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Subtidal hydrodynamics in a tropical lagoon: A dimensionless numbers approach

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ABSTRACT

Observations in a tropical lagoon of the Yucatan peninsula motivated a non-dimensional number analysis to examine the relative influence of tidal stress, density gradients and wind stress on subtidal hydrodynamics. A two-month observation period in Chelem Lagoon covered the transition from the dry to the wet season. Chelem Lagoon is influenced by groundwater inputs and exhibits a main sub-basin (central sub-basin), a west sub-basin and an east sub-basin. Subtidal hydrodynamics were associated with horizontal density gradients that were modified seasonally by evaporation, precipitation, and groundwater discharge. A tidal Froude number (Fr_0), a Wedderburn number (W), and a Stress ratio (S_0) were used to diagnose the relative importance of dominant subtidal driving forces. The Froude number (Fr_0) compares tidal forcing and baroclinic forcing through the ratio of tidal stress to longitudinal baroclinic pressure gradient. The Wedderburn number (W) relates wind stress to baroclinicity. The stress ratio (S_0) sizes tidal stress and wind stress. S_0 is a new diagnostic tool for systems influenced by tides and winds, and represents the main contribution of this research. Results show that spring-tide subtidal flows in the tropical lagoon had $\log(Fr_0) \gg 0$ and $\log(S_0) > 0$, i.e., driven mainly by tidal stresses (advective accelerations). Neap tides showed $\log(Fr_0) \ll 0$ and $\log(S_0) < 0$, i.e., flows driven by baroclinicity, especially at the lagoon heads of the east and west sub-basins. However, when the wind stress intensified over the lagoon, the relative importance of baroclinicity decreased and the wind stress controlled the dynamics ($\log(W) \gg 0$). Each sub-basin exhibited a different subtidal response, according to the dimensionless numbers. The response depended on the fortnightly tidal cycle, the location and magnitude of groundwater input, and the direction and magnitude of the wind stress.

1. Introduction

Subtidal circulation in estuaries can be approximated as the gravitational circulation, which arises from the balance between along-estuary pressure gradient and mixing by stress divergence. Pressure gradients tend to flatten isopycnals and increase stratification, while stress divergence contributes to inhibit stratification (Chen and Sanford, 2009). However, there are coastal water bodies that deviate from this scheme because of the influence of tidal stresses in driving residual flows (e.g. Li and O'Donnell, 2005). In estuaries where the ratio between tidal amplitude and depth is > 0.1 (Parker, 1991), subtidal hydrodynamics can be controlled by the baroclinic pressure gradient and by tidal stresses. This control may turn in favor of one forcing or the other depending on the fortnightly cycle. In neap tides, the residual flow is driven by the baroclinic pressure gradient. However, during spring tides tidal stress can become dominant. In this case, tidal rectification can dominate over baroclinicity (Valle-Levinson and Schettini, 2016).

Dimensionless numbers can diagnose the relative importance of processes that control subtidal hydrodynamics (Valle-Levinson and Schettini, 2016). They arise from scaling terms in the along-axis momentum equation (Kundu and Cohen, 2002). For example, a Froude number characterizes the relation between inertial and baroclinic forces (Kundu and Cohen, 2002). The Wedderburn number (Monismith, 1986) determines the relative importance between wind stress and baroclinic pressure gradient.

The objective of this study is to diagnose, through the

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application of dimensionless numbers, the relative importance of forces that control the subtidal hydrodynamics in a tropical lagoon subject to tidal, wind and baroclinic forcing. The objective is addressed with meteorological and oceanographic observations during the transition from dry to wet seasons in the summer of 2012 in a coastal lagoon (*Chelem*) in Yucatan, Mexico. We use the densimetric tidal Froude number (Valle-Levinson and Schettini, 2016) to evaluate the relevance of tidal stresses over the longitudinal baroclinic pressure gradient. In addition, we use the Wedderburn number (Monismith, 1986) to compare wind stress to the longitudinal baroclinic pressure gradient. To compare inertia (tidal stress) to wind stress we propose the "Stress ratio" as a diagnostic tool.

2. Study area

Tropical coastal bodies of water exhibit marked seasonal variations in baroclinicity. Some of them illustrate classical estuarine conditions (hypopycnal, e.g. Largier, 2010) in the wet season and hyperpycnal characteristics in the dry season (Valle-Levinson and Schettini, 2016). Little is known about the subtidal variations and processes that control tropical lagoons of the Gulf of Mexico, particularly in the Yucatan peninsula. A few reports have described the hydrographic conditions of Chelem Lagoon (Valdés-Lozano and Real, 1998; Mariño-Tapia et al., 2010), hereafter '*Chelem*', which is located between 21°10′ and 21°19′ North and 89°47′ and 89°37′ West (Fig. 1). It is a bifurcated coastal body of water, with two branches parallel to the coast. These branches are roughly oriented from East to West, the major and minor axes lengths are ~ 14 km and ~ 1 km and the surface area is ~ 14 km^2. *Chelem* has an approximate depth range from 0.7 to 3.5 m and has been modified several times since 1969. *Chelem* has a marina and a causeway in the west sub-basin. The causeway divides the lagoon and restricts the natural flow through two bridges that are 5 m-wide each. These modifications affected *Chelem's* hydrodynamics (Tenorio-Fernandez et al., 2016).

Chelem shows well-defined seasonality in wind and precipitation regimes. It receives freshwater inputs through groundwater discharge. This type of discharge is typical of most water bodies of the Yucatan peninsula because of its karst geology and no orographic elevation (Valle-Levinson et al., 2011). Groundwater discharges had been assumed to influence the lagoon, because of localized salinity distributions, but had not been positioned. In addition, there had been no descriptions on the spatial-temporal salinity variations in the lagoon. *Chelem* is influenced by two seasons: the dry season from March to June and the wet season from June to November. In the remaining months (December to February) there is light and sporadic rain, related to extreme events locally known as "nortes" (cold fronts with northerly winds, Valle-Levinson et al. (2011)).

Chelem tidal signals co-oscillate with those of the Yucatan Shelf and with those of the Gulf of Mexico (GoM) (Fig. 1a). The GoM main tidal constituents are the lunisolar diurnal (K_1), the lunar diurnal (O_1), and the principal lunar semidiurnal (M_2) (Kantha, 2005). The tidal regime on the Yucatan Shelf is mainly diurnal. Approximately 10 km east of *Chelem* inlet, at the port of Progreso, the diurnal harmonics K_1 and O_1 have amplitudes of ~17.7 cm and ~17.1 cm, respectively, and the main semidiurnal M_2 is ~6.0 cm (Kjerfve, 1981). Tenorio-Fernandez et al. (2016), found three principal spectral bands in water level data from *Chelem*: the most energetic

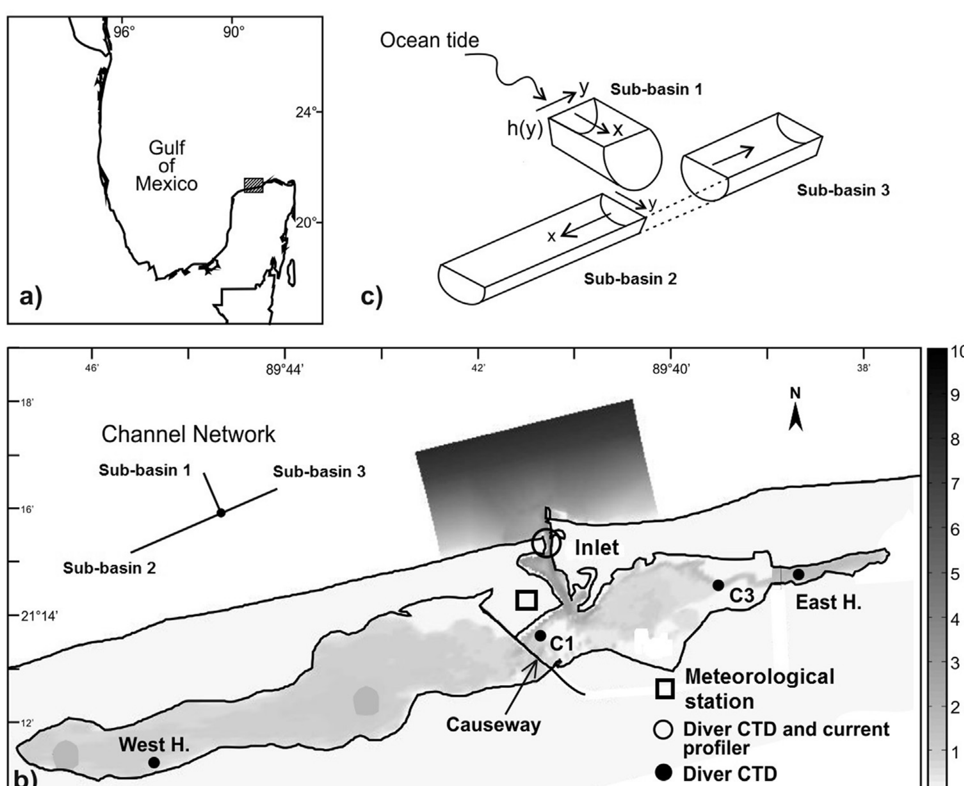

Fig. 1. (a) Location of *Chelem* Lagoon in the Yucatan peninsula, Mexico. (b) *Chelem* sampling locations with the black dots representing positions of moored Diver CTD, unfilled circle represents the location of the current profiler (Aquadopp) and Diver CTD moored at the inlet and gray contours show approximate bathymetry. The sub-basin network is represented on the upper left hand corner of this panel. (c) Schematic showing sub-basins 1, 2 and 3, with the x-axis representing the along-channel direction within all sub-basins (Tenorio-Fernandez et al., 2016).