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Wind-driven coastal upwelling and westward circulation in the Yucatan shelf

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ABSTRACT

The wind-driven circulation and wind-induced coastal upwelling in a large shelf sea with a zonally oriented coast are examined. The Yucatan shelf is located to the north of the Yucatan peninsula in the eastern Gulf of Mexico. This area is a tropical shallow body of water with a smooth sloping bottom and is one of the largest shelves in the world. This study describes the wind-driven circulation and wind-induced coastal upwelling in the Yucatan shelf, which is forced by easterly winds throughout the year. Data obtained from hydrographic surveys, acoustic current profilers and environmental satellites are used in the analysis. Hydrographic data was analyzed and geostrophic currents were calculated in each survey. In addition an analytical model was applied to reproduce the currents. The results of a general circulation model were used with an empirical orthogonal function analysis to study the variability of the currents. The study area is divided in two regions: from the 40 m to the 200 m isobaths (outer shelf) and from the coast to the 40 m isobath (inner shelf). At the outer shelf, observations revealed upwelling events throughout the year, and a westward current with velocities of approximately 0.2 m s^{-1} was calculated from the numerical model output and hydrographic data. In addition, the theory developed by Pedlosky (2007) for a stratified fluid along a sloping bottom adequately explains the current's primary characteristics. The momentum of the current comes from the wind, and the stratification is an important factor in its dynamics. At the inner shelf, observations and numerical model output show a wind-driven westward current with maximum velocities of 0.20 m s^{-1}. The momentum balance in this region is between local acceleration and friction. A cold-water band is developed during the period of maximum upwelling.

1. Introduction

The Yucatan shelf (YS), which is also known as the Campeche Bank, is located in the intertropical zone in the Gulf of Mexico (GoM) between the deep GoM and the Caribbean Sea basins (Fig. 1). The YS is characterized as a shallow tropical body of water, and its vertical heat flux at the surface is a maximum between April and August (Zavala-Hidalgo et al., 2002). Its coast is zonally oriented. The YS, which extends over 250 km, is the largest sea shelf in Mexico and one of the largest shelves in the world. The slope is smooth and is ~200 m/250 km on average. It is located next to a western boundary current, the Yucatan current (YC), that enters the GoM in the upper 800 m on the eastern side of the YS (Ochoa et al., 2001; Sheinbaum et al., 2002; Abascal et al., 2003). The YC has a mean velocity of 1.5 m s^{-1} (Sheinbaum et al., 2002; Abascal et al., 2003) and a maximum velocity of 3 m s^{-1} (Cetina et al., 2006). The distance between the YS and the YC is variable as the current separates and gets closer to the eastern boundary of the shelf (Moliniari and Morrison, 1988; Enriquez et al., 2010; Athié et al., 2012).

With respect to upwelling events at the eastern edge of the YS, Merino (1997) described an upwelling event that was caused by the variations of the YC and suggested a westward-northwestward circulation pattern over the shelf during this occurrence with velocities of approximately 0.10 m s^{-1}. In this event, relatively cold water was uplifted from a depth of 220–250 m to a depth of 10–70 m. The time estimated for this water to upwell from its depth and place of origin in the Caribbean Sea until it reached the YS was found to be around 46–139 h (Merino, 1997). Once over the shelf, it occupied the bottom layer of the YS and intensified the vertical and horizontal temperature stratification (Merino, 1997; Enriquez et al., 2013).

The entire region is primarily influenced by the trade winds, which are easterly winds, and by northeasterly wind events,

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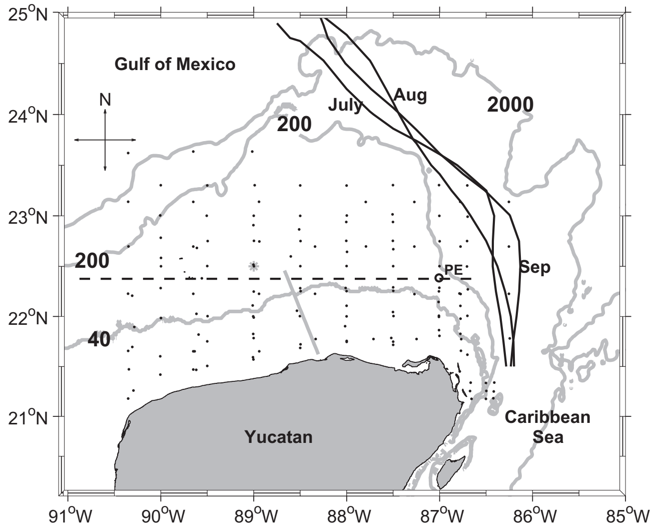

Fig. 1. Map of the Yucatan shelf. The black dots indicate the position where the CTD casts were carried out. The dashed line along latitude 22.375°N indicates the location where the upwelling index was calculated. The black circle (PE) indicates the location where the ADCP was moored at the bottom. The gray bold line that starts at longitude 88.3°W indicates the location of the sea level anomaly data that were used. The gray asterisk indicates the location of the density profile obtained from the output of the NEMO general circulation model. Sep, Aug and July stand for the path of the Yucatan current on September 2003, August 2007 and July 2009, respectively, following the 5 cm contour of the dynamic height (black lines at the east of the Yucatan shelf).

locally known as “Nortes”, from October to February (Gutierrez-de Velasco and Winant, 1996; Enriquez et al., 2013). The latter are strong wind events of short duration, caused by cold fronts (Gutierrez-de Velasco and Winant, 1996; Enriquez et al., 2013), which diminish or completely vanish the stratification in the YS (Tapanes, 1971; Merino 1997). Despite these, the easterly winds prevail throughout the year (Gutierrez-de Velasco and Winant, 1996; Enriquez et al., 2010). The hydrodynamics of the shelf have been mostly associated with this easterly wind stress pattern. With the use of numerical modeling simulations, it has been suggested that easterly winds produce a westward circulation. To mention, Martinez-Lopez and Pares-Sierra (1998) and Zavala-Hidalgo et al. (2003) found a westward flow induced by the wind stress with velocities between 5 and 18 cm s^{-1} (Martinez-Lopez and Pares-Sierra, 1998) and a maximum transport in July–August (Zavala-Hidalgo et al., 2003). In another study, Chang and Oey (2010) found that the wind increased the advection of heat from the Yucatan channel to the YS. More recently, Enriquez et al. (2010) showed that the momentum transferred from the YC when it encroaches upon the YS strengthens the westward flow over the YS. Using Lagrangian drifters, a mean sub-surface westward circulation has been observed with velocities of approximately 0.15 m s^{-1} and maximum velocities (0.20 m s^{-1}) during the summer (DiMarco et al., 2005). Regardless of these results, there is still no clear understanding of the YS circulation and some evidence indicates that the wind is not the only driving mechanism (Enriquez et al., 2010).

Associated with the wind effects, a relatively cold-water band is present along the coast between May and August (Zavala-Hidalgo et al., 2006), which is thought to be related to wind-driven coastal upwelling (Tapanes, 1971; Kindle and O’ Brien, 1974; Ruiz-Renteria, 1979; Zavala-Hidalgo et al., 2006). However, favorable coastal upwelling winds are present throughout the year. The present contribution suggests coastal upwelling events all year round.

This research aims to elucidate the wind’s influence and the stratification’s impact on both, the circulation in the YS and the coastal upwelling mechanism. In this study we use a set of hydrographic data and acoustic current profiles from moorings, a time series analysis of satellite data and the output of a general circulation model, The Nucleus for European Modeling of the Ocean (NEMO) (Jouanno et al., 2011) (hereinafter NEMO). For the analysis, the study area is divided in two regions from the 40 m to the 200 m isobaths (outer shelf) and from the coast to the 40 m isobaths (inner shelf). The results explain the westward circulation across the YS, clarify the coastal upwelling mechanism and explicate the cold-water band along the coast.

2. Data and methods

2.1. Hydrographic data

Hydrographic data were collected and provided by the Mexican Navy during three oceanographic surveys onboard a Mexican Navy research vessel. A conductivity-temperature-depth (CTD) profiler was used (SBE SeaCat) to obtain measurements from 20 to 26 September 2003, 1 – 8 August 2007 and 6 – 13 July 2009. Each survey covered most of the YS (black dots in Fig. 1). Only the upcast CTD data were used, due to malfunction of the sensor during the acquisition of downcast CTD data on the survey performed on July 2009, and processed using Sea Bird software. The thermodynamic properties of the seawater were derived from the raw data using the TEOS-10 functions (IOC et al., 2010). Water density maps were generated using objective mapping according to Jeronimo and Gomez-Valdes (2006).

The outer part of the YS, from the 40 m up to the 200 m isobaths, was assumed to be in geostrophic balance. However, given the shallow depth of the outer part of the YS, the geostrophic velocities were calculated from the CTD data using the geostrophic method for sea shelves as follows (Csanady, 1997):

$$u_g = \frac{1}{f\rho} k\times\nabla_H P = \frac{g}{f} k\times\nabla_H D, \tag{1}$$

where:

$$D = \int_{-h}^{z} \sigma dz,\ \sigma = 1 - \frac{\rho}{\rho_0},$$

$$D_B - D_A = \int_{-h}^{z} \sigma(B)dz - \int_{-h}^{z} \sigma(A)dz + \int_{-h}^{z} \sigma_b \nabla_H h.\ ds.$$

Where u_g are the geostrophic velocities, f is the Coriolis parameter, g is the acceleration of gravity, D is the dynamic height, ρ and ρ_0 represent the density at a given depth and the mean density of the sea water at each survey, respectively, and h is the sea bed, z is a given depth and σ_b is the density along the sea floor. The last integral is a line integral of the bottom density performed along the path between the location of the casts A and B. This method can be applied only if density is a function of depth and if.

$$J\left(\sigma_b, h\right) = 0, \tag{2}$$

where J is the Jacobian. The slope of the YS is constant along its zonal axis therefore $\frac{\partial h}{\partial x}$=0. In the YS bottom density variability along the x-axis is minimum such that $\frac{\partial \sigma_b}{\partial x}$=0. Besides the slope $\frac{\partial h}{\partial y}$=0.001 and thus tends to zero and (2) can be satisfied. Geostrophic currents were calculated using central differences. Interesting features exist off the shelf, but their analysis is beyond the extent of this research and so only the velocities over the outer shelf were analyzed. The inner shelf is not assumed to be in geostrophic balance given that its shallowness causes the surface and bottom boundary layers to overlap so the frictional terms