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Distribution of vertical diffusivity in the Bussol' Strait: A mixing hot spot in the North Pacific

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ABSTRACT

Strong vertical mixing in the Kuril Straits is believed to be an important contribution to the ventilation of the intermediate layer and water mass transformation in the North Pacific, especially for density greater than $27.1\sigma_\theta$. Furthermore, a recent modeling study has suggested that the vertical profile of vertical diffusivity is a key factor in the determination of thermohaline circulation in the North Pacific. Here we report the distribution of vertical diffusivity in the Bussol' Strait, the main conduit of water exchange and a possible central site of strong mixing in the Kuril Straits. Our analysis is based on a set of highly densed CTD observations, with a total of 127 casts across the strait in 2001. Vigorous density inversions occurred in the strait with the largest vertical displacement being over 250 m. We estimated the vertical diffusivity coefficient K_ρ from the Thorpe scale for all the CTD data. The vertical average of K_ρ estimated from all the casts is 60×10^{-4} m^2 s^{-1}. Overall, K_ρ is relatively small in the upper 300 m (density range approximately 26.5–$26.7\sigma_\theta$), whereas it is relatively large below a depth of 500 m (density range of $>26.8\sigma_\theta$), with a maximum at the depths of 1100–1700 m. The distributions of K_ρ and the amplitude of the diurnal tidal current are similar, suggesting that the mixing is caused by the strong diurnal tidal current. The amplification of the diurnal (tidal) current over slopes near the bottom causes the K_ρ maximum at depths of ~1100–1700 m. We also introduce an empirical relationship between K_ρ and the amplitude of the diurnal tidal current. The vertical diffusivity is one order of magnitude larger at the spring tide than at the neap tide, suggesting that there is extremely large variability of tidal mixing with the fortnightly modulation. In the intermediate layer at densities of 27.3–$27.6\sigma_\theta$, large K_ρ values ($>60\times10^{-4}$ m^2 s^{-1}) corresponds well to the colder and less-saline water mass characterized in the Bussol' Strait, confirming that water mass transformation occurs locally in the strait through strong diapycnal mixing.

1. Introduction

The Sea of Okhotsk is the main site for ventilation of intermediate water in the North Pacific, including North Pacific Intermediate Water (NPIW) (Talley, 1991; Warner et al., 1996). Ventilation of NPIW is derived from sinking of surface water associated with high sea-ice production along the northern shelf region of the Sea of Okhotsk (Shcherbina et al., 2003) and strong tidal (vertical) mixing in the Kuril Straits. Based on chlorofluorocarbon (CFC) data, Wong et al. (1998) have suggested that strong vertical mixing in the Kuril Straits is the primary contributor to the ventilation in the density range of $>27.1\sigma_\theta$. The Kuril Straits is also an important site for water mass transformation due to the strong tidal mixing. The water mass with a density of about $26.8\sigma_\theta$ has the largest thickness and thus the lowest potential vorticity in the Sea of Okhotsk (Yasuda, 1997; Itoh et al., 2003). In this density range, the Sea of Okhotsk is suggested as a possible source of the low potential vorticity of NPIW (Yasuda, 1997; Watanabe and Wakatsuchi, 1998), assuming a relatively small contribution of relative vorticity for large scale water mass distribution.

Several investigations have suggested that strong vertical mixing in the Kuril Straits has a substantial impact on the water mass distributions and thermohaline circulation in the North Pacific. Based on the results of an analytical model, Tatebe and Yasuda (2004) pointed out that upward diapycnal transport from deeper layers due to vertical mixing in the Kuril Straits could be an important factor in determining the extent of the Oyashio and cross-gyre western boundary transport. Nakamura et al. (2006),

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using an ocean general circulation model, have suggested that strong tidal mixing in the Kuril Straits enhances the ventilation of the NPIW layer. Kawasaki and Hasumi (2010), on the basis of both a general circulation model and a box model, showed that the thermohaline circulation of the North Pacific depends strongly on the vertical profile of the vertical diffusivity coefficient K_ρ in the Kuril Straits. When strong vertical mixing reaches the sea surface, localized upwelling of deep water occurs, resulting in a single meridional circulation cell in the North Pacific. On the contrary, when strong mixing does not reach the surface, downwelling occurs in upper layers, whereas upwelling occurs in lower layers around the Kuril Straits, resulting in a double circulation structure in the North Pacific. Although the results of these numerical studies have not been confirmed by observations, they demonstrate the potential importance of vertical diffusivity in the Kuril Straits.

It is therefore vital to evaluate the strength and vertical structure of vertical diffusivity in the Kuril Straits. In recent years, several studies have estimated the magnitude of vertical mixing in the straits. Tanaka et al. (2007, 2010a) mapped the depth-averaged K_ρ values around the Kuril Straits, based on a physical model fitted by tidal elevation from TOPEX/POSEIDON altimeter data. They have shown that the areal average of depth-averaged K_ρ around the Kuril Straits is $25\times10^{-4}\ m^2\ s^{-1}$, although K_ρ is amplified in several narrow to as much as ~$500\times10^{-4}\ m^2\ s^{-1}$. They pointed out that the vertical diffusivity of $200\times10^{-4}\ m^2\ s^{-1}$ given by Nakamura et al. (2006) is too large. Recent observational studies have used a microstructure profiler to try to measure vertical diffusivity directly in the Kuril Straits. Itoh et al. (2010, 2011) used a vertical microstructure profiler (VMP-2000) to estimate vertical diffusivity in the Urup Strait, which is located southwest of the Bussol' Strait (see Fig. 1 for the location). Direct observations of turbulent mixing have also been made with a VMP-2000 profiler at one station in the Bussol' Strait in 2006 and 2007 (Yagi and Yasuda, 2012b, hereafter YY12).

According to the mapping of K_ρ from the model (Nakamura and Awaji, 2004; Tanaka et al., 2010a), the region of enhanced K_ρ is widely distributed in and around the Bussol' Strait among the Kuril Straits. Ono et al. (2007) have suggested that, because of strong tidal mixing, the Bussol' Strait is an important site of water mass transformation within the Kuril Straits. Furthermore, anticyclonic eddies have been frequently observed near the Bussol' Strait (Bulatov et al., 1999; Ohshima et al., 2005), and they are likely caused by baroclinic instability associated with strong tidal mixing (Nakamura and Awaji, 2004; Ohshima et al., 2005). The Bussol' Strait therefore can be regarded as one of the mixing hot spots in the North Pacific. Furthermore, the Bussol' Strait is the deepest (sill depth of 2400 m) and widest (width of 80 km) strait of the Kuril Straits and thus is thought to be the main conduit for the exchange of water masses between the Sea of Okhotsk and the Pacific. In fact, most surface drifters (Ohshima et al., 2002) and profiling floats (target depth of 500–750 m; Ohshima et al., 2010) deployed in the Sea of Okhotsk flowed out into the North Pacific through the Bussol' Strait during the winter.

Across the Bussol' Strait at 13 stations, intensive observations were conducted aboard the Research Vessel *Prof. Khromov* in 2001 (hereafter *XP01*), using a Lowered Acoustic Doppler Current Profiler (LADCP) and Conductivity Temperature Depth (CTD) profiler. Katsumata et al. (2004) have revealed the mean, diurnal, and semi-diurnal exchange flow based on these LADCP observations, which were repeated over a 24-h period across the strait. The net transport was from the Sea of Okhotsk to the Pacific with the net value being about 9 Sv ($1\ Sv=10^6\ m^3\ s^{-1}$). The dominant diurnal tidal current reached an amplitude of $>1.0\ m\ s^{-1}$ in the western channel of the strait, even at depths greater than 1200 m. The amplification and dominance of the diurnal tidal current in

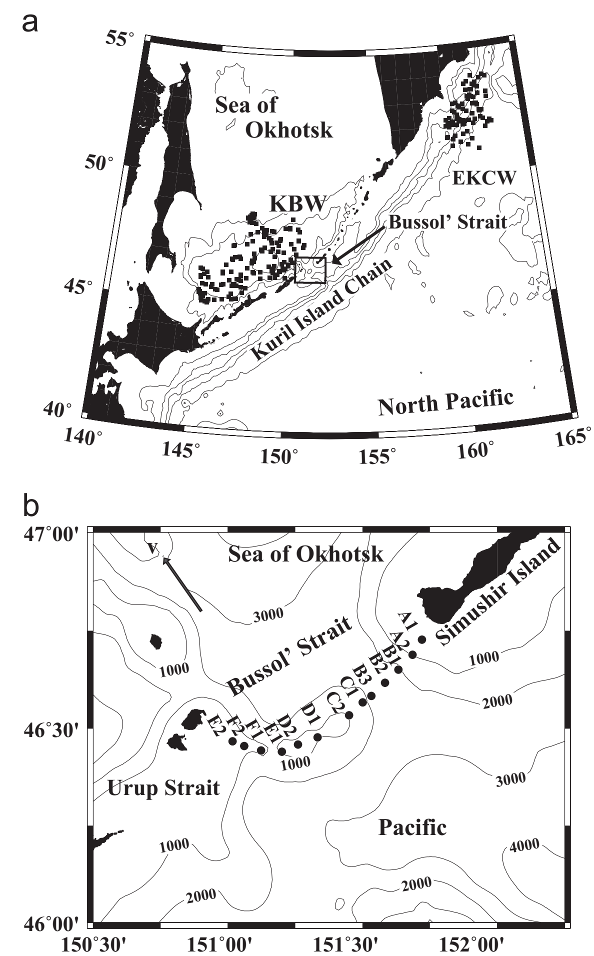

Fig. 1. (a) Bathmetric map of the Sea of Okhotsk and the Kuril Island Chain. Solid squares indicate the stations used for calculating the mean properties of East Kamchatka Current Water (EKCW) and Kuril Basin Water (KBW) in Fig. 8. (b) Enlarged map of the Bussol' Strait area designated by the rectangular box in (a), with the *XP01* cruise CTD stations (solid circles). The bathymetric data are derived from the General Bathymetric Chart of the Oceans (GEBCO).

the strait has also been demonstrated by surface drifters (Ohshima et al., 2002).

Ono et al. (2007), from *XP01* CTD data, found a unique water mass that is colder, less-saline, and has a higher dissolved oxygen concentration than Kuril Basin Water (KBW) and East Kamchatka Current Water (EKCW) in the density range 27.3–27.6σ_θ. These properties cannot be explained by isopycnal mixing between the two water masses. This suggests that these unique water properties are created by the vigorous vertical mixing across density surfaces in the strait. Generally, KBW shows the minimum value of potential vorticity around 26.8σ_θ. In the Bussol' Strait this minimum value becomes further lower than that of KBW (Ono et al., 2007). This suggests a possibility of the formation of low potential vorticity water around 26.8σ_θ in the Bussol' Strait.

Both the *XP01* and YY12 studies involved observations made in the Bussol' Strait with repeated casts over 24-h periods to resolve the mean and tidal components. The YY12 study used the VMP-2000 profiler to make direct observations of turbulence. However, the observations were made at a single station hence were not necessarily representative of the mean features of turbulence in the Bussol' Strait. In contrast, the *XP01* study did not involve direct observations of turbulence, but conducted intensive CTD and LADCP observations at 13 stations (total of 127 casts) across the strait from the shelf slope to the deepest part of the sill. In this study we estimated the distribution of vertical mixing in the