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Short communication

Towards the numerical simulation of the summer circulation in Todos Santos Bay, Ensenada, B.C. Mexico

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ABSTRACT

The general circulation of Todos Santos Bay was studied using the ROMS numerical model for the summer season. The model was forced with the California Current System and by synoptic winds, which are mainly towards the equator. The circulation is characterized by two systems: one at the exterior with a strong southward flow that enters to the bay but limited by the ~35 m isobath and the other at the rest of the bay. The circulation in the interior oscillates between two spatial structures: one in which the general circulation is anticyclonic for two–three days overall the bay producing a large eddy and a small cyclonic eddy in front of Ensenada's port, then the anticyclonic eddy evolves to produce the second spatial structure by splitting into two counter rotating eddies making the original anticyclonic one to be limited to the northern side of the bay and last three–four days and the small cyclonic eddy reverses its circulation. Such conditions are a consequence of the transport oscillations of the southward flow on the northwestern boundary and the mode with two eddies appears when the associated inflow is more intense. The transition between these two modes takes place in only one–two days. The time average circulation was also analyzed and the circulation with the two eddies dominates as it is of stronger currents and last longer.

1. Introduction

Todos Santos Bay (TSB) is a small bay (~180 km^2) in the Baja California west coast, approximately 100 km south of the Mexican–U.S. border (Fig. 1). It is connected to the Pacific Ocean through the lines between Todos Santos Island (TSI) and San Miguel Point (SMP), which has a longitude of 10 km, and TSI and Punta Banda (PB), which is approximately 5 km. Within these lines and the coast, the basin has a depth less than 50 m in about 80% of the area; the rest corresponds to a submarine canyon located between PB and TSI at the southwest of the bay.

In the last few years, the development of the city of Ensenada and the use of the bay has increased in many areas, such as tourism, port activities (e.g. navigational channel dredging and its associated discharge of the material into the bay), marine aquaculture, and pollution due to urban discharges. These conditions have raised many questions related to the management of the bay and consequently, there is now pressure to know the bay's circulation.

As we will show below, small changes in the surrounding California Current System (CCS) produces important changes in the bay's circulation. Following Lynn and Simpson (1987), the CCS is formed by: the equatorward California Current (CC), the poleward inshore countercurrent (IC), and the California Undercurrent (CU) which also flows to the north as a core of about 20 km wide at a depth of about 150 m attached to the continental shelf break. The two latter currents (IC and CU) are not always present. For example, a geostrophic study (Lynn and Simpson, 1987; Strub and James, 2000) reveals a dominant surface flow of 10 to 12 cm s^{-1} near the coast towards the equator. Also, these currents need the β-effect and an along the coast wind forcing in order to be generated according to numerical studies of Batteen (1997).

Within the TSB the synoptic northwestern winds (summer conditions) are dominant and its variability is due to the high pressure system variations centered to the west of California (Pavía and Reyes, 1983; Alvarez, 1977). There is also a significant sea level breeze component (Reyes and Parés, 1983).

Hydrographic data show that a thermocline develops during summer (Morales, 1977) and surface anticyclonic and cyclonic eddies in the northern and southern areas of the bay, respectively, have been inferred from these data (Argote et al., 1975). Direct current observations from few drifters (Alvarez et al., 1988; Durazo and Alvarez, 1988) showed tracks (with associated velocities of ~15 cm s^{-1}) during the months of March through August along the coast in the northern and southern areas. These tracks converge just north of the mouth of Punta Banda Estuary and then depart from the coast probably towards the eddies referred by Argote et al. (1975). Direct current measurements are also scarce. Fig. 1b

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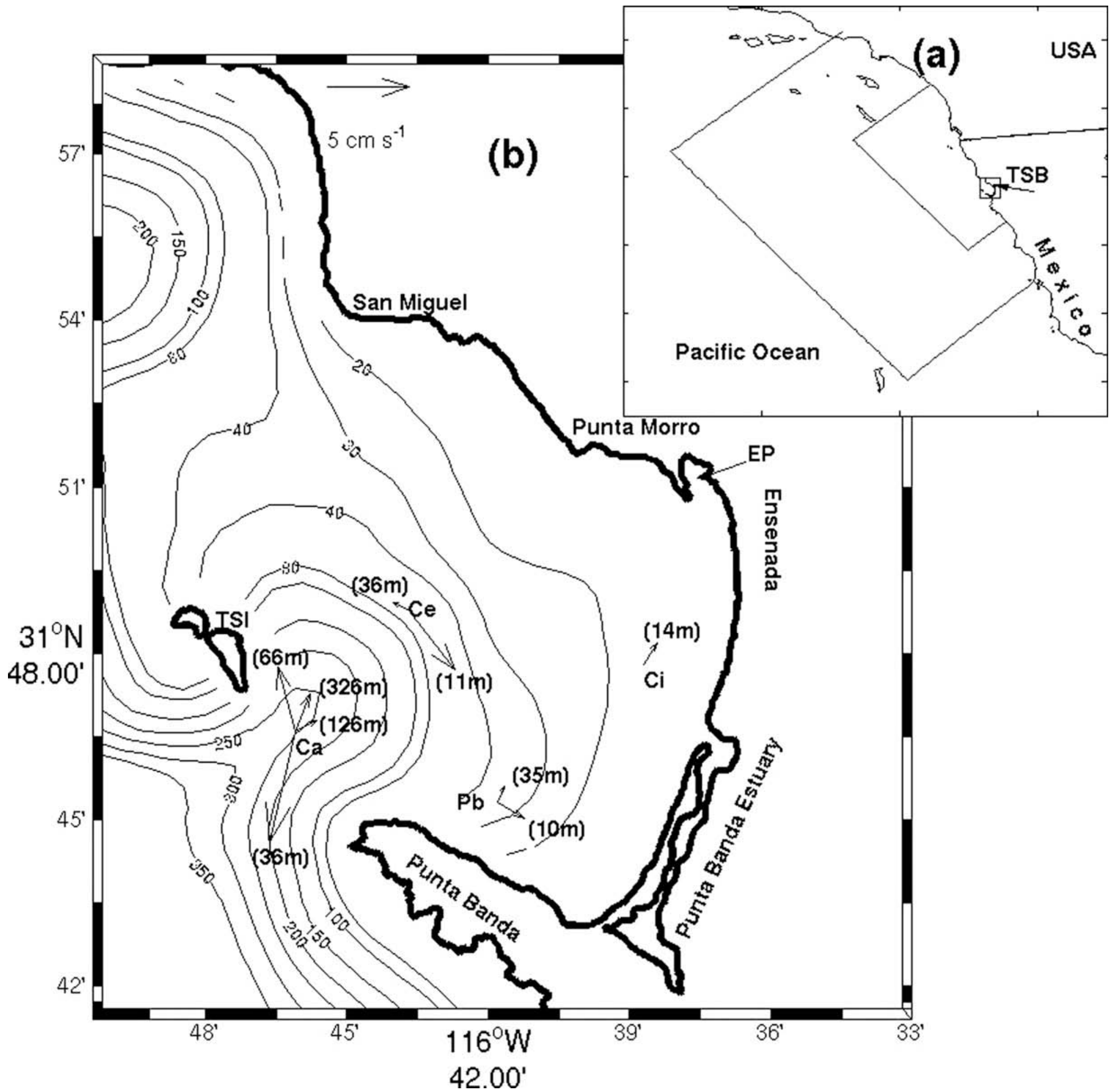

Fig. 1. (a) Location of Todos Santos Bay (TSB), the smallest rectangle. The larger rectangles correspond to the parent and child numerical model grids. In (b) TSB is enlarged and the smoothed bathymetry (in meters) is shown. Also shown in (b) are the mean velocities obtained from a set of observations (see Table 1). The acronyms Ca, PB, Ce and Ci stand for Canyon, Punta Banda, Central, and Ciprés sites, respectively. The figures in parenthesis in the vector velocities indicate the currentmeter depths. Finally TSI stand for Todos Santos Island.

shows the July time averages velocity vectors of these data, for each depth (García et al., 1995). The depths of the observations are indicated between parentheses in the figure. The Punta Banda (Pb), Cipres (Ci), and Central (Ce) stations currents are consistent with the southern surface cyclonic eddy. The Canyon (ca) station has the most intense velocities; it also shows outflow from the bay at the surface current meter (36 m depth) and an inflow at the rest of them (>66 m depth).

With a barotropic numerical model and a domain restricted to one very close to that of Fig. 1b (i.e., only the bay), Gavidia (1988), Argote et al. (1991) and Gutiérrez (1999) found that the wind dominates the forcing of the bay's circulation. In particular, they found that the tidal current produces insignificant residual circulation. These models are homogeneous and did not include the CCS, which is expected to influence the bay's circulation.

It is assumed that the circulation in the TSB is the result of the combined forcing of the California Current System, the tides and the winds. The induced motions and the restrictions imposed by the bay's geometry results in its final circulation. As a first step towards the study of the general circulation of the bay, the objective of this work is to implement a three-dimensional circulation model of TSB which include the California Current System forcing. At this stage we concentrate in July only as representative of the summer season. This model was forced with winds, temperature and salinity climatologies for this month.

2. Methodology

We used the Regional Ocean Modeling System Model (ROMS) developed at UCLA, Rutgers University, and Institut de Recherche pour le Developpement. This is a free surface, terrain-following ocean model, which solves the incompressible, hydrostatic primitive equations with potential temperature, salinity and an equation of state. The ROMS model has been successfully used to simulate the CCS (Marchesiello et al., 2003; Penven et al., 2005; Capet et al., 2004).

The ROMSTOOLS software (Penven et al., 2007) was used to generate the grid, the surface forcing, the initial conditions, and the nesting grid. Two-nested grids were created and for both of them the initial conditions were imposed from World Ocean Atlas 2005 (WOA) which has a 1 degree horizontal resolution. Fig. 1a shows both grids. The parent grid domain extends from 29° N to 34.8° N, and about 300 km offshore which should simulate properly the general CCS. The horizontal resolution is around 6.5 km (92×62 grid points) and the model time step is 4 min. The child grid domain extends from 31° N latitude to 33.5° N, and about 100 km offshore. The model time step is 80 s, and the horizontal resolution is about 700 m (362×178 grid points). The vertical grid in both cases has 20 sigma levels with surface refinement.

The forcing at the open boundary for the parent grid was also obtained from WOA, specifying the temperature and salinity fields of the July climatology in all the boundaries. Geostrophic velocities were calculated with a level of no motion of 500 m, with a global mass conservation constraint. At the sea surface wind stress and SST derived from QuikSCAT and Pathfinder, respectively, were used for both parent and child grids. Missing values from the data to the model grid in the forcing were interpolated/extrapolated by objective analysis. The open boundary conditions for the child grid were taken from the parent grid in one-way interaction. All the forcing variables are function of space only. The bathymetry is derived from ETOPO2 for the parent grid, while the child grid was corrected from measurements of TSB. The model was started from rest and run for one year after a spin-up of two months using the same forcing. From the third month the large scale circulation (namely the California Current System) reaches a quasi periodic state with small oscillations. These fluctuations are produced by instabilities of the mean currents (Marchesiello et al., 2003) and produces eddies and meanders that evolves continuously. As we show below, this small oscillations of the large scale flow produces large oscillation in TSB.

3. Results

The model in the parent domain reproduces (i) the general equatorwards flow of the climatological (WOA) summer conditions (not shown) and (ii) the conceptual scheme of the circulation along the coast (a cyclonic eddy and meanders) as described by Strub and James (2000) (not seen in the WOA data as the resolution is to coarse). We take the simulation on the parent grid as correct and do no further analyzes on it and concentrate in the circulation in TSB.

As shown in Fig. 1, some direct current meter observations are available in TSB; a comparison of these data (time averaged for July) with the one-month averaged velocities obtained by the model is shown in Table 1. The model velocities were interpolated to the depths of the current meters using the closest grid points to the stations. Independently of the position, the magnitudes are similar between the data and the model currents, and the angles of the currents points are in the same flow direction with the exception of Ca and PB stations at 66 m and 35 m, respectively. The time averaged velocities at 5 m depth from the model (Fig. 2) are consistent with the surface circulation proposed by Alvarez et al. (1988) as mentioned before. In general, there is a qualitatively good agreement between data and model within the bay. Now we describe the output of the model results.

Table 1
Temporal average of the magnitudes (|**V**|) and directions (Dir: true-north azimuth) of the observed and modeled currents at the indicated stations and depths.

Station	Depths (m)	$\lvert\underline{V}\rvert_{obs}$ (cm s^{-1})	$\lvert\underline{V}\rvert_{mod}$ (cm s^{-1})	Dir_{obs}	Dir_{mod}
Canyon (Ca)	36	6.9	6.6	193	178
	66	4.0	2.9	254	35
	126	1.4	2.3	64	17
	326	2.4	2.0	22	28
Central Bay (Ce)	11	4.7	2.6	142	186
	36	0.9	1.7	204	256
Punta Banda (PB)	10	1.8	1.3	123	163
	35	1.1	0.6	19	268
Cipres (Ci)	14	1.5	1.7	32	10

Outside the bay, the currents are basically southward along the coast with evolving mesoscale features such as eddies and meanders (not shown). These features produce variations in the transport through the northwest communication between TSB and the open ocean and two circulation structures within TSB are formed. Therefore we will show in Section 3.1 the time averaged circulation of the modeled time period and in Section 3.2 these two different circulation structures, which translates into a circulation that evolves oscillating back and forth from one structure to the other.

3.1. Time averaged currents

The monthly average currents, at 5 m depth, are shown in Fig. 2a and two areas with different circulation are identified; one in the vicinity of the TSI and the other at the east of the imaginary line from Punta Banda point to San Miguel point. These areas will be referred to as the exterior and the interior systems, respectively. The exterior system is characterized by a strong surface southward flow from the northwestern part of the bay and is limited to the east roughly by the 35 m isobath and exits the bay through the "Western" section (Fig. 2c) i.e., between Punta Banda and Todos Santos Is. (The velocities in the exterior area have been normalized in order to visualize better the velocities at the interior of the bay). The arbitrary northwest limit in Fig. 2b, the "Northern" section, has a depth less than 40 m, whereas the Western section is much deeper (>200 m). The normal inflow at the Northern section is stronger (>17 cm s^{-1}, Fig. 2b) than the normal outflow trough the Western section ($\sim$10 cm s^{-1}, Fig. 2c). The northern section shows a large lateral shear (Fig. 2b) between the exterior and interior systems. Vertical shear is also observed in both the exterior and interior system. The Western section shows an inflow below 60 m close to TSI (left of Fig. 2c).

The interior system over the shallow area of the bay is characterized by cyclonic and anticyclonic eddies. The velocities magnitude are lower ($\sim$8 cm s^{-1}) than those of the exterior system (Fig. 2a). The anticyclonic eddy, approximately 10 km in diameter, is located at the north of TSB. This anticyclonic circulation has an intense coastal flow that separates from the coast around the central area of the bay. Close to the exterior system, a portion of the anticyclonic flow is incorporated to the flow of the exterior system. The cyclonic eddy is much weaker ($\sim$2 cm s^{-1}) and smaller ($\sim$5 km) than the anticyclonic eddy and is located in the southern part of the bay in front of the Punta Banda estuary. Both eddies occupy almost all the water column.

The time averaged temperature (not shown) at the Northern section reveals a partial vertical temperature homogenization. At the exterior system this homogenization reaches the top 30 m of depth. Below 30 m the stratification is evident. At the interior zone the water column is basically well mixed over the top 10 m and increases from the Northern section to Punta Banda Estuary.

3.2. Todos Santos Bay circulation modes

Fig. 3 shows the two main circulation patterns within the bay. The bay's circulation oscillates back and forth between these two paths. One with a large anticyclonic eddy and the other with two counter rotating eddies. Both with a reversing smaller eddy in front of the Ensenada's port. Henceforth these general circulations

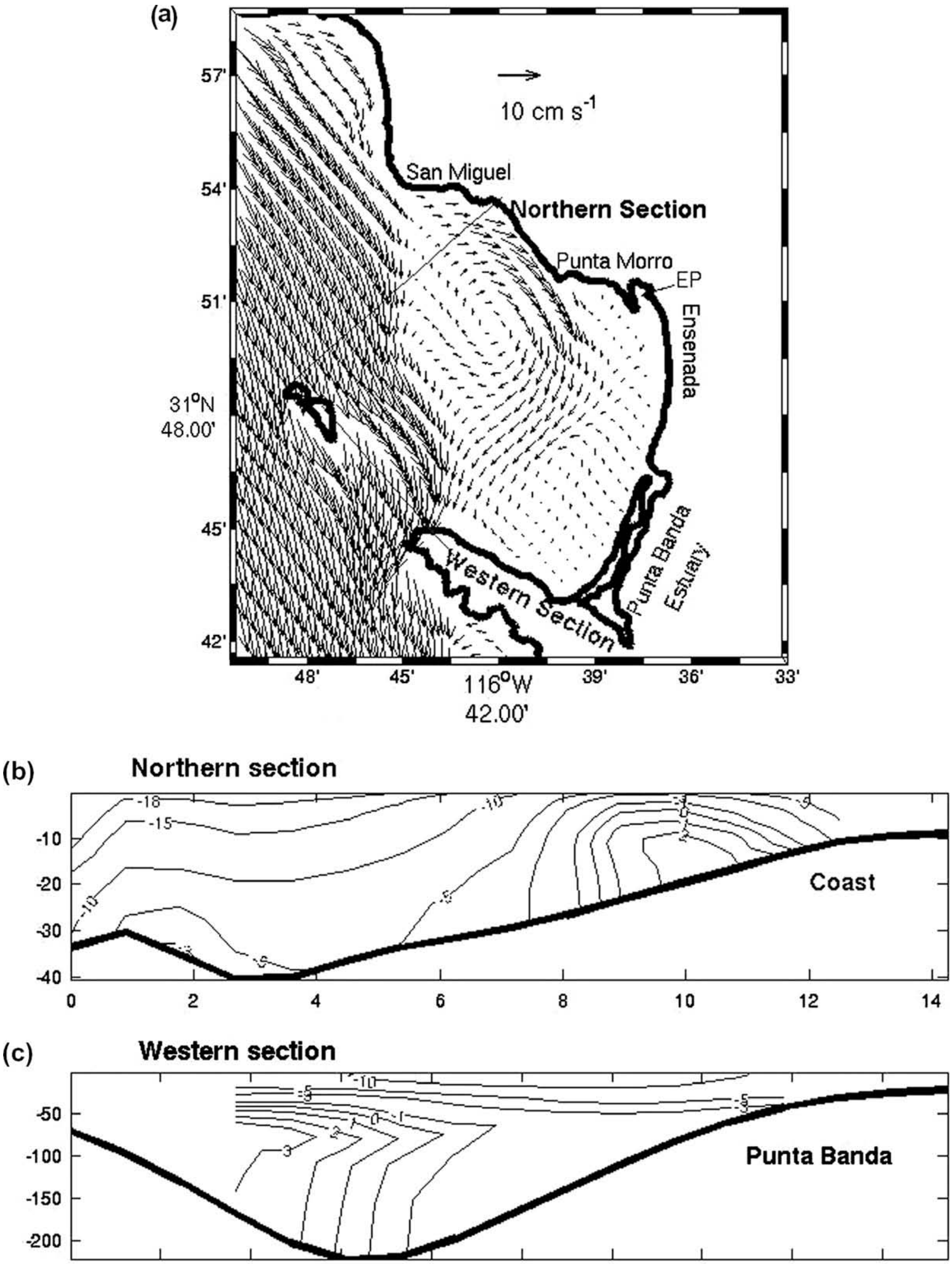

Fig. 2. Time averaged velocities (cm s^{-1}) at (a) 5 m depth; the positions of the Northern and Western vertical sections are shown. The velocity magnitudes at the western side are normalized to enhance the visualization inside the bay. (b) Normal velocity to the Northern section, the negative sign represents flow into the bay and the extreme right corresponds to the eastern coastline. (c) Normal velocity to the Western section, the negative sign represent flow out of the bay. The extreme right corresponds to the Punta Banda coast. Note the different vertical scales between both sections.

schemes will be referred as Mode A (Fig. 3a, and b) and Mode B (Fig. 3c and d), respectively. The transition between the modes occurs in one–two days. Mode A lasts two–three days, while Mode B three–four days. Note that the figures show the circulations at two different depths (5 and 15 m), these depths were selected because stratification is important below 10 m at the interior system.

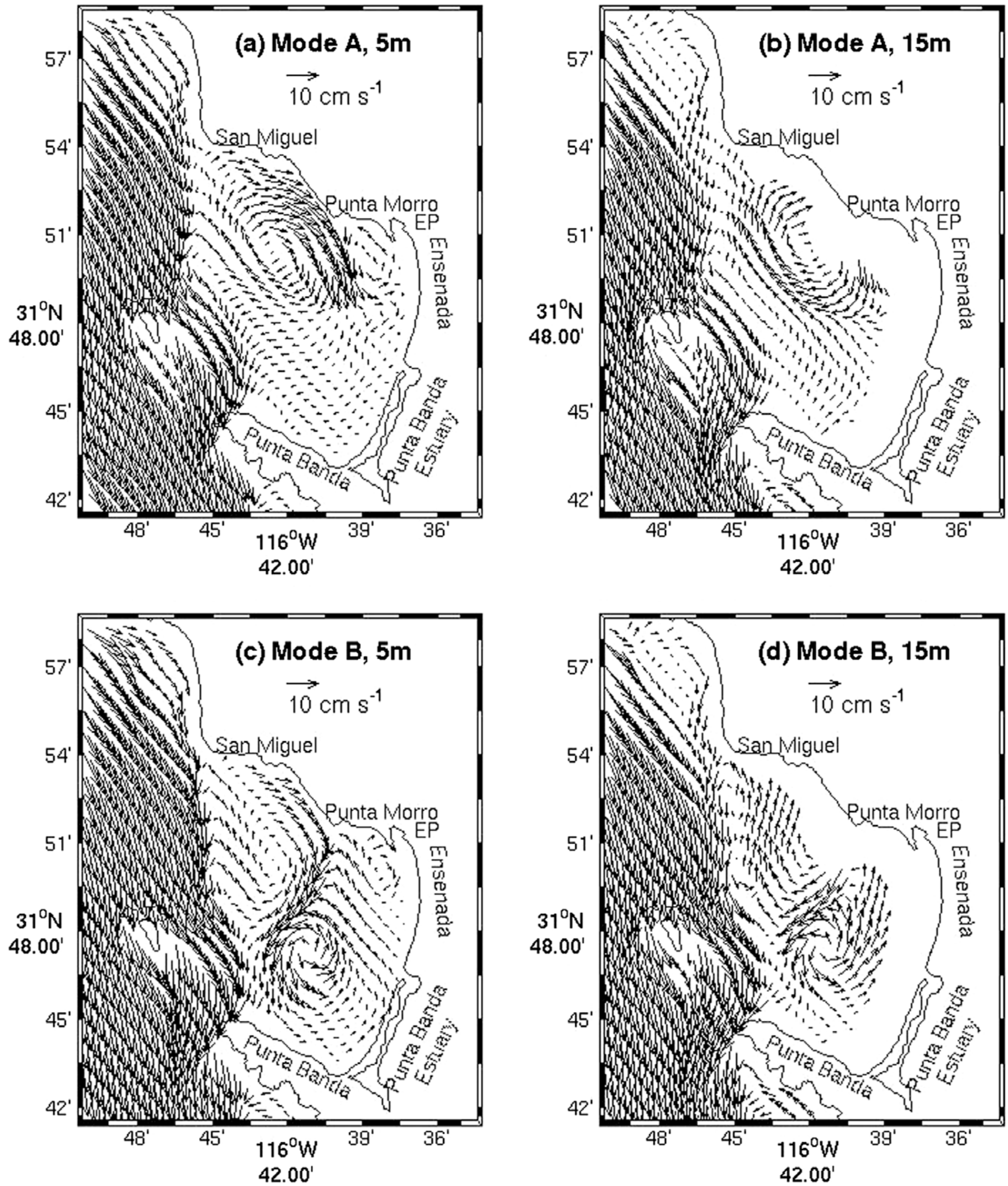

Fig. 3. Instant velocity fields for Mode A at (a) 5 m and (b) 15 m depth and for Mode B at (c) 5 m and (d) 15 m, respectively.

Modes A and B circulations have several similarities with the time average circulation. Both modes depict the exterior and interior circulation systems. The exterior systems in both modes are confined to the deeper area and present the largest velocities in the bay and shows very similar vertical structures. In the interior system, the common features are: (i) a piling of water (not shown) near the Punta Banda estuary and, (ii) a three-dimensional temperature structure (not shown) that shows a vertical homogeneous upper part of the water column (<10 m) with a latitudinal gradient; below this layer, the water column shows vertical stratification without horizontal gradient.

For Mode A the normal velocity at the Western section (not shown) is weaker (5 cm s^{-1}) at the surface than the time averaged normal velocity ($\sim$10 cm s^{-1}). The total transport through the Northern and Western sections in this mode are 13.91×10^3 m^3 s^{-1}. At the interior, the anticyclonic circulation now covers almost all the bay and large vertical shear is evident (Figs. 3a and b) mainly in the Punta Banda region (south of the bay) and close to the exterior area. Under this condition, at the upper layers (Fig. 3a) the interior of the bay merges with the flow of the exterior system but not at the lower layers (Fig. 3b). Also, in this scenario, a small ($\sim$3 km of diameter) cyclonic eddy in front to Ensenada's port is present.

Mode B shows both eddies as the time averaged currents. The cyclonic eddy has a higher velocity ($\sim 7\ \mathrm{cm\,s^{-1}}$) than the time average current cyclonic eddy (Fig. 3c and d). The magnitude of the velocity and size of the anticyclonic eddy is similar to the time averaged (Figs. 2a, and 3c). Mode B is less baroclinic (Fig. 3c and d) than Mode A (Fig. 3a and b). The interior system merges with the exterior flow, mainly in the Punta Banda region. Both eddies occupy most of the water column. The anticyclonic eddy is reduced in size and intensity compared to the anticyclonic eddy of Mode A. The total transport through the Northern and Western sections are larger ($23.89 \times 10^3\ \mathrm{m^3\,s^{-1}}$) than those of Mode A due to the intensification of the southward flow in the exterior area. The small eddy off Ensenada's port, in Mode B is now anticyclonic.

4. Discussion

The inflow at the bay's entrance (exterior system) is part of the strong currents that occur along the continental shelf outside the bay. This flow is vertically homogeneous at the top $\sim$50 m and flows southward at the western side of the bay roughly along the 35 m isobath. Small changes from this flow results in the two different structures of circulation shown in Fig. 3 and thus this flow acts on the interior system as a ''local boundary forcing''. This result is on opposition to the conclusion of Gavidia (1988), with a barotropic model, that the California Current does not affect the circulation of the bay.

The wind forcing, which is also equatorward, produces a southeastward surface transport from San Miguel point and Punta Morro point area to Punta Banda estuary area. Cold deeper water replaces the surface water and a local coastal front is produced and current departs from the coast at and Punta Morro (PM) and the anticyclonic eddy and the small cyclonic front Ensenada's port are produced.

On the other hand, the cyclonic eddy during Mode B, at the south of the bay is present when the transport through the Northern section is higher ($23.89 \times 10^3\ \mathrm{m^3\,s^{-1}}$) than in Mode A and the exterior flow approaches the coast reducing the size and intensity of the anticyclonic eddy. Part of the strong surface flow can't reach the southern exit and flows along Punta Banda to the Punta Banda Estuary bay giving rise to the southern cyclonic eddy. Similarly, this coastal current in front of Punta Morro is reduced and with the cyclonic eddy at the south produces the small anticyclonic eddy in front of Ensenada's port.

This structure of the bay's circulation just north of the mouth of Punta Banda Estuary coincides with the drifter tracks reported by Alvarez et al. (1988). Mode B last longer (3–4 days) and has more energetic (total kinetic energy) than Mode A (2–3 days). The time average circulation (Fig. 2), therefore, is dominated by Mode B. The small eddy in front of the bay's port is not present in the time average field as changes sign in the same position.

The general circulation along the open coast, although it is quite stationary, has a strong horizontal shear in the upper layer. This condition produces meanders off the TSB. The meanders pass front TSB and modifies the transport mainly at the northern entrance of the bay. This suggests that such meanders modulate the bay's circulation mainly at the region off the Punta Banda estuary forming the cyclonic eddy that appears and disappears. A similar situation has been reported for Monterey Bay with measurements by Rosenfeld et al. (1994), where meanders of the California Current system modified the interior bay's conditions.

5. Conclusions

In conclusion, the general summer circulation of Todos Santos Bay consists of a circulation that evolves from a large anticyclonic eddy that covers almost the entire bay (Mode A) to a two smaller counter rotating eddies (Mode B). During both modes an eddy in front of Ensenada's port is present but changing from anticyclonic to cyclonic. These two circulation modes are due to oscillations in the transport of an exterior flow that meanders along the front of the bay.

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