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Assessment of fine-scale parameterization of deep ocean mixing using a new microstructure profiler

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Abstract : Although global mapping of deep ocean mixing is essential for accurate modeling of global overturning circulation, each direct measurement using a microstructure profiler takes at least several hours so that it is difficult to extend it to the whole basin. To overcome this difficulty, some kind of empirical formula which can predict diapycnal diffusivity in terms of fine-scale parameters is desirable. In the present study, we carried out direct measurements of dissipation rates in the deep ocean at four locations (38°N, 31°N, 28°N, and 22.4°N) on the ship track from Dutch Harbor (the Aleutian Islands) to Honolulu using TurboMAP-D1 (the first domestic microstructure profiler for the deep ocean) to examine the validity of GREGG's empirical formula (GREGG, 1989), one of the most widely used fine-scale parameterization. The dissipation rates directly measured by TurboMAP-D1 were compared with those estimated by incorporating XCP data into GREGG's empirical formula. We find that GREGG's empirical formula tends to overestimate the dissipation rates except at 38°N, although the depth profiles of the dissipation rates are relatively well reproduced. It turns out that the empirical formula proposed by HENYEY *et al.* (1986) which takes into account latitudinal dependence provides much better fit to the directly measured dissipation rates. This warns us that dissipation rates in the deep ocean predicted using GREGG's empirical formula might exhibit spurious latitudinal distribution.

Keywords : *energy dissipation rates, deep ocean mixing, microstructure profiler, fine-scale parameterization*

1. Introduction

The climate is formed through the interactions among the atmosphere, oceans, and land surfaces. One cycle of global ocean overturning circulation is about 1500 years. To predict the long-term climate change, it is absolutely necessary to construct an accurate global overturning circulation model.

In the equilibrium state of the interior ocean, the structure of internal wave field whose vertical scales range from 10 km to 10 m is known to be well described by the GARRETT-MUNK model spectra (GARRETT and MUNK, 1975; CAIRNS and WILLIAMS, 1976). The energy supplied from winds and tides at large scales cascades down to small scales to induce deep ocean mixing. Turbulent mixing in the lower thermocline, in particular, plays an important role in transferring heat from the sea surface down to the deep ocean, reducing the density of cold deep waters and hence causing upwelling of them. Although global mapping of deep ocean mixing is essential for accurate modeling of overturning circulation, each direct measurement using a microstructure profiler takes, at least, several hours so that it is difficult to extend it to the whole basin. To overcome this difficulty, some kind of empirical formula is desired to predict diapycnal diffusivity in terms of fine-scale parameters which are much easier

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to observe.

Turbulent mixing in the deep ocean is thought to be strongly linked with the intensity of fine-scale vertical shear as well as density stratification. Since the distribution of fine-scale vertical shear and density stratification can be measured over a large area even within a limited available ship time using expendable current profilers (XCPs) and expendable conductivity, temperature, and depth profilers (XCTDs), global mapping of diapycnal diffusivity becomes possible so long as the reliable empirical formula is available.

Among the existing parameterization, "GREGG's empirical formula" (GREGG, 1989) is most widely used. GREGG's empirical formula is originally based on the results of eikonal calculations by HENYEY *et al.* (1986) given by

$$\langle \epsilon \rangle = F(f, N)\left\langle \frac{N^2}{N_0^2} \right\rangle \left\langle \frac{S_{10}^4}{S_{GM}^4} \right\rangle \ [\mathrm{Wkg}^{-1}] \quad (1)$$

with $F(f, N) = 8.1\times 10^6 f N_0^2 \cosh^{-1}\left(\frac{N}{f}\right)$

where $\langle \ \rangle$ denotes the average over large spatial and temporal scales; ϵ is the dissipation rates of turbulent kinetic energy; f is the Coriolis parameter; N_0=3 cycles per hour (cph) is a reference buoyancy frequency; S_{10} is the 10 m scale vertical shear; S_{GM} is the corresponding vertical shear in the GARRETT and MUNK internal wave field (GARRETT and MUNK, 1975; CAIRNS and WILLIAMS, 1976). It should be noted that, because of the f dependence of the relationship (1), the predicted energy dissipation rate diminishes as the latitude decreases (see Figure 1 of GREGG *et al.*, 2003).

GREGG (1989) carried out simultaneous measurements of turbulent energy dissipation rates (ϵ) and 10 m-scale vertical shear (S_{10}) at six locations between 11.5° N and 42° N off both coasts of the continental United States. Although these microstructure measurements were limited to, at most, the top 950 m, insufficient to assess the parameterization of deep ocean mixing, he found no appreciable latitudinal dependence of ϵ and showed that the best fit to the observed vertical profile of ϵ was attained by reducing the relationship (1) to

Table 1 : The locations of microstructure measurements.

		Latitude	Longitude
2003	St.1	38.00N	165.00W
August	St.2	31.00N	162.84W
Hawaii	St.3	28.00N	160.59W
	St.4	22.40N	158.45W

$$\langle \epsilon \rangle = 2\times F(f_{34^\circ}, N_0)\left\langle \frac{N^2}{N_0^2} \right\rangle \left\langle \frac{S_{10}^4}{S_{GM}^4} \right\rangle [\mathrm{Wkg}^{-1}] \quad (2)$$

In the present study, based on the microstructure data from the surface down to well below the thermocline obtained using the first domestic microstructure profiler for the deep ocean, we examine the validity of the GREGG's empirical formula (2). First, we carried out direct measurements of dissipation rates down to a depth of ~1600 m on the ship track from Dutch Harbor (the Aleutian Islands) to Honolulu. Then, the directly measured dissipation rates were compared with the dissipation rates estimated by incorporating XCP data into GREGG's empirical formula.

2. Observations

The field experiments were carried out at four locations listed in Table 1 on the ship track of Oshoro-Maru, the training vessel of the Faculty of Fisheries of Hokkaido University in August 2003 (Figure 1). During the cruise, we measured energy dissipation rates using TurboMAP-D1, buoyancy frequency using XCTDs, and vertical shear using XCPs. During each microstructure measurement, we deployed three sets of XCPs and XCTDs.

The instrument package called TurboMAP-D1 (about 2 m long with diameter 0.3 m; see Figure 2) is a free-rising, internally recording, first domestic microstructure profiler for the deep ocean with a shear probe, an FP07 (temperature sensor), a pressure sensor, and an accelerometer which can measure turbulent parameters ($\frac{\partial u}{\partial z}$ and $\frac{\partial T}{\partial z}$) as well as hydrographic parameters (temperature and depth). The accuracy of the shear probe is ±5% with a resolution of $10^{-4}\ s^{-1}$, while the accuracy of FP07 is 0.01℃ with a resolution of 10^{-4}℃. TurboMAP-

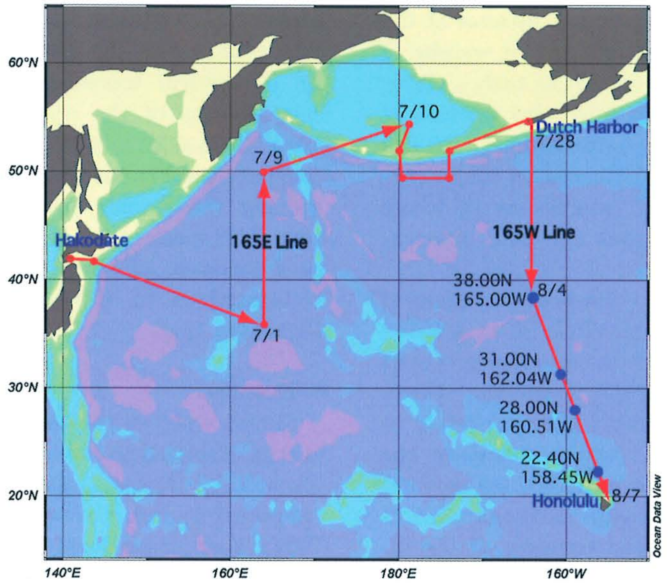

Figure 1 : The ship track of Oshoro-Maru and the locations of field experiments.

Figure 2 : A view of TurboMAP-D1.

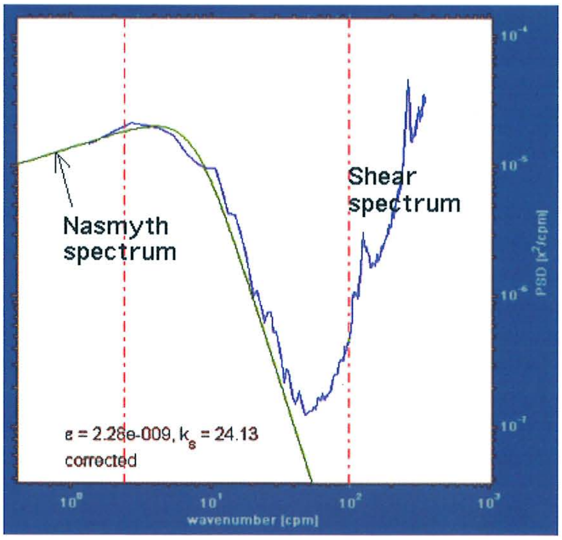

Figure 3 : The Nasmyth universal spectrum (green) corresponding to ϵ = 2.28×10^{-9} Wkg^{-1} fitted to the observed shear spectrum (blue) for the vertical warenumber band shown by the two red dash-dot lines.

D1 weighs 73 kg in the air, but because of the syntactic foam on the main body, it weighs −1 kg in the water. To minimize the body's vibration thereby permitting low-noise turbulence measurements, a brush is attached near the end of the instrument. Also attached on the instrument is a pinger which enables us to locate TurboMAP-D1 throughout the field observation.

First, TurboMAP-D1 is lowered at a speed of 1.5 ms^{-1} using a winch. When it is lowered down to a depth of ∼1600 m, the releaser works to separate TurboMAP-D1 from the winch. Then, TurboMAP-D1 starts uprising freely at a speed of ∼0.4 ms^{-1} while recording the microscale vertical shear up to the sea surface. Each microstructure measurement takes about 120 minutes including the recovery of the instrument. Using the microscale shear data, we can calculate the local energy dissipation rates given by

$$\epsilon = \frac{15}{2}\nu\overline{\left(\frac{\partial u}{\partial z}\right)^2} \tag{3}$$

where ν is the kinetic viscosity (OSBORN, 1980).

The raw data from TurboMAP-D1 is lowpass filtered. Then, the vertical shear spectrum is calculated using FFT. The FFT length is 512 points and 100 points are overlapped. Then, to give one spectrum for the various depth range, the spectrum for all the segments are averaged. The uncontaminated wavenumber range is determined excluding vertical wavenumbers$>10^2$ cpm where the instrumental noise is enhanced and several spikes caused by the instrument's pressure case occur. By fitting Nasmyth spectrum to the observed vertical shear spectrum (OAKEY, 1982), energy dissipation rate is evaluated (see Figure 3).

The XCP, on the other hand, is a free-fall instrument, which can measure horizontal velocity relative to a depth-independent constant from the sea surface down to a depth of ∼1600 m by sensing the electric field induced by seawater's horizontal movement in the earth's magnetic field.

Using XCP data, the vertical wavenumber Froude spectra calculated for each depth bin are compared to the corresponding GM76 model (GARRETT and MUNK, 1975; CAIRNS and WILLIAMS, 1976). The spectrum is not meaningful at vertical wavenumbers more than 0.04 cpm because of the uncorrelated instrument noise (NAGASAWA *et al.*, 2002). Therefore, we calculate the Froude number variance by integrating the Froude spectrum up to $k_z=0.04$ cpm. This means that, instead of S_{10}, S_{25} is used as a measure of shear level at high vertical wavenumbers in GREGG's empirical formula (equation (2)).

3. Results

Figure 4 shows the comparison between the energy dissipation rates measured directly by TurboMAP-D1 ($\epsilon_{\mathrm{Turbo}}$) and the dissipation rates estimated by incorporating the XCP data into GREGG's empirical formula ($\epsilon_{\mathrm{Gregg}}$). We can see that GREGG's empirical formula tends to overestimate the dissipation rates except at 38° N, although the depth profiles of the dissipation rates are relatively well reproduced. This reminds us the fact that, although GREGG's empirical formula is essentially based on HENYEY's eikonal calculations (HENYEY *et al.* 1986), it does not take into account the dependence on latitudes.

Figure 5 shows the comparison between $\epsilon_{\mathrm{Turbo}}$ and the dissipation rates estimated by incorporating the XCP data into the HENYEY *et al.*'s empirical formula (equation (1)) (ϵ_{HWF}). We can see that, compared to $\epsilon_{\mathrm{Gregg}}$, ϵ_{HWF} shows much better agreement with $\epsilon_{\mathrm{Turbo}}$. Table 2 shows vertically averaged ratio of $\epsilon_{\mathrm{Gregg}}$ to $\epsilon_{\mathrm{Turbo}}$ and that of ϵ_{HWF} to $\epsilon_{\mathrm{Turbo}}$. Obviously, $\epsilon_{\mathrm{Gregg}}$ is overestimated at all the stations, whereas ϵ_{HWF} seems to be rather underestimated, ranging from $0.6\times\epsilon_{\mathrm{Turbo}}$ to $1.1\times\epsilon_{\mathrm{Turbo}}$.

4. Summary

In the present study, we have examined the validity of GREGG's empirical formula (GREGG, 1989), one of the most widely used fine-scale parameterization to predict energy dissipation rates in the deep ocean. First, we have carried out direct measurements of dissipation rates in the deep ocean at four locations (38° N, 31° N, 28° N, and 22.4° N) on the ship track from Dutch Harbor (the Aleutian Islands) to Honolulu using TurboMAP-D1, the first

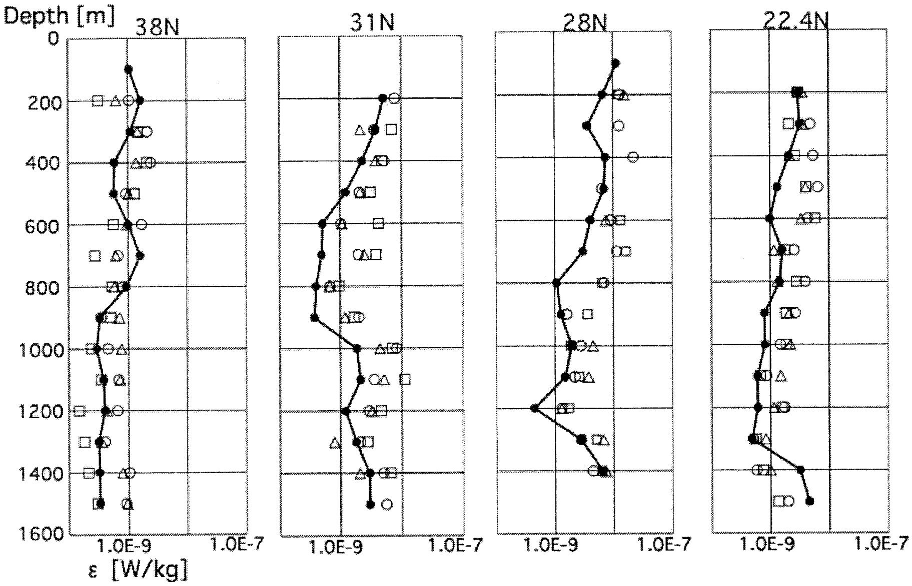

Figure 4 : Depth profile of energy dissipation rate ϵ at each location. The solid line shows $\epsilon_{\mathrm{Turbo}}$. Superimposed by circles, triangles and squares are $\epsilon_{\mathrm{Gregg}}$ calculated using the data from the first, second and third XCP deployment, respectively.

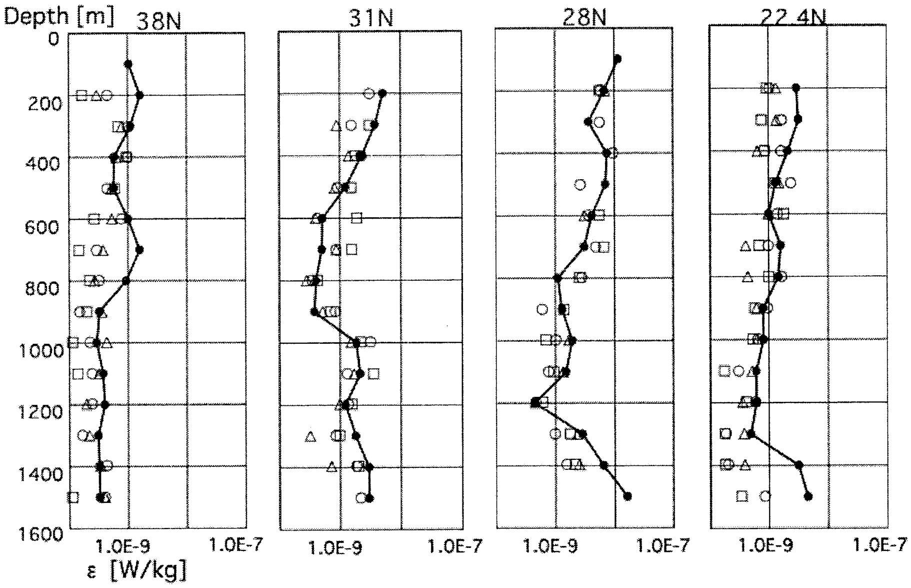

Figure 5 : As in Figure 4 but for the comparison between $\epsilon_{\mathrm{Turbo}}$ and ϵ_{IHWF}.

domestic microstructure profiler which can reach down to a depth of ~1600 m. The dissipation rates directly measured by TurboMAP-D1 have been compared with the dissipation rates estimated by incorporating XCP data into GREGG's empirical formula.

We have found that GREGG's empirical formula tends to overestimate the energy dissipation rates except at 38° N, although the depth profiles of the dissipation rates are relatively

Table 2 : Comparison between the vertically averaged ratio of $\epsilon_{\mathrm{Gregg}}$ to $\epsilon_{\mathrm{Turbo}}$ and that of ϵ_{HWF} to $\epsilon_{\mathrm{Turbo}}$.

Latitude[°N]	$\epsilon_{Gregg}/\epsilon_{Turbo}$	$\epsilon_{HWF}/\epsilon_{Turbo}$
38	1.46	0.66
31	2.73	1.07
28	3.07	0.97
22.4	2.52	0.64

well reproduced. Much better agreement with the directly measured values has been attained using HENYEY *et al.*'s empirical formula which takes into account latitudinal dependence of dissipation rates in the deep ocean. This warns us that dissipation rates in the deep ocean predicted using GREGG's empirical formula might exhibit spurious latitudinal distribution.

The result of the present study is offered as an important contribution toward the global mapping of deep ocean mixing which is indispensable for accurate modeling of global thermohaline circulation.

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