The Western Boundary Current in the Gulf of Mexico: The Mexican Current

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1 Introduction

The Gulf of Mexico represents a hot spot area characterized by a burgeoning population, which increased dramatically in the last century, reaching the 56.23 millions of people in 2010 distributed on an area of 617000 mi^2 (*NOAA*, 2001). Moreover, the Gulf distinguishes for great energy, natural and biological resources, hosting unique and delicate ecosystems of outstanding biodiversity.

This area is a semi-enclosed sea highly exposed to risk of overloading of nutrients and pollutants (*Morey et al.*, 2005). Oil spill activity is intense in the Gulf of Mexico, contributing to the 54% of the crude oil production and the 52% of the Natural Gas Production of USA (*NOAA*, 2001). The hydrodynamic features, the rate of ecological catastrophes (i.e. Hurricane Katrina, 2005; Deepwater Horizon MC252 oil spill accident in 2010) and the population density, make of great importance the study and the deep understanding of the processes, circulation patterns and dynamics of the Gulf. Currents such as the incoming Yucatán Current, the Loop Current and the outgoing Florida Current, are well studied examples of circulations that take place in the proximities and inside this region (Figure 1). However, at the western extremities of the Gulf of Mexico, in the second half of the 20th Century, a fast jet which behaves similarly to a western boundary current has been described and named: The Mexican Current (*Sturges and Blaha*, 1976).

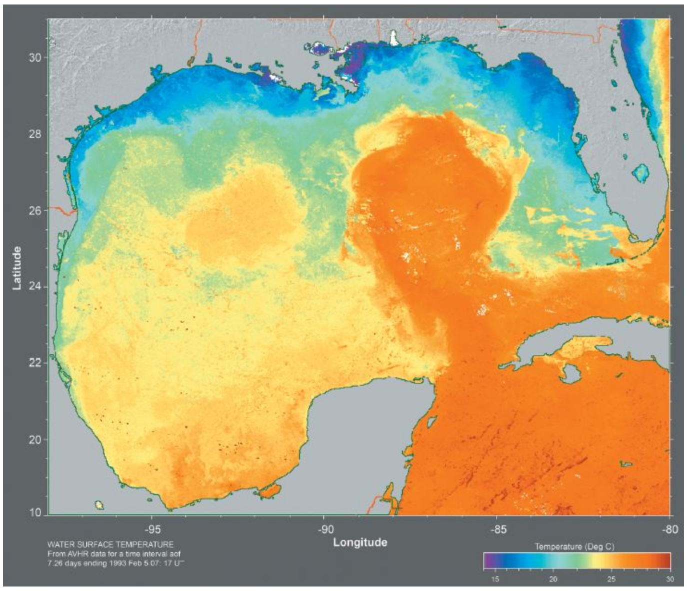

Figure 1: Seven-day AVHRR (Advanced Very High Resolution Radiometry) composite of sea-surface temperature (SST) for day ending on Feb/05/1998 presented by *Oey and Lee* (2003). The Loop Current is shown in an extended position into the Gulf, and an old ring further west. Note the appearance of a series of frontal eddies along the outer edges of the Loop Current and the old ring, a cyclone over the east Campeche Bank slope just north of the Yucatan Channel.

1.1 The history of the Mexican current: between the action of the Loop Current and the wind stress.

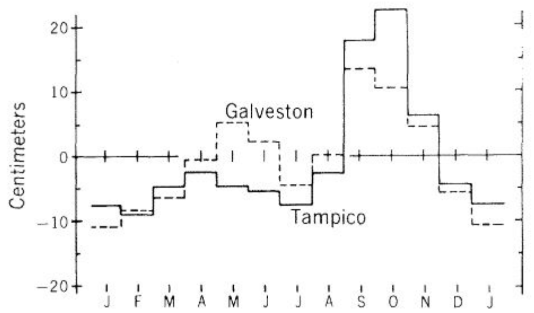

Figure 2: Annual trend of mean monthly tidal height at Galveston, Texas, and Tampico Mexico. Years of data are: Galveston, 1909 tc 1969; Tampico, 1942 to 1950 and 1952 to 1958. Source: *Sturges and Blaha* (1976).

The history of the Mexican current (MC) starts in the early 60's when *Ichiye* (1962) hypothesized that eddies may separate, detaching from the Loop Current, and drift to the western boundaries of the Gulf of Mexico, keeping the anticyclonic circulation which characterizes the Loop Current (Figure 1). This intuition was then confirmed by the *Nowlin* (1972) observations, on data collected between the 1958 and the 1964. The last realized that the central western Gulf is actually dominated by an anticyclonic gyre during the winter. *Nowlin* (1972), *Cochrane* (1972) and *Nowlin and Hubertz* (1972) thus believed that the reason behind the existence of these western anticyclonic gyres was in the action of the Loop Current. The importance of this phenomenon lies in its coupling with a southern cyclonic gyre, which interplays forming a cyclone/anticyclone pair. *Maul and Herman* (1985) well described the presence and the features of the cyclonic/anticyclonic pair in the western basin using hydrographic, STD and XBT data.

Four years after the *Nowlin* (1972) descriptions on the anticyclonic gyre, *Sturges and Blaha* (1976) turned upside-down the theory of the Loop Current influence, and stated that the driving force of the anticyclonic gyre and a Gulf Stream-like western boundary current (i.e. the MC) is the wind stress curl. This new point of view leaded to several interesting considerations. If the wind is the actual force that drives the anticyclonic circulation, speed and transport peaks should be detectable during the winter and the summer, when there is the max wind stress in the area.

Mainly by analysis of sea surface topography and tidal ranges between two stations in Galveston (Texas) and Tampico (Mexico), *Sturges and Blaha* (1976) reached interesting conclusions which link the MC to the wind. The abrupt change in sea level between August-September, associated with a strong change in increasing wind stress in the same period, and the higher sea level in Galveston compared to Tampico during the spring and lower in the fall (associated with a change of wind direction), gave strong suggestions about the involvement of the wind (Figure 2).

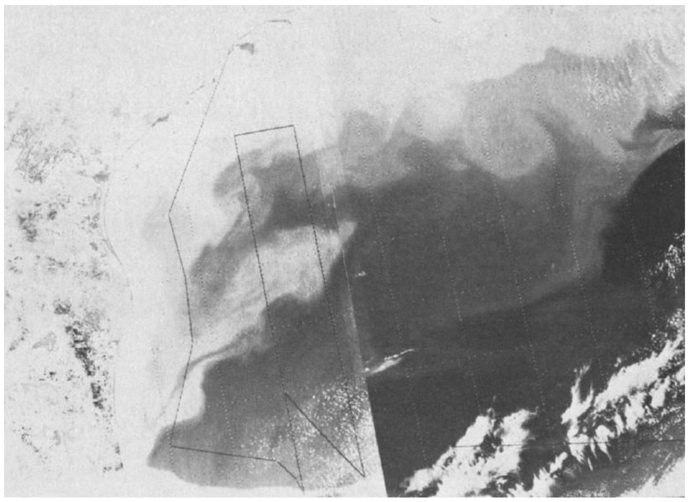

Figure 3: Satellite infrared composite image of the western Gulf of Mexico surface temperature. The two individual images comprising the composite were obtained on April 14 and 15 at approximately 1400 UT. Warmer temperatures correspond to darker shades; the land areas are relatively cold and appear near white or light gray. Source: *Brooks and Legeckis* (1982).

On the other hand, if the gyres derive from the Loop Current, they should persist almost yearly. *Behringer et al.* (1977) showed from the salinity variations that eddies drift westward in the Gulf. These authors then concluded that there are indications that the anticyclonic gyre may persist all the yearlong but has maximum in winter and summer as suggested by *Sturges and Blaha* (1976). The lasts made estimates for the speeds and the transport of the Gulf western current (70-100 cm s^{-1}; 10 Sv). These first assessments of the MC matched with the later study of *Brooks and Legeckis* (1982), who described a fast (74 cm s^{-1}) northeastward jet between the cyclonic/anticyclonic pair with a transport of 31.5 Sv. Ship samples and subsequent mapping by satellite infrared (IR) sensors allowed performing these estimates. From the early IR maps was already possible to recognize the large warm center (anticyclonic) eddy centered near 25.5°N, 92°W in the mid-Gulf, a warm filament northward and a northeastward advection of meander-filament structures along the gyres fronts (Figure 3).

2 The Mexican Current: flow pattern and dynamics

As we mentioned in the previous section, the Gulf of Mexico circulation is dominated by two major oceanographic system, on its Eastern part the Loop Current and on the Western part a pair of anticyclonic gyre coupled with a semi-permanent cyclonic gyre. The Mexican Current (MC) is the northward western boundary current of the anticyclonic gyre located South-West of the Mexican Gulf. The center of this gyre is around 24°N to 25°N at 92.5°W, and has a positive height of 20 to 30 centimeters depending of the season (*DiMarco et al.*, 2005). The MC extents between 23-25°N and 95-96.5°W where it is constraint by the continental shelf of Mexico (*Sturges*, 1993). As western boundary the MC is a strong current with a mean surface current of 15.3 cm s^{-1}, however it also presents an important variability with speeds peaking at 45 cm s^{-1} (record of ship drift in 1989) and lowest speeds recorded of approximately 7 cm s^{-1}. This variability is seasonal and affects the entire anticyclonic gyre which is strongest in summer and weakest in winter (Figure 4). The transport across the Mexican Current was found to have an average at 8.9 Sv, with a seasonal variability. In depth, the signature of the current is found until 1000 m (e.g., *Brooks and Legeckis*, 1982; *Sturges*, 1993; *Mahadevan et al.*, 1996; *DiMarco et al.*, 2005).

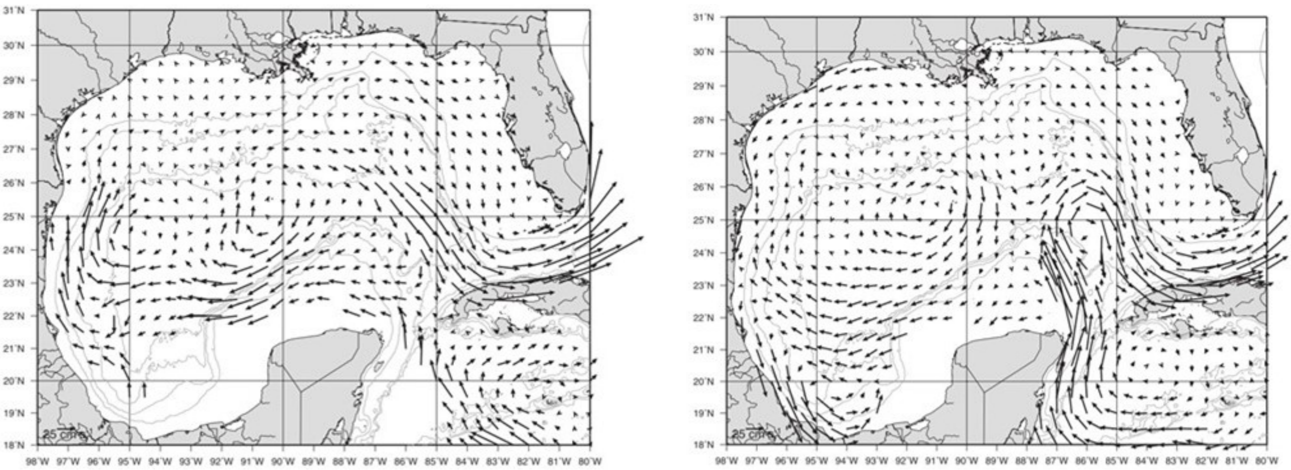

Figure 4: Near surface velocity for summertime (left) and wintertime (right). Velocities are estimated for release between 1989–1999. Shown are the 200-, 1000-, 2000-, and 3000-m isobaths. Adapted from *DiMarco et al.* (2005).

One of the important MC's driving mechanisms is the wind by the Ekman dynamics. The curl of the wind stress on the Gulf of Mexico, during the winter and summer is well correlated with the changes occurring in the mean speed of the surface flow of the MC (*Sturges*, 1993). The wind curl intensity peaks in spring and is minimum in fall. This large scale curl is formed over a wide region (800 km according to *Sturges* (1993)), it is stronger in the Southern part of the Gulf of Mexico around 18-24°N and decreases in intensity as it goes North. The wind stress forcing presents a baroclinic response of the surface flow (Figure 5) with a 1 month lag due to the coast proximity. According to *Merrell and Morrison* (1981), the average wind curl is approximately -12.3×10^{-9} dyn cm^{-3} which is enough to drive a anticyclonic circulation in the Gulf of Mexico, but not to explain the speed and the transport of the MC.

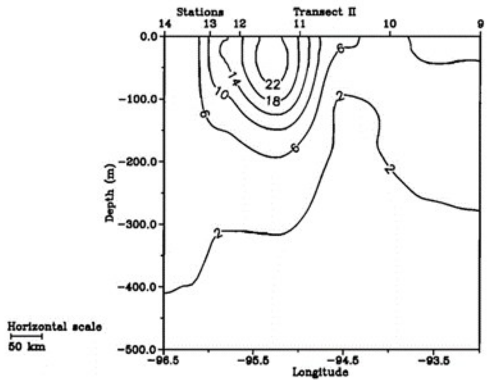

Figure 5: Latitudinal baroclinic flow, in centimeter per second, of the western boundary current during July-August 1985 at 25°N. Source: *Vidal et al.* (1999).

In fact the estimated transport due to the wind is on average approximately 5 Sv with a maximum transport in summer of 7.5 Sv and a minimum in winter of 2.5 Sv. Similarly to other oceanic basins, *Sturges* (1993) showed that the wind-driven circulation in the Gulf (i.e. the negative curl of the wind stress) is very important in modulating the anticyclonic gyre and is the primary source of the annual/seasonal MC variability. The author argued based on geostrophic computations that the winds are essential to reproduced observed velocity patterns. He obtained a 200 km wide MC with speeds of 24 cm s^{-1}, a value close to 22 cm s^{-1}, the speed calculated from the ship drift data in 1986.

Another essential MC driving mechanism is the Loop Current and its rings. *Merrell and Morrison* (1981), *Elliott* (1982), *Vidal et al.* (1999) have suggested the Loop Current rings are the primary mechanism that explain the formation and the maintenance of the MC and the anticyclonic gyre. The Loop Current rings are warm/salty core eddies that can detach from the current and propagate westward (Figure 6). The ring-shedding period vary from 6 to 11 months and the eddies westward propagation speeds are approximately 2-5 km day^{-1} (*Sturges and Leben*, 2000). The time of decay is $\sim$6-12 months for a single eddy traveling into the Gulf before reaching the Mexican coast.

Because of their large dimensions (200 km of diameter and vertical extension of 1000 m), they become relatively important features into the Gulf of Mexico, accounting for 7% of the volume of the entire Gulf (*Elliott*, 1982). These interesting features input a comparable amount of energy to the wind curl in the anticyclonic gyre, 2.8×10^4 J m^{-2} and 5.1×10^4J m^{-2} respectively. Although the eddy energy is less than the wind energy, it is more concentrated in space which makes it very important for the dynamics. When rings bump into the western boundary, their energy is transferred through convective mixing to the anticyclonic gyre enhancing its flow. The collision of the Loop Current anticyclonic rings against the western Gulf boundaries allows a transfer of mass, angular momentum and vorticity to the adjacent water masses, providing an energy that overwhelm the wind-driven circulation (*Vidal et al.*, 1999). After the collision, the eddy energy decreases with an e-folding time scale of approximately 300 days. Because the Loop Current has a ring shedding periodicity close to 11 months, the eddies could maintain the circulation year round and the decay of the energy could explain the seasonality of the intensity of the current.

As we highlighted in Section 1, the driving mechanism of the Gulf of Mexico circulation was a controversial topic between the 60's and 80's. Obviously, both circulation induced by wind and eddies are simultaneously happening in the Gulf, however, with the improvements in the numerical models we were able to compute the relative importance of each mechanism in the Gulf. The numerical simulations from *Hurlburt and Thompson* (1982) and *Elliott* (1982) suggested that the curl of the wind could not bring enough energy into the system to maintain the anticyclonic gyre as we observe it. Their hypothesis was confirmed by the numerical experiments performed by *Mahadevan et al.* (1996), who showed large scale circulation patterns in the Gulf of Mexico, can be well reproduced without any wind forcing.

To conclude, the Mexican Current appears to be driven by two important mechanisms: a year round wind-driven circulation with seasonal variability due to the increase of wind curl during the summer, and a ring-driven circulation due to the collision of warm-core rings with the Gulf of Mexico western boundary. The wind-driven background circulation is overwhelmed by the eddy forcing, and because of a decaying time of 11 month, this phenomenon is also enhancing the variability of the Mexican Current flow.

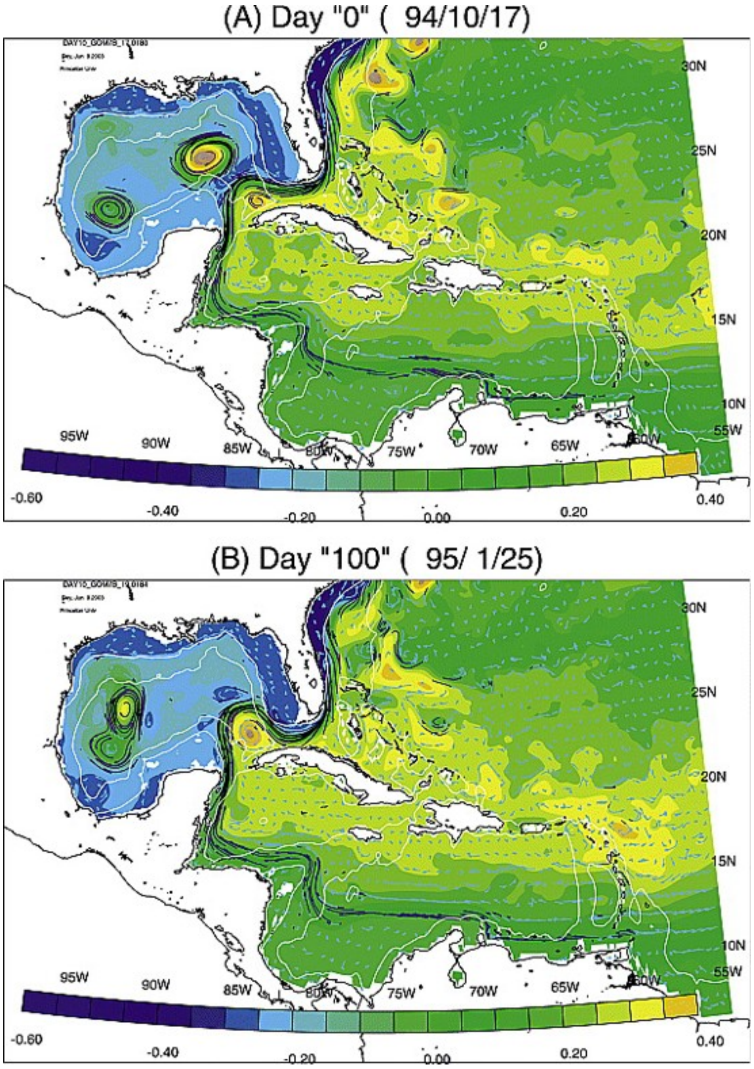

Figure 6: Numerical modeling of Eulerian trajectories showing (a) the formation of a Loop Current Eddy at day 0 and (b) the collision when the Loop Current Eddy has reached the western Gulf boundary and is merging with an older eddy at day 100. Superimposed to the image the color represent the surface elevation (in meter). Colors on trajectories indicate speeds (from light blue to black for increasing speed). Light contours are the 200 and 2000 m isobaths. Source: *Oey and Lee* (2003).

3 Biophysical Interactions: cyclonic/anticyclonic pair and coral dispersal

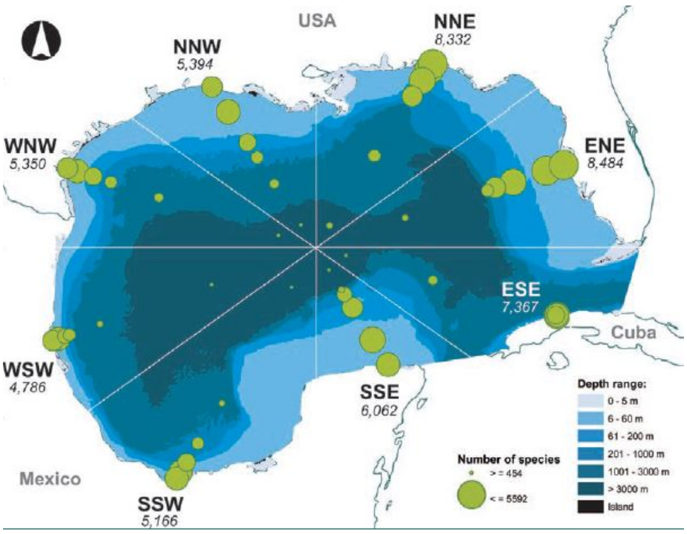

Figure 7: Total number of plant and animal species reported for each region. Sizes of circles are proportional to species numbers within each depth range of the Gulf of Mexico. Source: *NOAA* (2001).

The Gulf of Mexico is broadly recognized as a spot of outstanding biodiversity, in terms of plants, animals, ecosystems and landscapes. In this area there are half of the wetlands of the United States and nesting waterfowl. Colonial waterbird rookeries, sea turtles and fisheries are abundant in all its extension. The coastal boundaries represent, in particular, spots of high biodiverse habitats. In the Gulf of Mexico, mangrove forests, the greatest seagrass bed in the world in Florida Bay and coral reefs, are connected via complex biophysical processes, which drive the recruitment of new juvenile stages of fish, crustaceans and other taxa all around the area. As showed in Figure 7 the biodiversity decreases from the coasts to the deep central waters of the Gulf of Mexico (*NOAA*, 2001). Rich amount of species resides at the WSW boundary where the Mexican current flows (4786 species). Part of this number is represented by coral species, which not only contribute to the biodiversity, but also constitute landscape engineers, building calcified solid reefs, which host numerous fish and invertebrate. Corals disperse via a pelagic phase at the larval stage, and the circulating patterns of the currents of the Gulf play a critical role in that. *Lugo-Fernández et al.* (2001) studied the dispersal patterns of the coral larvae which are released at the Flower Garden Banks (FGB), west Gulf of Mexico. Simulated tracks revealed that the dispersal of coral larvae is strongly related to the cyclonic/anticyclonic nature of the circulation at the western boundaries. Larvae can exploit both the cyclonic gyre and local recirculating flows to self-seeding at the FGB (which is the most probable fate), where they were born and are more likely to survive. Other dispersal dynamics, using the offshore eddies, or continuous eastward movement, or also a cross basin transport, lead larvae to colonize the East of the Gulf of Mexico (Figure 8). Incredibly, the oil spill platforms constitute a suitable substrate for settlement, and the simulations revealed that corals can increase the reef extension by 38% by exploiting 129 platforms of the NW Gulf (*Lugo-Fernández et al.*, 2001).

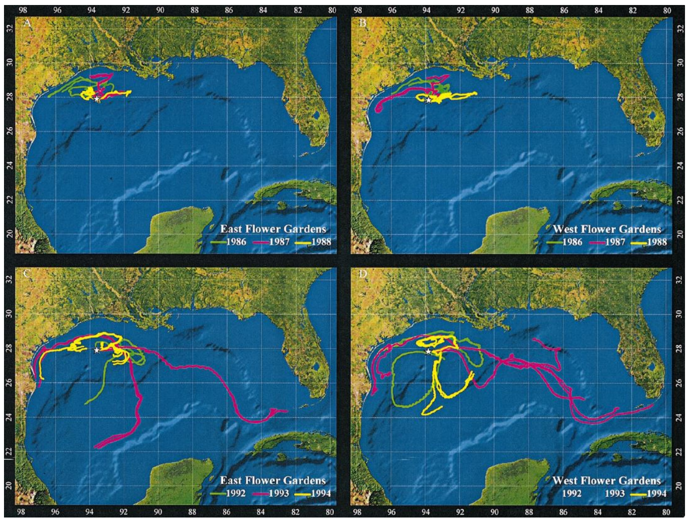

Figure 8: Simulated trajectories from (A) the East Flower Garden Bank 7 evenings after August full moon; (B) West Flower Garden Bank 8 evenings after August full moon showing recirculation ows over the FGB (Mode 4); (C) the East Flower Garden Banks 8 evenings after the August full moon; (D) West Flower Garden Bank, 8 evenings after the August full moon showing trajectories reaching Florida Reefs in 50 and 60 days, respectively (Mode 5). Source: *Lugo-Fernández et al.* (2001).

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