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Coral reef connectivity within the Western Gulf of Mexico

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ABSTRACT

The yearlong monthly mean satellite data of the geostrophic velocities, the sea surface temperature and the chlorophyll-*a* values were used to elucidate any possible pathway among the different coral reef systems of the Western Gulf of Mexico (WGM). The geostrophic current velocities suggested different pathways connecting the coral reef areas. The typical coastal alongshore pathway constricted to the continental shelf, and two open ocean pathway, the first connecting the Campeche Reef System (CRS) with the Veracruz (VRS) and Tuxpan-Lobos Reef Systems (TLRS), and the second pathway connecting the Tuxpan-Lobos Reef System with the Flower Garden Reef System (FGRS). According to the pathways there should be more larvae transport from the southern Gulf of Mexico reef systems toward the FGRS than the other way. The connection from the southern Gulf of Mexico toward the FGRS took place during January, May, July, August and September (2015), while the connection from the FGRS toward the southern Gulf of Mexico reef system took place during January and February (2015), this was also suggested via model outputs. The density radio (R) was used as a first approximation to elucidate the influence of the freshwater continental discharges within the continental shelf. All coral reef areas were located where the Chlorophyll-*a* monthly mean values had values bellow 1 mg m^{-2} with a density radio between 0 and 1, i.e. under the influence of continental discharges.

1. Introduction

The connectivity among coral reef systems within the Gulf of Mexico have previously been demonstrated by oceanographic numerical models (Anderberg, 2014), biological data (Murphy and Hurlbut, 1999; Carricart-Ganivet, 2004; Mumby and Hastings, 2008; Ortiz-Lozano et al., 2013; Johnston and Akins, 2016) and through genetic means (Villegas-Sancehz et al., 2013). The coral larvae trajectories within a reef system have also been described (Salas-Monreal et al., 2009; Chacon-Gomez et al., 2013). However the time that most planktonic and ichthyoplanktonic organism takes from one coral reef system to another, as well as the trajectories that planktonic organisms takes after leaving the reef system needs to be studied with more detail. Coral reefs are important since they shelter at least one quarter of all marine species (Sheppard et al., 2009). Owing to their high biodiversity they have more biological activity (feeding mechanisms, reproduction, and locomotion) than most marine ecosystems per unit area.

In the southern Gulf of Mexico, coral spawning occurs during the first ten days after the full moon of August (Gittings et al., 1994; Hagman et al., 1998; Lugo-fernandez et al., 2001; Chacon-Gomez et al., 2013). Tidal and wind induced currents are one of the most important mechanisms regarding the connectivity among coral reef systems (Salas-Monreal et al., 2009), bringing new recruits, which have a strong influence on community biomass, population persistence, resilience and species diversity (Schill et al., 2015). The dispersal of coral larvae enhances coral evolution (Veron, 1995). However, currents are not exclusives for coral larvae (Salas-Monreal et al., 2009). Coral larvae predator dispersal (Dight et al., 1990) and coral larvae disease (Rutzler and Santavy, 1983) are one of the most disturbing topics these days (Carricart-Ganivet and Beltran-Torres, 1998). One of the most extended coral species in the Gulf of Mexico are *Orbicela annularis*, *O. faveolata and O. franksi* (Weil and Knowlton, 1994) which have suffer from invasive species coming from other reefs. As an example, the lionfish (*Pterois volitans/miles*) which have successfully invaded the Gulf of Mexico and the Caribbean Sea is blamed for the reduction in biodiversity and biomass of coral reef systems (Albins, 2015). Thus, larvae of *P. volitans* are dispersed by ocean currents; this is a common behavior for most reef fishes during their larval stage (Thresher et al., 1989).

Hurricanes are one of the short-term mechanisms for coral reef organisms' connectivity (Andrefount et al., 2002), however due to the difficulty to take *insitu* data during an extreme natural event, this idea was only a theory before the availability of satellite images. These days

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it is possible to elucidate sea surface characteristics of the ocean during an extreme event using Coastal Zone Colour Scanner (CZCS) images obtained through satellites. CZCS have previously been used to confirm the connectivity in the Great Barrier Reef (Gabric et al., 1990), in the Mesoamerican Barrier Reef (Soto et al., 2009) and one source of coral stress in the Caribbean Sea, owing to river runoff from the Amazon and Orinoco rivers (Hallock et al., 1993). Using satellite geostrophic currents, sea surface temperature (SST), chlorophyll-*a* and a 30 days maximum dispersal larvae period (Schill et al., 2015) in the Western Gulf of Mexico (WGM) it is possible to elucidate larvae trajectories and the connectivity path among coral reef systems. Coral larvae and ichthyoplankton may have a higher survival possibility within the first 30 days of spawning, however, this time may varied depending on taxa, environmental tolerances of each organisms, adaptability, vertical migration, swimming ability and predators (Lester et al., 2007; Chacon-Gomez et al., 2013). The coral reef systems in the WGM are patchily distributed and less developed when compared to the Caribbean or the Great Barrier reefs which form large barriers. Among marine ecosystems, coral reefs are extremely sensitive to disturbances and their cover has declined drastically in the last decades (Richmond and Wolanski, 2011). The exchange of individuals among and within reef systems is crucial for their conservation and resilience (Jones et al., 2007). Therefore, the aim of this study is to elucidate the different pathways, which connect the reef systems, of the Western Gulf of Mexico.

2. Data and methodology

Yearlong time series of the geostrophic velocities (v), the sea level high (z), the sea surface temperature (SST) and the chlorophyll-*a* (Chl-*a*) were obtained for the Western Gulf of Mexico (WGM) as depicted in Fig. 1. The WGM was chosen in order to elucidate any possible pathway among those reef systems (Fig. 1). The chosen area includes the location of Campeche (north and south), Tuxtlas, Veracruz, Tuxpan-Lobos, and Flower Garden Reef Systems. All data were obtained from MODIS-Aqua and MODIS-Level 3 daily images. Data processing was performed in order to obtain the monthly geostrophic mean velocity (v), the sea surface temperature (SST) and the chlorophyll-*a* (Chl-*a*) dataset from 2010 to 2015. Due to the resolution of the dataset only the mesoscale process will be described here, even though most reef fish larvae have dispersal distances which ranges from 10 to 100 km (Cowen et al., 2006), other may be dispersed thousands of kilometers (Green et al., 2015).

The geostrophic velocity was obtained with a horizontal resolution of 0.25° from AVISO dataset (Arbic et al., 2012), while the SST and the Chl-*a* (https://doi.org/10.5067/AQUA/MODIS_OC.2014.0) dataset were obtained with a 9 km horizontal resolution. Data were interpolated in order to obtain a 5 × 5 km horizontal resolution grid in order to describe flow patterns within the WGM. Since one of the main goals of this study is to elucidate coral and reef fish larvae trajectories within the WGM, it was assumed that ichthyoplankton and coral larvae travels near the surface (Chacon-Gomez et al., 2013). In average coral reefs developed in the upper 50 m depth within the continental shelf and they are exposed to oceanic water conditions that favor coral development (Rezak et al., 1985; Deslarzes, 1998). However, all coral reefs within the WGM are periodically covered by resuspended sediments owing to winds and/or river discharges which may not favor their optimal development (Lugo-fernandez et al., 2001; Salas-Monreal et al., 2009). Finally, in this study it will be assumed that larvae may travel regardless of predators and that river discharges will create a physical barrier. Those barriers will be described according to the horizontal salinity and temperature variations (fronts). The trajectories of all larvae will be described using the vector of matrix addition obtained from the geostrophic velocities (v) dataset. This was done by

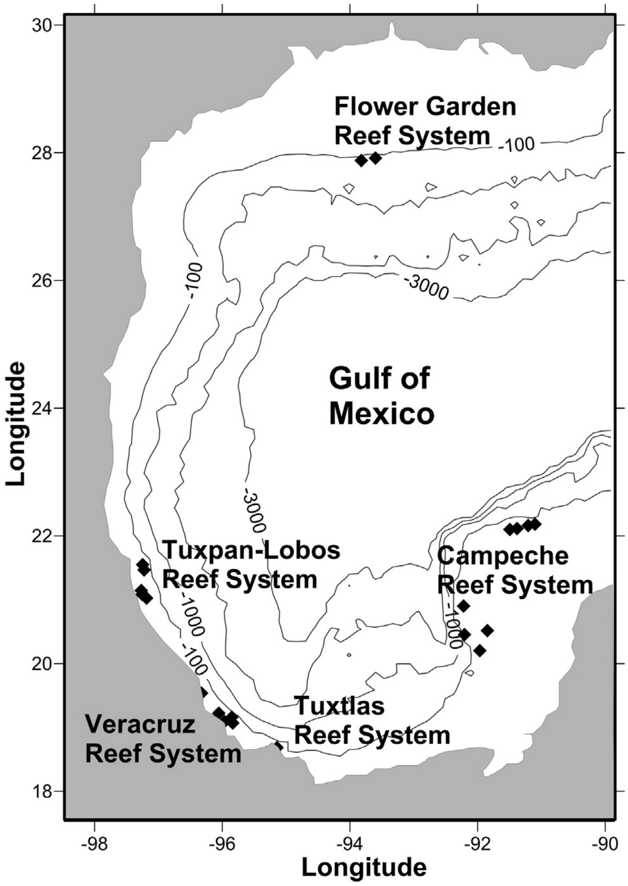

Fig. 1. Location of the coral reef areas and the bathymetry of the Western Gulf of Mexico.

Table 1
The correlation value (r^2) of the direction (Θ) and speed ($\overline{\overline{V}}$) between the monthly mean averaged geostrophic velocity from 2010 to 2015 and the monthly geostrophic velocities for each year.

Θ	2010	2011	2012	2013	2014	2015
January	0.76	0.71	0.74	0.76	0.71	0.75
February	0.69	0.70	0.62	0.64	0.59	0.70
March	0.70	0.68	0.68	0.69	0.62	0.69
April	0.74	0.69	0.72	0.76	0.70	0.74
May	0.70	0.68	0.71	0.79	0.68	0.75
June	0.76	0.72	0.74	0.72	0.69	0.74
July	0.75	0.71	0.78	0.74	0.76	0.74
August	0.72	0.71	0.74	0.72	0.71	0.75
September	0.68	0.69	0.68	0.69	0.64	0.67
October	0.69	0.72	0.71	0.69	0.63	0.69
November	0.72	0.71	0.76	0.78	0.71	0.68
December	0.74	0.76	0.74	0.73	0.75	0.72
$\overline{\overline{V}}$	2010	2011	2012	2013	2014	2015
January	0.68	0.64	0.63	0.75	0.76	0.75
February	0.64	0.67	0.68	0.78	0.77	0.79
March	0.67	0.66	0.67	0.71	0.76	0.78
April	0.67	0.68	0.67	0.72	0.78	0.77
May	0.71	0.75	0.74	0.82	0.84	0.81
June	0.71	0.72	0.72	0.78	0.79	0.78
July	0.78	0.81	0.76	0.84	0.86	0.87
August	0.71	0.74	0.76	0.79	0.84	0.82
September	0.75	0.74	0.73	0.78	0.79	0.75
October	0.74	0.68	0.67	0.72	0.71	0.75
November	0.68	0.64	0.63	0.67	0.72	0.74
December	0.62	0.68	0.67	0.72	0.78	0.76