Parameterization of Turbulent Diffusivity in the Deep Ocean

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Internal tide is a major source of energy for turbulent diffusivity in the deep ocean. In this study, as a first step toward a numerical modeling of global internal tide field, the distribution of the M_2 internal tide in the North Pacific is examined using a three-dimensional primitive equation numerical model. The numerical simulation shows that energetic internal tides are generated over the prominent bottom topographic features in the Indonesian Archipelago, the Solomon Archipelago, the Aleutian Archipelago and the Tuamotu Archipelago as well as over the continental shelf slope in the East China Sea, the Izu-Ogasawara Ridge and the Hawaiian Ridge. The energy conversion rate to the M_2 internal tide integrated over the whole model domain amounts to 273GW(1GW=10^9W), 84% of which is found to be generated over the prominent topographic features mentioned above. Reflecting the spatial distribution of the prominent topographic features, the energy level of internal tide in the western North Pacific is two to three orders of magnitude larger than that in the eastern North Pacific.

Keywords: Internal tide, Turbulent diffusivity, Internal gravity wave, Thermohaline circulation

1. Introduction

Oceanic tidal motions are composed of an astronomically driven surface (barotropic) tide and an internal (baroclinic) tide which arises as barotropic tidal current flows over bottom topographic features; resulting vertical current displaces the basic density stratification at tidal frequency. Surface tide has the maximum vertical displacement at the free surface and constant horizontal currents throuought depth, while internal tide is characterized by a large amplitude isopycnal displacement and depth-varying currents in the interior of the ocean. The amplitude of surface elevation due to internal tide is quite small compared with that of the isopycnal displacement typically by the order of 10^{-3}. Internal tide is also distinguished from surface tide by a small horizontal wavelength of the order of 100km.

It is widely recognized that internal tide plays important roles in large oceanographic contexts. Conversion from barotropic tide to internal tide can be an important process as sink of the oceanic tidal energy (Munk, 1997; Munk and Wunsch, 1998; Egbert and Ray, 2000). Internal tide is also considered to have strong influence on the oceanic general circulation, since much of the energy supplied to internal tide ultimately contributes to cross-isopycnal mixing in the deep ocean that is essential process to maintain the large-scale thermohaline circulation (Munk and Wunsch, 1998). Understanding the global distribution of internal tide is, therefore, crucial for accurate modeling of the oceanic general circulation. However, owing to the small spatial and temporal scales of internal tide, widespread observations have been difficult and scarce so that the global distribution of internal tide has not been definitely understood yet.

In the present study, as a first step toward a global modeling of internal tide, we investigate the distribution of the M_2 internal tide in the whole North Pacific using a three-dimensional primitive equation model that incorporates the realistic bottom topography, density stratification, and barotropic tidal forcing.

2. Numerical Experiment

Figure 1 shows the whole model domain covering the

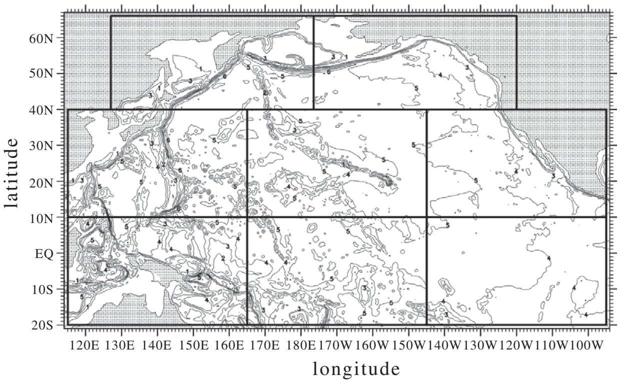

Fig. 1 The whole model domain together with the bottom topography (contour interval is 1km). Note that the whole model domain is divided into eight subregions as shown in the figure, and numerical simulation is performed separately for each subregion.

North Pacific with longitudinal range from 115°E to 95°W and latitudinal range from 5°S to 65°N. We divide the whole model domain into eight subregions as shown in Figure 1; numerical simulation is carried out separately for each subregion. A buffer area of 5° wide is introduced along the open boundaries of each subregion.

The governing equations are the full three-dimensional Navier-Stokes equations under the hydrostatic and Boussinesq approximations. The vertical eddy viscosity and diffusivity are parameterized following the Richardson-number formulation of Pacanowski and Philander (1981).

The governing equations are numerically integrated using the Princeton Ocean Model (Blumberg and Mellor, 1987) with horizontal grid spacing of 1/16° and 40 computational levels in the vertical. The model topography is constructed by averaging the bathymetric data of Smith and Sandwell(1997) within a 10km radius at each model grid point. The basic density field is determined from the annual mean temperature and salinity data of the National Oceanographic Data Center's World Ocean Atlas (Levitus and Boyer, 1994; Levitus et al., 1994).

In the present study, only the most prominent semidiurnal M_2 tidal forcing is considered. This tidal forcing is applied by prescribing barotropic tidal currents along the open boundaries through a forced gravity wave radiation condition (Cummins and Oey, 1997). Furthermore, we assimilate the surface tidal elevation data of Matsumoto et al.(2000) to simulate the realistic barotropic tidal field accurately.

The model is driven by the M_2 tidal forcing during 10 days from an initial state of rest. Time series data for the last 2 days are harmonically analyzed to calculate the amplitude and phase of the M_2 tidal response. From the calculated results, we separate the internal tidal response by subtracting the barotropic tidal response which is obtained from the same numerical simulation but omitting the density deviation terms in the Navier-Stokes equations.

3. Results

Figure 2 shows the distribution of the depth-integrated kinetic energy of the M_2 internal tide. The distribution of the M_2 internal tide in the North Pacific is found to be highly inhomogeneous, strongly reflecting the spatial distribution of bottom topographic features (see Figure 1). Particularly large amplitude internal tides are generated in the coastal and marginal seas over the prominent bottom topographic features in the Indonesian Archipelago and the Aleutian Archipelago and over the continental shelf slope in the East China Sea. Energetic internal tides are found to be generated over the mid-oceanic ridges such as the Hawaiian Ridge and the Izu-Ogasawara Ridge, and the open-ocean seamounts such as those in the Solomon Archipelago and the Tuamotu Archipelago. Around these prominent topographic features, the amplitude of isopycnal vertical displacement reaches more than 10m. Since these prominent topographic features are located mainly in the western North Pacific, there exists remarkable asymmetry in the internal tidal field; the energy level of the internal tide in the western North Pacific is two to three orders of magnitude larger than that in the eastern North Pacific.

To investigate the generation of the M_2 internal tide more in detail, we demonstrate in Figure 3 the distribution of the depth-integrated energy conversion rate from the M_2 barotropic tide to the M_2 internal tide. It can be confirmed that the generation sites of internal tide are identified more clearly by using the conversion rate, and the intense conversion actually occurs over the aforementioned prominent topographic features. Figure 3 also shows the conversion rate integrated within the area including each prominent topographic feature. It is found that the conversion rate over these prominent topographic features sums up to 228GW (1GW=10^9W), which corresponds to 84% of that integrated

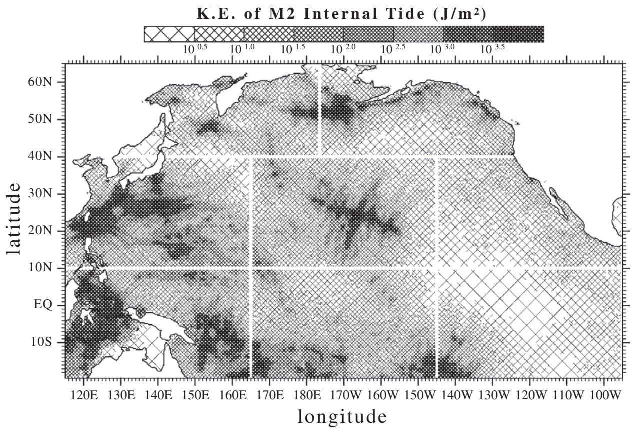

Fig. 2 Model-predicted distribution of the depth-integrated kinetic energy of the M_2 internal tide.

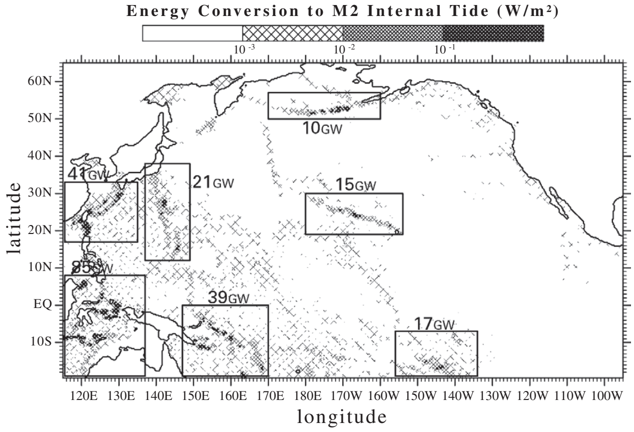

Fig. 3 Distribution of the depth-integrated energy conversion rate from the M_2 barotropic tide to the M_2 internal tide. The conversion rates integrated within the areas including the Indonesian Archipelago, the East China Sea, the Izu-Ogasawara Ridge, the Hawaiian Ridge, the Aleutian Archipelago, the Solomon Archipelago and the Tuamotu Archipelago are indicated.

in the whole model domain (273GW). In particular, the Indonesian Archipelago, the East China Sea and the Solomon Archipelago are important generation sites for the M_2 internal tide where the conversion rates reach 84GW, 41GW, and 39GW respectively.

4. Summary and Discussion

The spatial distribution of the M_2 internal tide in the whole North Pacific is investigated by using the three-dimensional numerical model. The numerical simulation shows that the generation of intense internal tides are restricted to occur over the several prominent topographic features located mainly in the western North Pacific. As a result, the level of internal tidal energy in the western North Pacific is two to three orders of magnitude larger than that in the eastern North Pacific.

This remarkable asymmetry suggests that most of the deep ocean mixing takes place in the western North Pacific. Considering that previous microstructure measurements to determine the rate of the deep ocean mixing have been made mainly in the eastern North Pacific (Nagasawa et al., 2000), previously observed vertical eddy diffusivity of the order of $10^{-5}m^2s^{-1}$ might not be representative one for the global ocean (Munk and Wunsch, 1998).

Using the results of previous studies that the M_2 mode conversion rate in the North Pacific is 23% of that integrated over the global ocean (Sjöberg and Stigebrandt, 1992), we can extend the present numerical results to obtain a global estimate of the M_2 mode conversion rate, 609 GW. This value corresponds to about 25% of the global tidal energy dissipation (Munk, 1997), although we should bear in mind that this is a very rough estimate considering the uncertainty of the numerical results of Sjöberg and Stigebrandt (1992).

For further investigations, a numerical simulation covering the whole global ocean is definitely required. In addition, to construct an accurate internal tide model, detailed comparisons are needed between calculated results and field observations around the prominent topographic features. These subjects remain to be studied in the future.

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海洋中における乱流拡散のパラメタリゼーションに関する研究

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内部潮汐波は海洋深層における乱流拡散過程の主要なエネルギー供給源の一つである。本研究では、グローバルな内部潮汐波場を解明するための第一段階として、北太平洋におけるM_2成分の内部潮汐波の分布を、プリミティブ運動方程式の3次元数値モデルを用いて明らかにした。その結果、大振幅の内部潮汐波が、インドネシア諸島・ソロモン諸島・アリューシャン諸島・ツアモツ諸島付近の海山、東シナ海の大陸棚斜面、伊豆-小笠原海嶺やハワイ海嶺といった顕著な海底地形上において励起されている様子が再現された。全モデル領域で積分したM_2内部潮汐へのエネルギー変換率は273GW (1GW=10^9W)に達し、そのうちの84%が上述の顕著な海底地形上でおこっていることがわかった。これらの海底地形の空間分布を反映して、西部北太平洋の内部潮汐波のエネルギーレベルが東部北太平洋に比べて2〜3オーダー高くなっていることが示された。

キーワード：内部潮汐、乱流拡散、内部重力波、熱塩循環