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Current–wave interaction in the Mississippi–Atchafalaya river plume on the Texas–Louisiana shelf

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ABSTRACT

Wave–current interaction over the Texas–Louisiana shelf, and its effects on the dispersal and mixing of the Mississippi–Atchafalaya river plume, have been investigated using the Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) Modeling System. The modeling system is driven by realistic wave and current conditions at the open boundaries and high frequency1-D wind measured from a nearby meteorological station. Skill analysis demonstrates that the model reproduces the wave and salinity fields reasonably well. Waves over the Texas–Louisiana shelf are dominated by locally forced wind seas, and generally propagate in the same direction as the winds. Investigation into the spatial differences in the effect of waves reveals two distinct dynamical regions: the Chenier shelf, the shelf region extending roughly offshore from Sabine Lake to Vermilion Bay, and the Louisiana Bight, the region between the Mississippi Delta and Terrebonne Bay. A variety of model runs are performed, where specific wave processes are either included or excluded, in order to isolate the processes acting in different regions. The Chenier shelf is mainly affected by wave enhanced bottom stress, whereas the Louisiana Bight is mostly affected by the surface wave induced mixing and 3-D wave forces. The wave enhanced bottom stress suppresses cross-shore exchange, and acts to trap more freshwater in the nearshore regions shallower than 50 m over the Chenier shelf. Wave enhanced bottom stress plays only a minor role in the Louisiana Bight, where the surface-trapped Mississippi plume rarely feels the bottom. The surface intensified wave mixing and 3-D wave forces reduce the surface salinity and weaken the stratification in the region associated with the thin recirculating Mississippi plume in the Louisiana Bight. Model results indicate that the surface wave mixing, the 3-D wave forces, and the wave bottom stress exhibit little interaction over the Texas–Louisiana shelf. Finally, we have demonstrated that the one-way coupling is capable of resolving the majority of wave effects over the entire shelf if the seasonal scale is of interest.

1. Introduction

Wave–current interaction is of prime importance in coastal water and nearshore regions (e.g. Lentz and Fewings, 2012; Prandle et al., 2000; Wolf and Prandle, 1999). Waves can be affected by the presence currents due to refraction, modification of bottom drag, and blocking (e.g., Vincent, 1979; Kudryavtsev et al., 1995; Ris et al., 1999). An impact of currents on waves modifies the wave frequency through Doppler shift, accompanied with a change in phase speed. Also, the water level has an influence on waves, by changing the depth felt by waves (e.g. Pleskachevsky and Kapitza, 2009). Conversely, the currents can be strongly forced and modified by waves. The effect of waves on mean flow are manifested through additional momentum and mass fluxes. Waves entering a shallow water region increase in amplitude and steepness, and finally break, resulting in onshore mass flux and changes of mean surface elevations called wave setup and setdown (Longuet-Higgins and Stewart, 1962). In the cross-shore direction, the vertical imbalance between the depth-uniform pressure gradient due to wave setup and the depth-varying momentum flux generates a near-bed seaward current, the undertow (Svendsen, 1984). While in the long-shore direction, the spatially non-uniform wave momentum flux provides a new forcing of a wave-driven longshore current (Longuet-Higgins, 1970).

The importance of different wave processes on a given coastal environment has also been identified in many previous studies. For example, wave set-up during hurricanes could make significant contributions to the total storm surge and inundation area, a study

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in Massachusetts Bay showed that more area was flooded when wave effects were included (Beardsley et al., 2013). Wave–current interaction increase the bottom friction felt by currents and thus increase bottom stress. Xu et al. (2011) showed that the enhancement of bottom stress due to waves plays a key role in sediment suspension dynamics over the Texas–Louisiana shelf. By including the wave breaking mixing to a circulation model, Carniel et al. (2009) showed that the observed surface drifter tracks were more accurately reproduced than models that did not include wave breaking in the Adriatic Sea. Also, studies in the Yellow Sea demonstrated that models including mixing due to wave breaking improve the simulation of surface boundary layer thickness (Zhang et al., 2011).

Given the importance of wave's effects on oceanic currents and turbulence, great effort has been dedicated to the theory and robust numerical simulation of wave–current interactions (McWilliams et al., 2004; Ardhuin et al., 2008; Mellor, 2008; Warner et al., 2008; Uchiyama et al., 2010; Kumar et al., 2012; Bennis et al., 2011, and many others). In order to provide a complete view of wave–current interactions, the three dimensional primitive equation are modified to account for waves. The difficulty in 3-D wave–current models is properly describing the wave forces and vertically distributing them (Bennis et al., 2011). Pioneering work done during the past decade represents wave forces either in a gradient stress tensor (Mellor, 2003, 2008) or in vortex force formalism (McWilliams et al., 2004); both have been applied to the Regional Ocean Modeling System (ROMS, Warner et al., 2008; Kumar et al., 2012; Uchiyama et al., 2010) and other models (CH3D: Sheng and Liu, 2011; FVCOM: Wang and Shen, 2010). Since the development of 3-D coupled wave–current models is relatively new, we need to systematically investigate the numerical approach to wave coupling and the dynamical influences of waves in our specific model domain.

The Texas–Louisiana shelf is a broad continental shelf with strong buoyancy forcing from the Mississippi–Atchafalaya river system. The Mississippi river is the 7th largest river system in the world, exporting about 530 $km^3\ yr^{-1}$ freshwater into the shelf. This huge input of fresh water greatly enhances stratification over the shelf (DiMarco et al., 2010; Schiller et al., 2011; Zhang et al., 2012). The circulation over the Texas–Louisiana shelf can be viewed as a bottom-trapped buoyancy-driven flow modulated by seasonal winds (Zhang et al., 2014). During non-summer when winds are generally from the east, downwelling favorable, the buoyant plume water hugs the coastline and moves downcoast. In summertime, upwelling favorable winds push the plume upcoast, and the plume is trapped over the Louisiana shelf and further offshore, increasing stratification there. Numerous observation and modeling studies have been conducted in this region (e.g., Cho et al., 1998; Morey et al., 2003; Etter et al., 2004; Schiller et al., 2011; Hetland and DiMarco, 2008; Zhang et al., 2012). Some previous studies have included wave effects. Sheng et al. (2010) applied a coupled ocean-wave model to study the surge level and coastal inundation in the Northeastern Gulf of Mexico and emphasized the importance of wave effects in the 3-D model than the 2-D model. Xu et al. (2011) recognize the importance of wave enhanced bottom stress and focus on its effects on sediment transport. However, none of these studies deal directly with wave–current effects in relation to currents and tracer distributions over the shelf.

Waves have the potential to affect river plume dynamics. Recently, using an idealized model, Gerbi et al. (2013) studied the effects of surface wave mixing on river plume dynamics during upwelling favorable winds, with the wave breaking parameterized in the two equation turbulence sub-model (Craig and Banner, 1994). Both the plume structure and the response time were modified when breaking wave mixing was included (Gerbi et al., 2013). In addition to surface gravity wave breaking, waves might also alter the plume dynamics through enhanced bottom stress or wave vortex forces; these processes have not yet been addressed for the Mississippi–Atchafalaya river plume system.

This study takes advantage of the newly developed modeling system COAWST (Warner et al., 2008, 2010) to study the wave–current interaction over the Texas–Louisiana shelf. The goals of this study are to identify how waves and currents interact in the presence of a large river plume, and how waves alter the fresh water distribution and stratification within the plume on the shelf scale. The surf zone dynamics are not included, since this specific study focus more on shelf processes and interactions between the inner- and mid-shelf. In this paper, we demonstrate that the fully resolved wave dynamics in the coupled model significantly modifies the plume structure and thus the stratification, not only during extreme weather conditions but also in fair weather conditions. Also, we find that different wave effects are dominant in different regions of the plume. Finally, we find that if seasonal scale is of interest, it is not necessary to include two-way coupling for our large domain, it is sufficient to specify the wave field through an independent simulation, and then apply those wave effects to the hydrodynamic model.

2. Methodology

The COAWST modeling system (Warner et al., 2008, 2010) is used in this study. The system couples the three-dimensional ROMS hydrodynamic model with the SWAN wind-wave generation and propagation model. Coupling with the Weather Research and Forecasting (WRF) model is deactivated in order to simplify the analysis and focus on wave–current interactions.

2.1. ROMS ocean model

The oceanic circulation model used in COAWST is the Regional Ocean Modeling System (ROMS) (Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005). ROMS is a hydrostatic, primitive equation ocean model that solves the Reynolds averaged form of the Navier Stokes equations. We use a model domain that covers much of the Mississippi and Atchafalaya river plume region, initially developed by Hetland and DiMarco (2008). An orthogonal curvilinear coordinate system is designed to follow the coastline (Fig. 1). High resolution is placed in the inner shelf region to resolve the river plume, with the highest between the Mississippi Delta and the mouth of Atchafalaya Bay. The grid spacing is less than 1 km in the cross-shelf direction and 2–3 km in the along-shelf direction over the inner shelf region but increases to as coarse as 20 km offshore near the open boundaries. The total number of grid points is 128×63. The model has 30 layers in the vertical with the minimum depth setting to 3 m. We use the Generic Length Scale (GLS, k–ε) turbulence closure scheme to calculate the vertical eddy viscosity and diffusivity (Umlauf and Burchard, 2003; Warner et al., 2005). In the absence of waves, a quadratic stress is exerted at the bed, assuming that a logarithmic velocity profile in the bottom boundary layer. The drag coefficient is determined by $C_d = \max(C_z, 0.0025)$ where $C_z = \kappa^2 / \ln\left(\frac{\Delta z}{z_0}\right)^2$, $\kappa = 0.4$ is von Karman's constant, and the bottom roughness parameter z_0 is chosen to be 1 mm (Hetland and DiMarco, 2012; Marta-Almeida et al., 2013).

The open ocean boundary condition for the barotropic component consists of a Chapman/Flather boundary condition for depth averaged flow and sea surface elevation (Chapman, 1985; Flather, 1976). The open boundary condition for the baroclinic component is Orlanski-type radiation condition (Orlanski, 1976). A nudging region is specified along the six outer cells of the model domain, where the ROMS model is nudged toward HYCOM daily data. The nudging time scale used is eight hours at the boundaries with a