Strong vertical mixing in the Urup Strait

Sachihiko Itoh,[1] Ichiro Yasuda,[1] Masahiro Yagi,[1] Satoshi Osafune,[1] Hitoshi Kaneko,[1] Jun Nishioka,[2] Takeshi Nakatsuka,[3] and Yuri N. Volkov[4]

Received 15 June 2011; revised 14 July 2011; accepted 18 July 2011; published 25 August 2011.

[1] Microstructure measurements were conducted in one of the Kuril Straits in the summer of 2007. Over the course of 1 day of repeated observations across the Pacific side of the steep sill of the Urup Strait, extremely strong mixing was observed during periods of Pacific-ward (down-sill) flows and during the transition from Pacific-ward to Okhotsk-ward (up-sill) flows, with a turbulent energy dissipation rate ε of 10^{-6} to 10^{-5} W kg^{-1} and vertical diffusivity of 10^{-1} to 5×10^{-1} m^2 s^{-1}. During the period of strong mixing, we observed homogeneous layers with a thickness of 300–600 m and potential density of 26.6–26.7 σ_θ, occupying the entire water column in one case. High values of ε within this layer indicate the injection of diapycnal flows from the upper and lower layers, possibly contributing to southward intrusion of intermediate water into the subtropical gyre. **Citation:** Itoh, S., I. Yasuda, M. Yagi, S. Osafune, H. Kaneko, J. Nishioka, T. Nakatsuka, and Y. N. Volkov (2011), Strong vertical mixing in the Urup Strait, *Geophys. Res. Lett.*, *38*, L16607, doi:10.1029/2011GL048507.

1. Introduction

[2] North Pacific Intermediate Water (NPIW), which has a wide distribution and a characteristic minimum in vertical salinity below the main pycnocline in the North Pacific subtropical gyre [*Sverdrup et al.*, 1942; *Reid*, 1965], originates in the Sea of Okhotsk [*Talley*, 1991; *Yasuda*, 1997]. Given that it does not outcrop at the surface in the open North Pacific, NPIW is thought to play a significant role in isolating atmospheric CO_2 within the ocean [*Tsunogai et al.*, 1993]. The source water of NPIW, a pycnostad with potential density of 26.6–27.0 σ_θ in the Sea of Okhotsk, is formed in the northwestern shelf region via sea-ice formation in winter [*Martin et al.*, 1998; *Itoh et al.*, 2003] and in the Kuril Straits due to tidal mixing [*Talley*, 1991; *Tatebe and Yasuda*, 2004; *Nakamura et al.*, 2006].

[3] Although the contribution to NPIW formation of strong tidal mixing around the Kuril Straits has been qualitatively described and is widely recognized [*Talley*, 1991; *Sarmiento et al.*, 2004; *Yamamoto-Kawai et al.*, 2004], details of this process remain poorly understood compared with the ventilation of intermediate water of the Sea of Okhotsk in the northwestern shelf region. The production rate of dense water in the shelf region was estimated to be 0.2–0.4 Sv (1 Sv = 10^6 m^3 s^{-1}) based on satellite images [*Martin et al.*, 1998] and 0.67 Sv based on historical hydrographic data [*Itoh et al.*, 2003].

[4] Regarding vertical mixing in the Kuril Straits, the results of numerical experiments with an Ocean General Circulation Model (OGCM) indicate that strong vertical mixing in this region with vertical diffusivity $K_\rho = 2.0 \times 10^{-2}$ m^2 s^{-1} results in improved model capability in reproducing NPIW [*Nakamura et al.*, 2006]. In contrast, a recent numerical study using a higher-resolution (eddy-permitting) OGCM without sea-ice (temperature and salinity in the shelf region were restored to climatology) also reproduced the NPIW, with an order-of-magnitude weaker vertical diffusivity (bottom-intensified K_ρ with a decay scale of 200 m; area-mean value of 2.5×10^{-3} m^2 s^{-1}) [*Tanaka et al.*, 2010]. Whereas, the vertical profile of strong vertical mixing may also be related to the water mass formation and circulations. *Kawasaki and Hasumi* [2010] suggested that the structure of meridional overturning cells in a model ocean may be highly sensitive to the vertical profile of K_ρ; however, a lack of direct microstructure measurements around the Kuril Straits means that little is known of the influence of tidal mixing on water modification in the density range of intermediate water in the Sea of Okhotsk (26.6–27.0 σ_θ) and in the North Pacific (26.6–27.2 σ_θ).

[5] The Urup Strait is a shallow passage with a steep sill between the North Pacific and the Sea of Okhotsk, located around 46°N (Figure 1). Although much smaller than major straits such as the Bussol' Strait, the importance of the Urup Strait in terms of the formation of the pycnostad in the Sea of Okhotsk (and hence NPIW) has been highlighted because of the vigorous tidal mixing in this area simulated in numerical experiments [*Nakamura and Awaji*, 2004]. We performed 1 day of continuous observations in this area for the first time, including microstructure measurements, in August of 2006 at a station (Station A) located on the Okhotsk side of the sill in Urup Strait, during neap tide [*Itoh et al.*, 2010]. Intense vertical mixing was observed to be related to two types of internal waves within the water column: propagating internal waves and large-amplitude internal waves occurred when the flow direction changed from up-sill to down-sill. However, the observed turbulent energy dissipation rate ε ranged from 1×10^{-9} to 3×10^{-8} W kg^{-1}, an order of magnitude smaller than that predicted by numerical experiments [*Nakamura and Awaji*, 2004; *Tanaka et al.*, 2007]. To address the lack of observation data during spring tide, we conducted a second series of

[1]Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan.
[2]Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan.
[3]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan.
[4]Far Eastern Regional Hydrometeorological Research Institute, Vladivostok, Russia.

0094-8276/11/2011GL048507

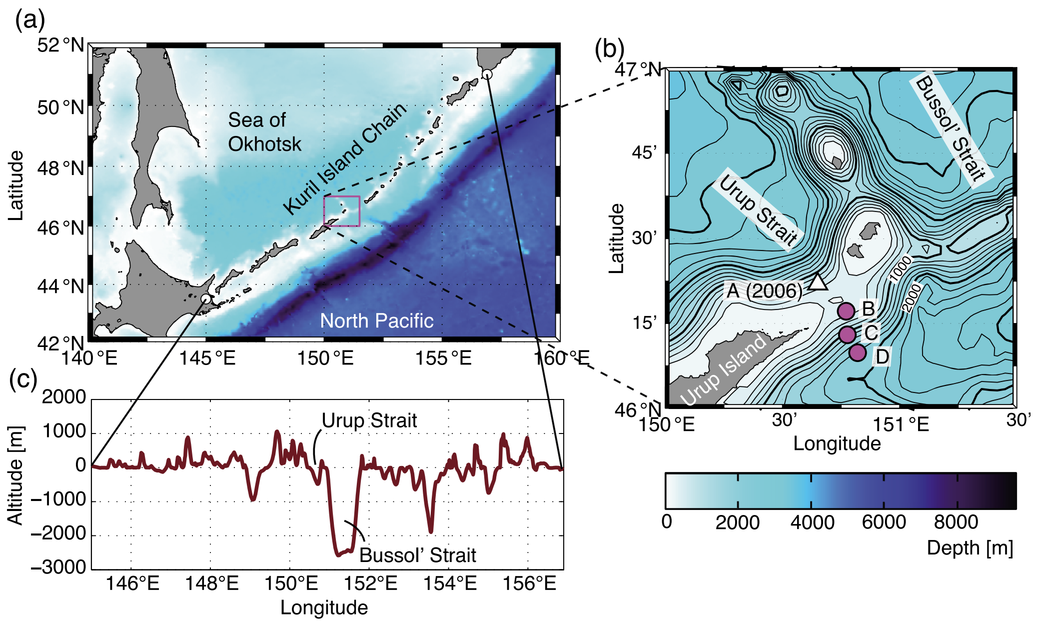

Figure 1. Geographical characteristics of the study site. (a) Bathymetric chart of the area around the Kuril Island Chain. (b) Detailed topographic features of the Urup Strait and locations of observation stations in 2006 and 2007. (c) Cross-section showing bathymetry from Hokkaido to the Kamchatka Peninsula.

1-day continuous observations in the Urup Strait in August of 2007, at three stations (B, C, and D) on the Pacific side during spring tide (Figure 1).

2. Data and Methods

[6] Observations were conducted at Stations B, C, and D on 11–12 (UTC) August 2007 from aboard R/V *Professor Khromov* of the Far Eastern Regional Hydrometeorological Research Institute, Russia, using a conductivity temperature and depth (CTD) system (SBE 911plus, SeaBird Electronics) and a vertical microstructure profiler (VMP) (VMP500, Rockland Scientific International). The CTD system was deployed down to 10 m above the bottom. Surface velocity was inferred from the ship drift during CTD observations. The VMP500 is a free-fall type instrument with two high-resolution shear probes (sampled at 512 Hz) and moderate-resolution but high-accuracy conductivity (SBE3) and temperature (SBE4) sensors.

[7] From the high-resolution shear profiles obtained by VMP, the turbulent dissipation rate ε was calculated based on theory and techniques commonly proposed in the literature. The procedures and parameters employed in the present case are the same as those described by *Itoh et al.* [2010]. Vertical diffusivity coefficients were calculated by $K_\rho = \Gamma\varepsilon/N^2$ [*Osborn*, 1980], where Γ is the mixing efficiency and N^2 is the buoyancy frequency, defined as $N = (-g/\rho_0 \partial\sigma_\theta/\partial z)^{1/2}$. For simplicity, Γ is assumed to have a constant value of 0.2.

[8] To measure chlorophyll-*a* concentrations, we filtered the water samples taken by each ascending CTD cast (except for the first CTD deployment at Station C during the 3rd transect, Figure 2c) through Whatman GF/F filters, extracted the residues with dimethylformamide, and measured fluorescence using a fluorometer (10 AU, Turner Designs, Inc.).

3. Results

[9] Over the course of 1 day, the cross-slope velocity inferred from ship drift changed its direction from Pacific-ward (1st transect) to Okhotsk-ward (3rd and 4th transects) and Pacific-ward again (6th transect) (Figures 2 and 3a). The maximum Okhotsk-ward (340°, approximately along the observation transect) and Pacific-ward (160°) velocities were estimated to be 2.1 m s^{-1} and 1.2 m s^{-1} near the sill top at Station B, during the elapsed hours of 14.4–14.7 and 24.8–25.2, respectively. During the Okhotsk-ward phase (Figures 2c and 2d), isopycnal surfaces typically above 26.8 σ_θ were deep on the Pacific (deeper) side and shallow on the Okhotsk (shallower) side. In contrast, during the Pacific-ward phases observed at the 1st and end of the 6th transects (Figures 2a and 2f), the isopycnal surfaces of 26.7–26.8 σ_θ were strongly depressed downward at Station C, with remarkable density inversions with vertical scales of up to 100 m. In the 2nd transect (Figure 2b), following a change in current direction, vertical displacements of isopycnal surfaces were small above 26.6 σ_θ; the 26.7 σ_θ surface was strongly depressed downward.

[10] The intensity of turbulence, represented by ε, also shows a difference between the phases of the Pacific-ward and Okhotsk-ward flows. ε was 10^{-9} to 10^{-6} W kg^{-1} during the Okhotsk-ward phase (Figures 2c and 2d), except for the profile at Station B at the sill top, which slightly exceeded 10^{-6} W kg^{-1}; in contrast, high dissipation rates were observed at Station C during the Pacific-ward phase (Figures 2a and 2f; ε values of 10^{-6} to 10^{-5} W kg^{-1}) and during the transition period from the Pacific-ward phase to

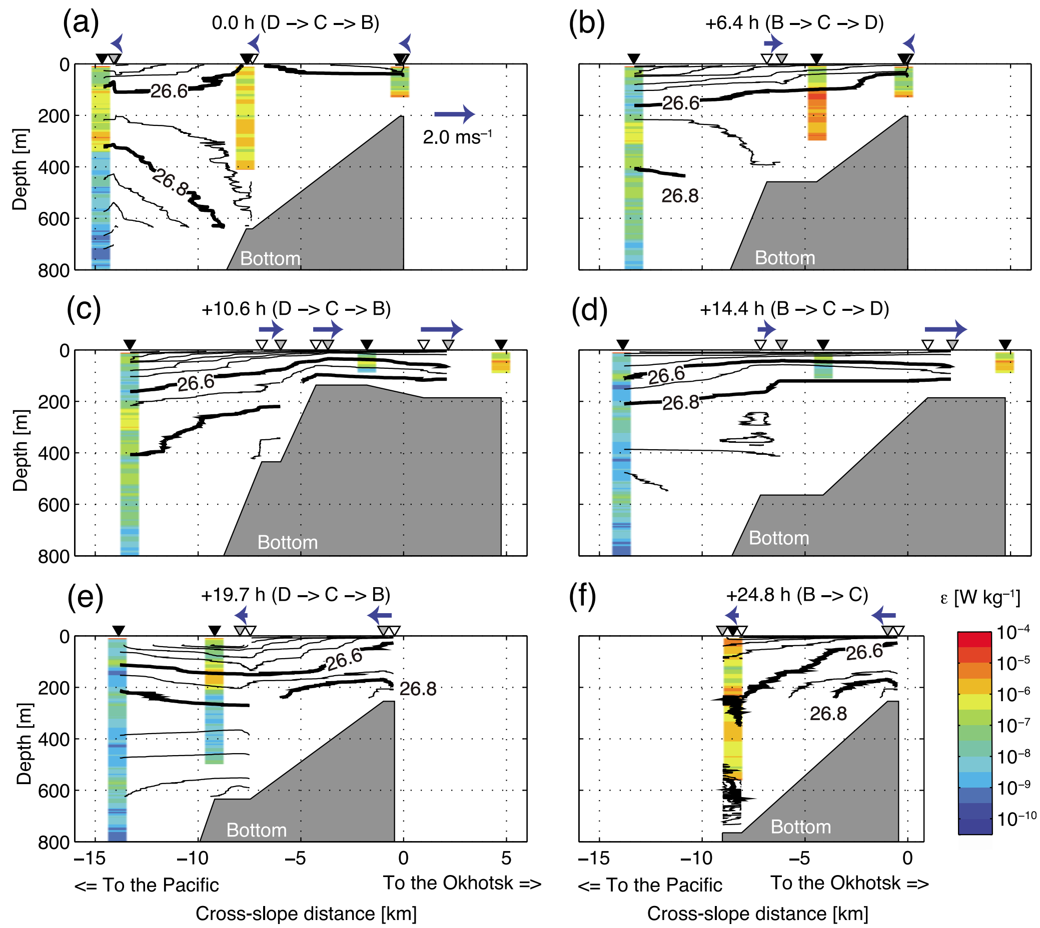

Figure 2. (a–f) Profiles of potential density σ_θ (contour lines) and turbulent energy dissipation rate ε (colored bars) for the six transects obtained during 1-day observations. The start time of each transect is shown in each panel along with the order of stations where observations were conducted. White, gray, and black triangles at the top of each panel indicate the positions of the start of CTD descending casts, CTD ascending casts, and VMP deployments, respectively, and arrows indicate the cross-slope velocity at the surface inferred from ship drift.

the Okhotsk-ward phase (Figure 2b). The corresponding vertical diffusivity was 10^{-1} to 5×10^{-1} m^2 s^{-1}, which is four orders of magnitude higher than that in the open ocean [e.g., *Ledwell et al.*, 1993]. This strong mixing occurred mainly in the layer between 26.6 and 26.7 σ_θ. In the three profiles at Station C during the Pacific-ward phase (1st, 2nd, and 6th transects), 26.6–26.7 σ_θ layers were thickened to be 300–600 m: almost the whole water column of approximately 600 m was occupied by this layer during the 1st transect (Figure 2a).

[11] Time series of the data obtained at Station C suggest the diurnal periodicity of the flow (Figure 3a), consistent with observations near the study site [*Katsumata et al.*, 2004]. Although ε fluctuation was not tightly synchronized to the velocity variation, the observed high dissipation rates within the mid-water column corresponded to the depression of isopycnal surfaces during the down-sill-flow phase (Figures 3b and 3c). Strong vertical mixing corresponding to the high dissipation rates was evidenced by chlorophyll-*a* concentration of the first two and the last profiles (Figure 3d). In addition to the homogeneity in the thick 26.6–26.7 σ_θ layers where dissipation rates were high, chlorophyll-*a* concentrations were detected with the value of 0.16–0.22 mg m^{-3} at depth of 400–600 m where light intensity is extremely low.

[12] The above pattern of the strong mixing suggests the occurrence and breaking of large-amplitude internal waves, as observed at Station A in 2006 [*Itoh et al.*, 2010]. In the present study, the internal Froude number calculated from the ship drift velocity periodically exceeded 1 near the sill top (Okhotsk-ward and Pacific-ward velocities of 2.1 m s^{-1} and 1.2 m s^{-1} yield Froude number values of 2.1 and 1.2 at Station B, respectively), whereas it did not exceed 1 at Station C (maximum Okhotsk-ward and Pacific-ward velocities of 1.3 m s^{-1} and 0.94 m s^{-1} yield Froude number values of 0.90 and 0.42, respectively). Thus, we also presume that the amplification and breaking of internal waves was related to supercritical flows around the sill top and their transition to subcritical flows with hydraulic jumps downstream the sill; the role of hydraulic processes was also implicated for the observations in 2006 during neap tide [*Itoh et al.*, 2010].

4. Discussion: Estimation of Diapycnal Volume Transport

[13] Vertical mixing results in a vertical density flux, which is compensated by mean diapycnal velocity; that is,

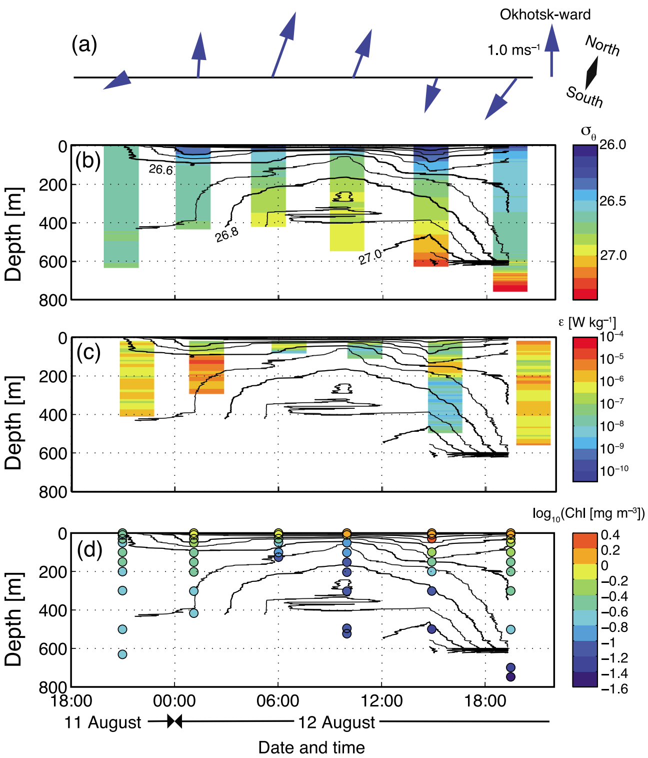

Figure 3. Time series of the observation data at Station C: (a) surface velocity inferred from ship drift, (b) potential density (descending casts), (c) dissipation rate (color bars) and (d) chlorophyll concentration (color circles). In Figures 3c and 3d, potential density are shown with contour lines. Surface velocity and potential density estimated from the second CTD deployment (for water sampling but at a shallower point) during the 3rd transect (Figure 2c) are not displayed in the figure.

$$w_d \frac{\partial \sigma_\theta}{\partial z_d} = -\frac{\partial}{\partial z_d}\overline{w_d{}'\sigma_\theta{}'} = -\frac{\rho_0 \Gamma}{g}\frac{\partial \varepsilon}{\partial z_d}, \tag{1}$$

where the central term indicates the diapycnal eddy density flux; and w_d and z_d denote diapycnal velocity and the diapycnal coordinate (upward is positive), respectively. This formulation is directly derived from the conservation equations of potential temperature and salinity on an isopycnal surface, ignoring cabbeling, compressibility, and double diffusion terms (by definition, tendency and horizontal diffusion terms are zero) [*McDougall*, 1984]. Although reliable atmospheric flux data are not available for this area, the flux is presumed to be negligible for the target layer below 26.6 σ_θ due to its thickness and the extremely strong mixing in the confined layer: a precipitation level required to balance the density flux caused by ε variation of 10^{-6} W kg^{-1} in 100 m layer becomes an unrealistically large value of ~25,000 mm/year. The mean diapycnal velocity is written as

$$\langle w_d \rangle = -\frac{\rho_0 \Gamma}{g}\left\langle \frac{\partial \varepsilon}{\partial \sigma_\theta} \right\rangle, \tag{2}$$

where the brackets indicate the temporal and/or horizontal mean. Equations (1) and (2) indicate that the strong layer-specific diapycnal mixing results in the injection of waters into the layer of interest from those located above and below.

[14] Because our observations in 2007 were conducted during spring tide, the mean profiles of ε and $\langle w_d \rangle$ were calculated including the data obtained in 2006 during neap tide (all of the available values of ε and $\partial\varepsilon/\partial\sigma_\theta$ were simply averaged), in order to represent the mean with reduced bias caused by the fortnightly cycle (Figure 4). The mean ε observed in 2007 is highest in the layer between 26.6 and 26.7 σ_θ, as stated above, with a peak value of approximately 2×10^{-6} W kg^{-1} at around 26.65 σ_θ. Although the mixing intensity observed in 2006 during neap tide was much weaker than that in 2007 during spring tide, the total mean profile still shows a peak at approximately the same layer in both cases, with a magnitude of about 1×10^{-6} W kg^{-1}.

[15] Mean diapycnal velocities were calculated from equation (2) for both the 2006/2007 and 2007 surveys. The upward and downward diapycnal velocities yield the following net injection rates into the layer of 26.60–26.68 σ_θ: 1.2×10^{-3} m s^{-1} in 2007 and 8×10^{-4} m s^{-1} in 2006/2007. According to an analytical model of the western subarctic gyre of the North Pacific [*Tatebe and Yasuda*, 2004], the net southward volume transport of intermediate water into the subtropical gyre is determined by the diapycnal volume transport into the intermediate layer, which is largely expected to occur in and around the Sea of Okhotsk.

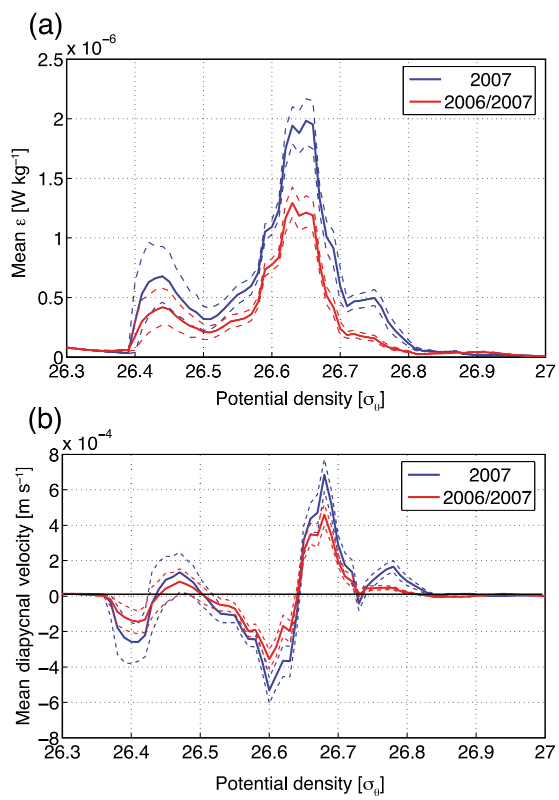

Figure 4. (a) Mean turbulent energy dissipation rate ε [W kg^{-1}] and (b) diapycnal velocity [m s^{-1}] with respect to potential density [σ_θ]. Thin dashed lines indicate 95% confidence intervals calculated by the bootstrap method.

[16] Because the strong mixing observed in the mid-water column in the Urup Strait was apparently related to large-amplitude internal waves, which were possibly intensified by the hydraulically controlled strong flow, it is suggested that similar processes occur in other shallow passages of the Kuril Straits. Considering the distribution of energy dissipation rates reported in a numerical tidal experiment by *Tanaka et al.* [2007], which well reproduced tidal elevations in the Sea of Okhotsk, we now evaluate the diapycnal volume transport in the entire Kuril Strait region. Because deeper peaks of ε are expected in deeper straits (e.g., the Bussol' Strait), which may cancel the upward volume transport across 26.70 σ_θ indicated in the Urup Strait, the present evaluation is made only for downward transport across 26.60 σ_θ. The results presented by *Tanaka et al.* [2007] suggest that the net energy dissipation rate due to the generation of internal waves from the K_1 barotropic tide integrated over the Kuril Strait region is 16 GW. Around the Urup Strait, the energy dissipation rate per unit area is 0.5–2 W m^{-2} (Y. Tanaka, personal communication, 2010). Assuming that vertical mixing in shallow straits (sill depth < 500 m, as is the case for 28% of the Kuril Straits along the line shown in Figure 1c) occurs similarly to that observed in the Urup Strait, we obtain a rough estimate of the mean downward volume transport across 26.60 σ_θ from the mean downward velocity of 4×10^{-4} m s^{-1}, yielding a value of (4×10^{-4} m s^{-1}) × (16 GW)/(0.5–2 W m^{-2}) × 28% = 0.9–3.6 Sv. This result is comparable to the net transport of 3.4 Sv from the Sea of Okhotsk estimated from observations [*Yasuda et al.*, 2002], and is greater than the formation rate of intermediate water by ventilation in the northwestern shelf region (0.2–0.67 Sv) [*Martin et al.*, 1998; *Itoh et al.*, 2003]. Although upward volume transport is not evaluated because of a lack of observation data for deeper straits, it is expected to have a positive effect on thickening of the intermediate layer, if a wider density range is considered.

[17] The above scenario is different from that proposed by *Tanaka et al.* [2010], who suggested that vertical mixing around the Kuril Straits has a relatively minor effect on the formation of NPIW. One possible cause of this discrepancy is the vertical profile of strong mixing; in contrast to the model employed by *Tanaka et al.* [2010], the strong mixing observed in the present study was not necessarily confined near the bottom but occurred within the water column at around 26.6–26.7 σ_θ, which directly thicken this layer.

[18] **Acknowledgments.** The authors thank the captain, officers, and crew of the R/V *Professor Khromov* and all onboard scientists for their help with observations and onboard analyses. We also thank Y. Tanaka for providing detailed results of his numerical experiments. This work was supported by the Ministry of Education, Science, Sports and Culture of Japan via a Grant-in-Aid for Scientific Research (S) (KAKENHI, 20221002).

[19] The Editor thanks one anonymous reviewer for assistance in evaluating this paper.

References

Itoh, M., K. I. Ohshima, and M. Wakatsuchi (2003), Distribution and formation of Okhotsk Sea intermediate water: an analysis of isopycnal climatological data, *J. Geophys. Res.*, *108*(C8), 3258, doi:10.1029/2002JC001590.

Itoh, S., I. Yasuda, T. Nakatsuka, J. Nishioka, and Y. N. Volkov (2010), Fine- and microstructure observations in the Urup Strait, Kuril Islands, during August of 2006, *J. Geophys. Res.*, *115*, C08004, doi:10.1029/2009JC005629.

Katsumata, K., K. I. Ohshima, T. Kono, M. Itoh, I. Yasuda, Y. N. Volkov, and M. Wakatsuchi (2004), Water exchange and tidal currents through the Bussol' Strait revealed by direct current measurements, *J. Geophys. Res.*, *109*, C09S06, doi:10.1029/2003JC001864.

Ledwell, J. R., A. J. Watson, and C. S. Law (1993), Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment, *Nature*, *364*, 701–703, doi:10.1038/364701a0.

McDougall, T. J. (1984), The relative roles of diapycnal and isopycnal mixing on subsurface water mass conversion, *J. Phys. Oceanogr.*, *14*, 1577–1589, doi:10.1175/1520-0485(1984)014<1577:TRRODA>2.0.CO;2.

Nakamura, T., and T. Awaji (2004), Tidally induced diapycnal mixing in the Kuril Straits and its role in water transformation and transport: A three-dimensional nonhydrostatic model experiment, *J. Geophys. Res.*, *109*, C09S07, doi:10.1029/2003JC001850.

Nakamura, T., T. Toyoda, Y. Ishikawa, and T. Awaji (2006), Effects of tidal mixing at the Kuril Straits on North Pacific ventilation: Adjustment of the intermediate layer revealed from numerical experiments, *J. Geophys. Res.*, *111*, C04003, doi:10.1029/2005JC003142.

Osborn, T. R. (1980), Estimates of the local rate of vertical diffusion from dissipation measurements, *J. Phys. Oceanogr.*, *10*, 83–89, doi:10.1175/1520-0485(1980)010<0083:EOTLRO>2.0.CO;2.

Reid, J. L., Jr. (1965), *Intermediate Waters of the Pacific Ocean*, 85 pp., Johns Hopkins Univ. Press, Baltimore, Md.

Sarmiento, J. L., N. Gruber, M. A. Brzezinski, and J. P. Dunne (2004), High-latitude controls of thermocline nutrients and low latitude biological productivity, *Nature*, *427*, 56–60, doi:10.1038/nature02127.

Sverdrup, H., M. W. Johnson, and R. H. Fleming (1942), *The Oceans, Their Physics, Chemistry, and Biology*, 1087 pp., Prentice Hall, Englewood Cliffs, N. J.

Talley, L. D. (1991), An Okhotsk Sea-water anomaly—Implications for ventilation in the North Pacific, *Deep Sea Res., Part A*, *38*, S171–S190.

Tanaka, Y., T. Hibiya, and Y. Niwa (2007), Estimates of tidal energy dissipation and diapycnal diffusivity in the Kuril Straits using TOPEX/POSEIDON altimeter data, *J. Geophys. Res.*, *112*, C10021, doi:10.1029/2007JC004172.

Tanaka, Y., T. Hibiya, and Y. Niwa (2010), Assessment of the effect of tidal mixing in the Kuril Straits on the formation of the North Pacific Intermediate Water, *J. Phys. Oceanogr.*, *40*, 2569–2574, doi:10.1175/2010JPO4506.1.

Tatebe, H., and I. Yasuda (2004), Oyashio southward intrusion and cross-gyre transport related to diapycnal upwelling in the Okhotsk Sea, *J. Phys. Oceanogr.*, *34*, 2327–2341, doi:10.1175/1520-0485(2004)034<2327:OSIACT>2.0.CO;2.

Tsunogai, S., T. Ono, and S. Watanabe (1993), Increase in total carbonate in the western North Pacific water and hypothesis on the missing sink of anthropogenic carbon, *J. Oceanogr.*, *49*, 305–315, doi:10.1007/BF02269568.

Yamamoto-Kawai, M., S. Watanabe, S. Tsunogai, and M. Wakatsuchi (2004), Chlorofluorocarbons in the Sea of Okhotsk: Ventilation of the intermediate water, *J. Geophys. Res.*, *109*, C09S11, doi:10.1029/2003JC001919.

Yasuda, I. (1997), The origin of the North Pacific Intermediate Water, *J. Geophys. Res.*, *102*, 893–909, doi:10.1029/96JC02938.

Yasuda, I., S. Kouketsu, K. Katsumata, M. Ohiwa, Y. Kawasaki, and A. Kusaka (2002), Influence of Okhotsk Sea Intermediate Water on the Oyashio and North Pacific Intermediate Water, *J. Geophys. Res.*, *107*(C12), 3237, doi:10.1029/2001JC001037.

S. Itoh, H. Kaneko, S. Osafune, M. Yagi, and I. Yasuda, Atmosphere and Ocean Research Institute, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8564, Japan. (itohsach@aori.u-tokyo.ac.jp)

T. Nakatsuka, Graduate School of Environmental Studies, Nagoya University, D2-1(510), Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan.

J. Nishioka, Institute of Low Temperature Science, Hokkaido University, N19W8 Sapporo, Hokkaido 060-0819, Japan.

Y. N. Volkov, Far Eastern Regional Hydrometeorological Research Institute 24, Fontannaya St., Vladivostok 690600, Russia.