Continental Shelf Research 114 (2016) 16–28

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Tidal dynamics in a frictionally dominated tropical lagoon

L. Tenorio-Fernandez [a], J. Gomez-Valdes [a,*], I. Marino-Tapia [b], C. Enriquez [c], A. Valle-Levinson [d], S.M. Parra [d]

[a] Physical Oceanography Department, CICESE, Ensenada, Baja California, Mexico
[b] Coastal Processes and Physical Oceanography, CINVESTAV-IPN Merida, Yucatan, Mexico
[c] Sciences Faculty, UNAM. Campus Sisal, Yucatan, Mexico
[d] Civil and Coastal Engineering Department, University of Florida, Gainesville, FL, USA

ARTICLE INFO

Article history:
Received 11 September 2014
Received in revised form
7 December 2015
Accepted 18 December 2015
Available online 20 December 2015

Keywords:
Choked coastal lagoon
Tidal hydrodynamics
Highly frictional
Chelem lagoon

ABSTRACT

This study examined the dynamics of tidal propagation inside a tropical lagoon. Sea surface elevation (inside) and current profiles (at the inlet) were examined over 60 days at the *Chelem* lagoon, which is a branched tropical lagoon located in the northern Yucatan Peninsula. Tides were predominantly diurnal with a wavelength at least 20 times longer than the total length of the basin. Spatial variations of sea surface elevation and the longitudinal transport were described in each branch by applying a linear analytical model and the results were compared to observations. Results showed that the coastal lagoon was highly frictional. The tidal signal was attenuated between 30% and 40% toward the lagoon heads, a result of the balance between pressure gradient and frictional forces. A causeway that chokes the western side of the lagoon allowed the propagation of the diurnal signal toward the west head of the basin but damped the semidiurnal signal. The causeway acted as a hydraulic low-pass filter, as in natural choked systems. The causeway's filter effect was included in the analytical model by optimizing the frictional parameters.

1. Introduction

Coastal lagoon hydrodynamics are influenced mainly by tides, winds, heat fluxes, and freshwater inputs. The dynamics of coastal lagoons are also shaped by inlet morphology. Coastal lagoons may be subdivided according to their inlet characteristics into leaky, restricted and choked systems (Kjerfve and Magill, 1989). Leaky lagoons are the longest and narrowest ($\sim 10^3$ and $\sim 10^2$ m, respectively), parallel to the coastline and their hydrodynamics are controlled directly by the ocean through many inlets. Restricted systems are typically oriented parallel to the coastline, have one or two inlets and a well-defined tidal circulation, where the dynamics are controlled by the adjacent ocean. Choked lagoons are usually found along high wave energy coastlines with marked littoral drift and have one or more narrow inlets. Dominant wind forcing and freshwater pulses that may produce intermittent vertical stratification characterize these lagoons. In choked systems, the tidal signal is altered or eliminated because the inlet acts as a dynamic low-pass filter (Kjerfve and Magill, 1989). Choked systems, especially those located in the tropics, are a very important part of the local ecology owing to their high primary and secondary production (Krumbein et al., 1981; Barnes, 1980). Therefore, understanding their dynamics is essential because they play an important ecologic and economic role (Albrecht and Vennell, 2007).

In general, the hydrodynamics of choked lagoons are poorly understood. Such is the case in most of the lagoons that line the Mexican coast of the Gulf of Mexico (GoM). Considering this dearth of knowledge in the tropics, the approaches that have been used in subtropical and temperate regions can also be applied to study these systems. The purpose of this investigation is to analyze the dynamics of tidal propagation inside a branched tropical lagoon with predominant diurnal tides. The tidal propagation dynamics of the lagoon were analyzed using a linear model proposed by Winant (2007). The present study optimized different frictional and geometric parameters on the basis of observations in the lagoon, following the approach by Henrie and Valle-Levinson (2014). Analyses of the data and of the analytical model output provided the frictional characteristics of the two branches of the lagoon.

2. Study area

The *Chelem* lagoon is located between 21°10′ and 21°19′N and between 89°47′and 89°37′ W (Fig. 1b). It is a branched tropical lagoon, which extends parallel to the coast in an E–W orientation,

* Corresponding author.
E-mail address: jgomez@cicese.mx (J. Gomez-Valdes).

http://dx.doi.org/10.1016/j.csr.2015.12.008
0278-4343/

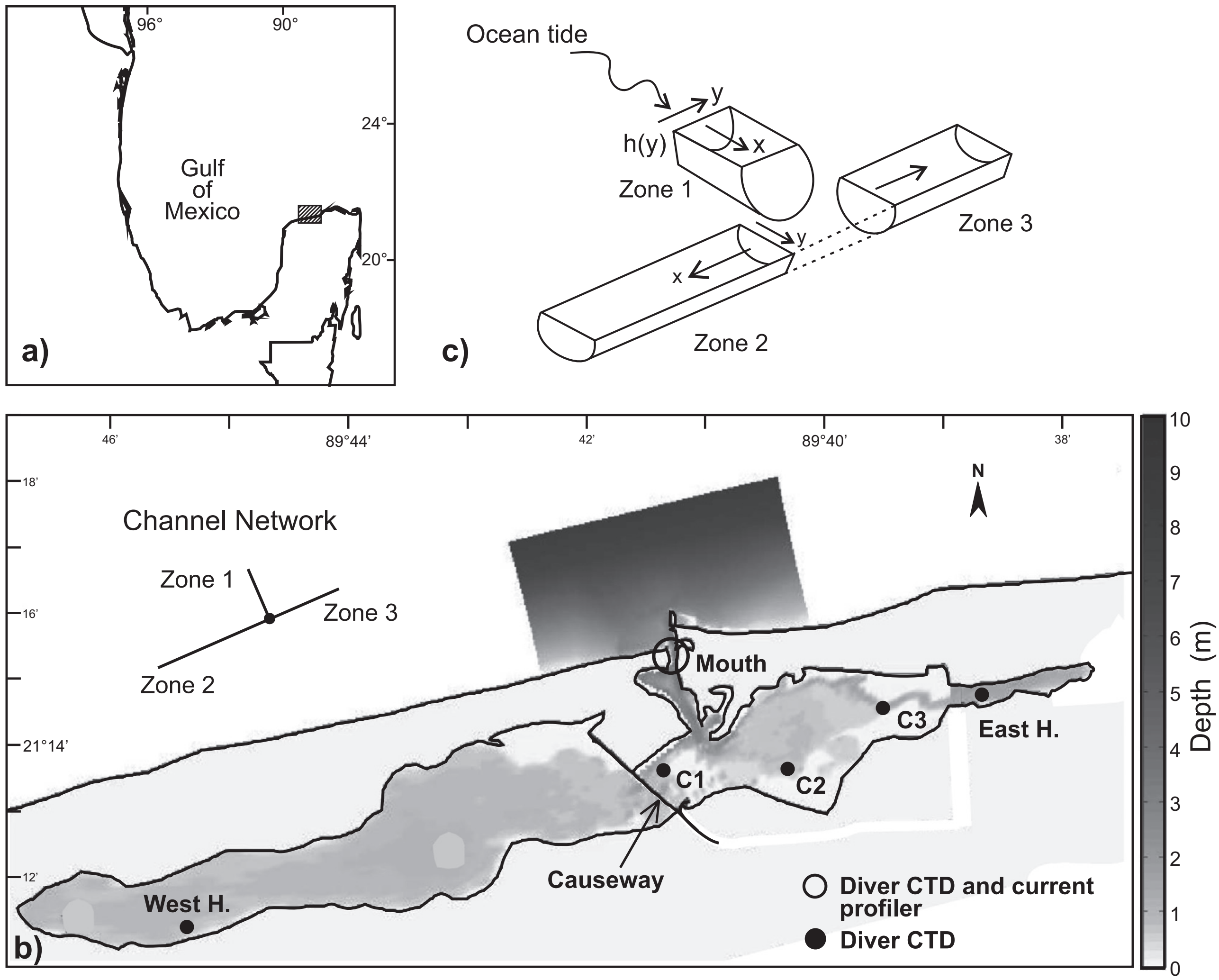

Fig. 1. (a) Location of *Chelem* in the Yucatan Peninsula, Mexico. (b) *Chelem* sampling locations with the black dots representing the locations of moored Diver CTD, a black ring represented the location of the current profiler (Aquadopp) and Diver CTD moored at the mouth, gray contours show approximate depth. At the left hand corner is represented the channel network. (c) Analytical model setup, showing Zones 1, 2 and 3, with the x axis representing the along-channel direction within all the zones.

and is shallow with depths ranging from 0.7 m to 3.5 m. Since 1969, many physical modifications have affected *Chelem*. The most drastic alteration was the construction of a causeway across the lagoon in the 1980s. This causeway divided the lagoon and severely restricted water circulation toward the western head. The causeway has two bridges, each one with 5 m-wide gap that allows some water flow and maintains the west head connected to the central lagoon. However, this restriction modifies the natural hydrodynamics (e.g., see Hill, 1994) and has already caused diverse environmental problems.

The lagoon is a network of three zones connected by the central lagoon area (Fig. 1b). Zone 1 is a meridional channel that connects the lagoon with the Yucatan Shelf. This Zone is the deepest, narrowest, and shortest (Table 1 shows the average dimensions of each zone). Zones 2 and 3 bifurcate from Zone 1 and are channels oriented westward and eastward, respectively. Zone 2 is the longest, shallowest, widest and is affected by the causeway. It is connected with Zone 1 only through the causeway gaps. Zone 3 extends from Zone 1 to the eastern head, which has medium length, medium width, and medium depth.

Chelem tidal signals are related with those of the Yucatan Shelf that are forced by the GoM tides (Fig. 1a). Tides in the GoM are the result of indirect tidal oscillations from the Atlantic Ocean and direct astronomical forcing (Zetler and Jansen, 1972). The main tidal constituents within the GoM are the lunisolar diurnal (K_1), the lunar diurnal (O_1), and the principal lunar semidiurnal (M_2); however, tide behavior varies along the coast (Kantha, 2005). The tides range from semidiurnal near Florida to diurnal at the Yucatan Peninsula according to tidal station information from the National Oceanic and Atmospheric Administration. David and Kjerfve (1998) found that at the *Terminos* lagoon in the neighboring Campeche state, Mexico (~400 km from *Chelem*) the tidal range is 0.3 m with diurnal dominance; this pattern continues all the way to the Yucatan Shelf.

Kjerfve (1981) studied the main tidal amplitudes and tidal phases along the Yucatan Shelf. He found that the amplitudes of the diurnal harmonics K_1 and O_1 at the *Progreso* harbor (located ~10 km east of *Chelem*) were 17.7 cm and 17.1 cm, respectively, with a M_2 as the largest semidiurnal amplitude harmonic; with a value of 6.0 cm. Martínez-López and Pares-Sierra (1998) used a three-dimensional model to study tidal dynamics in the Yucatan Shelf. However, the tides within *Chelem*, or any lagoon in Yucatan, have yet to be described.

The tidal signal inside semi-closed coastal basins is modified by friction, the Earth's rotation and morphology (Waterhouse et al., 2011). Frictional effects dominate over the Earth's rotation in shallow basins (Winant, 2007). For highly frictional basins, the relation between sea surface elevation and water velocity departs from the