Submesoscale Eddy-Induced Mixing and Dispersion of Radioactive Tracer Off the Northeastern Pacific Coast of Japan

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Recent studies have suggested that turbulent mixing by submesoscale eddies has an inevitable importance in oceanic dispersion of materials in continental shelves and nearshore areas. In this study, a downscaling oceanic dispersion modeling system is developed for the coastal margin off Fukushima, Japan, to investigate eddy-induced mixing of dissolved radionuclide. The system consists of a double nested Regional Oceanic Modeling System (ROMS) and the offline oceanic radionuclides dispersion model, SEA-GEARN-FDM. The oceanic initial and boundary conditions are given by an oceanic data assimilation system MOVE-WNP developed at Meteorological Research Institute/Japan Meteorological Agency. Surface wind stress is provided by the GPV-MSM atmospheric reanalysis, while surface heat and freshwater fluxes are from a monthly climatological dataset. The developed submesoscale eddy-resolving system is applied to the Fukushima accident occurred in March 2011. The direct release of radionuclides from the Fukushima Dai-ichi Nuclear Power Plant and the atmospheric deposition are taken into account. An extensive comparison between the model results and observation data demonstrates the model's capability of reproducing Cs-137 distribution.

A diagnostic vertical Cs-137 flux analysis demonstrates that ageostrophic secondary circulations induced by submesoscale eddies promote seasonally-varying subduction of the Cs-137 in spring. The fluctuating eddy components of vertical Cs-137 flux are extracted by removing the seasonal variations with a low-pass Butterworth filter in the frequency domain. The decomposition demonstrates that eddy components predominantly contribute to the vertical transport.

In order to investigate the source of Cs-137 subducted deeply into the ocean interior, the numerical experiment without atmospheric deposition is conducted. It is suggested that the Cs-137 originated from the direct release dominates in the deeper layer, whereas the airborne Cs-137 remains in the subsurface layer rather than subducting the deeper layer.

A High-Resolution Coastal Forecasting System with a 3DVAR Assimilation Optimal for a Semi-Enclosed Estuary

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Ocean data assimilation, which combines observations and numerical models to obtain the statistically best estimate of the ocean state, has widely been used for various purposes such as ocean monitoring, forecast, and reanalysis. Because of the progress of numerical ocean models and enhancement of ocean observation data such as Argo floats and satellite-derived sea surface data in the past decade, many researchers have developed realistic data assimilation systems for various ocean areas. However, in semi-enclosed estuaries including the Seto Inland Sea (SIS), Japan, data assimilation has rarely been adapted because satellite data and Argo floats, which are essential to successful oceanic predictions, are unavailable, whereas forecast is highly demanded such as for fisheries, vessel navigation, marine construction, offshore platform management, marine monitoring, etc.

In the present study, we develop a data assimilation system toward rigorous coastal predictions around Japan. The system consists of a three-dimensional variational (3DVAR) assimilation scheme compatible with Regional Oceanic Modeling Systems (ROMS) and a fine-resolution coastal modeling configuration based on ROMS encompassing a fairly extensive area around the SIS. The SIS, the largest estuary in Japan, has been equipped with a number of autonomous in-situ monitoring stations for vertical profiles of temperature and salinity, tens of tidal gages, as well as continuous surface current measurement using HF radars.

We first investigate a theoretical framework of the 3DVAR algorithm optimal for the high resolution configuration. Subsequently, the developed 3DVAR is coupled with the SIS ROMS model to compare the model outcomes against observed data. The 3DVAR ROMS model for the SIS is shown to perform much better than the accompanying forward model without assimilation with good model skill scores, and to reproduce quite complex flows in the SIS because of its complicated topography with more than 3,000 islands in there. Furthermore, we will share technical difficulties encountered during the experiment.

Numerical Simulations of the Interaction Between Internal Waves and the Kuroshio Current Over the Izu-Ogasawara Ridge

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This study reports physical oceanic processes over the Izu-Ogasawara Ridge, off the Japan mainland. It is well known that this area is strongly influenced by both tides and the Kuroshio current. In order to investigate the physical processes in the study area, we used three numerical modeling approaches: (1) the SUNTANS model, (2) the ROMS model, and (3) a one-way coupled ROMS-SUNTANS model. The SUNTANS model was forced with only tidal elevations and climatological stratification to reproduce the internal tides. Numerical results from SUNTANS showed strongly enhanced internal wave energy around islands located on the Izu-Ogasawara Ridge. For the ROMS model, we used triple nested domains embedded in the assimilative JCOPE2 oceanic reanalysis data and the domains were forced by spatially and temporally-variable climatological conditions and tides. The ROMS model reproduced physical processes associated with internal waves and the Kuroshio off the Japan coast. Tides significantly contributed to enhanced internal wave energy over the ridge except in the regions with strong Kuroshio currents. In addition to the two separated approaches, we attempted to develop the ROMS-SUNTANS coupling model, namely the high-resolution SUNTANS model nested into the ROMS domain. The coupled model showed small scale physical processes associate with tides, winds and eddies due to the Kuroshio, processes that are absent from the standalone ROMS and SUNTANS simulations.

Impact of the Kuroshio on Dispersal of Coral Spawn and Larvae Around Ryukyu Islands in the East China Sea

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Ryukyu Islands in the East China Sea are in a subtropical climate, hosting desirable environment for abundant coral ecosystem. Kamidaira et al. (2016) suggested that the Kuroshio warm water maintains warmer water temperature favorable to corals around Okinawa Main Island due mainly to intermittent transverse eddy heat transport. It is anticipated that the Kuroshio and associated eddy mixing also promote the transport and dispersal of coral spawn and larvae across the islands, whereas the area has suffered from coral bleaching in the recent decades. For optimal preservation and protection of the coral habitats around Ryukyu Island, we conduct a double nested high-resolution synoptic ocean modeling using ROMS with grid spacing down to 1 km coupled with an offline Lagrangian particle tracking model. The modeled dispersal of coral spawn and larvae released from about 20 major islands and lagoons are examined to quantify connectivity using Lagrangian probability density functions (PDFs) of the Lagrangian particles (e.g., Mitarai et al., 2009) among Ryukyu Islands.

We introduce 145 patches with a diameter of 1km around Sekisei Lagoon between Yaeyama and Ishigaki Islands close to Taiwan to compare with an in-situ surface drifter measurement. Lagragian particles are released from the patches in spring for 2012-2015 and are tracked for the advection time of 3 weeks suitable to representing active spawning and lifespan of coral spawn and larvae. The PDF analyses suggest that the particles mostly remain near the released areas, while about 10% of the particles are entrained by the Kuroshio to travel long distance, leading to inter-island connectivity. Some of these particles are further transported northeastward, and then partially trapped by the Kuroshio Counter Current formed between the Kuroshio and Main Island to approach Okinawa Main Island. We reveal that eastward current in the south the lagoon occurred shortly after the releases suppresses the entrainment and the resultant long-distance transport.

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Intrinsic Low-Frequency Variability in Transient Three-Dimensional Rip Currents

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The ROMS-WEC model (Uchiyama *et al*., 2010) based on an Eulerian wave-averaged vortex-force asymptotic theory of McWilliams *et al*. (2004) is applied to 3D transient rip currents in the surf zone on a surveyed topography under time-independent, alongshore-uniform offshore incident waves. Substantial depth-dependency is manifested in the 3D rip currents due to the vertical recirculation formed in the surf zone. The 3D rip currents are found to consist of pairs of counter-rotating longitudinal vortex tubes that promote surface convergence along the rip center. The vortex force plays the most dominant role in vorticity budget, other than the breaker acceleration torque that is the primary vorticity source. Overall, the vortex force torque preconditions vorticity reduction from the rip eddies, while it conversely recharges vorticity to the rip eddies in the shoreward of the bars (*viz*., *neck* region). These rip currents are intrinsically unstable and contribute about 70% to kinetic energy (KE) as eddy kinetic energy (EKE). The estimated dominant fluctuation period is about 18 minutes, which fits the very low frequency (VLF) band, consistent with a field measurement (Reniers *et al*., 2007). The EKE contained in the VLF band explains about 70% of the total EKE.

Inter-Annual and Seasonal Variability of Upper-Ocean Primary Production Along the Kuroshio Off Japan

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The Kuroshio is accompanied by intense eddy activities influencing on biogeochemical processes around its path. In general, localized upwelling due to mesoscale cyclonic eddies brings nutrient-rich subsurface water to the nutrient-depleted upper ocean to enhance near-surface primary productivity. However, a recent climatological modeling study has revealed that topographic eddy shedding as well as baroclinic instability around the Kuroshio front concurrently promote diapycnal eddy-driven downward nutrient transport in Enshunada Sea, Japan (Uchiyama *et al*., 2017). This downward transport competes with upwelling-induced nutrient supply, resulting in suppressing the near-surface productivity substantially as compared with that in the Kuroshio Extension region. In the present study, a synoptic, retrospective downscaling ocean modeling is carried out for the marginal seas along the Kuroshio off Japan based on ROMS (Shchepetkin and McWilliams, 2005; 2008) coupled with an NPZD biogeochemical model (Fasham *et al.,* 1990; Gruber *et al*., 2006). The model domain encompasses both the Kuroshio and its Extension regions in a submesoscale eddy-permitting configuration with horizontal grid spacing of 3 km. The simulation is conducted for 9 years from 2008 to 2016 to take into account variety of the Kuroshio path. We focus on inter-annual and seasonal variability of eddy-induced vertical nutrient fluxes that play an essential role in maintaining the upper-ocean primary productivity. For instance, mixed layer deepening and surface cooling provoke vigorous eddy activity in colder seasons that enhances diapycnal nutrient transport. We further discuss influences of the transient Kuroshio path, which occasionally takes meandered paths rather than relatively straight courses, on eddy generation and associated biogeochemical responses.