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Historical and Recent Climate Variability and Warming Signals in the Chaschoc–Sejá Lagoon Socio-Ecosystem (Tabasco, Mexico)

Variabilidad y calentamiento climático histórico y reciente en el socioecosistema lagunar Chaschoc-Sejá (Tabasco, México)

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ABSTRACT

This study characterizes historical (1984–2003) and recent (2004–2023) climate conditions in the Chaschoc–Sejá lagoon system, southeastern Tabasco, Mexico, using ERA5 reanalysis data and large-scale climate indices associated with ENSO, PDO, and AMO. Monthly temperature and precipitation were analyzed; trends were assessed using the Mann–Kendall test; drought variability was evaluated using the 12-month Standardized Precipitation Index (SPI-12); and teleconnection influence was examined using Pearson correlation analysis. The warming signal represents a robust local-scale expression of broader anthropogenic climate change. These results are consistent with previous national and international studies, which indicate a warming rate of approximately 10-2 °C/year. A temperature increase of 1.3 °C was observed in the last year of the study. On the other hand, precipitation variability remains strongly modulated by large-scale oscillations, particularly ENSO and PDO, which exhibit significant inverse correlations with SPI-12. In other words, during negative phases, humid events occur, and during warm phases, dry events occur in the study area.

Keywords: Climate oscillation; local warming; SPI; Chaschoc–Sejá lagoon system.

RESUMEN

El presente estudio caracteriza el clima histórico (1984–2003) y el reciente (1984–2023) del sistema lagunar Chaschoc–Sejá, localizado en el sureste del estado de Tabasco, México. Utilizando datos de reanálisis ERA5 e índices climáticos a gran escala asociados con ENSO, PDO y AMO, se analizaron la temperatura y la precipitación mensuales, se evaluaron las tendencias mediante la prueba de Mann-Kendall, se analizó la variabilidad de la sequía a través del Índice de Precipitación Estandarizado de 12 meses (SPI-12) y se examinó la influencia de la teleconexión mediante el análisis de correlación de Pearson. La señal de calentamiento representa una expresión robusta, a escala local, del cambio climático antropogénico más amplio. Estos resultados están en concordancia con estudios previos a nivel nacional e internacional, que reportan una tasa de calentamiento del orden de 10^{-2} °C/año. Y se ha registrado un incremento de 1,3 °C en la temperatura durante el último año del estudio. Por otro lado, la variabilidad de la precipitación sigue estando fuertemente modulada por las *oscilaciones a gran escala, en particular por ENSO y PDO, que presentan correlaciones inversas significativas con el SPI-12. Es decir, en fases negativas ocurren eventos húmedos y, en fases cálidas, eventos secos en la zona de estudio.*

Palabras clave: Oscilación climática; calentamiento local; SPI; sistema lagunar Chaschoc–Sejá.

Introduction

Mexico covers approximately 1.9 million km² and exhibits pronounced climatic diversity resulting from its complex physiography, latitudinal gradient, and the interaction between tropical and extratropical atmospheric processes. This diversity has historically been classified into seven major climatic ecoregions (García, 1974) and represents a fundamental factor shaping the availability of natural resources and exposure to hydrometeorological hazards. Recent studies have documented the high vulnerability of Mexican territory to climate change impacts, particularly in regions characterized by elevated exposure, socio-environmental sensitivity, and strong dependence on ecosystem services (Andrade-Velázquez & Medrano-Pérez, 2020).

In addition to anthropogenic climate change, natural climate variability significantly modulates temperature and precipitation across multiple temporal scales. The Intergovernmental Panel on Climate Change (IPCC) warns that droughts worldwide are becoming more frequent, intense, and prolonged. Human-induced climate change has altered the water cycle, accelerating evaporation and drying out soils in most inhabited regions. The IPCC notes that, if current emissions trends continue, large areas of the planet—including semi-arid regions of the Americas, southern Europe, and southern Africa—will suffer unprecedented water stress. This severely increases the risk of food insecurity, ecosystem collapse, and mass population displacements. In México, the climate is strongly influenced by the El Niño–Southern Oscillation (ENSO), which has been associated with persistent precipitation and temperature anomalies, as well as with the occurrence of droughts and floods (Magaña et al., 1998; Méndez & Magaña, 2010; Cavazos et al., 2013; Andrade-Velázquez & Medrano-Pérez, 2020). Complementarily, low-frequency oscillations such as the Pacific Decadal Oscillation (PDO; Méndez et al., 2010; Andrade-Velázquez & Medrano-Pérez, 2021) and the Atlantic Multidecadal Oscillation (AMO; Andrade-Velázquez et al., 2021; Montero-Martínez et al., 2022; Andrade-Velázquez & Montero-Martínez, 2024) exert a relevant influence on interdecadal precipitation variability and on the persistence of dry and wet periods across the country.

Climate characterization in Mexico has historically been challenging, largely due to limited spatial and temporal coverage of reliable meteorological observations, particularly in tropical regions and areas with complex hydrological dynamics (Montero-Martínez et al., 2018). In this context, atmospheric reanalysis datasets have become a robust alternative for studying historical and recent climate conditions. Datasets such as CRU (Harris & Jones, 2017) and ERA5 (Hersbach et al., 2025) integrate in situ observations, remote sensing data, and numerical modeling through advanced data assimilation techniques, enabling the generation of temporally consistent time series of key climatic variables. The analysis of such datasets is essential for improving the understanding of climate variability and change, and directly contributes to achieving Sustainable Development Goal 13 (Climate Action), particularly in developing countries.

At the same time, growing concern about the impacts of climate change has promoted nature-based adaptation approaches aimed at maintaining ecosystem functional stability and strengthening resilience to climatic disturbances (UNEP, 2023). However, ecosystems cannot be analyzed independently of the human societies that depend on them. This interdependence has led to the concept of socio-ecosystems, understood as complex adaptive systems in which human societies—together with their economies and cultures—constitute an integral part of the biosphere and continuously transform it (Berkes & Folke, 1998; Reyers et al., 2018). Among the most representative socio-ecosystems are wetlands, particularly continental lagoon systems, which provide multiple ecosystem services and sustain local productive activities (Barba-Macías et al., 2006).

Historically, human settlements have tended to establish near water bodies due to their importance for survival, transportation, food production, and economic development (Adán et al., 2017). In Tabasco, this society–water relationship is especially evident. The state is located within the basin with the highest surface runoff in Mexico, accounting for approximately 30% of the national total (INEGI, 2025). Within this context, lagoon systems are abundant and diverse, including *Las Ilusiones*, *Carmen-Pajonal-Machona*, *Chaschoc-Sejá*, *Grande*, *Los Mesías*, *San Pedrito*, and *Términos* lagoons (INEGI, 2021).

Lagoon socio-ecosystems play a key role in regional sustainable development. In general, systems with lower levels of anthropogenic intervention tend to maintain higher ecological integrity and greater capacity to cope with climate change impacts. The Chaschoc–Sejá lagoon system is located within the Usumacinta River sub-basin—one of the major rivers in Mesoamerica—which, unlike the Grijalva River, has not been significantly altered by large hydraulic infrastructure (García & Kauffer, 2011). This condition confers high value on the system as a reference site for studying the interactions among climate, natural variability, and socio-environmental processes in southeastern Mexico.

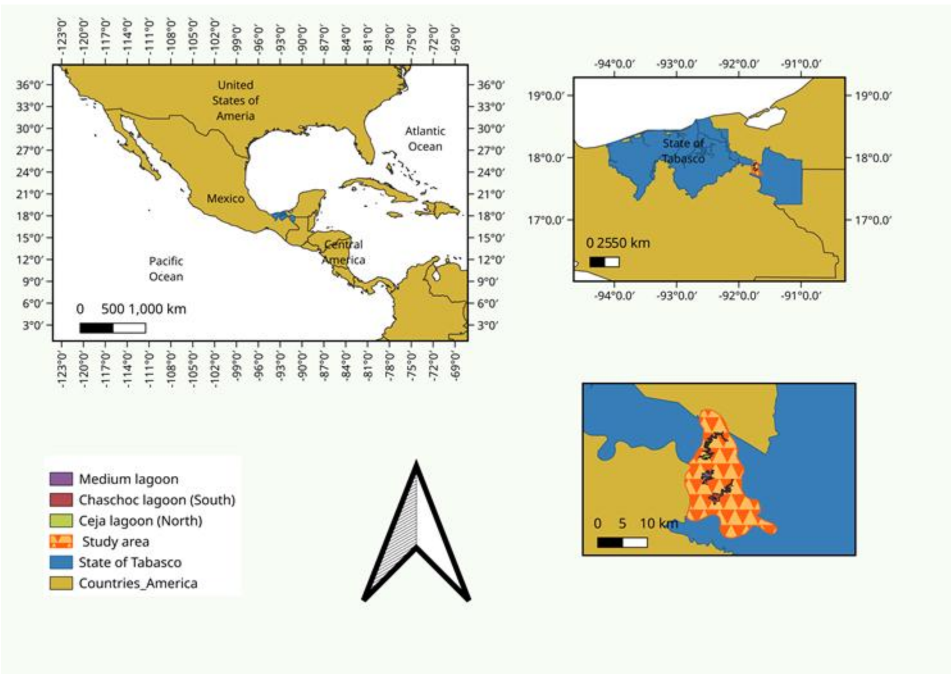
Within this framework, the present study focuses on the Chaschoc–Sejá lagoon system in southeastern Tabasco to analyze historical and recent changes in temperature and precipitation over the past four decades. The analysis aims to distinguish the signal associated with recent warming—primarily reflected in thermal trends—from the modulation exerted by large-scale climate variability (ENSO, PDO, and AMO) on the occurrence of dry and wet periods. This approach seeks to provide a robust climatic baseline for vulnerability assessment and adaptive management of a tropical lagoon socio-ecosystem, which is particularly exposed to the interaction between climate change and natural variability.

Materials and methods

Study Area

The study area corresponds to the Chaschoc–Sejá lagoon system (Figure 1), located in southeastern Tabasco, Mexico. The system lies within the Usumacinta River basin, whose mean discharge is approximately 3727 $m^3 s^{-1}$ (Kolb & Galicia, 2012).

Figure 1: Study area: Chaschoc–Sejá lagoon system located in Tabasco, Mexico.



The map shows the continental part in yellow, Tabasco state in blue, and the study area in orange. In this area are the three lagoons (purple, red, and green colors).

The region hosts high biological diversity, including fauna such as the white-tailed deer (Odocoileus virginianus), ocelot (Leopardus pardalis), paca (Cuniculus paca), collared peccary (Pecari tajacu), neotropical river otter (Lontra longicaudis), West Indian manatee (Trichechus manatus), puma (Puma concolor), scarlet macaw (Ara macao), keel-billed toucan (Ramphastos sulfuratus), hawk (Accipiter sp.), parrot (Amazona sp.), great curassow (Crax rubra), Morelet's crocodile (Crocodylus moreletii), American crocodile (Crocodylus acutus), green iguana (Iguana iguana), tropical gar (Atractosteus tropicus), and Mesoamerican slider turtle (Staurotypus triporcatus). Representative plant species include chicozapote (Manilkara zapota), mamey sapote (Pouteria sapota), ramón (Brosimum alicastrum), palo de lacandón (Dialium guianense), and canshán (Terminalia amazonia) (CONANP, 2025).

The nearest human settlements to the lagoon system are *Emiliano Zapata* and *Chablé*. The system comprises three main lagoons: (1) *Cejá*, (2) *Intermedia*, and (3) *Chaschoc*.

The rainy season generally extends from May to early February. It is primarily associated with the Intertropical Convergence Zone (ITCZ) and tropical cyclones during summer, and with cold fronts during winter, sometimes in combination with cyclonic systems until November. In contrast, the dry season (low-water period) is concentrated mainly between March and April.

Data

The climatic data used in this study correspond to the ERA5 reanalysis dataset, specifically mean air temperature and total precipitation, covering the period 1984–2023. This interval was divided into two 20-year periods: 1984–2003 (historical baseline) and 2004–2023 (recent period).

Values were extracted at two grid points from the ERA5 grid using bilinear interpolation, which has a spatial resolution of 0.25° × 0.25°.

Large-scale climate variability indices were obtained as follows:

- The Oceanic Niño Index (ONI) for ENSO (Huang et al., 2017);
- The Pacific Decadal Oscillation (PDO) index derived from ERSST v5 (Newman et al., 2016);
- The Atlantic Multidecadal Oscillation (AMO) index derived from ERSST v5 (Enfield et al., 2001).

All indices were analyzed over the same 1984–2023 period.

Methods

The methodology used has been reported in previous studies (Andrade-Velázquez et al., 2021; Andrade-Velázquez & Montero-Martínez, 2024). For the climatological analysis, temperature data were averaged on a monthly time scale, while precipitation was aggregated into monthly totals. Figures 2 and 3 show the annual cycle for both study points during the historical and recent periods, respectively.

$$S = \sum_{k-1}^{n_1-1} \sum_{j-k+1}^{n} sgn(x_j - x_k) \quad \text{(Eq. 1)}$$

where sgn denotes the sign function, x represents the variable of interest, and n is the length of the time series.

For precipitation, the Standardized Precipitation Index (SPI; WMO, 2012) was calculated. The SPI is based on fitting a Pearson Type III distribution to accumulated precipitation data (Guttman, 1999), expressed as:

$$f(x) = \frac{1}{a\Gamma} \frac{(x-a)^{b-1}}{a} exp\left(\frac{-(x-c)}{a}\right) \quad \text{(Eq. 2)}$$

where *a* is the scale parameter, *b* is the shape parameter, c is the location parameter, and *Γ* denotes the gamma function.

Table 1 presents the SPI classification thresholds according to WMO guidelines.

Table 1. SPI classification values according to WMO.

SPI Value	*Classification*
≥ 2.0	Extremely wet
1.5 to 1.99	Severely wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.49 to -1.0	Moderately dry
-1.99 to -1.5	Severely dry
≤ -2.0	Extremely dry

To determine the degree of influence of large-scale teleconnections, Pearson's linear correlation coefficient was calculated:

$$r_{xy} = \frac{Cov(x,y)}{Var(x)Var(y)} \quad \text{(Eq. 3)}$$

where *Cov(x,y)* represents the covariance between variables *x* and *y*, and *Var(x)* and *Var(y)* are their respective variances.

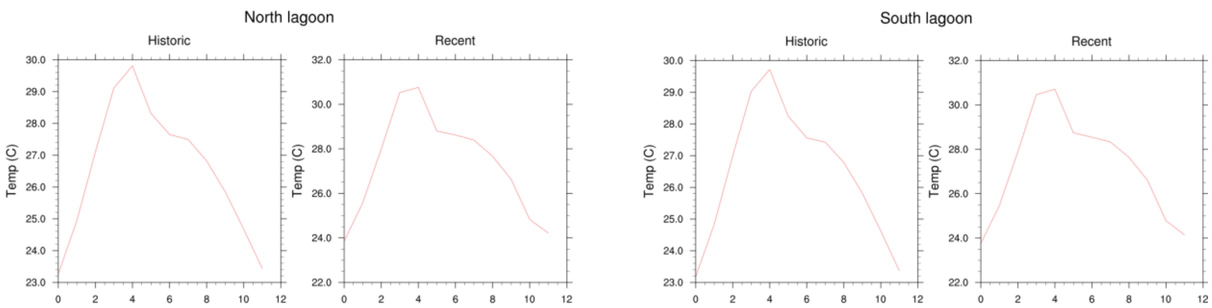
This methodology allows assessment of the annual cycles of temperature and precipitation over two time periods and identifies changes between the records. So, the anomalies and SPI let us determine variability within the time window and across years. Finally, the trends and Pearson's correlation help quantify the influence of large-scale climate factors on local climate conditions.

Results

Annual and Seasonal Cycle

The results for the annual cycle of temperature and precipitation are presented below. Figure 2 shows that during the historical period, temperatures ranged from approximately 22 °C to 30 °C at both study points, whereas in the recent period, values ranged from 24 °C to 32 °C. No significant differences were identified between the point located north of the Chaschoc–Sejá lagoon system and the point located to the south; this aspect is discussed further below.

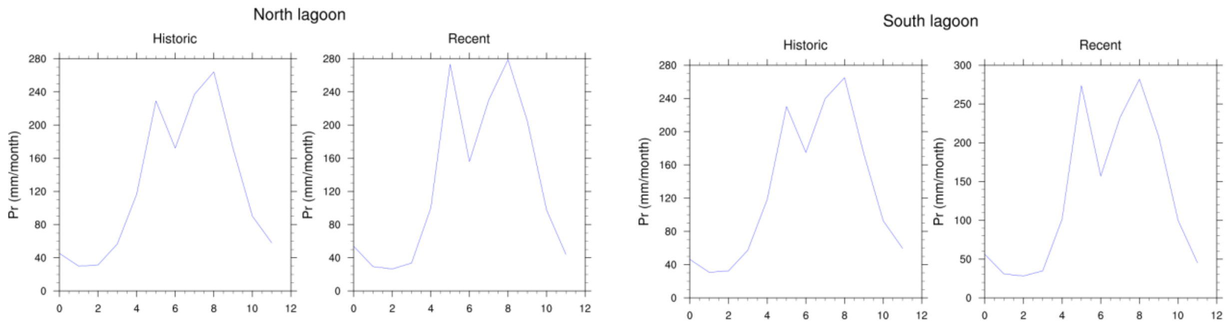
Figure 2. Annual temperature cycle for the historical and recent periods in the northern lagoon (left) and southern lagoon (right).



In both periods, a consistent seasonal pattern is observed, characterized by a progressive increase in temperature from January to May, with May being the warmest month. Thereafter, temperature decreases during summer and winter, generally remaining below 28 °C. This behavior is consistent with the region's characteristic thermal patterns and suggests that ERA5 adequately represents the study area's climatic conditions (Andrade-Velázquez & Montero-Martínez, 2023a).

Regarding precipitation (Figure 3), two well-defined maxima are identified: one during July–August and another between September–October. Between these peaks, a relative decrease in precipitation is observed in mid-August, corresponding to the midsummer drought (MSD) or intra-seasonal dry spell (Magaña et al., 1998), consistent with previous studies conducted in the region (Colorado et al., 2018).

Figure 3. Annual precipitatio*n cycle for the historical and recent periods in the northern lagoon (left) and southern lagoon (right).*



At the seasonal scale, maximum and minimum values of temperature and precipitation for both periods are summarized in Table 2.

Table 2. Seasonal maximum and minimum values of temperature and precipitation for the Historical (H) and Recent (R) periods.

Months	*Temperature Max (°C) H/R*	*Temperature Min (°C) H/R*	*Precipitation Max (mm/month) H/R*	*Precipitation Min (mm/month) H/R*
EFM	27.1/28	23.3/23.8	45.3/54	29.9/26.5
AMJ	29.8/30.8	28.3/28.8	229.2/273.2	56.7/33.6
JAS	27.7/28.6	26.8/27.7	264.1/278.9	172.2/156.1
OCN	25.6/26.6	23.4/24.2	171.5/204.8	58/44

Temperature Anomalies and SPI

Figures 4 and 5 show temperature anomalies and their trends for the historical and recent periods in the northern and southern lagoons, respectively. In both cases, a positive trend on the order of 10^{-2} °C $year^{-1}$ is identified, indicating sustained warming over time.

Thermal anomaly ranges vary between −2.0 and 3.0 °C (on a monthly scale) during the historical period, whereas in the recent period they range from approximately −1.8 to 4.0 °C. When aggregated annually, this corresponds to ranges of −0.9 to 0.8 °C year^{-1} during the historical period and 0.2 to 1.4 °C year^{-1} during the recent period, indicating greater amplitude and variability in recent decades.

Figure 4. Temperature anomaly and trend for the historical and recent periods in the northern lagoon.

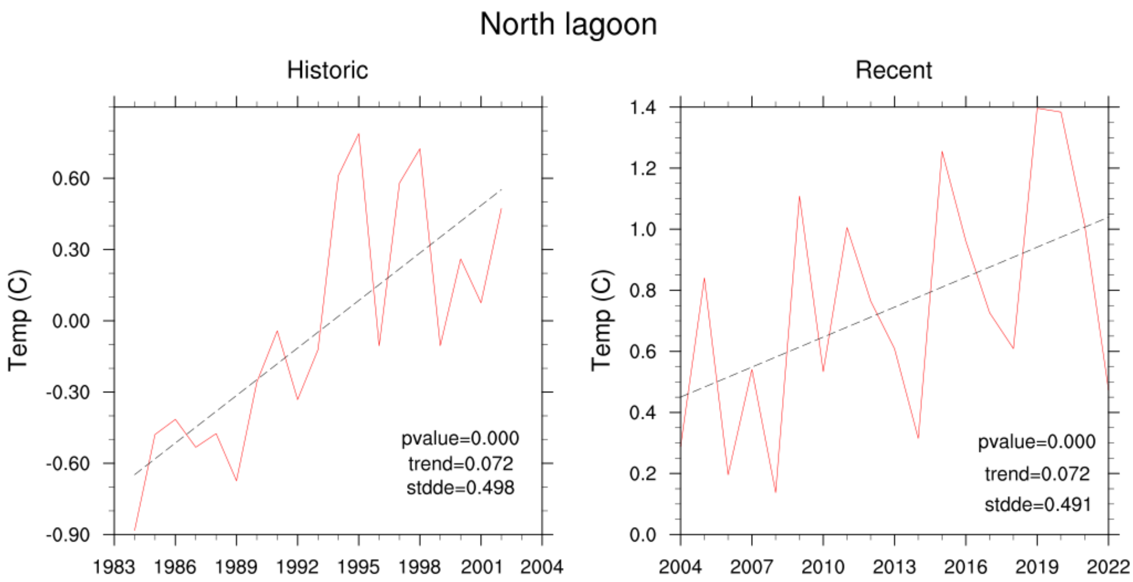
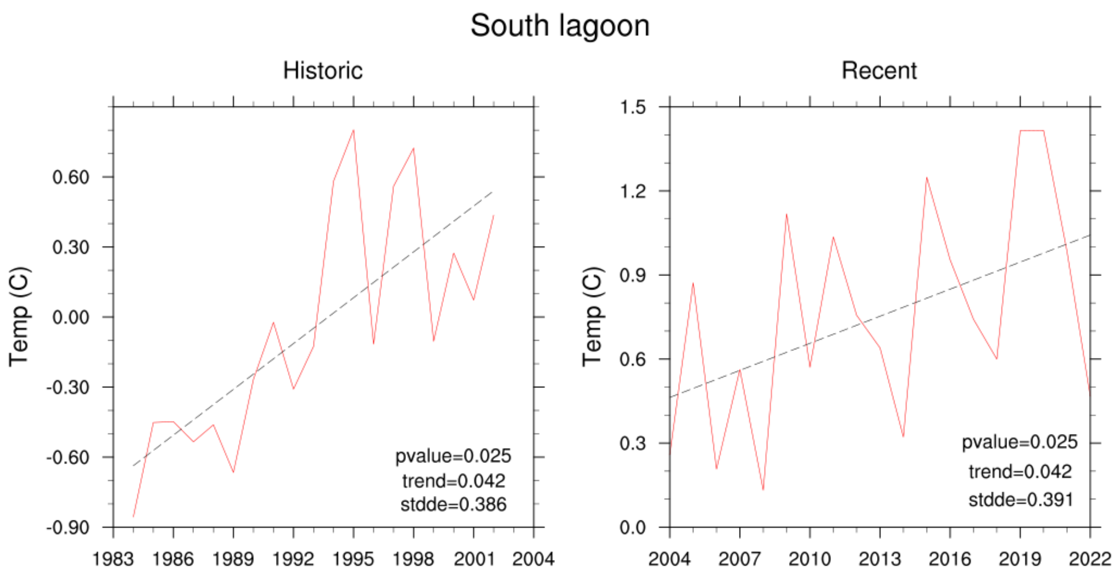


Figure 5. Temperature anomaly and trend for the historical and recent periods in the southern lagoon.



The SPI-12 index allows identification of dry and wet events during both study periods. Severe droughts were observed during 1986–1988, 1994–1996, 2002–2004, and 2015–2020. Severe wet events were recorded during 1988–1989, 1996–1997, 1999–2000, 2007, 2013–2015, and 2020–2021 (Figures S1 and S2).

Correlation analysis reveals an inverse and statistically significant relationship between the Pacific Decadal Oscillation (PDO) and precipitation (Figure 6), indicating that during warm PDO phases, precipitation tends to decrease. In contrast, during cold phases, it tends to increase. A similar pattern, though of greater magnitude, is observed between SPI-12 and the Oceanic Niño Index (ONI), representing ENSO variability. In contrast, the correlation with the AMO is positive but weaker in magnitude (Table 3).

Figure 6. Correlation between PDO (red), ENSO/ONI (blue), AMO (purple), and SPI-12 (green).

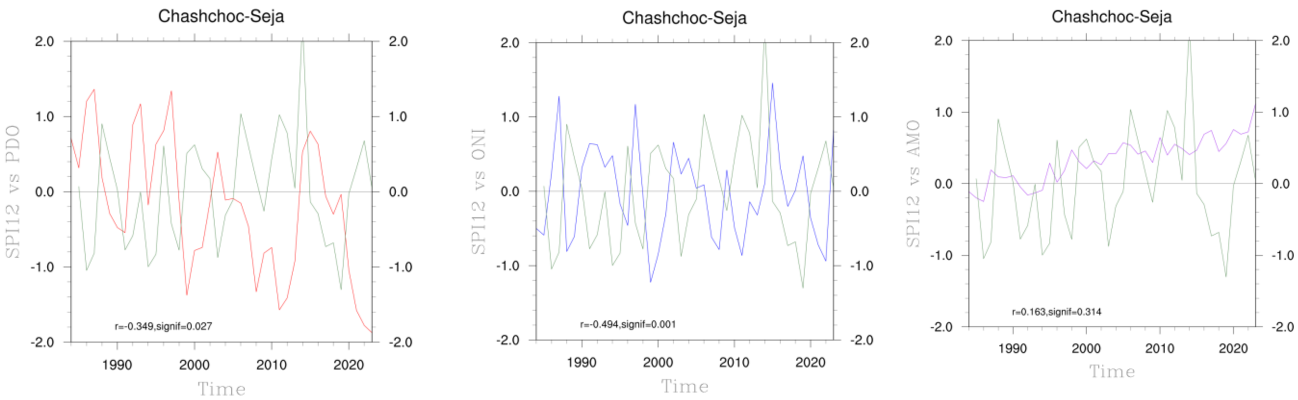


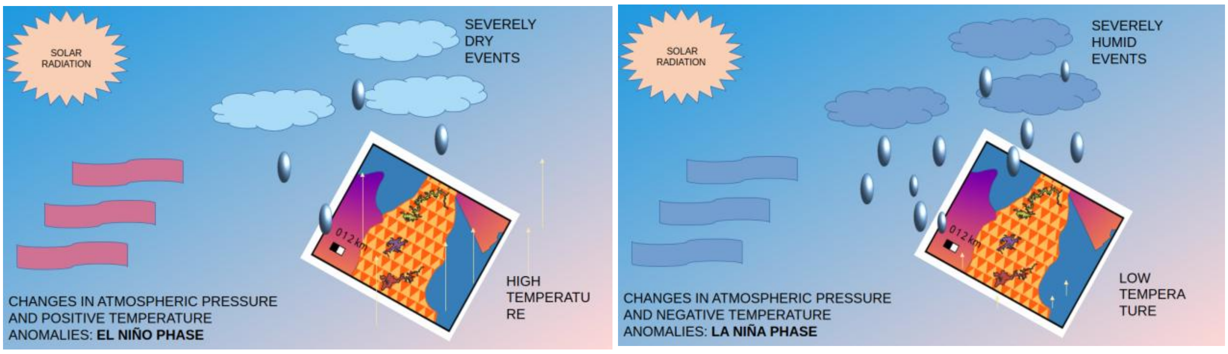
Table 3. Correlation coefficients and statistical significance between climate oscillations and precipitation.

	AMO/pval	*PDO/pval*	*ENSO/pval*
SPI-12	0.163/0.314	-0.349/0.027	-0.494/0.001
	DIRECT	INVERSE	INVERSE

Discussion

The results obtained reveal a clear signal of climate change in the Chaschoc–Sejá lagoon system, primarily evidenced by the observed increase in temperature. Concurrently, the influence of large-scale climate modulators on the occurrence of wet and dry events in the region is identified (Figure 7), allowing differentiation between the long-term warming signal associated with global climate change and the frequency modulation inherent to natural climate variability. This separation is fundamental for assessing the relative contribution of anthropogenic climate change and major climate oscillations to the dynamics of the lagoon system. Nevertheless, a detailed evaluation of changes in the frequency and intensity of extreme events remains an ongoing line of research and will be addressed in subsequent stages of the project.

Figure 7. Conceptual scheme of precipitation and temperature behavior in the lagoon system under ENSO influence.



The climatic characterization of the Chaschoc–Sejá lagoon system across two contrasting temporal periods allows identification of recent changes and their potential socio-environmental implications. Lagoon systems provide multiple ecosystem services to human communities and other species and play a key role in landscape dynamics. In this study, the most significant changes are concentrated in temperature, with anomalies occurring within relatively cooler ranges during the historical period and warmer ranges during the recent period, with an approximate difference of 1 °C. This finding is reinforced by the sustained positive trend observed since the historical period, on the order of $\sim10^{-2}$ °C year^{-1}, consistent with previous studies conducted in southeastern Mexico that attribute this behavior to global warming (IPCC, 2012; Andrade-Velázquez et al., 2021; Andrade-Velázquez & Montero-Martínez, 2023).

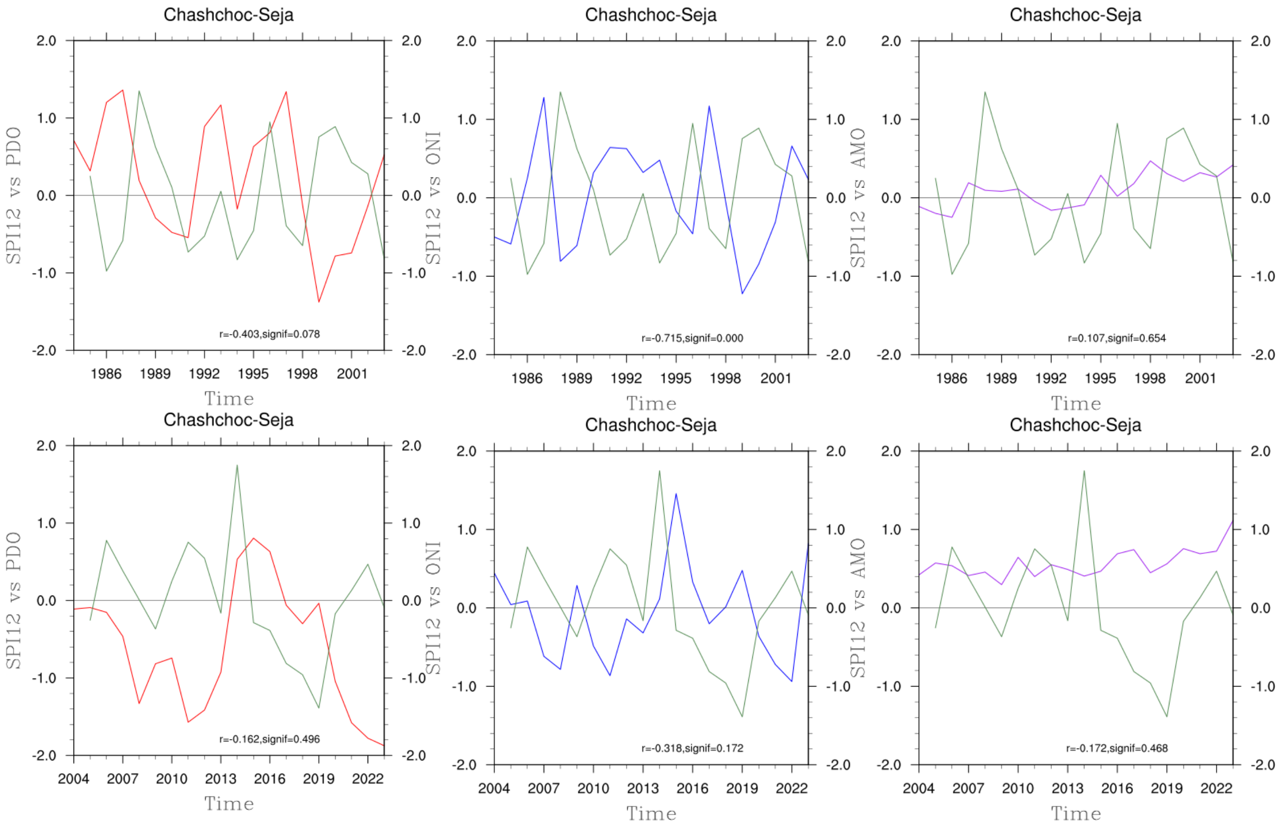
The observed thermal increase has direct implications for daily and productive activities in the region. Numerous studies have emphasized that inland water bodies are ecosystems particularly vulnerable to climatic stressors, such as rising temperatures, and that understanding their responses is essential for designing management and impact mitigation strategies (Williamson et al., 2008; Adrian et al., 2009). Likewise, the SPI-12 analysis shows that dry and wet events significantly modulate productive activities such as fisheries and agriculture. During the historical period, these events lasted between one and three years, with an approximate periodicity of three to six years. In contrast, during the recent period, prolonged and significant dry events were recorded, particularly between 2015 and 2021. Data from CONAPESCA (2021) indicate that fishery productivity declined in the state of Tabasco, particularly between 2019 and 2021, coinciding with the implementation of social support programs and the COVID-19 pandemic.

On the other hand, the National Meteorological Service has reported precipitation deficits in the region in recent years. However, these dry conditions have coexisted with an intensification of extreme precipitation events, as evidenced by the severe flooding that occurred in Tabasco in 2020 (GobMx, 2021; PERC, 2022). It is important to recall that these years also coincided with the cold phase (La Niña) of ENSO, highlighting the complex interaction between natural climate variability and the broader context of global warming.

The results of this study confirm that the Chaschoc–Sejá lagoon system is influenced by large-scale climate modulators, including ENSO, PDO, and AMO, which are intrinsic components of natural climate variability. Previous research has documented that the AMO has influenced climate trends in North Atlantic regions (Zhang et al., 2007). However, it is important to consider that global warming affects all components of the climate system, including the oscillatory modes themselves. Chen et al. (2024) indicate that although many studies on ENSO under global warming rely on numerical simulations, non-parametric analyses reveal a positive correlation between global temperature increases and ENSO phase frequency, suggesting a potential intensification of this phenomenon under warming scenarios.

Given that global warming manifests not only in the atmosphere but also in the ocean—which absorbs a substantial fraction of excess heat—it is reasonable to expect that oceanic climate oscillations may also be affected. Ramesh et al. (2019) report that interactions between ENSO and the AMO can generate significant regional climate changes and even oceanic responses, such as sea-level rise, when La Niña coincides with the warm phase of the AMO, which is associated with ocean thermal expansion. In this context, the results shown in Figure 6, where the AMO is in a positive phase, may imply an increased risk of sea-level rise in the coming years.

Figure 8. Correlation between SPI-12 and PDO, ENSO, and AMO during the historical and recent periods.



Finally, the comparative analysis between periods reveals that during the historical interval—characterized by relatively lower temperatures—dry events were less intense and the correlation between precipitation and climate oscillations was stronger than during the recent period (Figure 8). Although this relationship persists, its weakening in recent years suggests the influence of additional factors on regional precipitation, with the observed warming associated with climate change being particularly relevant. This finding reinforces the hypothesis that recent warming may be modifying traditional patterns of climate variability and their impacts on lagoon socio-ecosystems in southeastern Mexico.

Conclusions

This study characterized the historical and recent climate of the Chaschoc–Sejá lagoon system in southeastern Tabasco. It analyzed the interaction between climate-change signals and natural climate variability modulated by large-scale oscillations. Using updated climatic information derived from atmospheric reanalysis datasets and representative climate indices for ENSO, PDO, and AMO, a replicable methodological framework was developed that can be applied to other socio-environmental systems with inland water bodies across regions worldwide.

The results reveal a sustained temperature increase on the order of ~10^{-2} °C $year^{-1}$ since the historical period, along with a shift toward warmer thermal anomalies in the recent period, with an approximate difference of 1 °C between the two intervals. This thermal signal represents a robust local-scale expression of the broader anthropogenic warming trend documented regionally and globally and has direct implications for the ecological and socio-environmental dynamics of the lagoon system. These implications include processes affecting human communities, flora, and fauna, such as regional productive activities, species displacement, changes in vegetation cover, and alterations in physicochemical processes within the system, including water quality and lagoon hydrodynamics.

In contrast, precipitation exhibits strong modulation by natural climate variability, particularly by ENSO and the PDO, which show statistically significant inverse correlations with SPI-12. However, the recent period is characterized by an increased frequency of severe events, both precipitation deficits and excesses, reflecting an intensification of hydroclimatic extremes. This behavior suggests that although the influence of large-scale modulators persists, their explanatory power appears to have weakened in recent years, pointing to the intervention of additional factors associated with global warming.

The comparative analysis between periods indicates that dry and wet events have increased in both intensity and persistence over the last two decades, with potential impacts on key activities such as fisheries and agriculture, as well as on the functional stability of the lagoon socio-ecosystem. Furthermore, the positive phase of the AMO observed in recent years may imply additional risks associated with ocean processes, including sea-level rise, with potential repercussions for lagoon systems in southeastern Mexico.

Overall, this work is part of a broader multidisciplinary effort to strengthen local and regional knowledge of socio-ecosystems associated with inland water bodies, which are a central axis of sustainability. The findings provide a robust climatic baseline for vulnerability assessment, adaptive management, and the design of climate change adaptation strategies, and establish a foundation for future studies focused on the detailed characterization of extreme events and their socio-environmental impacts.

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