ANALYSIS OF YELLOW RIVER MIXING PROCESSES INTO THE BOHAI SEA VIA BARIUM AND RADIUM ISOTOPES

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Abstract
The mixing rate of dissolved substances from the Yellow River into the Bohai Sea is an important parameter in understanding the nutrient input to the coastal ocean. We present an assessment of the mixing rates under different discharge patterns using naturally-occurring short-lived radium isotopes. Radium and salinity measurements were collected along transects through the Yellow River salinity gradient and into the coastal Bohai Sea during three field expeditions. Mixing rates varied between 5 and 18 km^2/day and were strongly dependent on river discharge. The highest mixing rates are found just after periods of high discharge, while the lowest mixing rates occurred after periods of relatively low discharge.

Key words: Mixing rates, radium isotopes, tracers

Introduction
One of the key unknown aspects of the interaction between the Yellow River and the Bohai Sea concerns the rate of mixing of dissolved river-borne substances. The spatial extent to which riverine-derived nutrients can impact the Bohai Sea depends heavily on the rate at which they are mixed away from the river. This may determine, for example, the residence time of nutrients within a particular region of the coastal ocean. Assessment of mixing is thus essential in order to understand the relative importance of Yellow River nutrients with respect to the recent nitrogen over-enrichment found in the Bohai Sea.

The spatial extent of the mixing area of the Yellow River water can be assessed easily simply by mapping salinity in the coastal ocean. However, the incorporation of radioisotopes to this study adds a temporal component to the scope of riverine mixing. We employ the use of the short-lived radium isotopes, ^{224}Ra ($t_{1/2}$ = 3.66 days) and ^{223}Ra ($t_{1/2}$ = 11.54 days) to examine the mixing rates of these waters.

Radium and its stable analog, barium, exhibit the same behavior in estuarine systems. In the purely freshwater areas of a river, they remain attached to suspended particles. However, once these particles encounter saline waters, the radium and barium are largely removed from the particles into solution via ion exchange processes (Hanor and Chan, 1977; Li and Chan, 1979; Coffey et al., 1997; Moore, 1997; Martin and Akber, 1999; Nozaki et al., 2001). This "desorption" process represents an important input of radium and barium to the coastal ocean.

Methods
Field expeditions were performed in September 2004, May 2005, and September 2006 to evaluate the influence of river discharge with these coastal mixing rates (Fig. 1). Radium

concentrations were measured using the delayed coincidence counting technique described by Moore and Arnold (1996) along transects from the Yellow River offshore to the Bohai Sea.

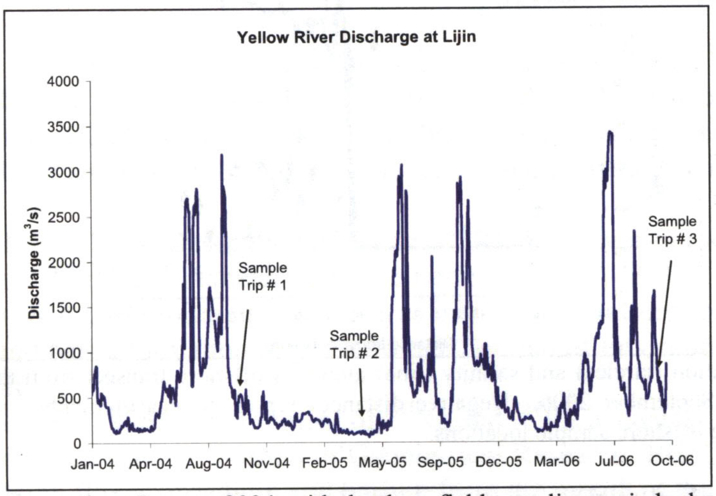

Fig. 1 Yellow River discharge since January 2004, with the three field sampling periods shown by the arrows.

For calculating mixing rates, we followed the method established by Moore (2000). In short, plotting the natural logarithm of the radium isotope activity over the transect offshore produces a relationship fit by a straight line equation:

$$m = \sqrt{\frac{\lambda}{K_h}} \quad (1)$$

where m is the slope of the best-fit line, K_h is the mixing coefficient with units of square distance per time, and λ is the decay constant, 0.189 d^{-1} for ^{224}Ra and 0.060 d^{-1} for ^{223}Ra.

Results and Discussion

A transect from the Yellow River estuary into the Bohai Sea (Fig. 2) shows that radium peaks within the estuary and decreases exponentially offshore. This decrease is due to a combination of radioactive decay and mixing and was modeled according to (1). Barium concentrations follow this same pattern, except its decrease is due only to mixing. Table 1 reports the calculated mixing rates for each of these sample periods as based on this data. The errors reported for each mixing rate are based on the uncertainty in the best-fit slope. For periods immediately following high discharges (i.e. September), the mixing rate is higher than that sampled in May after a period of low discharge.

While derived from radium distribution, these results are essentially a gauge of relative water movement. As such, these mixing rates can be readily applied to any dissolved materials that are carried offshore within the river plume. However, particle settling, turbulent processes, and resuspension effects prevent these results from being practical to suspended sediments or particle-bound substances.

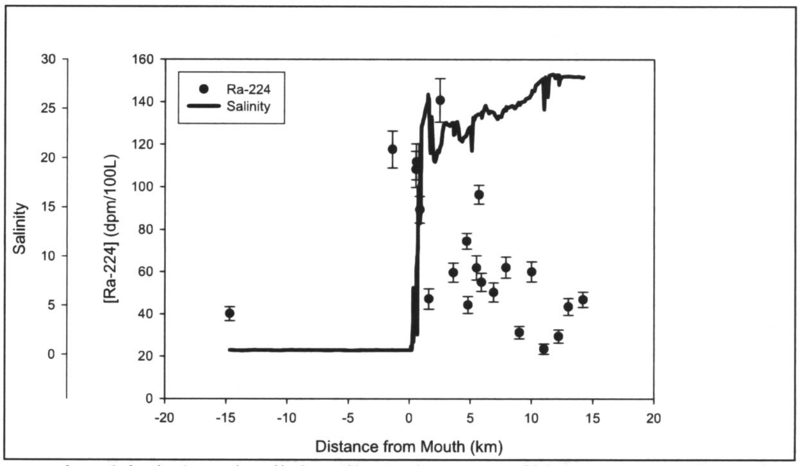

Fig. 2 Ra-224 concentration (circles) and salinity (line) along an offshore transect from the Yellow River. Data shown was collected in September 2006. Negative distances represent measurements within the river, whereas positive distances indicate offshore sample locations.

The model applied to these data neglects the contribution of advective mixing processes to the total mixing, assuming that eddy diffusive mixing is the dominant factor. While tidally-averaged fluctuations of water mass movement within the estuary are minimal, their relative importance to the total mixing remains unknown. One future goal of this project is to assess the river plume advection contribution to the overall mixing rates.

	Average River Discharge m^3/s	**Ra-224 K_h** km^2/d	**Ra-223 K_h** km^2/d	**Average K_h** km^2/d
Sep 2004	1222 ± 897	16.9 ± 2.74	19.8 ± 2.58	18.4 ± 2.66
May 2005	100 ± 16	4.93 ± 2.66	4.57 ± 1.30	4.75 ± 1.98
Sep 2006	779 ± 350	12.6 ± 4.64	13.7 ± 2.17	13.2 ± 3.41

Tab. 1 Offshore river water mixing coefficients (K_h) derived from Ra-224 and Ra-223 as well as the average values for the three sample trips. Uncertainties shown are based on the error in best-fit slope to the data. River discharge shown is a monthly average leading up to and including the period of the field trip.

Conclusions

Radium isotopes have proven to be useful tracers where the Yellow River plume water meets the Bohai Sea. Coastal mixing rates ranged between 5 and 18 km^2/day for three different sampling periods. The data clearly indicate that the mixing rates vary directly with the average river discharge for the month leading up to the sampling period. These mixing rate results may be applicable to any dissolved substances introduced to the Bohai Sea from the Yellow River.

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