Geofísica Internacional (2012) 51-3: 271-279

Original paper

Vertical structure of tidal flows at the entrance to Guaymas Bay, Mexico

José Gómez-Valdés*, Juan A. Dworak, Heriberto J. Vázquez and Manuel Paz

Received: June 06, 2011; accepted: February 07, 2012; published on line: June 29, 2012

Resumen

Se estudia la estructura vertical de los flujos de marea a partir de 144 días de observaciones realizadas por un ADP anclado al fondo en la entrada de la Bahía de Guaymas, cuya área es de 33.6 km^2 y se encuentra en una región semiárida. Se aplicaron métodos de análisis armónico a las series de tiempo de velocidad y a las series de tiempo de elevación del nivel del mar, para extraer los parámetros de las elipses de marea y para calcular amplitudes y fases de la marea. También se analizaron dos series de tiempo del nivel del mar adicionales obtenidas antes del experimento en sitios interiores de la bahía. Las corrientes barotrópicas de marea de mayor importancia fueron la K_1 y la M_2, estuvieron alineadas con la topografía de la entrada y mostraron amplitudes máximas de 7.8 ± 0.2 cm s^{-1} y 7.4 ± 0.3 cm s^{-1}, respectivamente. Mientras que la corriente de agua somera de mayor importancia fue la M_4, con una amplitud máxima de 1.0 ± 0.2 cm s^{-1}. Debido a que la bahía cumple con la condición de cuerpo de agua pequeño, los principales movimientos de marea mostraron características de onda estacionaria. La estructura del perfil vertical de la corriente fue parabólico, lo que sugiere que la corriente barotrópica fue afectada por procesos de capa límite, además el perfil promedio de las corrientes confirmó la formación de una circulación estuarina inversa. Las corrientes de marea diurnas rotaron contra las manecillas del reloj en la capa superior y con las manecillas del reloj en la capa inferior, lo que sugiere que fueron moduladas por la estratificación.

Palabras clave: mareas, corrientes, laguna semiárida, Golfo de California, Bahía de Guaymas.

Abstract

A 144-day bottom-mounted ADP experiment at the entrance to Guaymas Bay was used to examine the vertical structure of the tidal flows of a small basin (33.6 km^2) located in a semiarid region. Harmonic analysis techniques were used to extract the tidal ellipse parameters of the time series of ADP and to determine amplitude and phase of the tidal components of additional time series of tide height from two sites on the inner side of the bay taken before the experiment. The K_1-current and the M_2-current were the tidal currents of foremost importance; they were aligned with topography and showed amplitudes of 7.8 ± 0.2 cm s^{-1} and 7.4 ± 0.3 cm s^{-1}, respectively. The M_4-current was the principal shallow water tidal current with amplitude of 1.0 ± 0.2 cm s^{-1}. Because of the small embayment condition, the main tidal motions showed characteristics of a standing wave. The vertical structure of the tidal currents was parabolic, which suggests that the barotropic tidal currents were affected by boundary layer process, furthermore, the mean current profile confirmed previous indication of an inverse estuarine circulation. The diurnal currents rotated anticlockwise in the upper layer and clockwise in the lower layer, which suggests that they were modulated by stratification.

Key words: *tides, tidal current, semiarid lagoon, Gulf of California, Guaymas Bay.*

J. Gómez-Valdés*
H.J. Vázquez
Centro de Investigación Científica
y de Educación Superior de Ensenada
Carretera Tijuana Ensenada No. 3918
Zona Playitas, C.P. 22860
Ensenada, Baja California
México
Tel: +52-6461750500
Fax: +52-6461750547
**Corresponding author:* jgomez@cicese.mx

J.A. Dworak
M. Paz
Instituto Tecnológico de Guaymas
Km 4, Carr. al Varadero Nacional, 85950
Guaymas, Sonora
México
Tel: +52-6222216480, +52-6222215367
Fax: +52-6222216221

Introduction

Guaymas Bay (Figure 1) is a small semiarid coastal lagoon well connected to the Gulf of California by a single inlet. The basin has an area of 33.6 km^2. The inlet is 1.2 km wide, 13 m deep, and 2 km long. The bay features two shallow lagoons, one stemming to the west, the Guaymas Lagoon, and the other one to the northeast, the Empalme Lagoon, a relic of the Matape River's delta. Beyond the Empalme lagoon there is a very shallow body of water, the Estero el Rancho. Guaymas Bay is one of the main Mexico's fishing harbors with ample urban activity. On this bay, high rainfall takes place mainly from July to September and is scarce the rest of the year; freshwater entering the bay is mostly from runoff during the rainy season. The climate is semiarid with a yearly average temperature of ~ 25 ºC, reaching the maximum temperatures (~ 32 ºC) in August; during summer and autumn evaporation exceeds precipitation (Roden, 1958; Castro *et al*., 1994). The predominant winds are from SSW during spring and summer, NW during autumn, and N during winter.

Few reports on physical process of Guaymas Bay have been found in the literature, Valle-Levinson *et al*. (2001) documented the oceanographic conditions at the entrance to the bay for a lunar day in June 1999 and in February 2000. They found a reversal in water exchange patterns in late spring with respect to late winter. In late spring, an inverse estuarine circulation was established. In contrast, the literature about the Gulf of California, the adjacent sea of Guaymas Bay, is abundant. For example, the basic aspects of the tides of the Gulf of California are well known, the type of the tides off Guaymas Bay is mixed, mainly diurnal (Marinone, 1997).

Acoustical Doppler Profiler (ADP) observations at straits and inlets have been carried out frequently over the last decade, see e.g., Tsimplis (2000), Winant and Gutierrez de Velasco (2003), and Carrillo Gonzalez *et al*. (2007). These studies have revealed that the vertical structure of the tidal signal is complicated and varies, for example, by boundary layer and stratification effects. The main goal of the present study includes an analysis of the sea surface elevation and the vertical structure of the currents at the inlet of Guaymas Bay in which the focus of attention is on the tidal frequencies, using data from a bottom-mounted ADP, upward-looking, during the summer and autumn of 2000. Since tidal flows are determinant for the sediment budget and the dispersion of contaminants (Dyer

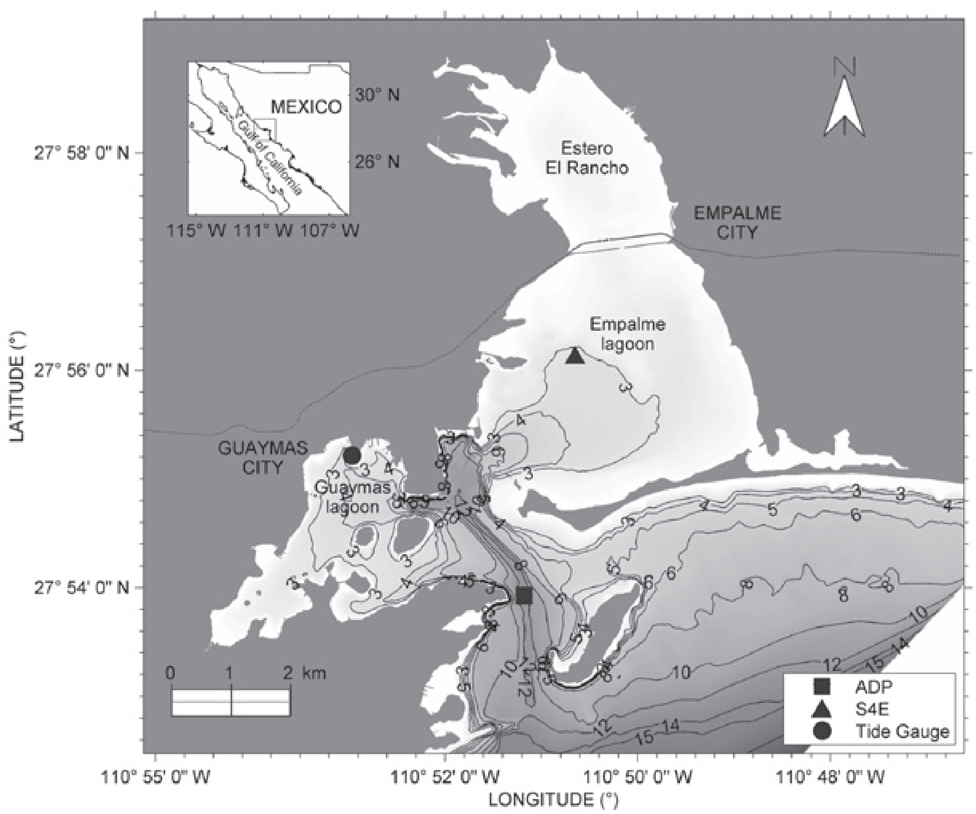

Figure 1. Geographical location of Guaymas Bay at the Gulf of California. Bathymetry with respect to LLW is displayed. The locations of the ADP, tide gauge, and S4 pressure sensor are also shown.

1997, 1-4 pp.), the correct separation of tidal motions from the long-term ADP mooring might provide a better understanding of the tidal-induced flows in this bay. In addition, the time series of the vertical structure of the currents provides an opportunity to test for the inverse estuarine circulation reported by Valle-Levinson *et al*. (2001).

Data and methods

A time series of velocity from a 1,500 kHz ADP, bottom-mounted, upward looking, at the entrance to Guaymas Bay, was the main data set used in this study. The time series spanned from 28 June 2000 to 19 November 2000. The instrument was deployed in the middle part of the navigation channel, at 0.95 m above the bottom, where the average water column depth was 13.2 m with respect to Mean Sea Level. The depth bin was 0.5 m, with a blanking distance of 0.40 m. The sampling frequency was 2 Hz and 2 min averages were stored each 20 min. Data reduction for the ADP included the removal of the upper 10 % water column due to the side-lobe effect. Because the first and the deepest bins were considered inaccurate, they were removed. Thus, the actual depth range of the profiles was from1.85 m from the bottom up to 11.35 m.

The ADP also registered sea surface elevation. To provide a better description of the tide in the bay, sea surface elevation data from two instruments deployed in the inner lagoons were also used. A long-time series, from 28 February 1970 to 25 November 1976, from a tide gauge at Guaymas Lagoon, as well as a short-time series, from 13 May 1999 to 19 June 1999, from an InterOcean S4 pressure sensor at Empalme Lagoon, were used. The location of these instruments are shown in Figure 1.

Sea surface level data was smoothed with a running-mean filter and sampled to hourly records. Tidal constituents amplitude and phase lag (A_k, g_k) were extracted from the time series by least-squares fitting, using a Rayleigh criterion of one and including nodal corrections (Godin, 1972; Foreman, 1977; Pawlowicz *et al*., 2002). Constituents P_1 and K_2 were estimated by inference, as suggested by Foreman *et al*. (1995). The internal relations between constituents P_1 and K_1 and between K_2 and S_2 taken from Godin *et al*. (1980) were used.

Reduction of tidal currents data was similar to the one performed on sea surface elevation data. To study the vertical structure of the tidal currents, the ellipse characteristics were extracted from the records of each bin using the least-square technique (Godin, 1988; Pawlowicz *et al*., 2002).

Results

A global view of the relative importance of the principal currents in the study area can be obtained from Figure 2, in which the spectra of sea surface elevation and vertically-integrated velocity are shown. Both spectra show high variance in low-frequency and tidal bands. The sea surface elevation spectrum shows a peak about 0.0403 cph (diurnal band) with the greatest variance, a second peak about 0.0806 cph (semidiurnal band), and a third peak about 0.1610 cph (quarter-diurnal band), whereas the kinetic energy spectrum shows that diurnal and semidiurnal motions are of the same magnitude. In the latter spectrum, it is also noteworthy the relatively high energy in the quarter-diurnal band. Since tidal motions are dominant on those spectra, our main goal here is to study these flows.

Sea surface elevation

Amplitude and phase of the main diurnal and semidiurnal constituents for the inlet site, Empalme Lagoon site, and Guaymas Lagoon site are shown in Tables 1-3, respectively. The dominant diurnal constituents are K_1 and O_1, its amplitudes at inlet site are about 27 and 19 cm, respectively. There are no significant differences in the amplitudes of the diurnal tides over the bay. The phase lag of K_1 between inlet site and Guaymas Lagoon site and between inlet site and Empalme Lagoon site are ~ 3 degrees and ~ 0 degrees, respectively. The dominant semidiurnal constituents are M_2 and S_2, its amplitudes at the inlet site are about 14 and 11 cm, respectively. Because of the bottom friction effect, there is a small reduction of the amplitude of the M_2 at the inner basins. The phase lag of M_2 between inlet site and Guaymas Lagoon site is 5 degrees, whereas it is 1 degree between inlet site and Empalme which is lower than the phase lag error at the Empalme site.

The characteristics of the tide of Guaymas Bay are as follows. Using the form number $(K_1 + O_1)/(M_2 + S_2)$, following Defant (1958), the type of tide is identified as mixed, predominantly diurnal. The fortnightly variation for semidiurnal tides ($|(M_2 + S_2) / (M_2 - S_2)| > 8$) is higher than for diurnal tides ($|(K_1 + O_1) / (K_1 - O_1)| > 5$) at all sites. Furthermore, M_4 tidal constituent is the one with the highest amplitude (~ 1 cm) for the shallow-water constituents. It is also noteworthy that the non-linear response of the water body to harmonic forcing is weak, as M_4 has practically the same amplitude throughout the basin and $M_4 / M_2 \sim 1 / M_2$. The phase difference between $2M_2$ and M_4 is about 310 degrees throughout the basin, which implies that Guaymas Bay is an ebb-dominant system according to Friedrichs and Aubrey (1988).

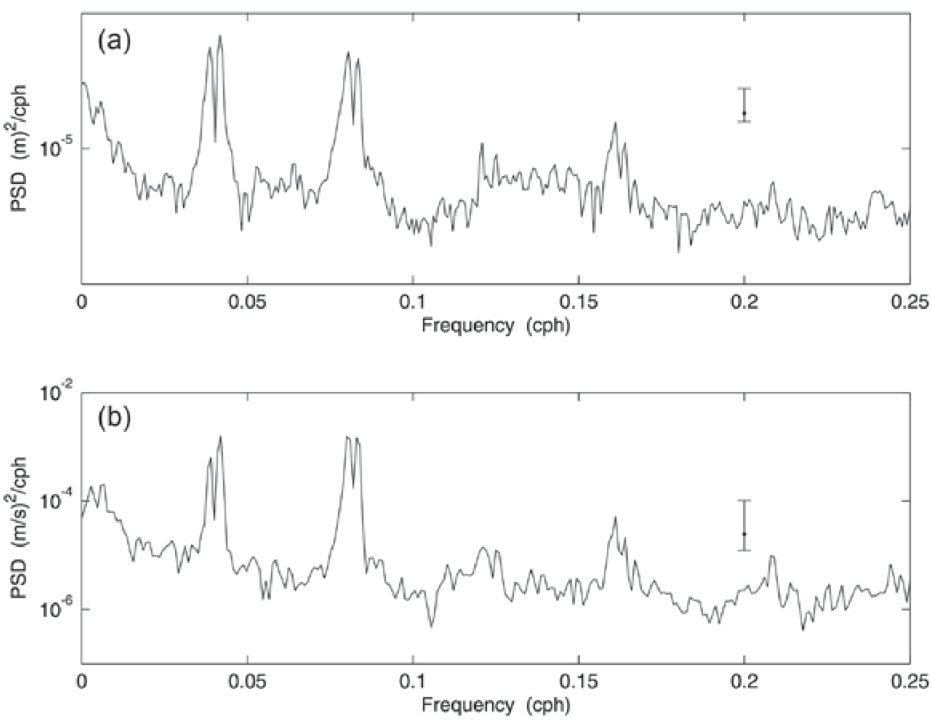

Figure 2. Spectral density estimates for (a) the sea surface elevation and (b) the velocity at the entrance to Guaymas Bay, using an ADP record 144-day long.

Table 1. Tidal constituents for the sea surface level at the entrance to Guaymas Bay. Amplitude (A) and phase lag (g) values and their respective errors (δa, δg) are shown.

Constituent	Freq (cph)	*A* (cm)	δa (cm)	g (°)	δg (°)
Q1	0.0372185	3.4	1.3	134	19
O1	0.0387307	18.8	1.2	166	4
K1	0.0417807	27.3	1.1	178	2
N2	0.0789992	3.6	0.4	165	6
M2	0.0805114	13.8	0.4	156	1
S2	0.0833333	11.1	0.4	134	2
M4	0.1610228	1.2	0.1	1	6

Phases are relative to UT. Time zone Z = -7. Tidal amplitude and phase are reported at 95 % confidence. Tidal constituents are above the noise level (signal-to-noise ratio > 1).

Tidal currents

The mean current (Z_0) and the vertical profile of the percentage of explained variance are shown in Figure 3. On the average, in the upper layer an input flow is established while in the lower layer there is an output flow. The thickness of the lower layer is greater than the thickness of the upper layer. The explained variance reaches its highest value at the middle of the water column. The hypothesis is that the combined effect on the tidal currents by bottom stress and surface stress in conjunction with stratification generates the observed patterns, where stratification is related to a gravitational flow induced by evaporation in the inner basins.

Table 2. Tidal constituents for the sea surface elevation at the Empalme Lagoon. Amplitude (A) and phase lag (g) values and their respective errors (δa, δg) are shown.

Constituent	Freq (cph)	*A* (cm)	δa (cm)	g (°)	δg (°)
Q 1	0.0372185	4.5	0.3	155	4
O1	0.0387307	19.4	0.3	168	1
K1	0.0417807	26.3	0.3	180	1
N2	0.0789992	3.7	0.3	167	5
M2	0.0805114	12.6	0.4	157	2
S2	0.0833333	9.9	0.4	145	2
M4	0.1610228	1.2	0.3	6	14

Phases are relative to UT. Time zone Z = -7. Tidal amplitude and phase are reported at 95 % of confidence. Tidal constituents are above the noise level (signal-to-noise ratio > 1).

Table 3. Tidal constituents for the sea surface elevation at the Guaymas Lagoon. Amplitude (A) and phase lag (g) values and their respective errors (δa, δg) are shown.

Constituent	Freq (cph)	*A* (cm)	δa (cm)	g (°)	δg (°)
Q1	0.0372185	3.6	0.2	161	2
O1	0.0387307	18.5	0.2	167	1
K1	0.0417807	27.9	0.2	183	0
N2	0.0789992	3.6	0.1	171	2
M2	0.0805114	13.5	0.1	160	1
S2	0.0833333	10.7	0.1	140	1
M4	0.1610228	1.4	0.1	26	2

Phases are relative to UT. Time zone Z = -7. Tidal amplitude and phase are reported at 95 % of confidence. Tidal constituents are above the noise level (signal-to-noise ratio > 1).

Two configurations of currents are presented: 1) the vertically-integrated velocity and 2) the velocity vertical profile. Table 4 shows the ellipse characteristics for the vertically-integrated velocity at the entrance to the bay. The most energetic components are K_1 (~ 8 cm s^{-1}) and M_2 (~ 7 cm s^{-1}). The diurnal tidal currents rotate anticlockwise (semiminor axis > 0), whereas the semidiurnal tidal currents rotate clockwise (semiminor axis < 0). The orientation of the tidal ellipses (Φ) is consistent with the bathymetric features along the main channel. The phase difference between the sea surface elevation and the velocity for the component M_2 and for the component K_1 are about 80° and 90°, respectively. The latter component shows a standing wave behavior. M_4-current shows an amplitude ~ 1 cm s^{-1}; because m = 0, it is completely elongated without rotation.

Figure 4 exhibits the vertical structure of the ellipse characteristics of the main diurnal and semidiurnal components. The semimajor axis magnitude reveals the following order $K_1 \approx M_2 > S_2 > O_1$, fluctuating between 8.3 cm s^{-1} and 4.4 cm s^{-1}. The semiminor axis magnitude is almost the same (0.4 cm s^{-1}) for the four components, fluctuating between -0.7 cm s^{-1} and + 0.7 cm

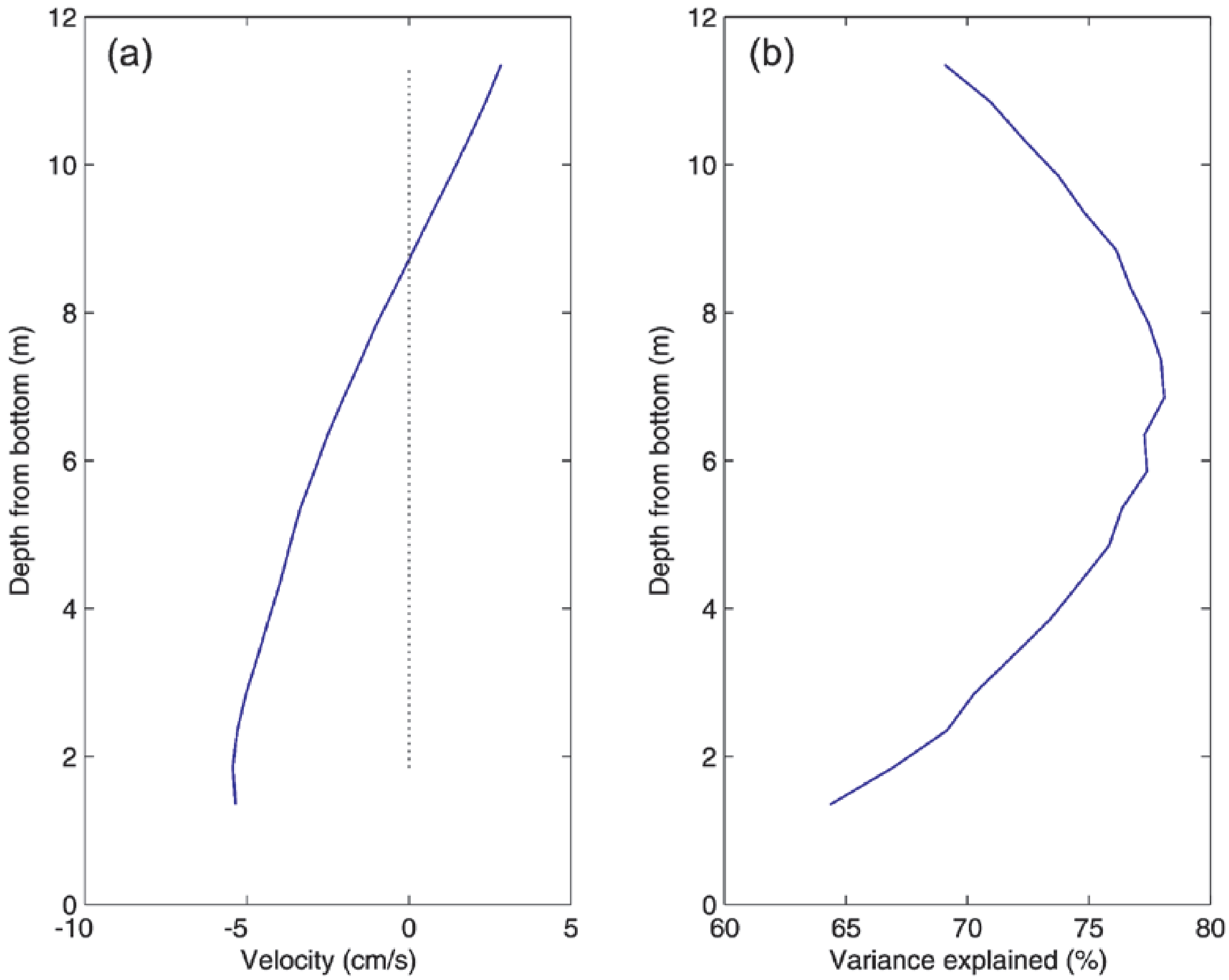

Figure 3. (a) Mean current (cm s^{-1}) and (b) percentage of explained variance.

Table 4. Tidal ellipse parameters for the vertically-integrated current at the entrance to Guaymas Bay. M is the semimajor axis, m is the semiminor axis, Φ is the inclination with respect to the East, and g is the phase lag; δ M, δ m, δ f, and δ g are estimate errors.

Constituent	M (cm s^{-1})	δM (cm s^{-1})	m (cm s^{-1})	δm (cm s^{-1})	Φ (°)	$\delta \Phi$ (°)	g (°)	δg (°)
Q_1	0.7	0.46	0.3	0.25	84	37	55	55
O_1	4.9	0.53	0.4	0.28	93	3	75	7
K_1	7.8	0.50	0.4	0.25	93	2	85	4
N_2	2.0	0.30	-0.1	0.24	93	7	79	10
M_2	7.4	0.34	-0.4	0.28	96	2	76	3
S_2	6.3	0.38	-0.3	0.23	97	2	51	3
M_4	1.0	0.24	0.0	0.14	100	7	290	12

Phases are relative to UT. Time zone Z = -7. Tidal ellipse parameters are reported at 95 % confidence. Tidal constituents are above the noise level (signal-to-noise ratio > 1).

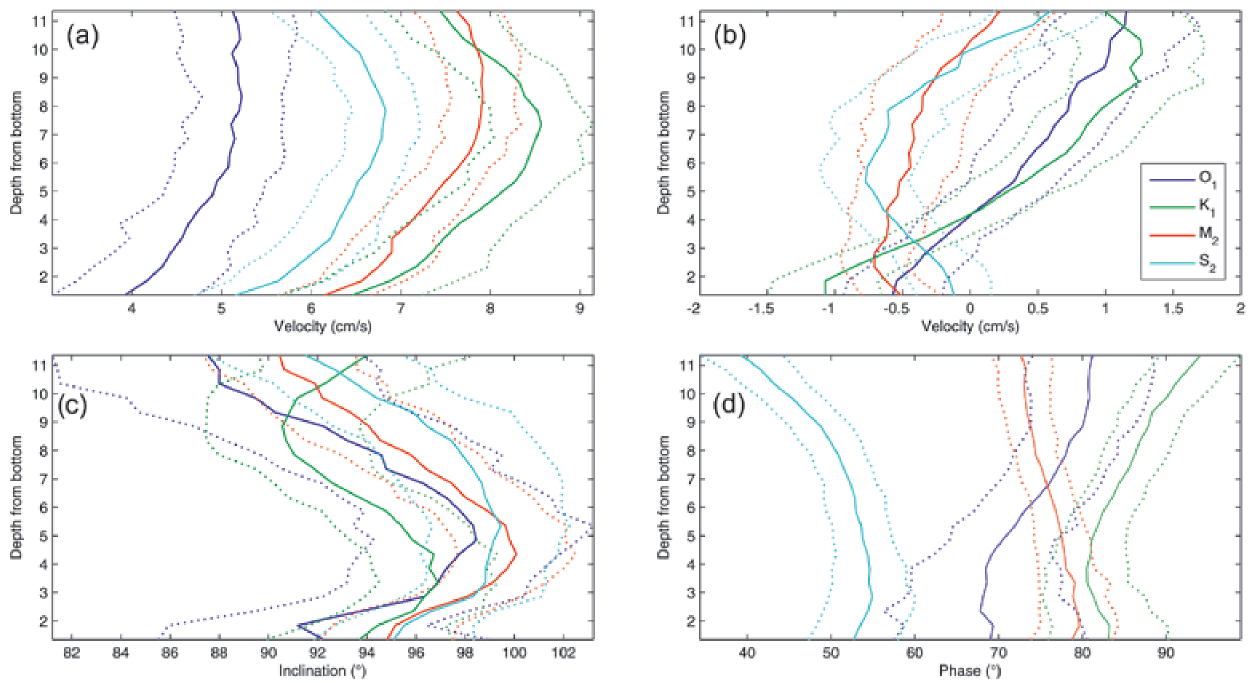

Figure 4. Vertical structure of the ellipse characteristics for the main tidal currents: (a) semimajor axis (cm s^{-1}), (b) semiminor axis (cm s^{-1}), (c) orientation of the semimajor axis, in degrees relative to East, positive counterclockwise, and (d) phase relative to tidal potential at Greenwich, in degrees. The dashed lines are the demarcation of the errors.

s^{-1}. All components show a parabolic profile. They are affected by boundary layer process (see e.g., Prandle, 2009). It is noteworthy that the magnitude of K_1-current is maximal at the middle of the water column. Diurnal components reveal anticlockwise rotation at the upper half of the water column and clockwise at the lower half, whereas the semidiurnal components show predominantly clockwise rotation in the entire water column. The orientation of the major axis is depth dependent and is consistent with the course of the main channel. The phase lag of the diurnal components diminishes from the surface to the bottom, whereas for semidiurnal components the phase lag is almost constant along the water column. It is also noteworthy that there is a phase lag difference of 30º between components M_2 and S_2. This result is explained by differences in their respective forcing mechanism: the Moon generates M_2 and the Sun generates S_2.

Discussion

Based on a 144-day ADP dataset at the inlet of Guaymas Bay, tides, tidal currents and its vertical structure have been presented for the first time. The diurnal component K_1 and the semidiurnal component M_2 are the dominant tidal motions. K_1 and M_2 exhibit a standing wave behavior. It is very well known that tidal dynamics in coastal waters depends on basin shape. To measure the relative importance of basin shape in the tidal flow field, Fagherazzi *et al*. (2003) define the adimensional parameter $\alpha = \omega L / (g H)^{1/2}$, where ω is the tidal frequency, L is the basin length, g is gravity, and H is depth. If α is small ($O(10^{-3})$), then the water level is in phase at every point in the basin. Taking representative values for the inlet of Guaymas Bay as L ~ 3 km, H ~ 10 m, it is found that for the diurnal tide ($\omega = 7.2 \times 10^{-5}\ s^{-1}$), $\alpha = 0.002$; thus, the short embayment hypothesis is valid for the inlet. Under these conditions, the tide is a standing wave. Therefore K_1 is standing in Guaymas Bay because its wavelength is larger than the length of the basin.

The M_2 tidal component also holds the small embayment hypothesis ($\alpha = 0.004$) and the phase shift between the inlet and the boundaries is small. Under this theory the velocity (U) scales as ωL. This length scale is related to the tidal excursion ($E = u\ T / \pi$), which is ~ 2 km for the diurnal components and ~ 1 km for the semidiurnal tides. As comparison, Fagherazzi *et al*. (2003) report that in San Diego Bay the M_2 tidal component is a standing wave. They report that $\alpha = 0.015$ for the semidiurnal tide. In Laguna San Ignacio, a small coastal lagoon on the Pacific coast of the Baja California peninsula, main tidal waves are also close to standing (Winant and Gutierrez de Velasco, 2003).

The M_4 tidal component, an overtide associated to the M_2 tidal component, is the shallow-water constituent of foremost importance. Overtides have been observed in coastal lagoons of the Gulf of California (Sandoval and Gómez-Valdés, 1997; Gómez-Valdés *et al*., 2003; Dworak and Gómez-Valdés, 2003; Dworak and Gómez-Valdés, 2005). For example, Dworak and Gómez-Valdés (2003) report that in Yavaros Bay, the M_4 tidal component is ~ 2 cm s^{-1}, and that at the inlet of this lagoon, M_2 tidal current is ~ 30 cm s^{-1}. In Guaymas Bay, the most important shallow water component is the overtide M_4 with magnitude ~ 1 cm s^{-1}. Thus the non-linear interactions are stronger in Yavaros Bay than in Guaymas Bay. This discrepancy between these two systems is explained for the fact that the linear momentum is stronger in the former system than in the latter. On the other hand, the $2M_2 - M_4$ phase relationship at the inlet for the sea surface elevation is of the order of 300 degrees, whereas for the velocity is of the order of 150 degrees. Hence the water body is ebb-dominant (Friedrichs and Aubrey, 1988), favorable to maintain healthy water quality in the bay. However, the tidal excursion for all components is not larger than the inlet length suggesting that exchange between the inner lagoons and the ocean might not be as adequate enough for maintaining the bay water quality. As well as in a stratified system, the relationship between flood and ebb are more complex, both processes are modified by baroclinic pressure gradient forces and by vertical mixing (Cudeback and Jay, 2000). In addition, because Li and Zhong (2009) demonstrate that fortnightly fluctuations of the tidal currents modify the residual current in estuaries (coastal lagoon), the strong spring-neap cycle in Guaymas Bay might have an important influence on the water exchange.

In the homogenous case, ellipse properties of tidal currents change with depth because of boundary layer effects (Prandle, 1982). The parabolic structure of the tidal currents is explained for the effect of the wind stress in the upper layer and the effect of the bottom stress in the lower layer. Under these conditions, the pressure gradient force induced a maximum of velocity at the middle of the water column (Kundu, 1990, 268 pp.). In the homogenous case, stratification modifies the tidal ellipse characteristics (Souza and Simpson, 1996). The diurnal currents rotate anticlockwise in the upper layer and clockwise in the lower layer. The pattern of the rotatory diurnal current is similar to the pattern of the rotary semidiurnal current in Rhine ROFI (Souza and Simpson, 1996), which is a very well known site where stratification effects are important in the tidal motions. The two-layer pattern at the inlet is in agreement with results obtained from an experiment of a lunar day at the entrance to the Guaymas Bay (Valle-Levinson *et al*., 2001), which implies that wind stress, bottom friction and stratification might be included in theoretical or numerical studies on tidal dynamics in semiarid coastal lagoon.

Acknowledgments

The field experiment was partially supported by CONACyT, México, grants P50185-2005 and CB-2007-82529, Cuerpo Académico Manejo de Zona Costera (SEP-PROMEP), and CICESE. J. Gómez-Valdés was visiting scholar at ITG during June 2010, when the final version of this paper was prepared. M. F. Lavín (Editor) and two anonymous referees helped to improve the manuscript.

Bibliography

Carrillo González F., Ochoa J., Candela J., Badan A., Sheinbaum J., González Navarro J.I., 2007, Tidal currents in the Yucatan Channel. *Geofísica Internacional*, 3, 199-209.

Castro R., Lavin M.F., Ripa P., 1994, Seasonal heat balance in the Gulf of California. *J. Geophys. Res.* 99, 3,249-3,261.

Cudaback C.N., Jay D.A., 2000, Tidal asymmetry in an estuarine pycnocline: Depth and thickness. *J. Geophys. Res.,* 105, 26,237-26,251.

Defant A., 1958, Ebb and Flow. The tides of earth, air, and water. The University of Michigan Press, USA, 121 pp.

Dworak J.A., Gómez-Valdés J., 2003, Tide-induced residual current in a coastal lagoon of the Gulf of California. *Estuarine, Coastal Shelf Sci.* 57, 1-11.

Dworak J.A., Gómez-Valdés J., 2005, Modulation of shallow water tides in inlet-basin system with a mixed tidal regime. *J. Geophys. Res.*110, Doi:10.1029/2003JC001865.

Dyer K. R.,1997, Estuaries a Physical Introduction. Wiley, Chichester, 195 pp.

Fagherazzi S., Wiber P.L., Howard A.D., 2003, Tidal field in a small basin. *J. Geophys. Res.*108, doi:10.1029/2002JC001340.

Foreman M.G.G., 1977, Manual for Tidal Heights Analysis and Prediction. Pac Mar Sci Rep 77-10, Inst Of Ocean Sci, Patricia Bay, Sidney, B. C., 69 pp.

Foreman M.G.G., Crawford W.R., Marsden R.F., 1995, De-tiding: Theory and practice. In: Lynch D.R. and Davies A.M. (Editors) Quantitative Skill Assessment for Coastal Ocean Models, Coastal Estuarine Studies 47, AGU, Washington, D.C., pp. 203-239.

Friedrichs C.T., Aubrey D.G., 1988, Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis. *Estuarine, Coastal Shelf Sci.,* 27, 521-545.

Godin G., 1972, The Analysis of Tides. Univ of Toronto Press, Toronto, 264 pp.

Godin G., 1988, Tides. Anadyomene, Ottawa, 349 pp.

Godin G., Paz-Vela R., Rodríguez N., Ortiz M., 1980, Revisión de los datos de mareas para la costa occidental de México disponibles en el CICESE e interpretación de los resultados (in Spanish). Centro de Investigación y de Educación Superior de Ensenada, Ensenada, B. C., México. 63 pp.

Gómez-Valdés J., Delgado J.A., Dworak J.A., 2003, Overtides, compound tides, and tidal residual current in Ensenada de la Paz, Baja California Sur, Mexico. *Geofísica Internacional,* 42, 623-634.

Kundu P.K., 1990, Fluid mechanics. Academic Press, San Diego, 638 pp.

Li, M., L. Zhong, 2009. Flood-ebb and spring-neap variations of mixing, stratification and circulation in Chesapeake Bay. *Cont. Shelf Res.* 1, 4-14 pp.

Marinone S.G., 1997, Tidal residual currents in the Gulf of California: is the M_2 tidal constituent sufficient to induce them? *J. Geophys. Res.*102, 8,611–8,623.

Pawlowicz R., Beardsley B., Lentz S., 2002, Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. *Comput. Geosci.* 28, 929-937.

Prandle D., 1982, The vertical structure of tidal currents and other oscillatory flows. *Cont. Shelf Res*. 1, 191-207.

Prandle D., 2009, Estuaries. Dynamic, Mixing, Sedimentation and Morphology. The vertical structure of tidal currents. Cambridge University Press, Cambridge, 236 pp.

Roden G.I., 1958, Oceanographic and meteorological aspects of the Gulf of California. *Pacific Sci.* 12, 21-45.

Sandoval F.J., Gómez-Valdés J., 1997, Tides and tidal currents in Ensenada de la Paz lagoon, Baja California Sur, Mexico. *Geofísica Internacional,* 36, 37-47.

Souza A.J., Simpson J.H., 1996, The modification of tidal ellipses by stratification in the Rhine ROFI. *Cont. Shelf Res.,* 16, 997-1,007.

Tsimplis M.N., 2000, Vertical structure of tidal currents over the Camarinal Sill at the Strait of Gibraltar. *J. Geophys. Res.,* 105, 19, 709-19 728.

Valle-Levinson A., Delgado J.A., Atkinson L., 2001, Reversing water exchange patterns at the entrance to a semiarid coastal lagoon. *Estuarine, Coastal Shelf Sci.,* 53, 825-838.

Winant C.D., Gutiérrez de Velasco G., 2003, Tidal dynamics and residual circulation in a well-mixed inverse estuary. *J. Phys. Oceanogr.,* 33, 1,365-1,379.