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

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.

キーワード：Microstructure、Turbulent Mixing、Mixing in the Oceans、Mixing in 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

波動間相互作用理論により推定された傾圧潮汐エネルギー減衰率の全球分布

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

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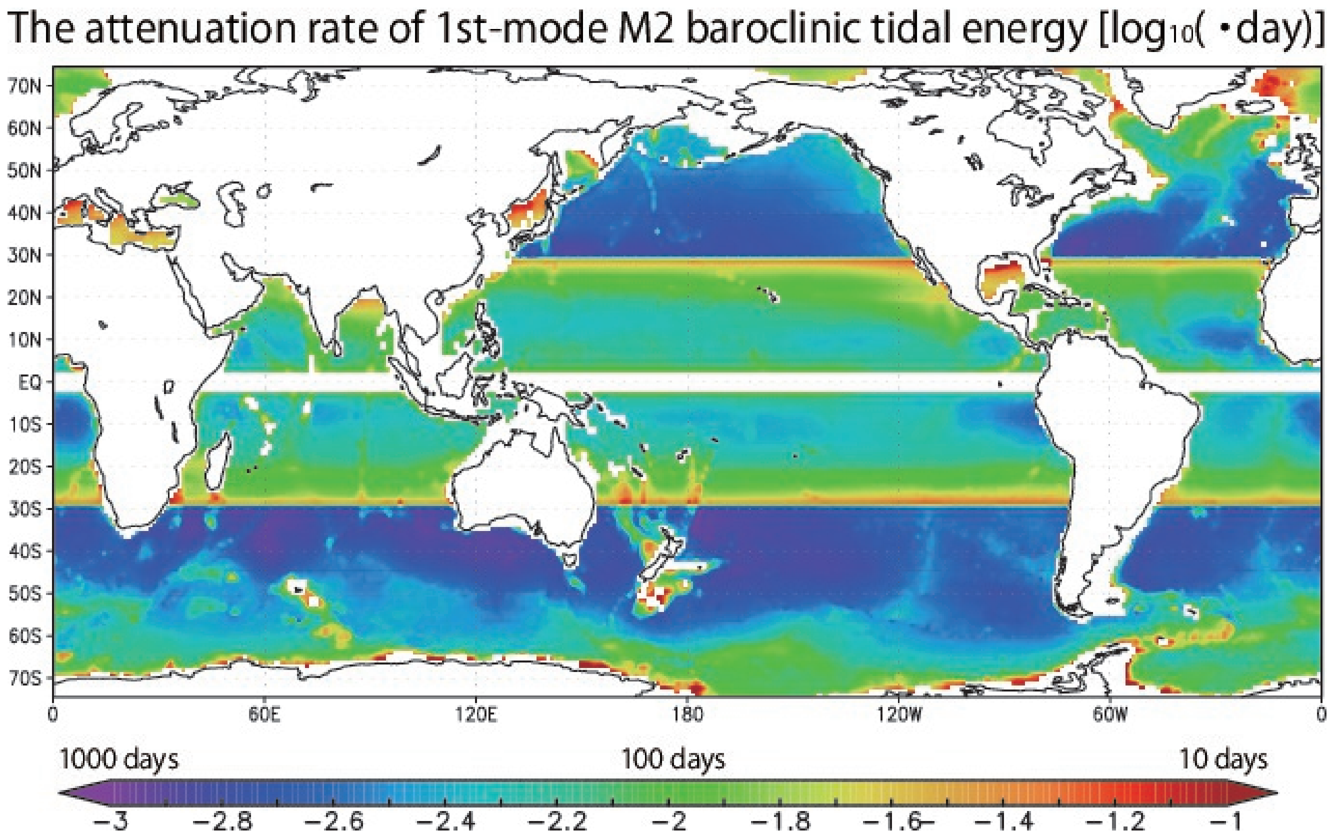
The baroclinic tides are thought to be the dominant energy source for turbulent mixing in the ocean interior. In contrast to the energy conversion from the barotropic to baroclinic tides, which has been clarified in recent numerical studies, the energy sink for low-mode baroclinic tides is less well 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.

キーワード：内部波動、傾圧潮汐、共鳴相互作用
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

アイコナール計算に基づく深海内部波場におけるエネルギー輸送に関する研究
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 ($R_\omega = 3$). 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 ε follow the scaling $\varepsilon \sim E^2N^2f$ 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.

キーワード：内部波スペクトル、エネルギー輸送、パラメタリゼーション、乱流、アイコナール計算
Keywords: Internal Wave Spectrum, Energy Transfer, Parameterization, Turbulence, Eikonal Simulation

深海底の凹凸地形上に形成される乱流ホットスポットの鉛直構造に関する数値的研究
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.

キーワード：深海混合、パラメタリゼーション、深層海洋循環、深海凹凸地形、潮汐流
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

南大洋の深層における乱流散逸過程に関する数値実験

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.

キーワード：南大洋、南極周極流、風下波、慣性振動、Garrett-Munk 背景内部波場
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

太平洋の熱帯不安定波から下向きに放射される風下波 -表層下の乱流混合過程へのエネルギー輸送-
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.

キーワード：鉛直乱流混合、エネルギーフラックス、内部波放射、風下波、熱帯不安定波、渦解像海洋大循環モデル
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

インドネシア多島海域内における内部潮汐波起源の乱流混合エネルギーの見積もり
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.

キーワード：内部潮汐波、潮汐混合、インドネシア多島海域
Keywords: Internal tides, Tidal mixing, Indonesian Archipelago

グリーン関数法による太平洋深層の鉛直拡散の最適化
An improved simulation of the deep Pacific Ocean using optimally estimated vertical diffusivity based on the Green’s function method

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An improved vertical diffusivity scheme is introduced into an ocean general circulation model to better reproduce the observed features of water property distribution inherent in the deep Pacific Ocean structure. The scheme incorporates (a) a horizontally uniform background profile, (b) a parameterization depending on the local static stability, and (c) a parameterization depending on the bottom topography. Weighting factors for these parameterizations are optimally estimated based on the Green’s function method. The optimized values indicate an important role of both the intense vertical diffusivity near rough topography and the background vertical diffusivity. This is consistent with recent reports that indicate the presence of significant vertical mixing associated with finite-amplitude internal wave breaking along the bottom slope and its remote effect. The robust simulation with less artificial trend of water properties in the deep Pacific Ocean illustrates that our approach offers a better modeling analysis for the deep ocean variability. This presentation is based on Toyoda et al. (2015) published in Geophysical Research Letter (42, 9916-9924, doi:10.1002/2015GL065940).

キーワード：鉛直拡散、データ同化、太平洋深層循環
Keywords: vertical diffusivity, data assimilation, Pacific Ocean

Evidence of tidal straining and its influence on the bottom mixing in the East China Sea

Evidence of tidal straining and its influence on the bottom mixing in the East China Sea

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In the coastal region under influence of freshwater inflow, the resulting strong horizontal density gradient sometimes causes tidal straining which strongly affects the mixing in the water column. We present here the results of field observations of current, hydrology and turbulence at two selected locations in the East China Sea where strong horizontal density gradient was found.
The hydrology structures of the whole water column at Stn. P01 and within the bottom 20 m at Stn. MT1 both showed semidiurnal variations associated with the dominant M_2 tidal flow. From the analysis of the time derivative of potential energy anomaly, we proved that tidal straining played a dominant role in controlling the variation of stratification at both stations. More specifically, the tidal straining eroded and intensified the stratification depending on tidal phases. Around the time of high tides, tidal straining was found to create unstable stratification which occupied the bottom 15 m at Stn. P01 and bottom 20 m at Stn. MT1. The associated Rayleigh number was estimated to be of the order of 10^{12}, much larger than the critical value 10^3, indicating the existence of convection. On the basis of the continuous high-resolution velocity measurement near the seabed, we showed that the mixing near the seabed is locally shear-induced during most of the time except during the unstable stratification period when the magnitude of dissipation exceeded that expected from the law of the wall by an order of magnitude.
Although the additional buoyancy production added by strain-induced convection can be one of the candidates to explain this discrepancy, the buoyancy flux calculated by the balance method is shown to be too small to make up for the existing discrepancy between dissipation and shear production. Another plausible candidate is the advection of turbulent kinetic energy (TKE) which should play an important role in the TKE budget during the period of convection.

キーワード：Tidal straining 、Bottom mixing、East China Sea
Keywords: Tidal straining , Bottom mixing, East China Sea

沖縄本島周辺海域における黒潮反流に伴う海洋構造の非対称性について

Impact of mesoscale recirculation of the Kuroshio on asymmetric oceanic structure around Okinawa Island in the East China Sea

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Okinawa Island is located in the subtropical region of Japan, hosting ecologically abundant coral reefs even though they lie at the northernmost extreme of the habitable region. The coral ecosystem in the west coast of the island is maintained by persistent intrusions of the Kuroshio warm water through eddy-induced lateral mixing (Kamidaira *et al*., 2016), while the Ryukyu Under Current is a major source of warm water from the lower latitude on the east coast. The island is situated on a ridge of the Ryukyu Arc that separates the shallow East China Sea (ECS) and the deep Ryukyu Trench (RT) to the Pacific Ocean, preconditioning oceanic asymmetry between the both sides of the island. In the present study, asymmetric oceanic responses around the island are investigated with a synoptic, triple nested downscaling ocean model based on ROMS. The model is forced by the JCOPE2 reanalysis as the outermost lateral boundary conditions and by the JMA GPV-GSM/MSM atmospheric reanalysis as the surface momentum boundary conditions. The horizontal grid spacing is decreased from 3 km in the outermost ROMS-L1 model, to 1 km in the intermediate ROMS-L2 model, and further down to 250 m in the innermost ROMS-L3 model. The L3 model has a 152 x 416 km domain and ten principal tidal constituents based on the TPXO 7.0 reanalysis is newly introduced to account for tides for more realistic reanalysis.

The harmonic analysis of the L3 model result highlights that semi-diurnal and diurnal tides propagate differently on the both sides of the island, yielding the asymmetric distributions in tidal amplitudes and phases. The tides are rather uniform with neither noticeable phase lags nor amplification on the RT side, whereas bidirectional propagation occurs on the ECS side originated from the northern- and southern-most tips of the island with prominent changes in amplitude near the shore. Similarly, the baroclinic energy flux demonstrates that the diurnal internal tides are not trapped topographically. Therefore the resultant clockwise circular propagation, which has been observed in several islands such as Izu Oshima and Sadogashima Islands where the local inertial period is shorter than the diurnal period, is interfered at the southernmost area off Okinawa Island. In addition, these two tips are areas of generation of the most energetic eddy kinetic energy (EKE). In particular, the upstream southernmost area sheds eddies that affect the nearshore area around the island. Remarkable enhancement of EKE is found around the shallow channel lying between Okinawa Island and Tokashiki Island (viz., Tokashiki Channel). These analyses clearly suggest that the southernmost area of the island around Tokashiki Channel plays substantial roles in controlling the asymmetric oceanic responses. The evaluated meridional volume flux normal to the channel indicates seasonal variability with prominent ECS to RT transport in spring, although RT to ESC transport is comparable to ESC to RT transport for the rest of the year. The transport along the channel is highly correlated with the volume transport of the northeastward drifting Kuroshio centered at 150 -200 km west of Okinawa. In spring, opposing southwestward transport is generated between the Kuroshio and the island, often referred to as the Kuroshio Counter Current (KCC). Surface vorticity indicates that the KCC is composed of clockwise-rotating, anti-cyclonic mesoscale eddies. Wavenumber kinetic energy spectra clearly shows seasonal transition from submesoscale-eddy dominance in winter to mesoscale-eddy dominance in spring. Relaxation of surface cooling and mixed

layer deepening from winter to spring lead to this transition that is responsible for seasonal exchange between the ECS and the RT.

キーワード：黒潮、黒潮反流、琉球海流、メソスケール渦サブメソスケール渦による乱流混合、領域海洋循環モデル
Keywords: Kuroshio, Kuroshio Counter Current, Ryukyu Under Current, meso - and submesoscale eddy mixing, ROMS

生態系モデルによる植物プランクトンの2次元パターン形成の研究

A study of two-dimensional phytoplankton pattern formation by an ocean physics-ecosystem modelling

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富山湾では，6月から7月の梅雨期に表層数mのクロロフィルaの活動が活発となり，湾内において反時計回りの渦状の分布がしばしばみられる（図1）．この特徴的な分布は富山湾の物理過程（移流，拡散）と生態系との関係から形成されると考えられるが，その詳細な形成・変動メカニズムは未解明である．そこで，衛星画像，海洋観測データ，および海洋物理過程を導入した生態系モデルを用い，この形成・変動の原因解明に取り組むことを研究の目的とする．
本研究では，生態系モデルとして単純なNPZモデルとし，これに水平2次元の移流拡散項を導入した方程式系に対し，差分法を用いて数値的に解くことによって，クロロフィルaのパターン形成メカニズムを調べた．海域の設定としては，富山湾規模の湾を考え100 km x 100 kmの海域で，モデルの水平解像度を1 km x 1 km とした．モデル計算に関して，拡散係数は10 m^2s^{-1} と一定にし，流れ場は反時計回りの循環場とし，プランクトンのパラメータは，マクロとミクロ，捕食・被食の関係を示す食植速度を変化させて複数の実験を行った．また，特にトレーサーとしての移流拡散方程式と生態系の反応のある移流を加味した反応拡散方程式に対する比較実験を行った．
物理過程だけの移流拡散方程式におけるトレーサーの挙動として，移流だけでは渦状の分布は形成されたが，初期のパッチが伸ばされるだけとなった．水平拡散だけの場合，渦状にはならず，円形に拡散していくだけとなった．移流と拡散の両方を加味した場合には，衛星のパターンに似た形状のトレーサーの分布を示したが，プランクトン量の急激な増加は見られなかった．これに対し，生態系のやり取りとしての反応を加えると顕著なプランクトン量の増減の変動がみられた．さらに，食植速度を大きくしたときや，ミクロパラメータの時，より衛星画像との良い対応がみられた．また，生態系と水平拡散，つまり反応拡散系の場合やさらに移流まで加えたとき，リング状の波動の進行がみられた．
NPZモデルに移流と拡散の効果を導入した移流を加味した反応拡散方程式系のモデルによって，富山湾の衛星画像で見られたクロロフィルaの分布に近いパターン（図1）を再現することができた．このことから，衛星画像で見られたパターンは海洋物理過程が反時計回りの渦の形状を決める主要因となっており，拡散だけでなく移流の効果が大きな役割を果たしていることが分かった．また，図1aから図1bへのパターン発達に関しては，1日で変化しており，移流拡散の時間現象スケールよりずっと速く，パターン発達に関して生態系の反応が重要な役割を果たしていることが分かった．様々なケースのモデル結果から得られたパターンにおけるリング状の波の進行は，反応拡散現象に現れるものと類似しており，今後より詳細に解析を行う．

キーワード：衛星画像、海洋物理過程、クロロフィルa、生態系モデル、富山湾、反応拡散
Keywords: Statellite imeage, Marine physical processes, chlorophyll-a, Ecosystem model, Toyama Bay, reaction-diffusion

Figure.1

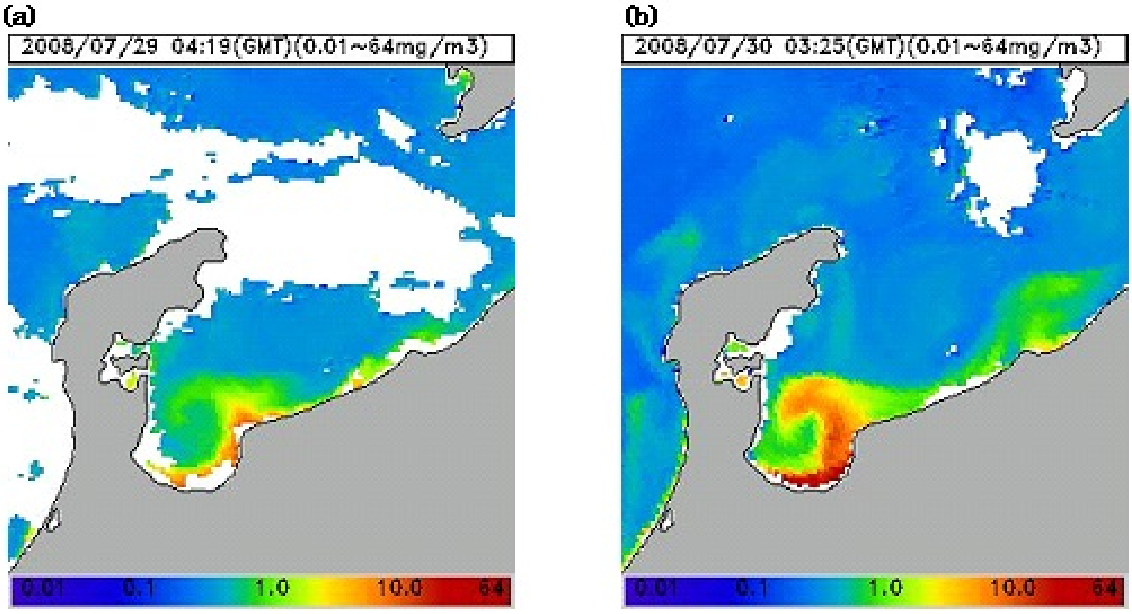
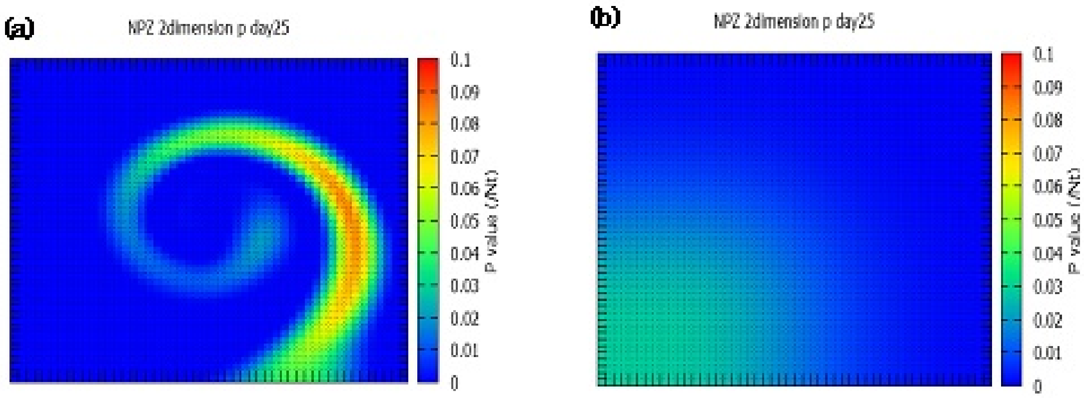
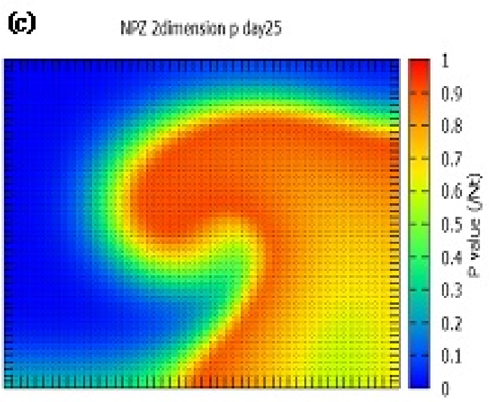


Figure.2





(a) advection only
(b) diffusion only
(c) advection, diffusion and reaction effect of ecosystem

Distribution of ^{236}U in the North Pacific Ocean

Distribution of ^{236}U in the North Pacific Ocean

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^{236}U is a mainly anthropogenic, rare uranium isotope with a half-life of 23.4 M yrs. In recent years, the development of accelerator mass spectrometry (AMS) has made the detection of ^{236}U in the general environment possible and research was conducted towards the application of this nuclide as oceanic tracer. ^{236}U seems well suited as oceanic tracer, because it has a well-defined, temporally resolved source function and shows conservative behaviour in seawater with a long residence time of ~ 5×10^5 yrs. In this work, we focus on the North Pacific Ocean, where no data on ^{236}U has been published so far and will present a new pre-treatment method to treat small size (1 L) seawater samples.
Seawater samples were collected from the North Pacific Ocean in GEOTRACES cruises with *R/V Hakuhomaru*, in 2011, 2012 and 2014 (KH-11-07, HK-12-4 and KH14-6). 1 L, 5 L and 20 L of seawater samples were collected from several depths in each site, and immediately after the sampling, the water was filtered with about 0.45 mm pore-size cartridge filters. ^{238}U concentrations in seawater were measured with ICP-MS after acidification. As for 1 L of seawater samples, uranium was purified with UTEVA resin , and precipitated in only 100 μg of iron carrier to prepare targets for the measurement of $^{236}U/^{238}U$ by AMS. In the 5 L and 20 L samples, no column separation for uranium was done, but actinide elements were separated by a simple co-precipitation with iron hydroxide, which leaves the possibility of detecting several actinides (U, Np, Pu) from one sample.
Using the newly constructed target preparation procedure for the measurement of ^{236}U in small sizes of seawater samples, 5-10 times higher ion currents were achieved compared to the conventional method and ^{236}U was successfully determined on all levels of the water column. Also, measurement times could be significantly reduced, which seems promising for future applications of ^{236}U as oceanographic tracer, when large numbers of samples from vast ocean areas need to be analysed in a timely and cost-efficient way. $^{236}U/^{238}U$ isotopic ratios were highest (7.6×10^{-10} to 1.4×10^{-9}) in shallow water. From surface level to a depth of about 1000-1500 m, all depth profiles showed a steep decrease in ^{236}U concentrations and $^{236}U/^{238}U$ ratios in deep water were in the order of 10^{-11}-10^{-12}. The inventories of ^{236}U on the water column were calculated as $(3.6–7.3)\times10^{12}$ atoms/m^2, which is significantly lower than for the Sea of Japan with $(1.4-1.6)\times10^{13}$ atoms/m^2. These results show the lower extent of vertical transport in the Pacific Ocean and are probably an indicator for lower precipitation rates in the North Pacific Ocean. ^{236}U distributions were in correspondence to the main water masses (as defined by physical oceanographic parameters) and ^{236}U concentration patterns were similar to those of ^{137}Cs, which has been conventionally used as oceanographic tracer in this area.

キーワード：U-236、North Pacific Ocean、AMS、Geotraces、global fallout
Keywords: U-236, North Pacific Ocean, AMS, Geotraces, global fallout

Impacts of wave spreading and multidirectional waves on estimating Stokes drift

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The Stokes drift velocity is an important quantity in categorizing the effects of ocean surface gravity waves and is increasingly used in models to parametrize wave-driven mixing or calculate sea surface transport. However, it is often overlooked that Stokes drift for a random sea is not easily generated from wind and wave data and large differences exist even between 1D and 2D spectral approximations. It is important to rectify these differences in order to compare model results and improve understanding.
Here, it will be shown that differences in Stokes drift magnitude and direction depend mainly on the interaction of different wave groups and the process of wave spreading. To illustrate, we will review various Stokes drift approximations and introduce a new 1D spectral approximation to include the systematic effects of wave spreading. This new approximation will be used with observational and global model data (buoy located at Ocean Weather Station P and WAVEWATCH III output respectively) to separate and quantify wave spreading and multidirectional wave effects on Stokes drift.

Keywords: Stokes drift, unidirectional waves, wave spreading

不規則波におけるStokes Drift効果を考慮した海洋・波浪結合モデルの構築
Development of the Coupled Ocean-Wave Model Considering Stokes Drift Effect on Random Wave

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1.Introduction
Much attention has focused recently on climate change of ocean areas in terms of coastal forcing and physical environments. IPCC AR5 (Intergovernment Panel on Climate Change, Fifth Assessment) published in a 2013 report the need for impact assessment for regional ocean environment, e.g. horizontal resolution of the order of 100m because of few ocean studies for that scale. Already little progress has been made in the development of numerical model applying to that ocean scale. This study develops the Coupled Ocean-Wave Model to carry out the calculation of regional ocean environments on a 500m horizontal resolution considering wave-induced transport on random waves incorporating the effect of Stokes Drift into the model. Two re-analysis calculations are performed, one considering the Stokes Drift on random wave and the other not, for Tanabe Bay in Wakayama as a verification of the model precision to compare with the field observation data.
2.Formulation of Stokes Drift on random waves
There is large interaction effect between currents and surface gravity waves in finite depth area such as in the coastal ocean. Wave-induced transport, a quantity known as Stokes Drift, on random waves is formulated to insert in the model. The Stokes Drift can be written as eq.1 (Kenyon et al., 1969). The distribution function of frequency spectrum and directional spectrum is approximated as the two-dimensional Gaussian spectrum and expressed as eq.2.
3.Test calculation on simple topography
Two runs are carried out for simple topography to confirm the effect of Stokes Drift on random waves. One (referred to as Wave2d) uses the model in which wave-induced transport is provided by random waves and the other (referred to as Wave1d) uses a model in which it is provided by regular wave. The topography has a single slit on middle of itself (fig.1). In comparison with Wave1d, in Wave2d Stokes Drift velocity on the large directional range is verified (fig.2).
Verification of model precision
Three runs are performed by horizontal resolution 500m and 20 vertical layers for Tanabe Bay in Wakayama prefecture. The additional run is carried out using only the Ocean model, i.e. not considering the effect of wave-current interaction. According to the comparison in velocity between these three results and observation data in, a correlation is observed between Wave2d and observation data (fig.3).
4.Conclusion
This study developed the Coupled Ocean-Wave Model to consider wave-current interaction on random wave. Wave2d simulation for Tanabe Bay was conducted and its output of velocity show qualitative correlation with observation data. This model can be adapted for accurate reproduction on a regional ocean scale, which can make it possible to project future climate on that scale.

キーワード：Stokes Drift、不規則波、波・流れ相互作用、領域スケール
Keywords: Stokes Drift, random wave, wave-current interaction, regional ocean scale

$$\mathbf{U}(z) = \frac{1}{\rho}\iint_{-\infty}^{\infty} F(\boldsymbol{k})\frac{\boldsymbol{k}}{\omega(k)}\frac{2k\cosh[2k(z+h)]}{\sinh(kh)}\mathrm{d}\mathbf{k} \qquad \text{(eq.1)}$$

ρ: water density, F: the two-dimensional energy spectrum, **k**: wave number vector, k: the magnitude of **k**, ω: angular frequency, h: total depth

$$\mathrm{E}(\omega,\theta) = \frac{m_0}{2\pi\sigma_\omega\sigma_\theta}\exp\{-\frac{1}{2}[\left(\frac{\omega-\omega_p}{\sigma_\omega}\right)^2 + \left(\frac{\theta-\theta_p}{\sigma_\theta}\right)^2]\} \qquad \text{(eq.2)}$$

ω, θ: frequency and direction, ω_p, θ_p: the principal frequency and direction, σ_ω, σ_θ : the deviation of frequency and direction, m_0: the variance of the surface elevation

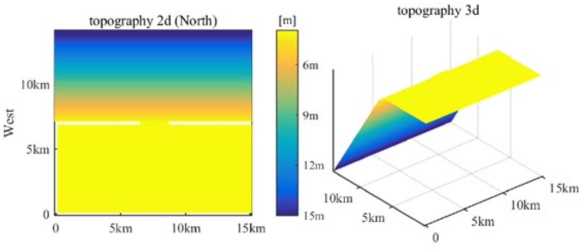

Fig.1: Topography data: left: 2 dimension, right: 3dimention

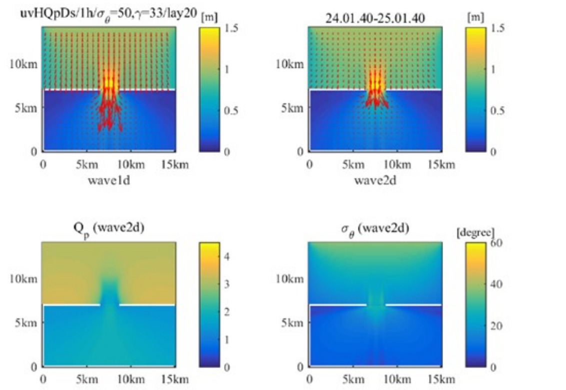

Fig.2: Stokes Drift Velocity: Upper left: Wave1d, Upper right: wave2d
Lower left: frequency deviation parameter, Lower right: directional deviation parameter

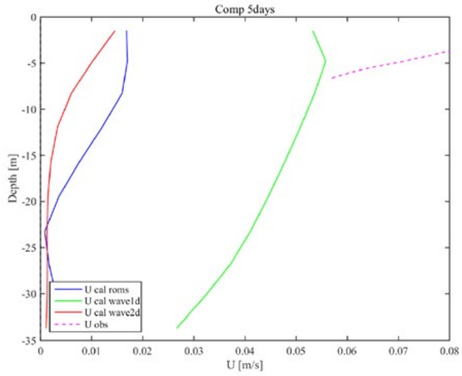

Fig.3: Velocity vertical profile: 5days mean: Blue: ROMS, Greem: Wave1d, Red: Wave2d, Magenta: Observation data