［課程博士・論文博士共通］

博士学位論文内容要旨
Abstract

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論文題目 Title	Observations and numerical simulations of mixing processes in shallow coastal regions (河口域周辺における混合過程に関する研究)		

Internal waves are ubiquitous and one of the energetic phenomena in stratified oceans and lakes. Large-scale internal waves (e.g., internal tides and internal seiche) increase their non-linearity with propagating into shallower areas. Highly non-liner motions of waves cause breaking of waves accompanied by strong turbulent mixing. Non-linear internal waves enhance turbulent mixing and transport waters, sediments, nutrients, irons and organic materials in oceans and lakes. In particular, coastal areas and continental shelves are known as “hot spots” of internal wave breaking sites. Internal waves contribute to water exchange between coastal waters and open ocean waters, which play a significant role in ocean circulations and ocean ecosystems. However, detail processes of internal waves and mixing processes in coastal areas have not been understood well due to lack of field surveys. Here, we present mixing processes associated with river plumes and internal waves from two approaches: (1) in-situ field surveys and (2) numerical simulations.

In order to observe detail features of physical structures in shallow coastal regions, we have developed a new, portable tow-yo instrument, Yoing Ocean Data Acquisition Profiler (YODA Profiler). Using the YODA Profiler, we were able to rapidly obtain high-resolution data in a shallow estuary. The results showed fine-scale complicated internal wave features, upslope propagating fronts and a patchy distribution of phytoplankton. We have also developed a statistical technique to estimate the rate of turbulent kinetic energy dissipation, ε, from conductivity data.

Observed results in Otsuchi Bay, showed fine features of river plumes and internal waves. A shallow river plume was generally presented in the bay, however rapid mixing events were observed during summer campaings with a time scale of *O* (1 hour). These events coincided with tidally induced internal bores (***1**) propagating on a slope. The isothermal displacement due to internal bores reached 20 m vertically in water depth of 40 m. The combined effects of the wind stress and the baroclinic flow due to the internal bore generated shear layer near the sea surface and enhanced river plume mixing. The vertical eddy diffusivity in the river plume during the mixing even reached 3.0×10^{-4} m^2s^{-1}. In addition to the field surveys, a fully non–hydrostatic numerical simulator, SUNTANS developed by Fringer et al. (2006), was used to understand mixing processes in the bay. Numerical simulations revealed that three forcing factor (barotropic tide, baroclinic internal tide and wind) are essential to understand mixing processes of the river plume.

The YODA Profiler and mooring surveys also showed details in non-linear internal bores propagating into the bay. The high-resolution thermistor array observation has revealed the high-frequency wave feature in the interface of the bore wave, likely induced by shear instability, and the vortex structure at the head of the bore wave. The vortex was accompanied by strong vertical motion induced strong vertical sediment resuspension andtentensified turbulent mixing. The rate of turbulent energy dissipation was approximately 10^{-6} Wkg^{-1} at the bore head. The vertical current

reached 0.03 ms^{-1} in the vortex and induced the ring-like strong vertical resuspension of sediments.Suspended particles detached from the sloping bottom and intruded into offshore above the thermocline from, forming an intermediate nepheloid layer (INL).

The strong turbulent mixing event was also observed when a receding bore runs into the next run-up bore, which indicates the collision of the receding bore and the run-up bore. This strong turbulent mixing event due to the collision of (crashing) non-linear bores has never been found before, we named this phenomena "*Crash mixing*". The high turbulent kinetic energy dissipation rate near the crashing site was 10^{-6} – 10^{-5} Wkg^{-1}. Observed results showed the high dissipation area also appear near the sea surface above the crashing site, not only near the bottom. The high-resolution thermistor array observation revealed that high frequency waves and shear instability motion during the crashing period.

In order to investigate the behavior of internal bores on shallow slopes, we conducted numerical simulations using SUNTANS. Numerical simulation reproduced internal bores, crash mixing and details of the vortex motion at the head of the bore, which showed excellent agreements with field observation results. We found that the Iribarren number (***2**) is a key parameter for mixing processes associated with internal bores. The Iribarren number is defined as following:

$$\xi = \frac{s}{\sqrt{a/\lambda}}$$

where s is the topographic slope (dz/dx), a/λ is the wave slope, a is the amplitude of the wave and λ is the length of the wave. Numerical results indicated that the low Iribarren number condition leaded to strong turbulent mixing along the slope. The vortex motion and crash mixing due to internal bores were enhanced in the low Iribarren number condition. This study also investigated sediment resuspension and sediments transport processes using numerical simulations. Simulations forced by first mode internal waves reproduced sediment resuspension and intermediate nepheloid layers (INLs). Results indicated that repeated internal bores contribute to the tertiary circulation, which transports mixed high turbidity water into the offshore. This circulation lead to the growth of INLs. The Iribarren number also controlled sediment resuspnesion. Strong turbulent mixing in the low Iribarren number condition lead to strong sediment resuspensionand causing INLs.

As the results of this study show, non-linear internal bores and high frequency internal waves dramatically alter physical processes and are essential to understand mixing processes in shallow coastal regions.

(*1) A bore refers a high tidal wave propagating into the upstream of a river or estuary. In the internal wave field, an internal bore refers an internal wave (dense water) advancing on a sloping bottom with highly non-linear motions.

(***2**) The Iribarren number is the parameter for classifying surface wave breaking types (Iribarren and Nogales 1949). Recent studies (e.g., Boegman et al., 2005, Walter et al., 2012) pointed out that this parameter can be a internal wave breaking parameter.