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Nutrient Fluxes through the Taiwan Strait in Spring and Summer 1999

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Transports of water and nutrients (N and P) through the Taiwan Strait were calculated using chemical hydrography and currents observed in May and August 1999. The surveys were conducted along a transect across the strait in the middle section. The velocity fields were determined by phase-averaging currents measured using shipboard Acoustic Doppler Current Profiler (ADCP) on two repeats, which were separated by 1.5 cycles of the dominant M_2 tide. Nutrient distributions were also derived from phase-averaged data. The volume transports determined from the two surveys were similar (2.0 Sv and 2.2 Sv, respectively). By contrast, the nutrient fluxes obtained in August (1.82 kmol N/s and 0.34 kmol P/s) were significantly higher than those in May (0.96 kmol N/s and 0.16 kmol P/s), apparently due to coastal upwelling under southwest monsoon in summer. The rather low N/P ratios (6.0 and 5.4 by atoms) of the nutrient fluxes were attributed to the widespread N-deficiency in the upper water column of the North Pacific. The nutrient fluxes were fed mainly through a meridional deep channel off southwest Taiwan. The nutrient contributions from the Taiwan Strait to the East China Sea in spring and summer are comparable to the total riverine contributions from the Changjiang (also know as the Yangtze River) and other smaller rivers for nitrogen, but 8–17 times larger than the latter for phosphate. Therefore, the Taiwan Strait inflow may serve as an important supplement for the P-limiting condition in the huge coastal plume in the East China Sea.

Keywords:
· Taiwan Strait,
· nutrient flux,
· throughflow transport.

1. Introduction

The Taiwan Strait, being 180 km wide, 350 km long and 60 m in average depth, is a shallow channel connecting the South China Sea and East China Sea (Fig. 1). The main topographic features include the Penghu Channel, the Taiwan Banks and the Changyun Rise, suggesting a large variation of water depths in the strait. Early hydrographic investigations by Chu (1963, 1971) identified three water masses in the strait, which are the China Coastal Water with low temperature and low salinity, the Kuroshio Branch Water with high temperature and high salinity, and the South China Sea Surface Water with intermediate temperature and salinity. Circulation in the Taiwan Strait has been extensively studied (see, for example, Chuang, 1985, 1986; Wang and Chern, 1988, 1989, 1992; Jan *et al.*, 1994, 1998). Generally, summertime currents are northward flowing through the strait, carrying the South China Sea Surface Water to the southern East China Sea. In winter, the northeast monsoon drives the China Coastal Water moving southward into the northern Taiwan Strait; while the windward flowing Kuroshio Branch Water is remotely driven and blocked south of the Changyun Rise. The throughflow volumetric transport roughly estimated by Wyrtki (1961) is about 0.5–1 Sv (1 Sv = 10^6 m^3/s) northward in summer and 0.5 Sv southward in winter.

In comparison with the rich hydrodynamic studies described above, the chemical hydrography measurements in the strait are relatively scarce. In the lack of observational data, Chen (1996) speculated that the nutrient fluxes from the Taiwan Strait might be negligible. However, Liu *et al.* (2000) suggested that the nutrient inputs from the strait may represent a sizeable contribution to the nutrient budget of the East China Sea, which was based on observations across the northern end of the strait. The discrepancy is evident and warrants further study. In this light, the main objective of this study is to measure the nutrient fluxes across the width of the strait through comprehensive investigations.

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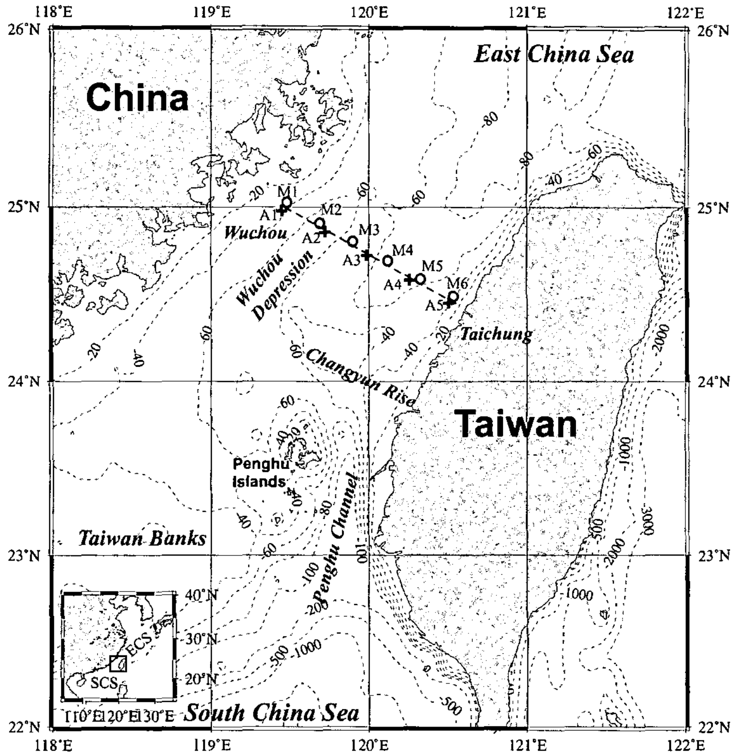

Fig. 1. Topography map of the Taiwan Strait and vicinity. The inset shows the location of Taiwan Strait relative to the East China Sea (ECS) and the South China Sea (SCS). The dashed line is the cruise track. The open-circles and crosses represent stations of the May and August cruises. Isobaths are in meters.

2. Observations and Methods

Two survey cruises were conducted on board the R/V Ocean Research I along a transect across the middle of the strait (dashed line in Fig. 1) in May and August of 1999. The sampling stations are shown in Fig. 1 in which open-circles are for the May cruise (May 23–25) and crosses for the August cruise (August 13–14). At each station, the distribution of temperature and salinity were measured using a SeaBird model SBE9/11 conductivity-temperature-depth (CTD) instrument. Water samples were collected using 20 liter Go-Flo bottles at depths of 2 m, 5 m, 10 m and every 10 m beneath on each CTD cast. The sub-samples for the determination of nitrate, nitrite, phosphate and silicate were frozen immediately with liquid nitrogen and stored frozen until they were analyzed in the shore-based laboratory. Phosphate, nitrite and silicate were measured by a Trident-222 multi-channel continuous flow analyzer. Nitrate was measured by a Nitrate Analyzer (Pai and Riley, 1994). The precision for nitrate (1.0–40.0 μM), phosphate (0.1–3.0 μM) and silicate (5–150 μM) are 0.4%, 0.5% and 0.7%, respectively.

Currents were measured using a ship-board RD Instruments Acoustic Doppler Current Profiler (ADCP) along the transect shown in Fig. 1. The vertical length of depth cell is 8 m and the blanking depth is 12 m. In order to remove the dominant semidiurnal tidal currents (Tang *et al.*, 1999), we made the current measurements along the same transect twice, i.e., on the first and the third legs criss-crossing the strait. The two repeats were separated by 18.62 hours so that the measurements were out of phase by 1.5 cycles of the M_2 tide. The water samples were obtained on the same two repeats. Ship speeds were controlled at a speed of 7–8 knots so as to maintain the data quality of the current measurement (Tang and Ma, 1995).

3. Results and Discussion

3.1 Background winds and currents

Winds over the Taiwan Strait are predominated by the two East Asia monsoons: the southwest monsoon in summer and the northeast in winter. Figure 2 illustrates daily mean wind sticks measured at a weather station on the Penghu Island from January to November, 1999 (data provided by the Central Weather Bureau of Taiwan). The northeast monsoon usually begins in mid September, peaks from October to January, and ends in early April. The southwest monsoon generally prevails in June and July and is much weaker than the northeast monsoon. Since wind stresses are nearly uniform over the strait,

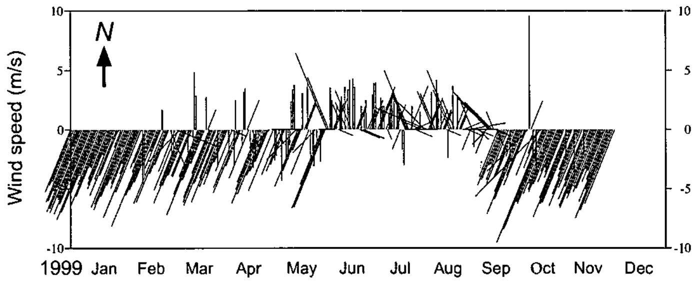

Fig. 2. Stick diagram of daily mean wind velocity in 1999 (January–November) at a weather station on the Penghu Island.

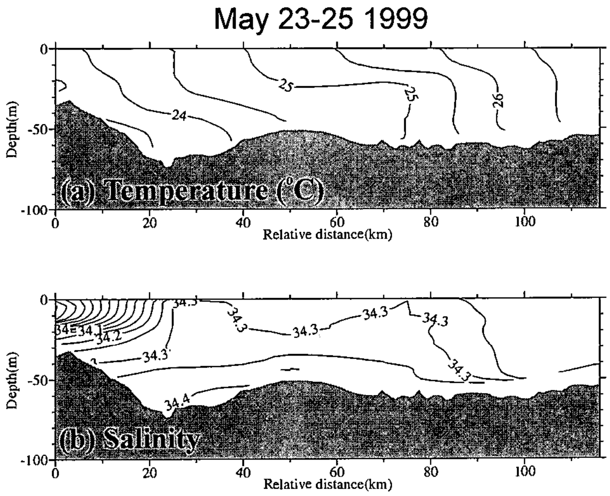

Fig. 3. Temperature (a) and salinity (b) distributions along the cruise track for the May cruise. The contour intervals are 0.5°C for temperature and 0.05 for salinity.

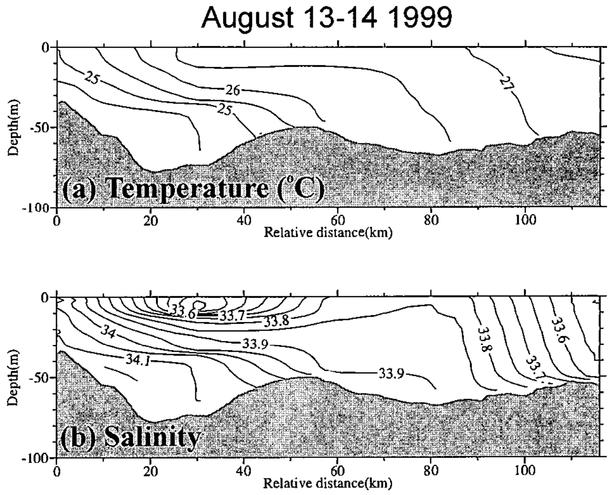

Fig. 4. Same as Fig. 3 but for the August cruise.

the wind sticks in Fig. 2 can be regarded as the typical annual variation for the strait. Currents in the strait are modulated by the annual cycle of wind forcing.

During the May cruise, which was in the intermonsoon period, there was no dominant wind direction (Fig. 2). The weakening of the northeasterly lead to northward intrusion of the once blocked warmer water (the Kuroshio Branch Water) in the Penghu Channel (Wang and Chern, 1988; Jan *et al.*, 1998); and currents were northward-flowing in the strait. The August cruise was under the southwest monsoon (Fig. 2), which drove the northward flowing of water from the northern South China Sea through the strait (Wang and Chern, 1992; Jan *et al.*, 1994).

3.2 Hydrography

Figures 3(a) and (b) show the temperature and salinity sections, respectively, obtained during May 23–25, 1999. The warmer water (>26°C) resided over the eastern reach of the strait; whereas the colder (<24°C) hugged the western bank of the strait (Fig. 3(a)). Salinity distribution (Fig. 3(b)) indicates that the most saline water (>34.4) was at the bottom of the Wuchou Depression with low salinity water on the flank of the high salinity bulge. The water with lowest temperature and salinity on the western side was apparently the residual of China Coastal Water originally intruding into the strait from the north in winter. The most saline water in the strait (Fig. 3) was the Kuroshio Branch Water which came from the Penghu Channel and extended over and beyond the Changyun Rise.

Figures 4(a) and (b) show the temperature and salinity sections obtained on the August cruise. The temperature distribution pattern was similar to that of May (Fig. 3(a)) with the temperatures about 1°C higher. In contrast, the salinity distribution was quite different. The most saline water extended upward from the bottom of the Wuchou Depression towards the western bank, which suggests upwelling of the subsurface water. The low salinity water separated from the western bank and formed a surface stream over the Wuchou Depression. Another low salinity water was near the eastern bank. The overall salinity was considerably lower than that observed on the May cruise. The cold and saline water in the Wuchou Depression was believed to originate from the deep Penghu Channel (Wang and Chern, 1992; Jan *et al.*, 1994), whereas the warm and less saline water came from the South China Sea surface water.

3.3 *Throughflow transport*

In order to calculate the flow volume transport, we used current data acquired on the first and third repeats of the survey. The distance of the transect is equally separated into 6 segments. Velocity data in each segment are averaged over each depth cell. Segment-averaged velocities of the first and third repeats were further averaged to eliminate the dominant semidiurnal tidal current. The processed velocities were rotated to normal and tangential components along the transect.

Figures 5(a) and (b) show normal velocity contours in the Wuchou-Taichung transect for the two cruises. The velocity structures of the two cruises were similar, and show two northward-flowing streams across the Strait: one was in the surface layer over the Wuchou Depression with speeds greater than 50 cm/s; and the other near the Taiwan coast with a speed of about 40 cm/s. Flow volume transports derived from normal velocities are 2.0 Sv and 2.2 Sv northward for the two cruises. Generally, the southwest monsoon enhances the northward flow rate in August. The higher estimate of volume transport for August seems reasonable.

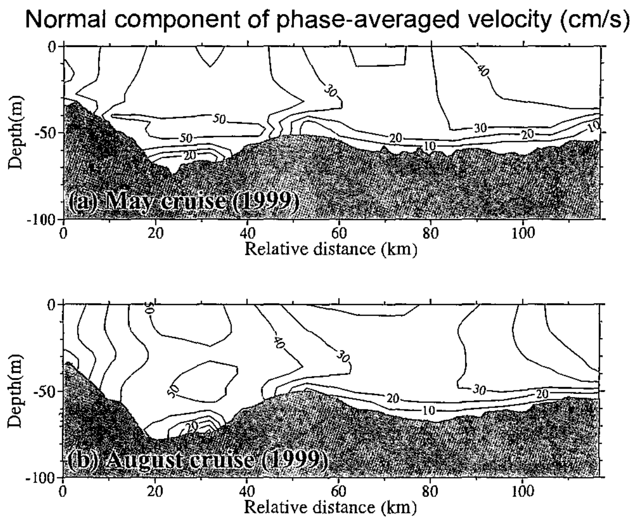

Fig. 5. Distributions of normal component of phase-averaged velocity along the transect for (a) the May and (b) the August cruises. The velocity contours are in cm/s.

It is noted that the phase averaging technique used for the present estimation of volume transport cannot remove signals of the diurnal tide as well as the wind driven current developed during the measurement. Using a data set acquired by a bottom-mounted ADCP deployed about 30 km north of Station A3 (Fig. 1) from July 18 to September 28, 1999, we found that the two types of signals mentioned above may introduce errors around 20% to the volume transport estimated for the summer cruise. Details will be presented on another opportunity. In fact, our estimate is quite close to the estimate of 1.9 Sv (Table 1) based on ADCP observations in August 1994 along an incomplete transect at the northern end of the Strait (Liu *et al.*, 2000).

Our estimates of volume transports in spring and summer are nearly twofold of Wyrtki's (1961) estimation of 0.5–1 Sv. The differences are obviously bigger than the error of our estimation. Based on linear momentum balance equations, Wyrtki's estimation was calculated using limited hydrographic and sea level data between Macau and Kaohsiung (a harbor in the southwestern Taiwan). Since this approach is somewhat crude, Wyrtki's estimation can only be regarded as a first order approximation. In comparison, our approach is based on direct measurement and agrees reasonably well with previous estimate of Liu *et al.* (2000). Of course, more observations are required to achieve a more accurate estimate of the mean volume transport in the Taiwan Strait.

3.4 *Nutrient distribution*

Figures 6(a) and (b) show the distributions of nitrate (including nitrite) along the transect for the May and August cruises. On the May cruise, the surface water was

Table 1. Comparison of observed volume and nutrient transports from different sources to the East China Sea shelf.

Input source	Water (Sv)	N (kmol s^{-1})	P (kmol s^{-1})	N/P	References
Taiwan Strait					
Spring	2.0	0.96	0.16	6.0	This study
Summer	2.2	1.82	0.34	5.4	This study
Summer	1.9	1.90	0.25	7.6	Liu *et al.* (2000)
Kuroshio upwelling off NE Taiwan	0.59–0.83	5.5–7.1	0.39–0.46	14.0–15.4	Liu *et al.* (2000)
River runoffs	0.035	2.1	0.020	105	Zhang (1996)

depleted in nitrate, while the highest concentration of nitrate (1.8 μM) occurred at the bottom of the Wuchou Depression with isopleths sloping downward toward the east. Nitrate distribution was totally different on the August cruise. The concentration of nitrate reached as high as 4.9 μM at the western bank and decreased rapidly towards the east. Most of the surface water in the middle part of the Strait was depleted in nitrate. The phosphate distributions (Fig. 7) mimic those of nitrate.

Based on previous hydrography observations (Wang and Chern, 1988, 1992), we infer that the major nutrient source is the bottom water from the Penghu Channel which was deflected northwestward into the Wuchou Depression due to the blockage of the Changyun Rise. The summer southwest monsoon induced coastal upwelling probably lifted the bottom water from the Wuchou Depression to the surface layer off the Chinese coast. Based on hydrography data, Xiao (1988) among others also suggested occurrence of coastal upwelling in summer in this area.

It is noted that N/P ratios in the strait waters were fairly low. The mean ratios of nitrate to phosphate concentrations were 5.2 ± 2.8 and 4.2 ± 3.2 (by atoms) for the May and the August cruises, respectively. These ratios are considerably lower than the Redfield ratio of 16 (Redfield *et al.*, 1963). However, this is consistent with previous findings that the upper water column in the North Pacific Ocean exhibits rather low N/P ratio (Fanning, 1992). The strong nitrogen deficiency in the Strait is contrary to the findings of Wong *et al.* (1998) in the coastal plume near the Changjiang River mouth, where nitrate is in excess due to phosphate deficiency in the riverine nutrients. Although some residual China Coastal Water was observed in the surface layer near the western bank in May, it was rather low in nutrients. The low N/P ratio suggests that the nutrients in the Strait water might be of a predominantly oceanic origin.

3.5 *Nutrient fluxes*

The nutrient fluxes across the Taichung-Wuchou transect were calculated using the normal velocities (Figs. 5(a) and (b)) and the concentrations of nutrients (Figs. 6(a), (b) and 7(a), (b)). Figures 8 and 9 show the nitrate and phosphate fluxes, which exhibit high similarity in distribution between the two nutrients respectively, but very different patterns between the May and August cruises. The high nutrient fluxes were confined near the bottom of the Wuchou Depression during the May cruise (Fig. 8(a)) but spread to the middle layer over the Wuchou Depression and toward the surface layer near the Chinese coast during the August cruise (Fig. 8(b)). The estimated nutrient fluxes in August were similar to those estimated along a transect at the northern end of the Strait in August 1994 (Liu *et al.*, 2000). The nutrient fluxes in the eastern Taiwan Strait were relatively low on both cruises. The coastal upwelling was the main cause for the higher nitrate and phosphate fluxes near the China coast during the August cruise. The total nutrient transports obtained on the May and August cruises were 0.96 and 1.82 kmol/s for nitrate and 0.16 and 0.34 kmol/s for phosphate (Table 1). The nitrate fluxes were much less than those from the Kuroshio upwelling off northeastern Taiwan (Liu *et al.*, 2000), but comparable to the total riverine contributions of dissolved inorganic nitrogen to the East

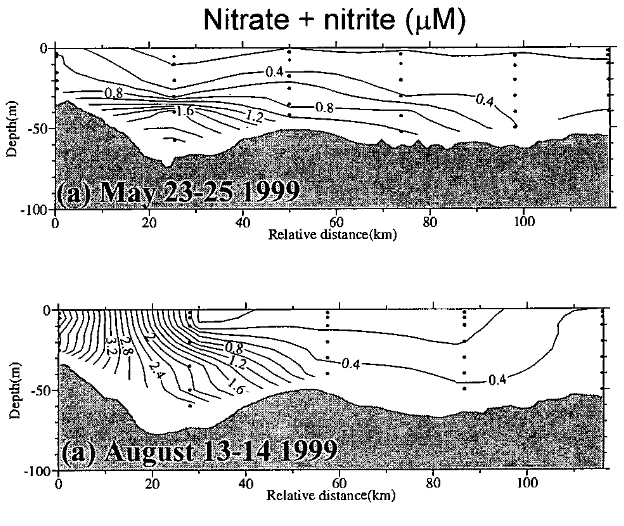

Fig. 6. Distributions of concentration of nitrate plus nitrite along the transect for (a) the May and (b) the August cruises. Contours are in μM.

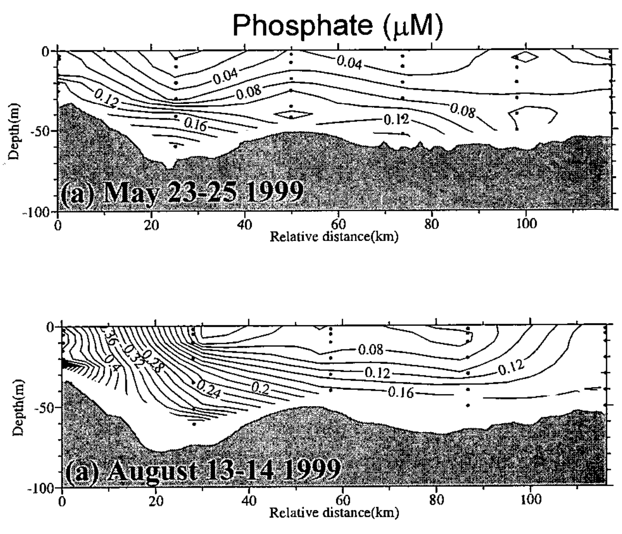

Fig. 7. The same as Fig. 6 except for concentration of phosphate. Contours are in μM.

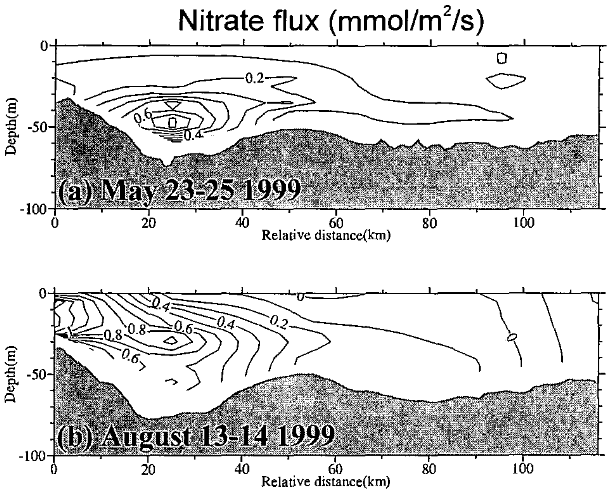

Fig. 8. Distributions of nitrate flux through the transect for (a) the May and (b) the August cruises. Contours are in mmol/m^2/s.

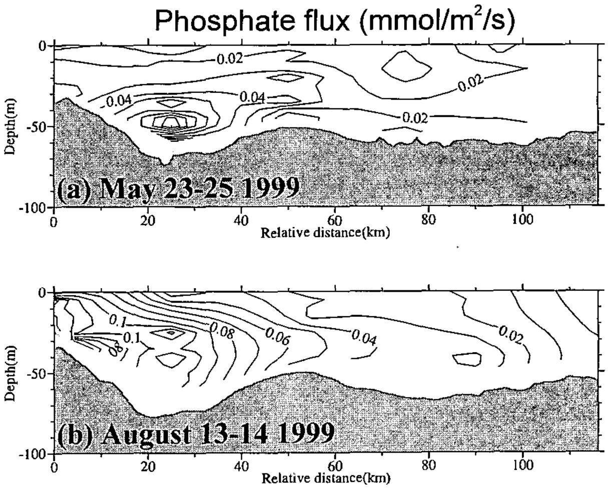

Fig. 9. Distributions of phosphate flux through the transect for (a) the May and (b) the August cruises. Contours are in mmol/m^2/s.

China Sea shelf (Zhang, 1996). In contrast, the phosphate fluxes from the Taiwan Strait were comparable to those from the Kuroshio upwelling but much higher than the riverine input by one order of magnitude.

The ratios between nitrate and phosphate fluxes were 6.0 and 5.4 (by atoms) for the May and August cruises, respectively (Table 1). The N/P ratios of the nutrient fluxes were higher than the mean ratios of the concentrations. This simply reflects the fact that the nutrient fluxes were dominated by the strong flow in the Wuchou Depression, where the seawater was more enriched in nutrients and relatively high in N/P ratio (mostly between 7 and 9). Even so, the N/P ratios of the nutrient fluxes were still much lower than the normal Redfield ratio. Waters in the Taiwan Strait were, therefore, nitrogen-deficient and phosphate-rich in spring and summer.

Since the Changjiang river plume in the East China Sea is P-limiting (Wong *et al.*, 1998), nutrient inputs from the Taiwan Strait may enrich phosphate in the East China Sea. By comparison, the Kuroshio upwelling provides nutrient fluxes with N/P ratio less than but close to the normal Redfield ratio (Table 1), which makes it less effective in compensating for the P-deficiency in the Changjiang river plume.

Another nutrient source with low N/P ratio for the East China Sea shelf water is the Kuroshio Surface Water (KSW), which also originates from the North Pacific. The KSW intrusion onto the shelf northeast of Taiwan is stronger in winter than in summer. As observed in March 1997, the N/P ratio of the intruding KSW approaches 2–3 near the surface and increases to about 15 at depths of 40 m or deeper (based on results of Liu *et al.*, 2000). However, a major fraction of the intruding KSW appears to re-join the Kuroshio after an excursion on the shelf in both seasons (Tang *et al.*, 2000). On the contrary, the Taiwan Strait northward flow has a more direct contribution to the shelf water. Nevertheless, the winter KSW intrusion significantly impacts on the salinity of the shelf water (Chao, 1990) and, therefore, may also influence the nutrient budget. However, its contribution is probably limited because of the rather low nutrient concentration in the KSW and the limited cross-shelf water exchange. The intruding KSW may be distinguished from the Taiwan Strait water by their high salinity. The mean salinity of the KSW is higher than 34.5 (based on results of Liu *et al.*, 2000), whereas that of the Taiwan Strait water is no more than 34.3 and could be as low as 34.0 as suggested by Figs. 3 and 4.

4. Summary

Results from chemical hydrographic surveys and current measurements along a transect across the Taiwan Strait in the middle section indicate that the throughflow transports in May (2.0 Sv) and August (2.2 Sv) were considerably larger than previous estimation (0.5–1 Sv) of Wyrtki (1961). The nutrient fluxes in August (1.8 kmol N/s and 0.34 kmol P/s) were almost twice as high as those in May (1.0 kmol N/s and 0.16 kmol P/s). A major source of nutrients for both months was the northward flowing current coming through the deep Penghu Channel fed by the Kuroshio Branch Water in May and the South China Sea Water in August. The much higher nutrient fluxes in August were due to nutrient enrichment near the China coast, where the water was high in salinity and low in temperature, indicating coastal upwelling under the prevailing southwest monsoon in summer. The August results were consistent with those obtained at the northern end of the strait on a previous cruise in August 1994. The nutrient contributions from the Taiwan Strait to the East China Sea in spring and summer are comparable to that of the Changjiang for nitrogen, but 8–17 times larger than the latter for phosphate. Therefore, the Taiwan Strait inflow may serve as an important supplement for the P-limiting condition in the huge coastal plume in the East China Sea.

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