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Thermohaline processes in a tropical coastal zone

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ABSTRACT

The detailed thermohaline structure of the northern Yucatan coastal zone was obtained for the first time in order to gain an insight into the interactions between various processes in this complex tropical environment of extreme evaporation and high precipitation rates. From the continent, it has water exchange with numerous coastal lagoons (ranging from brackish to hypersaline) and receives intense submarine groundwater discharges (SGD). In the summer of 2006 a high-resolution (500 m cross-shore and 5 km along-shore) oceanographic campaign was performed starting at Holbox Island down to the mouth of Celestun Lagoon. CTD profiles were measured at 1020 stations along 69 coastal cross-shore transects. Additionally, CTD data from 2 wider surveys, covering the continental shelf (Campeche Bank) and the southern Gulf of Mexico respectively were used to complement the results. From the thermohaline properties, two main water masses were identified: (a) the Caribbean Subtropical Underwater (CSUW), upwelled from the Caribbean, which was observed at the bottom very close to the coast in more than 260 km (from the upwelling region near Cape Catoche to approximately 89.5 W during the summer of 2006) and (b) the second dominant group was a mass of warm hypersaline water which originates in Yucatan due to the high temperature and evaporation rates. We call this water mass the Yucatan Sea Water (YSW) after finding evidence of its presence in various field campaigns both in the Yucatan Sea and further to the west in the southern Gulf of Mexico. All the water masses present in the Yucatan coastal zone showed pronounced variations with important dilution and salinisation effects. The permeable karstic geology of the region prevents the continental water from discharging into the ocean through surface rivers and instead the rainfall permeates directly to the aquifer and travels through caves and fractures towards the sea. Three main regions showed evidence of continental discharges from the coast: the central eastern region (~21.6 N, 87.75 W), around Dzilam Bravo (~21.4 N, 89 W) and, to a lesser degree, the western region of the coast (~21.1 N, 90.3 W). The latter two regions are the eastern and western intersections of the Chicxulub crater ring with the coast respectively.

1. Introduction

It is widely recognized that the most productive areas of the seas are found in the coastal ocean. The nutrient input has been so large that it is becoming an issue for eutrophication in the coastal zone (Deegan et al., 2012). These regions receive nutrient rich waters from offshore (i.e. upwelling, internal waves, water mass advection) and from the continent (i.e. lagoons, estuaries, and submarine groundwater discharges), generating intense exchange and mixing processes, where heat, salinity, nutrients, pollutants and organisms are involved. The conservative properties of seawater are modified within these shallow areas due to the thermodynamic processes that occur as different water types interact with each other and with the atmosphere. In regions with extreme weather conditions such as the tropics, where evaporation can exceed precipitation during dry season, but torrential rain also occurs at some point during the year, the thermodynamic transformations might induce water mass formation and other hydrodynamic processes with important implications far beyond their locality. Water mass advection is a very important process for cross and along-shelf exchange of properties and materials to neighboring coastal regions or to deeper areas of the ocean (e.g. Salas-Perez et al., 2012; Liu et al., 2000).

On the other hand, the high biological and ecological importance of tropical coastal regions is worldwide accepted; and so is the concern for the environmental damage arising from the lack of regulations protecting these complex and delicate ecosystems (Nittrouer et al., 1995). Furthermore, the lack of basic local studies has left most tropical regions (specifically those located in developing countries) with deficient or even inexistent conservation and

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management policies to aid the protection of these environments. The present investigation was designed to obtain the first high-resolution set of data providing thermohaline information of the coastal sea of the northern Yucatan peninsula. The aim was to understand the interactions between the coastal processes over a shallow continental shelf surrounded by deep-sea basins in a tropical environment. This was achieved through an intensive field campaign collecting CTD data in the coastal zone of Yucatan (from the coastline to 7 km offshore, reaching approximately the 7 m isobath). Additionally, coarser hydrographic measurements on the Yucatan shelf and on the southern Gulf of Mexico were included in this study to complement the detailed thermohaline coastal information.

The following sections include a description of the study area, of the methods used on the field and of the data processing. Next, the thermohaline distribution in the coastal zone will be explained and a synoptic view of the surface salinity and temperature fields will be described for the region. The dynamic processes driving the thermohaline structure are addressed, including the export of high salinity and warm coastal waters and the description of an upwelling event. Finally, the findings will be complemented with wider survey data in order to describe the regional implications of the thermohaline processes observed in the coastal zone of the Yucatan.

2. Study area

The northeastern region of the Campeche Bank, referred to here as the Yucatan Shelf (Fig. 1), lies between the Yucatan Channel and the Sigsbee Abysal Plain. This continental shelf receives different water masses from the Caribbean, and occasionally from the deeper regions of the Gulf of Mexico (Capurro-Filograsso and Reid, 1972; Jones, 1968; Nowlin, 1971), which converge on a wide, flat, and shallow continental shelf. The Yucatan coastal zone is configured by a system of coastal lagoons behind a discontinuous barrier island with large areas of coastal mangrove. Some lagoons are hypersaline whilst others have estuarine characteristics and may export brackish waters to the coastal sea (Herrera-Silvera et al., 2004). These differences are due to the excess of evaporation over precipitation in the region (~1800 and ~1290 mm/yr respectively (SMN, 1971–2000)) and to the large and unevenly distributed continental freshwater discharge routes. The karstic geology of the Yucatan Peninsula hinders the formation of surface rivers, but promotes the generation of fractures, faults and karstic galleries through which fast submarine groundwater discharge can occur (Gallardo and Marui, 2006). The structural heterogeneities in geological formations make it difficult to identify where all this water discharges. Initial estimates of SGDs on the coast of the Yucatan peninsula suggested discharges of 23,500 $m^3\ km^{-1}\ d^{-1}$ (Hanshow and Back, 1980), but recent measurements made on point source discharges on the northern Yucatan coast (Valle-Levinson et al., 2011) show that the discharge from a single underwater spring is close to 40,000 $m^3\ d^{-1}$ even during the dry season. Therefore the actual discharge of freshwater to the ocean remains largely unknown. On land, there is a preferential pathway of groundwater associated with a large crater ring, which was formed by a meteor impact in Chicxulub, Yucatan, at the end of the Cretacic era. A high concentration of sinkholes ("cenotes") is associated with the crater's outer ring (Hildebrand et al., 1991; Pope et al., 1991; Sharpton et al., 1993). Hence, visible submarine groundwater discharges exist in the Yucatan coastal sea where the crater rings intersect with the sea (Logan, 1969; Capurro-Filograsso and Reid, 1972; Alvarez-Gongora and Herrera-Silveira, 2006; ArandaCirerol et al., 2006; Herrera-Silvera et al., 2004), mainly in the regions of Celestun and Dzilam Bravo (Fig. 1).

The region is influenced by mixed tides with diurnal dominance, ranging from 1 to 0.15 m during spring and neap tides respectively. There are three distinct weather seasons: the dry season from March to early June; rainy season from June to October; and the locally named "Nortes" (Northerlies) season when storms and strong winds of short duration (O(1) days) occur due to the transit of cold fronts during the winter (November to February) (ArandaCirerol et al., 2006; Capurro-Filograsso and Reid, 1972).

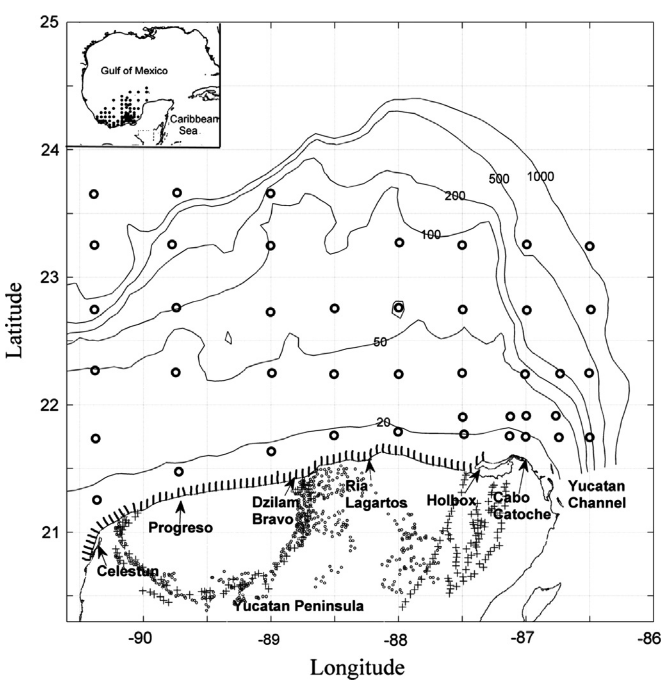

Fig. 1. Location of field measurement stations. Coastal CTD stations in July 2006 (black dots near the coast); larger scale surveys over the continental shelf in September 2005 and in the southern Gulf of Mexico (GOM) in September 2009 (gray circles). Crosses and dots inland, correspond to fractures and sinkholes respectively.

3. Methodology

An intensive field campaign was carried out from June 28 to July 12, 2006 measuring a total of 1020 conductivity, temperature and depth (CTD) profiles at stations along 69 transects. Each transect was 7 km long, initiated from the coast (~1.5 m depth) in a cross-shore direction with stations every 500 m. The measurements covered the northern Yucatan coastal zone with 5 km alongshore resolution (Fig. 1).

A CTD profiler SBE 19 plus was deployed by hand from a local fisherman's open boat of approximately 5 m long and each station was marked with a Garmin Global Positioning System (GPS). This manual handling and the dimensions of the boat made it possible to obtain measurements very close to the surface (0.5 m), down to the bottom and very close to the coast. The survey was started from the east at Holbox, and ended at Celestun (west end) after 13 days. The weather conditions during the field campaign, as measured in Progreso Port, were fairly stable with mean wind speed of 7 km/hr and a mild but clearly periodic oscillation (±2.3 km/hr) due to the effect of sea breezes (Fig. 2). Atmospheric temperatures also oscillated due to diurnal radiation fluxes showing a mean of 26.15 °C and a small standard deviation of 0.75 °C. The calibrated CTD data, sampled at 4 Hz, were processed with the standard procedure to obtain a vertical resolution of 0.1 m. T–S diagrams, horizontal distribution maps and vertical transects were obtained to describe the thermohaline characteristics of the coast during the summer of 2006. In order to include a broader view of the water masses at the regional scale, CTD data from 2 wider