Measuring Microstructure in the Global Ocean

*Michael Charles Gregg

Global estimates of mixing rates have recently been published based on internal wave intensities inferred from temperature, salinity and density profiles measured with Argo floats. The procedure is justified by comparisons of internal wave parameters with estimates of mixingrates from direct microstructure measurements. Those estimates in turn are based on comparisonsbetween microstructure measurements and the vertical spreading rates of tracers injected into the thermocline. Although microstructure is being measured from a wide variety of fixed and moving platforms, justification of the global estimates is based on sensors developed 40 years ago and whichresolve only a fraction of the estimated range of microstructure variability. To investigate issues about these measurements, such as mixing efficiency, new sensors are needed, mainly to resolve smaller spatial scales. The required spatial scales and sensitivities are estimated and compared with present and experimental sensors.

Keywords: Mixing, Microstructure, Turbulence

Turbulent Mixing in the Oceans and the Atmosphere

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In the global ocean, measurements of the dissipation rate of turbulence kinetic energy are now quite routine. The same cannot be said about the atmosphere. Such measurements have been difficult to make in the atmosphere, because an instrument similar to an oceanic microstructure profiler is not available. However, measurements have recently been made in the atmosphere using very high-resolution balloon-borne sensors. It is now possible to use these data to obtain a unified picture of turbulence in the oceans and the atmosphere. However, without knowledge of the scales involved, it is hard to assess the reliability of the observational data. By appealing to closure models of turbulence and imposing appropriate limits on turbulence scales, it is possible to remove questionable data and obtain a more accurate picture of mixing. In this talk, we will describe our approach and the results that lead to a Grand Diagram of Turbulence in the oceans and the atmosphere.

Keywords: Microstructure, Turbulent Mixing, Mixing in the Oceans, Mixing in the atmosphere

Surface Mixing and Its Implementation in Regional Ocean Models

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Many vertical mixing parameterizations exist for the Regional Ocean Modeling System (ROMS) and they give widely different results. How well these parameterizations reproduce surface mixing is critical for both climate and military applications. Using meteorological and oceanographic data from the Southern Ocean Time Series mooring south of Australia, different mixing parameterizations in ROMS were evaluated for their ability to replicate the surface mixed layer environment. Three different vertical mixing parameterizations were investigated: Nakanishi-Niino, Mellor-Yamada 2.5 and the Large-McWilliams-Doney Kpp profile. Nakanishi-Niino performed the best for this application using the criteria of the surface mixed layer depth and the structure of the upper ocean temperatures. Additionally, a sensitivity study was performed to determine the best set of parameters to use.

Keywords: vertical mixing, surface mixed layer

Geography of the attenuation rates of baroclinic tidal energy estimated using wave-wave interaction theory

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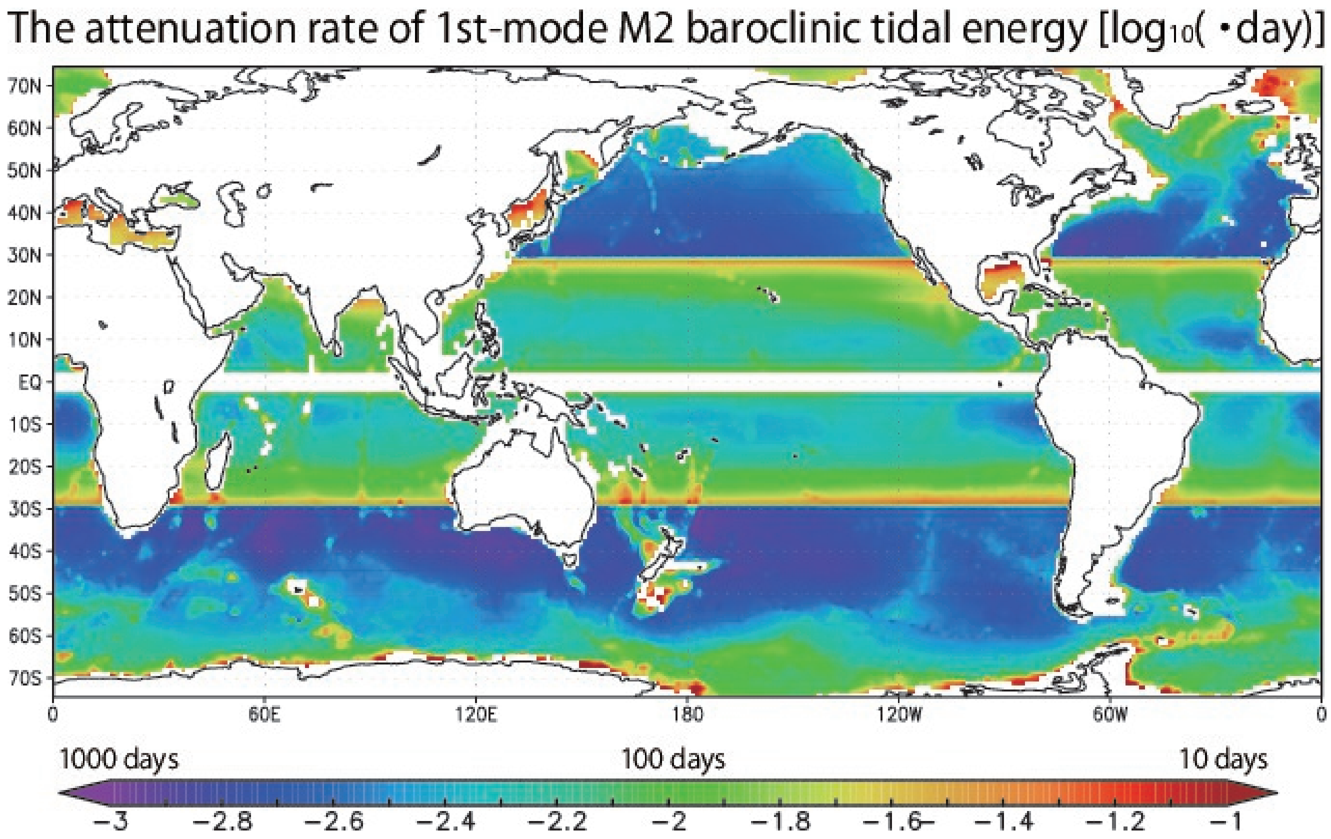
The baroclinic tides are thought to be the dominant energy source for turbulent mixing in the ocean interior. In contrast to the energy conversion from the barotropic to baroclinic tides, which has been clarified in recent numerical studies, the energy sink for low-mode baroclinic tides is less well understood. One responsible mechanism for such energy sink is nonlinear interaction between the baroclinic tides and background internal wave field. Although the theoretical basis for the resonant interactions among internal waves was established long ago, its practical applicability to the baroclinic tides has not been sufficiently discussed. In this study, we have extended the classical theory to demonstrate the geographical distribution of the attenuation rates of low-mode baroclinic tidal energy resulting from wave-wave interactions.
Our approach is basically following the weak turbulence theory, which describes the statistics of energy transfer through wavenumber space caused by weakly nonlinear interactions. It should be noted that our new formulation is applicable to low-mode internal waves, which are strongly subject to the effects of density structure and total depth.
We have calculated the attenuation rate of low-mode baroclinic tidal waves interacting with the background Garrett-Munk internal wave field. The results clearly show the rapid attenuation of baroclinic tidal energy at mid-latitudes caused by parametric subharmonic instability (PSI) which depends on density structures associated with the subtropical gyre, in agreement with field observation and numerical simulation. This study is expected to contribute to clarify the global distribution of the dissipation rates of baroclinic tidal energy.

Keywords: Internal waves, Baroclinic tide, Resonant interaction


The attenuation rate of 1st-mode M2 baroclinic tidal energy [log10(•day)]
70N
60N
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
50S
60S
70S
0
60E
120E
180
120W
60W
0
1000 days
100 days
10 days
−3
−2.8
−2.6
−2.4
−2.2
−2
−1.8
−1.6
−1.4
−1.2
−1

Eikonal Simulations for Energy Transfer in the Deep-Ocean Internal Wave Field near Mixing Hotspots

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In the proximity of mixing hotspots in the deep ocean, the observed internal wave spectra are usually distorted from the Garrett-Munk (GM) spectrum and are characterized by the high energy level E as well as the shear/strain ratio R_ω quite different from the corresponding value for the GM (R_ω = 3). On the basis of the eikonal theoretical model, Ijichi and Hibiya (IH) have recently proposed the finescale parameterization of turbulent dissipation rates in the deep ocean in terms of E and R_ω to reduce bias resulting from such spectral distortion. However, some simplifying assumptions are made in the theoretical model itself such as neglecting the vertical velocity associated with background internal waves and violating the WKB scale separation. To see the effect of such simplifying assumptions on the IH parameterization, this study carries out a series of eikonal simulations for energy transfer through various internal wave spectra distorted from the GM. Although the background vertical velocity as well as the strict WKB scale separation somewhat affects the calculated energy transfer rates, their parameter dependence is confirmed as expected from the IH parameterization; in other words, the calculated energy transfer rates εfollow the scaling $\varepsilon \sim E^2 N^2 f$ with N the local buoyancy frequency and f the local inertial frequency, and exhibit strong R_ω dependence quite similar to that predicted from the parameterization.

Keywords: Internal Wave Spectrum, Energy Transfer, Parameterization, Turbulence, Eikonal Simulation

Numerical Study of the Impacts of Ocean Bottom Roughness and Tidal Flow Amplitude on Abyssal Mixing

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Although an accurate representation of ocean mixing processes in global circulation models is essential for accurate climate predictions, parameterization of mixing over rough bathymetry remains uncertain. We perform here a series of eikonal calculations for a wide range of physical parameters to investigate the transfer of energy from upward propagating internal waves generated by tide-topography interactions to dissipation through nonlinear interaction with background three-dimensional Garrett-Munk-like internal waves.

Following the previous study (Mohri et al., 2010) and using a fixed N value, we assume that internal waves generated by tide-topography interactions can be classified into linear internal tides when $kU_0/\omega<1$ and quasi-steady lee waves when $kU_0/\omega>1$, where U_0 is the tidal flow amplitude, k the benthic bathymetric wavenumber, N the buoyancy frequency and $\omega$the semidiurnal tidal frequency. Of special note is that the vertical group velocity C_{gz} is inversely proportional to k for linear internal tides and proportional to kU_0^2 for quasi-steady lee waves, although the resonant interaction time is roughly inversely proportional to k for both cases. As a result, the resulting mixing hotspot becomes more restricted to the ocean bottom as bottom roughness increases for kU_0/ω <1, independent of the tidal flow amplitude, but it extends upward as the tidal flow amplitude increases for $kU_0/\omega>1$, independent of the bottom roughness. In both cases, we can find a trade-off relationship between the energy dissipation rate at the ocean bottom and its vertical extent.

The accuracy of global circulation models will be improved by reflecting these results in the parameterization of mixing over rough bathymetry.

Keywords: Abyssal Mixing , Parameterization, Global Overturning Circulation, Ocean Bottom Roughness, Tidal Flow

Samoan Passage near-inertial waves

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The Samoan Passage Abyssal Mixing Experiment (2012 - 2014) was designed to study transport, mixing, hydraulic control, and internal waves in the Samoan Passage (168.5-170W, 7.5-10S) where the majority of the transport of water, below 4000m depth, into the North Pacific occurs. The current work focuses on a sill at the entrance to the western channel. Observations in this subregion included four simultaneous short-term (~7 days) moorings: one located 2 km upstream of the sill and three, spaced 1 km apart, 3 km downstream of the sill; and one longer term (~18 months) mooring located on the sill. While near-inertial waves were observed throughout the passage, this sill region provides an opportunity to study downward propagating, near-inertial waves interacting with topography. A coherent signal in time and space was observed, which shows the wave propagating equatorward (northward) over the sill. Plane wave solutions with a vertical wavelength of 238m and a frequency of .35 cpd (1.04f) match the signals observed at the four simultaneous moorings. Maximum near-inertial energy was centered around the 1 degree C isotherm in the interface between the Antarctic origin bottom water and the overlying water. The two western most moorings upstream of the sill, show a single depth band centered around 4100m of maximum high near-inertial energy. The down stream and eastern upstream moorings both had a secondary lower magnitude near-inertial energy peak, in addition to the peak around 4100m, centered at 4300m. These deeper waves are more rectilinear (90% of KE rotating anti-cyclonic in time) than the waves observed at 4100m (70% of KE rotating anti-cyclonic in time). Interactions with topography, including generation of local vorticity, shadowing and flow steering, are important.

Keywords: Near-inertial waves, ocean, mixing

Dissipation processes of internal waves generated by geostrophic flows impinging on bottom topography

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In the Southern Ocean, bottom-reaching Antarctic Circumpolar Current (ACC) impinges on rough bathymetric features creating internal lee waves. Recent microstructure observations carried out in the ACC region showed the existence of bottom-enhanced turbulent dissipation which is thought to be explained in terms of breaking of internal lee waves emanating from rough ocean bottom (Sheen et al., 2013; Waterman et al., 2013).

On the basis of weakly nonlinear theory together with the results from numerical experiments, Nikurashin and Ferrari (2010) showed that geostrophic flows impinging on rough ocean bottom also excite vigorous inertial oscillations which then interact with high-wavenumber internal lee waves to create bottom-intensified mixing hotspots. However, their theory and numerical experiments are too much simplified to be applied to the realistic situation in the ACC region. For example, a background internal wave field is not taken into account in their study.

In the present study, we investigate (1) the behavior of internal lee waves in the presence of inertial oscillations, and (2) whether inertial oscillations play an important role even in the presence of the background internal wave field (Garrett-Munk internal wave field). For this purpose, we carry out a series of numerical experiments where a depth-independent geostrophic flow is assumed to impinge on idealized topographic features.

It is shown that, as the slope of bottom topography becomes steep, the generated internal lee waves partially break. The divergence of the vertical flux of horizontal momentum drives the inertial oscillations, which then extend upward to more than 1000m above the ocean bottom, interacting with internal lee waves emanating from the ocean bottom as well as the background internal waves. Of special interest is that the bottom-generated internal lee waves are mostly affected by the interaction with the inertial oscillations rather than with the background internal wave field, while increasing their vertical wavenumbers up to the breaking limit. Thus, we can conclude that steep bottom topography plays a key role in transferring energy from geostrophic flows to turbulent dissipation via the interaction between inertial oscillations and internal lee waves.

Keywords: Southern Ocean, Antarctic Circumpolar Current, internal lee wave, inertial oscillation, Garrett-Munk internal wave field

Enhanced mixing in the equatorial thermocline induced by inertia-gravity waves

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Observations show turbulence activity is enhanced in and above the equatorial thermocline. This enhancement is brought about in part by the generation, propagation and dissipation of wind-driven inertia-gravity waves (IGWs). Numerical experiments show that in a zonally symmetric model of a tropical ocean forced by a transient wind stress both IGW activity and the energy dissipation have a pronounced maximum in the thermocline close to the equator regardless of the latitudinal distribution of the energy input into the ocean's mixed layer by the wind. We show that this equatorial enhancement is caused by a combination of three factors: a stronger superinertial component of the wind forcing close to the equator, wave action convergence at turning latitudes for various equatorially trapped waves, and nonlinear wave-wave interactions between equatorially trapped waves. Amplification of IGWs also occurs due to refraction at the top of the thermocline. We show that the latter mechanism can operate at any latitude, but is limited in its capacity to amplify the Froude number associated with propagating IGW packets and requires short (shorter than the local inertial period) energetic wind bursts to produce enhanced mixing.

Keywords: Turbulence, Inertia-gravity waves, Equatorial

Downward lee wave radiation from Pacific tropical instability waves: A possible energy pathway to turbulent mixing

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Turbulent mixing in the equatorial Pacific Ocean is an important process that controls diapycnal heat transport and hence affects the intensity of air-sea interactions related to the global climate. It is recently shown that, in the eastern equatorial Pacific, strong mixing is induced in the thermocline by enhanced vertical shear associated with tropical instability waves (TIWs), which propagate westward along the equator at a speed of ~0.5 m s^{-1} with a wavelength of ~1000 km.

In this study, using a high-resolution ocean general circulation model, we show that the TIWs can play an important role in inducing turbulent mixing in the thermocline also in the central equatorial Pacific, although the thermocline is too deep to be directly affected by the vertical shear of the TIWs. The front of the TIW is clearly manifested as a narrow strip of strong convergence of horizontal surface flow, from which area downward and westward propagating internal waves are intermittently emanated. These internal waves can be interpreted as lee waves generated by the surface-flow convergence zone, which acts like an inverted obstacle moving along the stratified ocean surface by inducing downward flow. The associated downward energy flux below the surface mixed layer increases as the TIW structure becomes deeper toward the central equatorial Pacific, so that the energy pathway to turbulent mixing in the thermocline can be created. The downward energy flux integrated over the entire equatorial Pacific and averaged during January 2011 amounts to ~8.1 GW, occupying a significant fraction of the energy input to the TIWs.

Keywords: Turbulent Mixing, Vertical Energy Flux, Internal Wave Radiation, Lee Wave, Tropical Instability Wave, Eddy-Resolving Ocean General Circulation Model

Turbulence Mixing in Convectively Breaking Internal Solitary Waves

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Considerable efforts and progress have recently been made towards parameterizing the local and remote dissipation/mixing driven by internal tides and internal lee waves in the open ocean and towards establishing the impact of such parameterization on the accuracy of climate models. In contrast, no equivalent parameterizations exist for internal solitary waves (ISW) that operate well below the subgrid scale in larger-scale models. ISWs are subject to considerably different underlying physics, as it is unclear how to parameterize, at a first level, where and when the propagating waves break and, at the next level, how much turbulent mixing results and how wave-driven horizontal transport may be enhanced. In this regard, ongoing uncertainty exists regarding the relative placement of ISW-driven turbulence with respect to the regimes of weak wave-wave interaction and energetic stratified turbulence regimes and the transition between them (D’Asaro and Lien, 2000). Turbulence mixing within convectively breaking ISWs is hard to measure due to the fast propagating speed of ISWs and the intermittent nature of convective instability. A set of Lagrangian float observations was obtained within several convective breaking ISWs. Turbulent kinetic energy dissipation rates, eddy diffusivity, and associated turbulent fluxes are estimated using both Lagrangian and Eulerian inertial subrange methods. Numerical simulations of convectively breaking ISWs on shoaling slope will be performed using 3D LES model. Results of preliminary analysis of model derived turbulent fluxes will be compared with observations. Turbulence parameterizations associated with breaking ISW will be discussed.

Keywords: Lagrangian Observations, Convective Instability, Internal Solitary Waves

Internal tides and associated vertical mixing in the Indonesian Archipelago

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Tidal mixing in the Indonesian Archipelago contributes to regulation of the tropical atmospheric circulation and water-mass transformation in the Indonesian Throughflow. The present study quantifies the vertical diffusivity in the Indonesian Archipelago by driving a high-resolution three-dimensional numerical model and investigates the processes of internal tide generation, propagation, and dissipation. The numerical experiment shows that M_2 internal tides are effectively generated over prominent subsurface ridges. The conversion rate from M_2 barotropic to baroclinic energy over the whole analyzed model domain is estimated to be 85.5 GW. The generated internal tides dissipate 50 –100% of their energy in close proximity to the generation sites (“near-field”), and the remaining baroclinic energy propagates away causing relatively large energy dissipation far from the generation sites (“far-field”). The local dissipation efficiency q, therefore, has an extremely nonuniform spatial distribution, although it has been assumed to be constant in the existing tidal mixing parameterization for the Indonesian Archipelago. Compared with the model-predicted values, the existing parameterization yields the same order of vertical diffusivity averaged within the Indonesian Archipelago, but significantly overestimated (or underestimated) vertical diffusivity in the near-field (or the far-field). This discrepancy is attributable to the fact that the effects of internal wave propagation are completely omitted in the existing parameterization, suggesting the potential danger of using such parameterized vertical mixing in predicting the distribution of SST as well as water-mass transformation in the Indonesian Seas.

Keywords: Internal tides, Tidal mixing, Indonesian Archipelago

