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).

Keywords: vertical diffusivity, data assimilation, Pacific Ocean

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.

Keywords: Tidal straining , Bottom mixing, East China Sea

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.

Keywords: Kuroshio, Kuroshio Counter Current, Ryukyu Under Current, meso - and submesoscale eddy mixing, ROMS

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

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In the Toyama Bay, chlorophyll-a in the surface layer of a few meters activates in the rainy season of Jun to July, while forming the counterclockwise pattern (cf. Fig. 1). This characteristic distribution is found in the relationship between oceanic physical processes (advection and diffusion) and ecosystem in the Toyama Bay. However, the formation and development mechanisms are not revealed in detail. Then, we investigate to clarify the mechanisms of pattern formation using MODIS satellite image, ocean observation data, and physics-ecosystem modelling.
In this study, we used the NPZ model as an ecosystem model, introducing into the advection and diffusion terms as ocean physical processes in it. This horizontal two-dimensional system solved by finite differential method. The horizontal oceanic area is 100 km x 100 km referring to the width of the Toyama Bay and the horizontal resolution is 1 km x 1km. For the model calculation, we employed a horizontal diffusive coefficient of 10 $m^2 s^{-1}$ and performed the cyclonic circulation as a back ground flow field. The experiments are carried out for macro and micro planktons, and several values of grazing rate coefficient showing a relationship between the predictor-pray of planktons as the ecosystem parameters. We compared results between obtained from the pure advection-diffusion system and obtained from the reaction-diffusion system.
For advection only, although the distribution of the eddy appeared in the model area, only the initial plankton patch extended. For diffusion only, the plankton patch spread in the radial direction with an initial total amount. For both of advection and diffusion case, although the amount of plankton was less, the pattern was similar to the satellite image. In the advection-diffusion system, however,we cannot reproduce rapid increase of chlorophyll-a like the satellite image. The development on the amount of plankton appeared in the adding reaction effect of ecosystem. Moreover, for large grazing rate and micro plankton case, we were able to obtain more similar pattern of the satellite observation in the Toyama Bay.
It is conclude that we can reproduce the similar pattern of chlorophyll-a observed from the MODIS satellite image (Fig, 1) by the numerical simulation of an physics-ecosystem modelling. Thus, it was found that in the Toyama Bay, the cyclonic chlorophyll-a pattern was due to the physical advective effect mainly. The pattern development from Fig. 1a to Fig. 1b for about one day is much faster than the physical scale and is owing to the ecosystem reaction-diffusion. Ring waves appeared also in many experiments in our study. These phenomena correspond to ring waves in the reaction-diffusion system and we need to investigate more in detail.

Keywords: Statellite imeage, Marine physical processes, chlorophyll-a, Ecosystem model, Toyama Bay, reaction-diffusion

Figure.1

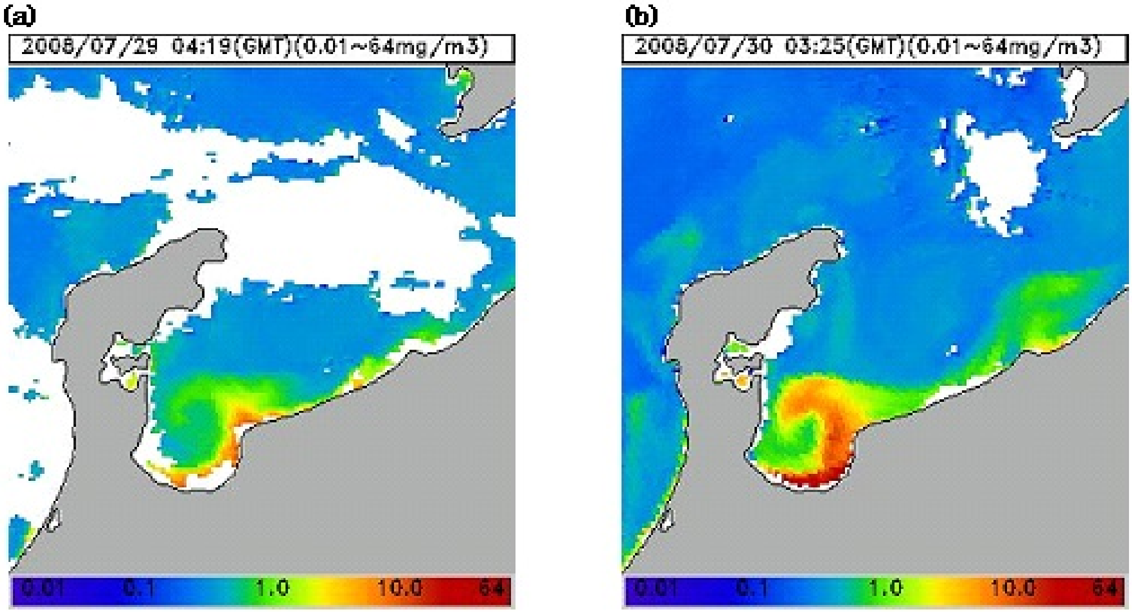
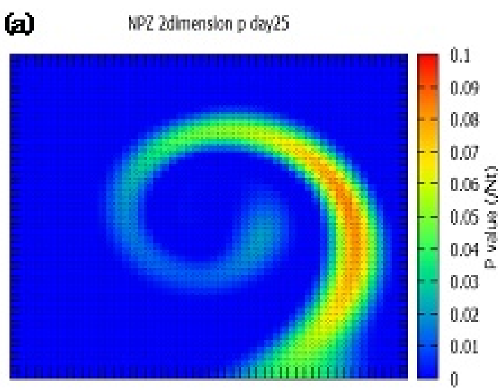
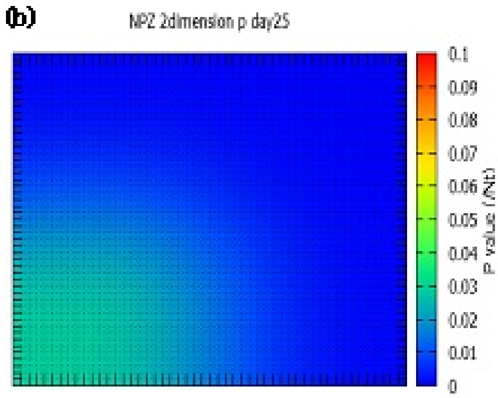
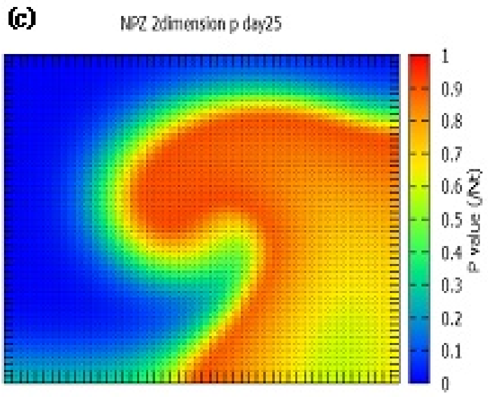


Figure.2







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

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

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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 $(3.6–7.3) \times 10^{12}$ atoms/m^2, which is significantly lower than for the Sea of Japan with $(1.4-1.6) \times 10^{13}$ 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.

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

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.

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

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

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

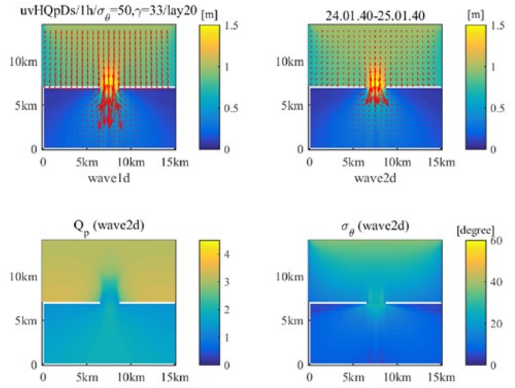

Fig.2: Stokes Drift Velocity: Upper left: Wave1d, Upper right: wave2d
Lower left: frequency deviation parameter, Lower right: directional deviation parameter

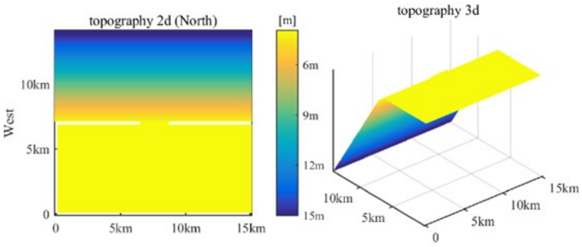

Fig.1: Topography data: left: 2 dimension, right: 3dimention

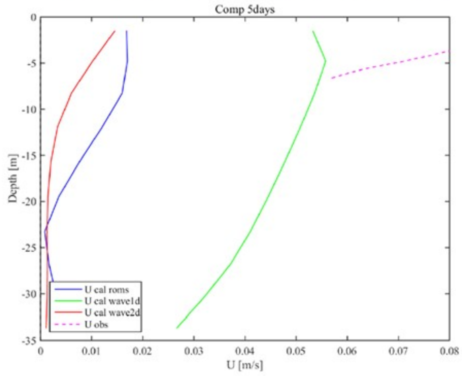

Fig.3: Velocity vertical profile: 5days mean: Blue: ROMS, Greem: Wave1d, Red: Wave2d, Magenta: Observation data