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Research Article

Atmospheric low- and high-pressure systems induce fluctuations in oceanographic variables of the southwestern Gulf of Mexico

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ABSTRACT. Low- and high-pressure systems traveling from the northeastern Pacific to the eastern Gulf of Mexico induce short-term fluctuations in ocean currents, water column temperature, sea level, and biovolume. Meteorological data from the National Oceanic and Atmospheric Administration (NOAA), North American Regional Reanalysis-National and the National Centers for Environmental Prediction (NARR-NCEP) for the western Gulf of Mexico in 2008, specifically from November 10th to 20th, were used to describe these fluctuations. Additionally, data from four Acoustic Doppler Current Profilers (ADCPs) deployed at four reefs in the northern part of the "Parque Nacional Sistema Arrecifal Veracruzano" (PNSAV) were analyzed. Results showed two main wind patterns: a southern one, locally named "Surada", associated with a low-pressure system over the Mexican mainland, which increases the air temperature of the western Gulf of Mexico to about 25°C; and "Norte" winds associated of the passage of high pressure over the study area, lowering the air temperature to 20°C. Both Surada and Norte alter the seasonal wind-driven circulation, which typically flows south in the fall and winter. However, these itinerant low- and high-pressure systems can reverse the seasonal wind-driven circulation for a few days. During Surada, the wind-driven circulation flows north, while Norte flows south with a residual almost anticyclonic current developing. These changes contribute to oceanographic variability in the PNSAV. These changes in marine circulation lead to variations in oceanographic parameters in the northern PNSAV, with important ecological and social consequences.

Keywords: Surada wind event; Norte wind event; anticyclonic circulation; biovolume; PNSAV; wind-driven current; Gulf of Mexico

INTRODUCTION

Itinerant low- and high-pressure systems are atmospheric forcing features that pass through the northern and western Gulf of Mexico (GM) annually from fall to spring. These systems generate two distinct wind patterns: one blowing from the north, locally named "Norte," and the other blowing from the south, locally named "Surada" (Salas-Pérez & Granados-Barba 2008, Vera-Mendoza et al. 2017). The origin of high-pressure systems is well known (Magaña 1986, Schultz et al. 1998, Vazquez-Aguirre 1999). Still, the presence of low-pressure systems during the boreal fall-spring period, which replaces high-pressure systems after they pass over the GM, is poorly understood. High-pressure systems frequently exhibit a positive signal from the Pacific-North American (PNA) high-pressure system over the confluence of the subtropical jet stream over the GM and the southeastern USA.

The advection of the subtropical jet stream causes the displacement of itinerant high-pressure systems. These systems are representative of the PNA pattern, leading to changes from high to low pressure in the GM (Magaña 1986, Schultz et al. 1998, Vazquez-Aguirre

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1999, Schultz 2005). When high-pressure systems travel through the eastern GM as high atmospheric pressure anticyclonic systems, they generate winds that blow from the north/northwest towards the south/southeast around the northern GM. The air temperature can drop as low as 20°C with rainfall in some areas (Salas-Pérez & Granados-Barba 2008). The sea surface circulation over the continental shelves of Tampico and Veracruz flows south during fall and winter (Zavala-Hidalgo et al. 2003, Dubranna et al. 2011, Salas-Pérez et al. 2012). However, these low- and high-pressure systems moving east over the GM can reverse the seasonal sea surface circulation for short periods. As a result of the high-pressure system passing over the northern GM and its prevailing winds, a couple of low-pressure systems develop: the first replacing the high former one on the west and the latter over the southern GM, causing a wind pattern from south/southeast to north/northwest direction.

The surface circulation changes in the same direction, enhancing a deep-water intrusion resulting from the intensification of the Campeche Gyre (Guerrero et al. 2020). This leads to a decrease in water column temperature and an increase in biovolume and sea level (Avendaño et al. 2017). During the "Surada" wind event, Ekman transport to the open ocean can occur, potentially causing an upwelling event. However, the internal platform where the instruments were anchored is shallow, less than 20 m deep.

When a high-pressure system is over the northern GM and a southward circulation is observed (Zavala-Hidalgo et al. 2003, Dubranna et al. 2011, Salas-Pérez et al. 2012, Salas-Monreal et al. 2018); low temperatures develop in the reef corridor of the southwestern GM (Zavala-Hidalgo et al. 2006, Salas-Pérez & Arenas-Fuentes 2011), leading to an increase in biovolume (Salas-Monreal et al. 2009) and sea level height due to wind effects (Arenas-Fuentes & Salas-Pérez 2005, Salas-Pérez et al. 2012). Seasonal winds, "Surada" and "Norte," are classified by wind speed as weak (<5 m s^{-1}), moderate (6-11 m s^{-1}), and strong (>12 m s^{-1}) (Pereyra et al. 1992). These winds are the main triggers of variability in the southwestern GM, inducing fluctuations in oceanographic parameters within the reef corridor. Four Acoustic Doppler Current Profilers (ADCPs) were moored along the northern area of the Veracruz Reef System (VRS) to understand the interactions between wind patterns, surface circulation, and hydrographic variables (temperature, biovolume, and sea surface height). Atmospheric (winds) and oceanographic (currents, temperature, biovolume, and sea surface height) data were analyzed for a short period from November 10 to 20, 2008; during which a shift from a low to a high-pressure system occurred.

The magnitude of wind speed, sea temperature, ocean circulation, sea level, and biovolume are shown during a shift from a low- to a high-pressure system. This information helps investigate coral ecology within the VRS, especially since this is the main spawning period for most of the corals that inhabit the VRS. Our findings show that itinerant atmospheric pressure systems passing over the GM and causing changes in the VRS are relevant to the ecosystem, particularly because of their timing coincidence with the coral and fish spawning season in the VRS. Economic activities such as tourism, shipping, and infrastructure on the mainland may also be affected (Walker et al. 1982, Tunnell Jr. 1992, Salas-Pérez & Jordán-Garza 2018).

MATERIALS AND METHODS

The VRS or "Parque Nacional Sistema Arrecifal Veracruzano" (PNSAV) is a marine protected area (Fig. 1) with at least 50 coral reefs (Liaño-Carrera et al. 2019). It is in the central-south portion of the western GM, between the geographical coordinates of 19º02'24"-19º16'00"N and 95º46'19"-96º12'01"W with an area spans 650 km^2 (Ortiz-Lozano et al. 2013). The protected natural area includes 50 coral reefs divided into two groups: the first is located to the north, in front of the cities of Veracruz and Boca del Río, and the second, in front of the town of Antón Lizardo and the municipality of Alvarado (Ortiz-Lozano et al. 2013). These reef systems are separated by the discharge of the Jamapa River, which is a sediment reservoir area (Salas-Pérez & Granados-Barba 2008, Salas-Monreal et al. 2009, 2018, Salas-Pérez et al. 2012, Avendaño et al. 2017). The bathymetry of the national park has maximum depths of 50 m (Riveron-Enzastiga et al. 2016), with shallow reef lagoons of approximately 2 m. The length of the coral reefs varies from 0.3 to 3.2 km (Salas-Pérez & Granados-Barba 2008, Salas-Pérez et al. 2012).

The sites where the ADCPs were moored are located on four platform reefs in the northern part of the VRS: Arrecife Blanquilla, with geographical coordinates 19°13.6'N, 96°05.8'W, 13 km away from the coast (Fig.1). The Blanquilla reef is the northernmost emerging coral reef in the entire western GM (Ortiz-Lozano et al. 2013). Anegada de Adentro Reef is located about 7.5 km from the coast, with geographical coordinates 19°13′0.7″N, 96°03′25.9″W. It has a reef surface area of 1.67 km^2 (Liaño-Carrera et al. 2019). Isla Verde is located 5.9 km away from the Port of

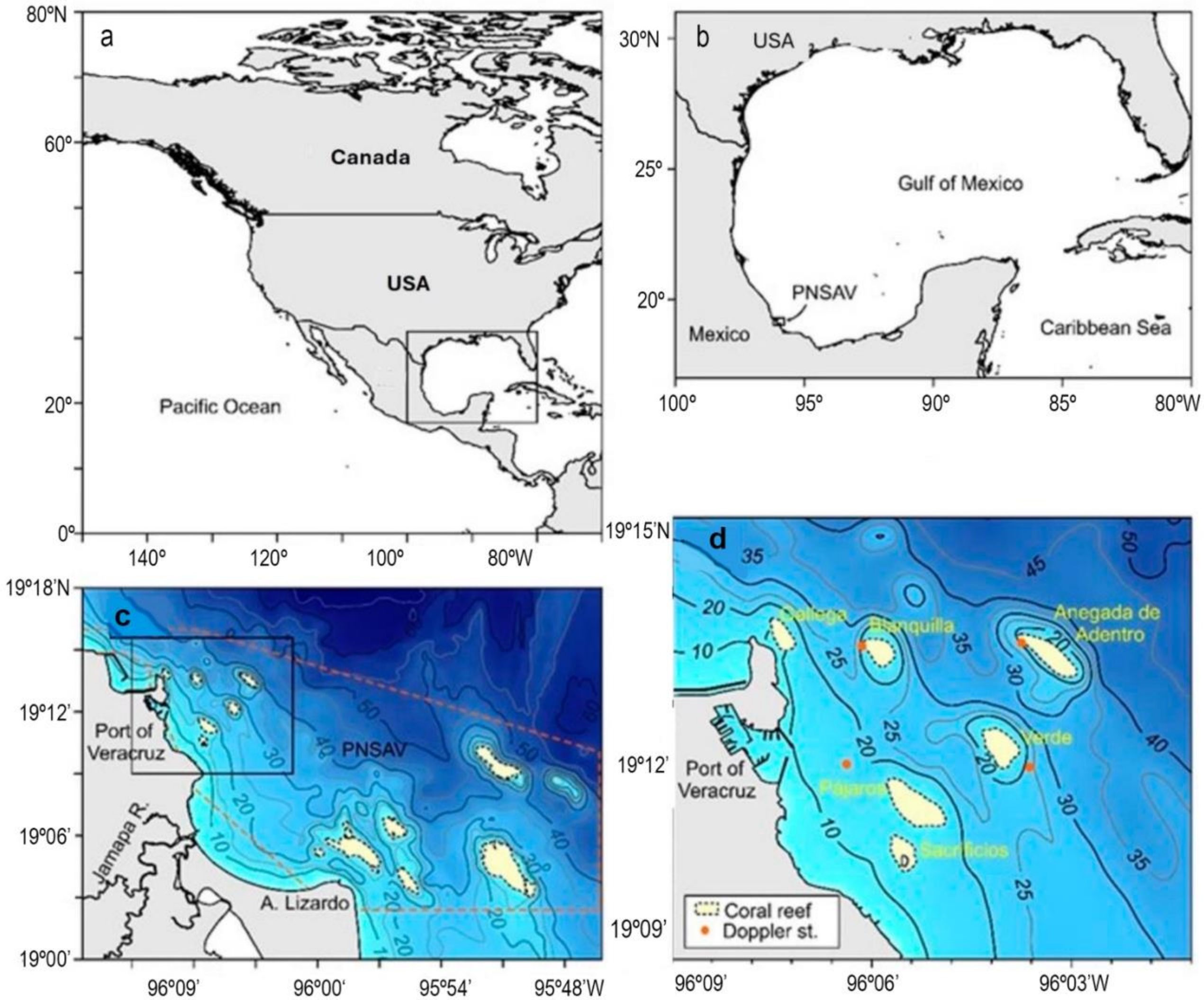

Figure 1. Study area. a) Map shows the largest study area to show the distribution of the itinerant low and high atmospheric pressure systems as a Rossby wave pattern. b) The area of the Gulf of Mexico, particularly its western area, is influenced by the winds generated by the passing of itinerant low and high atmospheric pressure systems. c) The Parque Nacional Sistema Arrecifal Veracruzano (PNSAV) is presented in their northern and southern areas, separated by the Jamapa River. d) The northern area of the PNSAV is shown in a chart to illustrate the locations where the ADCPs were deployed. The dark lines represent the depth, the coral reefs are drawn in yellow, and the discontinued line is the area of the PNSAV.

Veracruz at 19°11'50"N, 96°04'06"W. It has a maximum length of 1 km and a maximum width of 700 m, with a coral area of 1.45 km^2, and presents an emerged portion (island) toward the south of the reef, with 300 m long and 170 m in its widest part, with a substrate constituted by white sand and rubble (Liaño-Carrera et al. 2019). Its geographical coordinates are 19°00.5'N, 096°05.9'W, with a coral area of 0.62 km^2.

The four ADCP profilers moored at the VRS began recording on July 22, 2008, and ended on October 2, 2009. During that time, a traveling pressure system representative of the main goal of this work passed through the study area. Two Nortek Aquadop 400 kHz ADCPs were moored on the leeward side of Blanquilla and Anegada Adentro reefs, and another two 1 MHz Nortek Aquadop ADCPs on the southern side of Isla Verde and the northern side of Isla de Sacrificios. The profilers were anchored at approximately 20 m depth, with a vertical distribution of 2 m data logging every 15 min, a vertical whitening distance of 0.75 m from the surface, and 1 m to the bottom.

The ADCPs were used to measure the integrated vertical profiles of the horizontal marine current (u and v components), sea level, water column temperature, and absolute acoustic intensity related to plankton and zooplankton biovolumes. The size class (5-40 mm equivalent spherical radius) dominated the biovolume throughout most of the water column and is associated with phytoplankton and zooplankton sizes measuring with a bongo net (Salas-Pérez et al. 2012). The maximum depth of the reefs located in the northern area of the VRS is 20 m.

Daily wind vectors, sea-level atmospheric pressure, and air temperature were extracted from the National Oceanic and Atmospheric Administration (NOAA) by North American Regional Reanalysis-National Centers for Environmental Prediction (NARR-NCEP). The data analyzed in this study covers the period from November 10 to 20, 2008 (Salas-Pérez et al. 2012), a period in which itinerant low to high-pressure systems are usually observed in the study area. The oceanographic parameters were plotted after using a moving average filter of 24 h to remove the contribution of the diurnal tide signal (Salas-Pérez et al. 2008). The biovolume was not filtered due to the attenuation of the signal. Finally, a linear trend was computed to observe the main fluctuation pattern during the Surada and Norte wind events.

RESULTS

The NCEP-NARR reanalysis generated maps of daily atmospheric sea level pressure with air temperature and other maps of wind velocity.

From November 10th to 14th, 2008, a low-pressure atmospheric system moved from central North America to the western GM (Fig. 2). Air temperature varied between 24 to 27°C in the western GM. In Figure 2a (November 10th), the low-pressure atmospheric system had the lowest value at its center (<1,010 mb), while a high-pressure system was present in Central America, with a value at its center of more than 1,012 mb. A high-pressure atmospheric system was observed in the North Pacific with a value at its center of 1,024 mb. The distribution of the low and high atmospheric pressure systems resembles a Rossby wave pattern moving to the east. In Figure 2b (November 11th), the low atmospheric pressure system moves to the east, and the high atmospheric pressure system previously located in Central America (Fig. 2a) is now situated slightly north of the central region of Mexico.

Moreover, the North Pacific high-pressure atmospheric system moves its area of influence to the east. Figure 2c (November 12th) shows the North Pacific high-pressure atmospheric system moving eastward, influencing northern Mexico and the southern USA, causing the low-pressure atmospheric system to shift to the western region of the GM. Figures 2d (November 13th) and 2e (November 14th) display a similar distribution pattern of the itinerant low to high atmospheric pressure systems, with the low-pressure atmospheric system in the western area of the GM and the high-atmospheric pressure system in the northern area of Mexico and the southern area of USA. An interesting feature observed in the wind fields during the presence of a low-atmospheric pressure system centered in the central area of the USA and the western region of the GM (Figs. 3a,e) is the northward direction of the wind in the western area of the GM, generating a "Surada" wind event. This event affected the oceanic circulation of the VRS, resulting in a reversing flow, as shown in Figure 4, with velocities fluctuating from 25 cm s^{-1} to about 100 cm s^{-1}.

Conversely, from November 15th to 20th, 2008, Mexico and the southern USA were influenced by a high atmospheric pressure system (Fig. 5). In Figure 5a (November 15th), the high-pressure system centered in the Mexican North Pacific, the southern USA, and the eastern area of Florida while a low-pressure system was positioned off the Pacific coast of Honduras. The next day (Fig. 5b), the distribution of low- and high-pressure systems resembled a Rossby wave pattern, with a high atmospheric pressure system in the central area (Mexico and the southern USA) and the low atmospheric pressure systems in the western Pacific and eastern GM. In Figure 5c (November 17th), the high-pressure system remained in the northern GM, and the low-pressure system moved to the Atlantic coasts of Colombia and Venezuela (South America). In the next few days, a similar Rossby wave is shown (Figs. 5d-f). With the Rossby wave moving from west to east, the air temperature of the GM drops to about 20°C in the northern and western areas. With this high-pressure system from November 15th to 20th, 2008, the wind blows from north to south in the GM, generating a "Norte" (Fig. 6) opposite to the previous event (Fig. 2). These wind patterns caused a reversal of the marine current in the northern VRS, shifting from north to south with velocities ranging from 15 to 120 cm s^{-1} (Fig. 7). In general, the direction of the wind-driven currents is parallel to the coast and the bathymetry in both "Surada" and "Norte" wind events.

During the entire period from November 10th to 20th, 2008, the mean wind-driven coastal current exhibited an anticyclonic pattern for the first time. This shift

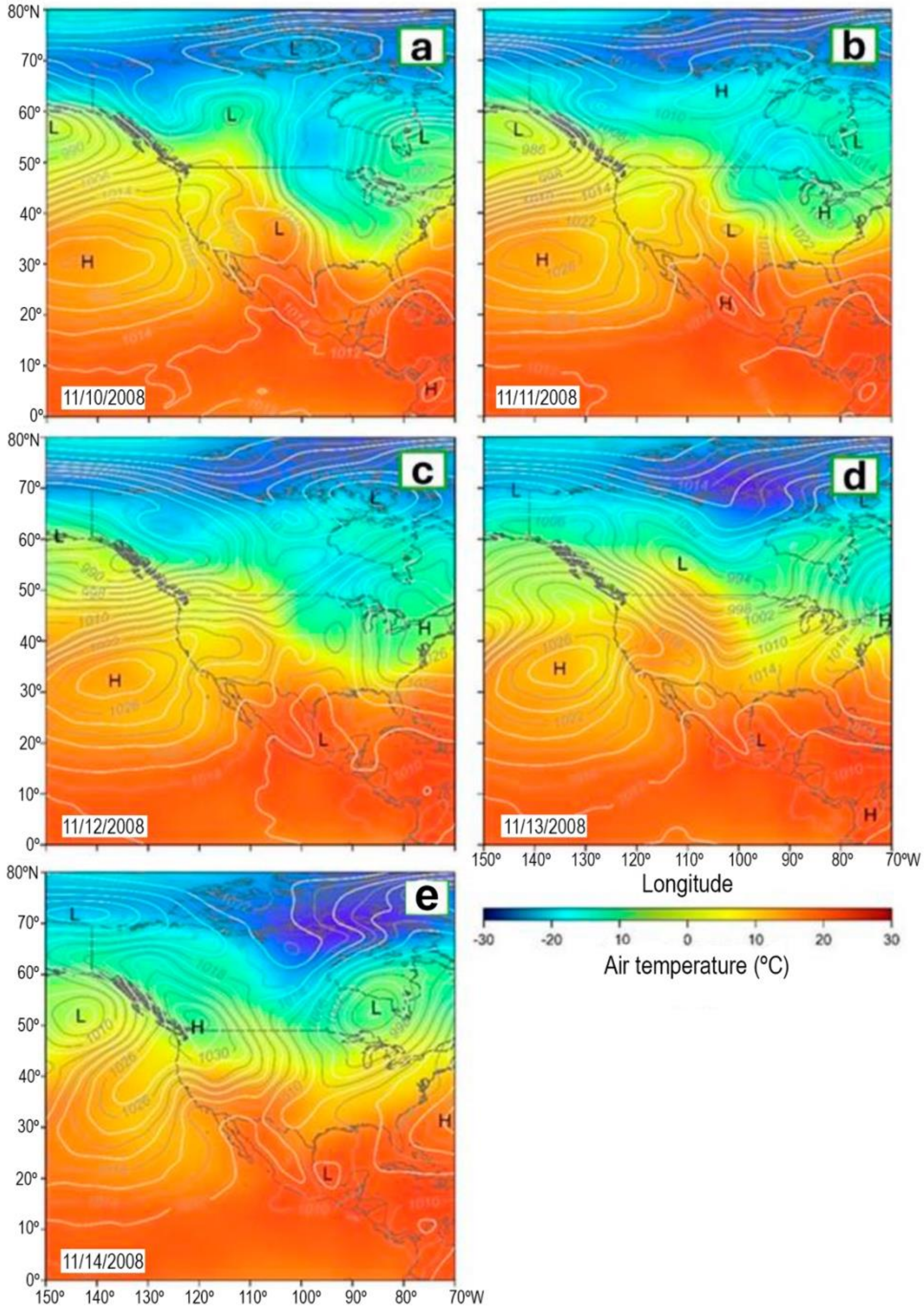

Figure 2. Distribution of the itinerant low (L) and high (H) atmospheric pressure systems in the Pacific, the continental area of North and Central America, and the Gulf of Mexico. From November 10th to November 14th, 2008. a) Date: 11/10/2008. b) Date: 11/11/2008. c) Date: 11/12/2008. d) Date: 11/13/2008. e) Date: 11/14/2008.

occurred due to a transition from a "Surada" to a "Norte" wind event in the northern area of the VRS, with mean velocities exceeding 20 cm s^{-1} (Fig. 8).

Figures 9 and 10 show the fluctuation in oceanographic parameters (biovolume, temperature, and sea level) over the specified periods. Figure 9 shows that during the "Surada" wind event, biovolume varied from a minimum of 60 to a maximum of 106. In contrast, the biovolume in the Anegada de Adentro Reef decreased from 106 to 75 between November 10th and 14th, 2008.

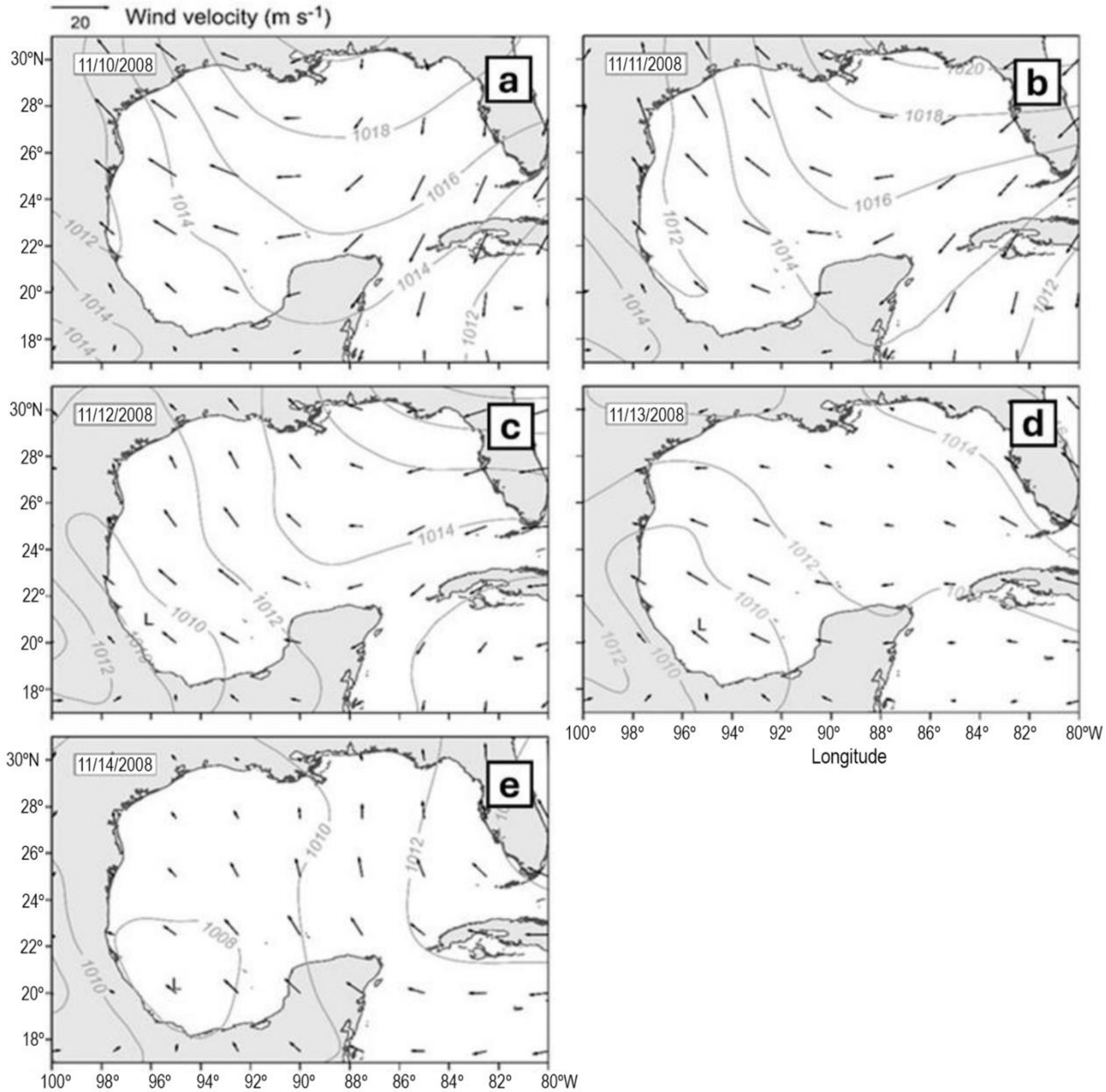

Figure 3. The wind pattern of a Surada event was generated in the Gulf of Mexico by a low atmospheric pressure system, mainly in its western area. a) Date: 11/10/2008. b) Date: 11/11/2008. c) Date: 11/12/2008. d) Date: 11/13/2008. e) Date: 11/14/2008.

Water temperature experienced slight fluctuations ranging from 26.6 to 27°C, but overall decreased over the entire period. Sea level varied from -0.4 m to 0.28 m, reaching its minimum value during the "Surada" wind event. The results did not indicate an upwelling event caused by Ekman transport, with an across flow from the coast to open sea during the period between November 10th and 14th, 2008.

At Isla Verde reef, biovolume decreased from 99 to approximately 77 during the "Surada" wind event, and water temperature followed a similar trend to that of Anegada de Adentro Reef, with a decrease of about 0.3°C during the "Surada" event. The sea level decreased -by approximately 0.1 m over the entire period.

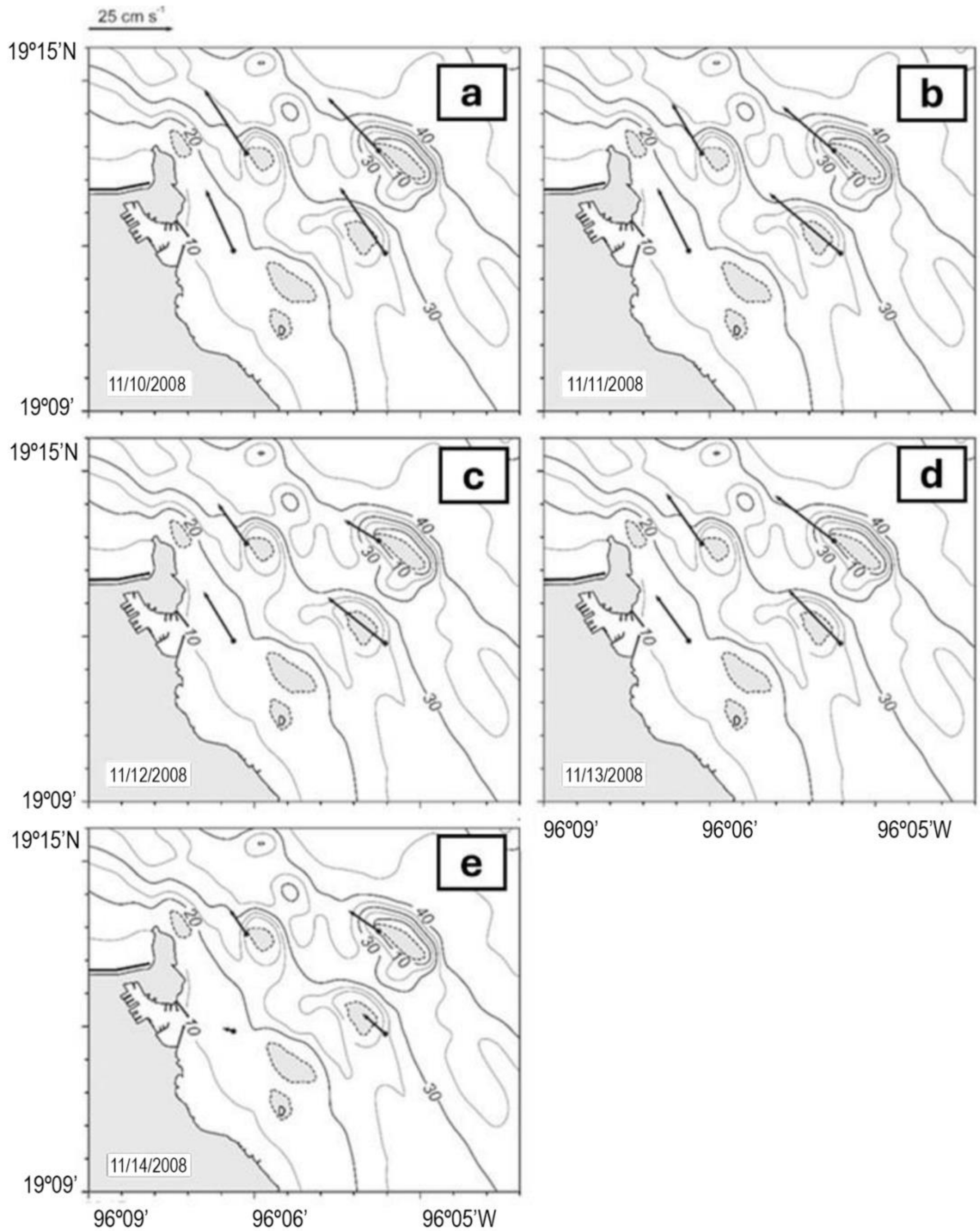

Figure 4. Wind-driven coastal marine current (generated by a low atmospheric pressure system in the continental area of North America) flows to the north due to the generation of a meteorological Surada event. a) Date: 11/10/2008. b) Date: 11/11/2008. c) Date: 11/12/2008. d) Date: 11/13/2008. e) Date: 11/14/2008.

At Sacrificios Reef, biovolume fluctuated from 90 to 64 throughout the period, and water temperature varied between 27 and 25°C. There was a notable reduction in water temperature of about 2°C. Sea level fluctuated between -0.38 to 0.3 m, with a tendency to decrease by approximately 0.08 m d^{-1} during the "Surada" wind event.

For Blanquilla Reef, biovolume ranged from 88 to 60, with large fluctuations observed between November 12^{th} and 14^{th}, 2008. Biovolume showed a positive trend

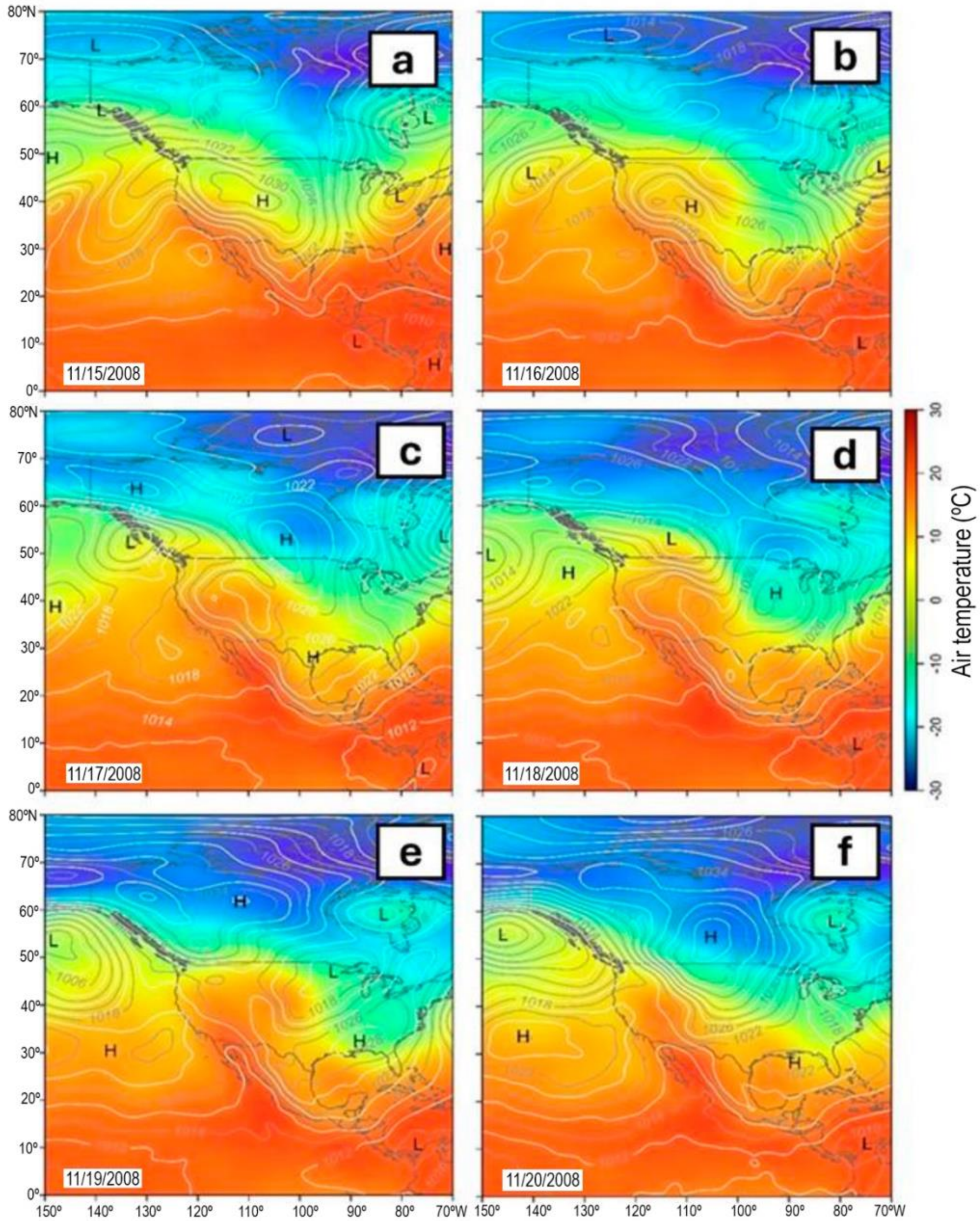

Figure 5. Distribution of the itinerant low (L) and high (H) atmospheric pressure systems in the Pacific, the continental area of North and Central America, and the Gulf of Mexico. From November 15th to 20th 2008. a) Date: 11/15/2008. b) Date: 11/16/2008. c) Date: 11/17/2008. d) Date: 11/18/2008. e) Date: 11/19/2008. f) Date: 11/20/2008.

during the "Surada" wind event. Water temperature and the sea level exhibited similar fluctuation patterns and trends as observed at Sacrificios Reef.

Figure 10 shows the fluctuation of the oceanographic parameters during the Norte wind event. Biovolume values ranged from 61 to 148 across all reefs. The tendency of the biovolume during the Norte wind event in the four reefs was negative, with an average decrease of about 67 units. Water temperature across all reefs fluctuated between 27 and 24°C, showing higher variability than the Surada wind event. On average, water temperature decreased during the Norte wind event by about 3°C. Sea level at the four reefs fluctuated from -0.6 to 0.3 m, with an overall positive trend and an increase of 0.3 m.

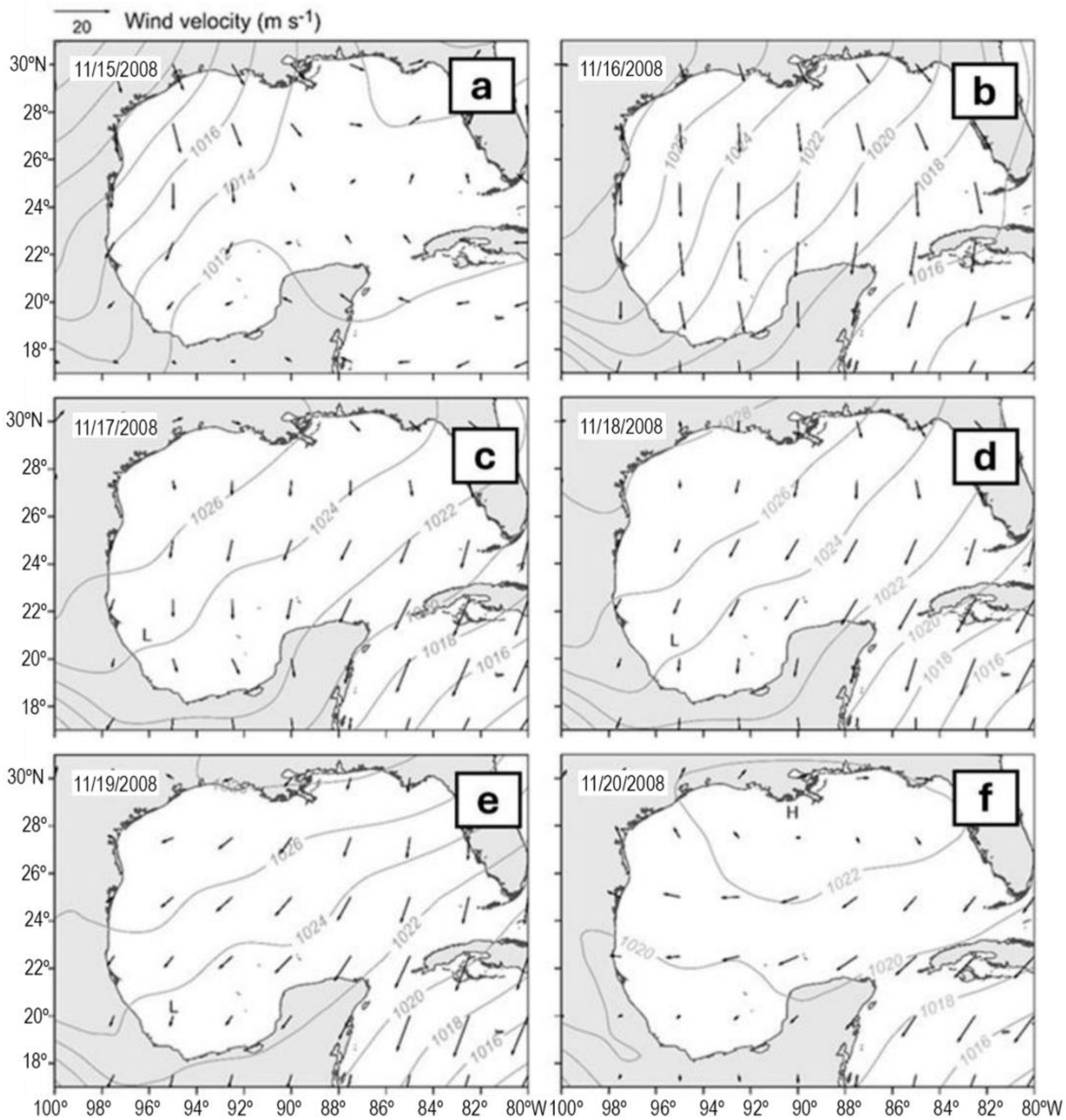

Figure 6. The wind pattern of a Norte event in the Gulf of Mexico, mainly in its northern area, by the itinerant of high atmospheric pressure systems. a) Date: 11/15/2008. b) Date: 11/16/2008. c) Date: 11/17/2008. d) Date: 11/18/2008. e) Date: 11/19/2008. f) Date: 11/20/2008.

DISCUSSION

The dataset from NARR-NCEP, combined with *in situ* measurements of oceanographic parameters, revealed the occurrence of "Surada" (November 10-14, 2008) and "Norte" (November 15-20, 2008) wind events over 10 days. These events influenced fluctuations in oceanographic parameters such as coastal currents, biovolume, water temperature, and sea level in the PNSAV (Mesinger et al. 2006, Salas-Pérez et al. 2012, Ortiz-Lozano et al. 2013).

The "Surada" and "Norte" wind events are generated due to itinerant atmospheric low- and high-pressure systems traveling from the Pacific Ocean to the eastern GM as a Rossby wave (Magaña 1986, Schultz et al. 1998, Vazquez-Aguirre 1999, Schultz 2005). This phenomenon occurs when a strong relationship exists between a persistent, narrow, high-amplitude 200-hPa ridge of the PNA over the western USA and a 200-hPa confluence jet stream over the GM (Schultz et al. 1998). The maintenance and tightness of the crest ensure that the uppermost level anticyclonic

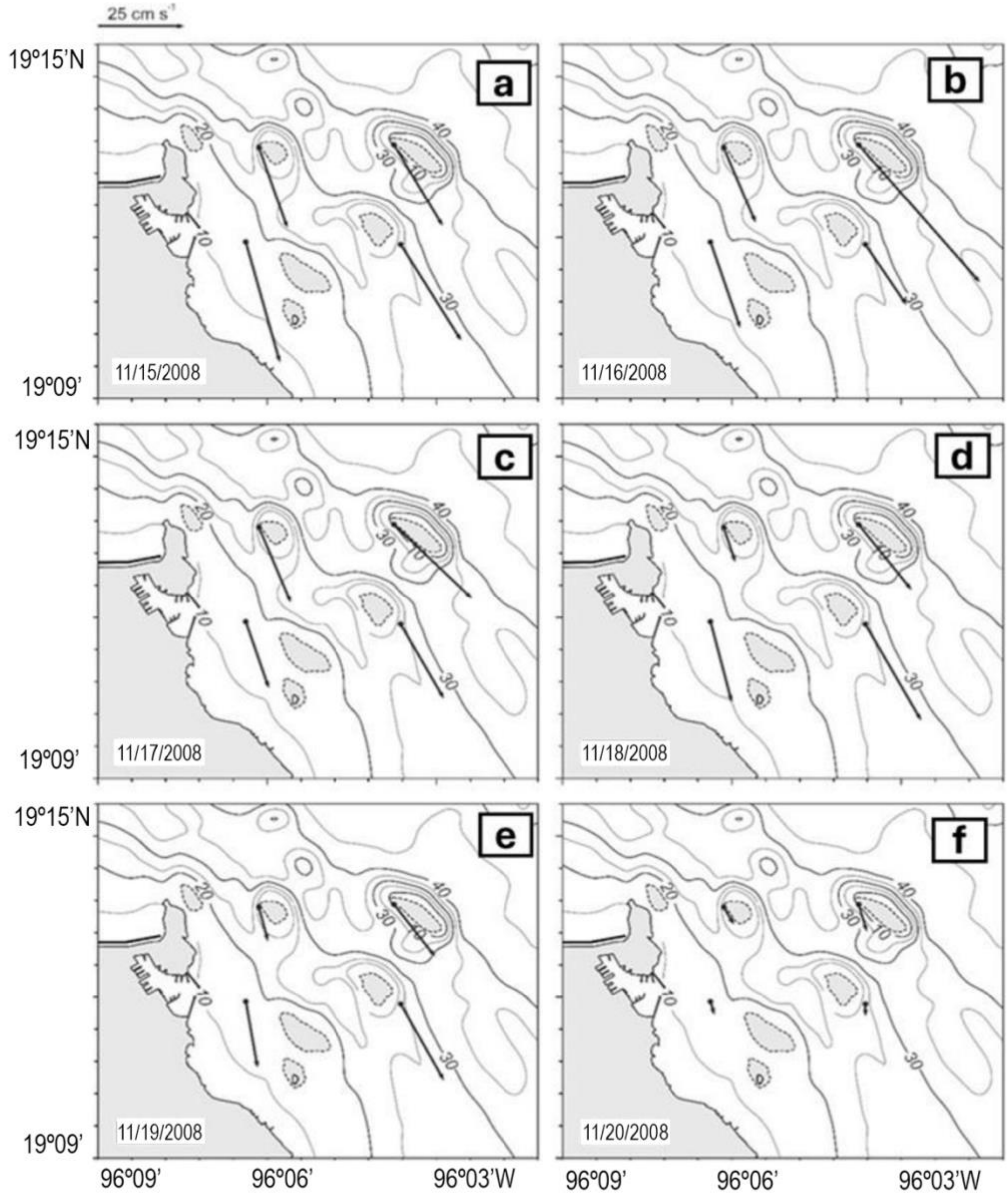

Figure 7. Wind-driven coastal marine current (generated by a high atmospheric pressure system in the continental area of North America flows to the south due to the generation of a meteorological Norte event. a) Date: 11/15/2008. b) Date: 11/16/2008. c) Date: 11/17/2008. d) Date: 11/18/2008. e) Date: 11/19/2008. f) Date: 11/20/2008.

vorticity advection (associated with lower-tropospheric height growths) on the eastern border of the ridge favors the equatorward movement of the lower-tropospheric anticyclone. Poleward of the confluence jet-entrance region, upper-level convergence is associated with strong subsidence over the low-level anticyclone. This results in strong low-level cold high atmospheric pressure systems and winds at the jet entrance region, increasing the cold advection into low latitudes (Schultz et al. 1998). The relationship between these meteorological variables becomes evident during a "Norte" wind event when high atmospheric pressure causes a shift in wind direction, with winds blowing mostly from the north and the northwest, leading to a drop in air temperature due to the advection of a cold air mass, bearing continental polar or Pacific maritime air, and an increase in wind speed (>12 m s^{-1}). Conversely, a "Surada" increases air temperature at the western GM, associated with a warm air mass from tropical latitudes and a low atmospheric pressure system, typically observed over the western continental area of Mexico. During this event, winds blow from the south with high wind magnitudes (>12 m s^{-1}) (Pereyra et al. 1992, Salas-Pérez & Arenas-Fuentes, 2011).

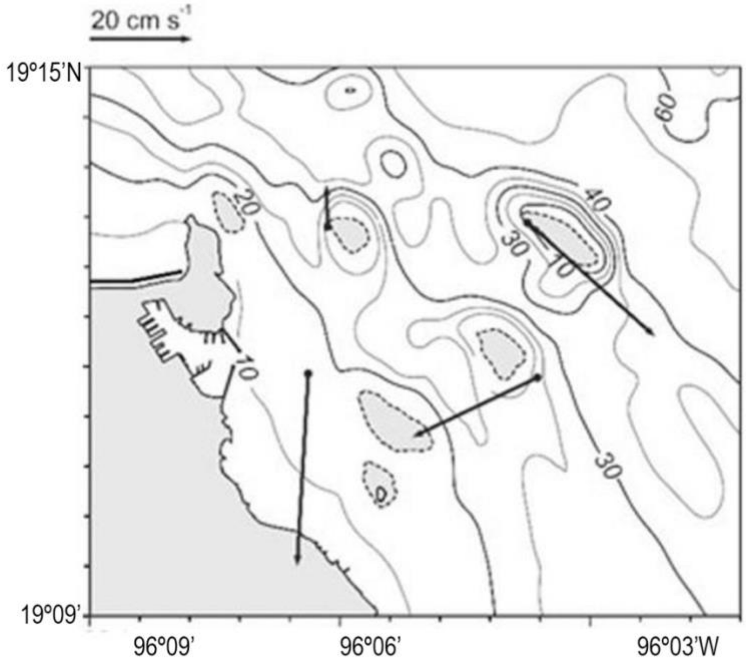

Figure 8. The mean wind-driven coastal marine current generated from November 10th to 20th, 2008, flowing in an anticyclonic current pattern.

During the summer season, local and mesoscale winds induce a northward current in the PNSAV and Tampico-Veracruz (TAVE) shelf (Zavala-Hidalgo et al. 2003, 2006, Salas-Pérez et al. 2012, Riveron-Enzastiga et al. 2016). However, an interesting event occurred in autumn (November 2008). A "Surada" wind event blew to the south/southwest for four days, inducing a coastal current flowing to the north parallel to the isobaths. No *in situ* measurements have formally reported this reversal of the seasonal wind-driven coastal current, which typically flows mainly to the south during this period (Zavala-Hidalgo et al. 2003, Dubranna et al. 2011, Salas-Pérez et al. 2012, Riverón-Enzastiga et al. 2016, Liaño-Carrera et al. 2019). Observations showed an intense alongshore velocity with magnitudes typically fluctuating between 50 and 150 cm s^{-1}. The conditions of a "Surada" wind event (with winds blowing from south/southwest to north/northwest) did not show an upwelling event due to Ekman transport with an across-shore flow from the coast to open sea from November 10th to 14th, 2008, because the marine circulation in the northern area of the PNSAV flowed north and almost parallel to the isobaths.

During the autumn to spring seasons, "Norte" wind events generate winds blowing from the north/ northwest, induced by itinerant high-atmospheric pressure systems on the TAVE shelf. These events induced a wind-driven coastal current to the south, traveling nearly parallel to the coastal area of the PNSAV, advecting cold water from the Texas-Louisiana shelf (Zavala-Hidalgo et al. 2006, Salas-Pérez et al. 2012, Salas-Pérez & Jordán-Garza 2018). Additionally, the coastal marine circulation during the second period (November 15th to 20th, 2008) aligns with the seasonal circulation observed during autumn-winter where the flow on the TAVE shelf is downcoast (Zavala-Hidalgo et al. 2003, Dubranna et al. 2011, Salas-Pérez et al. 2012, Riveron-Enzastiga et al. 2016, Salas-Pérez & Jordan-Garza 2018).

At the coastal scale, the distribution of the residual currents in the PNSAV can be attributed to the complex bathymetry and the presence of coral reefs and islands (Salas-Monreal et al. 2009, Salas-Pérez et al. 2012). These features indicate that bathymetry and local winds modulate the residual circulation at the PNSAV. Salas-Monreal et al. (2009) and Riveron-Enzastiga et al. (2016) agreed that around the reefs and islands, the abrupt bathymetric changes generate a series of cyclonic eddies due to the presence of the Cape of Anton Lizardo (Fig. 1). However, an important result of this study is the observation of the average current with an anticyclonic rotation from November 10th to 20th, 2008, due to the itinerant low and high-pressure events over the GM. This anticyclonic eddy could deplete the waters in its core and enrich them at its borders.

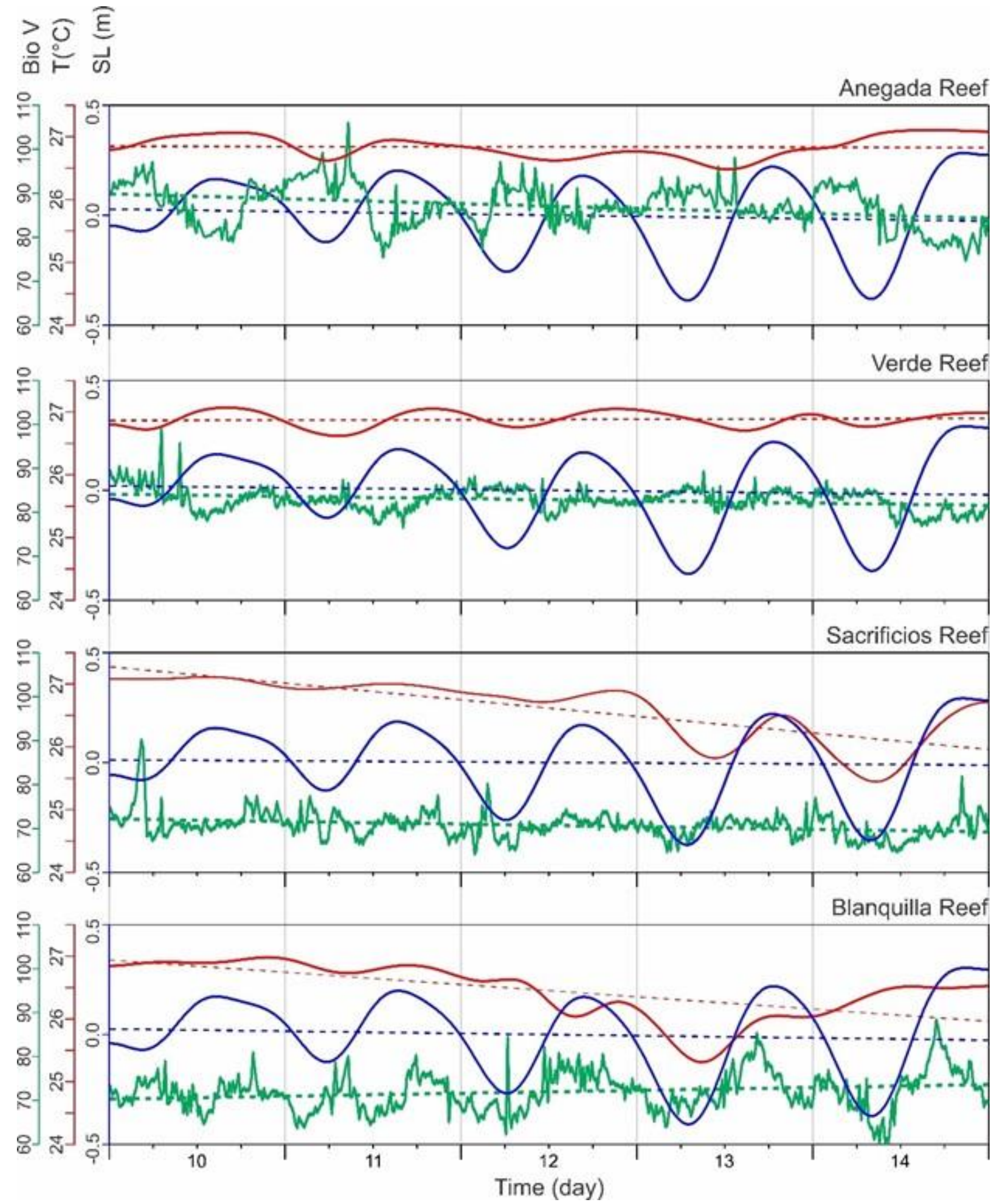

Figure 9. Oceanographic parameters (Bio: biovolume; T: temperature of the water column; SL: sea level fluctuation) measured *in situ* in the four areas of the northern Parque Nacional Sistema Arrecifal Veracruzano during the occurrence of a Surada event.

Sea level fluctuations during the "Surada" wind event did not significantly increase sea level in the four localities of the northern PNSAV. However, the trend was negative for the Anegada de Adentro and Isla Verde reefs (-0.12 m). In contrast, the trend was positive for Isla Sacrificios and Blanquilla reefs (0.08 m). The wind-driven flow, moving north and parallel to the isobaths in the reef corridor of the southwestern GM, did not show an upwelling event as theoretically described for a wind blowing from south to north with the coast to the left in the northern hemisphere (Zavala-Hidalgo et al. 2006). There was no Ekman transport across the coast and into the open sea, and the water mass was not replaced by an upwelling of bottom water, which significantly influences sea level. This phenomenon is similar to the intensification of the south/southeast winds that move water upstream in the summer (Zavala-Hidalgo et al. 2003, Riveron-Enzastiga et al. 2016, Salas-Pérez & Jordan-Garza 2018).

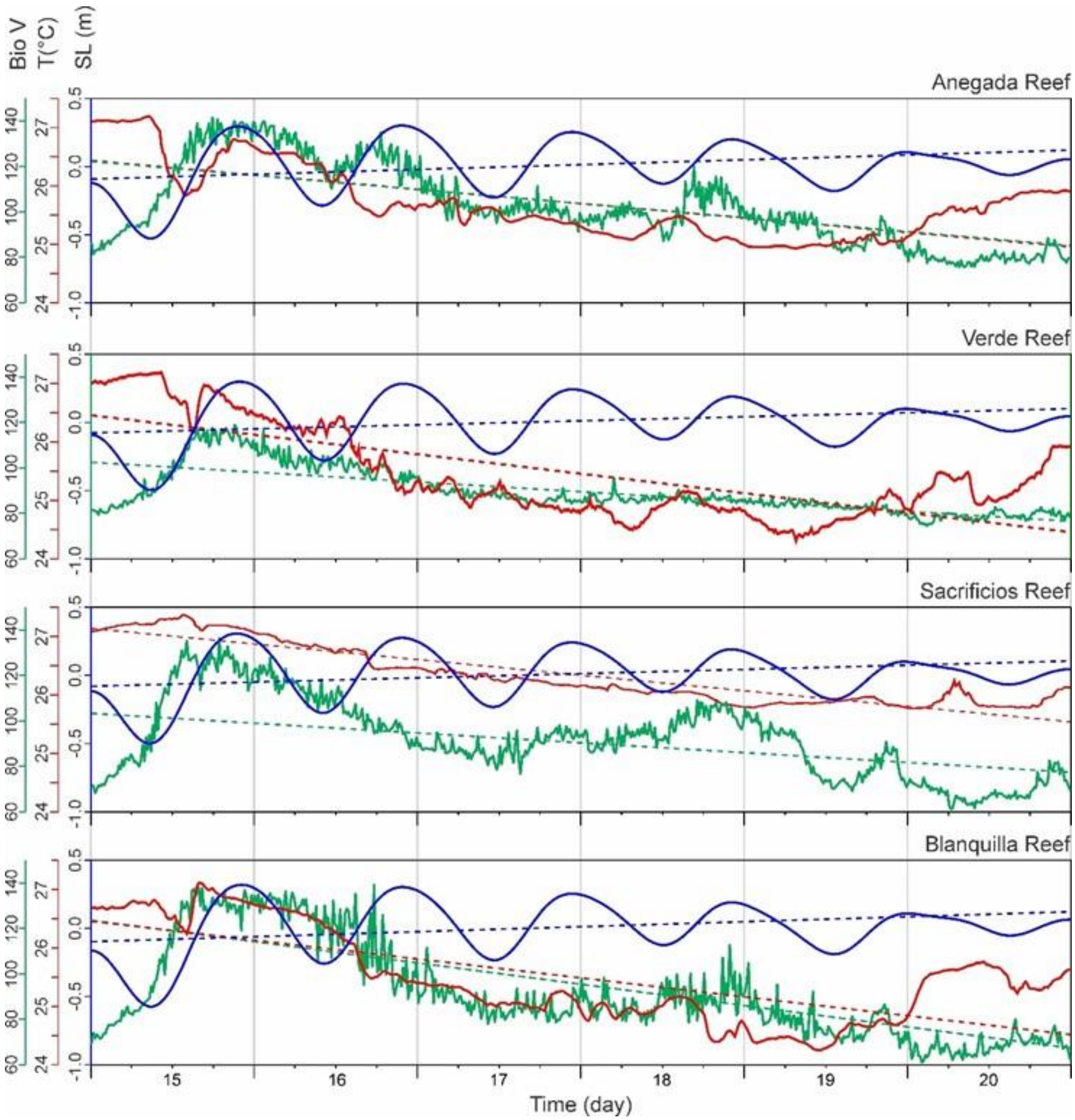

Figure 10. Oceanographic parameters (Bio: biovolume; T: temperature of the water column; SL: sea level fluctuation) measured *in situ* in the four areas of the northern Parque Nacional Sistema Arrecifal Veracruzano during the occurrence of a Norte event.

Moreover, no cold water was detected at the four localities in the northern PNSAV where the ADCPs were anchored. The temperature values fluctuated between 25 and 27°C, with mean temperatures of 26-27°C. In an upwelling event, mostly occurring in summer, the western GM typically experience cooler water temperatures (Zavala-Hidalgo et al. 2003, 2006).

A piling up of water, approximately 0.3 m, was observed during the "Norte" wind event (November 15-20, 2008) in the northern area of the PNSAV, within the reef corridor of the southwestern GM. This accumulation was due to the constant forcing of the winds in the region (Ramírez-Stout & Candela-Pérez 2003, Zavala-Hidalgo et al. 2003, 2006, Salas-Pérez & Granados-Barba 2008, Rivas 2017). Therefore, the wind pattern was the primary forcing mechanism affecting the sea level changes in this study area of the western GM (Vera-Mendoza et al. 2017).

A decrease in coastal sea surface temperature was also observed during the autumn-winter seasons due to winds associated with "Norte" events (winds blowing from the north/northwest) generated downwelling in the water column (Zavala-Hidalgo et al. 2006, Salas-Pérez & Arenas-Fuentes 2011). However, the coastal currents moved along the coast rather than across the PNSAV, as typical in a downwelling event. It is more accurate to associate this with fresh, buoyant coastal water advected from the northern area of the GM, particularly from the Louisiana-Texas shelf. This water exhibits low temperature and salinity values due to the influence of the Mississippi-Atchafalaya River system as other Texas and TAVE rivers located in the coastal zone of the northern area of the GM (Zavala-Hidalgo et al. 2006, Salas-Pérez & Arenas-Fuentes 2011). The absolute acoustic intensity (dB) obtained from the backscatter intensity of the ADCPs (Holliday & Pieper 1980, Ressler 2002) was used to compute plankton biovolumes (Salas-Pérez et al. 2012). The biovolume values estimated in this study might have been overestimated due to the presence of sediments discharged by the Jamapa River and the resuspension of sediments by mixing processes caused by the intense winds of the "Surada" and "Norte" wind events (Salas-Pérez et al. 2012). Despite this issue, during the 5 day "Surada" (November 10-14, 2008), biovolume values tended to decrease slightly from 90 to 60. This is because the mixing processes were less intense than during a "Norte" wind event, where biovolume values were higher, ranging from 61 to148. The variability of biovolume during the "Surada" wind event may be associated with the advection of waters from the Jamapa River to the northern area of the PNSAV (Salas-Pérez et al. 2012) and not due to upwelling. During autumn, the atmospheric "Norte" wind events mix the entire water column over the western continental shelf of the GM by eddy diffusion, increasing biovolume values (Zavala-Hidalgo et al. 2006, Salas-Pérez et al. 2012). However, during autumn and winter, "Norte" winds can also result in the advection of old bloom biological material from upstream (Zavala-Hidalgo et al. 2006). Hence, during the season of "Norte" wind events from November 2007 to March 2008, wind speed increased, and biomass values also increased in the PNSAV area (Okolodkov et al. 2011), which was not observed in this study.

CONCLUSION

The study shows that itinerant low-high atmospheric pressure system associated with Rossby waves advected from the jet stream and the PNA high atmospheric pressure system of the Pacific Ocean induce "Surada" (winds blowing from the south/ southwest) and "Norte" (winds blowing from the north/northwest) events during the autumn season.

The "Surada" winds increased the air temperature to 25°C in the western GM, while the "Norte" event decreased it to 20°C. The "Surada" wind event reverses the seasonal current of autumn for five days, causing the wind-driven current to flow to the north along the reef corridor of the southwestern GM. However, there are no favorable conditions to generate an upwelling event, which is more common during summer when winds blow from the south, generating a wind-driven current flowing north with the coastline to the left.

The residual current, resulting from the average effects of the "Surada" and "Norte" wind events, exhibits an almost anticyclonic current pattern in the northern area of the PNSAV. Previous studies reported that in summer, wind-induced eddies result from the presence of the Cape of Anton Lizardo. However, this study observed an anticyclonic eddy during autumn, specifically for the residual current resulting from the "Surada" and "Norte" wind events. This eddy likely interacts with the coral reefs and islands of the study area over an average of 10 days.

Wind velocities were the main mechanism affecting sea level variability over shorter periods, about five days. During a "Norte" wind event, there was a significant piling up of water in the northern coastal area of the PNSAV. In contrast, during a "Surada" wind event, the sea level experienced minimal fluctuation.

At the depth where the ADCPs were anchored, water temperature decreased during the "Norte" wind event due to the eddy diffusion mixing and the advection of cool water from the northern GM to the southwestern GM. In contrast, during the "Surada" wind event, the water temperature at the deployment depth remained warm.

Finally, during the "Surada" wind event, biovolume was high, likely due to the advection of the Jamapa River to the northern area of the PNSAV. In contrast, biovolume values were lower during the "Norte" wind event, suggesting that the advection of old bloom material and the increase in wind speed did not increase biovolume concentrations, contrary to previous studies.

Credit author contribution

J.J. Salas-Pérez: conceptualization, validation, methodology, formal analysis, writing-original draft, funding acquisition, project administration, supervision, review, and editing; A.G. Jordán Garza & D. Salas-Monreal:

review, and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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