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Effects of temporal variation in tide-induced vertical mixing in the Kuril Straits on the thermohaline circulation originating in the Okhotsk Sea

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ABSTRACT

Tidally induced vertical mixing is important for thermohaline circulation. Previous estimations of tidal mixing have aimed to obtain time-averaged values, and ocean general circulation models (OGCMs) typically parameterize such mixing using a temporally constant strength. However, tidal mixing is known to vary temporally during tidal or spring–neap cycles. Here, we investigate the effects of temporal change in tidally induced vertical diffusivity (κ_t) in the Kuril Straits using an OGCM. The results demonstrate that variations of vertical mixing on diurnal, 2-week, and 1/2-year timescales induce significant differences in the net effect of mixing and, therefore, in the thermohaline circulation originating in the Okhotsk Sea. For diurnal and 2-week variations, the strength of the tidal mixing effect depends on (1) the period and length of the duration over which κ_t is larger than the temporal average and (2) the amplitude of the temporal variation of κ_t, even if the time-averaged values are the same. This is explained by the relative importance of two states. In a quasi-equilibrium state, a larger κ_t results in weaker stratification and vice versa, and thus the net tidal mixing effect is weaker when κ_t is variable than when it remains constant. Conversely, in an adjustment stage just after an increase in κ_t, a larger κ_t acts on stronger stratification and vice versa, resulting in a stronger mixing effect. For a 1/2-year variation, the strength of the tidal mixing effect also depends on the phase relationship with seasonal variation in stratification. These results imply the necessity of considering temporal change when estimating tidal mixing from observations, specifying it in OGCMs, and understanding its effects.

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Introduction

Vertical mixing caused by tides (hereafter, tidal mixing) is a fundamental forcing of thermohaline circulation. Previous estimations of such vertical diffusion have typically aimed to obtain time-averaged values, and parameterizations of tidal mixing in simulations of thermohaline circulation have assumed that its strength is temporally constant (e.g., Munk and Wunsch, 1998; St. Laurent et al., 2002). However, in reality, tidal mixing varies temporally as tidal flow oscillates or modulates.

Temporal variations in tidal mixing cause temporal variability in circulation and water masses, as has been demonstrated for the cases of fortnightly modulation (e.g., Masson and Cummins, 2000) and the 18.6-year lunar nodal oscillation (e.g., Hasumi et al., 2008; Osafune and Yasuda, 2012; Tanaka et al., 2012). If such temporal variations in tidal mixing affected only temporal variability, their net effect on thermohaline circulation could be evaluated based on time-averaged values. However, the following simple argument suggests that the mean state is also affected.

To show the possible effects of temporal variation in tidal mixing on the mean state, we consider the vertical diffusion term (F_z) in an advection–diffusion equation of the potential density (ρ):

$$F_z = \frac{\partial}{\partial z}\left(\kappa_z \frac{\partial \rho}{\partial z}\right), \tag{1}$$

where κ_z is a vertical diffusivity coefficient. If κ_z is temporally constant, the time average of F_z is as follows:

$$\overline{F_z} = \frac{\partial}{\partial z}\left(\overline{\kappa_z} \frac{\partial \bar{\rho}}{\partial z}\right), \tag{2}$$

whereas, if κ_z varies temporally, this expression becomes

$$\overline{F_z} = \frac{\partial}{\partial z}\left(\overline{\kappa_z} \frac{\partial \bar{\rho}}{\partial z}\right) + \frac{\partial}{\partial z}\left(\overline{\kappa_z' \frac{\partial \rho'}{\partial z}}\right). \tag{3}$$

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Here, $\bar{\phi}$ and ϕ' denote the time average of ϕ and the deviation from this average, respectively. These equations indicate that the temporal variation in κ_z affects the mean state through the second term on the right-hand side of Eq. (3).

The above argument also holds for tidal mixing in the Kuril Straits, which connect the Okhotsk Sea and the North Pacific (Fig. 1). In the Kuril Straits, diurnal tidal flow is dominant and is sufficiently swift that it induces vigorous vertical mixing through the generation and breaking of internal lee waves and vertical shear associated with topographically trapped waves (Nakamura et al., 2000; Nakamura and Awaji, 2004; Itoh et al., 2010; Yagi and Yasuda, 2012). This strong tidal mixing affects the thermohaline circulation originating from the Okhotsk Sea as follows. Dense shelf water (DSW) is produced over the northwestern shelf of the Okhotsk Sea due to sea ice formation and spreads to the intermediate layer of the Okhotsk Sea and the North Pacific (e.g., Kitani, 1973; Alfultis and Martin, 1987; Talley, 1991; Yasuda, 1997; Gladyshev et al., 2003; Shcherbina et al., 2003; Fukamachi et al., 2004). Tidal mixing in the Kuril Straits increases surface layer salinity by causing salt transport from the saline subsurface layer to the fresher surface layer. The resulting surface water, with increased salinity, is in turn conveyed to the northwestern shelf and enhances DSW formation (Nakamura et al., 2004, 2006a; Matsuda et al., 2009; Sasajima et al., 2010), leading to the cooling/freshening of the intermediate layer in the Okhotsk Sea and the North Pacific (Nakamura et al., 2006b; Kawasaki and Hasumi, 2010).

Tidal mixing in the Kuril Straits also affects the circulations of materials such as chlorofluorocarbons, nutrients, and iron through the enhancement of DSW formation and vertical transport in the Straits (Wong et al., 1998; Yamamoto–Kawai et al., 2004; Sarmiento et al., 2004; Nishioka et al., 2007; Misumi et al., 2011; Uchimoto et al., 2011, 2014). Furthermore, the modulation of tidal mixing caused by the 18.6-year nodal cycle is considered to be a cause of bidecadal variation in apparent oxygen utilization, phosphate concentration, and the thickness of the intermediate layer (e.g., Ono et al., 2001; Osafune and Yasuda, 2006).

In this way, tidal mixing in the Kuril Straits has a considerable impact on thermohaline and material circulations in the Okhotsk Sea and the North Pacific. However, vertical mixing in the Kuril Straits changes rapidly and extensively during a single tidal cycle. The estimated κ_z increases from O (10^{-4}) to O (10^{-1}) $m^2\,s^{-1}$ or more when breaking events of large-amplitude internal waves or strong shear events are caused primarily by diurnal tides (Nakamura et al., 2000; Nakamura and Awaji, 2004; Itoh et al., 2010; Yagi and Yasuda, 2012).

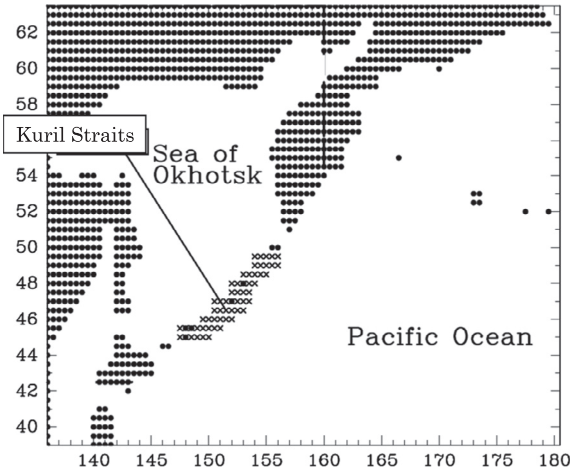

Fig. 1. Model region. Solid circles indicate land grids and crosses denote grids for which the tidal mixing was added.

In the present study, we investigated the effects of temporal variations in κ_z, focusing on the role of tidal mixing in the Kuril Straits in the thermohaline circulation. To achieve this, we conducted numerical experiments incorporating temporal variations in κ_t caused by diurnal tidal oscillation, the spring–neap cycle of a nearly 2-week period, and the modulation of a nearly 1/2-year period using an ocean general circulation model (OGCM). Although we adopted potential density in the above argument for the net effect of temporal variations in κ_t, other tracers can be utilized in a similar manner to show the net effect on material circulation; however, we did not investigate such effects on other tracers fully in the present study.

Section 'Model and experimental setup' summarizes the numerical model and experimental setup. The results are described for temporal variations of diurnal and 2-week cycles in section 'Results for diurnal and 2-week variations', and the underlying mechanism is proposed in section 'Mechanism'. Section '1/2-year variation and seasonal change' presents the combined effects of the 1/2-year variation and seasonal change in density stratification. The conclusions are summarized and discussed in section 'Summary and discussion'.

Model and experimental setup

Model and basic settings

The OGCM and model settings used in the spinup and control experiment were the same as those of Uchimoto et al. (2011). Their model simulated reasonably well the thermohaline circulation and associated distribution of chlorofluorocarbons. The OGCM adopted was the Center for Climate System Research Ocean Component Model (COCO) version 3.4 with a sea ice model (Hasumi, 2006). For tracer advection, a uniform third-order polynomial interpolation algorithm (Leonard et al., 1993) was used along with isopycnal and thickness diffusion coefficients of 100 and 300 $m^2\,s^{-1}$, respectively (Cox, 1987; Gent et al., 1995; Griffies, 1998). The turbulence closure scheme of Noh and Kim (1999) was used with background vertical viscosity and diffusion coefficients of 10^{-4} and 10^{-5} $m^2\,s^{-1}$, respectively. The partial step formulation was adopted for the bottom topography (Adcroft et al., 1997). The sea ice model adopted a two-category thickness representation with a zero-layer thermodynamic model (Semtner, 1976) and a dynamic component with an elastic–viscous-plastic ice rheology (Hunke and Dukowicz, 1997).

The model domain spanned the northwestern North Pacific, from 136°E to 179.5°W and from 39°N to 63.5°N (Fig. 1). The horizontal resolution was 0.5° in both the zonal and meridional directions. There were 51 levels in the vertical direction, with level thickness increasing from 1 m at the sea surface to 1000 m at the deepest level.

The model was forced at the sea surface by daily climatological atmospheric data describing heat, freshwater, and momentum fluxes based on the Ocean Model Intercomparison Project (OMIP) dataset (Röske, 2001), but seasonal variation was added to the Amur River runoff (Uchimoto et al., 2011). The sea surface salinity (SSS) was restored to the monthly climatology of the World Ocean Atlas 2001 (WOA01 Conkright et al., 2002) with 60 days of restoring time. In fact, the effective timescale is longer than 3 years if the salinity budget of the surface mixed layer (which extends to a depth of approximately 20 m) is considered, because the thickness of the model top layer is 1 m. The SSS restoration was not applied in the northern half of the Okhotsk Sea ($\geqslant$52°N) in wintertime (from December to April), because the wintertime SSS of WOA01

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