Distribution of Wind-Induced Turbulent Mixing in the Ocean

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The pattern and magnitude of the global ocean overturning circulation is believed to be strongly controlled by the distribution of diapycnal diffusivity below 1000m depth. Although wind stress fluctuation is a candidate for major energy sources of diapycnal mixing processes, the global distribution of wind-induced diapycnal diffusivity is still uncertain. It has been believed that internal waves generated by wind stress fluctuations at middle and high latitudes propagate equatorward until their frequency is twice the local inertial frequency and break down via parametric subharmonic instabilities causing diapycnal mixing. In order to check the proposed scenario, using a vertically two-dimensional primitive equation model, we examine the spatial distribution of "mixing hotspots" caused by wind stress fluctuations. It is shown that most of the wind-induced energy fed into the ocean interior is dissipated within the top 1000m depth in the wind-forced area and the energy dissipation rate at low latitudes is very small. Consequently, the energy supplied to diapycnal mixing processes below 1000m depth falls short of the value required to sustain the global ocean overturning circulation.

Keywords: wind stress fluctuations, energy dissipation rates, near-inertial waves, internal waves

1. Introduction

Diapycnal mixing processes in the thermocline are thought to determine the strength and pattern of the global ocean overturning circulation that controls the climate over much of the Earth. This is because a downward mixing of heat across the thermocline at low and middle latitudes decreases the density of cold deep waters allowing them to upwell into the upper ocean.

Munk and Wunsch (1998) estimated that diapycnal diffusivity of the order of 10^{-4} m^{2}s^{-1} was required from 1000m down to 4000m in depth to maintain the abyssal stratification. In order to reproduce diapycnal diffusivity ~10^{-4} m^{2}s^{-1} below 1000m depth, the required power is ~2.1TW (1TW = 10^{12} TW) (Munk and Wunsch, 1998). This energy flux is believed to be supplied from tide-topography interactions as well as wind stress fluctuations. Based on astronomical measurements, the global energy flux from tide-topography interactions is estimated to be ~0.9TW (e.g., Munk and Wunsch, 1998). On the other hand, using the damped slab model, Watanabe and Hibiya (2002) have clarified that the wind-induced annual mean global energy flux into the surface mixed layer becomes ~0.7TW. The wind-induced energy in the surface mixed layer then propagates downward into the deeper ocean, but the global distribution of strong diapycnal mixing (mixing hotspots) caused by wind stress fluctuations is still uncertain. Previous theoretical studies (e.g., Gill, 1984) suggested that wind-induced near-inertial energy was fed into the low vertical mode internal waves, which then propagated equatorward and became susceptible to wave breaking via parametric subharmonic instabilities (PSI) (McComas and Müller, 1981).

In this study, using a vertically two-dimensional primitive equation model, we examine the spatial distribution of mixing hotspots caused by wind stress fluctuations in the North Pacific. Incorporating the numerically predicted fine-scale vertical shear of horizontal velocity into the empirical relationship proposed by Gregg (1989), we clarify the latitudinal and depth dependence of wind-induced mixing hotspots.

2. Model description

In this study, we employ a vertically two-dimensional primitive equation model in a meridional cross section assuming that variables are zonally independent ($\partial / \partial x = 0$). Calculations are carried out for the model domain of 5632km in width (5°N–55°N) and 4096m in depth. Horizontal and vertical resolutions are 500m and 4m, respectively (11264 × 1024 grid points). Horizontal eddy viscosity A_h and horizontal eddy diffusivity K_h are both assumed to be 10^{-4}m^{2}s^{-1}, whereas vertical eddy viscosity A_v and vertical eddy diffusivity K_v are determined following the Richardson number (R_i) formulation of Pacanowski and Philander (1981).

As an initial condition, randomly phased Garrett-Munk (GM) internal waves (Munk, 1981) are embedded. We apply slip boundary condition at the top and the bottom surface and obtain quasi-stationary internal wave field by calculating nonlinear interactions among GM background internal waves for 5 days.

We use the Global Objectively Analyzed Data compiled by the Japan Meteorological Agency. Wind stress components with timescales longer than 6 days are filtered out since low-frequency responses in the ocean are beyond the scope of the present study. The calculated wind stress data are linearly interpolated onto the model grid. When the data is used as wind forcing, a linear interpolation to each time step is also employed.

In the present study, we carry out numerical experiments for the meridional section along the longitude 160˚E for 100 days starting from December 1, 1991 (day 1).

3. Results and discussions

We first estimate the energy flux into the surface mixed layer. The thick line in Fig. 1 indicates the wind-induced energy flux into the surface mixed layer averaged over 80 days from day 21 at each latitude. We can see that large amount of energy is supplied poleward of 30˚N. The mean energy flux into the surface mixed layer integrated over 10˚N–50˚N reaches 3.89×10^5Wm^{-1}.

Next, we estimate the energy dissipation rate ε_{ML} in the surface mixed layer. The thin line in Fig. 1 is the energy dissipation rate integrated from the ocean surface down to the base of the surface mixed layer at each latitude. Integrating over 10˚N–50˚N, we can find that about 90% (3.63×10^5Wm^{-1}) of the wind-induced energy is dissipated in the surface mixed layer with the remaining 10% (2.6×10^4Wm^{-1}) propagating downward into the ocean interior.

Since most of the energy is carried by low vertical mode internal waves, we evaluate the equatorward energy flux accompanied by the propagation of the lowest two vertical mode internal waves with frequencies $f_{30} < \sigma < f_{50}$ (f_θ is the local inertial frequency at latitude θ). The equatorward energy flux at 25˚N averaged over 80 days from day 21 is 4×10^3Wm^{-1}, which is only about 15% of the downward energy flux into the ocean interior.

Based on the results from extensive microstructure measurements, Gregg (1989) found an empirical relationship between the energy dissipation rate ε_{IW} and the 10m scale vertical shear variance S^2_{10} such that

$$\varepsilon_{IW} = 7 \times 10^{-10} L(N, f_\theta)(N^2 / N^2_0)(S^2_{10} / S^2_{GM10})^2 \text{ [Wkg}^{-1}] \quad (1)$$

where

$$L(N, f_\theta) = f_\theta \cosh^{-1}(N/f_\theta) / f_{30} \cosh^{-1}(N_0 / f_{30}), \quad (2)$$

and S^2_{GM10} is the 10m scale vertical shear variance for the GM internal wave field. Since the vertical resolution of the numerical model is 4m, we replace (S^2_{10}/S^2_{GM10}) in Equation (1) by (S^2_{25}/S^2_{GM25}) which can be obtained by integrating the shear spectrum up to 0.04cpm (vertical wavelength 25 m). Fig. 2 shows the energy dissipation rate at day 100 averaged for each depth range at each latitude. At ~45˚N, the estimated energy dissipation rate reaches 1×10^{-7}Wkg^{-1} for a depth of 200–500m so that the corresponding diapycnal diffusivity, $K_v \simeq 0.2\,\varepsilon_{IW}/N^2$ (Osborn, 1980) reaches 10^{-3} m^{2}s^{-1}, much larger than the GM background level ~10^{-5} m^{2}s^{-1} (Gregg, 1989). At low latitudes, in contrast, the estimated energy dissipation rate is ~10^{-9}Wkg^{-1} and hence the corresponding diapycnal diffusivity remains at the GM background level throughout the ocean depth although PSI is expected to occur.

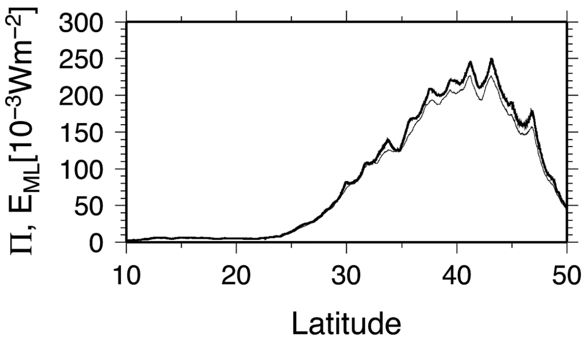

Fig. 1 The wind-induced energy flux into the surface mixed layer (thick line) and the energy dissipation rate integrated from the ocean surface down to the base of the surface mixed layer (thin line) averaged over 80 days from day 21 at each latitude along 160˚E.

At day 100, the energy dissipation rate integrated over the whole ocean interior along 160˚E becomes 2.2×10^4Wm^{-1}. Table 1 shows the ratio of energy dissipation rate for each range of latitude and depth to the total energy dissipation rate in the ocean interior. We can see that about 90% of the wind-induced energy supplied to the ocean interior is dissipated within the top 1100m depth in the wind-forced area (30˚N–50˚N). This contrasts to the scenario proposed in the previous studies that the wind-induced internal waves propagate equatorward until their frequency is twice the local inertial frequency and then break down via PSI causing diapycnal mixing.

4. Summary

Using a vertically two-dimensional primitive equation model assumed in a meridional section in the North Pacific, we have examined the spatial distribution of mixing hotspots caused by wind stress fluctuations. The numerical experiments have shown that large amount of energy is supplied poleward of 30˚N in response to the intermittent passage of the winter storms, but about 90% of the supplied energy is dissipated within the surface mixed layer. Furthermore, again about 90% of the energy penetrating down into the

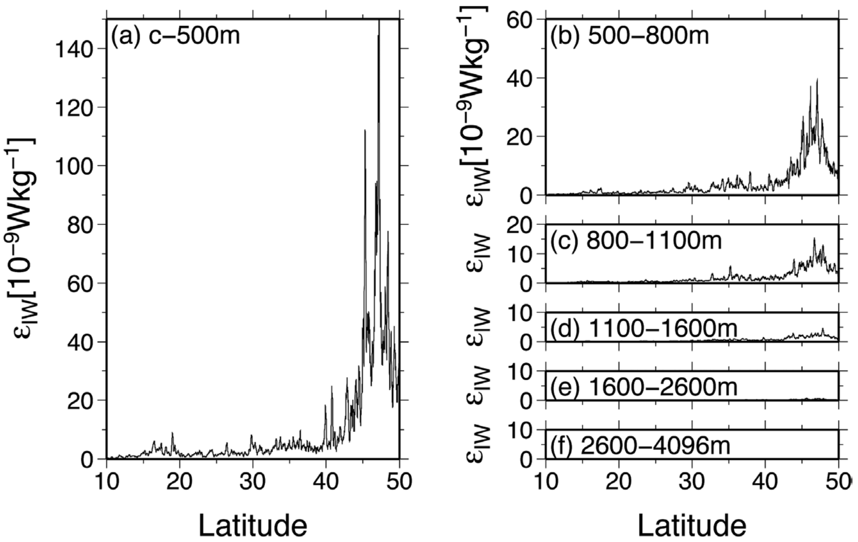

Fig. 2 The energy dissipation rate at day 100 averaged for a depth range of (a) *c*–500 m, (b) 500–800 m, (c) 800–1100 m, (d) 1100–1600 m, (e) 1600–2600 m, and (f) 2600–4096 m at each latitude along 160°E (mixed layer thickness *c* is 100 m, 150 m, and 200m for 10°N–20°N, 20°N–40°N, and 40°N–50°N, respectively).

Table 1 The ratio of energy dissipation rate for each range of latitude and depth to the total energy dissipation rate in the ocean interior ($2.2 \times 10^4 Wm^{-1}$) along 160°E (mixed layer thickness *c* is 100m, 150m, and 200m for 10°N–20°N, 20°N–40°N, and 40°N–50°N, respectively).

Depth[m]	10°N–20°N	20°N–30°N	30°N–40°N	40°N–50°N	10°N–50°N
c–500	3	4	7	43	57
500–800	1	2	4	17	24
800–1100	~0	1	3	7	11
1100–1600	~0	1	1	4	6
1600–2600	~0	~0	~0	2	2
2600–4096	~0	~0	~0	~0	~0
c–4096	4	8	15	73	100%

ocean interior is dissipated within the top 1000m depth in the wind-forced area. Although it has been believed that low vertical mode internal waves generated by wind stress fluctuations propagate equatorward and break down via parametric subharmonic instabilities causing diapycnal mixing, energy dissipation rate equatorward of 30°N remains at the GM background level and hence diapycnal diffusivity is $\sim 10^{-5}\ m^2s^{-1}$, much less than $\sim 10^{-3}\ m^2s^{-1}$ just below the surface mixed layer in the wind-forced area. Munk and Wunsch (1998) evaluated that energy flux as much as 2.1TW was required for diapycnal mixing processes below 1000m depth to maintain the abyssal stratification. Nevertheless, we have clarified here that the wind-induced energy flux penetrating deeper than 1000m is, at most, 0.1TW, much less than previously thought.

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大気擾乱によって海洋中に励起される乱流混合の空間分布

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深層海洋大循環は、北大西洋の北部で冷却されて沈み込んだ海水が、中・深層における乱流混合を通じて上層から浮力を得て徐々に湧昇することで形成されると考えられている。平均的な密度成層を維持するためには1000m以深でオーダー$10^{-4}m^2s^{-1}$の乱流拡散が必要とされる。乱流拡散過程に必要なエネルギーは大気擾乱や、海底地形と潮汐との相互作用によって生じる内部潮汐から供給されると考えられるが、このオーダーの乱流拡散をまかなうためには全球で約2.1TW (1TW = 10^{12}W) のエネルギーフラックスが必要となる。このうち、大気擾乱から海洋へ与えられるエネルギーフラックスは全球でおよそ0.7TWと見積もられているが、大気擾乱起源の乱流ホットスポットに関する考察はいままで十分にはなされていなかった。そこで、本研究では鉛直2次元モデルを用い、大気擾乱によって励起された内部波が形成する乱流ホットスポットの空間分布に関する考察を行った。

まず、大気擾乱によって海洋内部領域に供給されるエネルギーフラックスと低緯度方向へのエネルギーフラックスを定量的に見積もり、海洋内部領域に供給されたエネルギーフラックスのうち低緯度方向に伝播するのは、10%程度にすぎないことを示した。続いて、海洋内部領域でのエネルギー散逸率の分布を見積もった。主に高緯度域で励起された大気擾乱起源の内部波エネルギーは低緯度方向へ伝播しカスケードダウンを起こすことによって散逸すると考えられてきたが、供給された内部波エネルギーのおよそ90%が高緯度域の1000mより浅い深さで散逸することを明らかにした。すなわち、本研究の結果によれば、大気擾乱から海洋内部領域に供給されたエネルギーのうちおよそ90%にあたる約0.6TWのエネルギーが、その主要なエネルギー供給域である緯度30度から50度の1000m以浅で散逸してしまう。その結果、深層海洋大循環の維持に必要な深海乱流へ寄与する大気擾乱起源のエネルギーは0.1TWにも満たないことになる。

キーワード：風応力, 乱流拡散, 深層海洋大循環, 内部重力波