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Effect of stratification on current hydrodynamics over Louisiana shelf during Hurricane Katrina

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Abstract

Numerical experiments were conducted using the finite volume community ocean model (FVCOM) to study the impact of the initial density stratification on simulated currents over the Louisiana shelf during Hurricane Katrina. Model results for two simulation scenarios, including an initially stratified shelf and an initially non-stratified shelf, were examined. Comparison of two simulations for two-dimensional (2D) currents, the time series of current speed, and variations of cross-shore currents across different sections showed that the smallest differences between simulated currents for these two scenarios occurred over highly mixed regions within 1 radius of maximum wind (RMW) under the hurricane. For areas farther from the mixed zone, differences increased, reaching the maximum values off Terrebonne Bay. These large discrepancies correspond to significant differences between calculated vertical eddy viscosities for the two scenarios. The differences were addressed based on the contradictory behavior of turbulence in a stratified fluid, as compared to a non-stratified fluid. Incorporation of this behavior in the Mellor-Yamada turbulent closure model established a Richardson number-based stability function that was used for estimation of the vertical eddy viscosity from the turbulent energy and macroscale. The results of this study demonstrate the necessity for inclusion of shelf stratification when circulation modeling is conducted using three-dimensional (3D) baroclinic models. To achieve high-accuracy currents, the parameters associated with the turbulence closures should be calibrated with field measurements of currents at different depths.

Keywords: Hurricane Katrina; Louisiana shelf; Hydrodynamics; Baroclinic and barotropic models; Stratification

1. Introduction

Water column stratification is a prominent feature of most oceanic, shelf, and estuarine waters. Although mixing forces, including winds, waves, and tides, occasionally or continuously mix the water column, density gradients re-stratify the water column partially or fully, even in the vicinity of a hurricane's track (Keen and Glenn, 1999). Hence, these water bodies are always affected by some degree of stratification. Stratification highly modulates bio-geochemical processes across the water column and affects the concentration of different chemical substances (Katsev et al., 2010). Strong summertime stratification over the Louisiana-Texas continental shelf is the main physical contributor to the seasonal hypoxia, as it prevents re-oxygenation of bottom water (Wiseman et al., 1997; Allahdadi et al., 2013; Chaichitehrani, 2012). As a result of confinement by the stratification, colored dissolved organic matter (CDOM) is exposed to the sunlight and loses its properties through the photo-bleaching process (Tehrani et al., 2013; Chaichitehrani et al., 2014).

A relevant aspect of the stratification/de-stratification impact is the contribution in terms of modulating the

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circulation. Several studies have demonstrated the substantial effect of stratification on current hydrodynamics in different water bodies (Csanady, 1972; Park and Kuo, 1996; Saenko, 2006; Zhang and Steele, 2007; Allahdadi et al., 2011, 2017). Park and Kuo (1996) pointed out that, in an estuary, mixing across the water column can weaken the circulation by enhancing vertical momentum flux, while circulation may be strengthened by increasing salinity gradients along the estuary. For a large stratified lake, the interaction between wind stress and Coriolis force can produce complicated circulation structures (Csanady, 1972). Csanady (1972) used an analytical model to study the effect of wind stress on large stratified lakes and concluded that baroclinic Kelvin waves that cause substantial transport along the shore are major features of the response to spatially uniform wind. Baroclinicity significantly contributes to the formation of a cyclonic summertime circulation pattern in Lake Michigan (Schwab and Beletsky, 2003). As an example for shelf waters, a study for the Rine ROFI demonstrated that the progression of tidal waves in stratified waters could result in significantly different current patterns, as compared to cases with pre-mixed waters. Current observation data were used along with an analytical model to conclude that tidal ellipses were substantially different for stratified and mixed conditions (Visser et al., 1994). During the well-mixed periods, tidal currents were essentially rectilinear, with the major component directed along the coast, while the stratification enhanced the cross-shore component up to about 40% of the alongshore component. Over the Gorgeous Bank, a remarkable summertime stratification effect on amplification of current speed and transport, as well as a strengthening of the tidal mixing front, was reported (Naimie, 1996; Chen et al., 2003).

In the open ocean or large water bodies like the Gulf of Mexico, stratification contributes to the amplification of currents through inertial oscillations. In this case, stratification controls the rate of wind momentum exchange from the surface across the water column by controlling the vertical eddy viscosity (Davies, 1985). Studies using both observational data and numerical models have demonstrated the intensification effect of summertime stratification on shelf currents in the northern Gulf of Mexico (Chen and Xie, 1997; DiMarco et al., 2000).

Hurricane winds mixing the water column produce an extreme case of stratification/mixing effects on circulation. In this case, a rather complicated spatial and temporal pattern of mixing across the water column is produced (Elsberry et al., 1976; Price, 1981). Cooper and Thompson (1989) reported that skipping the stratification could have been one of the main reasons for discrepancies between measured and simulated current speeds in the northern Gulf of Mexico during Hurricane Eloise. Consideration of an initially stratified water column and the effect of turbulent mixing across the water column is essential to some 3D numerical models used for studying hurricane-induced currents (for example, Ly, 1994; Keen and Glenn, 1999; Ly and Kantha, 1993). Keen and Glenn (1999) simulated the hydrodynamics induced by Hurricane Andrew, which passed over the Louisiana shelf in 1992, and compared the results with available measurements at several stations. They examined both stratified and non-stratified models, and concluded that for moorings that are located within 1 RMW of the hurricane center, the results obtained from both stratified and non-stratified models agreed with the measurements. For stations farther than 1 RMW from the hurricane center, and especially farther than 2 RMW, results of the non-stratified model were significantly different from the measurements. This indicates that simulated current magnitudes are affected by the rate of turbulent energy exchange and dissipation within the water column (Allahdadi et al., 2011, 2017). The same approach was applied by Keen and Glenn (1998) to calibrating the simulated surface currents during Hurricane Andrew. They found that the overestimation/underestimation of surface/bottom currents was due to the small rate of turbulent energy dissipation. Hence, by changing the empirical parameter representing the dissipation term in the turbulent closure model, current speeds were modified to agree with the measurements. However, these studies did not address the detailed variations of currents in relation to stratification and turbulent mixing. This study attempted to examine the temporal and spatial variations of simulated currents in a stratified and non-stratified water column during a hurricane and address the role of vertical mixing in causing the differences between the simulated currents for different scenarios of the initial shelf stratification.

2. Materials and methods

2.1. Model formulation

The finite volume community ocean model (FVCOM), a 3D primitive equation ocean model, was used to implement the numerical tests and study the effect of stratification on hurricane-induced circulation in the northern Gulf of Mexico. The horizontal equations of motion in a 3D case (as included in FVCOM) consider the local acceleration term, nonlinear acceleration terms, Coriolis effect, pressure gradient, and vertical and horizontal internal friction terms. Eqs. (1) and (2) include all the mentioned terms for x and y directions, respectively:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=-\frac{1}{\rho_0}\frac{\partial P}{\partial x}+\frac{\partial}{\partial z}\left(K_{\mathrm{m}}\frac{\partial u}{\partial z}\right)+F_u \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-\frac{1}{\rho_0}\frac{\partial P}{\partial y}+\frac{\partial}{\partial z}\left(K_{\mathrm{m}}\frac{\partial v}{\partial z}\right)+F_v \tag{2}$$

where x, y, and z are east-west, north-south, and vertical Cartesian coordinate axes, respectively; u, v, and w are the current velocity components in the x direction, y direction, and z direction, respectively; t is time; f is the Coriolis parameter; P is the pressure; ρ_0 is the reference water density; K_{m} is the