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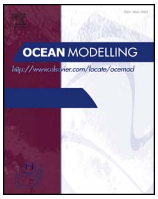

Vertical and horizontal resolution dependency in the model representation of tracer dispersion along the continental slope in the northern Gulf of Mexico

Annalisa Bracco[a,b,*], Jun Choi[a], Jaison Kurian[c], Ping Chang[c,d]

[a] School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332, USA
[b] Institute of Geosciences and Earth Resources, National Research Council of Italy, Pisa, PI 56124, Italy
[c] Department of Oceanography, Texas A&M University, College Station, Texas 77843-3160, USA
[d] Ocean University of China, Qingdao Collaborative Innovation Center of Marine Science and Technology, Qingdao 266100, China

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ABSTRACT

A set of nine regional ocean model simulations at various horizontal (from 1 to 9 km) and vertical (from 25 to 150 layers) resolutions with different vertical mixing parameterizations is carried out to examine the transport and mixing of a passive tracer released near the ocean bottom over the continental slope in the northern Gulf of Mexico. The release location is in proximity to the Deepwater Horizon oil well that ruptured in April 2010. Horizontal and diapycnal diffusivities are calculated and their dependence on the model set-up and on the representation of mesoscale and submesoscale circulations is discussed. Horizontal and vertical resolutions play a comparable role in determining the modeled horizontal diffusivities. Vertical resolution is key to a proper representation of passive tracer propagation and – in the case of the Gulf of Mexico – contributes to both confining the tracer along the continental slope and limiting its vertical spreading. The choice of the tracer advection scheme is also important, with positive definiteness in the tracer concentration being achieved at the price of spurious mixing across density surfaces. In all cases, however, the diapycnal mixing coefficient derived from the model simulations overestimates the observed value, indicating an area where model improvement is needed.

1. Introduction

In 2010 the blowout of the *Deepwater Horizon* (DWH) well at the Macondo Prospect (Mississippi Canyon Block 252, MC 252, in the De Soto Canyon), about 70 km offshore the southeast coast of Louisiana, caused a massive release of oil estimated between 6 and 8 × 10 ^{5} tons (Joye et al., 2011; McNutt et al., 2012). The uniqueness of the spill was not only the amount but also its depth, as it occurred in the open ocean approximately 1500 m below the surface. While the majority of the released oil rose to the surface, about a third remained confined in an underwater plume found between 1000 and 1300 m (Kleindienst et al., 2015; Joye et al., 2011). About six weeks after the blowout the deep plume extended over an area at least 35 km long and 2 km wide (Camilli et al., 2010).

From a modeling perspective, the *Deepwater Horizon* disaster presented opportunities and challenges. It was realized that, on one hand, a realistic representation of mesoscale structures did not guarantee an adequate forecasting of surface oil trajectories even for an enclosed sea such as the Gulf of Mexico (GoM) (Joye et al., 2016), and, on the other, our understanding of the modeling requirements to properly simulate transport and mixing both at the ocean surface and along the continental shelf was limited (Liu et al., 2011; Mariano et al., 2011).

At the ocean surface, images of oil slicks in spring 2010 pointed to the prevalence of structures in the submesoscale range (0.1–10 km; hours to few days) that control mixing in the Northern Gulf not only during January and February, when the mixed-layer is deepest (Callies et al., 2015; Mensa et al., 2013), but also in June–August, when the freshwater from the spring maximum riverine outflow reaches offshore (Luo et al., 2016).

At depth, the DWH incident challenged our understanding of the transport and mixing processes along the continental slope, and our ability to properly represent them in ocean circulation models. Observations of the deep-water plume that resulted from various campaigns immediately following the rupture of the wellhead in 2010 allowed the mapping of the oil directionality, but were insufficient to determine lateral and diapycnal mixing rates (Camilli et al., 2010;

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[*] Corresponding author at: School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332, USA.
E-mail address: abracco@gatech.edu (A. Bracco).

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Diercks et al., 2010). To gain such information, in August 2012 the Gulf of Mexico Integrated Spill Response (GISR) consortium (http://research.gulfresearchinitiative.org/research-awards/projects/?pid=137) injected a passive dye nearby the spill site at approximately 1100 m, a depth comparable to that of the DWH deep oil plume; the tracer was then followed over twelve months with a first cruise four months since its release (Ledwell et al., 2016). This experiment revealed that diapycnal mixing along the complex continental slope of the northern Gulf of Mexico was generally greater than observed in a handful of previous open ocean studies (e.g. Ledwell et al., 1993; 1998; Polzin and Ferrari, 2004; Sundermeyer and Price, 1998; Sundermeyer et al., 2005) and comparable to values found in portions of the Drake Passage (Mashayek et al., 2017).

A key motivation of this research is to establish modeling requirements that allow a representation of dispersion as reliably as possible in the event of future release of oil and gas into the Gulf at depth. Several modeling studies have focused on the factors that affected the time oil stayed in the water column, from microbial decay (Adcroft et al., 2010), to oil droplet size, variable oil flow rates from the wellhead, vertical current velocity, and biodegradation (Lindo-Atichati et al., 2016; North et al., 2015), but less attention has been placed on evaluating how the configuration of the circulation model may impact the overall dispersion.

In this paper, we will therefore explore the role of vertical and horizontal resolutions and vertical mixing parameterizations, as well as tracer advection schemes, in the representation of tracer dispersion (intended here as tracer transport and mixing) along the continental slope in the northern Gulf. We will focus on the representation of mesoscale and submesoscale circulations in the different configurations, their vertical confinement along the continental slope, and how they impact tracer dispersion.

Recently, Stewart et al. (2017) investigated vertical grid requirements to best suit horizontal resolution capabilities and found that at least 50 vertical levels are needed to resolve the first baroclinic mode, with an additional 25 levels per subsequent mode. Stewart and coauthors, however, focused their evaluation on the representation of sea surface height, overturning streamfunction and barotropic and baroclinic kinetic energy. The impacts of horizontal and vertical resolution on the representation of tracer transport and mixing along the continental slope in ocean models remain relatively unexplored. This is due, in part, to the fact that measurements of lateral and diapcynal dispersion in the deep oceans are quite rare (e.g. Kunze et al., 2006; Polzin et al., 1997; Waterhouse et al., 2014) and in the Gulf are limited to the study by Ledwell et al. (2016). Nevertheless, modeling tracer dispersion along continental slopes is relevant to a variety of applications, from predicting pathways of pollutants and the mixing of sediments and nutrients into the water column, to projections of ocean oxygen and carbon storage in coastal areas.

We shall show that both vertical and horizontal resolutions are important in realistic simulations of tracer dispersion, with the former playing a greater role in determining how diapycnal mixing is modeled.

2. Gulf of Mexico circulation

To a first approximation, the circulation in the Gulf is that of a two-layer system. The upper layer extends to about 800–1200 m depth and its most prominent features are the anticyclonic Loop Current (LC) and the Rings or Loop Eddies that detach from the LC at irregular intervals (Vukovich, 2012). In contrast, the mean circulation of the bottom layer is cyclonic off the continental slope or south of 26°N (Cardona and Bracco, 2016; DeHaan and Sturges, 2005; Hamilton, 1990; Weatherly, 2004) and vertically coherent (Hamilton, 2009), while it is characterized by numerous closed recirculations along the slope (Fig. 1). These recirculations are predominantly, but not exclusively, cyclonic, generated by the interaction of the flow with the complex bathymetry (Bracco et al., 2016).

Along the continental slope, topographic Rossby waves (TRWs) and vortex stretching contribute to the local – in time and space - intensification of the currents (DeHaan and Sturges, 2005; Dukhovskoy et al., 2009; Hamilton, 2009; Kolodziejczyk et al., 2012; Pérez-Brunius et al., 2013). Numerical simulations at submesoscale permitting resolution have shown that mesoscale and submesoscale eddies also form along the slope (Bracco et al., 2016). The largest eddy found in the northern portion is a bottom-intensified cyclone with a diameter of approximately 70 km and is generated by vortex stretching over the Mississippi Fan. Submesoscale eddies, whenever resolved, result from instabilities of near-bottom lateral-shear layers and shear layers generated by current bottom drag on the continental slope, as also found along the California slope (Molemaker et al., 2015). Numerical simulations have also revealed that the deep portion of the De Soto Canyon, located to the east of the Mississippi Fan, where both the DWH wellhead and the dye release by Ledwell and collaborators took place, is characterized by weak currents, cyclonic in their time average, and limited mesoscale or submesoscale variability compared to the rest of the slope (Bracco et al., 2016). Overall, dispersion in the De Soto Canyon is lesser than in the region to the west of the Fan, and material is transported mostly in the along-slope direction, through narrow boundary currents.

3. Modeling set-up

The ocean model in this study is the Regional Ocean Modelling System (ROMS) (Haidvogel et al., 2008; Shchepetkin and McWilliams, 2005), which is a primitive-equation, free-surface, split-explicit oceanic model. ROMS implements a "z-sigma" or "s" vertical coordinate (Lemarié et al., 2012; Shchepetkin and McWilliams, 2009) and horizontal curvilinear coordinates to solve the three dimensional hydrostatic equations. All configurations in this study use biharmonic horizontal mixing of momentum and COARE 3.0 bulk formulation (Fairall et al., 2003) for surface forcing. Vertical mixing is based on either the K-Profile Parameterization (KPP) scheme (Large et al., 1994) or the Mellor and Yamada (1982) (MY) scheme with level 2.5 closure and the Galperin et al., (1988) modification. This commonly adopted modification assumes that sources and sinks of turbulent kinetic energy balance each other in the stability functions of the MY scheme and accounts for the physically inappropriate dependence of the stability functions on the fluid Prandtl number as originally formulated.

The three-dimensional advection of tracers is obtained using either the second-order accurate, multidimensional positive definite advection transport algorithm (MPDATA) scheme (Margolin and Smolarkiewicz, 1998) or, in one case, the rotated split upstream-biased 3rd order transport scheme (SPLITUP) proposed by Marchesiello et al. (2009). MPDATA calculates an anti-diffusive velocity derived from the truncation error of the upstream advection scheme in order to reduce iteratively excessive diffusion. It is computationally efficient and commonly used by the biogeochemical community (Liu and Xue, 2009). In the SPLITUP run tracer diffusion is split from advection and is represented by a rotated biharmonic diffusion scheme along geopotential with flow-dependent hyperdiffusivity; vertical and horizontal tracer advection is achieved through a centered advection scheme of fourth-order spatial accuracy. The use of SPLITUP has the advantage of minimizing spurious diapycnal mixing but does not guarantee positivity of tracer concentrations. The SPLITUP integration was run only for 120 days.

The model domain covers the entire Gulf of Mexico (Fig. 1), with a closed boundary to the west. The open boundaries on three other sides use a combination of radiation and nudging schemes for both three-dimensional velocities and tracers. Chapman (1985) and Flather (1976) schemes are used for the free-surface and two-dimensional velocities, respectively.

Model initial and boundary conditions are extracted from the 6-h, 1/25° resolution hindcast performed with the Gulf of Mexico Hybrid