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Forcing agents and their relationship with the oceanography of the Veracruz Reef System National Park

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ABSTRACT

Oceanographic characteristics of the Veracruz coastal zone and its interaction with rivers, estuaries and coral reef environments, demonstrate the high environmental heterogeneity of the Veracruz Reef System National Park (PNSAV). The PNSAV is a system dominated by anisotropic reef currents which enhance the biological connectivity between the northern, southern, coastal zone and the open sea of the marine area surrounding the PNSAV, causing great biological diversity. Also, the presence of particular reef areas generates low energy environments. Based on the above, this paper describes a collection of forcing agents of marine flows in the coastal area of Veracruz and its effect on oceanographic processes that fluctuate at different scales of space and time, which are essential for the proper understanding of the transport of suspended particles and planktonic organisms.

Keywords: Reef hydrodynamics, Coastal dynamics, Reef systems, Western Gulf of Mexico Systems.

RESUMEN

Las características oceanográficas de la zona costera veracruzana y su interacción con ambientes tan particulares como las desembocaduras de ríos y de arrecifes coralinos, ponen de manifiesto la alta heterogeneidad ambiental del Parque Nacional Sistema Arrecifal Veracruzano (PNSAV). El PNSAV es un sistema arrecifal dominado por corrientes anisotrópicas que facilitan la conectividad biológica entre la porción norte, sur, la zona costera y el mar abierto de esta área marina, originando gran diversidad biológica. También, la presencia de zonas arrecifales genera ambientes particulares de baja energía propicios para la creación de puertos de abrigo. Con base en lo antes expuesto, el presente trabajo describe una recopilación de los agentes de forzamiento de los flujos marinos en la zona costera de Veracruz y su efecto en los procesos oceanográficos que fluctúan a diferentes escalas de espacio y tiempo. Mismos que son fundamentales para el adecuado conocimiento del transporte de partículas suspendidas y organismos plantónicos.

Palabras clave: Hidrodinámica arrecifal, Dinámica costera, Sistemas Arrecifales, Golfo de México Occidental.

INTRODUCTION

The Veracruz coastal zone (ZCV) is located on the western coast of the Gulf of Mexico, with a total length of 23,700 km^2 (SEMAR 2004). The ZCV, is characterized by its shallowness (70 m on average) and narrow structure (6 to 45 km), with sinuous contours on a seabed depth with sediments of different origin (terrigenous, biogenic or autígenos) with islands and a series of channels with variable dimensions (Ortiz-Lozano et al. 2007) which generally cause variability in oceanographic parameters.

Continental shelf at Veracruz

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The Veracruz Reef System National Park (PNSAV) is located in the coastal area off the port of Veracruz and the coast of Boca del Rio and Anton Lizardo (Fig. 1), where 28 known coral reefs (DOF 2012) are located. It is an important area for the maintenance of biodiversity since it is the habitat of different organisms with a commercial importance (Granados-Barba et al. 2007). This area is constantly affected by coastal estuarine systems adjacent to the PNSAV with freshwater input (Pritchard 1967). The interaction between the PNSAV and estuaries is mutual, since the heat flow, mass exchange of water and suspended particles, have a great influencing on the local dynamics of both marine areas.

The importance of studying the coastal zone even if it only covers about 8% of the total area of the oceans, relies on the fact that 80% of world catches fisheries and oil extraction (30%) come from this area, besides over 40% of the world population lives near this area (Gallup 1999; Rodriguez et al. 2007). The information regarding the Veracruz coastal zone is less than 50% of the existing information on the Gulf of Mexico, therefore it needs to be further investigated from an oceanographic approaches.

Some of the oceanographic studies in the PNSAV, are related to the transport of sediments or contaminants due to pressure gradients (Morelock et al. 1983), the dispersion of coral larvae (Harrison et al. 1983), aggregations of fish (Domeier and Colin 1997), transport of larvae of organisms in their planktonic stage (Shulman and Ogden 1987) and the distribution of sediment due to advective processes related to the variability of environmental parameters such as salinity, temperature, water density, water velocities (Salas-de-Leon et al. 2008) and winds (Salas-Perez and Granados-Barba 2008, Salas-Pérez et al 2008; Salas-Monreal et al 2009; Salas-Pérez et al 2012). Therefore, it is important to study from an interdisciplinary point of view the dynamics of oceanographic processes in the ZCV, in order to 1) understand the spatiotemporal hydrographic parameters variations and their impact on the dispersion of suspended particles that are discharged into that area through discharges from numerous rivers located in the Veracruz coastal zone; 2) to determine the areas of aggregation of organisms that allow local fisheries which are important for the economy of the state of Veracruz; and 3) to locate any possible hypoxic regions in the study area.

The ZCV has a rich biodiversity and is one of the places with a great human development because it is next the reef areas, ports and tourist activities (Sachs 2001; Ortiz-Lozano et al. 2007); however, few studies have allowed oceanographers to regionally characterize these coastal systems. Another area of great importance in the coastal area are the coral reefs, although they only cover 1% of the surface of the oceans, they are places of great biodiversity, which represented a significant proportion of marine diversity (Salas Monreal et al. 2009). Furthermore a multispecies fisheries are performed in those areas (Vargas-Hernández et al. 2002, Jiménez-Badillo and Castro-Gaspar 2007).

Coral reefs protect the coast line by acting as a barrier that rectifies the current and attenuates the energy of the tide (Gourlay 1996; Lugo-Fernandez et al. 1998; Wolanski and Spagnol 2000; Salas-Pérez et al. 2008). These bathymetric effects in turn generate a specific bathymetry which produce turbulent regions (Storlazzi et al. 2006; Legrand et al. 2006; Salas-Monreal et al. 2009) since the current rectification may generated upwelling or sinking water, which can reduce the transparency of the water and thereby restrict the depth at which the corals are properly developed (Hayward 1982).

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Forcing agents in the Veracruz Reef System National Park

Hydrographic forcing agents are all those forces that can change the current system status. These agents may change both the direction and the speed of water. One of the main forcing agents' of the subtidal variability of the coastal zone is the wind stress (Salas-Monreal 2002). In the Gulf of Mexico, especially in the southern area, winds from the east may produce accumulation of water, in the entire east coast (Salas-Monreal and Valle-Levinson 2008). The buildup of water against the coast by wind and term steric changes generated the increase in sea level, which is one of the factors that directly impact the human habitat. Traditionally, this increase has been observed by analysis of long time series using hydrostatic pressure (gauges) and series subduction of tectonic plates (Salas-de-Leon et al., 2008); however, at lower time scales, you may see this phenomenon fluctuating annually (Salas-Monreal and Valle-Levinson 2009) and it is these fluctuations combined with specific atmospheric conditions that causes flooding in coastal cities.

The mouths of the rivers are places where there is a strong interaction between the sea waters and inland waters. The importance of rivers to the coastal zone lies in the pressure gradient (horizontal changes in density). These gradients generate flow patterns, which determine the trajectories of particles in suspension (Salas-de-Leon et al. 2008).

Gradients are modified during each tidal cycle, particularly during the spring tides, when the vertical mixing of the water column occur, the vertical stratification is reduced and the primary productivity tends to increase (Ducklow 1982). Therefore, to understand the changes caused by the stratified flow or mixing processes in the coastal zone we need to understand the areas of concentration and dispersion of planktonic organisms and particles suspended in the water column (Wolanski and Sarsenski 1997; Genin 2004; Gao and Wang 2008; Salas-Monreal et al. 2009; Salas-Pérez et al. 2012).

It has been observed that the concentration of some pelagic fish species increases when the suspended particles increased during the rainy season, because the organic matter increases (Gao and Wang 2008). The study of the coastal zone in the eastern Gulf of Mexico is relevant to fisheries, since most of them are artisanal and represent a source of protein and income for coastal communities (Quiroga-Brahms et al. 2002; Fuentes-Mata et al. 2002).

MATERIAL AND METHODS

This study is an integration of oceanographic aspects (physical and biological) in which we reviewed and analyzed existing knowledge regarding the coastal area of the PNSAV (Fig. 1), emphasizing the river mouths and coral reef areas for being particular ecosystems. The hydrographic features, the current pattern and wind conditions at mesoscale (10-100 km) across the Veracruz continental shelf are described. The information obtained was complemented by theoretical approaches regarding the variability that may be generated locally by meteorological and oceanographic conditions (less than 10 km).

The information includes several spatial and temporal scales, with time series of over fifty years, to one day of series and space series ranging from a few meters to several kilometers. This range of data allows us to understand the PNSAV at different scales and provide a diagnosis of the studies that have been conducted in this area, which information can be inferred theoretically from them and what has

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not yet been investigated to understand the different PNSAV oceanographic processes.

RESULTS

Main forcing agents of the coastal areas of Veracruz

The coastal area off the port of Veracruz shows a current distribution related to the wind regime. The wind velocity varies throughout the year owing to the generation of different atmospheric processes (Salas-Perez and Granados-Barba 2008). During the winter, they generate currents flowing southward on scales of days, due to the generation of polar air masses from the north with average wind gusts of 40 km h^{-1}, which are known locally as "Norths" or “Nortes” (cold fronts). They also generate waves and in some years they can generate long periods of heavy rain (SEMAR 2002); however, during the season of “nortes”, winds can reach gusts of up to 100 km h^{-1}, resulting in well-mixed water column in the PNSAV (Salas-Perez and Arenas-Fuentes 2011).

During the summer, the prevailing wind comes from the south (Zavala-Hidalgo et al. 2003, Salas-Pérez et al. 2012), generating currents flowing from south to north on the outer continental shelf. The coastal zone may have the same current pattern as the external platform (Salas-Pérez et al. 2007) or may be modified in their direction (flowing from the outer continental shelf to the coast) by the mesoscale gyre of the Bay of Campeche (Salas-Pérez et al. 2012), which facilitate the migration of some

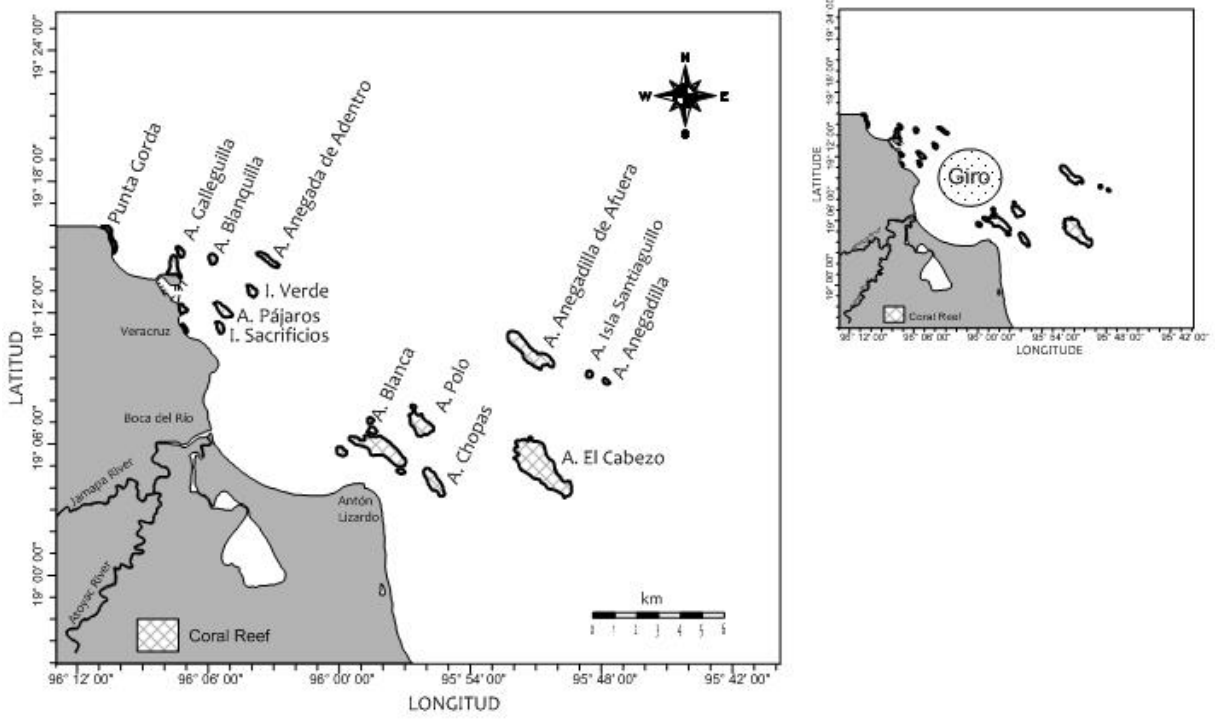

Fig. 1. Geographical location of the Veracruz Reef System National Park and the area of influence of the Gyre.

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fish such as the Sierra (Atlantic Spanish Mackerel) (Mitchill 1815) and dungarees (king mackerel) (Cuvier 1829) that are of commercially important for the state of Veracruz (CONAPESCA 2008).

During the fall, the easterly winds are presented, which are one of the main carriers of moisture, causing heavy rains in the PNSAV (SEMAR 2002). The PNSAV has a rainfall of 1000 and 1500 mm per year (INEGI 2000). This, increased freshwater discharge changing the well mixed water column by generating the pycnoclin, defined in the water column as a change of water density, which in turn serve as an environmental barrier to some species of plankton (Salas-Monreal et al. 2009).

The increase river discharges in the PNSAV generates horizontal gradients in density which generates currents movement of about an order of magnitude less than the wind generated currents; however, they cannot be discarded, since in the absence of strong and sustained winds, they may modify the current patterns of the PNSAV.

Although the winds dominate much of the ocean circulation in the Veracruzana continental shelf, these are not the only forcing of the PNSAV, since this area (PNSAV) is directly affected by the atmospheric and oceanographic processes occurring in the eastern Gulf of Mexico (GM). The low frequency marine circulation in the eastern GM is dominated by the loop current and the gyre of Campeche (Behringer et al. 1977; Carrillo et al. 2007). In addition, the trajectory of the anticyclonic gyres, arising from the Loop Current, have a life of up to 12 months and an area of approximately 300 km (Vazquez de la Cerda 1975; Elliott 1982; Monreal-Gómez and Salas de León 1997) of diameters, which are locally modified by the bathymetry of the continental shelf (Maul and Vukovich 1993; Hurlburt and Thompson 1980). This effect is most evident in the continental shelf since this is the place where the seabed changes abruptly, creating a cyclonic eddy south of the PNSAV and another in the continental shelf located north of Tampico-Veracruz state borders. Besides the two cyclonic eddies originated from the Loop Current, the cyclonic gyre of the Bay of Campeche migrates north during the summer off the continental shelf of the state of Veracruz (Vazquez de la Cerda 1975; Vasquez de la Cerda 1993) affecting the PNSAV (Salas-Pérez et al. 2012). All those gyre affect the local circulation of the PNSAV (Vidal et al. 1992; 1982 Elliott; Carrillo et al. 2007; Salas-Perez et al. 2012). The importance of the gyre in this area is related to the processes of vertical mixing of water, due to "fragmentation" of the gyre in the continental shelf of Tampico-Veracruz, the generated currents contribute to the formation of the common water of the Gulf of Mexico (Salas-Pérez et al. 2012).

In the PNSAV, gyres have been detected by numerical models, this is largely due to the complex bathymetry and river discharges that change the pattern of longshore current. However it has been possible to describe such gyres using *insitu* data (Salas-Monreal et al. 2009). This is due to the resolution of the sampling. The local currents are affected by both, the bathymetry, and continental water, as river discharges and underwater downloads (mainly drains) that are not included in studies using numerical models.

Weather effects in currents and sea level

The weather in the PNSAV is warm and humid, with summer rains and an average annual temperature ranging between 22 and 26ºC (INEGI 2000). The increase in the air temperature is reflected in the sea temperature,

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an increase in air temperature implies that the air mass moved north, generating currents flowing northward, with a higher temperature. This change in temperature, during the summer season, generates a rise in sea level, while the decrease in temperature, during the winter season, generates a decrease in sea level (Salas-Monreal and Valle-Levinson 2008). This is important not only for navigation purposes but also for some organisms that can feel changes in pressure generated in the water column.

This phenomenon can be observed yearly due to seasonal changes; however, if we would like to see changes due to climate change it will be necessary to have time series with a length over 30 years (Salas de Leon et al. 2006). A time series of sea level over 50 years on the main ports of the state of Veracruz (Tuxpan, Veracruz, Alvarado and Coatzacoalcos) revealed that the sea level is rising by about 1.4 mm per year (Salas de León et al. 2006). These types of processes are known as subtidal increases at low frequency on the sea level (changes in which the effect of the tide is filtered) and which may have an impact on the erosion of the coastal area, a process that can increase or reduce sediment in a particular area, in addition to those provided by the rivers.

Tides and waves

In spatial scales of hundreds of kilometers, tide in the coastal area of Veracruz (semidiurnal) are different to those reported for the port of Veracruz (Salas-Pérez et al 2008). In the PNSAV tides are diurnal (24 hr period) with an amplitude of about 0.50 m (Salas-Pérez et al. 2008). The diurnal tidal currents have an average speeds of close to 0.50 m s^{-1}. This is important since is half the normal current speed (1 m s^{-1}) in the PNSAV. The fortnightly tide (MSF) are also important because their amplitudes are in the same range of the semidiurnal tide (Salas-Pérez et al. 2008). The change in sea level over short periods of time are important for many planktonic organisms, which have a vertical migration behavior subject to tides. Tides can have a direct effect on the recruitment process of several organisms (Galindo-Cortés et al. 2010) and on the distribution of coral structures along the PNSAV (Jaureguizar and Guerrero 2009).

On a shorter scale of time (shorter wave lengths), the waves in the PNSAV are attributed to the wind regime. During the winter season the trade winds (winds from the east) generate waves with short period of time but high amplitude (Walsh 1962). According to Ortiz et al. (1996) waves in the downtown area of the City of Veracruz, where the PNSAV is located are due to:

1) Local winds, which generate moderate energy.

2) Winds from the north (northern wind), generating storm surges. When the north winds exceed 40 km h^{-1} they generate waves with great energy, producing great turbulence in the inner continental shelf.

The swell is also important throughout the Tampico-Veracruz platform; however, the swell in the PNSAV it is not very important, because of the presence of coral reefs which reduced its associated energy. The northern winds are the only atmospheric condition of importance to increase the wave energy and amplitude, generating waves of up to 4 m (Salas-Perez and Granados-Barba 2008). The natural protection of the coral reef areas is one of the main reasons to build Port facilities in the vicinities of the PNSAV.

In general in the PNSAV tide are of low energy due to the presence of reefs (Salas-Pérez et al. 2008; Salas-Perez and Granados-Barba 2008). The amplitude recorded by the tide gauge of Tuxpan (19 cm) are similar to those reported

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in the PNSAV. In both cases, the tidal amplitudes are lower than those reported in exposed areas such as Alvarado (25 cm) and Coatzacoalcos (22 cm) (Salas-Perez and Granados-Barba 2008), owing to the presence of coral reef areas.

A study using drifting buoys and anchors current-meters (ADCP) (Herrera-Cervantes 1987; Salas-Pérez et al. 2007; Salas-Perez and Granados-Barba 2008; Salas-Monreal et al. 2009) show that the major axis of the current tidal ellipse is oriented from south to north with a low amplitude of 10 cm s^{-1} for the K1 component and less than 7 cm s^{-1} for the M_2 component.

Longshore transport and waves

The coastal current in the coastal area during the winter season (December) has been inferred by grain size by Rosario-Hernandez and Tinoco-Blanco (1988). They found that in Punta Gorda (Punta Mocambo) the current velocity flows southward as in Anton Lizardo to Jamapa River, while in Punta Mocambo the Jamapa River discharge flows northward (Salas-Perez and Granados-Barba 2008). This creates a great dispersion of the organisms into the PNSAV, however the presence of the Rio Jamapa, could be a limiting factor in the exchange of organisms along the PNSAV.

The three rivers that directly affect the PNSAV are the La Antigua River, with an annual average discharge of 2.88 x 10^6 m^3 yr^{-1}, the Jamapa River with an average water input of 1.89 x 10^6 m^3 yr^{-1} and finally the Papaloapan River with an average river discharge of 36.19 x 10^6 m^3 yr^{-1} (Tamayo 1999). The discharge of these rivers can generate pressure gradients during the rainy season. During the summer the current pattern is reversed (Caballero-Rosas 1990; Salas-Monreal et al. 2009), forming a cyclonic eddy facing the Jamapa River, which generates low light penetration and high concentration of suspended sediment in the water column (Salas-Monreal et al. 2009). This may be one explanation for the distribution of coral reefs in the PNSAV, since they are divided into two clearly separated areas by the Jamapa River mouth and the formation of the cyclonic eddy.

Moreover, the PNSAV can be classified as "cold" tropical area in winter (19-23 ° C) and a eutrophic system (chlorophyll-a concentrations greater than 1.5 mg m^{-3}). While during the summer it can be considered as a warm water tropical area (29-30 ° C). These fluctuations in both oceanographic parameters (temperature and chlorophyll-a) are attributed to the river discharges and to the gyre of Campeche (Salas-Pérez et al. 2014).

At a smaller scale (tens of meters) the PNSAV can be distinguished by forming Lee waves (waves generated by bathymetric effects). Salas-Monreal et al. (2009) reported waves Lee at Sacrifice Island during the summer of 2007. These waves were generated by the combination of tidal currents and the formation of a warm-salty body of water from the reef lagoon, owing to evaporation. These waves are of great importance during the coral spawning season, as they use these divisions of density (fronts) as a means of transportation to the deeper parts of the reef.

DISCUSSION AND CONCLUSSIONS

Veracruz is a state with a predominantly coastal vocation, derived from the presence of more than 700 km of coastline and a network of watersheds exoreic which generate a strong interaction between the land portion and the marine portion of the continent (Ortiz-Lozano et

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al . 2007). From a comprehensive perspective, we can say that the different forcing agents and their relation to oceanography occur at different temporal and spatial scales in the Veracruz coastal area and they are related to meteorological and geomorphological aspects of the study area (PNSAV).

The oceanographic characteristics of the coastal area of Veracruz, as well as the presence of the estuaries and coral reef environments, determine the high environmental heterogeneity of the coastal zone. The complex environmental and natural resource, rich in natural processes highlight the need to generate interdisciplinary oceanographic studies to better understand their structure and function.

The state of Veracruz has a large coastal area with a significant environmental component; however, the number of studies in this area are limited, especially when you consider that the city of Veracruz is one of the oldest cities in America (1519). There is little information that can be used to establish a relationships between the different forcing agents and the oceanographic processes in the Veracruz coastal zone (ZCV). According to Jiménez-Hernández et al. (2007), the oceanographic studies in the ZCV have been poorly addressed in the available studies from 1891 to 2006, and they only represent less than 6% of the available literature of the area. This lack is enhanced because of the inadequate time-space scale of the information used to understand in detail the different process of the coastal zone (kilometers-day scale). Most oceanographic studies are aimed at understanding what happens in the external platforms in the Gulf of Mexico (Zavala-Hidalgo et al. 2003, Salas-de-Leon and Monreal-Gómez 2007 Dubranna et al. 2011, Pérez-Brunius et al 2013). However, since 2005 oceanographers have been conducting oceanographic studies in the ZCV (Arenas-Fuentes and Salas-Perez 2005, Salas-Pérez et al. 2007, 2008, 2012, 2014, Salas-Perez and Granados-Barba 2008, Salas -Monreal et al. 2009, Chacon and Salas-Monreal 2014) taking *insitu* data at smaller scales (less than one kilometer), with sampling periods under an hour and for at least one diurnal tide cycle.

Such studies would be valuable to understand the dynamics of the ZCV, but they represent a huge operational effort and a high monetary cost; therefore, they could be made in critical areas or priority, considering the ecosystem services they provide. An example is the case of the reef systems of Lobos-Tuxpan and the PNSAV. These studies are useful to determine the coastal areas that are vulnerable to extreme weather events such as hurricanes, tropical storms or strong winds from the north (northerns).

On the other hand, the ZCV is presented as a site dominated by strongly anisotropic currents that facilitate the connectivity between the southern portions to the northern areas of the state of Veracruz, which can be a major issue to determinate the biological diversity that characterizes the system. The main forcing of the PNSAV are the wind, which causes changes in the direction of the currents with periods of six months and generates waves between 0.50 to 4 m high. The pressure gradient generated by the river discharges were one order of magnitude smaller than those generated by the winds. The main rivers affecting the PNSAV are the Papaloapan, Jamapa and La Antigua Rivers, these rivers produce thermohaline changes, which in turn affect the water velocity (direction and magnitude) depending on the season of the year. The amplitude of the tides that had been reported in the continental shelf are of 0.15 m which are smaller than those reported for the PNSAV which are of 0.50 m. The tidally currents had a speeds of up to 0.50 m s^{-1}. Tide

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are one of the main forcing in the PNSAV, followed by the wind and the pressure gradient; however, the gyre of Campeche, which cause changes in current speed and in the thermohaline structure of the system cannot be neglected. The presence of particular reef areas generates low energy environments that serve as shelter for fish species of commercial interest.

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