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Process studies on the evolution of the Mississippi River plume: Impact of topography, wind and discharge conditions

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ABSTRACT

The Mississippi River (MR) outflow is the strongest buoyant input for the Gulf of Mexico (GoM). The high resolution numerical model Northern-GoM (NGoM) HYCOM is used to perform process oriented experiments that examine the relative role of the effects of topography, wind-driven circulation and discharge conditions on the plume waters fate. Simulations showed that the slope over the western and eastern shelf areas enhance the overall alongshore propagation of the plume and reduce the offshore expansion (stronger downstream and upstream currents). The direction of the buoyancy-driven currents is defined as downstream and upstream for the Louisiana-Texas (LATEX) and Mississippi-Alabama-Florida (MAFLA) shelf areas, west and northeast of the MR Delta, respectively. Flooding conditions and/or downwelling-favorable winds strengthen the downstream flow over the LATEX shelf; they also suppress the vertical mixing of the upper low salinity waters with the deeper ocean layers. However, flooding conditions do not enhance the offshore extension. Downwelling-favorable winds support the downstream current and deepen the plume. Upwelling-favorable winds reverse or eliminate the downstream current and enhance the northward transport of plume waters toward the MAFLA shelf, but also offshore. This cross-marginal transport effect is significant, as it facilitates interaction of low-salinity MR plume waters (which are rich in nutrients and sediments) with deep oceanic currents in the GoM basin interior. The separate and combined investigation of the factors that determine MR plume dynamics enlightens the relations and differences among the MR circulation patterns over the NGoM region. Calculations of freshwater transport are carried out to further discuss the dynamics and serve as the basis for quantifying the transport and fate of river-borne waters and associated biogeochemical materials.

1. Introduction

The Mississippi River (MR, Fig. 1) is the major source of freshwater, sediments and nutrients for the Gulf of Mexico (GoM) [*Hu* et al., 2005; *Milliman and Meade*, 1983] with an annual mean discharge of over 13,000 m^3/sec [*Morey* et al., 2003]. The MR accounts for 90% of the freshwater inflow to the GoM [*Rabalais* et al., 1996] and delivers highly productive waters that support 28% of the total U.S. fishery catch [*Rabalais* et al., 1991]. The transport and dispersion of MR waters is of extreme importance for the ecosystem state in the Northern Gulf of Mexico (NGoM) region, with implications on remote coastal ecosystems that can be reached when MR waters are transported along the Loop Current (a branch of the Gulf Stream system), see *Ortner* et al. [1995], *Schiller* et al. [2011], and *Schiller and Kourafalou* [2014]. The goal of this study is to determine the dynamical processes controlling the fate of MR waters, with focus on the impact of the shelf wind-driven circulation, the topographic characteristics and the discharge levels of the brackish waters.

The riverine waters exit through several passes into NGoM, the largest ones being the Southwest Pass, South Pass and Pass a Loutre [*Walker* et al., 1994]. The MR outflow is subject to strong vertical mixing due to supercritical conditions at the mouth of the passes [*Wright and Coleman*, 1971], which act as hydraulic constrictors for the outflow [*Armi and Farmer*, 1986]. The present study is focused beyond this near-field region at the mouth of the passes, on the continental shelf around the Delta, where the outflow is characterized by a bottom-attached saline front, and over the far-field areas of the Louisiana-Texas (LATEX) shelf, the Mississippi-Alabama-Florida (MAFLA) shelf and southern offshore deeper regions (Fig. 1). As the outflow spreads and shoals, it accelerates, increases vertical shear and triggers Kelvin-Helmholtz-like flow instabilities and turbulent mixing [*MacDonald and Geyer*,

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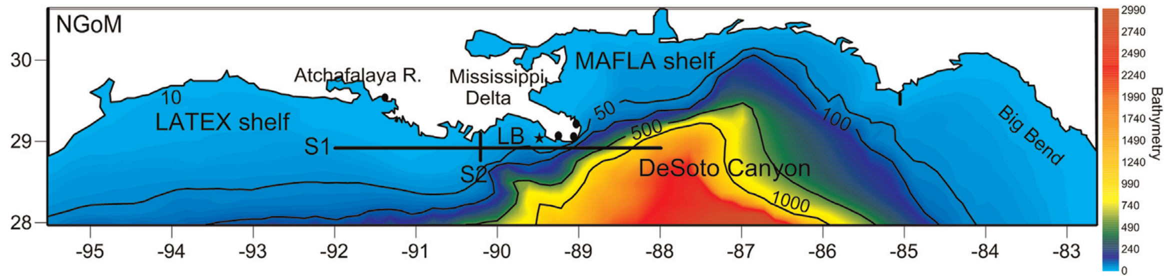

Fig. 1. Topography map (m) indicating the main features (deep basins, continental shelves, Atchafalaya River, Mississippi Delta location) of the North Gulf of Mexico (NGoM). Locations of the sections (S1 and S2) are also presented. Black star indicates the location of the wind effect calculations presented in Section 5.1. The Mississippi River input is distributed in three locations, from West to East: Southwest Pass, South Pass and Pass A Loutre (black dots). The Louisiana-Texas (LATEX) shelf and the Mississippi-Alabama-Florida (MAFLA) shelf are west and east of the Delta, respectively. The eastern-most Big Bend region is also presented. The Louisiana Bight (LB) is the easternmost LATEX area. The isobaths of 50 m, 100 m, 500 m and 1000 m are shown as solid gray lines.

2004]. Mixing and spreading of the MR plume are controlled by a variety of factors.

The buoyancy of the plume waters drives three distinct pathways that are common for large-scale rivers (defined as riverine systems where the Coriolis effect is important, *Garvine*, 1995): an anticyclonic bulge, a "downstream" coastal current in the direction of Kelvin wave propagation (toward the LATEX shelf) and an "upstream" current domain (toward the MAFLA shelf). These patterns have been identified in early studies on river plume dynamics in the presence of buoyancy forcing only [e.g. *Chao and Boicourt*, 1986; *Garvine*, 1987; *Kourafalou* et al., 1996].

The influence of local wind stress is a dominant mechanism for driving the circulation over the inner shelf [*Cochrane and Kelly*, 1986; *Li* et al., 1997; *Morey* et al., 2003; *Nowlin* et al., 2000], and the local wind controls the transport pathways of the MR plume [*Walker*, 1996; *Walker* et al., 2005]. Easterly winds (downwelling-favorable) drive westward surface currents along the south side of the Delta, enhance the downstream coastal current and extend the MR plume towards the Louisiana-Texas shelf, where broadening of the shelf reduces the interactions between the buoyant pathways and the offshore circulation [*Schiller* et al., 2011]. *Walker* et al. [2005] showed that this pattern can be interrupted by short term westerly winds, enhancing the northeastward ("upstream") and offshore transport of brackish waters. *Androulidakis and Kourafalou* [2013], based on realistic simulations during strong outflow conditions, showed that the flooding periods allow the MR plume to withstand certain wind effects that would cause wind induced transport of riverine waters. Flooding outflow conditions may also enhance the offshore freshwater volume, due to the increased supply of the low salinity pool, especially in the presence of ambient circulation that promotes the shelf transport. For example, the presence of the Loop Current and associated eddies near the Delta may substantially enhance offshore removal of high amounts of riverine waters during a flood [*Androulidakis and Kourafalou*, 2013].

The main study objective is to investigate the conditions that control the formation of the MR plume and the evolution of the main riverine pathways. We seek to examine the origin of known hydrodynamic plume patterns, like the offshore removal of brackish waters, the westward downstream and northeastward upstream currents, and the overall plume circulation over the NGoM region. Wind forcing, complex coastal topography and shelf bathymetry, along with strong discharge conditions, are integral parts of the plume dynamics. The impact of flood conditions in combination with the wind state on the plume circulation and characteristics is also under investigation. Several process oriented experiments were developed to elucidate the dynamics of the MR plume under different environmental forcing conditions, such as (a) buoyancy-driven only, (b) in the presence of winds and (c) under strong discharge rates (flooding conditions). The focus is on the investigation of the brackish plume fate due to specific topographic, atmospheric and discharge conditions. By elucidating the cross-marginal transport due to both shelf and offshore currents, new insights can be gained on the connectivity of the MR wetlands and remote coastal systems. For instance, it is known that offshore removed Mississippi waters can reach the Florida Keys [*Ortner* et al., 1995; *Hu* et al., 2005; *Schiller and Kourafalou*, 2014.]. Our methodology concentrates on the use of a high resolution (1/50°, ~1.8 km) regional hydrodynamic model of the NGoM region and on process-oriented numerical simulations.

This paper is organized as following: A description of the numerical model employed in this study is provided in Section 2 and the experiments set-up is described in Section 3. Results from process-oriented experiments are presented in Section 4, followed by a discussion about the vertical distribution and the shelf transport of plume waters in Section 5. A summary of conclusions is presented in Section 6.

2. Model description

2.1. The HYCOM model

The Hybrid Coordinate Ocean Model (HYCOM, http://hycom.org) is a primitive equation ocean general circulation model, designed as a finite-difference hydrostatic model in the context of the Global Ocean Data Assimilation Experiment (GODAE) [*Chassignet* et al., 2007]. Vertical coordinates remain isopycnic in the open, stratified ocean and they transform to *z* coordinates in the weakly stratified upper-ocean mixed layer, to terrain-following sigma coordinate in shallow water regions, and back to level coordinates in very shallow water [*Halliwell* et al., 2009]. Detailed description of the model is presented by *Bleck* [2002], *Chassignet* et al. [2003] and *Halliwell* [2004]. HYCOM contains five mixing schemes [*Halliwell*, 2004] and in this study we employ the K-Profile Parameterization model (KPP) [*Large* et al., 1994]. An explicit parameterization of the bottom boundary layer is also included [*Halliwell* et al., 2009]. The plume parameterization is based on the dynamical considerations explored by *Schiller and Kourafalou* [2010], who employed HYCOM in an idealised estuary to coastal basin system. Similar to *Schiller* et al. [2011], this parameterization is applied in the Mississippi River inflow NGoM domain (Fig. 1).

2.2. NGoM-HYCOM model

The NGoM-HYCOM model domain is a high resolution ($1/50° \times 1/50°$) implementation that covers the Northern Gulf of Mexico (Fig. 1). The high resolution character of the simulations is related to the small scale model cell (~2 km) in relation with the