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

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 salinity and the 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:

\[ Q_{RI} + Q_{P} + Q_{TSW} + Q_{SW} + Q_{TW} + Q_{IW} = Q_{E} + Q_{SSW} \] (1)
where $Q$ is the water flux in weight unit; subscripts $R_i$, $R$, $TSW$, $SW$, $TW$, $E$ 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:

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

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%), $TW$ (7.5%) 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) $Q_{SW} = 3Q_{TW} = 3Q_{IW}$, $Q_{TSW} = 8000$ Gt/6 months, $Q_{Ri} = 813$ Gt/6 months, and $Q_{E} = 420$ Gt/6 months. The salinities for the water masses, also assumed to be constant during the rainy season, are as follows: $S_{Ri} = 0.18$, $S_{SSW} = 33.1$, $S_{SW} = 34.3$, $S_{TW} = 34.9$, and $S_{SSW} = 33.8$.

With the above information and solving Eqs. (1) and (2), $Q_{SSW} = 22400$ Gt, $Q_{SW} = 5575$ 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: $Q_{SW} = 8Q_{TW} = 3Q_{IW}Q_{TSW} = 3200$ Gt/6 months, $Q_{Ri} = 404$ Gt/6 months and $Q_{E} = 280$ Gt/6 months [5]. The salinities remain the same as those in the wet season except that $S_{SW} = 34.5$, $S_{TW} = 34$ and $S_{SSW} = 33.8$. The resulting $Q_{SSW} = 28333$ Gt, $Q_{SW} = 16673$ 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 $1.7 \times 10^9$ respectively; $Q_{PO_4}$ is 0.11 and $0.33 \times 10^9$, respectively; $Q_{SiO_2}$ is roughly 5.6 and $16.7 \times 10^9$, respectively, all for six months (Table I). $Q_{NO_3}$ in KSW in summer and in winter are roughly 22.3 and $25.0 \times 10^9$ mol for six months, respectively; $Q_{PO_4}$ are roughly 1.67 and $1.88 \times 10^9$ mol for six months, respectively; $Q_{SiO_2}$ are about 22.3 and $25.0 \times 10^9$ mol for six months, respectively.

The new results still indicate that although $IW$ 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 $52.1 \times 10^9$ mol; $Q_{PO_4} = 3.2$ and $3.5 \times 10^9$ mol.
Q_{SiO_2} = 112 and 125 \times 10^9 \text{ mol all for six months. Alto-}
gether, the annual contributions by the Kuroshio are as fol-

ows: Q_{SW+TW} = 38.017 \text{ Gt/yr or 1.2 Sverdrups};
Q_{NO_3} = 148 \times 10^9 \text{ mol yr}^{-1}; Q_{PO_4} = 10.7 \times 10^9 \text{ mol yr}^{-1};
Q_{SiO_2} = 307 \times 10^9 \text{ mol yr}^{-1}. The TSW is relatively
richer in nutrients than the KSW: NO_3 = 2 \mumol \text{ kg}^{-1},
PO_4 0.2 \mumol \text{ kg}^{-1} and SiO_2 5 \mumol \text{ kg}^{-1}. The summer
and winter contributions of TSW to ECS in terms of

utrients are: 16.0 \times 10^9 \text{ mol and } 6.4 \times 10^9 \text{ mol nitrate, re-
spectively; } 1.6 \times 10^9 \text{ and } 0.6 \times 10^9 \text{ mol phosphate, re-
spectively; and } 40 \times 10^9 \text{ mol and } 16 \times 10^9 \text{ mol silicate, re-
pectively. These values compare with the river and ground
water fluxes of } 100 \times 10^9 \text{ mol yr}^{-1} \text{ for NO}_3, NO_2
and NH_4 \text{ together; } 0.9 \times 10^9 \text{ mol yr}^{-1} \text{ for PO}_4 \text{ and } 160 \times 
10^9 \text{ mol yr}^{-1} \text{ for SiO}_2 \text{ 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{align*}
Q_{SSN_{SS}} &= Q_{RI}N_{RI} + Q_{Re}N_{Re} + Q_{TSW}N_{TSW} + Q_{SW}N_{SW} \\
& \quad + Q_{TW}N_{TW} + Q_{IW}N_{IW} + Q_P N_P \\
& \quad - Q_{SSN_{SS}} - Q_{AS} - Q_{QB}N_B. \tag{3}
\end{align*}

N_P is updated to roughly 30 \times 10^9 \text{ mol yr}^{-1} \text{ for nitrate and}
ammonia together [2] and 0.7 \pm 0.5 \times 10^9 \text{ mol yr}^{-1} \text{ 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 \pm 4 \times 10^9 \text{ 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 \pm 4) \times
10^9 \text{ mol yr}^{-1}, while the offshore organic P transport rate is
(5.0 \pm 2) \times 10^9 \text{ 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 \pm 0.5 \text{ mol m}^{-2} (a daily rate of
52 \pm 20 \text{ mg m}^{-2}). The fluxes in figure 2 sup-
port 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 \times 10^9 \text{ mol yr}^{-1} based on Eq. (3). The organic
N burial rate is (112 \pm 48) \times 10^9 \text{ mol yr}^{-1} which is equi-
valent to a daily rate of 0.34 \pm 0.14 mmol m\(^{-2}\) [5], leaving
the sum of the offshore transport and the net degassing as
(183 \pm 72) \times 10^9 \text{ mol yr}^{-1}.

Taking the N/P ratio of the offshore transport portion as
16 and using the offshore P transport as (5 \pm 2) \times 10^9 \text{ mol
yr}^{-1} \text{ obtained in the preceding section, the offshore N trans-
port is (80 \pm 25) \times 10^9 \text{ mol yr}^{-1}. Accordingly, the
degassing of NH_3, N_2O and N_2 comes to (103 \pm 41) \times 10^9
mol N yr\(^{-1}\). Most of this is N_2 as the evasion rate of N_2O
is only 0.9 \times 10^9 \text{ mol yr}^{-1} (a daily rate of 2.79 \mumol 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 trans-
port. The riverine inputs are still smaller than the contri-
Figure 4. Schematic diagram of the annual silicate budget (numbers in $10^5$ 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

REFERENCES


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