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Internal tides and turbulent mixing observed in the Bussol Strait

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ABSTRACT

Repeated observations with a period of about 24 h of hydrography, current velocity, and microstructures were performed at three stations surrounding a seamount in the middle of the Bussol Strait, the deepest and widest one of the Kuril Straits, to reveal spatial and temporal variability of internal tides and associated turbulent mixing. It is found that isopycnal displacements are dominated by diurnal tidal components, which show phase differences (namely, time lags) between the three stations that can be explained by a first mode topographically trapped wave (TTW) propagating clockwise around the seamount. Furthermore, at the station located near the center of the strait where energy dissipation rates are largest, diurnal variations of isopycnals and velocities are amplified toward the ocean bottom, consistent with the vertical structure of the first mode TTW. At that station, vigorous turbulent mixing with the energy dissipation rate exceeding 10^{-6} m^2 s^{-3} and diapycnal diffusivity exceeding 10^{-1} m^2 s^{-1} was observed in deep layers when the diurnal tidal current consisting of the first mode TTW flows from the Okhotsk Sea to the North Pacific, enhancing the mean current. These spatial and temporal variation patterns are confirmed to be reproduced by a previous numerical model successfully for the isopycnals and velocities, and partially for the turbulent mixing. The total energy dissipation rate is, however, by up to a factor of 3–10 smaller than predicted by the numerical model although the observations were performed during spring tides, suggesting that the actual diapycnal mixing is overall weaker than the previous model estimate and/or that extremely strong mixing occurs within highly localized areas.

Introduction

The Kuril Straits area, separating the Okhotsk Sea from the North Pacific Ocean, is known as a region of intense diapycnal mixing resulting from breaking large-amplitude internal waves generated by strong diurnal tidal currents flowing over prominent topographic features (e.g., Nakamura et al., 2000; Katsumata et al., 2004; Ono et al., 2007). The induced diapycnal mixing has been regarded as one of the essential factors responsible for the maintenance of the thermohaline circulation in the North Pacific, as well as for the formation and transportation of water masses that are characterized by low salinity and are widely distributed in the intermediate layer of the Okhotsk Sea and the North Pacific (e.g., Tatebe and Yasuda, 2004; Nakamura et al., 2006; Uchimoto et al., 2011). Furthermore, diapycnal mixing in the Kuril Straits is recently hypothesized to influence bidecadal climate variability in the North Pacific through the 18.6-year nodal tidal cycle (Osafune and Yasuda, 2006; Yasuda et al., 2006; Hasumi et al., 2008; Osafune and Yasuda, 2012; Tanaka et al., 2012). It is also pointed out, however, that the numerical model results demonstrating the significant impacts of diapycnal mixing in the Kuril Straits on the various large-scale phenomena described above can differ not only quantitatively but also qualitatively depending on the employed value of diapycnal diffusivity and its vertical decay scale from the ocean bottom (Tanaka et al., 2010a; Kawasaki and Hasumi, 2010).

By comparing tidal elevation fields in the Okhotsk Sea obtained from a series of numerical experiments with those obtained from satellite altimeter data, Tanaka et al. (2007, 2010b) have quantified diapycnal diffusivity in the Kuril Straits in terms of the amount of tidal energy available for diapycnal mixing processes. They estimated that ∼30 GW of internal tide energy is lost to dissipation in the Kuril Straits to cause the area-averaged diapycnal diffusivity of $\sim 25 \times 10^{-4}$ m^2 s^{-1}. Tanaka et al. (2010b) investigated the generation, propagation, and dissipation processes of the internal tides

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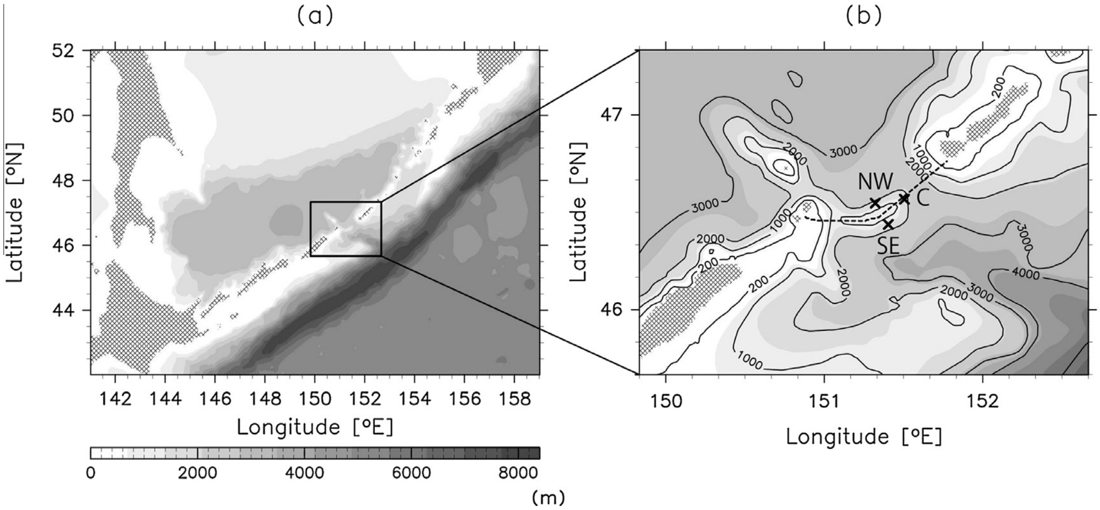

Fig. 1. Bathymetric maps of (a) the entire Kuril Straits and (b) the Bussol Strait (as represented by the rectangular box in Fig. 1a). The hatched areas are lands. Indicated by the cross symbols in Fig. 1b are the locations of the observation stations. The dashed line in Fig. 1b indicates the location of the vertical cross-section on which a modal structure of a TTW is calculated in Fig. 9.

in the Kuril Straits using a high-resolution three-dimensional numerical model. Their experimental design is briefly described in section 'Data and methods'. They have shown that since the diurnal K_1 tidal frequency is subinertial in this area, internal tides generated by the K_1 surface tides take the form of topographically trapped waves (TTWs), and most of them are dissipated while propagating clockwise around each island without freely radiating away from the straits. They have further shown that TTWs induce strong velocity shear near the ocean bottom causing bottom-confined intense mixing with a vertical decay scale ~200 m.

Although these estimates based on numerical experiments must be validated through comparisons with direct observations of turbulent mixing in the Kuril Straits, the number of direct observations are still insufficient except in the relatively shallow Urup Strait (Itoh et al., 2010; Itoh et al., 2011; Itoh et al., 2014). Moreover, although the existence of diurnal TTWs in the Kuril Straits has been confirmed by several observational studies, they are based either on vertical profiles of velocity at only one location (Yagi and Yasuda, 2012) or on trajectories of satellite-tracked surface drifters (Rabinovich and Thomson, 2001; Ohshima et al., 2002; Ohshima et al., 2005). The former is lacking evidence for propagation of TTWs, while the latter is lacking information on variations in deep layers where TTWs are amplified.

In this study, to identify propagating diurnal internal tides and to reveal spatial and temporal variability of the associated turbulent mixing, we conduct repeated observations with a period of about 24 h of vertical profiles of hydrography, velocity, and microstructures at multiple locations in the Bussol Strait, the deepest and widest one of the Kuril Straits. The relationships between turbulent energy dissipation rates and tidal and mean flow structures are presented to discuss the processes responsible for the intense diapycnal mixing. The observed results are also compared with the numerical model results by Tanaka et al. (2010b) to check the validity of their simulation as well as to infer the mixing intensity in the entire Kuril Straits.

Data and methods

Field observations with a period of about 24 h of hydrography, current velocity, and microstructures were carried out at three stations in the Bussol Strait (Station NW, Station SE, and Station C, Fig. 1 and Table 1), from aboard the R/V *Gordienko* of the Far Eastern Hydrometeorological Research Institute, Russia. The three stations were chosen to be along the ~1800-m isobath surrounding a seamount with a summit depth of ~800 m located near the center of the strait (Fig. 1), around which a previous numerical study (Tanaka et al., 2010b) predicted large-amplitude diurnal TTWs propagating clockwise (Fig. 2). The observations were conducted between approximately 1300 UTC 28 July and 1200 UTC 31 July 2011 (Table 1), during a diurnal spring tide.

Casts of a conductivity-temperature-depth (CTD) profiler (SBE 9plus, Sea-Bird Electronics) equipped with a lowered acoustic Doppler current profiler (LADCP; 300 kHz Workhorse, Teledyne RD Instruments) were made alternately with casts of a vertical microstructure profiler (VMP-2000, Rockland Scientific International). VMP-2000 is a tethered free-falling vertical profiler with two high-resolution shear probes and pumped standard CTD sensors (SBE-3 and SBE-4, Sea-Bird Electronics), providing vertical profiles of turbulent kinetic energy dissipation rate and seawater density simultaneously. At each station, CTD and LADCP data were obtained for six pairs of down and up casts, while VMP data were available for six down casts.

Velocity data at 5-m intervals were derived from the LADCP data after processed with conventional methods by Fischer and Visbeck (1993). Micro-scale velocity shear profiles obtained by VMP-2000 were divided into approximately 10-m-binned sub-profiles, for each of which power spectra of the shear were calculated, and they were verified to be consistent with the Nasmyth's universal spectrum (Oakey, 1982). The power spectra were then integrated over wavenumbers ranging from 1 m^{-1} to a wavenumber

Table 1
Station locations, their bottom depths, and start and end times of the observations. Note that the location and the bottom depth at each station listed below are for the middle of the total six casts, and each cast was conducted at a position slightly away from the middle point by less than ~1.5 km in distance and ~200 m in bottom depth.

Station	Latitude	Longitude	Bottom depth (m)	Start time	End time
NW (Northwest)	46°33′N	151°19′E	1788	JUL 28 12:54	JUL 29 12:02
SE (Southeast)	46°26′N	151°24′E	1760	JUL 29 13:20	JUL 30 11:49
C (Center)	46°34′N	151°30′E	1731	JUL 30 13:07	JUL 31 11:41