DOI: 10.3856/vol45-issue4-fulltext-15

Research Article

Wind forcing of sea level variability in a tropical coral reef area in the western Gulf of Mexico

Román Rodolfo Vera-Mendoza[1], David Alberto Salas-de-León[2]
David Salas-Monreal[3] & Modesto Ortiz-Figueroa[4]
[1]Posgrado en Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México
[2]Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México
[3]Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, México
[4]Centro de Investigación Científica y de Educación Superior de Ensenada, México
Corresponding author: Román Rodolfo Vera-Mendoza (roman_vera@hotmail.com)

ABSTRACT. Sea level, water temperature, and wind stress data were obtained from the Western Gulf of Mexico to elucidate the relationship between sea level changes and meteorological variables in a tropical coral reef system. Sea level and water temperature data were measured with a series of acoustic Doppler current profilers anchored at a depth of approximately 13 m in the Veracruz Reef System. The barometric and wind stress data were obtained from an automatic coastal weather station. Principal Component Analysis was applied to the series to determine the relative influence of the different meteorological variables on sea level. The seasonal variability of sea level is evident in the year-long data (September 2008 to April 2010) with a thermal expansion during the summer. Barometric pressure was found to be the second strongest forcing mechanism of sea level variability and not the first one. Opposite to what would be expected in protected coastal areas where the wind forcing mechanism on sea level may not be as important. The local winds were the main forcing mechanism of the sea level variability from March to September, while the meridional winds were more important than local winds from October to February.

Keywords: sea level variability, ocean-air interaction, tropical coral reef system, Gulf of Mexico, Veracruz Reef System National Park.

INTRODUCTION

The Gulf of Mexico is a large marine ecosystem that combines the tropical and mid-latitude ecological environments. The Veracruz Reef System National Park (VRSNP) is a protected area of 52×10^6 m^2 (DOF, 2012), located in the Western Gulf of Mexico. The VRSNP hereinafter is a productive system with great biodiversity and it represents a high economic input in terms of fisheries and tourism (Birkeland, 1997; Glynn, 1997), the VRSNP is more productive than most of the tropical coral reefs of the western Gulf of Mexico (Avendaño-Alvarez *et al.,* 2017). A detailed description of the study area, type of climate and marine current regime can be found in Avendaño-Alvarez *et al.* (2017). Coral reef systems, such as the VRSNP, are very fragile because they require stable conditions of temperature, solar radiation, salinity, turbulence, and current velocities, to survive (Hubbard, 1997; Carricart- Ganivet, 2004). Therefore, changes in sea level (other than tidal changes) can disrupt the vertical growth of corals (Vance, 1989). For that reason, knowledge of sea level variability is essential to fully understand the grow rate on coral reef areas. The VRSNP is used as a case study for tropical coral reef systems in coastal areas of the western Gulf of Mexico. Veracruz is one of the oldest cities in America (founded in 1519); however, few oceanographic studies have been conducted in the area (Granados-Barba *et al*., 2007; Jiménez-Hernández *et al*., 2007). This current work is the first study on the barometric forcing of sea level variability in a tropical coral reef area in the western Gulf of Mexico.

Previous studies

In Chesapeake Bay (USA), one of the most studied areas in North America, Salas-Monreal & Valle-Levinson (2008) found that sea level had a high correlation with local winds in summer and a low correlation

Corresponding editor: Nelson Silva

in winter. However, the thermosteric and halosteric effects were also important, producing sea level variations of up to 10 cm. In the Mediterranean Sea (Tsimplis, 1995), North Sea, and Baltic Sea (Marc, 2001), the variation in sea level was mainly induced by winds and barometric pressure. Marc (2001) and Tsimplis (1995) found that the best correlation in coastal areas is between sea level and wind stress. In shallow tropical coastal areas, like the VRSNP, a high correlation is expected between wind stress and sea level. However, a shallow reef system with high evaporation, such as the VRSNP (Salas-Monreal *et al.*, 2009), should also be influenced by thermosteric effects, unlike other areas at higher latitudes. Finally, the increase in river discharge (La Antigua, Jamapa, and Papaloapan rivers) during the rainy season may be another factor affecting the sea level variability in the VRSNP. For example, this was the case for Montevideo and La Paloma systems (Uruguay), where the mean sea level varied by 9 cm and 13 cm during the year, respectively, owing to the influence of Río de la Plata River (Mazzetta & Gascue, 1995).

Maul and Hanson (1988) found that the average increase in sea level in the VRSNP from 1953 to 1985 was 1.53 mm year^{-1}. However, using data from January 1966 to December 1976 in the western Gulf of Mexico, the sea level increased around 1.4 mm year^{-1} (Salas-de-León *et al.*, 2006). At Galveston (USA), Ciudad Madero (Mexico), Veracruz (Mexico), and Progreso (Mexico), annual sea level reaches a maximum from September to October, and two minima; one in July and the other in January (Zavala-Hidalgo *et al*., 2003). Using data from 1985 to 1986, Ramírez & Candela-Pérez (2003) found that the barometric pressure in the Gulf of Mexico was the most important meteorological forcing at low frequency, affecting the variability of the sea level. Salas-de-León *et al*. (2006) found that the monthly variability in sea level increased during the winter and summer, and decreased during the spring and autumn, mainly caused by the wind velocity.

Therefore, coastal coral reef areas, such as the VRSNP, are very fragile systems since they are been affected by changes in sea level (other than tidal changes) that can disrupt the vertical growth of corals (Vance, 1989). The aim of this work is to understand the mechanisms that affect the sea level variability in coastal tropical coral reef areas.

MATERIALS AND METHODS

The VRSNP has been described as a platform type coral reef system with two reef shapes: elongated ones (northwest-southeast) and semicircular ones with the same orientation (Gutiérrez *et al.*, 1993). The VRSNP depth goes from 25 m in the northern area, to 40 m in the southern area. Both areas are naturally divided by the Jamapa River, which has a mean river discharge of 1.89×10^9 m^3 year^{-1} (Riveron-Enzastiga *et al.,* 2016). The reef system is bounded to the north by La Antigua River (2.82×10^9 m^3 year^{-1}) and to the south by the Papaloapan River (39.17×10^9 m^3 year^{-1}) (Tamayo, 1999). Despite its proximity to the coast and the Jamapa, La Antigua, and Papaloapan rivers, no significant changes of salinity have been reported (Salas-Pérez *et al.,* 2008). However, during a tidal cycle, the salinity varies from 34 to 36.4 g kg^{-1} in an anchored station in front of the Port of Veracruz (Salas-Monreal *et al.*, 2009).

Eight ADCP stations were used to obtain sea level data and water temperature every second. The weather station and the eight acoustic Doppler current profilers (ADCP, 1200-kHz RDI) recorded data from September 2008 to April 2010. These data were averaged every 15 min. The eight ADCP stations were anchored at a depth of ~13 m (Table 1) during low tide the same day. The barometric pressure and wind velocity were obtained from an automatic weather station, installed in the village of Anton Lizardo (Fig. 1), inside the Mexican Navy facilities (Table 1). These data were matched with the sea level observations in the data set.

The sea level series were filtered using a Lanczos low-pass filter with a cutoff frequency of 0.8 cpd in a window of 26 h to remove the tidal effects and other high frequency fluctuations. Each one of the sea-level records referred to its corresponding annual mean. Some gaps were present in the time series due to organisms that stuck in sensors or interference by currents generated from nearby boats. The gaps in the data series were filled with the best linear regression between nearby stations, whereas less than 3 h gaps were filled with a linear interpolation between successive data of the same series. Time series of water temperature, barometric pressure, and wind velocity were used to determine their relative influence on sea level variability using the method of Principal Component Analysis (Salas-Monreal & Valle-Levinson, 2008).

The effect of the barometric pressure on sea level variability was removed by using the hydrostatic equation following the methodology of Gill (1982), and Salas-Monreal & Valle-Levinson (2008):

$$\Delta(\eta) = \frac{-\Delta p}{g(\rho)}$$

where $\Delta(\eta)$ = change of sea level, Δp = water column pressure change, g = acceleration due to Earth's gravity, and ρ = water density.

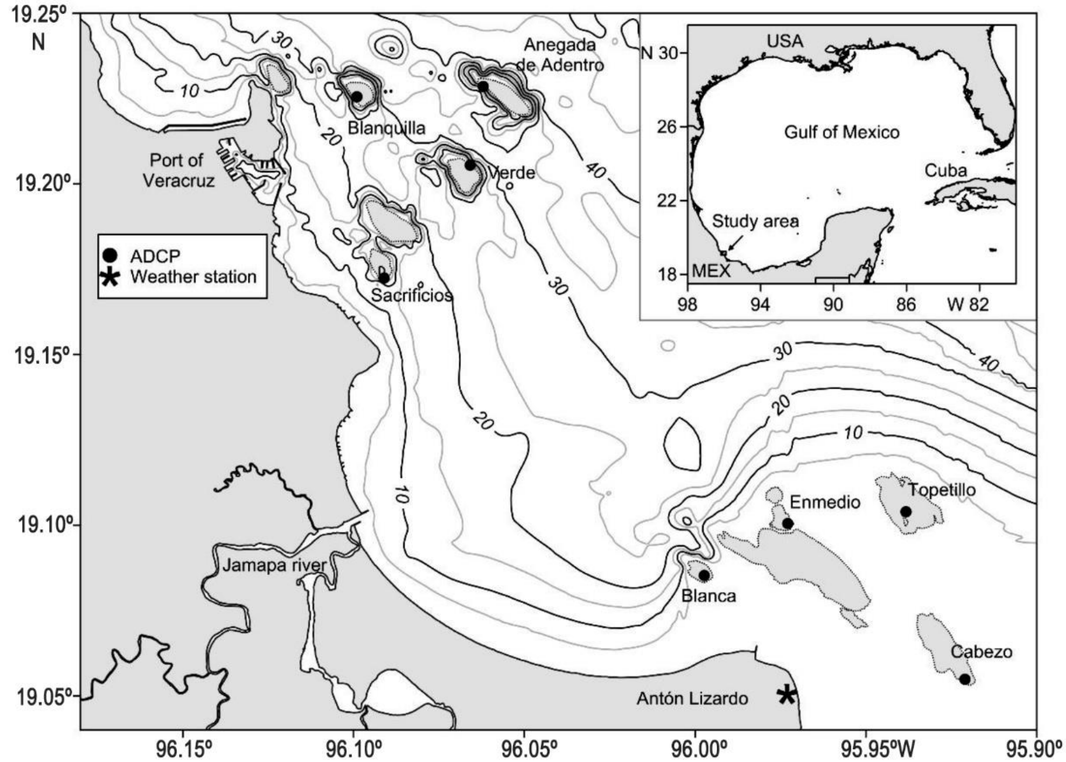

Figure 1. Study area and location of sampling instruments. The solid circles indicate where the ADCP's were anchored and the asterisk the weather station.

Table 1. ADCP's reefs names and weather station locations.

Reef	North latitude	West longitude
Topetillo	19.14778	95.84111
Cabezo	19.04944	95.82750
Enmedio	19.10139	95.93028
Blanca	19.08444	95.99778
Sacrificios	19.17361	96.09250
Verde	19.20583	96.06528
Anegada	19.22861	96.06167
Blanquilla	19.22528	96.10000
Weather Station	19.04944	95.97056

RESULTS

The sea level showed a diurnal signal with a fortnightly tidal modulation of approximately 50 cm from late August 2008 to February 2009, as was reported by Salas-Pérez *et al.* (2008). The sea level in the northern reef area (Verde and Sacrificios; Fig. 1) showed a maximum in October 2008 with a value of 30 cm in Verde (Fig. 2a) and 20 cm in Sacrificios (Fig. 2b). The lowest sea level value at both stations was observed in September (-40 cm).

In the southern reef area of Topetillo, Enmedio, Cabezo, and Blanca (Fig. 1), the sea level values were obtained from December 2009 to early April 2010. During this period, the sea level did not show a significant difference with respect to the northern reef area; all correlations were higher than 0.75. The maximum sea level values were up to 18 cm, from December to February. However, there was a slight decrease in late January and early February 2010 (approximately -10 cm; Figs. 2c-2f) coinciding with the presence of atmospheric cold fronts (hereinafter northers). The maximum values shown in Figure 2 during late January and February were not considered in the analysis because they correspond to interpolated data. In Anegada and Blanquilla stations (Fig. 1), where sea level was recorded from March to August 2009, the maximum sea level (18 cm) was observed during March, while the minimum values (-10 cm) were observed during April and early May. June and July showed a stable sea level pattern, with values near -5 cm (Figs. 2g-2h).

The water temperature in the northern reef area (Verde and Sacrificios) had the lowest values in September 2008 (29.8°C) and January 2009 (22.3°C) due to a period of strong rain (September) and northern events (September to January; Figs. 2a-2b). During the

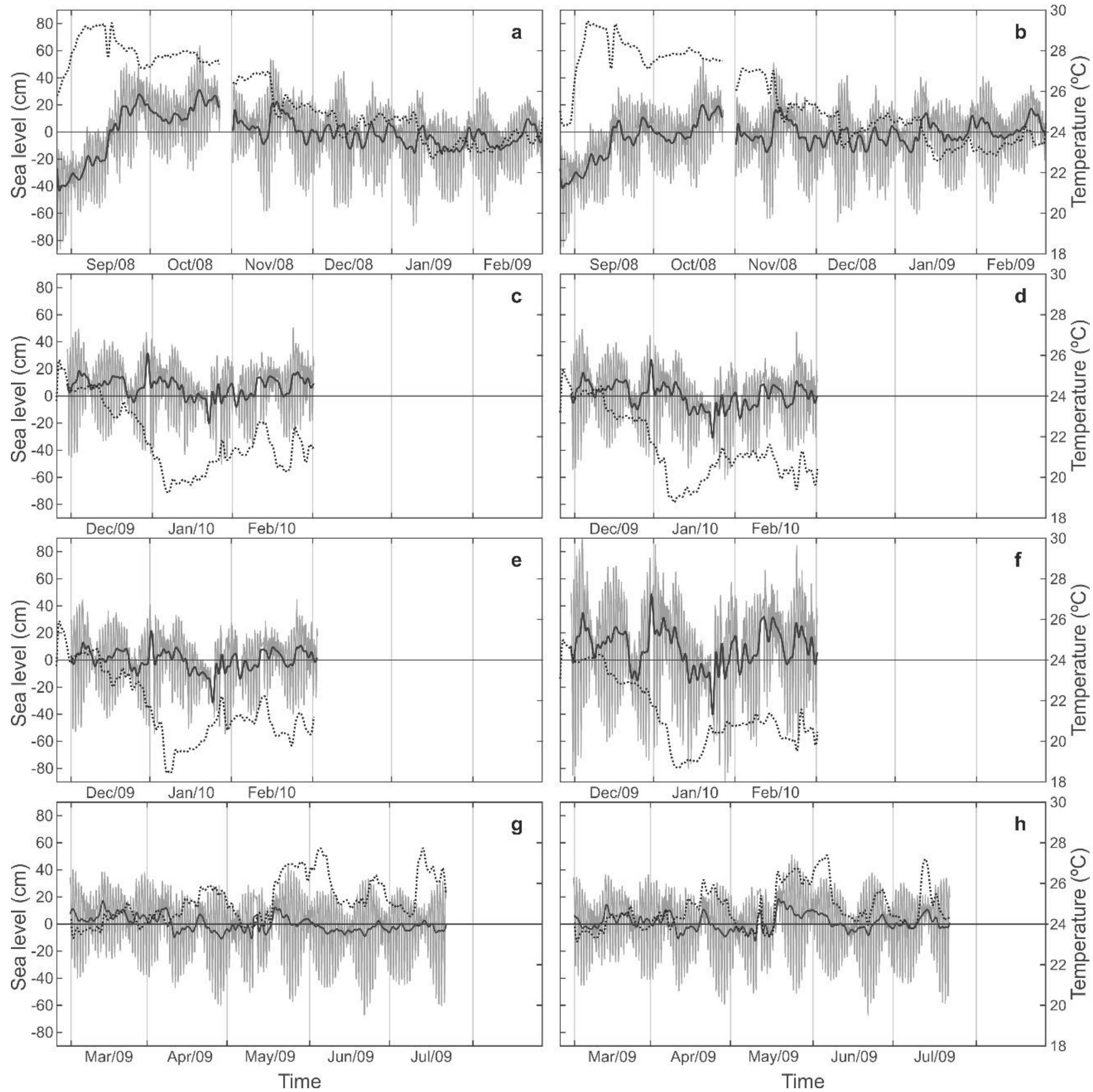

Figure 2. Sea level and sea temperature at a) Verde, b) Sacrificios, c) Topetillo, d) Enmedio, e) Cabezo, f) Blanca, g) Anegada de Adentro, and h) Blanquilla reef stations (solid gray line sea level original data, solid black line filtered, dotted line temperature).

winter, the strong winds mixed the entire water column, lowering the water temperature (Salas-Monreal *et al.*, 2009). The water temperature recorded at Topetillo, Enmedio, Cabezo, and Blanca reef showed a maximum in December 2008 (25.7°C), while the lowest temperatures were observed in January 2010 with a value of 18.8°C (Figs. 2c-2f). This was attributed to the northers and the associated strong northerly winds. In Anegada and Blanquilla, the temperature had a tendency to increase. The maximum water temperature was recorded in June 2009 (27.5°C) during summer (Figs. 2g-2h). In general, the highest temperatures were found during June and July in the summer (Salas-Pérez *et al.*, 2008). The maximum values were close to 30°C, while the lowest values of 18°C were observed during January and February (winter in the northern hemisphere) owing to winter cold air fronts. The water temperature varied from 30°C to 18°C within 6 months. This is a large temperature variation for a coral reef system (Salas-Monreal *et al.*, 2009), where organisms must adapt not only to the temperature change of close to 12°C from January to July, but also to changes in turbidity produced by the strong winds observed during winter cold fronts. Further, river runoff affects the turbidity of the costal water from mid-September to early November, which is the rainy season at VRSNP (Riveron-Enzastiga *et al.,* 2016).

Cold fronts are strongly related with the variation of the atmospheric pressure and wind velocities (Salas-Monreal & Valle-Levinson, 2008). The variation of the atmospheric pressure will enhance changes on the total sea level due to the atmospheric pressure which affects the total water pressure. The northwest winds and winter storms prevailed from August 2008 to February 2009. Trade winds have a northwest component at Veracruz because of the low pressure effect produce at the warm pool of the east Pacific (Gutiérrez-de-Velasco & Winant, 1996). However, this is also the prevailing wind direction throughout the year. Contrary to what was previously thought, that southeasterly winds were the prevailing winds during the summer (Salas-Pérez *et al.*, 2008), the data shown here prove that the prevailing winds are the northwesterly winds. The northwesterly wind velocity reached up to 13 m s^{-1} (Fig. 3a). The Figure 3b shows the dominant winds. The north northwesterly winds prevailed during December 2009 to January 2010. These winds had an average speed of 6 m s^{-1}. During February, the prevailing westerly winds had an average speed of 9 m s^{-1}. From March to April 2009, the dominant winds were from the north northeast with an average speed of 10 m s^{-1}, and at the end of April the average speeds decreased to 4 m s^{-1}. The northern events had the strongest variation on wind speed (Fig. 3c). The wind speed increased from less than 2 m s^{-1} to more than 13 m s^{-1} in less than 12 h. The most frequently winds in the study area were from the north and northwest throughout the year, followed by the southeasterly winds during the summer.

The barometric pressure had a seasonal pattern reaching high values from January to February 2009 (1027 hPa on average; Fig. 4a). The maximum was observed in January (1030 hPa) and the second highest barometric pressure was observed in April (1025 hPa; Fig. 4c). Both maximums were observed during northern events. The lowest barometric pressure of 1002 hPa was observed during a strong rain period.

Cold fronts were observed from October to April. The average time window between two successive cold fronts was of 6 days. During February, the barometric pressure oscillated with small amplitude (Fig. 4b). This is in agreement with the cold front events, because there were few and weak cold front events during this month. To elucidate the influence of the barometric pressure on sea level (SL), sea level data were plotted with and without the effect of the barometric pressure (Equation 1) (Fig. 5) The response of sea level without the barometric pressure was similar to that the one obtained with the barometric pressure (Figs. 5a-5c). Both series had good correlation for Verde (r = 0.97) (Fig. 5a), Topetillo (r = 0.83) (Fig. 5b), and Anegada (r = 0.93) (Fig. 5c). This suggests that the barometric pressure is less important than other factors influencing sea level variation since the sea level series with and without the barometric pressure effect was about the same. Therefore, the wind velocity is expected to be important for sea level variation in the VRSNP.

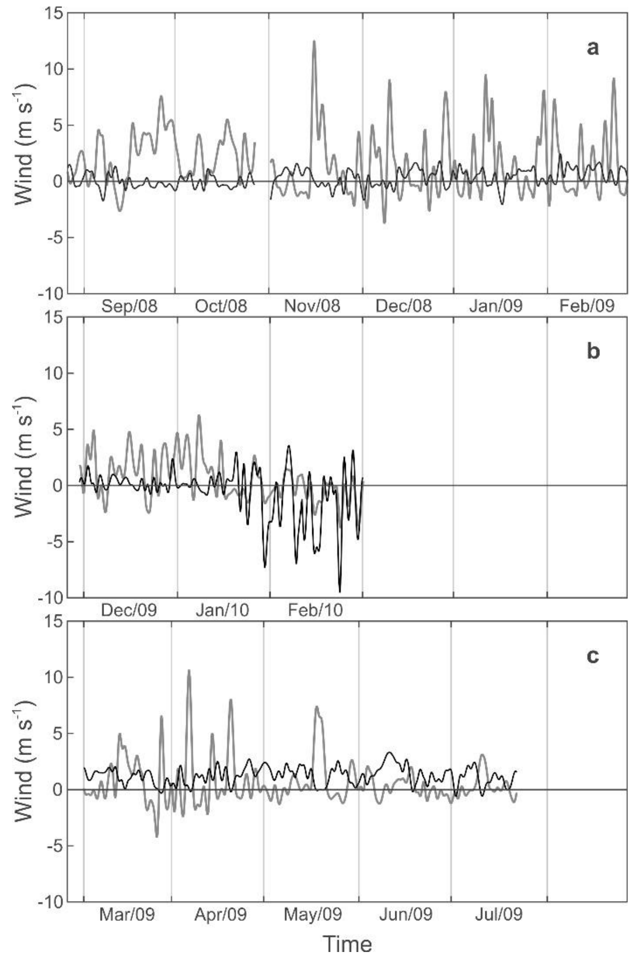

Figure 3. Wind speed and direction for a) August 2008 to February 2009, b) December 2009 to April 2010, and c) March to July 2009. The black line indicates the north-south component and the gray line indicate the east-west component. Positive values indicate a north or east direction.

The maximum sea level values without the effect of barometric pressure (Fig. 6) were observed during the last week of September and October 2008. This can be attributed to the northern wind (Fig. 6a). The strongest north-northwesterly winds were observed during September and October. The sea level without the effect of barometric pressure was correlated with the north-south and the east-west wind components. The correlation between the sea level and the north-south wind component was higher (>0.75) than the one obtained between the sea level and the east-west wind component (<0.65). This could be caused by the Coriolis

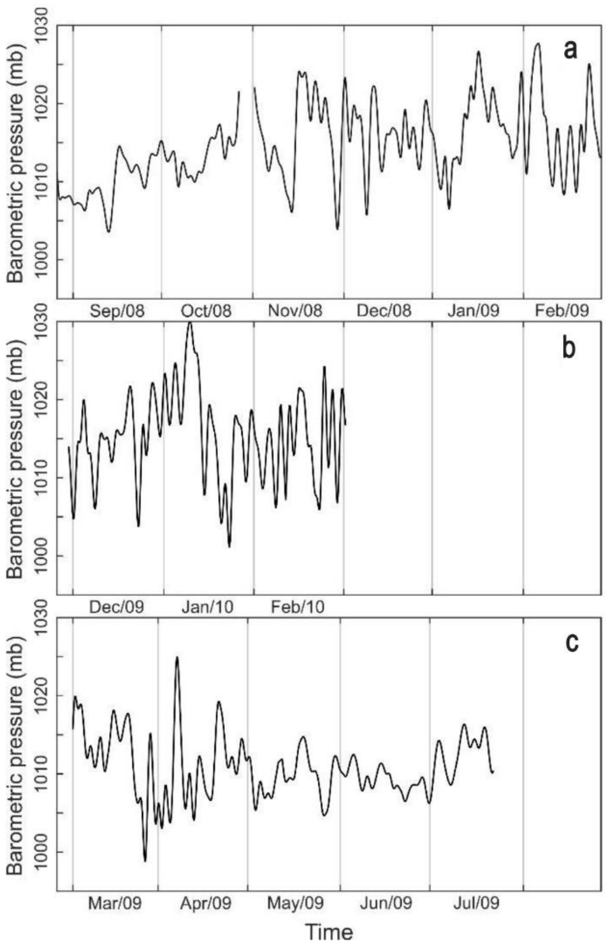

Figure 4. Barometric pressure for a) August 2008 to February 2009, b) December 2009 to April 2010, c) March to July 2009.

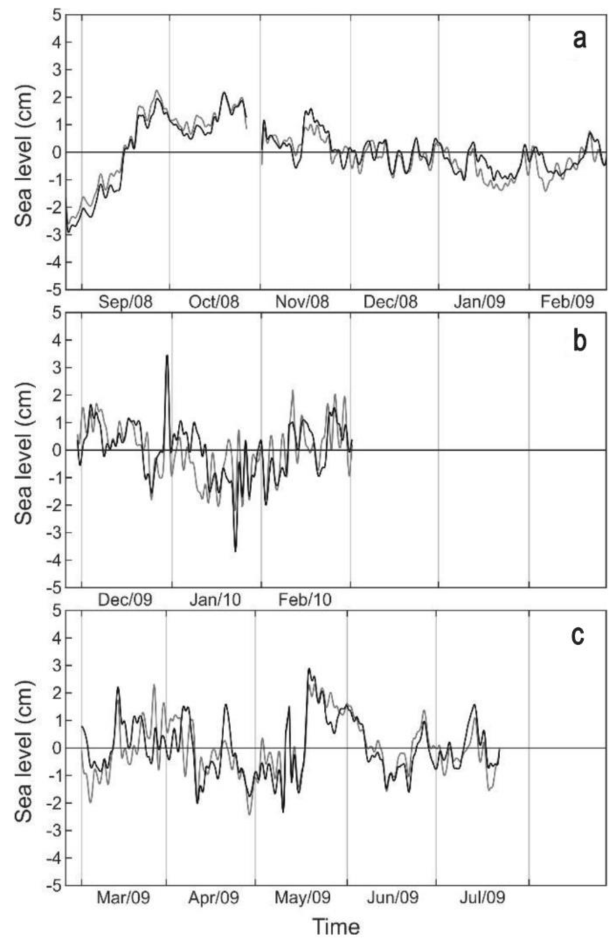

Figure 5. Sea level with (solid black line) and without (gray dotted line) the effect of the barometric pressure. a) August 2008 to February 2009 at Verde station, b) December 2009 to March 2010 at Topetillo station, c) March 2009 to July 2009 at Anegada station.

acceleration, which deflects the water towards the coast side under north-northwesterly wind conditions (Riveron-Enzastiga *et al.,* 2016), or perhaps by a combination of both, Coriolis acceleration and the deflection of the flow owing to reefs and islands (Salas-Monreal *et al.,* 2009). The sea level increased when the north-south wind speed component increased. However, there was a 6 h lag from both peaks (the maximum wind speed and the maximum sea level value; Fig. 6b). This pattern was observed for all the stations. The north wind component produced a sea level increase of more than 30%, while the southern wind component produced a sea level rise of more than 23%. However, the barometric pressure should not be neglected as it produced a sea level increase of up to 19%. This is the first time that the time lag between the maximum wind velocity and the maximum sea level is calculated for this area.

To determine the influence of the sea temperature, barometric pressure, and wind velocity on sea level, a principal component analysis was performed. The results show that the higher eigenvalue of the covariance matrix was 30.44% of the total variance (Table 2). The corresponding eigenvectors of the first mode, or principal component variable, indicate that the sea level had the highest correlation with the north-south wind component; the second mode corresponded to the east-west wind component, the third mode to the barometric pressure effect, and the fourth mode to the thermosteric effect (Table 3).

DISCUSSION

The results indicate that the wind velocity explains most of the variability of the sea level, followed by the barometric pressure and the thermosteric effect. The influence of the barometric pressure coincided with studies in the Gulf of Mexico by Ramírez & Candela-

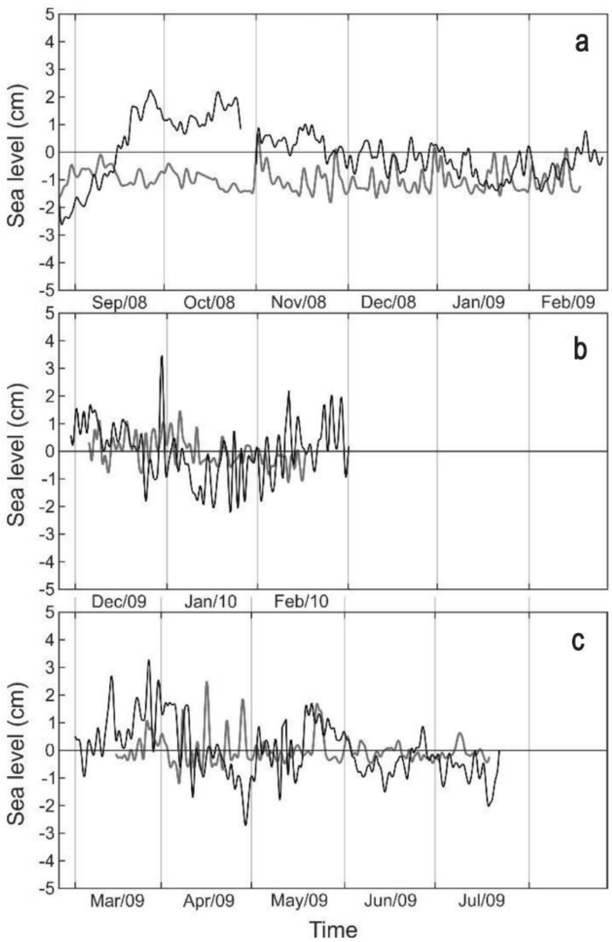

Figure 6. Sea level without the barometric pressure (soilid black line), and north-south wind component (gray dotted line). a) Verde station from August 2008 to March 2009, b) Topetillo station from December 2009 to April 2010, c) Anegada station from March 2008 to July 2009.

Pérez (2003) and in the Mediterranean Sea by Calafat *et al.* (2012), who reported a significant correlation of the inverted barometric effect with the sea level variability. In previous studies, the influence of the thermosteric changes on sea level variability were neglected (Miller & Douglas, 2007; Woodworth *et al.*, 2010; Sturges & Douglas, 2011). However, this differs from the present study in the western Gulf of Mexico (VRSNP), because the thermosteric effect produced more than 17% of the sea level variability. This was attributed to the fact that this is a tropical area with strong temperature and salinity gradients caused by seasonal changes from winter to summer and from the rainy to dry season (Avendaño-Alvarez *et al.*, 2017). The variability in sea level over long periods of time was correlated with the barometric pressure (Salas-Monreal & Valle-Levinson, 2008), however, during shorter periods of times, the wind velocities were the main mechanisms affecting the variability of the sea level.

The nearby rivers, such as La Antigua, Jamapa, and Papaloapan, have an influence on the temperature and salinity of the VRSNP (Salas-Monreal *et al.*, 2009) during the rainy season. For example, on the coastal area of Montevideo and La Paloma (Uruguay), the increased river flow from Río de la Plata River was well correlated with the increased sea level during the rainy season (Mazzetta & Gascue, 1995).

The results reported here are contrary to those reported by Ramírez & Candela-Pérez (2003), who stated that from 1985 to 1986 the barometric pressure was the main meteorological factor contributing to the sea level variability in the harbor of Veracruz. It was found here that the wind was the key forcing agent affecting the sea level changes on the VRSNP. Although the VRSNP has a maximum depth of 40 m, the maximum water speed was not limited by the action of bottom friction or bathymetric constrictions, such as reefs and islands, as in other shallow areas (Aboitiz *et al.*, 2008).

In Cadiz (Spain) the east-west winds (perpendicular to the coast) caused the water to flow against the coast, and the barometric pressure effect had a major influence on the sea level variability (Aboitiz *et al.*, 2008). Those result are different to the once found here. In this study, the parallel wind to the coast was the main forcing mechanism of the sea level variation, whereas the barometric pressure was the second mechanism affecting the sea level variability.

In some coastal areas, the wind effect on sea level pile up water in the opposite direction to the wind (Clancy, 1968). In this study, the observed wind velocity pattern suggested that the water pile up in the VRSNP occurred mainly during winter when the strongest north-south wind velocity events pile up the water against the coast.

Therefore, the wind pattern was the main forcing mechanism affecting the changes of sea level. The principal wind component influencing the sea level variation was the north-south component. The high-pressure systems determined the direction of the winds in the western Gulf of Mexico. During the fall and winter seasons, the water currents moved southward, while during the summer the intensification of the southeast winds move water northward (Caballero-Rosas, 1990; Zavala-Hidalgo *et al.*, 2003; Riveron-Enzastiga *et al.*, 2016).

The analysis of the sea level, the wind velocities, and the water temperature at a coral reef system in the western Gulf of Mexico, indicates that the sea level variations in the VRSNP had a significant seasonal va-

Table 2. Percentage of variance of the correlations between the main components and the variables.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Percentage of variance	30.44%	23.81%	19.13%	17.57%	9.02%

Table 3. Eigenvectors by mode or variable for each principal component (column). The components of each eigenvector indicate the correlations between the main components and each of the variables.

Variable	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Sea level	0.3946	-0.4262	0.4767	-0.6510	-0.1067
Temperature	-0.5029	-0.6571	-0.3836	-0.2257	0.3421
Barometric pressure	0.8714	0.0122	0.0250	0.1693	0.4593
E-W wind	-0.4558	-0.2281	0.7443	0.3989	0.1640
N-S wind	0.3821	-0.7247	-0.1664	0.4649	-0.2914

riation, with maximum values from autumn to winter and minimum values during the spring and summer, mainly caused by the wind velocity. The barometric pressure is the main forcing agent of the low frequency variability of the sea level in the VRSNP, followed by temperature. The northern wind component was the most important factor influencing the sea level variability at high frequency from September to March, while the southern wind component was the most important forcing from April to August.

The thermosteric effect on sea level variability was important in the VRSNP because of the high temperatures (tropical area) and the rainy season during the spring and summer. It was surprising to find that the barometric pressure effect was almost as important as the east-west wind component velocity on sea level variation. This was attributed to the fact that the reefs and islands protect the coastal area from the easterly winds. Furthermore, the presence of cold fronts on the western Gulf of Mexico enhances the inverse barometric effect on sea level variability.

It is important to document the wind effects on the sea level; since the global warming induces wind velocity changes that affect the coral reef ecosystems worldwide.

CONCLUSIONS

The results show that the wind velocity explains most of the correlation with the sea level variability, followed by the barometric pressure and the thermosteric effect. The wind pattern was the main forcing mechanism affecting changes in sea level. The principal wind component influencing the sea level variation was the north-south component. The sea level variations in the VRSNP had a significant seasonal variation caused by the wind velocity, with maximum values from autumn to winter and minimum values during the spring and summer. The barometric pressure is the main forcing agent of the low frequency variability, followed by the temperature. The northern wind component was the most important factor influencing the sea level variability from September to March, while the southern wind component was the most important forcing from April to August. The thermosteric effect on the sea level variability was important because of the high temperatures (tropical area) and the rainy season during the spring and summer seasons. It was surprising to find that the barometric pressure effect was almost as important as the east-west wind component velocity on sea level variation. This was attributed to the fact that the reefs and islands protect the coastal area from the easterly winds. Furthermore, the presence of cold fronts on the western Gulf of Mexico enhances the inverse barometric effect on sea level variability in the VRSNP.

ACKNOWLEDGEMENTS

CONACyT, México, sponsored R.R. Vera-Mendoza during his Ph.D. program. The authors would like to acknowledge the Instituto de Ciencias del Mar y Pesquerías, Universidad Veracruzana, and the Secretaría de Marina-Armada de México, for providing data, and of Jorge Castro for drafting the figures.

REFERENCES

Aboitiz, A., B. Tejedor, J.J. Muñoz & J.M. Abarca. 2008. Relation between daily variations in sea level and meteorological forcing in Sancti Petri Channel (SW Spain). Cienc. Mar., 34(4): 491-501.

Avendaño-Alvarez, O., D. Salas-Monreal, M. Marin-Hernandez, D.A. Salas-de-Leon & M.A. Monreal-Gomez. 2017. Annual hydrological variation and hypoxic zone in a tropical coral reef system. Reg. Stud. Mar. Sci., 9: 145-155.

Birkeland, C. 1997. Life and death of coral reefs. Chapman & Hall, New York, 539 pp.

Caballero-Rosas, A. 1990. Modelación hidrodinámica numérica de la circulación por viento en la zona costera del Puerto de Veracruz y sus proximidades. Master's Thesis, Universidad Veracruzana, Veracruz, 70 pp.

Calafat, F.M., D.P. Chambers & M.N. Tsimplis. 2012. Mechanisms of decadal sea level variability in the eastern north Atlantic and the Mediterranean Sea. J. Geophys. Res., 117(C9), C09022, doi: 10.1029/2012J C008285.

Carricart-Ganivet, J.P. 2004. Sea surface temperature and the growth of the west Atlantic reef-building coral *Montastrea annularis*. J. Exp. Mar. Biol. Ecol., 302: 249-260.

Clancy, E.P. 1968. The tides. Pulse of the Earth. Doublenday & Co., New York, 228 pp.

Diario Oficial de la Federación (DOF). 2012. Diario Oficial de la Federación 29 de noviembre. México D.F., 29 pp.

Gill, A.E. 1982. Atmosphere ocean dynamics. Academic Press, New York, 642 pp.

Glynn, P.W. 1997. Bioerosion and coral reefs growth: a dynamic balance. In: C. Birkeland (ed.). Life and death of coral reefs. Chapman & Hall, New York, pp. 68-95.

Granados-Barba, A., L.G. Abarca-Arenas & J.M. Vargas-Hernández. 2007. Investigaciones científicas en el sistema arrecifal veracruzano. Universidad Autónoma de Campeche, Campeche, 304 pp.

Gutiérrez-de-Velasco, G. & C.D. Winant. 1996. Seasonal patterns of wind stress and wind stress curl over the Gulf of Mexico. J. Geophys. Res., 101(C8), 18127-18140, doi: 10.1029/96JC01442.

Gutiérrez, D., C. García-Sáez, M. Lara & C. Padilla. 1993. Comparación de arrecifes coralinos: Veracruz y Quintana Roo. In: S.I. Salazar-Vallejo & N.E. González (eds.). Biodiversidad marina y costera de México. CONABIO-CIQRO, México, D.F., pp. 785-806.

Hubbard, D. 1997. Reefs as dynamics systems. In: C. Birkeland (ed.). Life and death of coral reefs. Chapman & Hall, New York, pp. 43-67.

Jiménez-Hernández, M.A., A. Granados-Barba & L. Ortiz-Lozano. 2007. Análisis de la información científica en el sistema arrecifal veracruzano. In: A. Granados-Barba, L.G. Abarca-Arenas & J.M. Vargas-Hernández (eds.). Investigaciones Científicas en el Sistema Arrecifal Veracruzano, Universidad Autónoma de Campeche, Campeche, pp. 1-16.

Marc, L.F. 2001. Analysis and representation of regional sea-level variability from altimetry and atmospheric-oceanic data. Geophys. J. Int., 145(1): 1-18, doi: 10.1046/j.1365-246x.2001. 00284.x.

Maul, G.A. & K. Hanson. 1988. Sea level variability in the Intra American Sea with concentration on Key West as a regional example. In: G.A. Maul (ed.). Implications of climatic changes in the wider Caribbean region. UNEP (OCA)/CAR/W.G.1/INF, 3: 89-102.

Mazzetta, G.V. & F.J. Gascue. 1995. Estudio comparativo del comportamiento de la salinidad, la temperatura y el nivel medio del mar en las costas de Montevideo y La Paloma. Atlántica Río Grande, 17: 5-16.

Miller, L. & B.C. Douglas. 2007. Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise. Geophys. Res. Let., 34(16): L16602, doi: 10.1029/2007GL030862.

Ramírez, O.S. & J. Candela-Pérez. 2003. Respuesta del nivel del mar al forzamiento atmosférico en las costas del Golfo de México. Ser. Oceanol., 1: 76-84.

Riverón-Enzástiga, M.L. N. Carbajal & D. Salas-Monreal. 2016. Tropical coral reef system hydrodynamics in the western Gulf of Mexico. Sci. Mar., 80(2). doi: http://dx.doi.org/10.3989/scimar.04259.15B.

Salas-de-León, D.A., M.A. Monreal-Gómez, D. Salas-Monreal, M.L. Riveron-Enzastiga & N.L. Sánchez-Santillán. 2006. Inter annual sea level variability in the southern Gulf of Mexico. Geophys. Res. Let., 33, L08610, doi: 10.1029/2006GL025832.

Salas-Monreal, D. & A. Valle-Levinson. 2008. Sea-level slopes and volume fluxes produced by atmospheric forcing in estuaries: Chesapeake Bay. J. Coast. Res., 24(2A): 208-217.

Salas-Monreal, D., D.A. Salas-de-León, M.A. Monreal-Gómez & M.L. Riverón-Enzástiga. 2009. Current rectification in a tropical coral reef system. Coral Reef, 28: 871, doi: 10.1007/s00338-009-0521-9.

Salas-Pérez, J.J., D. Salas-Monreal, V.A. Arenas-Fuentes, D.A. Salas-de-León & M.L. Riveron-Enzastiga. 2008. Tidal characteristics in a coral reef system from the western Gulf of Mexico. Cienc. Mar., 34(4): 467-478.

Sturges, W. & B.C. Douglas. 2011. Wind effects on estimates of sea level rise. J. Gephys. Res., 116(C06), doi: 10.1029/2010JC006492.

Tamayo, J.L. 1999. Geografía moderna de México. Trillas, México, D.F., 400 pp.

Tsimplis, M.N. 1995. The response of sea level to atmospheric forcing in the Mediterranean sea. J. Coast. Res., 11(4): 1309-1321.

Vance, P.V. 1989. Efectos ecológicos de incrementos en el nivel del mar y temperaturas superficiales oceánicas en manglares, arrecifes, praderas marinas y playas arenosas de Puerto Rico: evaluación preliminar. Sci. Cienc., 16: 27-39.

Woodworth, P.L., N. Pouvreau & G. Wöppelmann. 2010. The gyre scale circulation of the north Atlantic and sea level at Brest. Ocean Sci., 6: 185-190, doi: 10.5194/os-6-185-2010.

Zavala-Hidalgo, J., S.L. Morey & J.J. O´Brien. 2003. Seasonal circulation on the western shelf of the Gulf of Mexico using a High resolution numerical model. J. Geophys. Res., 108(C12), 1-19, doi: 10.1029/2003JC 001879.

Received: 13 June 2016; Accepted: 20 April 2017