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Langmuir turbulence in horizontal salinity gradient

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ABSTRACT

Langmuir circulation (LC) is believed to be one of the leading causes of turbulent mixing in the upper ocean. Large eddy simulation (LES) models that solve the Craik–Leibovich equations are used to study LC in the upper ocean, yielding new insights that could not be obtained from field observations or turbulent closure models alone. The present study expands our previous LES modeling investigations of LC to real ocean conditions with large-scale environmental motion due to strong horizontal density gradient, which is introduced to the LES model through scale separation analysis. The model is applied to field observations in the Gulf of Mexico when a measurement site was impacted by fresh water inflow. Model results suggest that LC can enhance turbulence in the water column and deepen the mixed layer (ML) with or without the large scale motions, being consistent with previous studies. The strong salinity gradient is shown to be able to reduce the mean flow in the ML, align Langmuir cells with the pressure gradient direction and inhibit turbulence in the ocean surface boundary layer.

1. Introduction

Langmuir circulation (LC), often represented by windrows on the water surface, which are caused by buoyant materials such as gas bubbles in horizontal counter-rotating cells aligned in the wind direction, is believed to be one of the leading causes of turbulent mixing in the upper ocean (Li et al., 1995; Skylingstad and Denbo, 1995; Kukulka et al., 2009; Kukulka et al., 2010; McWilliams et al., 1997; Hamlington et al., 2014). It is important for momentum and heat exchange across the mixed layer (ML), and can directly impact dynamics and thermodynamics in the upper ocean and the lower atmosphere including the vertical distributions of chemical, biological, optical, and acoustic properties.

The dynamical origin of LC is understood as wind-driven shear instability in combination with Stokes drift. The prevailing theoretical interpretation of Langmuir cells is derived by Craik and Leibovich (1976) who introduced effects of waves on Eulerian mean flow into the Navier–Stokes equations. Based on their theory, large eddy simulation (LES) models have been developed to simulate phase-averaged (over high-frequency surface gravity waves) equations for oceanic currents in the surface boundary layer and their interactions with surface gravity waves (Skylingstad and Denbo, 1995; McWilliams et al., 1997). These equations have additional terms proportional to the Lagrangian Stokes drift of the waves, including vortex and Coriolis forces and tracer advection.

LES models have been used to simulate LC in the upper ocean, yielding new insights that could not be obtained from field observations and turbulent closure models. Due to its high computational cost, LES models are usually limited to a finite domain with hundreds of meters at each horizontal direction and cannot resolve large-scale flows. Furthermore, most LES models used in the LC simulations use periodic boundary conditions in the horizontal directions, which assumes the physical properties (i.e. temperature and salinity) and expected flow patterns in the area of interest are of a periodically repeating nature so that the small LES domain is representative for a larger area. Using periodic boundary conditions can significantly reduce computational effort, and it is a good assumption for isotropic shear turbulence. However, LC is anisotropic (McWilliams et al., 1997) and has been observed to be modulated by crosswind tidal currents (Kukulka et al., 2011; Martinat et al., 2011). Idealized LES studies also indicate that LC could interact with oceanic fronts (Hamlington et al., 2014) and standing internal waves (Chini and Leibovich, 2005; Polton et al., 2008).

The present study expands our previous LES modeling investigations of Langmuir turbulence to real ocean conditions with large-scale environmental motion that features fresh water inflow into the study region. The outline of this paper is as follows. A brief description of the implementation of large-scale temperature and salinity variations in the LES model, the observations in the Gulf of Mexico, and the experiment set up are given in Section 2. Results are analyzed in Section 3, and discussion and concluding remarks are presented in Section 4.

2. Method

2.1. Observations in the Gulf of Mexico

A comprehensive field experiment took placed in the Gulf of Mexico

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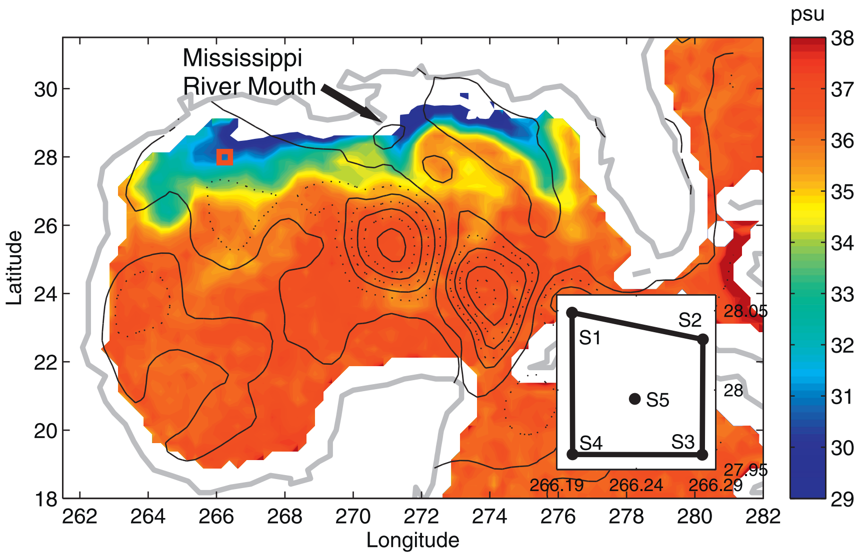

Fig. 1. Composition of 8-days (July 7–14) level 3 map gridded sea surface salinity product (color) derived from NASA "Soil Moisture Active Passive" satellite mission and 7-days (July 13–19) sea surface height anomalies (solid and dotted contour lines in cm) obtained from University of Colorado (UC) Colorado Center for Astrodynamics Research. The red open square represents the location of the field measurements with detailed station locations given in the small insert map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from 2 July to 22 July 2016 and was a part of "Turbulence in the Ocean Surface Boundary Layer" project funded by the Naval Research Laboratory. It was conducted on the outer shelf in the Gulf about 190 km southeast of Galveston, TX (Fig. 1). The experiment took place after high discharges from the Mississippi/Atchafalaya River System into the Gulf in the first six months of 2016 with the 2016 mean discharge of 18,531 m^3/s that was higher than the long-term mean discharge value of 16,792 m^3/s. The Mississippi discharge was above the long-term mean between January 1, 2016 and June 15, 2016, and it varied between 18,531 m^3/s and 37,661 m^3/s. It dropped below the 2016 and long-term means just before the experiment began (discharge data are from https://nwis.waterdata.usgs.gov). As show by the NASA sea surface salinity (SSS) in Fig. 1, the fresher water spread along the coast to the east and west of the river mouths, and also slowly pushed southward. The experimental site was located within a strong salinity gradient region (~ 5 psu per ~ 100 km).

Temperature, conductivity (salinity), and pressure observations were collected using Sea-Bird Electronics (SBE) 37-SM MicroCAT instruments at the four corners of a nearly square 10 km by 10 km box (S1 to S4). These water properties were measured at 7 levels in the top 11 m, then every ~ 7 m between 11 m and 50 m, and every 10 m when deeper than 50 m. Additional measurements were collected at the center of the box at station S5. At this location, a Wirewalker (Pinkel et al., 2011) collected detailed temperature (SBE 3) and conductivity (SBE 4) profiles at very fine vertical resolution (< 3 cm) from near the bottom to ~ 2 m below the sea surface (Fig. 2). A 1200 kHz Teledyne RDI acoustic Doppler current profiler (ADCP) with a wave package deployed at ~ 10 m below the sea surface delivered current velocity profiles (Fig. 7a, b), pressure, and echo intensity. These observations were used to estimate surface wave parameters and spectra (e.g. Terray et al., 1999), which are given in frequency bands range from 0.0083 to 0.9927 Hz with a 0.0156 Hz frequency band width. An example of the wave spectra is given at 14:17 UTC on July 13 in Fig. 3d. It clearly shows that most of the wave energy is concentrated in the frequency bands lower than 0.5 Hz. The 300 kHz bottom-mounted ADCPs were also deployed to measure current profiles at 5 mooring sites (S1 – S5). Meteorology observations such as wind speed and direction (Fig. 3a), air temperature, solar radiation, and relative humidity, were collected by sensors mounted on the research ship (R/V Pelican) that remained inside or just outside the study area during the entire experiment.

2.2. Model description

The LES model used in this study was first introduced by McWilliams et al., (1997) to solve the flow components using the wave-phase-averaged Craik–Leibovich theory (e.g., Craik and Leibovich, 1976; Suzuki and Fox–Kemper, 2016) with the effect of wave on current through the vortex force, Stokes–Coriolis force, Lagrangian mean advection associated with Stokes drift, and a wave-averaged increment to pressure that arises through conservative wave–current interactions.

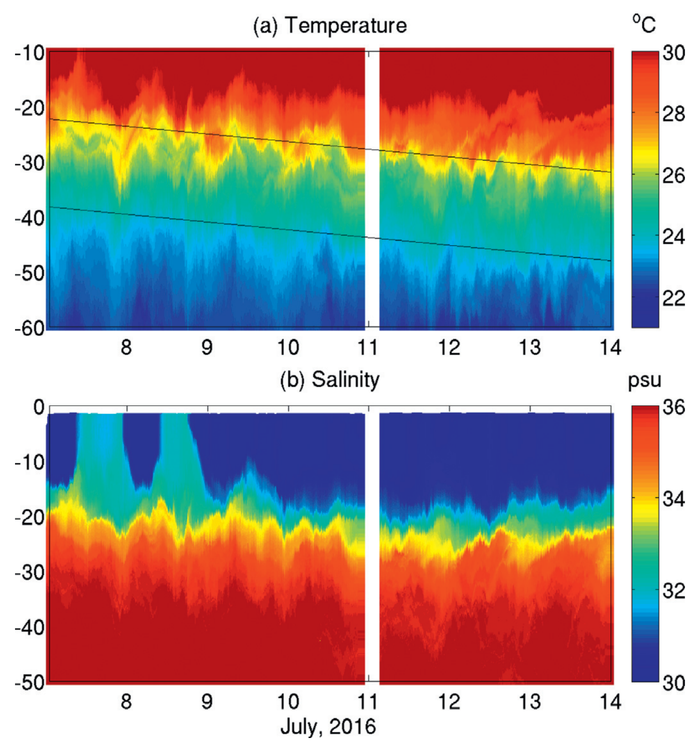

Fig. 2. Vertical profiles of (a) temperature and (b) salinity at S5 from July 7 00:00 UTC to July 14 00:00 UTC. The dashed lines in (a) are added to emphasize the slopping of temperature with time.

The filtered Craik–Leibovich momentum equation is given as (McWilliams et al., 1997)

$$\frac{D\vec{u}}{Dt} + f\vec{z} \times (\vec{u} + \vec{u}_s) = -\nabla\pi - g\vec{z}(\rho/\rho_0) + \vec{u}_s \times \vec{\omega} + SGS, \tag{1}$$

where g is the gravitational acceleration, $D/Dt = \partial_t + \vec{u}\cdot\nabla$, $\vec{u}$ (u, v, w) is the current velocity vector, $\vec{u}_s$ (u_{sx}, u_{sy}) is the Stokes drift vector, and