Continental Shelf Research 151 (2017) 40–52

Contents lists available at ScienceDirect

Continental Shelf Research

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

Nearshore circulation on a sea breeze dominated beach during intense wind events

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ARTICLE INFO

Keywords:
Sea breeze
Land breeze
Norte
Surf zone
Swash zone
Nearshore circulation
Nearshore hydrodynamics

ABSTRACT

A field experiment was conducted on the northern Yucatan coast from April 1 to April 12, 2014 to investigate the role of intense wind events on coastal circulation from the inner shelf to the swash zone. The study area is characterized by a micro-tidal environment, low-energy wave conditions, and a wide and shallow continental shelf. Furthermore, easterly trade winds, local breezes, and synoptic-scale events, associated with the passage of cold-fronts known as Nortes, are ubiquitous in this region. Currents were measured concurrently at different cross-shore locations during both local and synoptic-scale intense wind events to investigate the influence of different forcing mechanisms (i.e., large-scale currents, winds, tides, and waves) on the nearshore circulation. Field observations revealed that nearshore circulation across the shelf is predominantly alongshore-directed (westward) during intense winds. However, the mechanisms responsible for driving instantaneous spatial and temporal current variability depend on the weather conditions and the across-shelf location. During local strong sea breeze events ($W > 10$ m s^{-1} from the NE) occurring during spring tide, westward circulation is controlled by the tides, wind, and waves at the inner-shelf, shallow waters, and inside the surf/swash zone, respectively. The nearshore circulation is relaxed during intense land breeze events ($W \approx 9$ m s^{-1} from the SE) associated with the low atmospheric pressure system that preceded a Norte event. During the Norte event ($W_{max} \approx 15$ m s^{-1} from the NNW), westward circulation dominated outside the surf zone and was correlated to the Yucatan Current, whereas wave breaking forces eastward currents inside the surf/swash zone. The latter finding implies the existence of large alongshore velocity shear at the offshore edge of the surf zone during the Norte event, which enhances mixing between the surf zone and the inner shelf. These findings suggest that both sea breezes and Nortes play an important role in sediment and pollutant transport along/across the nearshore of the Yucatan shelf.

1. Introduction

Nearshore circulation plays an important role in the transport of pollutants, phytoplankton, and sediment between the inner shelf and coastal waters (Nittrouer and Wright, 1994; Hendrickson and MacMahan, 2009; Grifoll et al., 2015). However, the relative role of the different physical processes and their coupling while driving transport across the shelf remains poorly understood in some regions due to the lack of concurrent field observations at different water depths.

The Northern Yucatan peninsula is characterized by the influence of intense winds mainly associated with local sea/land breezes and synoptic-scale events associated with cold-front passages (Figueroa-Espinoza et al., 2014). Sea breezes are a local phenomenon that occur at coastal locations owing to differential heating of the land and the ocean

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http://dx.doi.org/10.1016/j.csr.2017.10.008
Received 23 February 2017; Received in revised form 12 August 2017; Accepted 16 October 2017
Available online 19 October 2017
0278-4343/

(Masselink and Pattiaratchi, 1998a; Gille et al., 2003). Sea breezes develop when solar radiation and the differing rates at which land and water heat up create a landward meso-scale pressure gradient force. Thus, cool marine air moves toward the land, is lifted vertically at the sea breeze front, and often forms a closed circuit via a return flow and a diffuse region of descending air currents located offshore (Miller et al., 2003). Gille et al. (2003) analyzed winds from NASA QuikSCAT scatterometer measurements to diagnose sea breezes globally. The analysis shows that significant sea breezes occur at locations around the world, including the western Mediterranean Sea, the west coast of Africa, western Madagascar, western Australia, and the northern Yucatan peninsula.

Intense wind events from the NNW are common on the Yucatan peninsula during winter months (Figueroa-Espinoza et al., 2014). These wind events, termed Nortes, usually occur from September through April and are part of synoptic-scale disturbances from mid-latitudes, characterized by a cold front passage with sustained intense winds associated with high pressure systems (Appendini et al., 2012). The duration of a Norte varies from one to several days and may have an adverse impact on different activities in the Gulf of Mexico such as the oil industry, fisheries, maritime transportation, and tourism (Appendini et al., 2013). Therefore, owing to the high frequency of occurrence, both sea breezes and Nortes must play an important role in controlling the costal dynamics on the Yucatan coast.

Previous studies on the northern Yucatan peninsula mainly focused on the circulation occurring in deeper waters on the continental shelf. More specifically, on investigating the mechanisms of coastal upwelling in the northeastern region (e.g. Merino, 1992, 1997; Reyes-Mendoza et al., 2016; Ruiz-Castillo et al., 2016), the dispersion of red tide across the shelf (e.g. Enriquez et al., 2010), the role of wind stress in the alongshelf circulation (e.g., Gutiérrez de Velasco and Winant, 1996; Zavala et al., 2003; Ruiz-Castillo et al., 2016), and thermohaline processes (e.g., Furnas and Smayda, 1987; Enriquez et al., 2013).

Merino (1997) analyzed hydrographic thermohaline data to describe the Yucatan shelf dynamics and to demonstrate the occurrence and structure of coastal upwelling. Moreover, using data from the National Centers for Environmental Prediction, Zavala-Hidalgo et al. (2003) show that the variability of the monthly mean surface current is poorly correlated with the alongshore wind stress. Enriquez et al. (2010) conducted a numerical study to investigate the mechanisms governing dispersion in the Yucatan shelf, finding that the westward circulation is strongly controlled by the Yucatan Current jet and weakly correlated with wind stress. The latter finding corroborated the results by Zavala-Hidalgo et al. (2003) and recent field observations (i.e., Reyes-Mendoza et al., 2016). Ruiz-Castillo et al. (2016) investigated the wind-driven circulation on the continental shelf using in situ and satellite data finding that the 0.20 m s^{-1} westward current at the outer and inner shelf is mainly driven by the intense winds. Coronado et al. (2007) found that the Yucatan Current (YC) modulates the sea level through geostrophic coupling and influences the sea level at the Puerto Morelos fringing reef lagoon. Despite the relatively low energy wave conditions (annual mean significant wave height $\overline{H_s} = 1$ m), beach erosion along the Yucatan coast is severe (Appendini et al., 2012) and is associated with sediment transport gradients induced by coastal structures (e.g., Lira-Pantoja et al., 2012; Medellín et al., 2015; Ruiz-Martínez. et al., 2015). Appendini et al. (2012) estimated a net westward alongshore transport rate that ranges between 20,000 and 80,0000 m^3 yr^{-1} along the northern Yucatan peninsula. More recently, the analysis of a post-nourishment beach evolution at Progreso Yucatan suggested that swash zone sediment transport could be significant in sea breeze dominated environments (Medellín et al., 2015).

Studies focused on the understanding of nearshore hydrodynamics in sea breeze dominated environments are scarce despite their important role on cross-shelf circulation (Hendrickson and MacMahan, 2009), wave generation (Ponce de León and Orfila, 2013), circulation (Sonu et al., 1973; Masselink and Pattiaratchi, 1998a), and morphological response (Masselink and Pattiaratchi, 1998b, 2001; Gallop et al., 2011) on many coastlines around the world. In the present study concurrent field observations of wind, waves, sea level, and currents were collected to investigate the influence of different forcing mechanisms on the nearshore hydrodynamics of a sea breeze dominated beach during both local and synoptic-scale intense wind events (i.e., sea breeze, land breeze, and Norte events). The winds, waves, and beach characteristics in the study area are described in Section 2. Section 3 describes the field experiment and data analysis. Field observations of atmospheric/oceanographic conditions and the associated hydrodynamics at different cross-shelf locations during the events are presented in Section 4. Furthermore, the relative importance of the forcing mechanisms, at different cross-shore locations, during local and synoptic-scale winds is analyzed. Finally, a summary is presented in Section 5.

2. Study site

2.1. Site description

The study area is located on a sea breeze dominated barrier island beach in Sisal Yucatan, Mexico (21° 09′ 56.20″ N, 90° 02′ 26.44″ W; 807320 m E, 2343344 m N). More specifically, the instrument array was deployed near the midpoint between the downtown pier and the east jetty at Sisal Port (Fig. 1a). The Yucatan shelf is 200 km wide with a mean slope of 1:1000 (Enriquez et al., 2010). The area is tropical with no river input to the coastal ocean. The peninsula is permeable due to carbonate geology with groundwater seeps and springs emanating in the coastal ocean (Capurro and Reid, 1972; Pope et al., 1991; among many others). Tides are mixed semi-diurnal with a range of 0.80 m (microtidal).

The beach profile is comprised of a low dune of 0.5 m height from mean low tide level and two roughly shore-parallel subtidal sandbars (see Figs. 1b and 2). The shoreline orientation is 14° south of the E-W orientation and the annual beach width variability is 10 m at the field site location. The beach is made of carbonate medium sand, with d_{50} (median diameter), ranging from 0.2 to 2.0 mm in the surf zone (Wellmann, 2014) at the middle frame (Fig. 1b). Biogenic materials are present on the beach, and a large fraction of whole or partially broken shells are present on the foreshore and migrate across the swash zone.

2.2. Weather conditions

The Yucatan Peninsula is a low-lying, low terrain roughness area that allows a large landward penetration by onshore winds. The climate is influenced by large-scale circulation patterns at the limit between tropical and arid zones (Orellana et al., 2009). The mean annual temperature is around 26 °C, with January (~ 23 °C) and May (above 27 °C) the coldest and hottest months, respectively. The region is dry, classified BSh (Köppen classification) with mean rainfall below 600 mm per year. However, rainfall totals may vary between 350 mm and more than 900 mm, depending on the incidence of heavy rain events such as hurricanes.

The region has three weather seasons: (1) dry season (March to mid-June), (2) rainy season (mid-June to October), and (3) Nortes season (November-February). The latter is characterized by synoptic-scale events associated with short-duration high-pressure systems with rain and strong winds that originate from large masses of cold polar air from high latitudes (Medina-Gomez and Herrera-Silveira, 2009). Most of the Nortes originate in the great plains of the USA and Canada, and propagate south across the Gulf of Mexico.

Fig. 3 shows the wind rose for Sisal, corresponding to wind measurements from the 3D anemometer (for a detailed description of the instrumentation see Section 3.1) located 12.5 m above the terrain, for the period from August 2011 to August 2012. The more intense and most frequent winds come from the north and northeast, respectively.