NOTE AND CORRESPONDENCE

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Material Exchange Between the East China Sea and the Kuroshio Current

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ABSTRACT

The water exchange rate between the continental shelf water of the East China Sea and the Kuroshio Current waters is estimated to be about 22000±9000 km^3/yr or 0.7±0.3 Sverdrups which is about 25 times the value of the major river runoffs in the region. The implication is that the chemistry of the continental shelf water is mostly influenced by the Kuroshio water inputs. Inputs of dissolved particle-reactive trace elements into the continental shelf water from the major rivers and the upwelled subsurface Kuroshio water are efficiently sequestered by suspended particles and subsequently removed to the bottom sediments. The Okinawa Trough sediments are important sites for receiving the dispersed fine suspended particles and associated particle-reactive trace elements from the continental shelf.

(Key words: Coastal exchange, East China Sea, Kuroshio Current)

The continental shelf of Yellow Sea and East China Sea has a total area of about $0.9 \times 10^6 km^2$ (water depth of less than 100 fathoms) and is one of the largest continental shelves in the world. The East China Sea is bounded by the Kuroshio Current in the east. Two of the world's major rivers i.e. Yangtze (Changjiang) River and Yellow (Huanghe) River also discharge into the East China Sea and the Pohai Gulf of the Yellow Sea respectively. The mean water and suspended sediment discharge rates are respectively, 850km^3/yr and 490×10^6 tons/yr for Yangtze River, and 35 km^3/yr and 900×10^6 tons/yr for Yellow River (Milliman and Meade, 1983). The average compositions of river water and suspended particles from these two rivers are summarized in Table 1. How much of river inputs have ended up in the continental shelf and the Okinawa Trough sediments, and how much have been exported out to the open ocean need to be addressed.

The general mixing patterns between the surface waters of the Kuroshio Current and the continental shelf during summer and winter seasons are given by Niino and Emery (1971). The intrusion of high temperature, high salinity water of Kuroshio Current along

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Table 1. Average compositions of waters and suspended particles from the Yangtze and Yellow Rivers, as well as the upwelled Kuroshio sub-surface water and average Okinawa Trough sediments.

	Water				Solids		
	Yangtze River	Yellow River	Upwelled Kuroshio		Yangtze	Yellow	Okinawa Trough
Ca mmol/l	0.69	1.1	10	Si %	27	27	20
Mg	0.30	0.98	53	Al	9.7	8.0	8.6
Na	0.19	2.2	460	Fe	5.5	3.2	3.6
K	0.053	0.08	9.9	Ca	2.8	6.0	10
Cl	0.13	1.5	540	Mg	1.4	1.3	-
SO_4	0.29	1.6	28	Na	0.5	0.9	1.7
HCO_3	1.8	3.2	2.1	Ti	0.5	0.4	0.3
PO_4 μmol/l	0.26	0.15	0.88	P	0.12	0.11	0.07
NO_3	29	13	13	Mn ppm	1000	800	2600
SiO_2	110	85	19	Ba	560	600	-
DOC	180	150	100	Sr	150	220	550
POC	600	11000	---	Zr	160	140	-
PIC	480	37000	---	V	160	110	-
pH	7.9	8.1	8.1	Zn	110	75	84
Q km^3/yr	870	34	---	Cr	83	72	66
TSS g/l	0.38	10	---	Cu	70	33	27
				Ni	78	38	67
				Co	25	12	14
				Pb	65	<35	32
				Be	2.0	1.6	-

Note: Gan et al. (1983), Cauwet and Mackenzie (1991) for river water data, Li et al. (1984) for river suspended particle and Zhao et al. (1984) for the Okinawa Trough sediments.

the south and west coasts of Korean Peninsula are respectively the Tsushima Current and the Yellow Sea Warm Current. Another warm saline water intrusion northeast of Taiwan Island is the Taiwan Warm Current. The low temperature, low salinity waters along the mainland coast are southward flowing Yellow Sea Coastal Current and Zhejiang Coastal Current. The hydrographic transects across the continental shelf clearly show the intrusion of the Upwelled Subsurface Kuroshio (USK) water across the shelf break onto the continental shelf and underneath the less saline continental shelf water (Chen and Bychkoz, 1992; Gong, 1992; Liu *et al.* 1992).

As shown schematically in Figure 1, the water budget for the continental shelf water is controlled by river inputs (Q_r), evaporation (Q_v) and precipitation (Q_p) over the continental shelf, Kuroshio waters mixing into the shelf (Q_m), and the output of the shelf water to the Kuroshio waters (Q_s). By water mass balance, Q_s should be equal to $Q_m+Q_r+Q_p-Q_v$ at a steady state. According to Oberhuber's (1988) compilation, the net precipitation over evaporation in the area is about 17 cm/yr or $Q_p-Q_v = 140\pm10$ km^3/yr as compared to the river input, Q_r, of 885 km^3/yr.

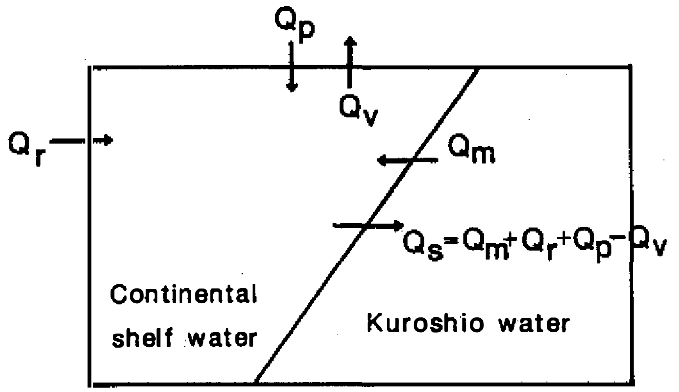

Fig. 1. The schematic diagram for the continental shelf surface water budget on the East China and Yellow Seas, where Q_r = runoff inputs from Yangtze and Yellow Rivers, Q_p = precipitation input, Q_v= evaporation output, Q_m= mixing rate of the Kuroshio waters into the continental shelf and Q_s= output rate of the shelf water to the Kuroshio waters.

Assuming a steady state, the salt mass balance in the continental shelf water requires:

$$Q_r \cdot S_r + Q_m \cdot S_k = (Q_m + Q_r + Q_p - Q_v) s_s$$

or $$Q_m = (Q_r + Q_p - Q_v) \cdot S_s/(S_k - S_s) - Q_r \cdot S_r/(S_k - S_s)$$

where S_r, S_k and S_s are respectively salinity of river water, Kuroshio water, and the continental shelf water.

The next question is what is the representative S_s of the shelf water which exchange with the Kuroshio waters? The salinity transects across the East China Sea (Chen and Bychkov, 1992) indicate that the salinity of 33 ± 0.2 per mil is a reasonable boundary to separate between the continental shelf water with steep salinity gradient and the Kuroshio waters with low salinity gradient. Therefore, 33 ± 0.2 per mil is chosen here for S_s. Similarly, the main Kuroshio waters which exchange with the shelf water are the Kuroshio Surface Water with typical salinity of 34.4 per mil, and the Upwelled Subsurface Kuroshio Water with typical salinity of 34.6 per mil. Therefore, S_k of 34.5 ± 0.1 per mil is chosen here. Whereas, S_r is about 0.2 per mil. Substituting these numbers into the above equation, one obtains Q_m to be about 22000 ± 9000 km^3/yr or 0.7 ± 0.3 Sverdrups, which is about 25 times the value of Q_r. Interestingly, the mixing rate between the shelf water and the Tsushima Current water was estimated to be about 0.6 ± 0.2 Sverdrups, based on $^{228}Ra/^{226}Ra$ mass balance (Nozaki, 1989). The estimated volume of the shelf water (V_s) with salinity less than 33 ± 0.2 per mil is about 2 to 3 10^4km^3. Therefore, the mean residence time of the dissolved non-reactive salts in the shelf water is about 1 year ($=V_s/Q_s$), which is relatively long compared to that of the New York Bight water (3 to 4 months; Li *et al.* 1979). Q_m of about $25 \cdot Q_r$ implies that the chemistry of the continental shelf water is mostly influenced by the Kuroshio water inputs except near the river mouths or when the concentration of a given dissolved element in the rivers is more than 25 times of that in the Kuroshio water. Also the exchanged Kuroshio waters are most likely dominated by the Upwelled Subsurface Kuroshio Water and to a lesser extent by the Surface Kuroshio Water (Chen and Bychkov, 1992; Gong, 1992; Lin *et al.*, 1992).

The net material exchange between the continental shelf water and the Kuroshio water, X, can be approximated by $X = Q_m \ (C_s - C_k)$, where C_s and C_k are respectively the concentrations of a given material in the continental shelf and the Kuroshio waters. For example, the average nitrate concentration of the shelf water of the East China Sea is about 1 μM and of the Upwelled Subsurface Kuroshio Water about 15 μM (Gong, 1992; Liu *et al.*, 1992), therefore, the net flux of nitrate from the Kuroshio water to the shelf water is at most about 310×10^9 moles N/yr [$=22 \times 10^{15}$ l/yr$\cdot$(15$-$1) μMoles N/l]. For comparison, the river nitrate flux is only 26×10^9 mole N/yr. These nitrate can support an average new production of about 80 mg C/m^2/d over the continental shelf of the East China Sea (assuming Redfield ratio of C/N = 106/16). At a steady state, this new production should also be removed from the surface shelf water back to the Kuroshio waters and/or bottom sediments. If the average total primary production by phytoplankton over the East China Sea continental shelf is about 500 mg C/m^2/d or greater (Koblenz-Mishke *et al.*, 1970), then the f-factor (= new production/total primary production) would be about 0.16 or less. The f-factor of 0.66 given by Gong (1994) is probably an overestimate. Certainly, new measurements of the primary production and independent estimate of the f-factor in the East China Sea are badly needed.

According to McKee *et al.*, (1984), the residence time of ^{234}Th in the water column with respect to its removal to the seabed ranges from a half day near the Yangtze River mouth to about 11 days in midshelf water. This range is much smaller than those for coastal environments without a major sediment source such as New York Bight (about 10 to 30 days; Kaufman *et al.* 1981). This range of 0.5 to 11 days is also much shorter than the residence time of dissolved non-reactive salts in the continental shelf water (about one year). Therefore, the inputs of dissolved particle-reactive elements into the continental shelf water from the Yangtze River, Yellow River and the Upwelled Subsurface Kuroshio Water should be efficiently sequestered by suspended particles and removed to the bottom sediments. For comparison, the residence time of ^{234}Th in the surface 100 meters of the Kuroshio Current, northeast of Taiwan, is about 70 days (Wei, 1991), which is similar to that of the Gulf Stream surface water in the New York Bight (Kaufman *et al.* 1981, Li *et al.* 1979).

Once the particle-reactive elements in the water column are sequestered by suspended particles, they end up mostly in the fine-grained bottom sediments in the region. The distribution of fine-grained mud patches on the continental shelf of the East China Sea and the Yellow Sea is closely related to the cyclonic gyre systems in the area (Hu, 1984). Usually a cyclonic gyre induces upwelling within the gyre and accumulates fine-grained sediments underneath. In contrast, an anticyclonic gyre induces downwelling within the gyre and flashes out fine sediment particles (Hu, 1984). Another important mud patch is on the lower continental slope and the Okinawa Trough. The mud patch sediments are also high in organic carbon content (0.5 to 1%; Niino and Emery, 1971). From the ^{210}Pb profiles in the sediments, the typical sediment accumulation rate for the inner shelf mud patch next to Yangtze River mouth is estimated to be about 2.1 g/cm^{2}yr (or 3 cm/yr for density of 0.7g/cm^3), and for the outershelf mud patch about 0.15 g/cm^{2}yr (DeMaster *et al.* 1985). For comparison, if the suspended particle inputs from the Yangtze and Yellow Rivers are evenly distributed on the whole continental shelf, the average sediment accumulation would be about 0.15 g/cm^2 yr. The sediment accumulation rates in the southern end of the Okinawa Trough range from 0.5 g/cm^2yr at depth of 900m to 0.08 g/cm^2yr at 1600 m, whereas there are no sediment accumulation at the depth interval between 400 to 800 meters (Y. Chung, personal communication).

Assuming an average sedimentation rate of 0.3g/cm^2yr, the total flux of sediments in the Okinawa Trough (total area of about 0.09 $\times$ $10^6 km^2$ for depth greater than 900m) would be about 300 $\times$ 10^6tons/yr. If one half of these sediments were ultimately originated from the Yellow and Yangtze rivers and other half from local sources such as Ryukyu islands, then about 10% of the suspended particle loadings from the major rivers may have been depositing in the Okinawa Trough. Additional data on the accumulation rate and compositions of sediments in other areas of the Okinawa Trough are needed to improve this kind of estimation.

As shown by DeMaster *el al.* (1985), the high fluxes of excess ^{234}Th to the inner-shelf mud patch relative to the predicted fluxes from the water column production (2.2 to 27.6 times) strongly suggest lateral transport and deposition of ^{234}Th from offshore waters to near-shore on the time scale of about 100 days (about 4 half lives of ^{234}Th). In contrast the relative fluxes (the observed over the predicted from water column production plus atmospheric inputs) of excess ^{210}Pb in the same mud patch are only 0.2 to 2.6 times on the time scale of about 100 years (about 4 half lives of ^{210}Pb). The implication is that any particle reactive elements in the continental shelf waters would be rapidly sequestered by particles and deposited in the inner-shelf mud patch on a 100 days time scale, but subsequently be dispersed out from the area on a 100 years time scale (DeMaster *et al.* 1985). Because the observed fluxes of both excess ^{234}Th and excess ^{210}Pb in the mid-shelf sandy sediments and in the outer-shelf mud patch are all below the predicted fluxes from water column production plus atmosphere inputs (DeMaster *et al.* 1985), the continental slope and Okinawa Trough sediments should be important sites for receiving the dispersed fine particles and associated particle reactive elements from the continental shelf. Indeed, the fluxes of excess ^{210}Pb and excess ^{230}Th in the Okinawa Trough sediments (900 to 1600m) northeast of Taiwan are respectively 4 to 10, and 10 to 50 times of those predicted from water column production plus atmospheric inputs for ^{210}Pb (Y Chung, personal communication). The average content of Mn in the Okinawa Trough sediments is about 0.3% (Table 1) and the highest value can be as high as 0.7% (Zhao *et al.* 1984), as compared to about 0.1% for the river suspended particles (Table 1). It is often suggested that manganese oxide particles or coatings are the most efficient scavengers for ^{210}Pb, ^{230}Th and other trace metals in the oceans (Bacon *et al.* 1976; Li, 1982). It will be instructive to see how effective the Okinawa Trough sediments also accumulate anthropogenic pollutants such as ^{239,240}Pu, ^{137}Cs, pesticides, trace metals etc.

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