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Near-inertial motions in the DeSoto Canyon during Hurricane Georges

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ABSTRACT

Hurricane Georges passed directly over an array of 13 moorings deployed in the DeSoto Canyon in the northern Gulf of Mexico on 27–28 September 1998. Current velocity data from the mooring array were analyzed together with a primitive-equation model simulation with realistic hurricane forcing, to characterize the generation and propagation of the hurricane-generated near-inertial waves. The model successfully reproduces the observed mean (sub-inertial) and near-inertial motions. The upper ocean response is strongly impacted by the canyon 'wall': a strong jet is formed along the slope, and the near-inertial motions on the shelf are rapidly suppressed. The model results moreover suggest that strong near-inertial waves in the mixed layer are mostly trapped in an energy flux recirculating gyre around the canyon. This gyre retains the near-inertial energy in the canyon region and enhances the transfer of near-inertial energy below the mixed layer. Additional simulations with idealized topographies show that the presence of a steep slope rather than the canyon is fundamental for the generation of this recirculating gyre. The near-inertial wave energy budget shows that during the study period the wind generated an input of $6.79 \times 10^{-2}\ \mathrm{Wm^{-2}}$ of which about 1/3, or $2.43 \times 10^{-2}\ \mathrm{Wm^{-2}}$, was transferred below the mixed layer. The horizontal energy flux into and out of the canyon region, in contrast, was relatively weak.

1. Introduction

The mixing caused by the breaking of internal waves in the deep ocean may provide enough power to maintain the deep ocean's stratification against the upwelling of cold water originating from the high latitudes, thus determining the meridional overturning circulation (Alford, 2003; Munk and Wunsch, 1998). Internal tides and near-inertial waves together dominate most of the internal wave spectrum in the ocean. Whereas internal tides are primarily generated by barotropic tidal flows over topography, near-inertial waves are mainly excited by wind forcing at the surface ocean (Alford et al., 2007; Gill, 1984; Pollard, 1970). This causes an intermittent signal of near-inertial motions (D'Asaro, 1985).

The temporal and spatial structures of near-inertial waves depend on the characteristics of wind forcing. Strong winds associated with hurricanes and tropical cyclones commonly produce a three-dimensional wake of energetic near-inertial waves (e.g., Brink, 1989; Brooks, 1983). The clockwise rotation of wind vectors in concert with the near-inertial currents maximizes the wind power input to the surface ocean (Large and Crawford, 1995; Price, 1981), which occurs to the right of the cyclone track in the Northern Hemisphere. The translation speed of the hurricane and its duration (with respect to the Coriolis period) are important to reinforce the near-inertial energy (Skyllingstad et al., 2000). Finally, the scale and the translation speed of the traveling cyclone set the horizontal scale of the near-inertial waves in the ocean surface layer (Kundu and Thomson, 1985).

There is a need for understanding how near-inertial waves propagate and how the initially large horizontal scales associated with the scales of the forcing (wind) are transferred to the mixing small scales. Many studies have investigated those issues through field observations as well as theoretical and numerical model approaches (e.g., the Ocean Storms Experiment (D'Asaro et al., 1995). A commonly used method to understand the propagation of near-inertial waves is the decomposition into dynamical vertical modes (e.g., D'Asaro et al., 1995; Gill, 1984; Kundu and Thomson, 1985). Another method is to estimate the energy flux from the velocity-pressure correlation or from the inferred vertical group velocity (e.g., Alford, 2003; Furuichi et al., 2008; Kunze et al., 2002; MacKinnon and Gregg, 2003; Nash et al., 2005).

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In the Gulf of Mexico there have been many studies of the propagation of near-inertial motions generated by hurricanes using moored instruments. Shay and Elsberry (1987) observed a rapid baroclinic near-inertial ocean response throughout the water column during the passage of Hurricane Frederic. Keen and Glenn (1999) found baroclinic near-inertial waves on the outer shelf and slope but barotropic response near the coast (depths < 20 m) during Hurricane Andrew. Jaimes and Shay (2010) contrasted the near-inertial response between cyclonic and anticyclonic background flows during hurricanes Katrina and Rita. Also, Teague et al. (2007) using a large instrument array, examined different vertical structures of near-inertial waves on the shelf and slope during Hurricane Ivan. They found that near-inertial amplitudes below the thermocline reached two maxima, one just after the passage of the hurricane and the other 4 days later. The vertical propagation of near-inertial motions was consistent with upward phase propagation and downward energy propagation from the mixed layer to the thermocline and below. Additionally, near-inertial motions were stronger and lasted longer on the slope than on the shelf.

The objective of this paper is to determine the upper ocean response in the DeSoto Canyon region in the northern Gulf of Mexico during Hurricane Georges using both observations and a suit of model simulations. The Science Application International Corporation (www.saicocean.com) deployed an intensively instrumented current meter array in the Desoto Canyon from April 1997 to April 1999 as part of the DeSoto Canyon Eddy Intrusion Study (Hamilton et al., 2000; Wang et al., 2003). Previously, Jarosz et al. (2007) described the near-inertial currents based on records between April 1997 and March 1998. They found an increase in inertial amplitudes from the shelf break to offshore. Also, using a one-dimensional bulk mixed-layer model, they showed that near-inertial currents were effectively generated by the shifting winds accompanying passages of cold fronts. We concentrate on the Hurricane Georges, which passed over the mooring array at the end of September 1998. We use a three-dimensional ocean circulation model to fully explore the nature of hurricane induced mean and near-inertial motions.

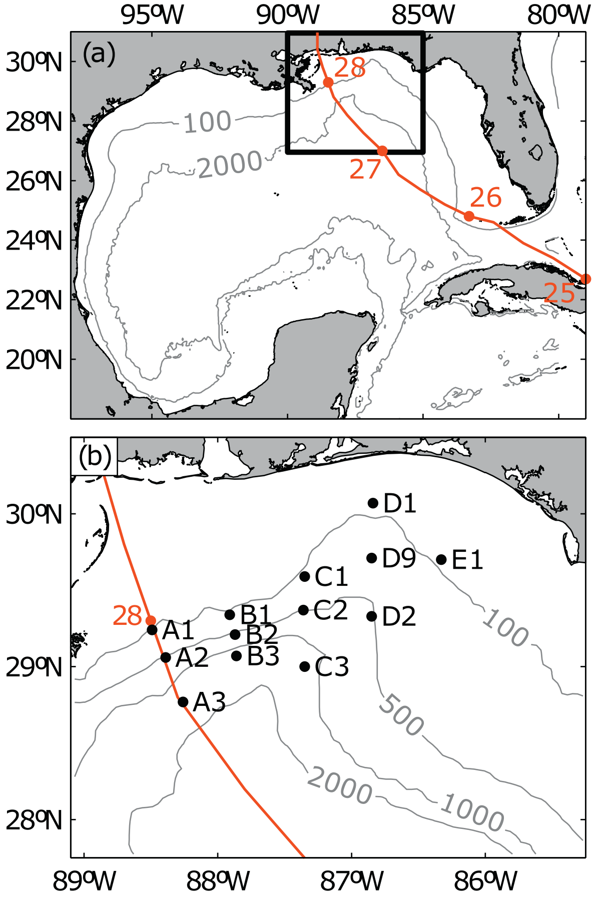

Fig. 1. (a) Bathymetry (m, gray lines) of the Gulf of Mexico showing the model domain in the DeSoto Canyon region (thick black line). (b) Bathymetry (m, gray lines) of the DeSoto Canyon region showing the mooring locations (black dots). Hurricane Georges' track (red line) and 00:00 UTC-date positions (red dots) are marked. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Data and methods

2.1. Observational data

The data used in this study were collected as a part of the DeSoto Canyon Eddy Intrusion Study (Hamilton et al., 2000). We concentrate on the period from 23 September to 6 October 1998, when Hurricane Georges passed over the DeSoto Canyon region. We use velocity time series from 13 moorings (Fig. 1) located over isobaths of 100 m (A1, B1, C1, D1, and E1), 200 m (D9), 500 m (A2, B2, C2, and D2), and 1300 m (A3, B3, and C3). The instrumentations, locations and deployment levels are listed on Table 1. The upward-looking acoustic Doppler current profilers (ADCPs) measured at 4 m depth intervals, except for D9 where the interval was set at 8.7 m. The original velocity time series were smoothed applying a Lanczos filter with a cut-off period of 3 h.

2.2. Ocean circulation model

The model used in this study is a parallel version of the Princeton Ocean Model (POM), which is a terrain-following, free surface, primitive equation ocean circulation model (Blumberg and Mellor, 1987; Jordi and Wang, 2012). The model solves the primitive equations on a horizontal Arakawa C grid and a vertical sigma-level grid under the hydrostatic and Boussinesq assumptions. The numerical scheme is leapfrog in time and centered in space. It also uses mode-splitting in the vertical. Horizontal mixing is parameterized according to the Smagorinsky diffusion scheme and vertical mixing coefficients are calculated with a level 2.5 Mellor–Yamada turbulence closure scheme. The bottom friction follows the quadratic law with the drag coefficient set at 0.0025.

The model domain covers the DeSoto Canyon region (from 90ºW to 85ºW and from 27ºN to 31ºN) in the northern Gulf of Mexico (Fig. 1a). The horizontal grid size is 3.5 km with 130 × 130 grid points. In the vertical there are 31 sigma-levels concentrated toward the surface, so that near-inertial waves generated in the mixed layer can be better resolved. The model was run from 23 September to 6 October 1998. The initial temperature and salinity fields were horizontally uniform based on the National Oceanographic Data Center (NODC) climatology for September in the region. These initial profiles have a pycnocline at ~50 m depth. On the boundaries, a radiation condition was used for velocities, and an advective condition for temperature and salinity with the inflows set equal to the initial temperature and salinity. Near-inertial motions are thus not included in the boundary conditions. We consequently limited our analysis in a region of the model domain (hereafter subdomain, Fig. 1b) to avoid artifacts in the propagation of near-inertial motions in the vicinity of the boundaries. Subsequent computations and figures are focused only on this subdomain.

Only the wind forcing was applied to the model since it was extreme during the hurricane and the model was integrated for a limited short period. Surface wind fields were obtained from the National Oceanic and Atmospheric Administration