


CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA




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NUMERICAL MODELING OF THE CIRCULATION OF THE GULF OF CALIFORNIA: A BRIEF HISTORY

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A brief history of the numerical modeling of the circulation of the Gulf of California (GC) is presented. It started from homogeneous models in one- and two-dimensions studying the tidal propagation along the Gulf, tidal dissipation, generation of residual currents and the wind-induced currents. More complete inhomogeneous models followed, also in a one-, two- and three-dimensions fashion. Obviously, details of the circulation with the latter models were better modeled but also new findings came. Understanding sometimes the physics of observations or measurements, which includes the reality with all time and spatial scales unfiltered, is difficult. The actual state of the art of the models of the GC are close to be functional (not operational yet) and will be a useful tool to understand both the dynamics of the Gulf and, combined with biological models, the behavior of some fisheries which would allow the decision makers to properly manage some important fisheries of the Gulf.

1. INTRODUCTION

The physical oceanography of the Gulf of California (GC) has been studied since the early 1940's. Observations from ships, instrumental arrays, satellite measurements and numerical modeling have advanced the understanding on how its general circulation is driven and a comprehensive review of the actual knowledge can be consulted in Lavín and Marinone (2003). Briefly, "the engine" behind the Gulf's circulation is the result of the combined forcing of the Pacific Ocean (PO) through its opening, the atmospheric forcing/interaction over its entire surface, and the local stirring induced by bathymetric features such as sills, capes and basins. Obviously, this large spectrum produces several features which interact and produces many structures with a broad band of spatial and temporal scales. However, the time scales from hours (due to tides) to seasonal (due to the earth's journey around the sun) are pretty well studied.

Due to the large communication with the PO, the water masses of the Gulf are the same as the adjacent ocean, namely, Pacific Deep, Pacific Intermediate, Subtropical Subsurface, California Current, Tropical Surface, plus the Gulf of California Water (GCW), locally produced in the northern Gulf (Bray and Robles 1991). Another particular feature of the Gulf, related to the production of the GCW, is that the Gulf is an evaporative basin that gains heat in the annual average.

Also, because of the direct communication with the PO, features such as currents, coastal trapped waves, tides and El Niño signals, freely enter the Gulf and dominate the Gulf's circulation, especially at the seasonal scale (Ripa 1997). The seasonal surface circulation induced by the PO is in phase with that produced by the monsoonal winds over the surface resulting in a summer cyclonic and winter anticyclonic circulation. The tides of the Gulf are in co-oscillation with the PO and the semidiurnal components are near resonance resulting in a four fold increase in amplitude at the head of the Gulf. The associated tidal currents increase accordingly and especially at the midriff islands area where extensive mixing occurs (Paden *et al.* 1991). This intense mixing over the sills, interpreted as tidal pumping, dominates the mean and low frequency deep circulation (López *et al.* 2006, 2008) around Ángel de la Guarda Island. Many mesoscale features are produced by local processes that interact with this seasonal circulation and produce structures such as plumes, jets, fronts, gravity currents, etc., which still needs to be studied.

In this chapter, a brief chronological story of the numerical modeling studies of the Gulf's circulation is presented. Some of these models have focus on known features of the Gulf circulation and dynamics; others have resulted in key contributions to the present knowledge of the physical oceanography of the Gulf. As there are many numerical models adapted to the Gulf, here they are presented in three groups as follows: Section 2 and 3 are devoted to homogeneous (barotropic) and inhomogeneous (baroclinic) models, respectively, adapted to or developed for the GC. Section 4 presents global models that have zoom into the Gulf. Within each group, the models are presented almost in chronologically order and Tables 1, 2 and 3 present (almost) all of them, with their forcing, some basic characteristics and the main topic modeled/studied. There will be no critical analyses about the validation of their results, for that the reader should consult the original papers; only the achieved goal is highlighted and taken as valid. Finally, in Section 5 different applications with interdisciplinary focus are presented.

2. HOMOGENEOUS MODELS: ONE-, TWO-, AND THREE-DIMENSIONAL

Homogeneous models were initially devoted to study the tides in the Gulf with both, one- and two-dimensional models (see Table 1). The first numerical model was the two-dimensional (2D) model of Grijalva (1972), who reproduced the general behavior of the M2 tidal constituent, *i.e.*, the propagation of the tide around the Gulf with its amplification due to resonance. His model included a non linear parameterization of the friction term but excluded advection. Stock and Filloux (1975) and Stock (1976) followed with both one-dimensional (1D) linear model and a 2D model including also non linear friction only. He made the first calculations of the energy dissipation from a numerical model (Filloux 1973, calculated the tidal energy dissipation from few observations before) due to the tides and studied the resonance behavior of the different tidal constituents.

As mentioned before, the semidiurnal band is close to resonance. A direct consequence of this amplification is the large tidal currents that are produced, and their interaction with topography leads to tidal rectification (Zimmerman 1978), that is, the generation of mean or residual currents. Quirós *et al.* (1992) first modeled the residual currents produced by the M2 component with the use of a full nonlinear model. Only over the shallow northern Gulf and in the midriff archipelago, the currents were found significant.

Two more one-dimensional models followed (De León and Ripa 1989, Ripa and Velázquez 1993) with the intention to model the general behavior of the tides along the Gulf exploiting the fact that they are simpler and faster than the 2D models (in a computational sense) to explore, for example, the dependence of dissipation with different parameters. But, with the development of more powerful computers, the two- and three-dimensional (3D) models were pursued as they give much more detailed information.

In the second half of the 1990s several two- and three-dimensional models were reported (see Table 1). All of them were fully nonlinear and focused on the residual flow (tidal rectification) generation with one or many tidal constituents and more calculations of tidal energy dissipation. Tidal rectification was known to be important in the northern Gulf and at the islands area, where also more energy dissipation happens. Marinone (1997) found that the residual currents are mainly produced by the M2 tidal constituent, difficult to 'see' from observations only. The effect of the wind and topographic stress on the residual circulation was studied by Argote *et al.* (1998) and Marinone (1998) (see also Salas de León *et al.* 2003, and Makarov and

TABLE 1. One-, two- and three-dimensional homogeneous models. These models were only forced by tides and winds. In the forcing column W stands for wind, and M2, N2, K1, O1 are tidal constituents. MTC mean that more than the previous 4 tidal constituents were included. L and FNL stands for linear and fully nonlinear, respectively, and NA for not available.

Numerical study	Forcing	Characteristics	Resolution	Modeled
Grijalva (1972)	M2	2D, non-linear friction	7×7 km	Elevation and tidal currents - First model
Stock and Filloux (1975)	M2	1D, L	NA	Energy flow and dissipation
Stock (1976)	M2, S2, N2, K1	2D, non-linear friction	10×10 & 20×20 km	Energy dissipation, resonance character, shape of the 'modeled' Gulf
Quirós *et al.* (1992)	M2	2D, FNL	7×7 km	Elevations, tidal currents and residual circulation
De León and Ripa (1989)	M2	1D, L	6.6 km	Energy dissipation, amplitudes and phases along the Gulf
Ripa and Velázquez (1993)	MTC	1D, L	6.6 km	Amplitudes and phases along the Gulf
Argote *et al.* (1995)	M2	2D, FNL	6.6×6.6 km	Elevation, tidal currents and energy dissipation
Marinone (1997)	MTC	2D, FNL	6.5×6.5 km	Mean and low frequency residual circulation, momentum and energy budgets
García-Silva and Marinone (1997)	M2	2D, FNL	14×14 to 2×2 km	Effect of grid size on mean residual circulation
Carbajal and Backhaus (1998)	MTC	2D, FNL	10.2×9.4 km	Residual current and energy budget
Marinone (1998)	M2 and W	2D, FNL	6.5×6.5 km	Effect of topographic stress on mean residual currents
Argote *et al.* (1998)	M2 and W	2D, FNL	6.6×6.6 km	Effect of tidal and wind forcing on mean residual currents
Garcia-Silva and Marinone (2000)	MTC	2D, FNL	6.5×6.5 km	Tidal dynamics and energetics

TABLE 1 (CONTINUED).

Numerical study	Forcing	Characteristics	Resolution	Modeled
Marinone (2000)	M2, S2, K1, O1	2D and 3D, FNL	6.5×6.5 & 4.6×3.9 km and 12 layers & 20 σ levels	3D modeling of tidal currents
Salas de León *et al.* (2003)	M2	3D, FNL	5.1×4.7 km, 12 layers	Effect of tidal stress on residual currents
Makarov and Jiménez-Illescas. (2003)	Potential vorticity conservation	2D, FNL	7.8×9.2 km	Stationary currents due to planetary and topographic effects

Jiménez-Illescas 2003 whom focus more on theoretical aspects such as tidal stress and potential vorticity conservation). The inclusion of the wind forcing produces stronger currents, especially along the coast at the southern half of the Gulf.

An interesting result comparing 2D and 3D modeling of the tides showed that the tidal heights are better modeled with a simple two-dimensional model, while the three-dimensional model reproduced better the tidal currents (Marinone, 2000).

Diagnostic analyses such as momentum, vorticity and energy budgets, effects of tidal stress, and combinations of the forcing are included in many of the papers (from the models) to explain different features. With these models, tidal heights and currents, the associated residual circulation, and the circulation produced with the wind forcing with the rectified tidal currents were well studied. But perhaps the most important lesson from these models was the building of knowledge as a reference towards the understanding of the general circulation which is rich in thermohaline structure, such as water masses, sea surface temperature, heat and salt fluxes, etc.

As examples of the results obtained by these homogeneous numerical models, Figure 1 shows the amplitudes of the M2 and K1 tidal constituents which are the largest of the semidiurnal and diurnal bands, respectively, and the factor form which measures the relative importance of the diurnal to semidiurnal bands. Note that the amphidromic point is shifted to the west, which is due to the energy dissipation as the tidal wave propagates around the Gulf. If there were no energy dissipation, the amphidromic point would be at the center of the Gulf. These results were recreated from the model of Marinone (2003) but were obvious since Grijalva (1972).

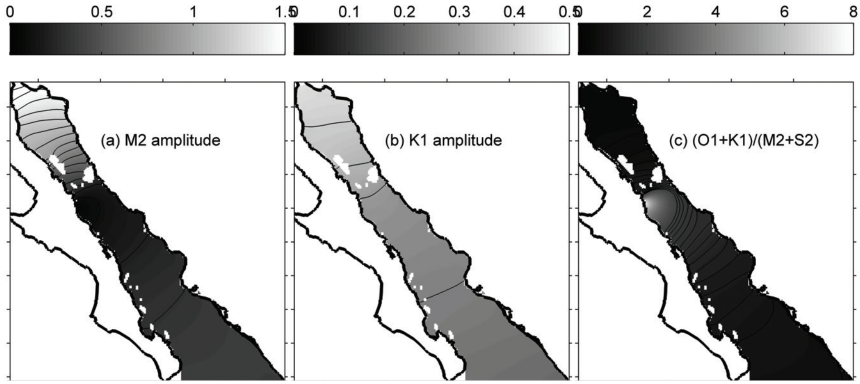

FIGURE 1. Amplitude of the largest semidiurnal and diurnal tidal (a) M2 and (b) K1, respectively, and (c) factor form calculated as the sum of the amplitudes of the K1 and O1 diurnal constituents divided by the sum of amplitudes of the M2 and S2 semidiurnal constituents.

3. INHOMOGENEOUS MODELS: ONE-, TWO-, AND THREE-DIMENSIONAL

The first three-dimensional baroclinic model was that of Carbajal (1993) (see Table 2). He studied the general circulation with a stratified Gulf but forced only with the tides and the winds. No structure of the hydrography or associated currents in the opening was included. Many results are presented in this work about the baroclinic circulation of the currents due to the M2 tidal component, winds and their combinations.

A key simple linear "one-dimensional" two-layer numerical model for the understanding of the origin of the seasonal variability of the Gulf's circulation was that of Ripa (1997). He demonstrated that most of the dynamics and thermodynamics are controlled by the PO, with the wind stress and heat fluxes playing a secondary role. No tidal forcing was included in his analyses. Beier's two-dimensional two-layer linear model followed and corroborated Ripa's result but found that the wind stress forcing is almost as important as that of the PO. This model was used also to study the seasonal evolution of the circulation and the effect of the stratification on the circulation of the northern Gulf (Beier and Ripa 1999 and Palacios-Hernández *et al.* 2002).

TABLE 2 (RIGHT). One-, two- and three-dimensional inhomogeneous models. In the forcing column W stands for wind, M2, N2, K1, O1 are tidal constituents. MTC mean that more than the previous 4 tidal constituents were included. PO, H and E mean forcing by the Pacific Ocean, heat, and evaporation, respectively. L and FNL stands for linear and fully nonlinear, respectively, and NA for not available.

Studies	Forcing	Characteristics	Resolution	Modeled
Carbajal (1993)	MTC and W	3D, FNL	10.2×9.4 km, 12 layers	Tidal currents and general circulation
Ripa (1997)	W, H, PO	L, 1D	2 layers	Relative importance of the three forcing at the annual scale
López (1997)	W, H, W	3D, FNL	6.6×6.6 km, 19 levels	Water mass formation
Beier (1997)	W, H, PO	L, 2D	6.6×6.6 km, 2 layers	Sea level and surface annual circulation, heat balance
Beier and Ripa (1999)	W, H, PO	L, 2D	6.6×6.6 km, 2 layers	Annual surface circulation, heat balance
Palacios *et al.* (2002)	W, H, PO	L, 2D	6.6×6.6 km, 2 layers	Effect of the seasonal stratification on the circulation
Marinone (2003)	MTC, W, H, E, PO	3D, FNL	3.9×4.6 km, 12 layers	Mean and seasonal circulation, SST, heat and salt balances
Martinez and Allen (2004a,b)	Meso-scale waves from PO	3D, FNL	3.0×3.0 km, 50 σ levels	Propagation of waves
Marinone and Lavín (2005)	MTC, W, H, E, PO	3D, FNL	3.9×4.6 km, 12 layers	Tidal currents ellipses
Allende (2005)	W, H, PO	3D, FNL	NA	Energetics of physical processes
Mateos *et al.* (2006)	MTC, W, H, E, PO	3D, FNL	3.9×4.6 km, 12 layers	Eddy formation
Marinone (2007)	MTC, W, H, E, PO	3D, FNL	3.9×4.6 km, 12 layers	Deep circulation at large islands area, tidal mixing
Marinone (2008)	MTC, W, H, E, PO	3D, FNL	1.3×1.5 km, 12 layers	Deep circulation at large islands area, tidal mixing
Gómez (2008)	W, H, PO, MTC	3D, FNL	E-O 3 km N-S 3.3-5.6 km 20 levels	Effect of tidal mixing on SST
Zamudio *et al.* (2008)	Nested models	3D, FNL	7.8×9.2 km, 20 z-levels	Generation of eddies during summer

The only model dealing with water mass formation in the Gulf of California is that of López (1997). Modeling only the northern Gulf with wind, surface heat flux and evaporation forcing found that water mass is formed in the shallow areas where the water cools and sinks and then follows a cyclonic circulation. The latter modeled winter circulation is in accordance with future findings with more complete models, as shown below.

Then, a combination of the previous models and forcing with a multi-layer baroclinic model by Marinone (2003) followed. The numerical model is the same as that of Carbajal (1993) but the forcing is inspired on all the knowledge mentioned before, *i.e.*, by the PO through temperature, salinity and sea level at tidal and climatological time scales and at the sea surface by climatological winds, heat and freshwater fluxes in order to model the mean and seasonal circulation. The relative importance of the different forcing to reproduce the SST and the general circulation in different regions was determined. In general, the PO and the winds largely determine the overall seasonal circulation of the Gulf but the contribution to the mean circulation by the tides was found (with a full 3D baroclinic model) to be important in the northern Gulf and islands region. Also, from this model, the tidal currents ellipses were modeled overall the Gulf (Marinone and Lavín 2005) for a broad number of tidal constituents.

The propagation of coastal trapped waves entering the Gulf was modeled by Martínez and Allen (2004a, b). They found that most of their energy, when reaching the sill area, returns through the Peninsula side and a small fraction enters the northern Gulf where it is dissipated. Bravo (2011) studied the propagation of internal tides produced by the interaction of the barotropic tide and sills at the central Gulf.

The bottom circulation around Ángel de la Guarda Island proposed by López *et al.* (2006, 2008) was modeled by Marinone (2007, 2008) after a refinement of the model of Marinone (2003) in which the horizontal resolution was reduced by a factor of three. This deep circulation is persistent along the year and explains the cold surface and nutrient rich waters of Canal de Ballenas by means of a deep convergence of the currents that leads to a semi-permanent upwelling. Also, Gómez (2008) modeled the effect of the bathymetry and the tides on the generation of cold SST of the northern Gulf.

The propagation and generation of anticyclonic eddies in the southern Gulf was modeled by Zamudio *et al.* (2008) with a series of nested models and found that they are not locally generated and are produced by the remote forcing of the Pacific, in accordance with previous models of the Gulf.

As examples of the results obtained with the inhomogeneous models, Figure 2 shows the surface seasonal circulation induced by the seasonal forcing of the PO

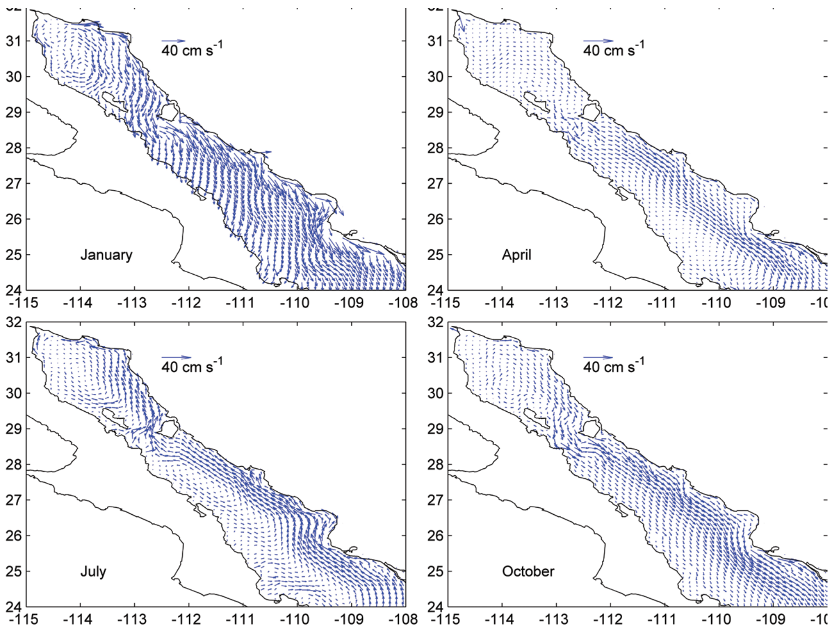

FIGURE 2. Surface seasonal circulation. The currents represent the average of the indicated month. The model was forced with tides and climatological temperature and salinity fields at the mouth, climatological heat and freshwater fluxes and winds at the sea surface. Only one every eleven vectors are plotted for clarity.

(climatologic temperature and salinity fields and the tides), wind, heat, freshwater fluxes and tides. The northern Gulf is dominated during winter by the basin wide cyclonic gyre and during summer by the anticyclonic gyre. The southern Gulf develops a strong coastal surface current at the mainland side. Figure 3 shows the bottom circulation around Ángel de la Guarda Island for February and September for the last and penultimate model layers. This circulation is persistent almost all year round. The results of Figure 2 and 3 were obtained from the model of Marinone (2008).

4. THREE-DIMENSIONAL GLOBAL MODELS: ZOOM INTO THE GC

The first model of this kind (see Table 3) is that of Zamudio *et al.* (2002) who study also the propagation of coastal waves into the Gulf, however, this model only 'sees' half the Gulf. López *et al.* (2005) using two models, one the same as Zamudio *et al.* (2002) and the other a model that includes the entire Gulf, studied the effects of

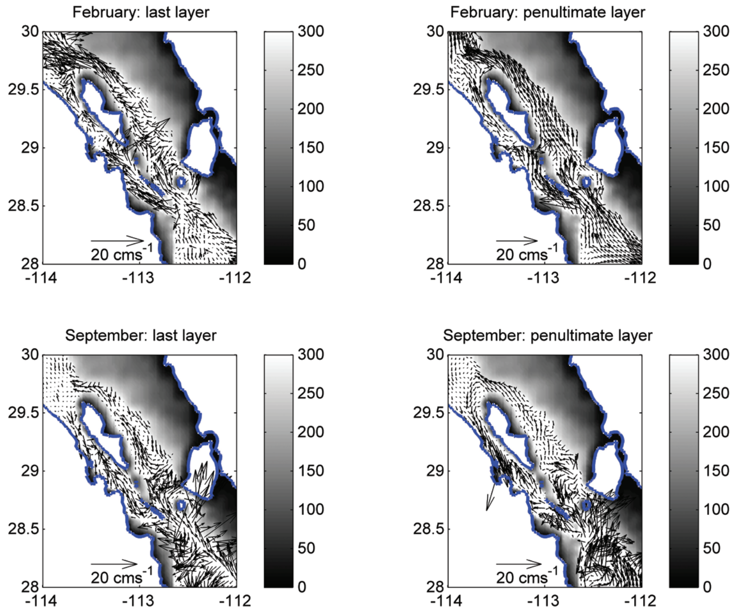

FIGURE 3. February and September bottom circulation. Shown for each month are the last and penultimate model layer velocities for each mesh point. The model was forced with tides and climatological temperature and salinity fields at the mouth, climatological heat and freshwater fluxes and winds at the sea surface. Only one every three vectors are shown.

TABLE 3. Output of large scale numerical models zooming into the Gulf of California. FNL stands for fully nonlinear.

Studies	Forcing	Characteristics	Resolution	Modeled
Bravo (2011)	W, H, PO, MTC	3D, FNL	E-O 3 km N-S 3.3-5.6 km 20 levels	Internal waves
Zamudio *et al.* (2002)	Nearly global, operational, only half Gulf	3D, FNL, baroclinic	2.0×2.3 km, 7 layers	Incursion and evolution of coastal trapped waves generated outside the Gulf
López *et al.* (2005)	Two global models	3D, FNL, baroclinic	2.0×2.3 km, 7 layers and 7.8×9.2 km, 19 vertical-levels	Effect of El Niño on flow exchange

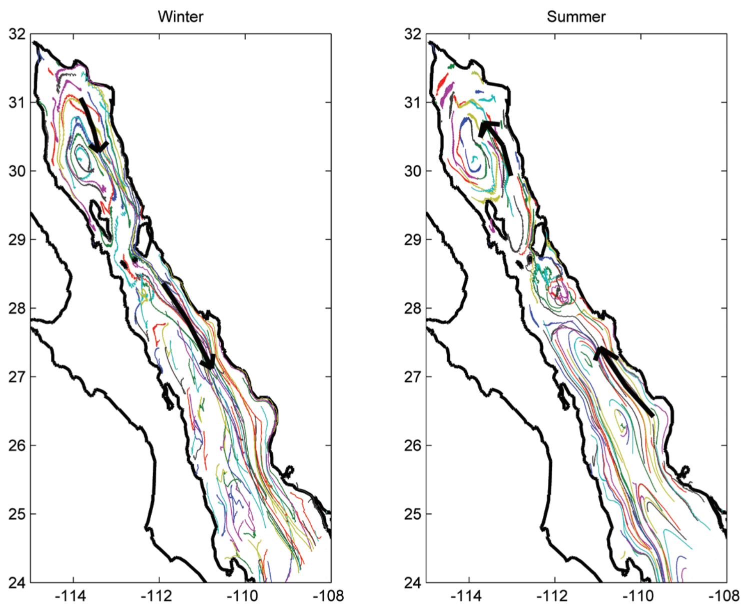

FIGURE 4. Lagrangian circulation for the months of January and July. The trajectories are obtained by integrating the instantaneous velocity fields whose time averaged current are shown in Figure 2. The trajectories follow a three-dimensional path, but the figure shows only the horizontal expression. The arrows are visual aids to indicate the flow direction.

El Niño on the exchange of water within the Gulf. He found an increased inflow in the upper part of the water column compensated with an increased outflow at underlying waters as compared to 'normal' years.

5. APPLICATIONS OF THE NUMERICAL MODELS

The results from Marinone's model (2003) which cover time scales from tidal to seasonal made possible the development of an online tool that predicts sea level and currents overall the Gulf. This tool is available at http://Gulfcal.cicese.mx/ and produces the variables with several options (in a friendly way) to the user. The options range from different regions of the Gulf, different layers, dates, etc. Also, the variables can be reconstructed in such a way that tidal currents and seasonal circulation can be obtained separately.

From the numerical models the Lagrangian circulation of the GC has been characterized in many papers (*e.g.*, Velasco and Marinone 1999, Gutiérrez *et al.* 2004, Marinone 2006, Marinone *et al.* 2008) both with homogeneous and inhomogeneous models and in two- and three- dimensions. Figure 4 shows one-month trajectories

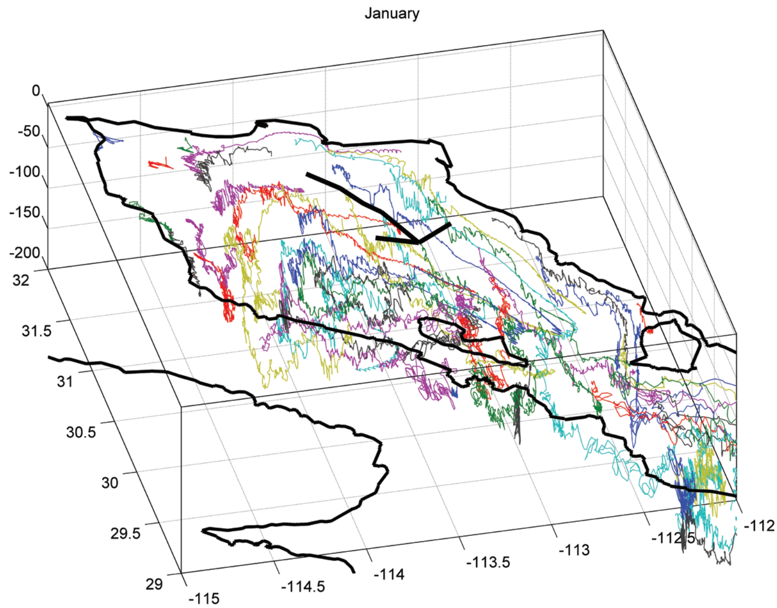

FIGURE 5. Three-dimensional view of some of the trajectories shown in Figure 4 for January. The arrow is a visual aid to indicate the anticyclonic surface flow direction.

for January and July, representatives of the winter and summer circulation. From this type of results, one can visualize the fate of a float (pollutant or any passive tracer), which are not strictly the same as those inferred by eye by observing the Eulerian currents (see Figure 2), especially when strong horizontal and/or vertical shears are present in the velocity field.

The currents shown in Figure 2 are the horizontal component of the surface layer, and the path shown in Figure 4 is only the horizontal expression, however the particles are moving in the three dimensions advected by the full 3D velocity field as, for example, shown in Figure 5 for the northern Gulf. Several applications with this information have been used to study the possible path of larvae and tracers. With these Lagrangian models several indexes such as the time that particles take to leave or escape from a determined area, preferred paths of circulation, final destination after some time, etc., can be constructed, by demand, which can be very useful to characterize the water movements for different applications that require the knowledge of the distribution and evolution of certain properties.

Studies of connectivity, in which the possible destination from one region to another, without the proper knowledge of the species behavior have been done for the northern Gulf (Marinone *et al.* 2008, Peguero-Icaza *et al.* 2008, Sánchez-Velasco *et al.* 2009). The management of the different fisheries needs a proper knowledge of population connectivity/dispersal as well. Useful information can be generated from these models to test and understand the effect of reserves in marine fisheries as did Cudney-Bueno *et al.* (2009). Both, biology and physics are indispensable to properly model the fate of different species in their journey from spawn to settlement. Obviously, with fishes it is more difficult than with species that settle as they dominate the circulation at will when they are adults.

6. FINAL REMARKS

At present, models of the Gulf of California are still in the process of improving and incorporating more realistic forcing. Several projects are also including the behavior of different key species of the Gulf in order to understand and properly manage their fisheries. However, the models results need to be continuously challenged and the best way to do so is to continue measuring the different variables at the sea.

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Exploring Mexico's northwest, the Baja California Peninsula, its surrounding oceans, its islands, its rugged mountains, and rich seamounds, one feels diminished by the vastness and the greatness of the landscape while consumed by a sense of curiosity and awe. In a great natural paradox, we see the region's harsh arid nature molded by water through deep time, and we feel that its unique lifeforms have been linked to this desert and sea for thousands of years, as they are now.

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