On the three-dimensional numerical modeling of the deep circulation around Ángel de la Guarda Island in the Gulf of California

S.G. Marinone

Department of Physical Oceanography, CICESE, Km 107 Carretera Tijuana-Ensenada, 22860 Ensenada, B.C., México

Abstract

A three-dimensional nonlinear baroclinic model is used to model the circulation in the Ballenas Channel, Gulf of California, México, which was inferred from current meter observations over three sills that surround the area. The suggested circulation consists of deep inflow that follows two paths: the first one is a direct spill of water through San Lorenzo sill into Ballenas Channel, the second one, a larger route that starts at San Esteban sill, then flows north of the island passing over Tiburón and Delfín basins, and then turns to the south reaching the North Ballenas Channel sill and then spills into Ballenas Channel. Following the latter result, a previous modeling effort to reproduce the circulation was partially obtained, the long path was not reproduced and it was believed that finer horizontal resolution was needed. In this work, the bathymetric resolution was increased by a factor of three and the full path of this deep circulation is now obtained and corroborated.

1. Introduction

The large islands area of the Gulf of California (Fig. 1) has long been recognized by its colder SST as compared to their surrounding waters both by hydrographic measurements (Argote et al., 1995) and by satellite (Soto-Mardones et al., 1999). The classical explanation has been that the large tidal currents produce severe mixing (Paden et al., 1991). Recently López et al. (2006) (hereafter LCA) used current meter observations to propose that this low SST is due to a deep inflow to the Ballenas Channel (BC) through its northern and southern entrances, the San Lorenzo (SL, 400 m depth) and San Esteban (SE, 600 m depth) sills and the North Ballenas Channel sill (NBC, 600 m depth), as “gravity currents” with a corresponding outflow by continuity in the upper levels over the same sills. The circulation that LCA suggest is (see diagram in Fig. 1b) that deep water enters the Ballenas Channel by the south directly through (a) San Lorenzo sill and (b) through a longer path that starts with water passing San Esteban sill, filling the Tiburón basin (TB), then reaching Delfín sill (DS, 400 m depth) and filling Delfín basin, and following to NBC sill and finally entering the BC. Between the southern tip of Ángel de la Guarda Island (AGI) and the northern tip of San Lorenzo Island the maximum depth is only ~ 200 m and thus there is no deep water exchange between TB and BC. They argue that these deep inflows converge at depth in BC and must produce upwelling. Marinone (2007) modeled the circulation proposed by LCA and found partial agreement: same deep southern entrance through the SL and SE sills but the circulation through the North Ballenas Channel sill was blocked and returned on the upper part of the water column along the east side of AGI. Marinone (2007) suggested that the disagreement could be due to a poor resolution of the bathymetry, particularly around the northern area of AGI and the NBC sill.

The objective of this work is to provide numerical evidence of the circulation around Ángel de la Guarda Island as a result of increasing three-fold the resolution of the model of Marinone (2007).

2. Numerical model and analysis

The numerical model used is the same as Marinone (2007), who used a smooth version of the gulf's bathymetric data of the Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE). In this work the data are unsmoothed and the grid was interpolated by a factor of three and new data from San Esteban and San Lorenzo areas, and from the upper gulf, from CICESE’s cruises were incorporated. The difference resulted in a model’s bathymetry with more realistic deeper sills and basins around the study area.

A very brief description of the model is given here now; for more details see Marinone (2003) and references therein; the model equations are shown in Appendix. The model is the three-
dimensional baroclinic Hamburg Shelf Ocean Model (HAMSOM) developed by Backhaus (1985) and adapted to the Gulf of California (GC) by Marinone (2003). The domain has a mesh size of $0.83^\circ \times 0.83^\circ$ ($\approx 1.31 \times 1.54$ km) in the horizontal, and 12 layers in the vertical with the lower levels fixed at 10, 20, 30, 60, 100, 150, 200, 250, 350, 600, 1000 and 4000 m. The maximum depths just south of our study area are $\approx 800$ m so the vertical resolution is considered enough. At the open boundary the model is forced with tides (M2, S2, N2, K2, K1, O1, P1, Ssa, and the Sa components) and climatological hydrography from CICESE’s historical database. At the sea surface climatological heat and fresh water fluxes are imposed. For wind forcing two cases were used: (a) a spatially homogeneous up- and down-gulf annual sinusoid (the source of this seasonal wind is justified following Ripa, 1997) and (b) winds derived from QUIKSCAT data. (Both runs gave basically the same deep currents and here are shown those from case (a)).

A one-year simulation is used to relate the annual average and to show the three-dimensional circulation, focusing on the flow at the depths of the sills. Instantaneous currents are used to compute trajectories of particles released at different locations. Transport across different cross-sections (see Fig. 1) was calculated for the summer and winter periods, as well as for the annual mean, for Section I that includes NBC sill, Section II which is just west of SL sill, Section III that includes SE sill, and Sections IV and V to check continuity.

3. Results

The seasonal circulation obtained in this new version of the model’s bathymetry is the same as that obtained by Marinone (2003) which has been validated with observations. As noted before, the deep circulation around Ballenas Channel was in disagreement only in the northern entrance to the channel (Marinone, 2007). The surface circulation in the northern gulf changes from cyclonic to anticyclonic once a year. In the southern gulf it changes twice a year. This last statement has been reported only three times: Ripa and Marinone (1989) with hydrographic data in the central gulf, and, by Marinone (2003) and Zamudio et al. (2008) with numerical models. The communications between the northern and southern parts are basically restricted to up- or down-gulf flow, through the channels between the large islands.

Here, only the currents in the lower layers of this area are shown in Fig. 2. The circulation now reproduces completely the description of LCA, the speeds are stronger than those modeled by Marinone (2003, 2007), and therefore more comparable to observations. The currents flow up-gulf all year long at depth over SL and SE sills. Over NBC sill, there is a short period of time when the bottom current that entered from SL flows to the north and passes over the North Ballenas Channel sill.

The transports are also in agreement with the previously reported measurements. In Table 1 it is shown, for two selected months and for the annual average, the transports for the different model layers normal to the sections close the NBC, SL and SE sills. The transports at depth are always into Ballenas Channel and up-gulf over San Lorenzo and San Esteban sills, respectively, although not always as strong as during the months shown and therefore the annual average is smaller. In general, the transports over San Lorenzo sill are larger than those over San Esteban and North Ballenas Channel sills in agreement with LCA.

As pointed out by LCA and Marinone (2007), these inflows to the Ballenas Channel throughout the year imply a constant upwelling via continuity. To visualize these paths of circulation, particles were seeded at sill depths in different location of the area. Particles starting at the North Ballenas Channel and at San Lorenzo sills enter the channel (where they experience very large vertical excursions) and exit the channel through the upper layers above the sills and between the channel between Ángel de la Guarda and San Lorenzo islands. The trajectories of the particles starting from San Esteban sill reach Ballenas Channel surrounding Ángel de la Guarda Island in about two months. The tracks of a few particles for summer and winter are shown in Fig. 3a and b, respectively, and their depth average at the same time is shown in Fig. 3c and d. Note that while the surface circulation during the periods chosen is in opposite directions, the flow at depth is always up-gulf. Many particles also...
go to the upper levels without traveling all the path just mentioned, and are advected in different directions as the gulf’s circulation has a strong seasonal variation. However, at depth, the path is almost stationary around AG. As an example for the deep tracks, the trajectories of particles starting (more than a thousand but only shown one every ten tracks) at depths larger than 400 m are shown in Fig. 4. Two preferred surface exit routes are present in this period of time, one through San Lorenzo sill and the other between Ángel de la Guarda and San Lorenzo islands. From the total of 1100 particles seeded below 400 m, 74% leaves the channel in these two months (all with different destinations depending in the time in which they reach the upper layers).

4. Discussion and conclusions

The deep flows at San Esteban and San Lorenzo sills are always up-gulf, independently that the currents at the rest of the gulf evolve reversing direction seasonally. South of the sills, over the range of depths of the sills (400–600 m), the mean currents in Fig. 2 show anticyclonic circulation with stronger currents flowing up-gulf from the peninsular side. However, at these depths the circulation changes seasonally from cyclonic to anticyclonic, but in either case the currents still flow north where it turns around the gulf, from the mainland to the peninsular side and vice versa (not shown). Just south of the sills, in general the gulf’s bathymetry narrows (like a funnel), causing the currents to impinge over a “ramp” independently of the direction of the currents. This flow carries the subsurface subtropical waters from the Pacific and spills up-gulf over the sills (see scheme in Fig. 1) into Ballenas Channel and Tiburón basin. Later, this water becomes the Gulf of California water (López et al., 2008).

The result obtained here is in agreement with the observations of LCA. The bathymetric improvements, with respect to that of Marinone (2003, 2007) (with a lower resolution and deeper sills),

<table>
<thead>
<tr>
<th>Nominal depth</th>
<th>November</th>
<th>July</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBC</td>
<td>SL</td>
<td>SE</td>
<td>NBC</td>
</tr>
<tr>
<td>0–10</td>
<td>0.008</td>
<td>0.008</td>
<td>–0.033</td>
</tr>
<tr>
<td>10–20</td>
<td>0.009</td>
<td>0.007</td>
<td>–0.034</td>
</tr>
<tr>
<td>20–30</td>
<td>0.010</td>
<td>0.007</td>
<td>–0.035</td>
</tr>
<tr>
<td>30–60</td>
<td>0.038</td>
<td>0.010</td>
<td>–0.113</td>
</tr>
<tr>
<td>60–100</td>
<td>0.051</td>
<td>0.002</td>
<td>–0.142</td>
</tr>
<tr>
<td>100–150</td>
<td>0.047</td>
<td>–0.006</td>
<td>–0.163</td>
</tr>
<tr>
<td>150–200</td>
<td>0.030</td>
<td>0.006</td>
<td>–0.120</td>
</tr>
<tr>
<td>200–250</td>
<td>–0.013</td>
<td>0.023</td>
<td>–0.039</td>
</tr>
<tr>
<td>250–350</td>
<td>–0.119</td>
<td>0.004</td>
<td>–0.095</td>
</tr>
<tr>
<td>350–600</td>
<td>–0.056</td>
<td>–0.433</td>
<td>0.162</td>
</tr>
<tr>
<td>600–1000</td>
<td>–0.335</td>
<td>–0.292</td>
<td>–0.511</td>
</tr>
</tbody>
</table>

| Net | –0.005 | –0.707 | –0.400 | –0.092 | –0.851 | –0.511 | –0.021 | –0.450 | –0.226 |
| II + III + IV + V | 0.005 | 0.028 | 0.007 |
made the up-gulf flow to the east of AGI now able to reach and pass the North Ballenas Channel sill. This result again proves that the better the resolution the better the model results. It does not mean that the model now is reproducing everything about the circulation of the gulf; however, this result is an important step towards a better modeling of the circulation of the Gulf of California.

The particle tracking depicts reasonably well the circulation around Ángel de la Guarda Island, however, the overflows behave as gravity currents, and the advection of the particles does not take into account their density. The path of the particles corroborates the assumption of LCA and López et al. (in press) that, having current meters only over the sills, the flow must go through Delfín basin to reach the North Ballenas Channel sill.

The deep flows that enter BC converge in the lower levels of the water column within BC and diverge at the upper level, producing upwelling. However, this deep cold water (rich in nutrients) must mix with the northern gulf water; otherwise, the deep flow from the sills would fill completely the water column below the deepest sill and the process could stop. This is not happening, tidal currents or entrainment of upper water of the gravity currents (as discussed by Kida et al., 2008), mix these waters producing water that is less dense than the subsurface subtropical water that intrudes over the sills as gravity currents, and the process is then maintained. The strength of the tidal currents over the sills is not strong enough to block these overflows like in some silled fjords during spring tides (when high mechanical energy is present) that inhibits the heavy flow upstream (de Young and Pond, 1988; Leblond et al., 1991).

Actually, a run without tides (not shown) still produced a similar deep circulation, it was weaker and the long path flow is not able to pass the North Ballenas Channel sill at times.

In conclusion, the numerical model with the improved resolution now reproduces the general circulation implied by LCA, consisting of (1) a deep up-gulf starting at San Esteban sill and flowing around the east and north of Ángel de la Guarda Island that reaches the North Ballenas Channel sill and fills the Ballenas Channel and (2) a deep flow entering the BC from San Lorenzo sill. These flows converge and produce strong upwelling all year round resulting in enriched waters in nutrient and cold surface waters.

Acknowledgments

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Appendix I. The model equations

The model equations are vertically averaged equations for each layer; for momentum
\[
\frac{\partial u}{\partial t} = -hu^{-1}v_{H}(yhu) - uh^{-1}\Delta(w) - fu - \rho_0^{-1}\frac{\partial p}{\partial x} + H^{-1}\Delta(\tau_x) + v\nabla^2 u,
\]

\[
\frac{\partial v}{\partial t} = -hv^{-1}v_{H}(yvh) - vh^{-1}\Delta(w) - fu - \rho_0^{-1}\frac{\partial p}{\partial y} + H^{-1}\Delta(\tau_y) + v\nabla^2 v,
\]

for continuity,
\[
w_{zd} = \frac{\partial (uH)}{\partial x} + \frac{\partial (vH)}{\partial y} + w_{zu},
\]

and the overall continuity equation is
\[
\frac{\partial \eta}{\partial t} = -\nabla \cdot \nabla \eta,
\]

while for temperature and salinity,
\[
\frac{\partial (T, S)}{\partial t} = -\nabla \cdot (\nabla T + \nabla S) - h^{-1}\Delta(T, S)w + K_h\nabla^2 (T, S) + \frac{\partial (T, S)}{\partial z}K_v,
\]

and the hydrostatic equation is
\[
\frac{\partial p}{\partial z} = -\rho g.
\]

The different symbols are as follows: \(\nabla = (u, v)\) is the horizontal velocity, \(w\) is the vertical velocity, \(\nabla^2 = (U, V)\) is the transport for each layer, \(f\) is the Coriolis parameter, \(P = (\eta - z)\rho_0 g + p(x, y, t)\) is the total pressure, \(p\) is the baroclinic pressure, \(\rho_0\) is the reference density, \(h\) is the layer thickness which is equal to \(H\) (the nominal thickness), except in the first and last layers where it accommodates the surface elevation, \(\eta\), and the topography, respectively. \((x, y, z)\) are the northward, eastward and upward coordinates. The operator \(\Delta(\ldots)\) is the difference of \((\ldots)\) taken between the upper \((zu)\) and lower \((zd)\) surfaces of the layer, \(\nabla = (\nabla_H, \frac{\partial y}{\partial z})\), and \(\nabla_H = (\frac{\partial y}{\partial x}, \frac{\partial y}{\partial y})\).

The vertical stresses are \(\tau_x = A_v\frac{\partial y}{\partial z}\), and \(\tau_y = \beta R_i\) is the vertical eddy coefficient (Kochergin, 1987). \(R_i\) is the Richardson number, \(\alpha = 10 m^2\) and \(\beta = 10\). The surface and bottom stress boundary conditions are \(\tau_x = C_{db}\sqrt{w(u^2 + v^2)^{1/2}}\) and \(\tau_y = C_{sb}\sqrt{w(u^2 + v^2)^{1/2}}\), respectively, \(V_w = (U_w, V_w)\) is the wind velocity, \(C_{db}\) and \(C_{sb}\) are drag coefficients for the air/water interface and for the sea bottom, respectively. Finally, \(K_h\) and \(K_v\) are the horizontal and vertical eddy diffusion coefficients for scalar quantities, which in the model are equal to \(\tau_x\) and \(\tau_y\) the horizontal and vertical eddy viscosities.

The model became periodically stable after four years and the results for this study were obtained from the fifth year of the model run; the time step used was 60 s.

References


