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Observational evidence for tidal straining over a sloping continental shelf

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ABSTRACT

Straining of a horizontal density gradient by tidal currents acts to periodically produce and destroy near-bottom stratification, which has been shown to modulate turbulence in the bottom boundary layer (BBL). Previous observations of such periodic variations have been limited to the coastal ocean and estuaries, where horizontal density gradients are maintained by river runoff or differential heating. In the present study, we show evidence for the existence of tidal straining over the continental shelf, outside any regions of freshwater influence, where horizontal density gradients are likely to result from the projection of the interior vertical stratification onto sloping topography. Based on microstructure data obtained in the East China Sea, we demonstrate that the tidal current shear interacting with the cross-isobath density gradient results in semidiurnal switching between unstable and stable stratification in the lower part of the BBL. The cycle of turbulent dissipation is quarter-diurnal, corresponding to the semidiurnal variation of tidal current shear. In addition, a noticeable diurnal modulation in stratification as well as a significant diurnal cycle of turbulent dissipation are observed in the upper part of the BBL, where the time evolution of stratification is dominated by tidal advection, rather than tidal straining.

1. Introduction

On the continental shelf and in the coastal ocean, turbulent mixing in the bottom boundary layer (BBL) is one of the key mechanisms for the dissipation of kinetic energy, for the transport of scalars such as heat, salt, nutrients, and sediment, and for the fluxes across the sediment–water interface. In the BBL, where the current speed is reduced to zero towards the bottom due to friction, straining of a horizontal density gradient acts both to produce and destroy stratification during the tidal cycle. This process, often referred to as "tidal straining", is known to trigger periodic modulations of near-bottom turbulence with some important implications for mixing and residual transports inside the BBL. The cycling between unstable and stable stratification induced by tidal straining is often called "Strain-Induced Periodic Stratification (SIPS)" (Simpson et al., 1990), which has been so far observed mainly in the coastal ocean (Simpson and Souza, 1995; Rippeth et al., 2001; Fisher et al., 2002) as well as in estuaries (Nepf and Geyer, 1996; Stacey et al., 1999a). A necessary prerequisite for the existence of SIPS is a background horizontal density gradient, typically maintained by river runoff in a "Region of Freshwater Influence" (ROFI) (Simpson, 1997), or, less frequently, by differential heating of the water column (e.g. Becherer et al., 2015).

Recent observations in lakes and modeling studies, however, suggest an alternative mechanism for the generation of quasi-horizontal density gradients in the vicinity of *sloping* topography, which results in a similar periodic modulation of near-bottom stratification and turbulence. This mechanism is associated with the cross-isobath (i.e. approximately horizontal) density gradient resulting from the projection of the interior vertical stratification onto the slope (see Umlauf and Burchard, 2011, Fig. 1). For the case of a uniform slope with slope angle α and a linear vertical stratification in the interior, i.e. above the strongly turbulent BBL, the cross-isobath (upslope) density gradient is given by $-(\rho_0/g)$ $N_\infty{}^2\sin\alpha$, where N_∞ is the buoyancy frequency outside the BBL; g ($=9.81\ \mathrm{ms}^{-2}$) is the acceleration due to gravity; and ρ_0 is the reference density of water (Umlauf and Burchard, 2011). In lakes, the interaction between this cross-isobath density gradient and the

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near-bottom current shear due to internal wave motions has been shown to result in a periodic generation and destruction of near-bottom stratification (Lorke et al. 2005, 2008), which is in many respects similar to SIPS. During periods of upslope flow, deeper, denser water flows on top of less dense water that moves more slowly due to friction, resulting in unstable stratification, and subsequently in "Shear-Induced Convection" (ShIC) (Lorke et al., 2005). Conversely, during periods of downslope flow, less dense, shallower water flows on top of denser water, which enhances stratification in the BBL. Modeling studies have shown that this process occurs over a wide range of parameters and geometries (Umlauf and Burchard, 2011; Becherer and Umlauf, 2011). Although previous observations of the above process have been limited to lakes, a similar behavior is expected to occur wherever an oscillating current shear interacts with horizontal density gradients. In contrast to SIPS, tidal straining over sloping topography requires neither river runoff nor differential heating to create horizontal density gradients, and is therefore likely to occur in much wider areas of the continental shelf. Due to the relatively recent discovery of this process, however, field data supporting the modeling studies mentioned above are so far lacking.

In the present study, we show first observational evidence for the existence of tidal straining over a sloping continental shelf outside any ROFI, using microstructure data obtained in the East China Sea (ECS) in summer. The ECS has a broad continental shelf and slopes with strong tidal currents (Larsen et al., 1985; Yoshikawa et al., 2010), which is favorable for the occurrence of ShIC, and is also known as one of the regions of intense primary productivity. The observations were carried out at about 400 km to the east-northeast of the mouth of the Changjiang River (Fig. 1a), suggesting that the effect of horizontal density gradients maintained by river runoff are negligible or at least of minor importance. The vertical extent of the Changjiang diluted water (CDW), a mixture of the discharged freshwater and the surrounding seawater (Beardsley et al., 1985), is confined to the surface mixed layer near the observation site (Yoshikawa et al., 2012) so that the CDW contributes to maintaining the interior vertical stratification rather than generating horizontal density gradients in the BBL.

In the following sections, we describe field observations and instrumentation (Section 2), followed by our observations of tidally-periodic stratification and mixing in the BBL (Section 3), investigate the roles of semidiurnal and diurnal tidal currents in the time evolution of potential density (Section 4), discuss a difference in the relative importance of tidal straining and advection between the upper and lower parts of the BBL (Section 5), and finally summarize our results (Section 6).

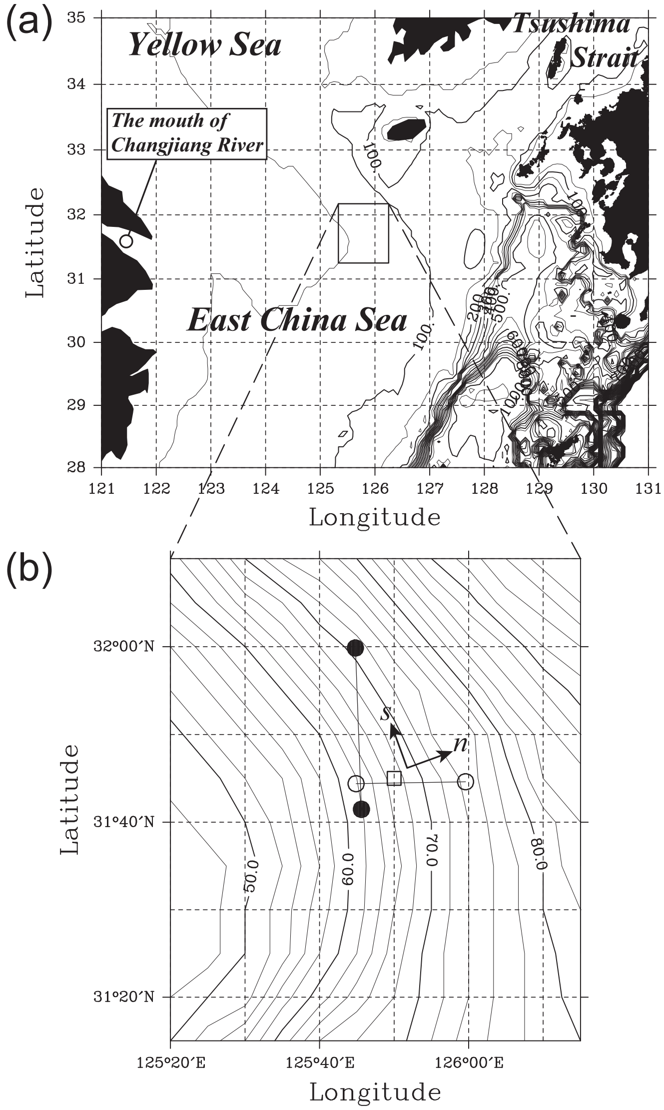

Fig. 1. (a) Map of the East China Sea and (b) an enlargement of the area indicated by the rectangle in panel (a). Bathymetric contours are shown every 50 m and 2 m in panels (a) and (b), respectively. Black shading in panel (a) indicates land. Panel (b) includes the location at which the ADCP and TurboMAP-5 were deployed (open square) as well as the CTD stations used for calculating zonal and meridional gradients of potential density (open and closed circles, respectively). Positive cross-isobath (n) and along-isobath (s) directions are indicated by axes in panel (b). Note that the n-axis points downslope.

2. Observations

The observations were carried out at a position of 31°44.9′N, 125°50.0′E, where the water depth and the inertial period are about 68 m and 23 h, respectively, over the continental shelf of the ECS (Fig. 1) on July 16–21, 2011 during a cruise of the training ship *Nagasaki-Maru* of Nagasaki University. At 1640 JST (Japan Standard Time) on July 16, we deployed an ADCP (Teledyne RD Instruments (RDI), Workhorse 600 kHz) mounted in a trawl-resistant bottom mount in an upward-looking orientation on the seabed composed mostly of muddy sand. The ADCP was operated in the standard RDI "mode 1", sampling and recording the along-beam velocities at 1.3 Hz during 20-min bursts every half hour. The vertical bin size was set to be 1 m, and the depth of the first bin was 65 m, i.e. 3 m above the seabed. In the present study, the ADCP data in the depth range of 30–65 m was used, where the "percentage of good data" (a quality indicator suggested by RDI) was the maximum value of 100 during the entire period of the observations (i.e. all the single-ping data were judged good). From the along-beam velocities averaged over 20 minutes (1600 pings), the cross- and along-isobath components of horizontal velocity (U and V) as well as the zonal and meridional components of horizontal velocity (u and v) were calculated at time intervals of half hour. The cross-isobath (n) and along-isobath (s) directions are indicated in Fig. 1b. The Reynolds stresses estimated by applying the variance method (Lu and Lueck, 1999; Stacey et al., 1999b) directly to the single-ping data were too noisy to be used in the present analysis. Within about 500 m of the ADCP, we deployed a microstructure profiler (JFE Advantech, TurboMAP-5) that samples the micro-scale vertical shear and the micro-scale temperature at a rate of 512 Hz as well as temperature, conductivity, pressure, turbidity, fluorescence, and the acceleration of the instrument at a rate of 64 Hz while falling freely at a speed of 0.5–0.6 ms^{-1} (Wolk et al., 2002). The dissipation rate of turbulent kinetic energy (ε) was calculated from