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Response to Liu's comments on "The Kuroshio Intermediate Water is the major source of nutrients on the East China Sea continental shelf" by Chen (1996)

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Abstract – Exchanges between the East China Sea (ECS) and the Kuroshio have been recalculated by taking into consideration the intra-annual variation of salinity on the shelf. Flux through the Taiwan Strait, previously unavailable data in the Yellow Sea and in the central and northern ECS, denitrification and ground water fluxes are now also considered. The Kuroshio Intermediate Water remains the major source of nutrients on the East China Sea continental shelf, with slightly more upwelling in the dry season than in the wet season. © Elsevier, Paris

East China Sea / Kuroshio Intermediate Water / upwelling / nutrient budgets / denitrification

Résumé – Réponses aux commentaires de Liu sur « l'eau intermédiaire du Kuroshio, principale source de nutriments sur le plateau continental de la mer de Chine orientale » par Chen (1996). Les échanges entre la mer de Chine orientale et le Kuroshio ont été calculés en utilisant de nouvelles données : variation intra-annuelle de la salinité sur le plateau continental, flux à travers le détroit de Taïwan, ainsi que des données qui n'étaient pas disponibles pour la mer Jaune et pour le centre et le nord de la mer de Chine orientale, la dénitrification et les flux d'eau à travers le fond. L'eau intermédiaire du Kuroshio reste la principale source de nutriments sur le plateau continental de la mer de Chine orientale, avec une remontée d'eau un peu plus importante pendant la saison sèche que pendant la saison humide. © Elsevier, Paris

Mer de Chine orientale / eau intermédiaire du Kuroshio / upwelling / bilan de nutriments / dénitrification

In 1996, I used a simple steady state box model to study the exchanges between the Kuroshio and the East China Sea (ECS). That the Kuroshio Intermediate Water (KIW) is indeed the major source of nutrients on the ECS has been reinforced by Liu and by the more detailed calculations below. It is also apparent, however, that the assumption I made of a steady state is inaccurate in describing the intra-annual variation of fluxes in a dynamic shelf environment. Another point is that in the 1996 paper I did not consider the flux through the Taiwan Strait due to a lack of data. In a more recent paper [5], however, the Taiwan Strait data have been included in the calculations of carbon and nutrient budgets on the ECS continental shelf. Since then, I have collected even more data on the Taiwan Strait. Furthermore, previously unavailable data in the southern Yellow Sea and in the central and northern ECS have now become available [10].

The following findings in this response are updated results after the intra-annual variations of salinity and the fluxes through the Taiwan Strait are taken into consideration. In addition, denitrification and ground water input of nutrients are now considered, and more recent riverine fluxes are used.

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

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

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

The salt balance is:

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

where S is salinity; subscripts denote the same waters as for Eq. (1). Q_A denotes the accumulation or release of salt, taken as 16 Gt. Chen et al. [1] estimated that 70 % of the water near the shelf break northeast of Taiwan comes from the Kuroshio made up of SW (30 %), TW (25 %) and IW (15 %). These were the bases I used in the 1996 paper. However, since then, other data along the ECS shelf break now suggest a smaller contribution from IW [3, 10]. Thus, for the Kuroshio waters that move onto the shelf, the fluxes are assumed to be in the following proportions, i.e. in the rainy season (May–October) $Q_{SW} = Q_{TW} = 3\ Q_{IW}$. $Q_{TSW} = 8000$ Gt/6 months, $Q_{Ri} = 813$ Gt/6 months, and $Q_P - Q_E = 420$ Gt/6 months. The salinities for the water masses, also assumed to be constant during the rainy season, are as follows: $S_{Ri} = 0.18$, $S_{SSW} = 33.1$, $S_{SW} = S_{IW} = 34.3$, $S_{TW} = 34.9$, and $S_{TSW} = 33.8$.

With the above information and solving Eqs. (1) and (2), $Q_{SSW} = 22\ 240$ Gt, $Q_{SW} = Q_{TW} = 5575$ Gt and $Q_{IW} = 1858$ Gt for the six-month wet season. Q_{SSW} includes the outflow through the Tsushima Strait. The fluxes of each component in the dry season (November–April) are as follows: $Q_{SW} = 8\ Q_{IW}$, $Q_{TW} = 3\ Q_{IW}$, $Q_{TSW} = 3200$ Gt/6 months, $Q_{Ri} = 404$ Gt/ 6 months and $Q_P - Q_E = -280$ Gt/6 months [5]. The salinities remain the same as those in the wet season except that $S_{SW} = 34.5$, $S_{TSW} = 34$ and $S_{SSW} = 33.8$. The resulting $Q_{SSW} = 28\ 333$ Gt, $Q_{SW} = 16\ 673$ Gt, $Q_{TW} = 6252$ Gt and $Q_{IW} = 2084$ Gt for the six months. The annual water fluxes are given in *figure 1*.

The onshore fluxes of nutrients due to SW are small: Q_{NO_3} in summer and winter are roughly 0.6 and 1.7×10^9 respectively; Q_{PO_4} is 0.11 and 0.33×10^9 mol, respectively; Q_{SiO_2} is roughly 5.6 and 16.7×10^9 mol, respectively, all for six months (*table I*). Q_{NO_3} in KSW in summer and in winter are roughly 22.3 and 25.0×10^9 mol for six months, respectively; Q_{PO_4} are roughly 1.67 and 1.88×10^9 mol for six months, respectively; Q_{SiO_2} are about 22.3 and 25.0×10^9 mol for six months, respectively.

The new results still indicate that although KIW contributes the least to the upwelled water on one hand, it contributes the most to the nutrient fluxes on the other. The summer and winter fluxes are respectively: $Q_{NO_3} = 46.5$ and 52.1×10^9 mol; $Q_{PO_4} = 3.2$ and 3.5×10^9 mol;

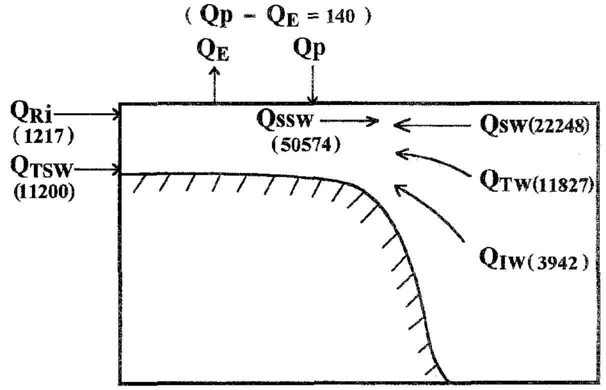

Figure 1. Schematic diagram of the annual water budget (numbers in Gt).

Table I. Nutrient Fluxes (10^9 mol) for Waters Entering or Leaving the East China Sea Shelf

	NO_3		PO_4		SiO_2	
	Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
SW	0.6	1.7	0.11	0.33	5.6	16.7
TW	22.3	25.0	1.67	1.88	22.3	25.0
IW	46.5	52.1	3.16	3.54	112	125
Subtotal	148.2		10.7		307	
TSW	16.0	6.4	1.6	0.64	40	16
Total seawater influx	168.6		12.9		363	
SSW	2.2	2.8	0.44	0. 57	44.5	56.7
Ri	100		0.9		160	
Dissolvable form in rain and dust	30			0.7	0.7	

Q_{SiO_2} = 112 and 125 × 10^9 mol all for six months. Altogether, the annual contributions by the Kuroshio are as follows: $Q_{SW+TW+IW}$ = 38 017 Gt/yr or 1.2 Sverdrups; $Q_{NO_3} = 148 \times 10^9$ mol yr^{-1}; $Q_{PO_4} = 10.7 \times 10^9$ mol yr^{-1}; Q_{SiO_2} = 307 × 10^9 mol yr^{-1}. The TSW is relatively richer in nutrients than the KSW: NO_3 = 2 μmol kg^{-1}, PO_4 0.2 μmol kg^{-1} and SiO_2 5 μmol kg^{-1}. The summer and winter contributions of TSW to ECS in terms of nutrients are: 16.0 × 10^9 mol and 6.4 × 10^9 mol nitrate, respectively; 1.6 × 10^9 and 0.6 × 10^9 mol phosphate, respectively; and 40 × 10^9 mol and 16 × 10^9 mol silicate, respectively. These values compare with the river and ground water fluxes of 100 × 10^9 mol yr^{-1} for NO_3, NO_2 and NH_4 together; 0.9 × 10^9 mol yr^{-1} for PO_4 and 160 × 10^9 mol yr^{-1} for SiO_2 based on fluxes from Chinese and Korean rivers [8, 11].

The offshore transport of organic matter in the suspended sediments from the ECS shelf can be calculated by the following equation where, N denotes nutrients, Re the release from sediments, AS the air–sea exchange, B the nutrients buried, and SS denotes suspended sediments transported offshore:

$$\begin{aligned} Q_{SS}N_{SS} = {} & Q_{Ri}N_{ri} + Q_{Re}N_{Re} + Q_{TSW}N_{TSW} + Q_{SW}N_{SW} \\ & + Q_{TW}N_{TW} + Q_{IW}N_{IW} + Q_PN_P \\ & - Q_{SSW}N_{SSW} - Q_{AS} - QQ_BN_B. \end{aligned} \tag{3}$$

N_P is updated to roughly 30 × 10^9 mol yr^{-1} for nitrate and ammonia together [2] and 0.7 ± 0.5 × 10^9 mol yr^{-1} for dissolvable phosphate and silicate [7, 8, 9].

The relevant known fluxes for P are provided in *figure 2*. The resultant sum of the offshore transport and the net annual burial rates is 13.5 ± 4 × 10^9 mol yr^{-1}. Assuming that all of this is in the organic form, the annual new production of organic phosphorus on the shelf is 15 ± 5 mmol m^{-2}. The total organic P burial rate is (8.5 ± 4) × 10^9 mol yr^{-1}, while the offshore organic P transport rate is (5.0 ± 2) × 10^9 mol yr^{-1} (*figure 2*). Taking the Redfield C/P ratio as 10^6 for phytoplankton, the annual new organic carbon production rate is 1.59 ± 0.5 mol m^{-2} (a daily rate of 52 ± 20 mg m^{-2}). The fluxes in *figure 2* support the fact the rivers play only a very minor role as they contribute only 7 % of the P input.

I now proceed with the nitrogen budget which is more complicated because denitrification converts nitrate to NH_3, N_2O and N_2 which degas at the air-sea interface. On the other hand, nitrogen fixation by planktons, especially by an abundance of *Trichodesmium* [4], utilizes N_2. As the first step, I calculated the sum of offshore transport, net burial and the net nitrogen release from the surface ECS as 296 × 10^9 mol yr^{-1} based on Eq. (3). The organic N burial rate is (112 ± 48) × 10^9 mol yr^{-1} which is equivalent to a daily rate of 0.34 ± 0.14 mmol m^{-2} [5], leaving the sum of the offshore transport and the net degassing as (183 ± 72) × 10^9 mol yr^{-1}.

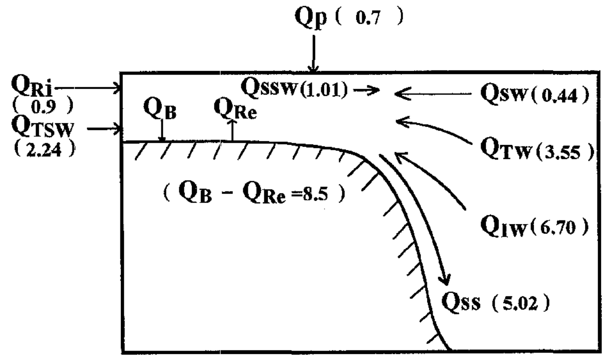

Figure 2. Schematic diagram of the annual phosphorus budget (numbers in 10^9 mol yr^{-1}).

Taking the N/P ratio of the offshore transport portion as 16 and using the offshore P transport as (5 ± 2) × 10^9 mol yr^{1} obtained in the preceding section, the offshore N transport is (80 ± 25) × 10^9 mol yr^{-1}. Accordingly, the degassing of NH_3, N_2O and N_2 comes to (103 ± 41) × 10^9 mol N yr^{-1}. Most of this is N_2 as the evasion rate of N_2O is only 0.9 × 10^9 mol yr^{-1} (a daily rate of 2.79 μmol m^{-2}; S. Tsunogai, pers. comm., 1995), and the evasion rate of the highly dissolvable NH_3 is probably small.

The nitrogen budgets are given in *figure 3*. *Figure 4* shows the silicate fluxes, but there is no information on the sedimentation on the shelf nor on the offshore transport. The riverine inputs are still smaller than the contri-

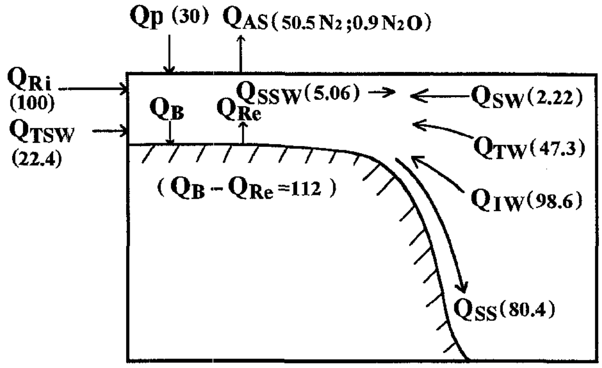

Figure 3. Schematic diagram of the annual nutrient budget (numbers in 10^9 mol yr^{-1}).

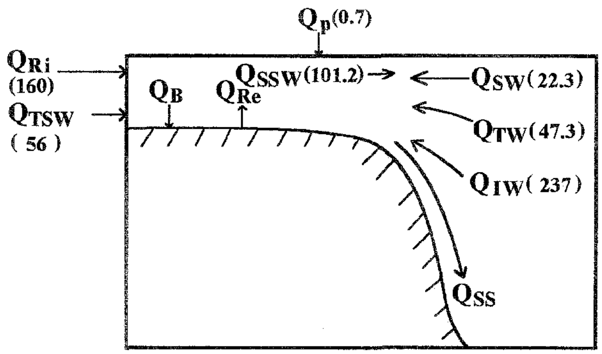

Figure 4. Schematic diagram of the annual silicate budget (numbers in 10^9 mol yr^{-1}).

bution from the incoming water masses but the differences are not as dramatic as those for phosphorus.

The box model could be still further improved by dividing the ECS into several boxes, each with several layers. Organic matter, effects of El Nino on the upwelling and the intra-annual accumulation or release of nutrients on the shelf should also be accounted for in the mass balance calculations when sufficient data become available. It should be noted that it has been known for years that subsurface Kuroshio water upwells onto the ECS shelf. My contribution in the 1996 article was to identify that it is the intermediate water, not just any subsurface water, that contributes most nutrients to the ECS. Data from four cross-sections along the ECS shelf break were used to come to the conclusion. Chen and Wang [6] further identified the source of the upwelled intermediate water as originating from the South China Sea.

As a final note, I should mention that a large portion of Lius article discusses the effect of density. It was I, however, who told Liu that Eqs. (1) and (2) should be used with caution as the units may come out wrong if Q is taken to be in volume unit. Since salinity is essentially the mass of salt per kilogramme of seawater, multiplying a volume of seawater by salinity would give a strange unit. Further, all calculations given above should conserve mass, instead of volume as Liu first attempted to do in his original manuscript. Subsequently Liu revised all his calculations by taking the appropriate seawater density into consideration.

Acknowledgement

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