Mixing Efficiency in the Ocean

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Mixing efficiency is the ratio of the net change in potential energy to the energy expended in producing the mixing. Parameterizations of efficiency and of related mixing coefficients are needed to estimate diapycnal diffusivity from measurements of the turbulent dissipation rate. Comparing diffusivities from microstructure profiling with four simultaneous tracer releases has verified, within observational accuracy, 0.2 as the mixing coefficient over a 30-fold range of diapycnal diffusivities. Although some mixing coefficients can be estimated from pycnocline measurements, at present mixing efficiency must be obtained from channel flows, laboratory experiments and numerical simulations. Reviewing the different approaches demonstrates that estimates and parameterizations for mixing efficiency and coefficients are not converging beyond the at-sea comparisons with tracer releases, leading to recommendations for a community approach to address this important issue.

Estimating eddy diffusivities in the ocean

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Away from the surface and bottom boundaries, the interior of the oceans is stably stratified in general, and mixing occurs there due to turbulence generated by shear instability and under appropriate conditions, double-diffusive convection. The resulting eddy diffusivities of momentum and scalar properties are determined by the gradient Richardson number *Ri* in the case of shear instability and the density ratio R_{rho} in the case of double diffusive convection. However, in oceanic regions susceptible to double-diffusive convection, velocity shear may not be negligible, in which case, both *Ri* and R_{rho} play a role in determining the intensity of mixing and hence the prevailing diffusivities. Which mode of mixing dominates, depends on the precise values of these parameters. For low Richardson numbers, shear driven instability prevails and for high Richardson numbers, double diffusion can dominate. As such, when measuring eddy diffusivities in the ocean interior, it is essential to deploy a microstructure profiler along with an ADCP so that the precise location of the oceanic region in the *Ri* - R_{rho} parameter space can be determined. In this talk, we provide an overview of theoretical, observational and numerical model studies of eddy diffusivities in the ocean, with particular emphasis on double diffusive convection, and present some results from recent observational campaigns.

Keywords: Ocean mixing, Double diffusive convection, Salt fingers, Diffusive convection, eddy diffusivities

The Probability Distribution of Kinetic Energy Dissipation Rate in Ocean

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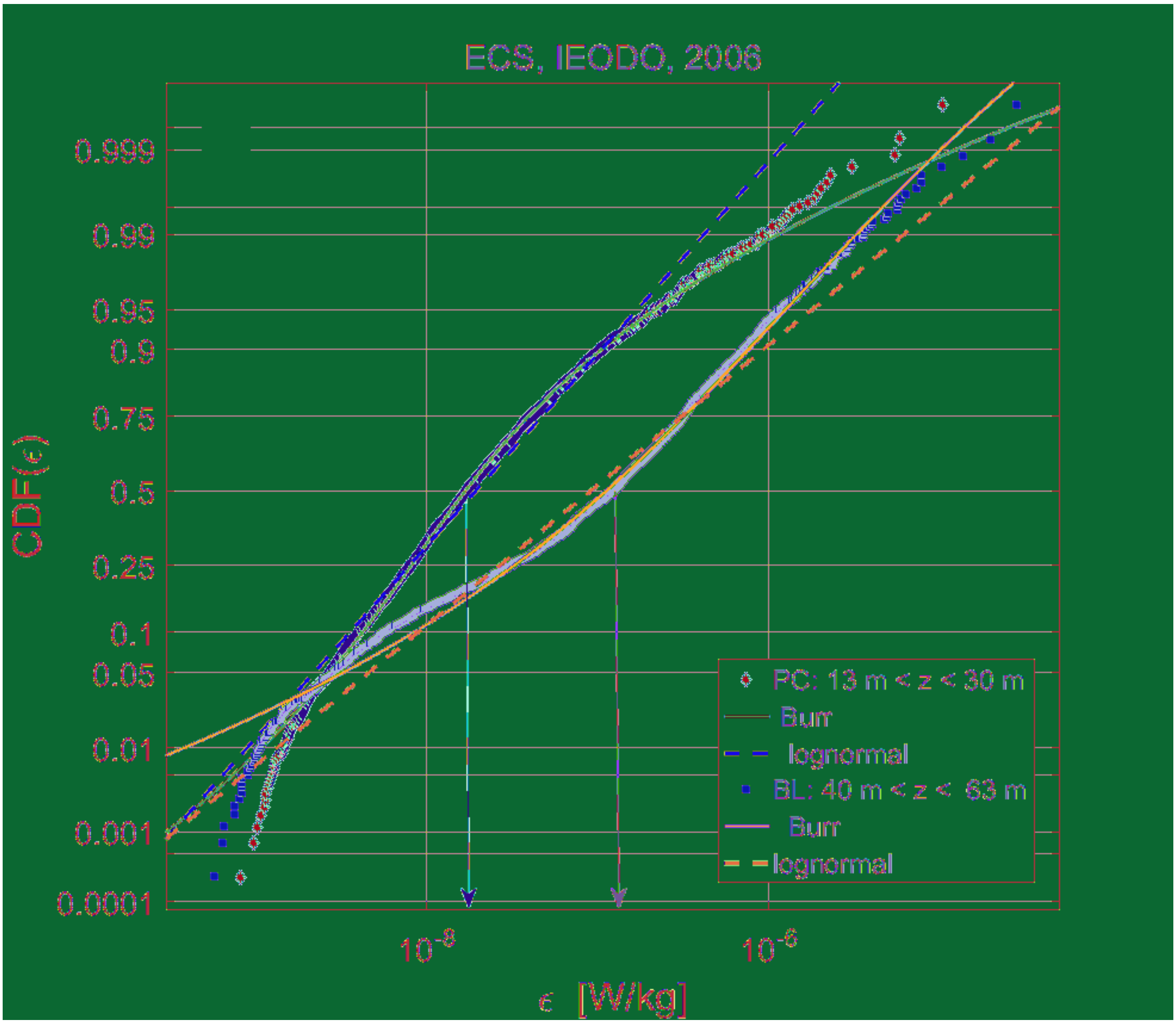
Ocean turbulence is highly intermittent in space and time with characteristic vertical scales of active turbulent zones (patches), varying from tens of centimeters up to several or sometimes tens of meters. The patches are separated by layers of relatively low turbulence activity, which is usually quantified in terms of the turbulent kinetic energy dissipation rate *eps* averaged over particular volumes or radius *r*. Such spatial inhomogeneity of dissipation has been specified as "mesoscale" or "external" intermittency in order to be distinguished from "internal" or genuine intermittency of *eps*, which is attributed to random distribution of vortex filaments within turbulent regions, where they stretch and dissipate energy in isolation. Internal intermittency of *eps* belongs to inertial-convective and diffusive subranges, between an outer turbulent scale L_o ~ 1 m or less in stratified ocean and the dissipative Kolmogorov scale L_K of the order of less than 1 cm. The refined similarity hypothesis of Kolmogorov [1962] assumes random fluctuations of dissipation rate in the inertial-convective subrange and the probability distribution of the dissipation intermittency is lognormal. Although the lognormal model and its modifications has been successfully applied to various turbulent flows under high Reynolds numbers, it appears to be mathematically ill-posed. Yet, many researchers regard lognormal distribution as reasonably good practical approximation for *eps* that characterizes internal/genuine intermittency of turbulence generated continuously or by individual events/overturns.

The lognormal model has been applied to *eps* measured in well-mixed relatively deep turbulent boundary layers near the sea surface and near the ocean floor and in large turbulent overturns (~10 m or more in diameter) that are observed in the ocean interior. However, conventional equidistant estimates of *eps*, which are usually calculated over relatively small vertical domains (typical averaging distance *l* = 1-2 m), represent a random field of the dissipation samples observed at various stages of turbulence evolution. The probability distributions of this dissipation field in a specific region can characterize external/mesoscale intermittency of turbulence influenced by larger scale dynamical processes, which depends on energy sources and ambient stratification. It has been recently shown that the probability distribution of the logarithm of the dissipation rate in a strongly stratified pycnocline can follow the generalized extreme value distribution due to rare random generation of energetic turbulence events, which form patches of high dissipation rate, while most of the background turbulence is confined to weakly dissipative regions at final stages of turbulence decay.

The notion that the probability distribution of the dissipation rate measured in stratified ocean by airfoil sensors substantially deviates from the classic lognormal approximation, often to follow the Burr probability distribution, is discussed here based on several field campaigns carried out by the authors during the last decade. The measurements have been taken in the East China Sea, Northern Bay of Bengal, to the south and to the east from Sri Lanka, and in the Gulf Stream region to the east from the North Carolina shelf. The background dynamics in the regions is characterized by distributions of the buoyancy frequency N^2 and buoyancy Reynolds number Re_b.

Keywords: turbulence, dissipation rate, intermittency, probability distribution



Submesoscale resolving ocean simulations with multiple ocean mixing parameterizations

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Motions with higher degree of ageostrophy appear in the oceanic simulations when sub-mesoscale eddies and associated boundary layer processes begin to be resolved in ocean models. These are quintessentially related to horizontal density gradients related to oceanic fronts. These motions have O(1) Rossby and O(1) Richardson numbers, much larger vertical exchange than their large scale counterparts and appear at O(1-10 km) scales in the ocean. There has been much recent interest in their interaction with both relatively smaller and larger scales. We focus on the former.

We have conducted simulations for forced submesoscale eddy resolving simulations using multiple ocean mixing closure schemes using a non-hydrostatic three dimensional process study ocean model (PSOM) including k-epsilon models and K-Profile parameterization, for both mid-latitude deep ocean mixed layers (e.g. North Atlantic) and spicy subtropical oceans with shallow mixed layers but higher density gradients (e.g. Indian ocean). We show that ocean mixing matters for the sub-mesoscale as the rate of re-stratification near oceanic fronts is sensitive to the ocean mixing parameterization. We discuss both its physical and ecosystem implications.

Keywords: submesoscale, ocean fronts, mixing parameterization

Revisiting fine-scale parameterizations for enhanced tidal mixing over a rough ocean bottom

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Although an accurate representation of ocean mixing processes into global circulation models is essential for accurate climate predictions,, existing parameterizations of mixing over rough bathymetry have plenty of room for improvement. For example, they do not take into account the fact that, as tide-topography interactions strengthen ($k_H U_0/\Omega > 1$), the generated internal waves transform from linear internal tides to quasi-steady internal lee waves where U_0 is the amplitude of the tidal flow dominating the background flow in the Garrett-Munk (GM) internal wave field, k_H is the horizontal wavenumber of the bottom topography, and Ω is the semidiurnal tidal frequency.

In the present study, using a fixed value of the buoyancy frequency, we perform a series of eikonal calculations to examine the energy transfer from upward propagating quasi-steady internal lee waves to dissipation through nonlinear interactions with the background GM internal waves in a vertical two-dimensional plane. It is shown that the vertical structure of the mixing hotspot becomes dominated by U_0 rather than k_H; as U_0 increases, the fraction of energy dissipated at the ocean bottom decreases and the energy dissipation region extends vertically upward off the ocean bottom. These calculated results can be interpreted in terms of the vertical group velocity, C_{gz}, and the life time, τ, of the upward propagating quasi-steady lee wave packet. For a fixed density stratification, as k_H increases while keeping U_0 constant, C_{gz} becomes larger but becomes smaller so that the vertical decay scale of the energy dissipation rate remains nearly constant, whereas C_{gz} becomes larger but remains unchanged as U_0 increases while keeping k_H constant so that the vertical decay scale of the energy dissipation rate rapidly increases. This means that the resulting mixing hotspot extends further upward as U_0 increases, independent of k_H. This is in contrast to the result of the previous study by *Iwamae et al.* [2009] and *Iwamae and Hibiya* [2012] who showed that the concentration of the mixing hotspot becomes more focused nearer the ocean bottom as k_H increases, independent of U_0, although a trade-off relationship is found between the fraction of energy dissipated at the ocean bottom and the vertical extent of the energy dissipation region off the ocean bottom. A possible explanation for this difference is that C_{gz} and τ are both inversely proportional to k_H for linear internal tides.

The results of this study should be reflected in the parameterization of mixing over rough bathymetry to improve the accuracy of ocean general circulation models.

Keywords: Bottom-intensified turbulent mixing, Quasi-steady lee waves, Vertical group velocity, Nonlinear interaction time, Tidal flow amplitude, Ocean bottom roughness

The Dependence of Tidal Effects Including Internal Tides and Mixing on Latitude

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The effects of latitude on internal tides, internal waves and mixing were investigated using Regional Ocean Modeling System (ROMS) simulations by shifting a small domain with a seamount from 20.6° to 28.6° S. The critical latitude is the latitude where the inertial frequency equals the tidal frequency, which for the K_1 constituent is 30° and O_1 is 27.6°. Linear internal wave theory says that internal tides are trapped and will not propagate poleward of their respective critical latitudes. The same topography and hydrography from Barcoo Seamount off New South Wales collected during SS0906 were used in all simulations.
The largest diurnal tides occurred near the critical latitudes and for 3-6° equatorward of critical latitude. The diurnal internal tides equatorward of the diurnal critical latitudes propagated in beams in agreement with linear theory. At the diurnal critical latitudes, diurnal energy peaked. Poleward of critical latitude, the diurnal internal waves had a signature which encompassed more of the water column vertically and they did not propagate in a beam-like pattern. By 8° poleward of the K_1 critical latitude, critical latitude effects had ceased. Poleward of the diurnal critical latitudes, significant diurnal internal tidal energy shifted to the semidiurnal constituents, harmonics, and high frequencies. As a result, semidiurnal internal tidal energy peaked just poleward of the diurnal critical latitude, as did energy at the tidal harmonic frequencies, 3, 4, 6, 8, cpd. Bispectra confirmed these energy transfers. Tidal residuals, mean velocities generated by the tides, were latitude and depth dependent, with the largest residuals near the critical latitudes and within 6 ° poleward of them. The latitudes 4-6° poleward of the K_1 critical latitude had the highest vertical temperature diffusivities along the flanks of the seamount and they showed the largest temperature changes in the neighbourhood of the permanent pycnocline, 500-100 m depth. The average diffusivities of both temperature and momentum increased with increasing latitude until near the critical latitude, where they dipped at both critical latitudes. Poleward of the critical latitudes, the diffusivities peaked 4° poleward of the K_1 critical latitude and then decreased with increasing latitude. Due to vertical shifts in the location of the higher diffusivities, changes in potential temperature and salinity were significantly larger and of the opposite sign for the latitudes 4-6° poleward of the K_1 critical latitude than for the other latitudes.

Keywords: mixing, internal tides, critical latitude

How the Tokara strait cultivates the Kuroshio

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Previous studies have reported clear signs of vigorous turbulent mixing in the Kuroshio due to the presences of shallow and steep topographies in its path (e.g., Hasegawa et al., 2004 and 2008, Chang et al., 2016). Turbulent mixing is one of the most important processes supplying nutrients to the surface euphotic zone from the deep water; however, a quantitative understanding of the turbulent vertical nutrient flux is still limited. On November 2016, we have conducted intensive survey around the Tokara strait by drifting the T/V Kagoshima-maru with the Kuroshio's stream and passed across the shallow (~100 m) sill while deploying a submersible ultraviolet nitrate analyzer (Deep SUNA by Satlantic) attached on a turbulence ocean microstructure profiler (TurboMAP-L by JAC). Occurrence of a flow separation and a hydraulic jump on the sill have been identified from a high resolution velocity survey. The rate of dissipation of kinetic energy reaches $O(10^{-5}$ W kg$^{-1})$, and the turbulent vertical nitrate flux reaches $O(1$ mmol m^{-2} day$^{-1})$, which is the highest value ever reported for the open ocean.

Keywords: Turbulence, Mixing, Topography, Nutrient, Nitrate, Flux

Observations of bands of strong turbulence associated with high wavenumber near-inertial wave shear below the Kuroshio origin using a tow-yo microstructure profiler

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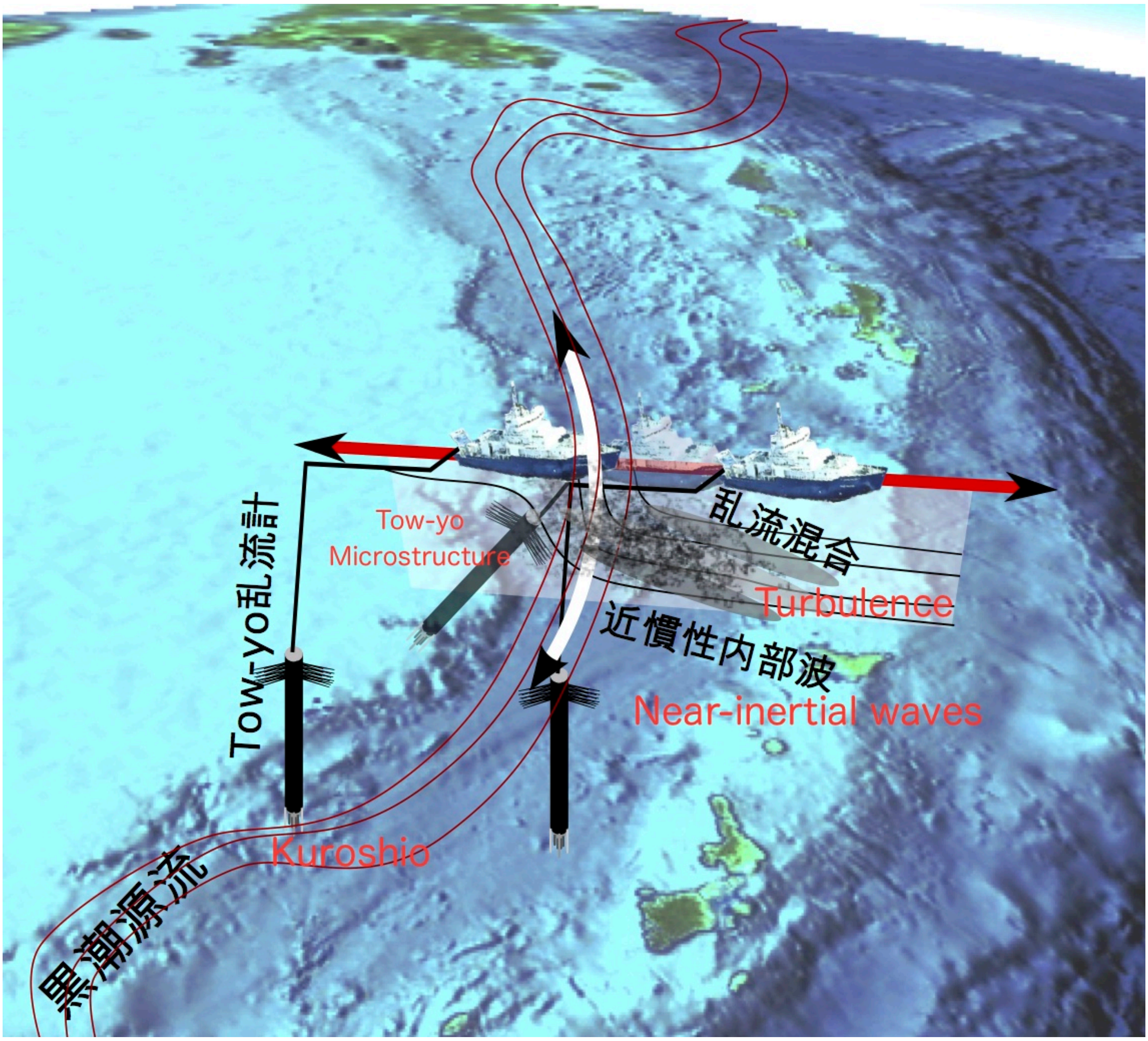
The upstream Kuroshio flows through Okinawa trough and Tokara island chains. In these regions, latitude is near 28.9 degree N, as known as the critical latitude, where M_2 internal tides can be converted to near-initial internal waves of high vertical wavenumber through parametric subharmonic instability and associated strong turbulent mixing is expected (MacKinnon and Winters 2005, Hibiya and Nagasawa 2004). Furthermore, the Kuroshio has to go through the region near the continental shelf of East China Sea and shallow seamounts near the Tokara strait, where the lee wave generation by the geostrophic current over the topography and associated near-inertial waves (Nikurashin and Ferrari 2011) are likely to occur. Also, the Kuroshio is forced to meander to flow southward after it approaches off Kyushu, where the spontaneous generation of near-inertial internal waves is possible (Nagai et al. 2015). The in-situ observations by Rainville and Pinkel (2004) using the ADCP and LADCP show that large amplitude near-inertial wave shear of high vertical wavenumber is found in and below the Kuroshio thermocline. These near-inertial internal waves can be trapped on the south side and/or underneath the Kuroshio due to its strong negative relative vorticity and vertical shear of the horizontal geostrophic flow (Kunze 1985, Whitt and Thomas 2013), and possibly break into microscale turbulence. However, the in-situ observations of microscale turbulence is very limited in these regions. In this study, in-situ observations of microscale turbulence near the Tokara strait were conducted during Nov. 12-20 2016 using R/T/V Kagoshima-maru. The new underway tow-yo microstructure profiler (Underway-VMP) was used, and we successfully measured turbulence along and across the Kuroshio Front with 1-2 km lateral resolution. The shipboard ADCP measurements show bands of high vertical wavenumber shear nearly along isopycnal, which are reminiscent of the results by Rainville and Pinkel (2004). The ray path calculated assuming quiescent condition suggests that the observed shear bands are caused by the internal waves of near-inertial frequencies. The hodograph of shear and rotary spectra suggest that these internal waves propagate energy both up and downward directions. The measured turbulent kinetic energy dissipation rates along and across the Kuroshio show bands of strong turbulence >$O(10^{-7}$ W/kg) clearly associated with the high vertical wavenumber near-inertial shear, suggesting that propagating near-inertial waves underneath the Kuroshio induces the strong turbulent mixing. The comparison of observed turbulent dissipation rates with the strain based internal-wave parameterization by Kunzel et al. (2006) shows certain proportionality between the observations and the parameterization, which supports the conclusion that the measured strong turbulence is caused by the observed high vertical wavenumber near-inertial waves. The estimated vertical eddy diffusivity using the method of Osborn (1980) with observed dissipation rates and stratification, shows $O(10^{-4}$ m^2/s) of eddy diffusivities on average within these bands of turbulent layers. These results suggest that the high vertical wavenumber near-inertial waves propagating in and below the Kuroshio near the Tokara strait could cause large impacts on the local watermass formations, tracer and momentum mixing, and associated biogeochemical responses in its downstream.

Keywords: Kuroshio, near-inertial shear bands, bands of strong turbulent layer



Assessment of the existing fine-scale parameterizations of deep ocean mixing in the Antarctic Circumpolar Current regeon

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The intensity of the observed deep ocean mixing is obviously falling short of the required value to sustain the global overturning circulation. The most likely candidates for this missing mixing are breaking of near-inertial waves induced by strong westerly wind and internal lee waves generated by Antarctic Circumpolar Current (ACC) impinging on rough topography in the Southern Ocean. Quantification of the turbulent mixing in the Southern Ocean is, therefore, an important issue to elucidate the structure of the global overturning circulation.

Because of the difficulty of direct microstructure measurements, it is common to employ finescale parameterizations (especially, Gregg-Henyey-Polzin (GHP) parameterization) to estimate turbulent energy dissipation rates. In these parameterizations, however, turbulent dissipation rates are assumed to be predicted as the rate of energy transfer to small dissipation scales by wave-wave interactions within the background internal wave spectrum and the effects of geostrophic current shear and mesoscale eddies, both of which are ubiquitous in the Southern Ocean, are not taken into account.

In this study, we carried out simultaneous measurements of microscale turbulence and finescale shear/strain in the Southern Ocean, south of Australia to assess the validity of the existing finescale parameterizations in the ACC region where geostrophic flows and mesoscale eddies coexist with the background internal wavefield.

Although the turbulent dissipation rate and derived diapycnal diffusivity were overall small, the internal wave energy was larger than the Garrett-Munk (GM) value. The finescale shear/strain ratio (R_ω) well exceeded the GM value at the stations south of Southern ACC Front, suggesting that the local internal wave spectra were significantly biased to lower frequencies.

Through the comparison of the turbulent dissipation rates inferred from parameterizations with the directly measured values, we find that GHP and Ijichi-Hibiya (IH) parameterizations, both of which take into account the spectral distortion in terms of R_ω, can well predict the observed turbulent dissipation rates in many places, while the shear-based parameterization (the strain-based parameterization) tends to overestimate (underestimate) the observed values, consistent with the large value of R_ω.

However, at the stations where the vertical shear of mean flow, presumably associated with geostrophic flows and/or mesoscale eddies, is enhanced, even GHP and IH parameterizations tend to overestimate turbulent dissipation rates by up to a factor of 3. At one of these stations, in particular, we find dominant downward-propagating near-inertial waves with their vertical wavenumbers possibly doppler-shifted up to the breaking limit at the critical layer. The overestimated turbulent dissipation rates mentioned above might be explained by the fact that the near-inertial wave energy lost at the critical layer is not completely dissipated but partially transferred to the background mean flow.

Keywords: Antarctic Circumpolar Current, Southern Ocean, deep ocean mixing, finescale parameterizations

Submesoscale cascade processes in the S. China Sea

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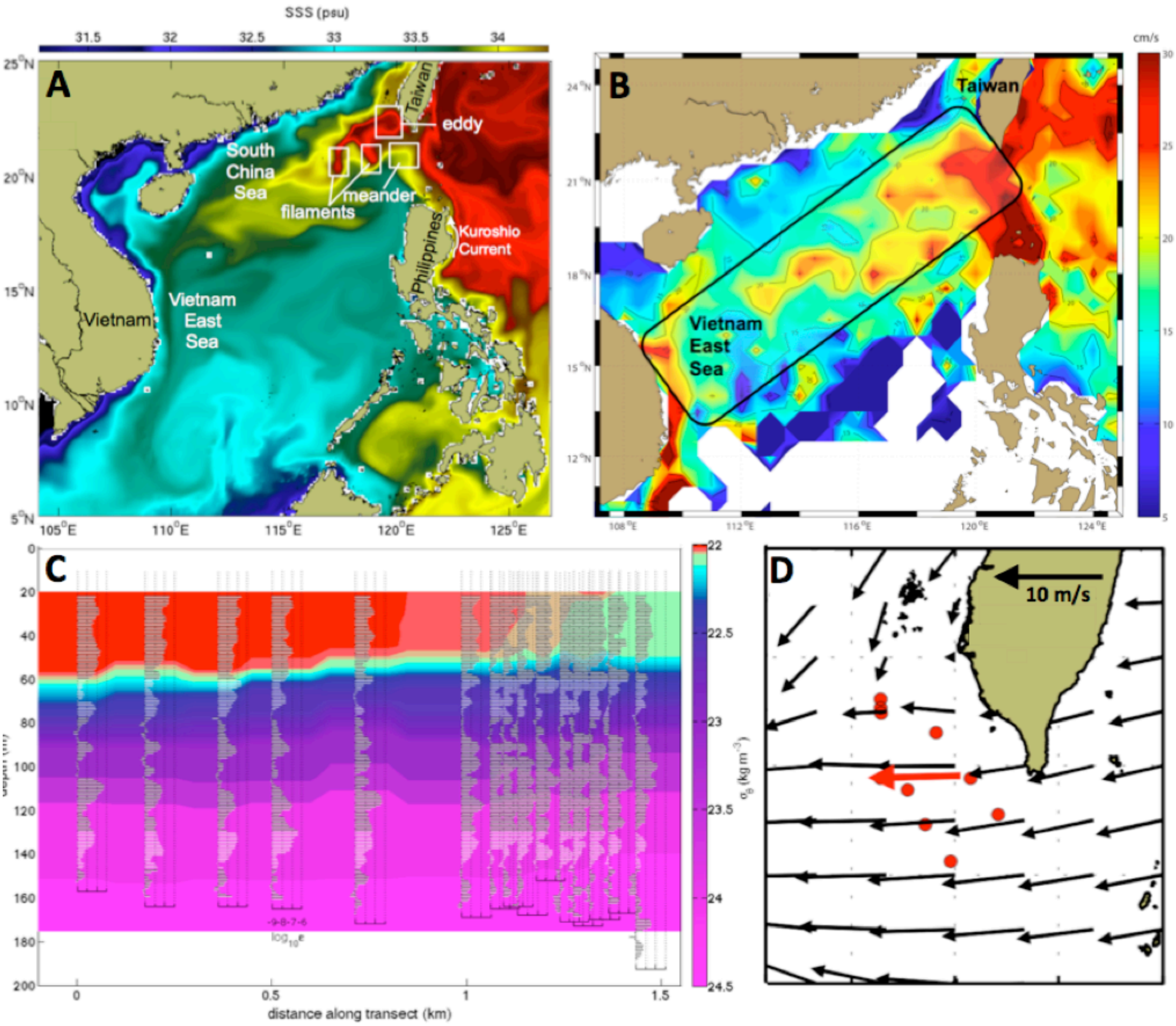
The S. China Sea is understood to be one of the most energetic regional seas in the global ocean. The combination of the Kuroshio Current, the monsoon, strong tides, and the dramatic topography of the Luzon Strait lead to a rich physical forcing environment. In addition to the enhanced internal wave environment that has been the focus of much work (ASIAEX, NLIWI and IWISE), the region southwest of Taiwan has been documented as a maximum in eddy kinetic energy. However, outside of the realm of internal wave processes, the physics of the submesoscale cascade of energy has been poorly studied.

Here, we describe a new examination of submesoscale processes in the S. China Sea. The focus is on the class of oceanographic variability that is poorly constrained in models including eddies, vortices and filaments, and their interactions with smaller-scale phenomena (Fig. 1A). While the whole S. China Sea system is of interest, including the Vietnam East Sea, the initial survey work has focused on the region just southwest of Taiwan. In this region, the Kuroshio Current feeds warm-salty water through the Luzon Strait. As the Current meanders into the Luzon Strait, it sheds eddies and filaments, which in turn interact with the local wind forcing. Along the southern tip of Taiwan, the wind field is complicated by the blocking effects of high mountains on the eastern side of Taiwan, with easterly winds south of Taiwan, and northerly winds in the Taiwan Strait. This combination of eddies, filaments, and wind lead to an active submesoscale cascade.

Keywords: Mixing, Monsoon, Cascade


SSS (psu)
31.5
32
32.5
33
33.5
34
A
South China Sea
filaments
meander
eddy
Taiwan
Kuroshio Current
Philippines
Vietnam
Vietnam East Sea
105°E
110°E
115°E
120°E
125°E
25°N
20°N
15°N
10°N
5°N
B
Taiwan
Vietnam East Sea
cm/s
C
distance along transect (km)
log10ε
σθ (kg m⁻³)
D
10 m/s

Non-hydrostatic simulations of tidally-induced mixing in the Halmahera Sea: A possible role in the transformation of the Indonesian Throughflow waters

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The Indonesian Throughflow (ITF) carries the relatively warm and saline Pacific waters into the Indian Ocean. These waters are significantly transformed while passing through the Indonesian Archipelago and eventually influence the large-scale ocean circulation such as Agulhas and Leeuwin Currents. Most OGCMs are, however, incapable of reproducing the transformation of the ITF waters, since tidal forcing is neglected in such models.
In the present study, we focus on the Halmahera Sea where the saline bias of the existing OGCMs is most significant. In order to clarify the physical mechanisms that control the water-mass transformation in the Halmahera Sea, we first drive a high-resolution (dx, dy ~ 180 m) non-hydrostatic three-dimensional numerical model incorporating realistic tidal forcing and bathymetric features. On the basis of the calculated results, we next evaluate each of the effects of tidally-enhanced vertical and horizontal mixing on the transformation of the ITF waters. It is shown that, although the water-mass transformation is dominated by the vertical mixing induced by breaking of internal tides, non-negligible contribution is found from the horizontal mixing enhanced by the sub-mesoscale eddies resulting from tidal flow interaction with complicated land configurations.

Keywords: Tidal mixing, Indonesian Throughflow, Water-mass transformation, Sub-mesoscale eddies

Mapping of vortex and internal waves interaction-induced mixing in the North Pacific from OFES30 output

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Breaking of internal waves are a major source of mixing that contributes to upwelling of nutrients, driving force of thermohaline circulation, water mass formation. The breaking of internal waves have been studied in the context of quiet ocean without a background flow. Recently, some studies have pointed that the interaction between a vortex and internal gravity waves affects the mixing. Those previous researches handle the interaction problem with WKB like methods which assume a scale separation between a large vortex and small waves. However, in the ocean, there are many small, strong vortices like submeso-scale ones are ubiquitous. These vortices violate the scale separation assumption, so that a WKB like approach is invalid. The interaction in this range is never covered in the past studies. We numerically investigated the interaction in a wide parameter range including submeso-scale vortices and long internal waves. Then, the result is applied to the output of a high resolution ocean general circulation model, and the energetic interaction-induced mixing region is mapped. Model settings, datasets and results are described below. MODEL SETTINGS: A three dimensional non-hydrostatic model named “kinaco” is used to simulate the interaction of a vortex and waves. As initial conditions, Barotropic cyclone is put on the center of the model region and internal gravity waves that propagate toward the vortex are put on near an end of the model region. The experiments are controlled by a parameter which scales advection by a vortex, arises from our non-dimensional analysis of the shallow-water system. DATA SETS: The output of OFES30 (Masumoto et al., 2004; Sasaki et al., 2012) is used to estimate the distribution and structure of vortices in the North Pacific Ocean. Interaction-induced mixing is estimated for each vortex for internal waves of M2 tidal frequency. Results: From numerical experiments, dynamics of the interaction is classified to three regimes; First, Incident waves are scattered in two particular directions and vortex only works as catalyst. Second, a part of the incident waves are trapped into the vortex core, residual are scattered to various directions. Third, in strong non-linear vortex case, almost all incident waves are trapped, forming spiral shape, then shrinking rapidly in the radial direction, resulting in increase of vertical wavenumber. The vortex is also affected by shrinked waves through divergence of wave activity flux. As the overall tendency, both increasing rate of vertical wave number and trapped rate of the incident waves energy show monotonic increase with increasing value of the non-dimensional parameter. This suggests that the parameter should be an indicator of interaction-induced mixing. This indicator is estimated using OFES30 output. Remarkably, an extent of regions with large interaction-induced mixing is considerable in the North Pacific Ocean.

Keywords: internal wave, submeso-scale vortex, mixing

Wind-induced mixing in the North Pacific

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Temporal variability of the winter input of wind energy flux (wind power) and its relationship to internal wave fields were examined in the North Pacific. The dominant long-term variability of the wind power input, estimated from the mixed layer slab model, was inferred from an empirical orthogonal function analysis and corresponded to the strength and movement of the Aleutian Low. Responses of the internal wave field to the input of wind power were examined for two winters with a meridional float array along 170°W at a sampling interval of 2 dbar. Time series of the vertical diffusivities inferred from density profiles were enhanced during autumn and winter. After comparing diffusivities inferred from densities sampling at 2-dbar and 20-dbar intervals, we used Argo floats with a vertical resolution of 20 dbar to detect spatial and temporal variability of storm-related mixing between 700 and 1000 dbar in the North Pacific for 10 years. Horizontal maps of seasonal inferred diffusivities also suggested that the diffusivities were enhanced in autumn and winter. However, it is unlikely that there is a simple linear relationship between the input of wind power and the inferred mixing.

Intra-seasonal Variations of Upper-Ocean Mixing in Western North Pacific

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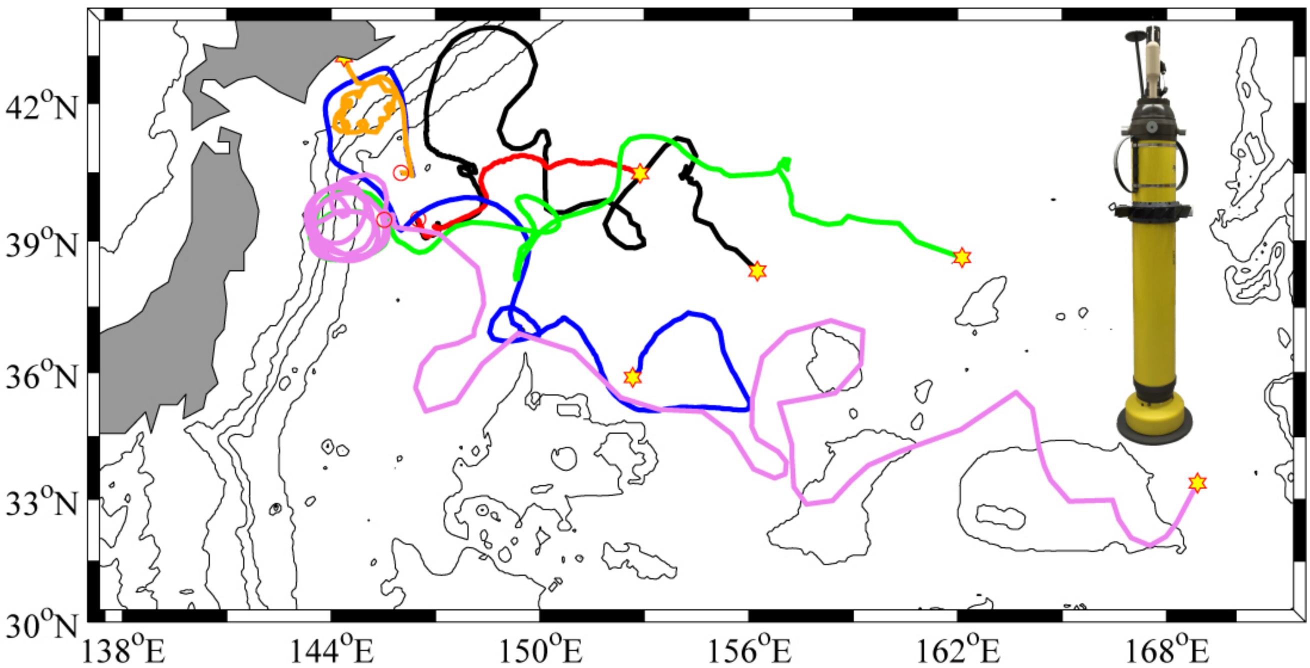
Previous studies suggest that the strongest inertial wind power injected into the ocean occurs in the western North Pacific during fall storm inertial wave generation. The energy pathway of these storm-driven inertial waves is not well known. Studies based on mooring observations suggest that only 15-25% of inertial wave energy propagate away from the forcing field as low modes, implying that 75-85% of the inertial wave power dissipated in the nearfield. Deployed in late August 2016, six microstructure EM-APEX floats collected nearly 5-months of measurements of water mass, horizontal current, and turbulence in the Kuroshio-Oyashio confluence. Intra-seasonal variations of turbulent mixing in the surface mixed layer and thermocline are revealed. Preliminary results will be presented. Turbulence kinetic energy dissipation rates, averaged over the upper 120 m, increase from ~5 x 10^{-9} W kg^{-1} at the late summer to 10^{-7} W kg^{-1} by mid-fall, a factor of 20 enhancement in two months. This enhanced turbulent mixing is correlated with increased inertial wind power from the passage of multiple fall tropical cyclones and lows, elevated upper-ocean inertial wave energy and mixed-layer deepening. Strong near-inertial waves propagate vertically to nearly1000-m depth and last as much as one week after storm passage.

Keywords: Storm Forced Inertial Waves, Upper Ocean Turbulence Mixing, Kuroshio-Oyashio Confluence



The role of wind gusts in upper ocean diurnal variability.

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Upper ocean processes play a key role in air-sea coupling, with variability on both short and long timescales. The diurnal cycle associated with diurnal solar insolation and night-time cooling, may act, along with stochastic wind variability, on upper ocean temperatures and stratification resulting in a diurnal warm layer and a nonlinear rectified effect on longer timescales.

This study describes diurnal changes in temperature in the upper 10 m of the water column for a location in the equatorial Indian Ocean, using observations from the Dynamics of the Madden-Julian Oscillation field campaign, a high vertical resolution 1-D process model, and a diurnal cycling scheme *[Large and Caron, 2015]*. Solar forcing is the main driver of diurnal variability in ocean temperature and stratification. Yet wind gusts regulate how fast the solar radiation warmed water is mixed to greater depths in time. Wind gusts are much stronger than diurnal winds. Even using no diurnal winds and stochastic wind gusts as input in a 1-D process model yields an estimate of diurnal temperature that compares well with observations.

A new version of the *Large and Caron [2015]* parameterization scheme (LC2015) provides an estimate of upper ocean diurnal temperature that is consistent with observations. LC2015 has the advantage of being suitable for implementation in a climate model, with the goal to improve SST estimates, hence the simulated heat flux at the air-sea interface. Yet LC2015 is not very sensitive to the inclusion or omission of the high-frequency component of the wind.

Keywords: Diurnal variability, Wind gusts, Upper ocean temperature

Turbulence induced by near-surface inertial oscillations and its impact on sea surface temperature variability

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It is well known that inertial oscillations in the surface mixed layer impact the evolution of sea surface temperature (SST) through turbulent mixing. SST is a key parameter controlling the climate and its variability. On the diurnal timescale, diurnal warm layers are observed to form in diverse oceanic regions under calm conditions. Properly modeling their formation and erosion in tropical areas is key to improving simulations of intraseasonal variability. Inertial oscillations may be present even under fairly calm conditions and are an important factor impacting both the formation and erosion of diurnal warm layers. We will present and discuss results from observations and modeling studies. We focus on the role that inertial oscillations play in the dynamics of diurnal warm layers and SST, through the analysis of several case studies, covering different background regimes and a variety of strengths of the inertial oscillation. Our results, suggest the important role that background stratification plays, both directly and indirectly (via internal wave radiation) in moderating the exchange of heat between surface and thermocline, more so than the intensity of the turbulence at the mixed layer base.

Keywords: turbulence, inertial oscillations, sea surface temperature , mixing, stratification

Turbulent Control of the Thermal Structure in Continental Shelf Seas

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Microstructure measurements made using a buoyancy driven ocean glider are used to investigate the mechanisms controlling the seasonal thermal structure of a temperate continental shelf sea. The autonomous nature of the Ocean Microstructure Glider (OMG) permits resolution of turbulence and mixing within the near surface region. We use these data to investigate the varying controls from wind, wave and buoyancy forcing on the formation and maintenance of seasonal stratification and the contribution from tidal boundary mixing and internal mixing from internal gravity waves and wind-triggered inertial motions. We will characterize the relative effects of wind and wave forcing on turbulence in the upper ocean later using the turbulent Langmuir number (La_t) and examine the observed variability in surface forcing relative to subsequent changes in heat and momentum transfer to the upper ocean and thermocline. We find that wind and wave effects appear well balanced (typified by a La_t~0.3) and that turbulence can be well described by a classic law of the wall profile, scaled with the surface friction velocity alone. During a brief period when waves do dominate we find that turbulence scales directly with Stokes drift. Rather than following an z^{-1} decay, turbulence under these conditions is driven deep into the upper mixed layer. The relative importance of surface driven turbulence on the overall thermal structure is investigated and balanced against contributions from internal and bottom boundary mixing mechanisms.

Keywords: Ocean Turbulence, boundary layer, ocean gliders

Kinetic Energy Flux Budget Across Air-sea Interface

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The kinetic energy (KE) fluxes into subsurface currents (EF_c) is important boundary condition for vertical mixing in ocean circulation models. Traditionally, numerical models assume the KE flux from wind is identical to the KE flux into subsurface currents, that is, no net KE is gained (or lost) by surface waves. This assumption, however, is invalid when the surface wave field is not fully developed. When the surface wave field grows in space or time, it acquires kinetic energy, hence, reduces the KE fluxes into subsurface currents compared to the fluxes from wind. In this study, numerical experiments are performed to investigate the KE flux budget across the air-sea interface under both uniform and idealized tropical cyclone winds. The wave fields are simulated using the WAVEWATCH III model under various wind forcing. The difference between the KE flux from wind and that into ocean currents is estimated using an air-sea KE budget model. To address the uncertainty of these estimates resides in the variation of source functions, two source function packages are used for this study: the coupled wind wave model by Moon et al (2004) and the ST4 source package by Ardhuin et al (2010). Simulated KE flux into the ocean currents are found to be consistent with field observations by Terray et al. (1996) and Drennan et al (1996). It is significantly reduced relative to the KE flux input from wind under growing seas. The reduction can be as large as 20%, and the variation of this ratio is highly dependent on the choice of source function for the wave model. Our results also suggest that the normalized KE flux by the friction velocity cube (u_*^3) may depend on both wave age and friction velocity (u_*), and a new parameterization for EF_c is proposed.

Keywords: turbulent kinetic energy, surface gravity waves, high winds

Turbulence estimation using fast response thermistors attached to CTD frames

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Turbulence observations have been limited because of difficulty in microstructure measurements. In order to efficiently obtain more turbulence data down to the ocean floor without spending extra ship-time, we introduce a new method using a fast response thermistor attached to a CTD frame. Turbulence intensity from CTD-attached profilers is evaluated by comparing it with free-fall vertical microstructure profilers measured at the same location within 2 hours. Turbulence intensity from the CTD-attached profilers is roughly comparable with the one from the free-fall profilers. Whereas, excessively overestimated data are sometimes observed for the CTD-attached method, and regarded to be abnormal since those data are deviated from log-normal distributions and correspond to the small fall rate W ($W < 0.5$ m/s) and the large standard deviation of W ($W_{sd} > 0.1$ m/s). Temperature gradient spectra also tend to be disturbed in that case. The overestimated data are capable to be removed by the simple criterion of $W_{sd}/W > 0.2$. As a result of the data screening, thermal and energy dissipation, χ and ε, from CTD-attached and free-fall profilers are consistent within the factor of 3 in the range of $10^{-10} < \chi$ [℃^{2}/s] (ε [W/kg]) $< 10^{-7}$ (10^{-8}) for 50m-bin averaged data, respectively. Observations using CTD-attached profilers are performed covering a wide range of the northwest Pacific Ocean, and turbulence distribution from the surface to the deep ocean is estimated.

Keywords: physical oeanography, turbulence, micro temperature, oceanic observations, microstructure profiler

Estimates of eddy diffusivities using fast response thermistors

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We assess the performance of the CTD (conductivity-temperature-depth profiler) system equipped with a microstructure profiler called MicroRider (MR, manufactured by Rockland Scientific Inc.) in measuring microstructure in the deep ocean through the field observation carried out in 2017. Temperature overturns were detected by the fast response thermistor (FPO-7). The overturning scales (the Thorpe scale L_T) are converted into energy dissipation rates, which are then compared with those directly measured by Vertical Microstructure Profiler (VMP) in the same region in 2016. We find that, although the difference between the eddy diffusivities obtained by MR and VMP is large in the upper layer, it diminishes as the measuring depth increases. This motivates us to introduce the ratio R_{OT} of the Ozmidov scale L_O to the Thorpe scale L_T which depends on the density stratification. We define the value of R_{OT} as $\alpha N/N_{ave}$ (N is the buoyancy frequency, and N_{ave} is the average value of N) and estimate suitable α. It is found that, compared to the case using constant ratio $R_{OT} = 0.8$, the root mean square (rms) between the eddy diffusivities obtained by MR and VMP is decreased by an order. Thus, using the corrected factor R_{OT} obtained in this study, the eddy diffusivities estimated by MR become comparable to those directly measured by VMP, except for the layers affected by the background temperature inversions and double diffusion.

Keywords: Thorpe scale, Temperature overturn, MicroRider

Development of deep profiling floats with turbulence sensors

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A float-type repeatable microstructure profiler is developed, and tested in the ocean. The Deep NINJA float (Tsurumi Seiki) equipped with turbulence sensors (Rockland Scientific International Inc.) repeatedly measures turbulence-intensity and CTD down to 4000 m depth with shear probe and FP07 fast thermistor. A field test was conducted in the Shinsei-maru KS-16-10 cruise in August 3-11, 2016.

The profiler completed 8 dives in the Sagami Bay. At each dive, ascending speed and duration of engine operation were monitored by changing pump volume etc. to seek optimal operation for turbulence observations. We also examine to what extent CTD pump or engine operation influence on observed turbulence data. The engine generates noise which sometimes interfere shear probe measurements and might have some influence on thermistor measurements. Noise of CTD pump operation is not detected. Availability and limitation of the measurement are being investigated.

Evaluation of Mixing Coefficients in the Deep Ocean

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On the basis of an accumulation of observational results obtained mostly in the upper ocean, the mixing coefficient Γ in the Osborn's diapycnal diffusivity model is usually treated as a constant, $\Gamma = 0.2$. However, it has not been fully addressed whether Γ remains constant throughout the deep ocean. To address this issue, we estimate Γ using deep profiles of the turbulent kinetic energy dissipation rate ε and the temperature variance dissipation rate χ_T obtained in various regions such as the Izu-Ogasawara Ridge, the Emperor Seamounts, the Aleutian Ridge, and the Southern Ocean. The estimated Γ is surprisingly variable, possibly depending on the density ratio R_ρ, the buoyancy frequency N, and the buoyancy Reynolds number $Re_b = \varepsilon/(\nu N^2)$ with ν as the kinematic viscosity. While the estimated Γ remains to be around the conventional value of 0.2 in the temperature-stratified upper ocean with $R_\rho > 2$ or $R_\rho < -1$, Γ tends to increase to ~1 not only in the salinity-stratified upper ocean with $|R_\rho| << 1$ but also in the deep ocean. The increasing trend of Γ in the deep ocean appears to be related to the decreasing trend of N and/or the increasing trend of Re_b. This study thus suggests that the diapycnal diffusivity in the deep ocean might be significantly larger than ever thought.

Keywords: Mixing coefficient, Diapycnal diffusivity, Density ratio, Buoyancy frequency, Buoyancy Reynolds number

Detailed water properties of mesoscale vortex pairs in the Sea of Japan: direct observations using an underwater glider

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The Sea of Japan is a marginal sea bounded by the Asian landmass and the Japanese islands. Warm, saline Kuroshio waters enter the sea via the Tsushima Strait to form the Tsushima Warm Current. The Subpolar Front extends roughly along 40ºN to the Tsugaru Strait. Large horizontal density gradients across the front maintain a surface-intensified jet with a lateral scale of *O*(10 km) and speeds exceeding 0.5 m s^{-1}. The region offshore of Sado Island and the Noto Peninsula (i.e., along the southern margin of the central Sea of Japan) is characterized primarily by an eastward jet flows along the Subpolar Front and the Tsushima Warm Current and mesoscale eddies formed around the main currents. The anomalous intrusion of such currents and eddies into this region cause perturbations of temperature and salinity, which raise serious concerns for the set-net fisheries and aquaculturists in the region. Although earlier studies have investigated those synoptic-scale and mesoscale structures, their details remain unclear owing to insufficient in-situ data.

We successfully completed for the first time a spatially high-resolution survey with an underwater glider (Seaglider, Kongsberg Underwater Technology Inc.) along a Jason-2 satellite altimeter track #86 off Sado Island from 20 April through 2 June 2016. The Seaglider repeatedly profiled temperature and salinity from the ocean surface to roughly 900 m depth with an along-track profile separation 2–3 km, which is sufficient to resolve the mesoscale structures. A total of 257 profiles were obtained during a two-round-trip observation (four transects; referred to as "Transects 1–4").

We applied principal component analysis using a time series of the absolute sea surface height (SSH) from 1993 to 2015 by AVISO and a correlation matrix method. Horizontal distribution of SSH of the first principal component are approximately in phase over the interested study domain with intraseasonal variations, whereas that of the second principal component (PC2) shows the existence of a vortex pair off Sado Island with primarily interannual variation.

A large variability of mesoscale frontal/eddy structures and water properties was revealed by the glider observations; Transects 1 to 4 were respectively characterized by a cyclonic eddy, a vortex pair, an anticyclonic eddy, and baroclinic jets (no eddies). We detected the vortex pair consisting of northern anticyclonic eddy and southern cyclonic eddy along Transect 2, almost corresponding to that of PC2. The paired anticyclonic and cyclonic eddies have distinct water properties and spatial structures. The anticyclonic eddy had a diffusive-convection favorable vertical structure near the surface layer (< 50 m depth) characterized by water being colder and fresher than those at the underlying subsurface layer. The counterpart of the cyclonic eddy was salt-fingering favorable which is warmer and more saline at the surface layer. In the cyclonic eddy, horizontal interleaving structures were also observed. With the horizontally high-resolution data obtained by the glider observations we will investigate the mixing processes and their spatial/temporal variability within the vortex pair system from statistical and quantitative approaches.

Keywords: underwater glider, vortex pairs, spatiotemporal change, subpolar front

Fine-scale structure and mixing across the front between the Tsugaru Warm and Oyashio Currents in summer along the Sanriku Coast, east of Japan

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High-resolution shipboard observations were made across the front between the Tsugaru Warm Current (TWC) and the Oyashio in July 2013. Fine structure in the frontal zones were successfully captured with an Underway Conductivity–Temperature–Depth (UCTD) profiler deployed with a typical horizontal interval of 2–3 nautical miles. The front characterized by marked horizontal gradients in temperature and salinity extended from the subsurface onto the shelf. Along this frontal layer, the minimum frequency for internal waves became substantially lower than the local inertial frequency, mainly due to the strong vertical shear of the geostrophic velocity. Turbulent energy dissipation rates ε (vertical diffusivity K_ρ) were frequently elevated along the front and its offshore side up to 3×10^{-8} W kg^{-1} (10^{-4} m^2 s^{-1}), which may have been caused by an "internal tide chimney", trapping low-frequency internal waves within the band of strong shear. At the onshore side of the TWC on the shelf, strong mixing with ε (K_ρ) exceeding 10^{-6} W kg^{-1} (10^{-3} m^2 s^{-1}) was also observed. A large portion of the water columns in the frontal area provided suitable conditions for double diffusion; in some layers with moderate turbulence, temperature microstructures indicative of double diffusion were observed. The vigorous mixing processes around the front are likely to modify the properties of the TWC downstream, which could then produce a latitudinal gradient in environments along the coast.

Keywords: Tsugaru Warm Current, Oyashio, Front, Vertical mixing, Internal tide chimney

Turbulent mixing within the Kuroshio in Tokara Strait

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Strong turbulent mixing within the Kuroshio are observed using a microstructure profiler in Tokara Strait. The Kuroshio current is greatly modified at shallow seamounts. The vertical diffusivity in the Kuroshio at the lee of the seamount is enhanced nearly 100 times from the upstream site to K_{rho} ~ $O(10^{-3})$–$O(10^{-2})$ m^2 s^{-1}. In the 70-m thick shear enhanced turbulence layer, the flow is in favor of shear instability. A one-dimensional diffusion model using the observed eddy diffusivity reproduces the observed water mass transformation. However, the estimated diffusion time scale is at least 10 times longer than the advection time scale and suggests much stronger turbulence mixing in the vicinity of the seamount. Our study suggests that a better prediction of current and water mass properties of the Kuroshio requires an accurate parameterization of interactions of the Kuroshio with topography and the associated turbulent mixing.

Strong vertical turbulent nitrate flux in the Kuroshio across the Tokara Strait and the Izu Ridge

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In the oligotrophic Kuroshio / Kuroshio Extension region, vertical turbulent mixing is considered to be an important driver to supply nutrients to maintain the biological production in the euphotic zone and high fisheries productions (e.g. Kaneko et al. 2013). Besides, in the intermediate layer below the euphotic zone, vertical mixing is also thought to be an important process to transport nutrients upward from the North Pacific Intermediate Water (NPIW, e.g. Reid 1965), which provides a nutrient source to the Kuroshio as suggested by Sarmiento et al. (2004). However, due to the lack of sufficient data on turbulence and nitrate, where and how much nitrate is supplied along the Kuroshio / Kuroshio Extension from down below and what impact this nitrate flux would have on the primary production have not been fully quantified yet.
In the present study, by using observational data on turbulence intensity and nitrate, we estimate the vertical turbulent nitrate flux near the Tokara Strait and the Izu Ridge, where the Kuroshio flows over steep bottom topography. The vertical mixing within the Tokara Strait is often found 1-2 orders of magnitude larger than the background value of $K\rho = O(10^{-5})$ [m^2/s] and is intermittently enhanced to $\varepsilon = O(10^{-6})$ [W/kg] and $K\rho = O(10^{-1})$ [m^2/s] at 26 –26.5 σ_θ. The vertical turbulent nitrate flux, F_{NO3}, is thus often enhanced by 1-2 orders of magnitude from the background value of $F_{NO3} = O(10^{-3})$ [mmolN/m^2/day] and intermittently reaches $F_{NO3} = O(1)$ [mmolN/m^2/day]. The mean nitrate flux across the whole Tokara Strait $\langle F_{NO3} \rangle = O(10^{-1})$ [mmolN/m^2/day] just below the euphotic zone and at about 26.5 σ_θ. In the proximity to the Izu Ridge within the Kuroshio, the mean nitrate flux with the same order of magnitude is also observed both just below the euphotic zone and at about 26.5 σ_θ. These results suggest that these two mixing hotspots in the Kuroshio may provide large portion of the new production in the euphotic zone and may draw sufficient nitrate upward from the NPIW to impact the downstream.

Keywords: turbulent mixing, nitrate flux, Tokara Strait, Izu Ridge, Kuroshio

Long-range propagation and associated variability of internal tides in the South China Sea

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The variability of internal tides during their generation and long-range propagation in the South China Sea (SCS) is investigated by driving a high-resolution numerical model. The present study clarifies the notably different processes of generation, propagation and dissipation between diurnal and semidiurnal internal tides. Internal tides in the SCS originate from multiple source sites, among which the Luzon Strait is dominant, and contributes approximately 90% and 74% of the baroclinic energy for M_2 and K_1, respectively. The tidal beams from the Luzon Strait can travel across the deep basin and finally arrive at the Vietnam coast and Nansha Island more than 1000-1500 km away. During propagation, M_2 internal tides maintain a southwestward direction, whereas K_1 exhibit complicated wave fields because of the superposition of waves from local sources and island scattering effects. After significant dissipation within the Luzon Strait, the remaining energy travels into the SCS and reduces by more than 90% over a distance of ~1000 km. Inside the SCS, the K_1 internal tides with long crests and flat beam angles are more influenced by seafloor topographical features and thus undergo apparent dissipation along the entire path, whereas the prominent dissipation of M_2 internal tides only occurs after their arrival at Zhongsha Island.

Keywords: internal tides, energy cycle, Mixing

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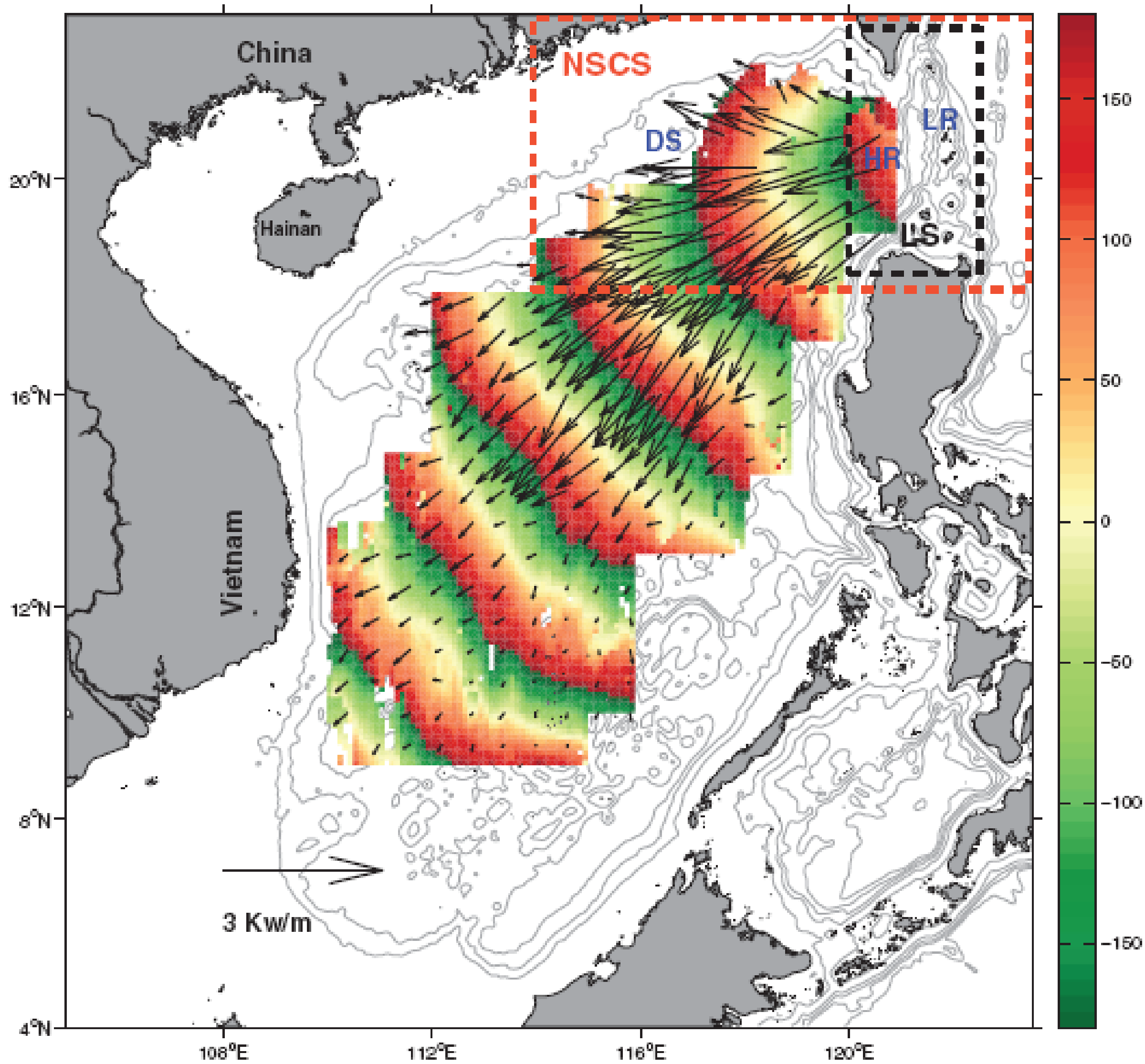

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Fission of internal solitary waves over shoaling topography cascades tidal energy to turbulence

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The tides are a major energy source of small-scale turbulence, and therefore diapycnal mixing, in the world's oceans. An understanding of the processes responsible for the cascade of energy from tides to turbulence is important in identifying when and where this mixing will take place. Internal solitary waves (ISWs) generated by tide-topography interactions are ubiquitous in the world's oceans and are thought to be important sources of mixing. Whilst the understanding of the dynamics and energetics of ISWs have been greatly advanced in the past a few decades, identification of the processes and mechanisms responsible for their dissipation is limited. Here we present velocity and turbulence measurements from the South China Sea, together with process-orientated numerical simulations, to demonstrate the key role of ISW fission, into groups of high-frequency internal waves over rough topography, in the dissipation of tidal energy. The results show that, as a result of the fission, wave-induced velocity shear is elevated over significant time periods coincident with a period of enhanced turbulent dissipation. We suggest that the enhanced dissipation is a result of instability and breaking of the high-frequency internal waves. The finding reveals an important pathway of tides-to-turbulence cascade and generation of turbulence and mixing in the ocean interior, having important implications for understanding ocean dynamics as well as its ecological and climatic impacts.

Keywords: internal solitary waves, tides, turbulence, energy cascade, fission

Seasonal Variation of M_2 internal tides and tidal surface currents of the North Atlantic

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Following the global study of Kodaira et al. (2016), a high resolution regional ocean model is used to study the M_2 internal tides of the North Atlantic with a particular focus on their seasonal variation. The regional model has a grid spacing of 1/36 degree and is based on MITgcm. The predicted tidal variation of sea surface height is shown to be in reasonable agreement with altimeter observations. Tidal surface currents are also evaluated by comparing them with estimates based on the recently available hourly drifter dataset of Elipot et al. (2016). The large scale features in the maximum speed of surface tidal current derived from the drifter observations and model predictions are in reasonable agreement, particularly in the vicinity of known generation sites for internal tides. The higher wavenumber variations, previously explained by Kodaira et al. (2016) in terms of phase locking of the barotropic tide and mode-1 baroclinic response, do not line up exactly. Possible explanations are provided. We next examine seasonal variability. Both observed and predicted surface currents change with season. We interpret this variation in terms of seasonal changes in the vertical structure of mode-2 internal tides. By way of contrast, the model predictions indicate only small seasonal changes in the vertically integrated horizontal kinetic energy and the barotropic to baroclinic energy conversion rate.

Kodaira et al., 2016. *JGR Oceans*, *121*(8), 6159–6183.
Elipot et al., 2016. *JGR Oceans*, *121*(5), 2937–2966.

Keywords: internal tide , drifter observation

Observations of small island wakes in the Kuroshio: flow-pattern evolution, shear instability and turbulent mixing

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Evolution and turbulent mixing of Green Island wake (~5 km in diameter) was investigated in the alongshore flowing Kuroshio (1-1.5 ms^{-1}) east of Taiwan with shipboard ADCP and echo sounder, Underway CTD and microstructure profiler. Repeated 12 cross-wake and 4 along-wake surveys in the lee of Green Island reveal transects of wake evolution and downstream eddy propagation, respectively. In the cross-wake section, the cyclonic and anti-cyclonic recirculation alternatively presents at a period of ~12.5 hours, in agreement with a 1-month moored measurement. A resonance effect with semidiurnal tide is the most likely explanation for the observed period. The repeated along-wake surveys depicted that a cyclonic eddy shed downstream at a speed of 0.34 ms^{-1}, 1/3 of the upstream current speed. A cross-wake microstructure survey reveals an average TKE dissipation rate of $O(10^{-7})$ WKg^{-1} and an enhanced value of $O(10^{-5})$ WKg^{-1} at the horizontal shear line, separating the mean flow and the recirculation in the leeward side of the island. The depths of enhanced turbulence are co-located with the strong vertical shear of horizontal velocity, where the Kelvin-Helmholtz billows with a vertical scale of ~30 m are observed in the echo sounder image. Presumably, the tilting of the lateral boundary-induced vorticity likely causes the strong vertical shear.

Keywords: Kuroshio, island wake, turbulent mixing

Water Mass Analysis of Tsushima Strait by Multiple Tracers and seasonal contribution of various origin.

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Tsushima strait is an important pathway for connecting the East China Sea (ECS) and the Sea of Japan. In order to monitor currents in this region, various in-situ temperature and salinity datasets were used for developing numerical simulation models. However, the water origin of currents in this region lacked of systematical understanding. Because of shallow depth and various currents pass through, the chemical properties of Tsushima Strait water changed rapidly. Multiple tracers analysis is a comprehensive method to approach detailed and instantaneous status of water mass. This study used Rare Earth Elements (REEs), $\delta^{18}O$, combing with CTD data (Temperature, Salinity, Fluorescence) and routine data (Nutrients, Dissolved Oxygen), to analyze water mass mixing of Tsushima Strait.

All samples (3 seasons, from 5 cruises) were collected at Tsushima Strait (Line 129.38E, 34.88N to 130.15E, 33.83N) from 2015 May to 2016 October used T/S Nagasaki Maru (Nagasaki University). The salinity, temperature, DO and fluorescence data were collected by CTD, the DO samples were measured on-board by automatic titration. Nutrients and $\delta^{18}O$ samples were stored for laboratory analysis. The REEs samples were filtered by 0.2 μm membrane filter and acidified to pH 1.5 by hydrochloride acid in clean booth immediately, then extracted by NOBIAS PA1 chelate resin (Hitachi High-Tech) and measured by ICP-MS (Element 2, Thermo Fisher Scientific) in a cleanroom on land.

CTD and multiple tracers datasets show that: (Ⅰ)The Changjiang Diluted Water (CDW) and Kuroshio Intermediate Water (KIW) are important end members of this region, according to the temperature-salinity diagram. (Ⅱ)Fluorescence vertical profiles and horizontal sections shows unbalanced distribution. High fluorescence mainly occurred in subsurface layer of east channel in spring and fall, especially shallower than the thermocline in fall. (Ⅲ)Post-Archean Average Australian Shale (PAAS) normalized REEs patterns show similar water mass mixing in this region in different season, and high Ce/Ce* suggests the particle influence. These results suggest the nutrients origin of Tsushima Strait water might be CDW. Further, to understand the dominant water mass, we calculated the mixing ratios by least square method with five parameters, including salinity, Dy/Ho, Ho/Er, Er/Tm and Tm/Yb. End member dataset included Yellow Sea Cold Water (YSCW), Taiwan Warm Current (TWC), KIW and CDW (Private communication, Hongliang Ma, Ocean University of China). Calculation result suggests the two sides of Tsushima Strait water were dominated by different origin over 3 seasons. The west channel show clear stratification. YSCW and CDW influenced the surface and the subsurface layer in spring and fall, however, the layer deeper than 100 m was dominated by KIW. The east channel was mainly controlled by CDW throughout the year. Results also suggests CDW is the vital water origin of Tsushima Strait, according to the collaboration of CDW domination region and high fluorescence layer. The water mass distribution and seasonal changes in Tsushima Strait were revealed in this study, and multiple tracers are efficient method for the water origin analysis. Our results and method will provide evidence for improving current simulation models.

Keywords: Water mass analysis, Rare Earth Elements, Tsushima Strait

Dynamics of Water mass in the East Japan Basin using Multiple Chemical Tracers

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The Sea of Japan is a semi-closed ocean area, which results to an independent circulatory system. Especially in the East Japan Basin, various previous reports of deep circulation were established (Senjyu et al., 2005; Hatta and Zhang, 2006). However, the details of water masses were not clarified, because of limited observation stations. This study used multiple chemical tracers to analyze the dynamics of the deep water in East Japan Basin, and to clarify the existence of water advection in this region. Samples were collected from GEOTRACES JAPAN KH-10-02 cruise (Leg 2, June 21 to July 6, 2010). Dissolved oxygen (DO) and nutrients of seawater were analyzed on board. Rare earth elements (REEs) were extracted by chelate resin (NOBIAS Chelate PA-1) and measured by HR-ICP-MS on land.

The results of the four observation stations CR34 (140.00E, 45.67N), CR41 (138.93E, 44.20N), CR47 (138.21E, 42.82N), CR58 (135.92E, 40.43N), which located from northern to central region of East Japan Basin, were shown as follow. With comparing the DO and PO_4-P vertical profiles of CR41 and CR47, PO_4-P shows excess refer to the Redfield ratio, suggests the influence of particles. According to the REEs data, the CR41 and CR47 showed the same HREEs (Heavy REEs) patterns, indicates the advection from CR47 to CR41. Meanwhile, the same HREEs patterns also showed by CR41 500m and CR34 bottom water, suggests the advection from CR34 to CR41. Further, CR34 bottom water is influenced by resuspended particles or water masses out of East Japan Basin, which inferred by the higher LREEs (Light REEs) in CR34 bottom. In future, it is important to clarify the wide regional deep circulation with the biogeochemical observation in the northern part of Japan Sea and Okhotsk Sea.

Keywords: Water mass analysis, Rare Earth Elements, East Japan Basin

Small scale structure in temperature and salinity over the Mindanao Dome

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In June-July 2011, Japan Meteorological Agency carried out the regular observation in the Pacific Northwest along the longitude line of 137 E. Continuous observation data were obtained every minute from a Thermo Salino Graph. Small scale spikes in both temperature and salinity are found between the latitude 5 N and 10 N over the Mindanao Dome, where cold-salty waters are upwelled. It should be noted that the area where the small scale structure was observed correspond to warm pool.

Soundings of temperature and salinity from the Conductivity Temperature Depth profiler showed that upwelled water are present up to 50 dbar in 8 N. The sharpest spike structures in temperature and salinity is found in 7N and 9N, where Dissolved Oxygen is supersaturated; These data indicate that the active mixing occurs.

Thermohaline staircase, extending vertically for a few of dbars, are found in some latitudes.
In case of 5 N, the height of staircase is about 4 dbar and the roughly estimated buoyancy frequency is about 0.007 (1/sec). The horizontal scale of the spike is about 1 km.

What causes the small scale structure of temperature and salinity over the Mindanao Dome? It is well known that thermohaline staircases are often observed when salt finger convection occur. However, the observed horizontal scale is about 1km and the vertical scale is about 10 m; The shape of the cell is not "finger".

Second, it is possible that internal gravity wave is generated by convection (Michael Le Bars at al.,2015). They experimentally investigate the dynamics of a turbulent convective layer adjacent to a stable stratified layer. This condition is very similar to the vertical profile of Mindanao Dome area. They find that the convectively excited internal waves propagate in the stratified zone. I will describe the comparison between the ship observation and the results of their experiment.

Keywords: internal gravity wave, salt finger, Mindanao Dome

An observed variability of Chlorophyll-a during 2015-2016 El Nino event in Mindanao Dome

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The 2015-2016 El Nino was considered as one of the strongest on record, comparable to the 1982-1983 and 1997-1998 events that triggered widespread climate and ecosystem changes in the Pacific and in regions beyond. Mindanao Dome area is an important upwelling system of the Western Philippine Sea. This study aims in examining the variability of Chlorophyll-a and related physical parameters of the Mindanao Dome to assess the impact of the recent 2015-2016 El Nino event. This assessment was based on the data derived from observed satellite data and available data from underwater sensors on Triangle Trans-Ocean Buoy Network (TRITON) buoys. Results indicate that the Mindanao Dome region has been chronically enriched in Chlorophyll-a levels during this event. This increased primary productivity may influence the overall ocean productivity of the area.

Keywords: El Nino, primary productivity, western Philippine Sea, satellite data, TRITON buoy