The Kuroshio intermediate water is the major source of nutrients on the East China Sea continental shelf

East China Sea
Kuroshio
Nutrients
New production
Residence time

Mer de Chine orientale
Kuroshio
Nutriment
Production nouvelle
Temps de résidence

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ABSTRACT

The Kuroshio subsurface waters upwell onto the East China Sea (ECS) shelf and contribute a large amount of nutrients to the ECS. This contribution is many times more than the inputs from the Yangtze and the Yellow Rivers.
The residence time of the ECS shelf water is estimated at 1.3 ± 0.4 years. The new production rate of phytoplankton is 73 ± 22 mg C/m^2/day and the net burial rate of organic carbon is 41 ± 23 mg C/m^2/day.

RÉSUMÉ

L'eau intermédiaire du Kuroshio, principale source de nutriments sur le plateau continental de la mer de Chine orientale.

La remontée des eaux subsuperficielles du Kuroshio sur le plateau continental de la mer de Chine orientale constitue un apport considérable de nutriments, supérieur aux apports des fleuves, Yangtze et Fleuve Jaune.
Le temps de résidence de l'eau du plateau continental de la mer de Chine orientale est estimé à 1,3 ± 0,4 années. La production nouvelle du phytoplancton est de 73 ± 22 mg C/m^2/jour et le taux net de sédimentation du carbone organique est de 41 ± 23 mg C/m^2/jour.

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INTRODUCTION

The continental shelf of the Yellow and East China Seas has a total area of about 0.9 × 10^6 km^2 and is one of the largest in the world. It is also one of the most productive areas of the world oceans. Two of the largest rivers in the world, the Yangtze River (Changjiang) and the Yellow River (Huanghe), empty into the shelf with large nutrient inputs.

On the slope side of the shelf is the Kuroshio which flows northeastward along the eastern margin of the continental shelf. Water around the shelf edge is often found to form isotherms, isohalines, and iso-nutrient contours that shoal westward near the shelf then concave upward near the shelf break (Ruo, 1989; Wong *et al.*, 1989*a*, *b*, 1991; Chen *et al.*, 1990, 1991; Ruo and Chen, 1991; Liu *et al.*, 1992; Ito *et al.*, 1994). These results provide a strong indication that the subsurface water of the Kuroshio is upwelled along the shelf slope. But this conclusion is only qualitative rather than quantitative.

Since the Kuroshio originates from the subtropical and tropical regions with low nutrient contents near surface, if only near-surface Kuroshio water moves onto the shelf the water would not contribute much to the high productivity of the East China Sea (ECS). Chen *et al.* (1990, 1995) and Ito *et al.* (1994), however, have shown that even the North Pacific Intermediate Water (NPIW) contributes up to 30 % in the upwelling and cross-shelf mixing. This would provide a significant source of nutrients since NPIW is high in nutrients.

However, previous mass balance calculations for the East China Sea did not take into consideration that NPIW plays a significant role in the fresh water, salt and nutrient fluxes (*e.g.* Li, 1995). Further, the fresh water fluxes show a large seasonal variation in the ECS thus it would be expected that the upwelling rate would too, heretofore unstudied. Recognizing that the waters on the ECS are never at a steady state, I nevertheless divided the year into two seasons. With the ability to calculate the mixing percentages of various water masses across the continental shelf (Chen *et al.*, 1990, 1995), it is now possible to quantitatively estimate Kuroshio's contribution of nutrients to the shelf in the dry and raining seasons separately. The study areas of Chen *et al.* (1990, 1995; September, 1988 and December, 1988, 1989 data) and Ito *et al.* (1994; May-June, 1987 data) are given on Figure 1.

METHOD

The Kuroshio surface water (SW), Kuroshio Tropical Water (TW), Kuroshio Intermediate Water (IW) and the Shelf Surface Water (SSW) make up the major water masses near the shelf break (Chen, 1988; Chen *et al.*, 1995). Although the major currents are parallel to the isobath the SSW has a net transport offshore because of the fresh water discharge from rivers, while SW, TW and IW have net onshore transports. River input, precipitation and evaporation also contribute to the water budget (Fig. 2).

The water balance for the shelf at a steady state is:

$$Q_{Ri} + Q_P + Q_{SW} + Q_{TW} + Q_{IW} = Q_E + Q_{SSW} \qquad (1)$$

where Q is the water flux, subscripts Ri, P, SW, TW, IW, E and SSW denote river input, precipitation, Kuroshio Surface Water, Kuroshio Tropical Water, Kuroshio Intermediate Water, evaporation and Shelf Surface Water, respectively.

The salt balance is:

$$Q_{Ri} \cdot S_{Ri} + Q_{SW} \cdot S_{SW} + Q_{TW} \cdot S_{TW} + Q_{IW} \cdot S_{IW} = Q_{SSW} \cdot S_{SSW} \qquad (2)$$

where S is salinity, subscripts denote the same waters as for eq. (1)

As an example, the percentages of SSW, SW, TW and IW at a cross-section off the northeast corner of Taiwan in September and December, 1988 and in December, 1989 have been calculated and can roughly represent the raining season and the dry season respectively, assumed to be constant during the six months (Chen *et al.*, 1990, 1995). Chen *et al.* (1995) estimated that 70 % of the water near the shelf break northeast of Taiwan come from Kuroshio with SW contributing 30 % out of the 70 %; TW contributing 25 % and IW contributing 15 %. Thus for the Kuroshio water that move onto the shelf the fluxes are in the same proportions, *i.e.* in the raining season (May through October)

$Q_{SW} = 2Q_{IW}$,

$Q_{TW} = 1.5\ Q_{IW}$. $Q_P - Q_E = 420\ km^3 / 6$ months (Oberhuber, 1988; Fang, 1992; Zhang and Yao, 1992; Yanagi, 1994) and

$Q_{Ri} = 813\ km^3 / 6$ months (Kim, 1992).

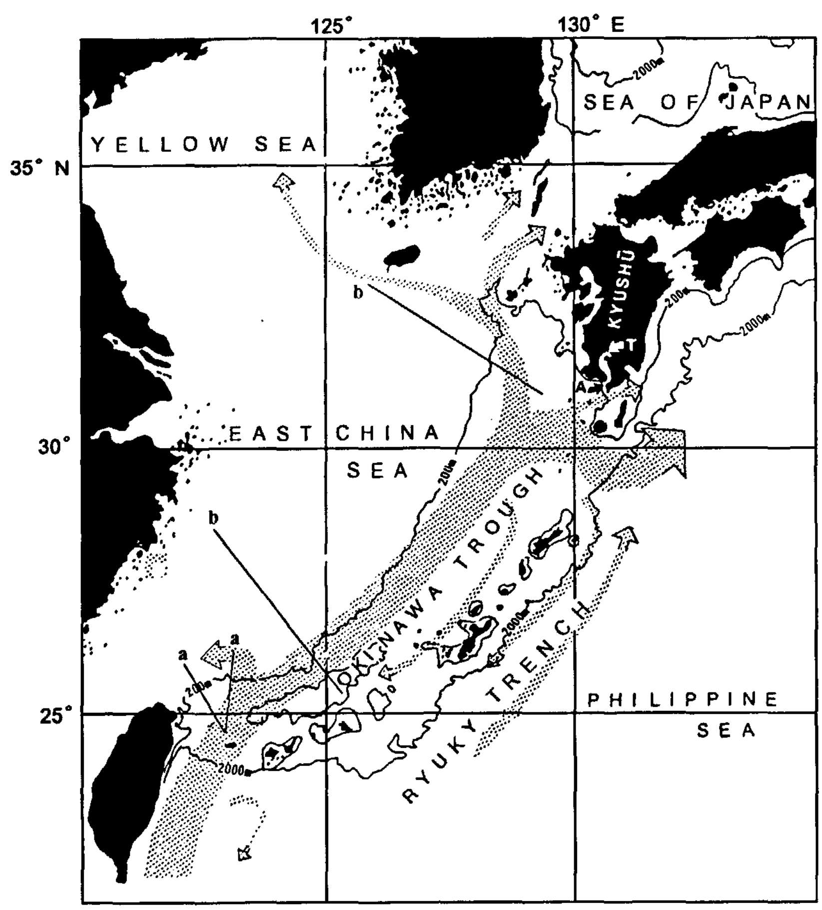

Figure 1

The study areas of (a): Chen et al. *(1990, 1995) and (b): Ito* et al. *(1994).*

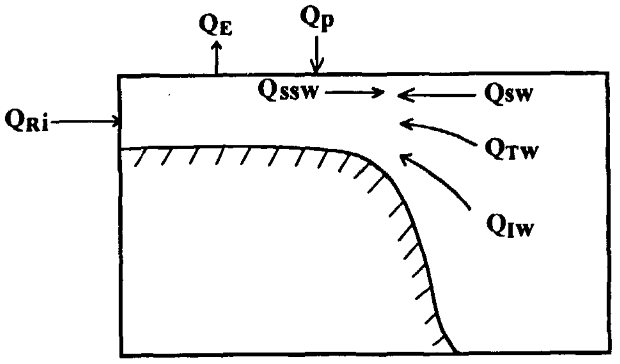

Figure 2

Schematic diagram for the water budget.

The salinities for the water masses, also assumed to be constant during the raining season are as follows:

S_{Ri} = 0.18 (Gan *et al.,* 1983), S_{SSW} = 33.1, S_{SW} = 34.5, S_{TW} = 34.9 and S_{IW} = 34.3 (Chen *et al.,* 1995).

RESULTS

With the above information and solving for eqs (1) and (2), Q_{SSW} = 28 593 km^3, Q_{SW} = 12 160 km^3, Q_{TW} = 9 120 km^3 and Q_{IW} = 6 080 km^3 for the six-month wet season. Q_{SSW} includes the outflow through the Tsushima Strait but the exchange through the Taiwan Strait is neglected.

Chen *et al.* (1990, 1995) calculated the mixing ratios of SSW, SW, TW and IW at two cross-sections northeast of Taiwan in the dry season. Kuroshio water made up 90 % of the shelf water with SW contributing 63 % out of the 90 %; TW contributed 20 % and IW contributed 7 %. Assuming the fluxes of each component were in the same proportion, they were as follows: in the dry season (November-April) $Q_{SW} = 8\ Q_{IW}$, $Q_{TW} = 3\ Q_{IW}$, Q_{Ri} = 404 km^3/6 months (Kim, 1992) and $Q_P - Q_E = -280$ km^3/6 months for six months (Oberhuber, 1988; Fang, 1992; Zhang and Yao, 1992; Yanagi, 1994), S_{Ri} = 0.18 (Gan *et al.,* 1983), S_{SSW} = 33.8, S_{SW} = 34.5, S_{TW} = 34.9, S_{IW} = 34.3. The resulting Q_{SSW} = 5 380 km^3, Q_{SW} = 3 504 km^3, Q_{TW} = 1 314 km^3 and Q_{IW} = 438 km^3 for six months. Note the upwelling is much reduced because of the much smaller fresh-water influx.

Since the Kuroshio Surface Water is very low in nutrient contents ($NO_3 \le 0.1$ µmol/kg, $PO_4 \le 0.02$ µmol/kg, $SiO_2 \le$ 1µmol/kg), the onshore fluxes of nutrients due to SW are small: Q_{NO3} in summer and in winter are roughly 1.22 × 10^9 mol and 0.35 × 10^9 mol, respectively; Q_{PO4} is 0.24 × 10^9 mol and 0.07 × 10^9 mol, respectively; Q_{SiO2} is roughly 12.2 × 10^9 mol and 3.5 × 10^9 mol, respectively, all for six months. The Kuroshio Tropical Water has smaller water fluxes than the Kuroshio Surface Water but since the nutrient concentrations are much higher (NO_3 ~ 4 µmol/kg, PO_4 ~ 0.3 µmol/kg, SiO_2 ~ 4 µmol/kg), the nutrient fluxes due to TW are larger than that due to SW: Q_{NO3} in the summer and in the winter are roughly 36.5 × 10^9 mol and 5.2 × 10^9 mol for six months, respectively; Q_{PO4} are roughly 2.7 × 10^9 mol and 0.4 × 10^9 mol for six months, respectively; Q_{SiO2} are roughly 36.5 × 10^9 mol and 5.2 × 10^9 mol for six months, respectively.

The Kuroshio Intermediate Water contributes the least to the upwelled water but has the highest nutrient concentrations (NO_3 ~ 25 µmol/kg, PO_4 ~ 1.7 µmol/kg, SiO_2 ~ 60 µmol/kg), thus contributing the most to the nutrient fluxes. The summer and winter fluxes are respectively: Q_{NO3} = 150 × 10^9 mol and 11 × 10^9 mol; Q_{PO4} = 10.2 × 10^9 mol and 0.7 × 10^9 mol; Q_{SiO2} = 360 × 10^9 mol and 25 × 10^9 mol, all for six months. Altogether, the annual contributions by the Kuroshio are as follows: $Q_{SW+TW+IW}$ = 32 616 km^3/yr or 1.04 Sverdrups; Q_{NO3} = 205 × 10^9 mol/yr; Q_{PO4} = 14.3 × 10^9 mol/yr; Q_{SiO2} = 442 × 10^9 mol/yr. These values compare with the river fluxes of 29 × 10^9 mol/yr for NO_3 and NH_4 together; 0.23 × 10^9 mol/yr for PO_4 and 87 × 10^9 mol/yr for SiO_2 (Gan *et al.,* 1983).

The above estimations for Kuroshio were based on two cruises off northeast Taiwan. This is the region where the Kuroshio inpinges upon the East China Sea and where most exchanges are expected, thus the data collected in this region are perhaps the most representative. An investigation of the cross-sections of T, S and nutrients along the ECS shelf indicate that they are all similar (Stommel and Yoshida, 1972; Chen *et al.,* 1990, 1992; Ito *et al.,* 1994). These fluxes have an error of approximately 30 %. But even changing these fluxes by a factor of 2 or more would not affect the conclusion that the Kuroshio contributes several times more nutrients to the East China Sea than the rivers.

It is also possible to use the simple box model to calculate the offshore transport of particulate organic matter from the East China Sea shelf (Fig. 3):

$$Q_{Ri} \cdot N_{Ri} + Q_{Re} \cdot N_{Re} + Q_{SW} \cdot N_{SW} + Q_{TW} \cdot N_{TW} + Q_{IW} \cdot N_{IW} + Q_P \cdot N_P = Q_{SSW} \cdot N_{SSW} + Q_B \cdot N_B + Q_{SS} \cdot N_{SS}. \quad (3)$$

where N denotes nutrients, Re denotes the release from sediments, B denotes the nutrients buried, and SS denotes suspended sediments transported offshore.

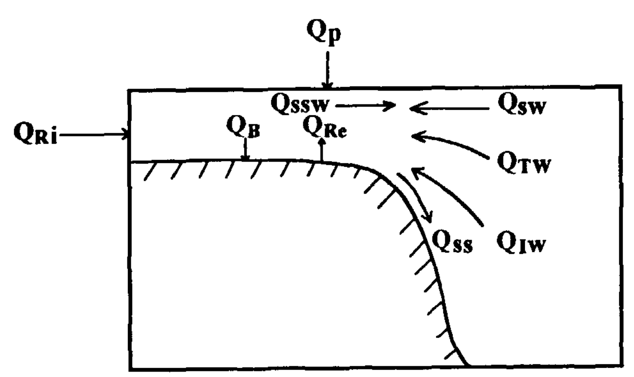

Figure 3

Schematic diagram for the nutrient budget.

By rearranging eq (3), we can obtain the net offshore sediment transport as:

$$Q_{SS} \cdot N_{SS} = Q_{Ri} \cdot N_{Ri} + Q_{Re} \cdot N_{Re} + Q_{SW} \cdot N_{SW} + Q_{TW} \cdot N_{TW} + Q_{IW} \cdot N_{IW} + Q_P \cdot N_P - Q_{SSW} \cdot N_{SSW} - Q_B \cdot N_B \quad (4)$$

where N_{Ri} is taken as 33 µmol/kg for NO_3 and NH_4 together, 0.26 µmol/kg for PO_4 and 98 µmol/kg for SiO_2 (Huang *et al.,* 1983); Q_P is roughly 1 400 km^3/yr (Kim, 1992), N_P is roughly 10 µmol/kg for nitrate and ammonia together, and is negligible for PO_4 and SiO_2 (Chen *et al.,* 1994); N_{SSW} is 0.1, 0.02 and 2 µmol/kg for NO_3, PO_4 and SiO_2 respectively. The sum of the offshore transport and the net annual burial rates are thus 245 ± 75 × 10^9 mol, 13.8 ± 5 × 10^9 mol and 492 ± 190 × 10^9 mol for nitrogen, phosphorus and silica, respectively. Most of these originate from the Kuroshio instead of the rivers. Note the evasion of N_2O is neglected as the rate (2.79 µmol/m^2/day; S. Tsunogai, pers. comm. 1995) is less than 0.5 % of the burial rate.

By taking a C/N ratio of 8.2 for suspended sediments (Chen *et al.,* 1996) a net of 2 009 ± 600 × 10^9 mol organic carbon is buried or transported offshore per year, which is 73 ± 22 mgC/m^2/day. This is equivalent to the new production rate, or is approximately 15 % of the primary production rate (Fei *et al.,* 1987; Guo, 1994; Chen, 1995; Shiah *et al.,* 1995). Li (1995) estimated the new production rate at 80 mg C/m^2/day.

By taking a sedimentation rate of about 0.3 ± 0.12 g/cm^2/year and the organic carbon content of about 0.5 ± 0.2 % (Huang *et al.,* 1983; Demaster *et al.,* 1985; Yanagi, 1994; Hong *et al.,* 1995), the resulting amount of net organic carbon burial rate is 1 125 ± 550 × 10^9 mol C per year or 41 ± 23 mg C/m^2/day. The difference between 2 009 × 10^9 and 1 125 × 10^9 mol/yr is the offshore transport of suspended materials, at 884 ± 800 × 10^9 mol organic carbon per year or 32 ± 30 mg C/m^2/day. The precisions of the above estimates are, however, insufficient to accurately quantify this transport.

Residence Time

Nozaki *et al.* (1989) claimed to have provided the first time constraint for the ECS shelf water to exchange with the Kuroshio based on the ^{228}Ra/^{226}Ra data. They believed that «There is no evidence that a significant amount of the shelf water is transported to the east of Kyushu so that the shelf water is mainly lost by mixing into the Tsushima Current». Consequently they divided the volume of shelf water (4.5 × 10^4 km^3) by the outflow of the shelf-derived water, and reported 2.3 ± 0.8 years as the mean residence time of the ECS shelf water. Nozaki *et al.* (1991) confirmed this estimate but we believe that this is the upper limit as the ECS shelf water clearly mixes into the Kuroshio (Chen *et al.* 1995).

Li (1995) estimated the residence time based on the box model similar to Figure 2 but did not differentiate the seasonal effect nor separated the Kuroshio water into the three vertical components. He estimated the Kuroshio flux at 22 000 ± 9 000 km^3/yr and the volume of the shelf water at about 2 to 3 × 10^4 km^3. Consequently Li estimated the residence time as 1 year. Had he used the volume of the shelf water as 4.5 × 10^4 km^3, he would have obtained a residence time of 2.05 ± 0.8 years. Yanagi (1994) also considered the salt balance and obtained the Kuroshio flux at 28 500 km^3/yr which gives a residence time of 1.6 years.

Tsunogai *et al.* (1995) found that the mean alkalinity of the shelf water was higher than the Kuroshio water and assumed that this excess comes from the rivers. By assuming that the biological uptake of bicarbonate is negligibly small, they divided the total excess alkalinity by the river discharge of bicarbonate and obtained the residence time of 0.8 ± 0.3 years.

The biological productivity on the ECS shelf, however, is rather high and is on the order of 0.5 gC/m^2/day. Much of this is remineralized and the alkalinity is released back into the water column. Thus only the amount buried (41 ± 23 gC/m^2/day from the preceding section) reduces the excess alkalinity. Assuming an organic to inorganic carbon ratio of 4, the buried inorganic carbon is 8.2 ± 4.6 mgC/m^2/day. This is equivalent to 1.4 meq/m^2/day, or 0.45 × 10^{12} eq/yr for ECS if the inorganic carbon is taken as carbonates.

The excess alkalinity amounts to 1.08 × 10^{12} eq (Tsunogai *et al.,* 1995). The average river discharge of alkalinity is 1.08 meq/kg or 1.59 × 10^{12} eq/yr (Huang *et al.,* 1983). Dividing the excess by the difference of river discharge (1.59 × 10^{12} eq/yr) and the buried (0.45 × 10^{12} eq/yr) gives the residence time of 0.95 ± 0.3 years.

The above calculations did not consider the seasonal effect. It is evident from the mass balance of the preceding section that the ECS shelf is flushed more efficiently in summer than in winter. Nevertheless, the mean residence time of the shelf water can be calculated by dividing the volume of water on the shelf, 4.5 × 10^4 km^3 (Nozaki *et al.,* 1989; Yanagi, 1994) by the annual Q_{SSW} (33 973 km^3). The result is 1.3 ± 0.4 years.

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