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Analysis of Trends in Sea Level in the Central Coast of the Gulf of Mexico, 1999-2018

Análisis de tendencias del nivel del mar para la costa central del golfo de México 1999-2018

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Abstract. There is scientific consensus about a 0.20-meter rise in the global mean sea level over the period 1901-2018 (IPCC, 2021). This is a global figure, but the phenomenon is not occurring evenly throughout the world, so studies at smaller scales are relevant. This article describes the quantitative analysis performed to determine the current and future sea-level behavior on the central coast of the Gulf of Mexico and determine whether or not it shows a rise similar to the one reported on a global scale. The aim was to determine the sea level trend observed in the region.

Based on the methodological approach of Zavala-Hidalgo *et al.* (2011), we selected three stations belonging to Mexico's National Mareographic Network to characterize the sea level height on the central coast of the Gulf of Mexico: Coatzacoalcos (18°09' N, -94°26' W); Frontera (18°32' N, -92°38' W), and Veracruz (19°12' N, -96°08' W). Daily and annual cycles were plotted to determine the current behavior of the sea level. Subsequently, using hourly records, graphs of the temporal evolution of tides were constructed for the years available in each time series. Each of these graphs was associated with a trend line describing the sea-level variations over time, and a numerical value for each trend line was calculated along with its associated uncertainty. Finally, we estimated future values for sea-level height in the region using extrapolations. These predictions were compared with other databases for the qualitative analysis.

The first results obtained indicate a stable and constant behavior of sea level on the central coast of the Gulf of Mexico, with well-defined daily and annual cycles. The overall sea-level trend in this region is -1.86 mm year^{-1} from 1999 to 2018. The general trend in the first decade was +3.6 mm year^{-1} and in the second, -1.26 mm year^{-1}. In the period 2000 to 2010, the mean sea level on the central coast of the Gulf of Mexico rose by about 0.03 meters. The period 2011 to 2018 shows a reduction in sea level of approximately 0.008 meters. Predictions constructed with extrapolations estimated a future rise of about 0.47 to 1.07 meters by 2200 considering the trend observed in the first decade and a reduction of 0.41 to 0.02 meters by 2200 considering the trend in the second decade.

The overall trend observed in the period 1999-2018 for the central coast of the Gulf of Mexico corresponds to a decrease in sea level in the region, but its effects have not been observed. The first decade of the period considered shows a constant rise in sea level until 2010. From 2011, the increase was slower and more progressive. The corrected segmented trend for the first decade is consistent with the global average trend established by the IPCC (2021). The negative trends do not coincide with any values reported in the literature. Our sea-level projections underestimate the rise compared to those associated with RCPs 2.6, 4.5, and 8.5.

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Two of the three mareographic stations considered in the present study did not record data over a full year (2011) and resumed reporting data with values lower than those at the start of the suspension. The nature of this gap in the time series was not determined in the present study, but it may be associated with instrument recalibration. The effect of this recording suspension on the results presented is unknown, although a potential causal relationship is not ruled out.

Keywords: sea level height, Gulf of Mexico, sea-level trends, tidal cycles, sea-level predictions.

Resumen. Hay consenso científico sobre un aumento en el nivel medio del mar global de alrededor de 0.20 metros durante el periodo 1901-2018 (IPCC, 2021). Este es global, pero no homogéneo, por lo que resultan relevantes los estudios a escalas menores. En este artículo se describe el análisis cuantitativo que se realizó para determinar el comportamiento actual y a futuro de la altura del nivel del mar en la costa central del golfo de México y determinar si presenta o no un aumento similar al reportado a escala global. Se busca determinar la naturaleza del comportamiento observado en el nivel del mar de la región.

Tomando como base metodológica el trabajo de Zavala-Hidalgo *et al.* (2011), fueron seleccionadas tres estaciones pertenecientes a la Red Mareográfica Nacional para caracterizar la marea en la costa central del gofo de México: Coatzacoalcos (18°09' N, -94°26' W); Frontera (18°32' N, -92°38' W) y Veracruz (19°12' N, -96°08' W). Se graficaron los ciclos diarios y anuales para determinar el comportamiento actual de la marea. Posteriormente, utilizando registros horarios, se construyeron gráficas de la evolución temporal para los años disponibles en cada serie de tiempo. A cada una de estas gráficas se le asoció una línea de tendencia que describía las variaciones de la marea con el tiempo y fue calculado un valor numérico para cada línea de tendencia junto a su incertidumbre asociada. Finalmente, haciendo uso de extrapolaciones se estimaron valores a futuro para la altura del nivel del mar en la región. Estas predicciones fueron comparadas con las de otras bases para el análisis cualitativo.

Los primeros resultados obtenidos indican un comportamiento estable y constante de la marea en la costa central del golfo de México, con ciclos a escala diaria y anual bien definidos. La tendencia global del nivel del mar en esta región es de -1.86 mm año^{-1} para el periodo 1999 a 2018. La tendencia global para la primera década es 3.6 mm año^{-1}; la tendencia global para la segunda década es -1.26 mm año^{-1}. En el periodo 2000 a 2010, el nivel medio del mar en la costa central del golfo de México aumentó en un orden de 0.03 metros. En el periodo 2011 a 2018 se observa una disminución en el nivel del mar de aproximadamente de 0.008 metros. A través de las predicciones construidas con extrapolaciones se estimó un aumento a futuro de alrededor de 0.47 a 1.07 metros hacia 2200, considerando las tendencias de la primera década, y una disminución de 0.41 a 0.02 metros hacia 2200, tomando en cuenta las tendencias de la segunda década.

La tendencia global observada en el periodo 1999-2018 para la costa central del golfo de México corresponde a un descenso en la altura del nivel del mar en la región, pero sus efectos no han sido observados en el litoral centro del golfo de México. La primera década del periodo considerado presenta un aumento constante del nivel del mar hasta el 2010. A partir de 2011 el aumento es más lento y progresivo. La tendencia segmentada corregida de la primera década coincide con la tendencia media global establecida por el IPCC (2021). Las tendencias negativas no coinciden con ningún valor establecido por la literatura consultada. Las proyecciones de altura de nivel del mar subestiman el aumento respecto de las proyecciones asociadas a las RCP 2.6, 4.5 y 8.5.

Dos de las tres estaciones mareográficas utilizadas en este artículo cortan sus registros un año entero –2011– y reanudan los datos con valores inferiores al inicio del corte. En este trabajo no se determinó la naturaleza de este hueco en las series de tiempo, pero se conjetura que esté asociado a recalibraciones del instrumento. Se desconoce el grado de influencia que este corte en los registros tiene en los resultados presentados, aunque no se descarta una posible causalidad.

Palabras clave: altura del nivel del mar, golfo de México, tendencias del nivel del mar, ciclos de marea, predicciones del nivel del mar.

INTRODUCTION

Hydrometeorological and climatic events are complex phenomena that result from the interaction of several spheres on planet Earth combined with processes within and outside it that also influence them. To characterize the climate of a region based on meteorological time series or estimate subsequent values, it is essential to consider and identify the climatic interactions between the ocean-continent and the atmosphere. The most significant of all these interactions is likely the one between the ocean and the atmosphere. Oceans cover 71% of the Earth and play a key role in most atmospheric phenomena, including the provision of moisture, transporting momentum and energy, and storing heat in oceans and the atmosphere (IPCC, 2019).

Multiple studies have sought to identify the main impacts of global warming on ocean waters. The major effects include the rise in surface water temperature, acidification, loss of Arctic and Antarctic ice cover, imbalance in oxygen content in deep water, and rise in mean sea level in coastal areas worldwide (Cazenave and Cozannet, 2014). Of all of the above, the rise-decline in mean sea level is the effect representing the most worrying threat and potential hazard to coastal inhabitants (McGranahan *et al.*, 2007).

Sea level refers to the average height of the sea surface between high and low tides. Temporal changes in tides and waves are averaged to determine a stationary water level, thus identifying whether the sea level has changed or the height of the land above sea level has varied (British Geological Survey, s.f.). This and other oceanographic variables allowed for identifying trends – generally positive – in ocean height behavior at different temporal and spatial scales (IPCC, 2021).

This increase observed at the local level can be attributed to countless phenomena, from continental movements, coastal management, thermodynamic processes, orographic modifications due to infrastructure construction, extreme hydrometeorological events, to the presence/absence of El Niño. At the global level, there are different time scales through which various phenomena influence the mean sea level. Thus, pointing out a single cause is intricate. However, the most recent assessment by the IPCC (2021) considers human activity the key driver of this rise in mean sea level since 1971 (IPCC, 2021).

Due to long-term movements of the Earth's surface over long periods, local-scale changes may be observed even though the absolute height of the oceans remains unchanged, or changes cannot be identified despite the varying height (British Geological Survey, s.f.).

Analyses of the evolution in sea-level height have been carried out in different coastal regions worldwide, most detecting an increase. In Australia, White *et al.* (2014) obtained an increasing trend of +1.6 ± 0.2 mm year^{-1} for the period 1966–2010; for southern Europe, Marcos and Tsimplis (2008) estimated a positive trend of +1.5 ± 0.1 mm year^{-1} during the 20th century. Studies such as these are considered to calculate global average trends, hence the importance of conducting regional or local analyses in various parts of the world.

The special Intergovernmental Panel on Climate Change report on oceans and the cryosphere (IPCC, 2019) established an average sea level rise of +0.16 meters from 1902 to 2015 and an average global trend of +3.6 mm year^{-1} from 2006 to 2015. According to the sixth assessment report of the IPCC (2021), a global mean sea level rise of approximately +0.20 meters has been recorded from 1901 to 2018, with an updated trend in the mean sea level of +3.7 mm year^{1}.

In line with the evolution observed so far, the global annual rate is expected to increase and remain over the next centuries; some future scenarios estimate a rise of between +0.30 and +2 meters by 2200, depending on the management of greenhouse gas emissions (IPCC, 2021).

In Mexico, studies of changes in the mean sea level have started to emerge, each with its own methods, objectives, and databases. To note, like most studies at the global level and despite the pragmatic differences between them, the studies conducted in the coastal areas of Mexico report a positive trend in sea level in the region, consistent with the reports issued by the IPCC (2019, 2021) and previous studies.

Zavala-Hidalgo *et al.* (2011) analyzed the sea-level behavior on the Mexican coast from data recorded in 16 stations of the National Mareographic Service at *Univerisdad Nacional Autónoma de México*. They used monthly averages of the longest available series and considered only years with data for all months to avoid biases from seasonal variation. A positive trend was identified in the Pacific and Gulf of Mexico basins. Generally, a positive but irregular trend was established on the Mexican Pacific and Atlantic coasts.

Regional events also influence the data used to construct trends, and this complicates the characterization of a unique trend, although patterns can be derived for each coastal region of the country. Ruiz-Ramirez *et al.* (2014) found an overall rise in sea level in Mexico; it rises at a greater rate on the Gulf and Pacific coasts (+3.8 and +3.5 mm year^{-1}, respectively), while the Mexican Caribbean shows a lower rate of increase (+1.6 mm year^{-1}) relative to the overall average considered in the study.

OBJECTIVES

This article has a local scope, limited to the central coast of the Gulf of Mexico. Our results are expected to be consistent with the literature on sea-level trends at different scales. Therefore, the primary objective is to compare recent sea-level trends in this region with the values reported by Zavala-Hidalgo *et al.* (2011) and Ruiz-Ramirez *et al.* (2014) for the Mexican coasts and, in turn, with the global average reported by the IPCC (2019, 2021).

For a coastal region, anomalies in its adjacent waters will involve various risks and impacts. Factors such as topography, the extent of the coastal plain, and infrastructure will largely determine what effect of global warming on the ocean represents the greatest risk and involves the greatest vulnerability. Conde Alvarez and Palma Grayeb (2006) state that the rise in mean sea level poses a significant risk for human settlements on the Gulf of Mexico's coast, given their vulnerability to floods and tidal waves, among other responses. The analysis and characterization of the coastal plain and an assessment of the most vulnerable areas and mareographic data are essential for coastal states. It is necessary to understand the root cause of the issue using a reliable methodology for decision-making since natural disasters can determine the distribution of the population (Rodríguez Villafuerte. 2006; Gómez Villerías *et al.*, 2022). Coastal planning would save losses and damage in key sectors such as energy and is necessary for risk management and an optimum location of houses.

In this context, the Gulf of Mexico littoral was selected as a study area to assess whether the effects of global warming reported by the IPCC (2021) and observed on the Mexican coasts in previous studies occur in this coastal region (Zavala-Hidalgo *et al.*, 2011; Ruíz-Ramírez *et al.*, 2014).

The small-scale temporal behavior of sea level was characterized by calculating daily and annual cycles and constructing time series of annual averages. The large-scale temporal behavior of sea level in the region was characterized based on predictions of the future. Numerical results are also displayed graphically to visualize and identify the patterns or anomalies found.

MATERIALS AND METHODS

In the present study, we quantitatively described the behavior of the mean sea level in the Gulf of Mexico littoral by analyzing hourly mareographic data for three stations of the Secretariat of the Navy's National Mareographic Network, using the procedure described by Zavala-Hidalgo *et al.* (2011). This study was carried out using the historical hourly records for three stations located on the Gulf of Mexico coast: Coatzacoalcos, Veracruz (18°09' N, -94°26' W); Frontera, Tabasco (18°32' N, -92°38' W); and Veracruz, Veracruz (19°12' N, -96°08' W) (Figure 1) to quantitatively describe the behavior of the mean sea level on the Gulf of Mexico coast. It should be noted that the tidal data used do not consider the geophysical changes that may influence relative sea-level height measurements.

To estimate values of sea-level trends in the Gulf of Mexico littoral, the tide was first characterized through daily and annual cycles. In addition, we used the calculated trend values to construct graphs of future sea-level behavior for the next century through extrapolations. These graphs were then compared with other sources and are discussed at the end.

For the three sites, evolution time series were constructed for the years available at each database (1999 to 2018 at Frontera and 2000 to 2018 at Coatzacoalcos and Veracruz), averaging the values for a given year at each station — annual average databases. In general, the stations have relatively high percentages of missing data, especially the Coatzacoalcos station, with only 55% of the data available. Frontera was the station with the most information and the only one to have data for a full year. Years with no data were excluded from trend calculation.

A variation on the methodology of Zavala-Hidalgo *et al.* (2011) is the auto-correlation analysis for the annual average databases. Figure 2 shows the autocorrelation function for annual averages. A semi-cyclic behavior is observed that is not complete because the length of the series only covers 18 years. Data were processed under this premise.

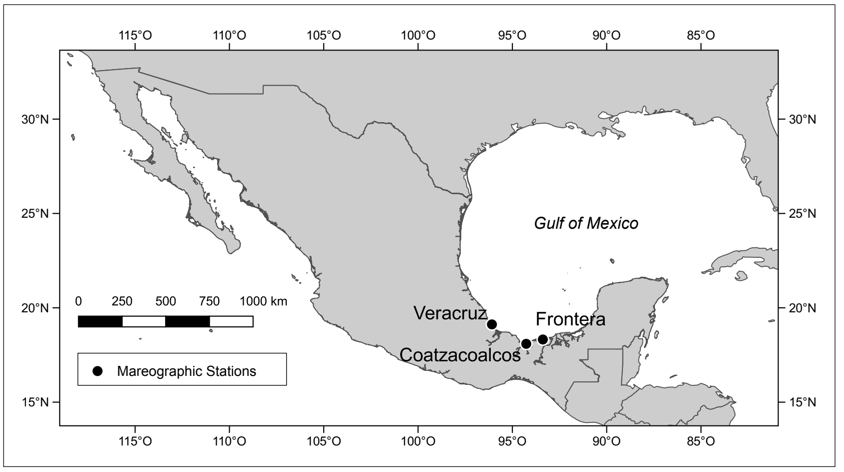

Figure 1. Location of the stations that define the region "central coast of the Gulf of Mexico".

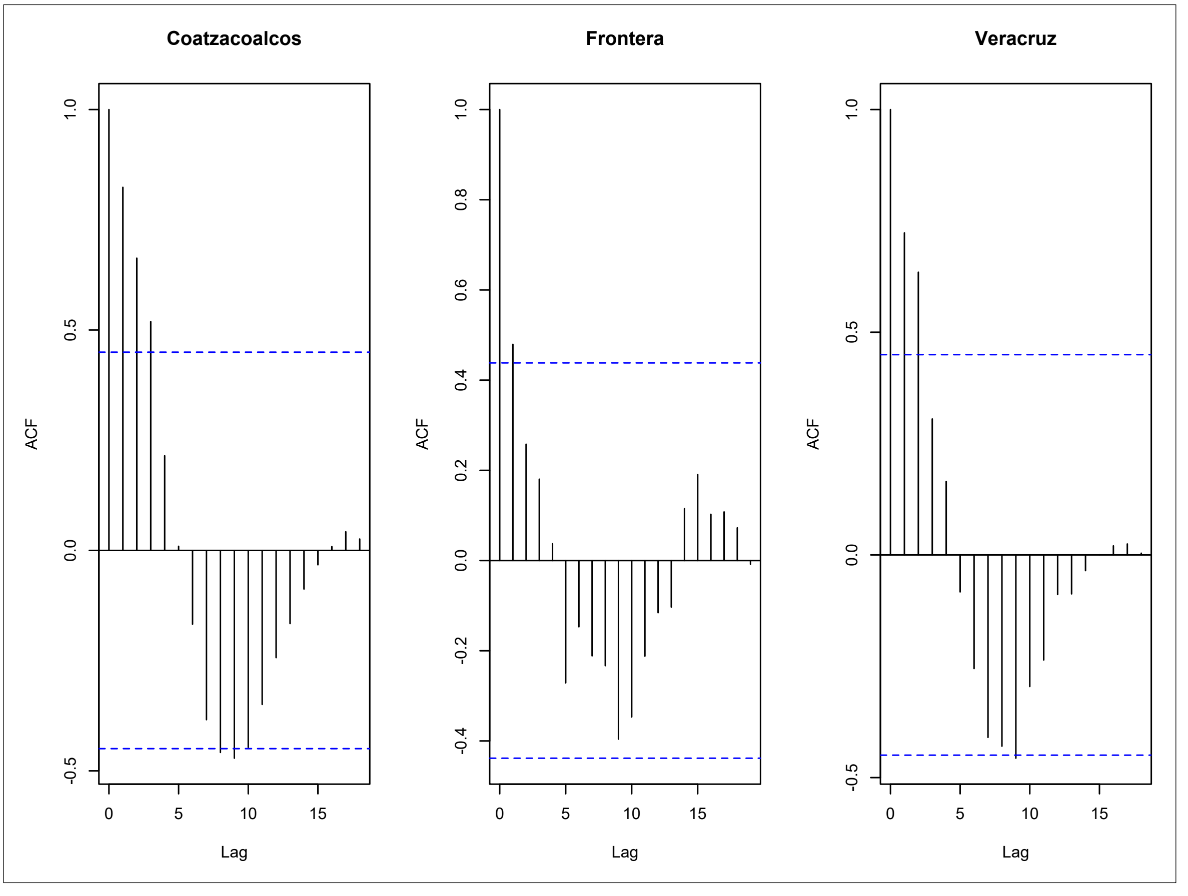

Figure 2. Auto-correlation function (Y-axis) for annual average (X-axis) databases.

Subsequently, a trend line was fit to each evolution time series using the least-squares linear regression method.

An uncertainty interval was calculated for each trend value, as defined by Zavala-Hidalgo *et al.* (2011) as the product of the critical value by the typical error (TE):

$$ET = \frac{\sigma}{\sqrt{|n|}} \quad (1)$$

Where σ is the standard deviation and n is the size of the hourly data series. The critical value was calculated with a significance level of 0.01 (1%) and n-2 degrees of freedom. The calculations described and all the products reported in this article were made using the Rstudio software (Rstudio, 2018).

Given that we found full years with missing data, this study calculated three different types of trends: the overall trend, considering time series as a single segment; the segmented trend, calculated for each uninterrupted period of data; and the corrected trend, considering the entire series after the missing data are imputed. Data were imputed based on the average value of the respective station. This substitution followed the procedure by the Secretariat of the Navy in the calculations for the tide prediction calendars (CECOPROD, personal communication, 6 January 2022).

According to the IPCC glossary (2013), a prediction is the result of an attempt to estimate the actual evolution of the variable in the future from a particular state of the system. In this study, using extrapolations based on the segmented trends calculated for each site, we estimated the future sea-level height using prediction graphs for the central coast of the Gulf of Mexico up to the year 2200. The same glossary establishes the term 'forecast' as a synonym in this context.

These graphs were compared with sea level predictions constructed by the Central Climate (2020), corresponding to the Representative Concentration Pathway (RCP) scenarios 2.6, 4.5, and 8.5. For the graphs included in the Results section, RCP predictive lines are based on the 50th percentile for each emission scenario.

Sea level estimates related to RCPs 2.6, 4.5, and 8.5 calculated by the Central Climate (2020) are based mainly on the work of Kopp *et al.* (2014) and Kopp *et al.* (2017). These results also consider IPCC's global predictions and, in some cases, recent investigations of potential ice cap instability in Antarctica (DeConto and Pollard, 2016). The pollution scenarios from greenhouse gas emissions include "rampant pollution" (technically, RCP 8.5), "moderate reduction in concentrations" (RCP 4.5), and "extreme reduction in concentrations" (RCP 2.6). This latter assumption represents a peak in emissions near 2020, followed by a sharp decline close to zero in 2070 (Climate Central, 2020). The estimates of this server were used because of data availability, the coincidence in the locations used in this study, and the robustness of its references.

RESULTS AND DISCUSSION

The first graphical results obtained were daily and annual tidal cycles at each station, which served to get a first approximation of the sea-level behavior on the central coast of the Gulf of Mexico.

All available values in the series with the same hour indicator were averaged to obtain the mean daily behavior for each site (Figure 3 a, b, and c). Similarly, all available values in the series with the same monthly indicator were averaged to obtain the mean annual behavior at each site (Figure 4 a, b, and c).

As described above, the results of this study include three different trends. To simplify this section, the graphical trend results are included only after missing data are imputed.

Figure 5 (a, b, and c) represents the corrected time series and their overall associated trends. Figure 6 (a, b, and c) shows corrected segmented trends for the central coast of the Gulf of Mexico. The latter cover the periods from 2000 to 2010 for Coatzacoalcos and Veracruz, 1999 to 2010 for Frontera, and 2011 to 2018 for the three stations.

Frontera stands out for being the only time series without discontinuities; however, segmented and corrected segmented trends were nonetheless calculated for the period 2011-2018, which includes the only uninterrupted period common to

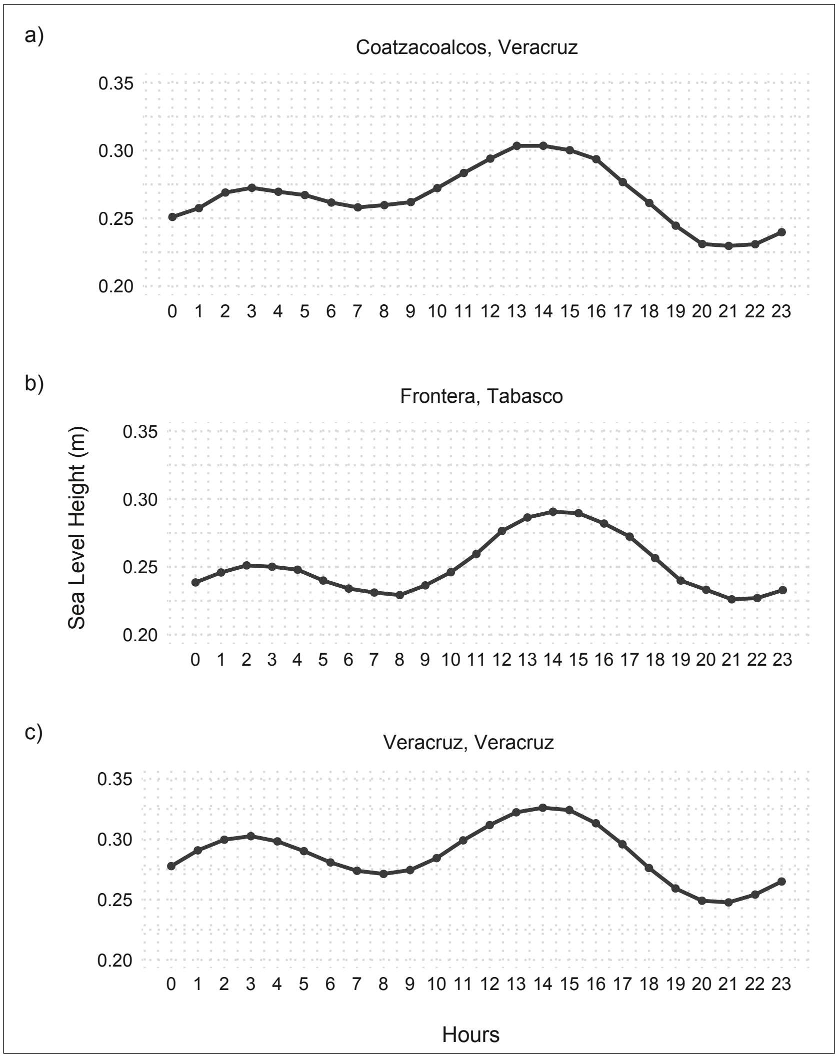

Figure 3. Characterization of daily cycles in a) Coatzacoalcos, b) Frontera, and c) Veracruz.

the three sites: 2012–2018. Table 1 contains the numerical values of the trends with their associated uncertainty.

Finally, using the trends whose behavior coincides with the results of Zavala-Hidalgo *et al.* (2011), sea-level height values were extrapolated for the following century. These data were graphically compared with the predictions on the Climate Central (2020) webpage to find similarities or disparities and draw discussion. Figures 7, 8, and 9 illustrate the behavior of each prediction for different emission scenarios against the predictions calculated in the present study. The data available in Climate Central (2020) included predictions for Coatzacoalcos but not for Frontera or Veracruz, so the last two stations were compared with neighboring sites: Ciudad del Carmen (18°38’ N, -91°50’ W) and Alvarado (18°46’ N, -95° 46’ W), respectively.

The key findings of the study are briefly discussed for each time scale.

Daily and Annual Cycles

The mean daily and annual behavior of the stations and the corrected trends represent the current sea-level behavior on the central coast of the Gulf of Mexico. The reference period covers 19 years, and a well-defined behavior can be observed throughout

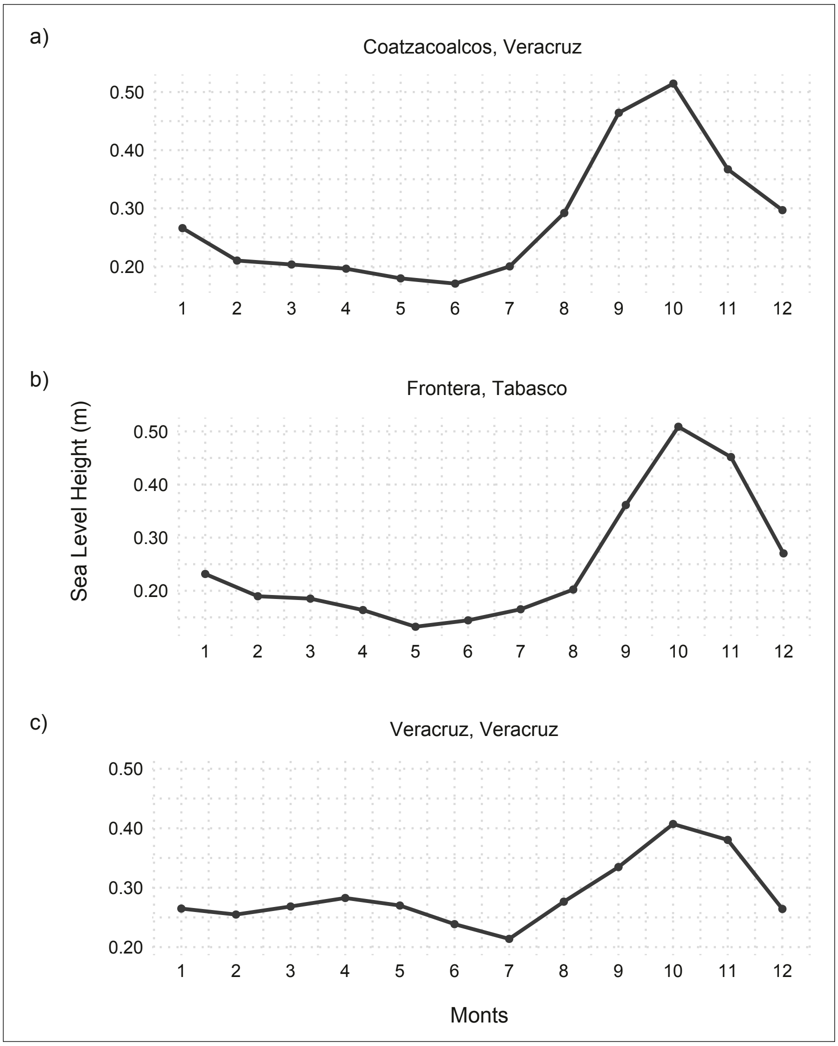

Figure 4 Characterization of annual cycles in a) Coatzacoalcos, b) Frontera, and c) Veracruz.

the day (Figure 3) and throughout the year (Figure 4). These figures show that sea level has followed a regular behavior in the region to date, in line with its cyclical nature. No major disturbance is apparent. Daily maxima occur around 2 and 14 solar hours, and minima are identified around 7 and 21 hours. This is observed throughout the central coast of the Gulf of Mexico. This tidal behavior related to daily cycles is consistent with the data reported by of Salas-Pérez *et al.* (2008) for the Gulf of Mexico.

The annual peak occurs around the autumn months, namely in October, likely because of storm tides (Rosengaus Moshinsky *et al.*, 2021). The annual minimum takes place from May to July along the whole central coast of the Gulf of Mexico.

Sea-Level Trends

In general, the overall corrected trends for each site and the overall mean trend for the whole central coast of the Gulf of Mexico show negative values, that is, a descending mean sea level in the region. This behavior contrasts with the results reported in the literature at both the local level (Zavala-Hidalgo *et al.*, 2011; Ruiz-Ramirez *et al.*, 2014) and the global level (IPCC, 2021).

Each series of corrected segmented trends contain a segment with a positive trend and a segment

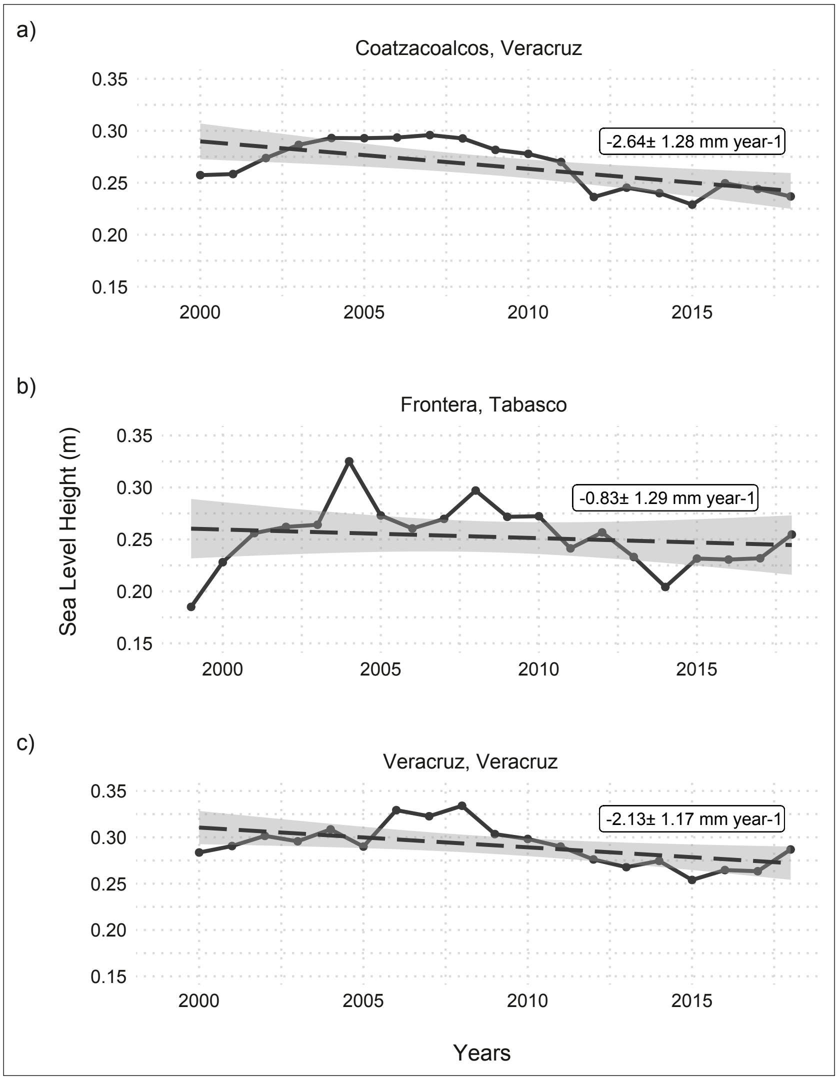

Figure 5. Evolution of sea level with the corrected overall trend in (a) Coatzacoalcos, (b) Frontera, and (c) Veracruz..

Table 1. Corrected overall and segmented trends for the stations located at the central coast of the Gulf of Mexico.

Years analyzed	Period	Trend Coatzacoalcos	Trend Veracruz	Years analyzed	Period	Trend Frontera
19	2000/ 2018	-2.64 ± 1.28 mm year^{-1}	-2.13 ± 1.17 mm year^{-1}	20	1999/ 2018	-0.83 ± 1.29 mm year^{-1}
11	2000/ 2010	2.46 ± 1.78 mm year^{-1}	2.70 ± 1.75 mm year^{-1}	12	1999/ 2010	5.64 ± 1.67 mm year^{-1}
8	2011/ 2018	-2.28 ± 1.75 mm year^{-1}	-1.39 ± 1.68 mm year^{-1}	8	2011/ 2018	-0.13 ± 2.03 mm year^{-1}

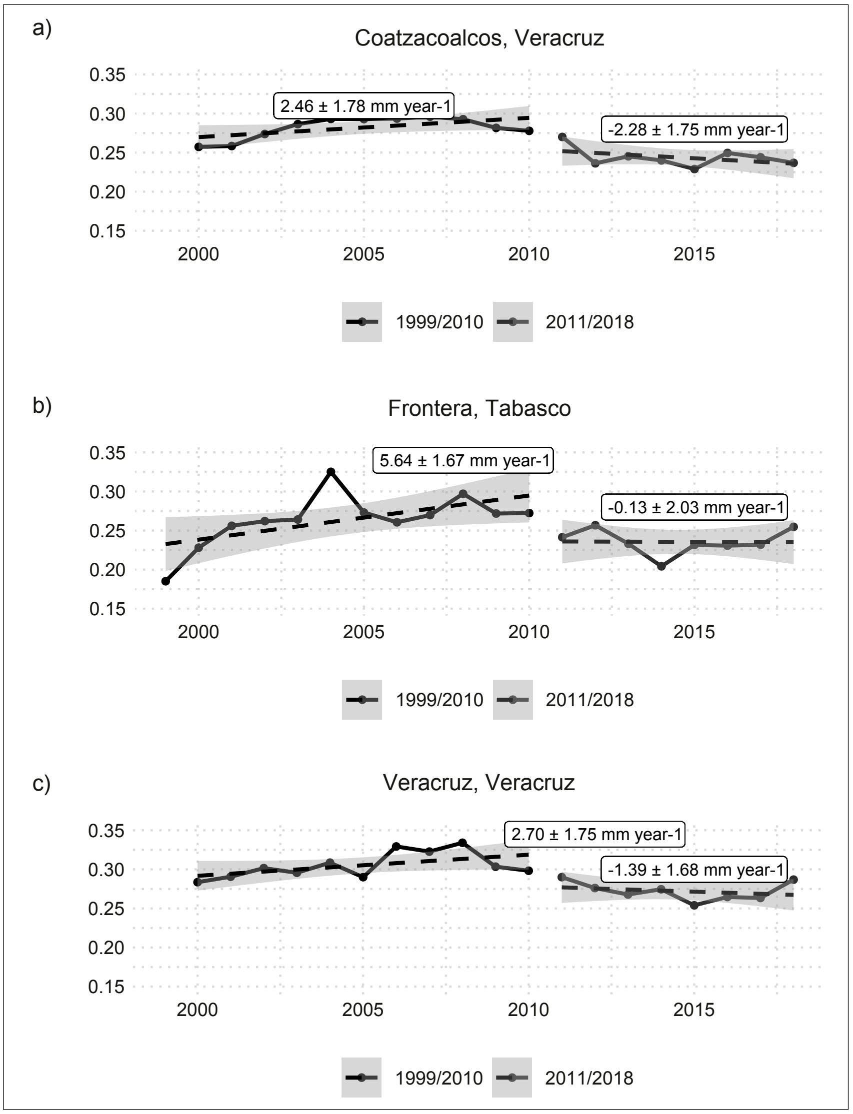

Figure 6. Evolution of sea level with corrected segmented trend in a) Coatzacoalcos, b) Frontera, and c) Veracruz.

with a negative trend. At the three stations, the first period physically corresponds to a rise in mean sea level, the magnitude of which follows an irregular pattern. The second period physically corresponds to a decrease in sea level: however, a slight recovery after 2015 is evident.

According to the first segment — 1999 to 2010 for Frontera and 2000 to 2010 for Coatzacoalcos and Veracruz —, sea level rose at Coatzacoalcos (+2.46 ± 1.78 mm year^{-1}) and Veracruz (+2.70 ± 1.75 mm year^{-1}) at a ratio lower than the average value established by Ruíz-Ramirez et al. (2014) for the Gulf of Mexico (3.5 mm year^{-1}). On the other hand, sea level at Frontera rose at a higher rate (+5.64 ± 1.67 mm year^{-1}) than this average value.

According to the second period of corrected segmented trends — 2011 to 2018 for the three stations —, sea level decreased more rapidly in Coatzacoalcos (-2.28 ± 1.75 mm year^{-1}), followed by Veracruz (-1.39 ± 1.68 mm year^{-1}), and Frontera (-0.13 ± 2.03 mm year^{-1}).

Averaging the overall trend values for each site, a mean overall trend value was calculated for

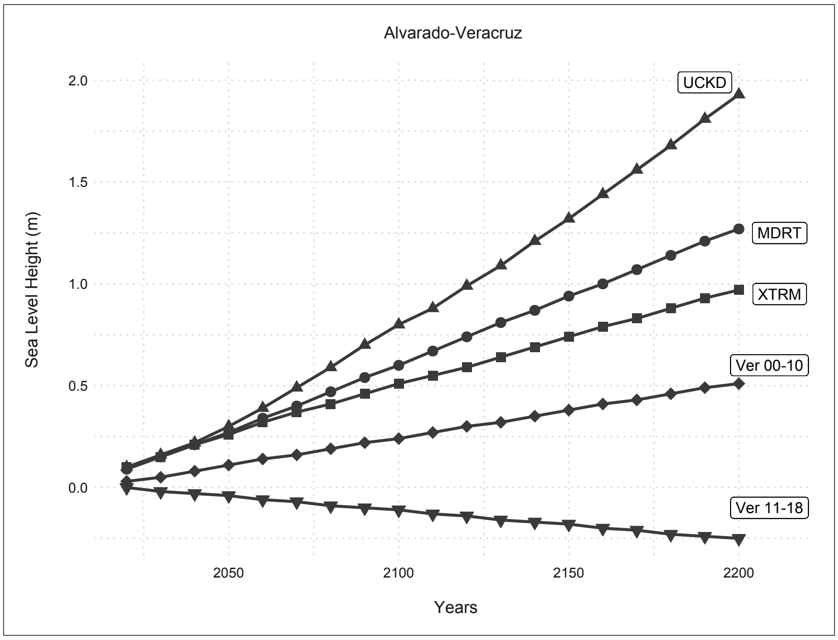

Figure 7. Comparison of predictions in Alvarado, Veracruz. The XTRM, MDRT, and UCKD lines correspond to RCPs 2.6, 4.5, and 8.5, respectively.

Note: Lines 00-10 and 11-18 show the results of corrected segmented trends calculated for Veracruz.

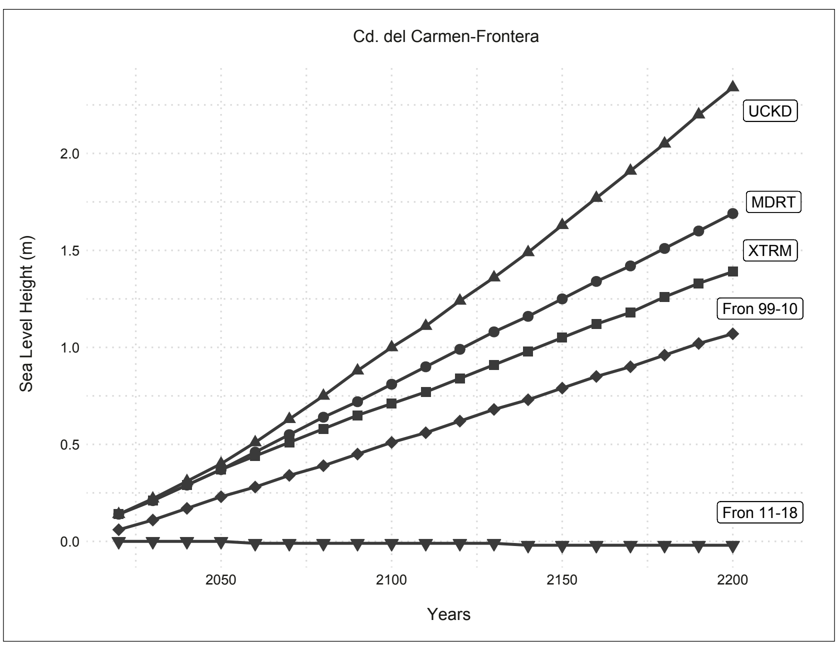

Figure 8. Comparison of the predictions for Ciudad del Carmen, Campeche. The XTRM, MDRT, and UCKD lines correspond to RCPs 2.6, 4.5, and 8.5, respectively.

Note: Lines 99-10 and 11-18 show the results of corrected segmented trends calculated for Frontera.

the central coast of the Gulf of Mexico; the result indicates a decrease of about -1.86 mm year^{-1} for the period 1999 to 2018. Similarly, regional averages were calculated for the two periods of segmented trends. The period from 1999 to 2010 showed an average increase of approximately 3.6 mm year^{-1}, consistent with the global average trend established by the IPCC (2019, 2021). The period from 2011 to 2018 showed an average trend of -1.26 mm year^{-1}.

All sets of databases show a decline in their records after 2011, which, coincidentally, is a whole year of missing data in the Coatzacoalcos and Veracruz databases. In this study, the degree

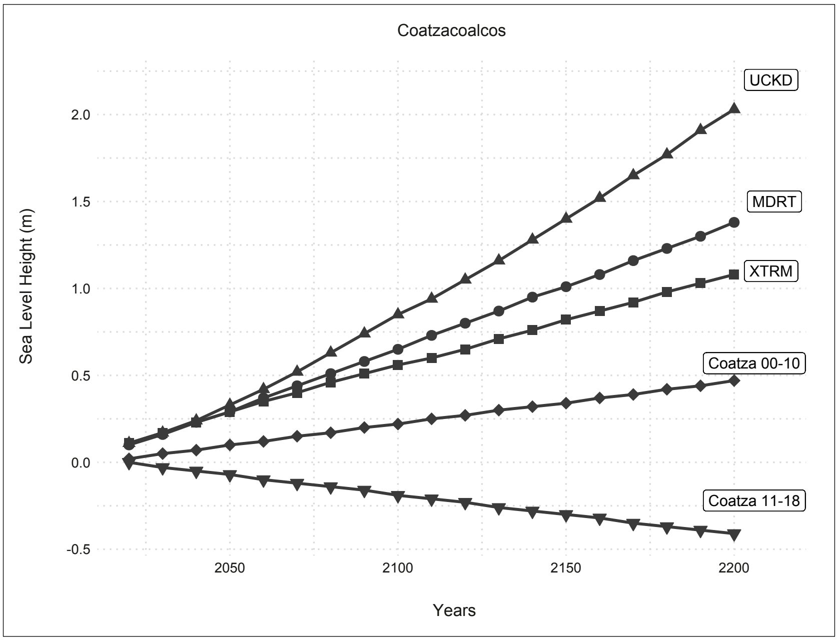

Figure 9. Comparison of the predictions for Coatzacoalcos, Veracruz. The XTRM, MDRT, and UCKD lines correspond to RCPs 2.6, 4.5, and 8.5, respectively.

Note: Lines 00-10 and 11-18 show the results of corrected segmented trends calculated for Coatzacoalcos.

of influence of this drop on the negative outcome of post-2010 overall and segmented trends is unknown — but not ruled out.

The average overall trends are negative for the Coatzacoalcos (-2.64 ± 1.28 mm year^{-1}) and Veracruz (-2.13 ± 1.17 mm year^{-1}) stations, contrasting with the positive trends calculated by Zavala-Hidalgo et al. (2011): +2.9 ± 1.5 mm year^{-1} for Coatzacoalcos and +1.9 ± 0.6 mm year^{-1} for Veracruz. The average overall trend for the central coast of the Gulf of Mexico is -1.86 mm year^{-1}, which also differs from the positive trend of 3.8 mm year^{-1} established by Ruíz-Ramírez *et al.* (2014) for the Gulf of Mexico littoral and the overall trend of +3.7 mm year^{-1} established by the IPCC (2021).

The sea-level decrease suggested by the findings in the present work would imply physical responses such as an advancing coastline and a persistent expansion of wetlands. These responses have not only not been observed on the central coast of the Gulf of Mexico, but the opposite processes have been identified in recent decades (Landgrave and Moreno-Casasola, 2011; Hernández Santana *et al.*, 2007).

The temporal evolution graphs — regardless of their treatment — showed an abrupt minimum by 2011. The methodological limitations of the present study did not allow determining whether this behavior is due to a recalibration of the instrumentation in the mareographic network or to any external factor. However, the authors of the present study consider that this decrease is most probably the strongest influence on the negative result pf trends and associated predictions.

Predictions on the Sea Level

Considering the values used for calculating the only average trend that coincides and is consistent with the global average (3.6 mm year^{-1}), the future behavior of sea level in the region was estimated. To contrast and complete the analysis, the same procedure was performed with the segmented trends for the period closest to the present time, i.e., 2011 to 2018. This estimate is considered for the sea-level forecast on the central coast of the Gulf of Mexico.

Predictions based on the first study period —1999 to 2010— describe an upward and gradual rise over time, estimating an average rise in sea level between +0.47 and +1.07 meters by the end of the 22nd century. This result is similar to the +0.40- to +1-meter rise established by Yáñez-Arancibia *et al.* (2010).

Unlike the increase described by the trends based on the first segment, the predictions based on the post-2011 negative trends describe a persistent negative behavior of mean sea level, estimating a decrease of approximately -0.41 to -0.02 meters at the end of the 22nd century. This decrease does not appear to be related to any results from previous studies. This set of predictions is the only one estimating a decrease in sea-level height.

The graphical comparison of predictions reveals a contrast between the lines based on emission scenarios (RCP) and those based on the trends calculated in the present work. No trend line for the central coast of the Gulf of Mexico was identical to the lines estimated by Central Climate (2020). The only scenario in which they exceed the lines resulting from the predictions of this work corresponds to the 5th percentile of RCP 2.6, which represents a strict cut-off and a reduction in global emissions. So, with poorly regulated management of greenhouse gases and emissions, we can expect an increase that will double — or even triple — the values calculated in the present work.

CONCLUDING REMARKS

The responses of ocean dynamics, like almost any response on our planet, depend on several factors and may occur in multiple forms. In this sense, identifying ocean responses caused directly or indirectly by the anthropogenic effects of natural causes is a complex task.

This work aimed to evaluate the contribution of global warming — through the increase in heat content in the ocean and the melting of ice sheets — to the rise in mean sea level. However, multiple factors affect the average sea level on different temporal and spatial scales, two of the most important ones being the total volume of seawater and the movements of the subsoil and the seabed, which affect the size and shape of ocean basins. In addition, dynamic factors such as wind, atmospheric pressure, ocean currents, and waves also play a central role (Mimura, 2013).

In the present study, the sea level on the central coast of the Gulf of Mexico showed a negative trend, even after the imputation of missing data of about -1.86 mm in the year^{-1} over the period 1999-2018. The period 2000 to 2010 showed a steady rise in sea-level height of about 3.6 mm year^{-1}, consistent with the global average established by the IPCC (2019, 2021). The period 2011 to 2018 shows a decrease in sea level of approximately -1.26 mm year^{-1} with a slight recovery in post-2015 records. The magnitude of trends across the sites analyzed does not show a clear increase or decrease pattern on a spatial scale.

The negative trends for the periods 1999–2018 and 2011–2018 do not coincide with any values reported in the literature consulted for the present work.

The prospects for the future behavior on the central coast of the Gulf of Mexico underestimate the rise in sea level relative to the values predicted by RCPs 2.6, 4.5, and 8.5 of Central Climate (2020). According to the trends for the period 1999 to 2010, a rise of approximately 0.47 to 1.07 meters is expected in the region by the end of the 22nd century; in contrast, estimates based on trends from 2011 to 2018 predict a decrease of about -0.41 to -0.02 meters in sea level is expected by the end of the present century.

The negative results in the analysis of the current behavior may derive from several causes: continental movements, the presence or absence of El Niño and La Niña events, or mesoscale hydrometeorological events.

The three series used had a relatively high percentage of missing data — approximately 50%. In this regard, it is essential to continue recording measurements at the stations studied and improve the quality of records. More extended time series and a larger dataset will improve the estimation of sea-level trends and reduce the associated uncertainty.

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