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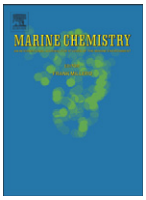

Evaluation of surface water mixing and associated nutrient fluxes in the East China Sea using ^{226}Ra and ^{228}Ra

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ABSTRACT

Advection and diffusion are recognized as two important processes in the mixing and exchange of coastal waters and associated nutrients. In this study, Ra isotopes (^{226}Ra and ^{228}Ra) are surveyed in the East China Sea (ECS) to investigate the advection and diffusion processes. Both one-dimensional (1D) and two-dimensional (2D) advection–diffusion models are applied to estimate the cross-shore and along-shore eddy diffusivities and advection velocities. The advection velocity is basically small in magnitude, suggesting its secondary role in transport. The cross-shore 1D model gives promising results on the diffusivity by 4.93×10^5 cm^2 s^{-1}. Sensitivity analysis shows that the cross-shore diffusivity is less sensitive whereas the along-shore diffusivity is quite sensitive to advection velocity. Introducing benthic Ra flux in the model decreases the eddy diffusivity. A quisi-2D method generates an along-shore diffusivity by 2.50×10^7 cm^2 s^{-1}, which is within the sensitivity range thus reliable. Based on the estimated diffusivity and advection velocities, we calculate the offshore nutrient fluxes (mol m^{-2} d^{-1}) by 0.44 for dissolved inorganic nitrogen (DIN), 0.012 for dissolved inorganic phosphorous (DIP) and 0.26 for dissolved inorganic silicates (DSi). The along-shore fluxes (mol m^{-2} d^{-1}) are 6.44 for DIN, 0.10 for DIP and 2.92 for DSi. Compared with nutrient inputs from other sources, e.g. river, sediments, and ocean, the horizontal mixing-derived nutrient fluxes contribute only <4% N, <1% P and <2% Si to the nutrient requirements for primary productivity in the study area. This study stresses the role of advection and diffusion in the material transport, i.e. nutrients and stoichiometry in the ECS.

1. Introduction

The coastal seas exchange large amounts of matter and energy with the open ocean because virtually all terrigenous materials (e.g., water, sediments, dissolved and particulate nutrients, etc.) enter the coastal zone in surface runoff and/or groundwater discharge. With regard to different time and space scales, such processes can be better understood by using radium isotopes with different half-lives as a tracer (Hancock et al., 2000). Radium isotopes are produced from the U/Th decay series and are present in the Earth's crust (Osmond and Ivanovich, 1992). Ra is continuously released into the ocean boundaries by river, coastal salt marshes, etc. (Moore, 1987) and then is transported offshore by advection and diffusion. The chemical interactions at the sediment–water or rock–water interfaces show a strong Ra signal along the coastline and at the sediment–water interface (Charette et al., 2007). In that sense, radium isotopes are widely used in tracing water movement in the ocean (Koczy et al., 1957; Koczy, 1958; Ivanovich and Harmon, 1992).

Advection–diffusion model is deployed together with Ra isotopes in studying the nutrient transport. Simplified one-dimensional (1D) diffusion model is initially derived to examine the regional-scale mixing of the South Atlantic Bight by assuming that the mixing is diffusion-dominated and the system is in a steady state (Moore, 2000). Hancock et al. (2006) also use the 1D model in evaluating the diffusion processes while the influence of the cross-shore variation of depth, and benthic Ra flux are discussed. A recent theoretical investigation by Li and Cai (2011), using an analytic model with advection, indicates that the estimated eddy diffusivity is highly sensitive to advection, suggesting that the advective transport of radium isotopes may not be negligible.

Sometimes we are more concerned for two-dimensional (2D) problems when the study area is complex in horizontal hydrodynamics. Thus 2D advection–diffusion model is needed, in which the along-shore transport is included. In considering both advection and diffusion processes, ^{226}Ra and ^{228}Ra are combined to solve the problem (Rengarajan et al., 2002). Earlier attempts in this direction are made by Somayajulu et al. (1996), in which a 2D eddy diffusion model is used to fit the measured ^{228}Ra/^{226}Ra profiles for the purpose of deducing the horizontal eddy diffusivities in both zonal and meridional directions from the western continental margins of India to the open Arabian Sea. Later, Rengarajan et al. (2002) works with a 2D model when considering both advection and diffusion processes by using both ^{228}Ra and ^{226}Ra dataset. Even though, it is still not able to solve the fully coupled advection and diffusion equation, suggesting further assumptions are needed.

In this study, we survey the ^{226}Ra and ^{228}Ra activities in the surface waters of the East China Sea (ECS). Related datasets are also collected from literatures with careful selection. Then we firstly apply a 1D

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model in the cross-shore direction in considering diffusion only, advection only, and both advection and diffusion, respectively. Further a 2D horizontal model is introduced to study the along-shore processes. Apparent diffusivity and advection velocity are derived. A sensitivity study is conducted to examine the influence of advection velocity on diffusivity. A quasi-2D method is proposed to estimate the actual along-shore diffusivity. The impact of benthic Ra flux on the cross-shore diffusion is evaluated by a simple but reasonable method. Based on the estimated eddy diffusivity and advection velocity, we calculate the nutrient fluxes in a fishing ground in the ECS.

2. Material and method

2.1. Study area

The ECS is upon an open epi-continental shelf with a depth normally shallower than 200 m (Fig. 1). It is connected with the Yellow Sea to the north, Pacific Ocean to the east and South China Sea to the south. The Fujian-Zhejiang coast, in the inner shelf of the ECS, is influenced by multiple water masses: Changjiang Diluted Water (CDW), Zhejiang-Fujiang Coastal Current (ZFCC), Taiwan Warm Current (TWC) and Kuroshio offshore (Beardsley et al., 1985; Lee and Chao, 2003). The Changjiang River (Yangtze River) provides a substantial input of freshwater, sediment and nutrients into adjacent seas (Zhang, 1996). Seasonal variation in the expansion of the Yangtze River plume has a profound effect on the distribution of water masses in the ECS. In summer, the majority of the CDW extends southward along the Fujian-Zhejiang coast, except for a part that flows to the northeast into the Jiangsu coastal area (Beardsley et al., 1985). The ZFCC, carrying the Yangtze River's brackish water and sediment, flows southward in winter and northward in summer along the inner shelf (Liu et al., 2007). To the east of the ZFCC, the broad shelf is dominated by the northward TWC, whose strength is stronger in summer (Lee and Chao, 2003; Liu et al., 2003). On the eastern boundary, the Kuroshio moves northward along the shelf break and intrudes into the ECS. In spring and summer, Kuroshio bottom water intrusion dominates while its surface and middle water intrusion is significant in autumn and winter (Sun, 1987; Su, 2005; Lee and Matsuno, 2007; Chen, 2009).

The Zhejiang-Fujian coasts are rocky type with rugged coastlines. A number rivers discharge into the ECS along the coast, including the large Yangtze and Qiantang River (Fig. 1), and small Yong River, Ling River, Ou River, Feiyun River, and Ao River. They supply the major terrigenous material to the ECS. The bottom sediment over the ECS consists of relic sands in the middle shelf, a muddy belt along the coast and also a giant sub-aqueous delta offshore the Yangtze Estuary (Qin and Zhen, 1982). The ^{228}Ra activities in the bottom sediments are documented by 5–15 Bq kg^{-1}(Chen et al., 1982).

The broad continental shelf area of the ECS is a highly valuable fishing ground. Due to abundant riverine nutrient input and a current convergence, there forms one of China's most productive near-shore fishing ground, the Zhoushan Fishing Ground, close to the Yangtze Estuary. This ground is around 20–70 m water depth with water temperature

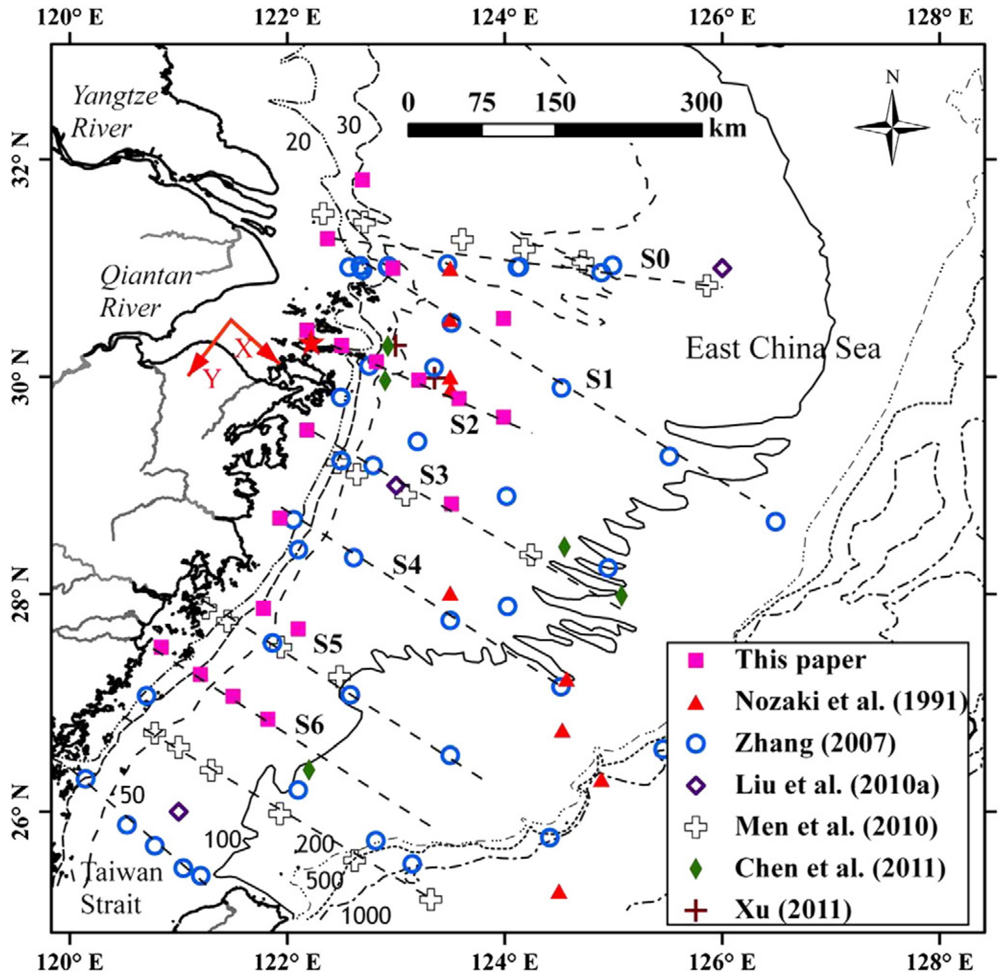

Fig. 1. Sampling stations along the Fujian-Zhejiang coast in the East China Sea. The collected data from Nozaki et al. (1991), Zhang (2007), Liu et al. (2010a), Men et al. (2010), Chen et al. (2011) and Xu (2011) are plotted. The cross-shore dashed lines show the location of the sections in 1D model. The star denotes the origin from where the distances in both *x* and *y* directions are computed for 2D model calculations. The numbers by the depth contours indicate the depth information.