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Study of water mixing in the coastal waters of the western Taiwan Strait based on radium isotopes

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ABSTRACT

Radium is considered to be a useful tracer for studying the physical processes of seawater. In this work, three naturally occurring radium isotopes, $^{224}Ra_{ex}$, ^{226}Ra and ^{228}Ra, were measured in the coastal zone of the western Taiwan Strait during the summer seasons. Based on the distributions of the three radium isotopes and the salinity, we conclude that the water mixing pattern in the study area in summer consists of diluted water flowing from the Jiulong River to the open sea towards the east and southeast, and open sea seawater flowing inward from south to north. The submarine ground water discharges in the estuarine region, as suggested by the radium and salinity data. The residence times of the Jiulong River estuary, ranging from 7 to 49 d, were estimated using the radium isotope pairs $^{224}Ra_{ex}$ and ^{226}Ra.

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1. Introduction

The exchange of material between the continental margin and the open sea plays a key role in global biogeochemical cycling. Physical mixing in estuaries and the coastal ocean is responsible for the dispersion of land-based anthropogenic inputs (e.g., nutrients and pollutants), sediment-generated nutrients and metals, as well as algal blooms, plumes and spills (Torgersen et al., 1996). The processes of physical mixing, which include advection and diffusion, are integral to the understanding of the exchange and transport of material at the land–sea interface. The eddy diffusion coefficient and advection velocity are the most important parameters in physical oceanography and are used to express the rates of the eddy diffusion and advection, respectively. However, these parameters are difficult to quantify because these systems are exceedingly complex due to their small-scale temporal and spatial variability. Chemical tracers offer promise but few techniques have been developed to study this complex region. However, naturally occurring radium isotopes provide a useful tool for the study of these marine processes (Moore, 2000).

Four radium isotopes, ^{223}Ra, ^{224}Ra, ^{226}Ra and ^{228}Ra, are delivered to the ocean by river inputs, bottom sediment inputs and submarine ground water discharge (SGD). Radium isotopes are soluble and preserved in seawater. Consequently, they can be used individually as tracers or in pairs to study ocean-mixing processes. Radium-226 ($t_{1/2} = 1602$ y) is a suitable tracer for marine processes with time scales of a thousand years. Radium-228 ($t_{1/2} = 5.75$y) is a valuable natural tracer of water mixing on the order of 1–30 y but is of little use in delineating relatively short-term processes. Radium-224 ($t_{1/2} = 3.66$ d) is a useful tracer for marine processes that occur within a 1- to 10-dscale. Radium-223 ($t_{1/2} = 11.4$ d) is another useful tracer for marine processes that occur within several weeks. In coastal waters and the open sea, radium isotopes have been used to provide important information about mixing processes, including diffusion (Moore, 2000; Rengarajan et al., 2002), pore-water and surface water exchange (Bollinger and Moore, 1993; Webster et al., 1994), water transport rates (Turekian et al., 1996; Turekian et al., 1996) and groundwater outflow (Rama and Moore, 1996; Krest and Harvey, 2003).

The Taiwan Strait, the channel connecting the South China Sea and the East China Sea, is located between mainland China and Taiwan Island. The Jiulong River, the second largest river in the Fujian province, discharges into the coastal area of the western Taiwan Strait, with an annual average river flow of 1.48×10^{10} m^3; it is the major source of freshwater to the coastal area. The geographical setting determines that this area receives wastewater with high nutrient and pollutant loading from both the Jiulong River catchment and urban (Xiamen City) sewage (Cao et al., 2005).

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Since the mid-1980s, eutrophication and the excessive growth of benthic algae, which causes a deterioration in the quality of seawater, have accelerated in the Jiulong estuary and coastal ocean (Chen et al., 1993; Hong et al., 1999). Thus, many physical, chemical and biological studies have focused on the fate of these nutrients and pollutants. In this work, the mixing processes in the western Taiwan Strait were studied and the residence times of the surface seawater of Jiulong River estuary were estimated using radium isotopes.

2. Sampling and methods

2.1. Sampling stations

Water samples were collected in June 2009 on the "Yanping 2" vessel. The sampling period is typical of summer conditions. The temperature of the seawater is high with ~24–~28 °C. The sampling stations and detailed information are shown in Fig. 1 and Table 1. There are 34 stations distributed in transects A–F. Vertical sampling was performed at stations A5, B2, C3, D4, and E6. All other stations were surface sampling stations.

All the errors in this table were calculated using an error transfer formula, including counting error, background error and efficiency error.

2.2. Sampling and analysis

Approximately 70 L of seawater was pumped and collected into a plastic container. The seawater was pumped sequentially through the flowmeter, then columns A, B and C at the rate of ~400 mL/min. Column A was used to filter suspended solids. Column B and column C were MnO_2-fiber columns with12 g MnO_2-fiber inside. Column B was used to determine the activities of the radium isotopes in the seawater, and column C was used to determine the extracting efficiency. A previous study showed that greater than 99% of radium isotopes could be extracted by the 12 g MnO_2-fiber at a seawater flow rate of less than 500 mL/min (Chen et al., 2011). After sampling, the sample fibers were carefully shaken to remove water and were stored in plastic bags for the measurement of the radium isotopes.

Radium-224 activity was measured by the ^{220}Rn emanation method (Men et al., 2013). After sampling, the samples were shaken to remove water. Nitrogen gas was introduced to carry the original ^{220}Rn and ^{222}Rn in the MnO_2-fiber sample column out of the measurement system over the first 5 min and then to carry the ^{220}Rn that emanated from the samples into the Rn–Th analyzer (FD-125, Beijing Nuclear Instrument Factory, Beijing, China) to determine the ^{224}Ra activity (Fig. 2). With a very short half-life of 55.6 s, ^{220}Rn can reach equilibrium with ^{224}Ra in several minutes. The ^{222}Rn emanating from ^{226}Ra does not interfere with the measurement of ^{220}Rn. A standard of ^{232}U–^{228}Th–^{224}Ra (A11416, National Physical Laboratory, UK) in equilibrium was used to determine the efficiency of the measurement system.

The level of ^{224}Ra supported by its parent ^{228}Th was corrected using separate measurements. After the first measurements were complete, the MnO_2-fiber samples were aged for approximately 6 weeks to allow for the supported ^{224}Ra to equilibrate with ^{228}Th absorbed onto the MnO_2-fiber. The samples were measured again to determine the ^{224}Ra supported by ^{228}Th. The differences between the two measurement results are the excess ^{224}Ra activities ($^{224}Ra_{ex}$), which are reported in this paper.

The ^{226}Ra activity was measured using the ^{222}Rn emanation method (Yang et al., 2007). Briefly, the MnO_2-fiber was removed from the plastic bag and placed into a diffusion tube, which was sealed and evacuated. After 5–20 d, when the ingrown ^{222}Rn reached a significant level, the ^{222}Rn was introduced into an evacuated scintillation counting cell. After being sealed in the cell for 3 h until reaching an equilibrium of ^{222}Rn with its daughters, their activities were measured using the Rn–Th analyzer. A ^{226}Ra standard (GBW04312, National Institute of Metrology, China) was used to determine the efficiency of the measurement system.

The MnO_2-fibers were then stored for more than 1 y after the measurement of ^{226}Ra, after which the ^{228}Ra activity was measured through determining the ^{224}Ra growing from ^{228}Ra by the aforementioned method.

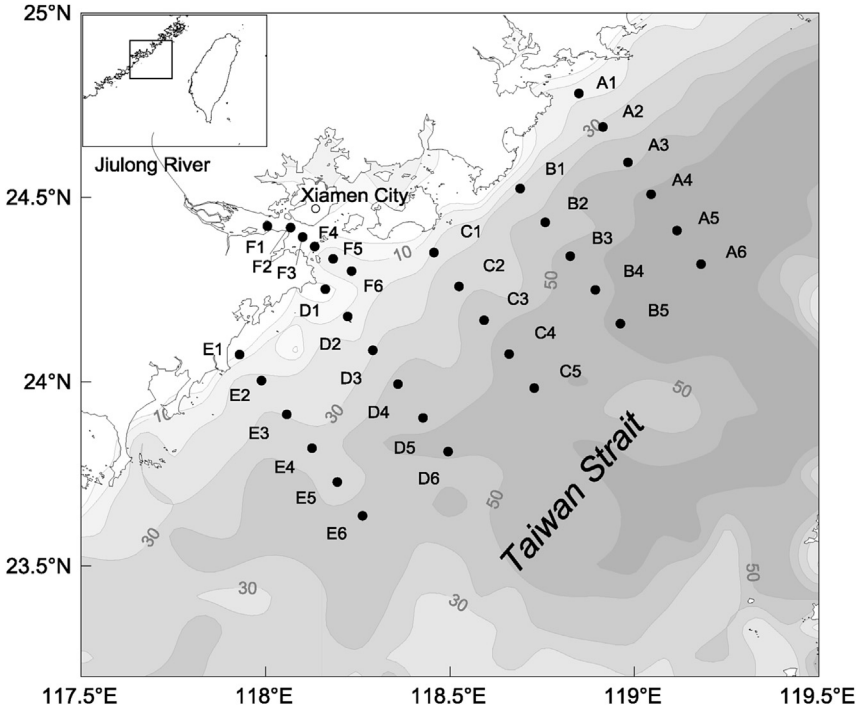

Fig. 1. Map of sampling stations with the isobaths.

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