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Submesoscale currents in the northern Gulf of Mexico: Deep phenomena and dispersion over the continental slope

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ABSTRACT

This study examines the mesoscale and submesoscale circulations along the continental slope in the northern Gulf of Mexico at depths greater than 1000 m. The investigation is performed using a regional model run at two horizontal grid resolutions, 5 km and 1.6 km, over a 3 year period, from January 2010 to December 2012.

Ageostrophic submesoscale eddies and vorticity filaments populate the continental slope, and they are stronger and more abundant in the simulation at higher resolution, as to be expected. They are formed from horizontal shear layers at the edges of highly intermittent, bottom-intensified, along-slope boundary currents and in the cores of those currents where they are confined to steep slopes. Two different flow regimes are identified. The first applies to the De Soto Canyon that is characterized by weak mean currents and, in the high-resolution run, by intense but few submesoscale eddies that form near preferentially along the Florida continental slope. The second is found in the remainder of the domain, where the mean currents are stronger and the circulation is highly variable in both space and time, and the vorticity field is populated, in the high-resolution case, by numerous vorticity filaments and short-lived eddies.

Lagrangian tracers are deployed at different times along the continental shelf below 1000 m depth to quantify the impact of the submesoscale currents on transport and mixing. The modeled absolute dispersion is, on average, independent of horizontal resolution, while mixing, quantified by finite-size Lyapunov exponents and vertical relative dispersion, increases when submesoscale processes are present. Dispersion in the De Soto Canyon is smaller than in the rest of the model domain and less affected by resolution. This is further confirmed comparing the evolution of passive dye fields deployed in De Soto Canyon near the Macondo Prospect, where the *Deepwater Horizon* rig exploded in 2010, and at the largest known natural hydrocarbon seep in the northern Gulf, known as GC600, located a few hundred kilometers to the west of the rig wellhead.

1. Introduction

Processes and dynamics occurring in oceanic submesoscale currents (horizontal length scales between ~100 m and ~10 km, and time scales between a few hours and a few days) have been shown to impact stirring and dispersion of natural and anthropogenic tracers in the upper ocean. Submesoscale circulation patterns can modify the mixed layer stratification, and manifest as ageostrophic fronts and, whenever these fronts are unstable, meanders and eddies (Capet et al., 2008b; Fox-Kemper et al., 2008; McWilliams et al., 2009; Taylor and Ferrari, 2011; Thomas et al., 2008). The generation of submesoscale fronts and consequent instabilities has been investigated in a number of papers (Capet et al., 2008a; Haine and Marshall, 1998; Holmes et al., 2014; McWilliams et al., 2009; Thomas and Ferrari, 2008; Thomas et al., 2013).

A heuristic description of front generation relevant to this work is presented in Lévy et al. (2012). Submesoscale ageostrophic frontogenesis arises whenever the steepness of density surfaces approaches O(1) (Capet et al., 2008b). In the oceanic interior any density anomaly generated by the stirring and straining of the mesoscale field is quickly damped by overturning circulations

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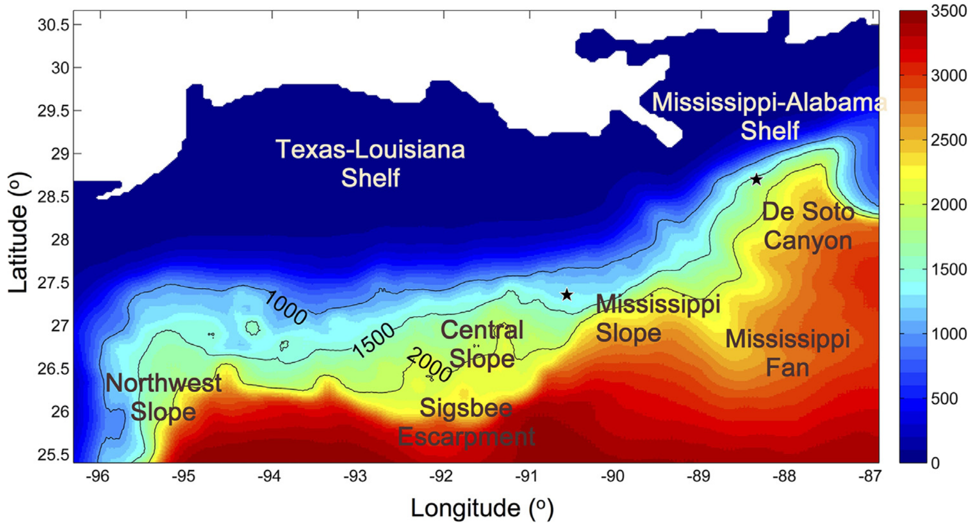

Fig. 1. Bathymetry over the northern Gulf (HR) domain. The 1000, 1500, and 2000 m bathymetric contours are indicated by the black lines and major topographic features are named. The sites where the Eulerian passive tracer is released are indicated by black stars.

that reduce the local steepness in the density field to restore geostrophic balance, with the end result that almost flat density surfaces are maintained (Klein et al., 2008). At the top and bottom of the ocean, on the other hand, those overturning circulations cannot effectively reduce the density fronts generated by the mesoscale turbulence due to the presence of the air–sea and bottom boundaries, and the fronts sharpen (Lévy et al., 2012). Such sharpening leads to submesoscale frontogenesis and eventually to ageostrophic secondary circulations that limit frontal intensification by generating submesoscale eddies (Fox-Kemper et al., 2008).

Several recent studies attempt to characterize submesoscale dynamics near the oceanic surface (Boccaletti et al., 2007; Capet et al., 2008a,b; Thomas and Ferrari, 2008; Thomas et al., 2008) and to quantify their role on the transport and mixing with numerical tools (Gula et al., 2014; Klein and Lapeyre, 2009; Koszalka et al., 2009; Lévy et al., 2010, 2011; Zhong et al., 2012; Zhong and Bracco, 2013) and with targeted field campaigns (D'Asaro et al., 2011; Poje et al., 2014; Shcherbina et al., 2013).

Little is known, however, about those dynamics and their effects at depth, near the sea floor, with the exception of the California Current System, where numerical simulations have shown that ageostrophic submesoscale motions contribute to the generation of long-lived subsurface anticyclones through centrifugal instability (Dewar et al., 2015; Molemaker et al., 2015). In this work we investigate the impact of submesoscale dynamics along the continental slope in the northern Gulf of Mexico (hereafter GoM).

The GoM basin is characterized by a broad, highly variable slope that hosts a large number of natural hydrocarbon seeps (Garcia-Pineda et al., 2009) found predominantly at depths greater than 1000 m. It was impacted by the largest deep-water oil spill ever recorded following the explosion of the *Deepwater Horizon* rig on April 20, 2010. The spill discharged approximately 3×10^8 kg of gas and 6-8 $\times 10^8$ kg of oil, about a third of which was confined in underwater plumes found in several layers between 700 m and the oceanic seafloor (Joye et al., 2011).

In this paper we address two main questions with the goal of improving our understanding of transport and mixing along continental slopes:

- Are submesoscale dynamics relevant to the circulation along the continental slope in the northern Gulf of Mexico, and if so what are the mechanisms responsible for their generation?
- Which role, if any, does model resolution play in the representation of transport and mixing of passive, neutrally buoyant tracers released along the slope?

We consider two simulations of the northern Gulf of Mexico, performed with 5 km and 1.6 km horizontal grid resolutions and spanning 3 years, from January 2010 to December 2012; the first resolves fully the mesoscale dynamics, while the second one is submesoscale permitting (i.e., has partial resolution). We concentrate on dynamics relevant for the deep layer in the GoM, considering only depths equal or greater than 1000 m. After analyzing the vorticity structures that characterize the flow in the two runs, we present dispersion statistics from an ensemble of deployments of neutrally buoyant Lagrangian particles released along the continental slope. Finally, we discuss the evolution of Eulerian passive tracers deployed at two sites over 1 year, and quantify the tracer diffusivities. While the simulations we consider are not directly relevant to the 2010 oil spill—particular realizations of oceanic eddies are inherently unpredictable without observational constraints—the answers to the questions above may guide better hindcasting and forecasting capabilities for deep pollutant releases.

2. Model setup, domain and forcing fields

The Gulf of Mexico circulation is simulated with the Regional Oceanic Modeling System (ROMS) in the version developed by the Institut de Recherche pour le Développement (IRD), ROMS-Agrif 2.2 (Debreu et al., 2012). The model domain covers the whole Gulf of Mexico (GoM), but we concentrate on its northern portion and specifically on the area comprised between −96.31°W and −86.93°W and 25.40°N–30.66°N, indicated as northern GoM in the following (Fig. 1). This region contains a large number of natural hydrocarbon seeps (MacDonald et al., 2002) and coincides with the area that was the most affected by the *Deepwater Horizon* spill in 2010 (Joye et al., 2011). In this work we consider two integrations differing only in their horizontal grid resolutions of 5 km (LR, for low resolution) and 1.6 km (HR, for high resolution). HR is obtained exploiting the two-way nesting capabilities of ROMS-Agrif 2.2 in the focus area. The vertical resolution is 70 stretched, terrain-following layers, and is enhanced near the surface and the bottom. The enhancement near the bottom together with the implementation of the pressure-gradient algorithm proposed by Shchepetkin and McWilliams (2003) based on a high