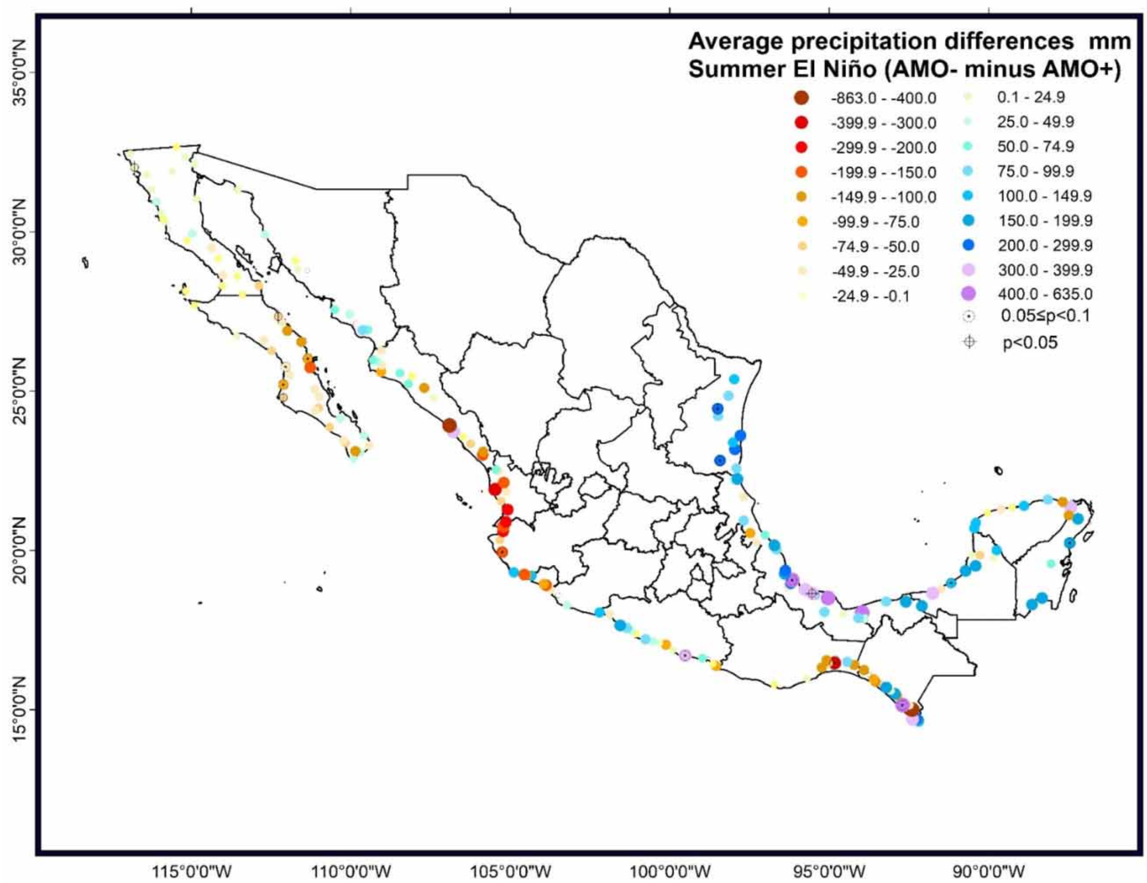


Figure 5 | Difference between mean precipitations during summers considered Niño according to AMO phases (Niño summer with negative AMO – Niño summer with positive AMO) expressed in mm. The values of the differences are represented by a combination of size and color indicated in the legend.

On the Pacific coast, the pattern is less clear; areas with opposite modulation alternate along this side. Main coastal areas with greater precipitation with Niño summers and AMO− are located toward south Chiapas, from south Guerrero to Michoacan, from north Sinaloa to Sonora and the northern Baja California peninsula. Areas with greater precipitation with Niño summers and AMO+ are found from northern Chiapas to southern Guerrero, from northern Jalisco to southern Sinaloa and the southward Baja California peninsula. Few stations exhibit significant differences; these indicate values between 37 and 399 mm more rainfall with warm AMO or between 12 and 636 mm with cold AMO during Niño summers. This alternated pattern suggests that the modulation of El Niño effects by AMO is more variable and complex on the Pacific coast.

In the case of Niña summers, 20 were classified as such within the analyzed period; 11 during positive phase AMO and 9 during negative. In general, summer precipitation in coastal areas tends to increase above average during these events, with the exception of northern Sinaloa, Sonora and the Baja California peninsula, where rainfall is below average. Precipitation increase values can reach as much as 22% above average at some stations on the Atlantic coast and 30% on the Pacific coast; the amount of the reduction can reach 76% below the mean toward the north of the west coast (data not shown in figures).

The AMO also modulates the effect of cold ENSO events on precipitation during the summers. As can be seen in Figure 6, on the Atlantic coast, in general, from the Yucatan peninsula to southern Veracruz and in a small area in the north-central Veracruz coast Niña summers are wetter with a positive AMO. Toward south-central Veracruz and the coastline from northern Veracruz to Tamaulipas Niña summers are wetter during a negative AMO. The frequency of significant differences, or those close to significance, is low and their values indicate that, on average, between 166 and 214 mm more rain may accumulate in the first mentioned areas and between 170 and 293 mm in the second ones. It should be mentioned that in some analyzed stations of Tamaulipas and central Veracruz precipitation during Niña summer and AMO+ reach values below average and in most of the stations of east and north of Yucatan peninsula with AMO – .

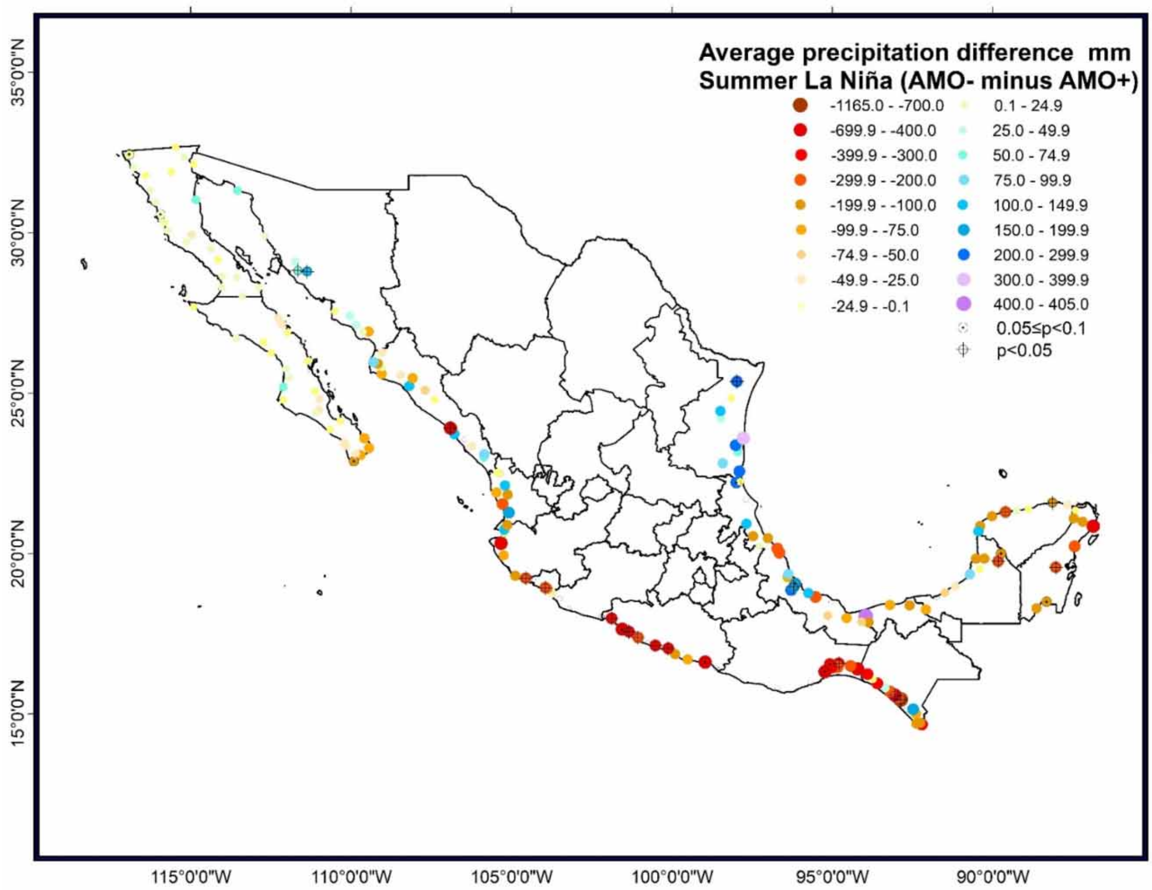


Figure 6 | Difference between mean precipitations during summers considered Niña according to AMO phases (Niña summer with negative AMO – Niña summer with positive AMO) expressed in mm. The values of the differences are represented by a combination of size and color indicated in the legend.

On the Pacific coast, Niña summers are wetter on average during the warm phase of the AMO in most of the included stations from Chiapas to north Jalisco and in the Baja California peninsula. There are few statistically significant differences and these indicate that the extra precipitation values can range between 209 and 1,165 mm in the southern regions of the west coast and between 5 and 104 mm in the southeast peninsular area. The coasts of Sonora and the north side of the Baja California peninsula predominate stations where Niña summers tend to be rainier during a negative AMO than positive. Differences vary between 7 and 107 mm. Also, main results regarding the modulation of ENSO effects by the AMO are given in Table 1.

DISCUSSION

The positive correlations with the AMO obtained in this study for the coastal areas of the Yucatan peninsula and from Chiapas to Michoacan are consistent with those reported previously in the literature, as well as the negative correlations obtained for the regions of northern Veracruz, southern Tamaulipas, and toward the north of the Baja California peninsula (Alvarez-Olguin & Escalante-Sandoval 2017). Although the aforementioned study was carried out by grouping stations with homogeneous precipitation regions and for the June–August season, these similarities may be due to the existence of a large percentage of stations, grouped within the same regions, showing similar individual correlation values. Despite these similarities, it is observed that correlations at the level of individual stations can vary and present a much more complex pattern of teleconnections which may explain, in part, other differences with respect to the observations reported by these authors. The negative correlations toward the north of the country and the positive ones in the north of the Yucatan peninsula also are in agreement with results reported for southern regions of the USA (Enfield *et al.* 2001). The former shows a continuous zone of influence of the AMO from southern Texas extending to northern Veracruz in the east and from northern California to northern Sinaloa and the center of the Baja California peninsula on the west coast. The second one points out another zone of opposite influence of the AMO that extends from the Florida peninsula to the Yucatan peninsula, probably related by their geographic proximity and longitude.

One of the main contradictions that can be found with respect to values reported in the literature is the results obtained for some areas of the Yucatan peninsula. Curtis (2008) reports negative correlations in the northeastern region and Azuz-Adeath *et al.* (2019) do so for the whole state. Since discrepancies can be attributed to methodological differences, one station in the area was chosen to perform additional individual analysis. For this purpose, the Chicxulub station (code 31007, latitude: 21.293889, longitude: −89.608333) was chosen because it presents a correlation index value between accumulated precipitation and the average value of the AMO index among the highest in that region (r: 0.34, p: 0.014). The correlation between the average AMO value precipitation, in the period from June–September, and two variables, the average daily precipitation (r: 0.333; p: 0.016), and the number of days with precipitation (r: 0.423, p: 0.002) were calculated as part of this additional analysis.

These results indicate that, during a positive AMO, daily precipitation and rainfall days tend to increase. If we compare these two variables for warm AMO (3.35 mm and 28 days) with those for cold AMO (2.4 mm and 23 days), although the differences are small, they are significant in both cases (p: 0.012 and p: 0.021, respectively). With this brief analysis, it seems that this contradiction can be attributed to differences in the data grouping techniques, time series treatment, months included in the study, and/or employed methodology and their results would have different interpretations. It is expected that other disagreements with respect to different areas can be explained in the same way.

The correlations between precipitation and AMO as well as mean differences can be linked to general climatic patterns associated with the AMO as reported in the literature. Both observed data and simulations have established that the ITCZ tends to move latitudinally depending on the phases of the AMO (Moreno-Chamarro *et al.* 2020). In southern Mexico, summer precipitation is influenced by ITCZ position (Méndez & Magaña 2010). The northward shift during the boreal summer in positive AMO brings the zone of influence of the ITCZ closer to the southern region of Mexico, which explains, in part, the observed increase in mean precipitation associated with this phase of AMO in the northern Yucatan peninsula and the coastal areas from Chiapas to Guerrero. The southward shift during the negative phase is associated with the decrease in mean precipitation in the same region during this phase

Other climatological factors that vary associated with the phases of AMO are the intensity and location of the North Atlantic Subtropical High (NASH) or Azores anticyclone, the strength of the trade winds and thus the surface and low-level wind patterns. During an AMO positive phase, NASH tends to weaken and this occurs with greater intensity toward the western flank, which results in a decrease in the speed of the trade winds from the north and in turn a change in the circulation patterns associated with the Caribbean Low-Level Jet (CLLJ) (Curtis 2008; Hu & Feng 2008). This jet has great importance in moisture transport from the Caribbean to most parts of Mexico (Perdigón-Morales *et al.* 2021), and also modulates convection and tropical waves activity, which have a great influence on summer precipitation (Serra *et al.* 2010).

In the case of the northeastern coastal region, rainfall is lower when the AMO is positive; this may be associated with the diminishing of moisture transport by low-level easterly and southeasterly winds from the Caribbean and the Gulf of Mexico. These regions constitute the main sources of moisture for this area during the rainy season (Perdigón-Morales *et al.* 2021). The excessive weakening of these surface and low-level winds, or the preponderance of winds from the opposite direction coming from the continent with low moisture content, would explain the precipitation decrease during warm AMO (Curtis 2008). The weakening of these winds is also associated with a decrease in the number of tropical waves reaching the region, and a decrease in convective activity and precipitation (Méndez & Magaña 2010). In the northern Yucatan Peninsula, precipitation averages tend to be higher than average in positive AMO. This is associated with a decrease in wind velocity, which can locally favor convection and increase the probability of rainfall (Magaña *et al.* 1999). During the cold phase, CLLJ strengthening is associated with a decrease in precipitation in this area (Perdigón-Morales *et al.* 2021). The strengthening of the jet also generates a decrease in the development and convective activity of tropical waves over the Caribbean Sea and southern Mexico, and therefore a decrease in precipitation (Méndez & Magaña 2010).

On the west coast, from Chiapas to central Guerrero, an increase in summer precipitation during warm AMO, in addition to the aforementioned northward displacement of the ITCZ, is associated with variations in the surface winds regime. In this AMO phase, southwesterly and westerly winds predominate (Curtis 2008; Hu & Feng 2008). Although the main source of humidity in this region is the Caribbean Sea, to a lesser extent, humidity also comes from regions of the northeastern Pacific and the northwest of the Isthmus of Tehuantepec (Perdigón-Morales *et al.* 2021). The flow of humidity from these other moisture sources associated with a weakening of surface and low-level winds favor humidity convergence, convection and an increase in precipitation (Magaña *et al.* 1999). The contiguous area, between central Guerrero and southern Sinaloa also show the same tendency, but to a lesser extent and strength. This lower association between summer rainfall and AMO may be due to several factors; first, to its more northerly position with a decreasing influence of the ZCIT. Secondly, this larger area includes regions with differences in their precipitation regimes (Alvarez-Olguin & Escalante-Sandoval 2017); with additional moisture sources other than those in the southern region; and also with a modulation of precipitation by the CLLJ different from the south (Perdigón-Morales *et al.* 2021). The heterogeneity of the region could explain these results.

In the Baja California peninsula, two regions where AMO effects are more noticeable and opposite are noticed: the southernmost peninsular area and the northwest coast, when summer rainfall tends to be higher with AMO+ and AMO −, respectively. During the cold AMO, surface winds from the northwest are recorded throughout the region (Curtis 2008; Hu & Feng 2008) and they bring moisture from the west coast of the USA, and the Gulf of California, both of which are important moisture sources for the northwestern region (Ordoñez *et al.* 2019). Also, the Gulf of California low-level jet (GCLLJ) tends to strengthen and this is associated with an increase in precipitation not only in the northern Baja California peninsula, but also in Sonora (Hu & Feng 2008). Although the Gulf of Mexico and the Caribbean Sea are not the main moisture sources of this area, it has been documented that the moisture transport into northwestern Mexico from these Atlantic zones is associated with increased precipitation in the region (Ordoñez *et al.* 2019). Since the trade winds strengthen during the cold AMO, it is plausible to think about this as another factor that contributes to increasing precipitation in the northwest with a negative AMO. Besides these facts, there is a significant decline in surface wind speed next to the northwest coast of Baja California Peninsula and also a significant increase in the southern peninsular extreme (Curtis 2008). This would allow convective activity in the northwest and diminish it in the south. During the warm AMO, the opposite occurs but surface winds, on average, come from the west in the north and from southeast in the south. The association between precipitation and these opposite changes in surface wind speed and directions according to AMO phases in Baja California peninsula would help explain the observed south–north gradient regarding the AMO influence in this area and locations of meteorological stations with significant correlations and mean differences are concentrated.

AMO conditions also influence ENSO effects on summer precipitation in Mexico. The positive phase of the AMO reinforces the pattern of observed correlations observed along the coasts, which are negative along most of its length except for Sonora and Baja California peninsula, where they are mostly positive. El Niño events exert their effects over most of Mexico during the summer through some mechanisms like the increase of subsidence and the modulation of trade winds over the Caribbean and the Gulf of Mexico according to the development phase of the ENSO event (Wang 2007; Bhattacharya & Chiang 2014). 14 out of 15 summers classified as Niño, were in the development phase (before peaking) and only one was in the decaying phase (post-peak). The developing phase is associated with the strengthening of the CLLJ (Bhattacharya & Chiang 2014), an intensified jet tends to decrease the development and activity of tropical waves in the Caribbean Sea and, conversely, increases the number of tropical waves reaching the northeastern region in the Gulf of Mexico (Méndez & Magaña 2010); but its strengthening decreases the number of Atlantic tropical storms, in general (Serra *et al.* 2010). All those facts together are helpful to explain why, in general, on the Atlantic coast, summers with El Niño events tend to be drier when they occur coupled with a warm AMO. Despite this generalization, at some stations summer rain can reach values above the historical average during one of the AMO phases. This suggests a stronger local influence of the AMO rather than El Niño.

On the Pacific coast, effects of the interaction of AMO and El Niño events seem to be more complex. Niño summers are less dry with warm AMO from central Chiapas to southern Guerrero and from Colima to southern Sinaloa; the opposite occurs in the regions of southern Chiapas and from central Guerrero to northern Michoacan. During developing El Niño events CLLJ velocity increases and also other associated low-level jets such as Tehuantepec and Papagayo, and that decreases the influence of the ITCZ (Amador *et al.* 2016), most noticeable during the positive phase of the AMO. It cannot explain this alternated pattern by itself, therefore, interactions of all elements modulated by El Niño events with other local aspects seem to predominate in some areas.

On the northwestern coast, it is observed that Niño summer precipitations during a negative AMO tend to be greater on the coasts of Sonora and the north of the Baja California peninsula; the opposite occurs in the south of the peninsula. This distribution generally matches with the precipitation pattern associated with AMO phases. It appears that AMO just reinforces ENSO effects although some interactions could distort this pattern in the central area and some locations in the southeastern extreme.

During summers classified as Niña, precipitation at meteorological stations on the east coast generally showed a tendency to present values above average (data not shown). The modulation of this effect by AMO results in summers with wetter La Niña events during the warm phase of the AMO predominantly in the Yucatan peninsula; but the opposite in the north of Veracruz and Tamaulipas. This is coincident with the combination of phases when precipitation averages are higher, considering each climatic oscillation separately. In the case of the Yucatan peninsula it can be explained by a weakening of the trade winds in general (Curtis 2008; Hu & Feng 2008) and particularly of the CLLJ (Amador *et al.* 2006; Wang 2007). Two other factors are also related to this increase in precipitation: first, the northward displacement of the ITCZ during La Niña events (Amador *et al.* 2016) which reinforces its greater influence during the positive phase of the AMO in southern Mexico, and second, the increase in tropical wave activity measured over the east and west coasts of the Yucatan Peninsula during summers with La Niña events (Dominguez *et al.* 2020). In the case of the northeastern zone, higher precipitation during Niña and negative AMO summers may be associated with a smaller decrease in CLLJ compared with that which would occur during Niña and positive AMO summers.

On the Pacific coast, La Niña events during the summer generally increase precipitation from Chiapas to Sinaloa. In the remaining portion of the region, Sonora and the Baja California peninsula, for the most part, the opposite occurs. During an AMO positive phase, Niña summers are wetter from Chiapas to Jalisco. This fact can be explained mainly by the aforementioned increase in the influence of the ITCZ in southern Mexico and of the tropical wave activity in the northeastern Pacific near Mexico, during these summers (Amador *et al.* 2016; Dominguez *et al.* 2020). In the southernmost region, a greater number of stations with significant differences can be noted when analyzing precipitation means of Niña summers according to AMO phases than in the case of AMO combinations for El Niño events or AMO alone (see Figures 2, 4 and 6). This suggests interactions between the combined effects of ENSO and the AMO, probably due to influences on some factors that both oscillations modulate in common, such as the CLLJ that can enhance or interfere with ITZC influence. Although, in general, Niña summers tend to be wetter, at some stations summer rain can reach values below the historical average. In these cases, as with El Niño, the influence of the AMO seems to be stronger than La Niña effects locally.

Drier Niña summers are observed during a positive AMO on northwest coastal regions of Sonora and the north of the Baja California peninsula, while toward the peninsular south, the opposite occurs. This pattern partially coincides with that obtained for the differences in precipitation according to AMO phases, but the latter is more homogeneous. This suggests a greater influence of the AMO at the regional level, but also the existence of interactions of this oscillation with the effects of La Niña events at the local level, probably through the complex modulation of surface winds and the GCLLJ.

CONCLUSIONS

The influence of the AMO and its modulation on ENSO effects in coastal areas of Mexico was analyzed but no using grouped data. On both, the east and west coasts, as well as on the California peninsula, a general tendency is observed for greater precipitation northward, associated with an AMO negative or cold phase; and southward with an AMO positive or warm phase. These results vary in terms of latitude in the three mentioned regions and exceptions of this pattern can be found locally. The areas showing larger differences in average summer rainfall according to AMO phases are northern Yucatan and northeastern region on the Atlantic coast; and south of the Pacific coast. Regarding ENSO effects modulation, on average, on the Atlantic coast, Niño summers tend to be less dry with a cold AMO; on the Pacific coast, alternating bands are observed. Niña summers tend to be wetter southward during a warm AMO and northwards with a cold AMO.

In spite of this generalization, there is a huge variability among individual stations. Mean differences, on average, range from a few millimeters up to 467 mm concerning AMO conditions, or up to 863 and 1,165 mm considering AMO modulations during Niño and Niña summers, respectively. These variations are not observed when performing averaged grouped data analyses. Such differences must be taken into account for better and more realistic water management planning at the local scale rather than at the state or hydrological region level. Also, the obtained results could be employed for different time scale strategies. Considering the two different average periodicities of these oscillations, these data are useful for long-term programs, since the AMO remains for a long period of time in conditions; and for a short or medium term, due to the much higher ENSO frequency. Besides, it would broaden the panorama of climatological knowledge about Mexico and provide more information for the development of climate change adaptation measures at the local level. For the long periods of less rainfall, associated with the AMO, crop changes and looking into the genetic pool for more drought-resistant varieties could be very helpful, especially for rain fed agriculture. Regarding intensified droughts linking AMO and El Niño, warning systems and insurance programs could mitigate damages. Construction of small water reservoirs and household retention methods associated with decentralized water management mechanisms could diminish the marginalization of small and isolated localities.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Alvarez-Olguin, G. & Escalante-Sandoval, C. 2017 Modes of variability of annual and seasonal rainfall in Mexico. *Journal of the American Water Resources Association (JAWRA)* **53**(1), 1144–1157. doi:10.1111/1752-1688.12488.

Amador, J., Alfaro, E., Lizano, O. & Magaña, V. 2006 Atmospheric forcing of the eastern tropical Pacific: a review. *Progress in Oceanography* **69**(2–4), 101–142. doi:10.1016/j.pocean.2006.03.007.

Amador, J., Durán-Quesada, A. M., Rivera, E. R., Mora, G., Sáenz, F., Calderón, B. & Mora, N. 2016 The easternmost tropical Pacific. part II: seasonal and intraseasonal modes of atmospheric variability. *Revista de Biología Tropical* **16**(1), 23–57. doi:10.15517/RBT.V64I1.23409.

Azuz-Adeath, I., González-Campos, C. & Cuevas-Corona, A. 2019 Predicting the temporal structure of the atlantic multidecadal oscillation (AMO) for agriculture management in Mexico's coastal zone. *Journal of Coastal Research* **32**(1), 210–226. doi:10.2112/JCOASTRES-D-18-00030.1.

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

Bravo Cabrera, J. L., Azpra Romero, E., Zarraluqui Such, V., Gay García, C. & Estrada Porrúa, F. 2010 Significance tests for the relationship between 'El Niño' phenomenon and precipitation in Mexico. *Geofísica Internacional* **49**(4), 245–261. Available from: http://revistagi.geofisica.unam.mx/index.php/RGI/article/view/132/119

Bravo-Cabrera, J. L., Azpra-Romero, E., Zarraluqui-Such, V. & Gay-García, C. 2017 Effects of El Niño in Mexico during rainy and dry seasons: an extended treatment. *Atmósfera* **30**(3), 221–232. doi:10.20937/ATM.2017.30.03.03.

Chen, H. & Xu, Z. 2020 Decadal-to-multidecadal variability of seasonal land precipitation in northern hemisphere in observation and CMIP6 historical simulations. *Atmosphere* **11**(2), 195–208. doi:10.3390/atmos11020195.

Curtis, S. 2008 The Atlantic multidecadal oscillation and extreme daily precipitation over US and Mexico during the hurricane season. *Climate Dynamics* **30**, 343–351. doi:10.1007/s00382-007-0295-0.

Dominguez, C., Done, J. & Bruyère, C. 2020 Easterly wave contributions to seasonal rainfall over the tropical Americas in observations and a regional climate model. *Climate Dynamics* **54**, 191–209. doi:10.1007/s00382-019-04996-7.

Enfield, D. B., Mestas-Nuñez, A. M. & Trimble, P. J. 2001 The Atlantic multidecadal oscillation and its relation to rainfall and rivel flows in the continental U.S. *Geophysical Research Letters* **28**(10), 2077–2080. doi:10.1029/2000GL012745.

Fang, X. & Xie, R. 2020 A brief review of ENSO theories and prediction. *Science China Earth Sciences* **63**(4), 476–491. doi:10.1007/s11430-019-9539-0.

Gong, Y., Li, T. & Chen, L. 2020 Interdecadal modulation of ENSO amplitude by the Atlantic multi decadal oscillation (AMO). *Climate Dynamics* **55**, 2689–2702. doi:10.1007/s00382-020-05408-x.

Hu, Q. & Feng, S. 2008 Variation of the North American summer monsoon regimes and the Atlantic multidecadal oscillation. *Journal of Climate* **21**(11), 2371–2383. doi:10.1175/2007JCLI2005.1.

Kayano, M. T. & Capistrano, V. B. 2014 How the Atlantic multidecadal oscillation (AMO) modifies the ENSO influence on the South American rainfall. *International Journal of Climatology* **34**(1), 162–178. doi:10.1002/joc.3674.

Magaña, V., Amador, J. & Medina, S. 1999 The midsummer drought over Mexico and Central America. *Journal of Climate* **12**(6), 1577–1588. doi:10.1175/1520-0442(1999)012%3C1577:TMDOMA%3E2.0.CO;2.

Méndez, M. & Magaña, V. 2010 Regional aspects of prolonged meteorological droughts over Mexico and Central America. *Journal of Climate* **23**(5), 1175–1188. doi:10.1175/2009JCLI3080.1.

Moreno-Chamarro, E., Marshall, J. & Delworth, T. 2020 Linking ITCZ migrations to the AMOC and North Atlantic/Pacific SST decadal variability. *Journal of Climate* **33**(3), 893–905. doi:10.1175/JCLI-D-19-0258.1.

Ordoñez, P., Nieto, R., Gimeno, L., Ribera, P., Gallego, D., Ochoa-Moya, C. & Quintanar, A. 2019 Climatological moisture sources for the Western North American Monsoon through a Lagrangian approach: their influence on precipitation intensity. *Earth System Dynamics* **10**(1), 59–72. doi:10.5194/esd-10-59-2019.

Perdigón-Morales, J., Romero-Centeno, R., Ordoñez, P., Nieto, R., Gimeno, L. & Barrett, B. 2021 Influence of the Madden-Julian oscillation on moisture transport by the Caribbean low level Jet during the midsummer drought in Mexico. *Atmospheric Research* **248**, 105243. doi:10.1016/j.atmosres.2020.105243.

Serra, Y. L., Kiladis, G. N. & Hodges, K. I. 2010 Tracking and mean structure of easterly waves over the intra-Americas Sea. *Journal of Climate* **23**(18), 4823–4840. doi:10.1175/2010JCLI3223.1.

Singh, J., Ashfaq, M., Skinner, C., Anderson, W. & Singh, D. 2021 Amplified risk of spatially compounding droughts during co-occurrences of modes of natural ocean variability. *npj Climate and Atmospherc Science* **4**, 7. doi:10.1038/s41612-021-00161-2.

Trenberth, K. E. 1997 The definition of El Niño. *Bulletin of the Amererican Meteorological Society* **78**, 2771–2777. doi:10.1175/1520-0477(1997)078%3C2771:TDOENO%3E2.0.CO;2.

Wang, C. 2007 Variability of the Caribbean Low-Level Jet and its relations to climate. *Climate Dynamics* **29**, 411–422. doi:10.1007/s00382-007-0243-z.

Yang, Y., An, S., Wang, B. & Park, J. 2020 A global-scale multidecadal variability driven by Atlantic multidecadal oscillation. *National Science Review* **7**(7), 1190–1197. doi:10.1093/nsr/nwz216.

First received 7 May 2022; accepted in revised form 25 January 2023. Available online 6 February 2023