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A downscaling method for simulating deep current interactions with topography – Application to the Sigsbee Escarpment

Steven L. Morey *, Dmitry S. Dukhovskoy

Center for Ocean – Atmospheric Prediction Studies, The Florida State University, Tallahassee, FL 32306-2840, United States

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ABSTRACT

A nesting approach is applied to dynamically downscale the deep circulation from a basin-scale model in regions of complicated topography where deep dynamics may be poorly resolved. The method is applied to nest a high vertical and horizontal resolution Navy Coastal Ocean Model (NCOM) domain covering the north-central Gulf of Mexico within a HYbrid Coordinate Ocean Model (HYCOM) Gulf of Mexico domain. The northwestern Gulf of Mexico has a very steep topographic feature, the Sigsbee Escarpment, over which localized bottom-intensified currents with short cross-isobath length scales have been observed in water depths between 1500 m and 3000 m. It has been hypothesized that these intense currents are related to the presence of the Loop Current or Loop Current Eddies, strong upper ocean mesoscale circulation features in the Gulf. A modeling system is required that can resolve the short length scales of topography and the currents, resolve the vertical trapping of the currents, and realistically simulate the mesoscale upper and deep ocean circulation features. The multi-model nesting approach described here simulates these intense currents with characteristics very similar to observations, and demonstrates the connectivity to the larger scale ocean circulation features.

1. Introduction

In the Gulf of Mexico (Gulf), the Loop Current (LC) and the Loop Current Eddies (LCEs) are the dominant upper-ocean circulation features. The LC enters the Gulf as a northward-flowing current through the Yucatan Channel, penetrates some distance northward, and then turns toward the east and south forming a "loop" before exiting through the Straits of Florida. The LC is an unstable current that aperiodically penetrates far to the north before detaching its loop as an anticyclonic LCE, which drifts generally toward the west, and then retreats toward the south. This stochastic behavior of the LC's northward penetration and eddy shedding has been characterized by Sturges and Leben (2000) and Leben (2005). The latter shows that over a 31-year record of combined satellite altimeter data and thermal imagery , the average interval between LCE shedding events is 9.4 months, with a range of between one-half month and over 18 months. The LC and LCEs can have near-surface velocity magnitudes exceeding 2 m/s.

A large number of numerical modeling studies of the Gulf have focused on simulating these important upper circulation features, beginning with Hurlburt and Thompson (1980). However, deep currents (below 1000 m) have remained somewhat a mystery until recently as oil and gas exploration activities have moved into deeper water. In the northwestern Gulf of Mexico, several oil and gas prospects have developed near a steep topographic feature called the Sigsbee Escarpment (Fig. 1). Moorings placed on the 2000 m isobath at the base of the escarpment in September, 1999, as part of a US Minerals Management Service-funded (currently the Bureau of Ocean Energy Management – BOEM) effort recorded intense currents near the bottom (10 m above the bottom) near 1 m/s (Fig. 2) (Nowlin et al., 2001; Hamilton and Lugo-Fernandez, 2001). More recent observations by the offshore industry, including members of DeepStar® (a Global Deepwater Technology Development Project led by Chevron, www.deepstar.org), have captured other events and characterized the short cross-isobath trapping scale of the currents (Morey et al., 2010). During times of observed strong currents, the LC is frequently extended far to the northwest with a LCE often separating from the current. The extreme deep currents, which appear to be consistent with Topographic Rossby Waves (TRWs), are not coherent with the localized upper-ocean flow in the observations. However, the presence of the LC and its associated eddies in the vicinity in these cases has led to the conjecture that the deep currents along the escarpment may be linked to the upper-ocean circulation.

Due to the paucity of deep measurements, the dynamics of these deep currents with short spatial scales, and the potential role of the Loop Current or eddies in their genesis, remain unclear. A numerical modeling approach is needed to further explore the physical mechanisms driving these phenomena, and to potentially

* Corresponding author. Tel.: +1 850 644 0345; fax: +1 850 644 4841.
E-mail address: morey@coaps.fsu.edu (S.L. Morey).

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lead to forecast capability of the associated strong currents. Challenges for applying numerical models to this problem include: (1) The need for high vertical resolution near the bottom at all depths along the escarpment to resolve the bottom-intensified currents, while (2) at the same time requiring a realistically simulated large-scale upper ocean and deep ocean circulation in a model with high enough horizontal resolution to resolve steep topography and the trapping scale of the deep currents (<1 km resolution) that can be tractably integrated for long time periods.

A solution to the first issue was given by Dukhovskoy et al. (2009), in which a new vertical grid was developed. A commonly-used terrain-following ("sigma") vertical coordinate can be configured to maintain high vertical resolution near the bottom at all depths. However, over steeply sloping topography, the well-known truncation error problem arises (Mellor et al., 1994, 1998; Mihailović and Zanjic, 1984). Dukhovskoy et al. (2009) introduced what was termed a "Vanishing Quasi-Sigma" (VQS) vertical coordinate that maintains high resolution near the bottom and reduces numerical errors associated with steeply sloping grid surfaces in traditional sigma-coordinate models (Fig. 3). This coordinate was implemented in the Navy Coastal Ocean Model (NCOM) and applied to a 30-arcsec horizontal resolution domain covering the Sigsbee Escarpment region. The model was able to simulate strong deep currents with cross-isobath and vertical trapping scales similar to observations with greatly reduced numerical errors compared to a classic sigma-coordinate model. However, to drive the deep currents, the model was nested within a larger-scale NCOM simulation with identical vertical grid, and the nesting method allowed mismatches to occur between the outer and inner model nests (Morey and Dukhovskoy, 2012). The primary reasons for these mismatches were differences in the westward propagation speeds of the deep and upper ocean eddies in the outer and inner nests, possibly due to differences in the model topography and/or interactions with the smallest resolvable eddies in the two model domains. This complicated the analysis of the currents along the escarpment in relation to the large-scale circulation.

A solution to the second issue is the subject of this work. A number of basin-scale models for the Gulf of Mexico with different numerical solution methods, horizontal and vertical grids, data assimilation methods, and other features offer multiple options for providing simulations of the large-scale upper ocean and deep circulation. Several recent efforts have focused on evaluating these models for potential forecasting uses (Oey et al., 2005; Mooers et al., 2012; Zhang et al., 2012). One such model is the HYbrid Coordinate Ocean Model (HYCOM), developed as part of the Global Ocean Data Assimilation Experiment to become the next-generation operational ocean modeling system for the US Navy and the National Oceanic and Atmospheric Administration (Chassignet et al., 2007). This model has high horizontal resolution (1/25°, or about 3.5 km) compared to other models of similar sized basins, which permits it to simulate the large gradients associated with many upper ocean circulation features. The data assimilation capability of the HYCOM also allows it to be run as a hindcast/nowcast/forecast system. However, the model grid spacing is not adequate for resolving the small cross-isobath length scales of the currents and topographic irregularities along the Sigsbee Escarpment. Vertical resolution in these basin-scale models is also often inadequate for resolving the bottom intensification that has been observed.

A multi-model nesting approach is applied to take advantage of the capabilities of the different modeling systems needed for simulating deep ocean processes and their interaction with topography and with large-scale upper ocean and deep circulation features. The NCOM with VQS vertical grid is applied over the Sigsbee Escarpment region at 30 arcsec (approximately 800 m) horizontal resolution. This model is nested within a 1/25° Gulf of Mexico Hybrid Coordinate Ocean Model (HYCOM) that can be either data assimilative or free-running. In addition to the commonly used nesting approach at the lateral boundaries, this downscaling methodology constrains the upper ocean temperature and salinity, and thus velocity through the model's dynamic adjustment, of the high-resolution nest toward the outer model fields. The deep circulation in the interior of the nested region is permitted to evolve features with larger gradients over smaller spatial scales, with finer resolution topography. Comparisons of the large-scale and nested model solutions with each other and with observational data show the utility of this dynamical downscaling approach. Analysis of the simulations suggests possible mechanisms for the genesis of the strong currents along the escarpment in relation to the large-scale circulation.

2. Methodology

2.1. NCOM VQS simulation

The high-resolution nested domain used in this application (Fig. 1) is an application of the NCOM with the VQS vertical coordinate as described in Dukhovskoy et al. (2009). NCOM is a three-dimensional primitive equation ocean model (Martin, 2000),

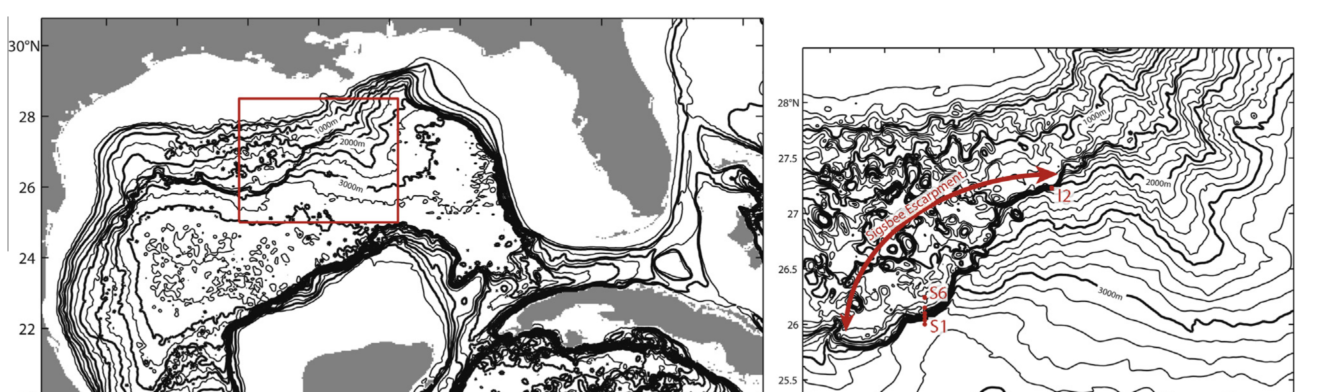

Fig. 1. Left: Bathymetry of the 1/25° Gulf of Mexico HYCOM (outer model). Contour lines are drawn every 250 m with thicker contours drawn at 500 m intervals. Right: Bathymetry of the 30 arcsec nested NCOM model domain (highlighted by the red box in the left image). Contour lines are drawn every 100 m with thicker contours drawn at 500 m intervals. Locations of the I2 and SEBCEP S1-S6 (intermediate mooring sites not labeled, but are numbered sequentially from south to north) moorings are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)