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Exchange of water masses between the East China Sea and the Kuroshio off northeastern Taiwan

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Abstract—At least six water masses take part in the mixing processes between the East China Sea and the Kuroshio off northeastern Taiwan: the Kuroshio Surface Water (SW), Kuroshio Tropical Water (TW), Kuroshio Intermediate Water (IW), East China Sea Water (ECSW), Coastal Water (CW) and the Taiwan Strait Water (TSW). SW is depleted in nutrients and normalized alkalinity but has the highest temperature and pH of all these waters. TW has relatively high temperature, and the highest salinity of all waters. The salinity maximum in the Kuroshio is usually between 100 and 300 m deep, with large interannual and seasonal variability. IW is characterized by a salinity minimum, high nutrient content and alkalinity, but low pH and oxygen. ECSW is low in salinity, temperature and nutrients, but high in oxygen and normalized calcium and alkalinity. CW has low salinity and nutrient content but is high in normalized alkalinity. TSW is generally depleted in nutrients. The characteristics of the above mentioned waters are discussed. The mixing percentages of SW, TW, IW, and the composite Shelf Surface Water (composed of ECSW, CW and TSW) off the northeast corner of Taiwan in September 1988 and December 1989 are calculated.

INTRODUCTION

It has been known for 50 years, or longer, that blocking of the Kuroshio (Black Stream) by the East China Sea continental shelf break off the northeast corner of Taiwan is responsible for the generation of a shelf-slope circulation pattern that triggers a major exchange between the East China Sea and the western North Pacific Ocean. This temporally and spatially variable exchange engages waters of deep ocean origin and of strong fluvial influence. The interaction of these two water types is similar to that found inshore of the Gulf Stream off the southeast coast of the United States (BLANTON *et al.*, 1981; ATKINSON, 1985). The circulation that promotes and sustains this exchange consists of a complicated system of Kuroshio branch currents, meanders, upwelling and frontal eddies (UDA, 1941; LIU *et al.*, 1992).

The Kuroshio water is characterized by high salinity, and is relatively easy to identify in the East China Sea. It is, however, difficult to quantify the mixing percentages of water masses near the East China Sea shelf break. Early attempts to study the mixing processes involving four or more water masses were mostly qualitative (MILLER, 1950; YANG, 1984;

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Fig. 1. Station locations. Depth contours are in m.

LI and LU, 1987). We report in this paper two sets of data collected off northeastern Taiwan, one collected in September 1988 and one in December 1989. We also make an attempt to quantify the mixing percentages.

EXPERIMENTAL

Fourteen stations were occupied by R.V. *Ocean Researcher I* on 11–14 September 1988 (cruise 179) along a transect normal to the 200-m isobath at the shelf break of the East China Sea (Fig. 1). Eight of these stations were reoccupied during 16–18 December 1989 (cruise 237). Stations 1–7 were located on the shelf in the East China Sea with depths of approximately 100 m. Stations 8–11 were on the continental slope. Stations 12–14 were located in the Okinawa Trough. The water depth at the deepest stations exceeded 1400 m (RUO, 1989; CHEN *et al.*, 1991).

The profiles of temperature, salinity and total fluorescence were measured by a Seabird SBE 9/11 CTD. The CTD was pumped and the sampling rate was 24 Hz. The sensors were calibrated just before the 179 cruise by the Northwest Regional Calibration Center. Discrete samples were obtained for the determination of dissolved oxygen, phosphate, nitrate, silicate and pH onboard ship. Oxygen was measured by the Winkler titrimetric method (CARPENTER, 1965) with a precision of about $\pm 0.5\%$. Phosphate was determined by the molybdenum blue method (MURPHY and RILEY, 1962). Silicate was measured by the silicomolybdenum blue method (FANNING and PILSON, 1973). Nitrate was determined by reducing nitrate to nitrite and then determining the nitrite formed by the azo dye method (STRICKLAND and PARSONS, 1972) with a flow injection analyzer. pH was measured on the NBS scale with a glass electrode/calomel electrode pair at 25°C (CHEN, 1984; RUO, 1989;

WONG *et al.*, 1989a,b). Alkalinity was measured by Gran Titration (BRADSHAW *et al.*, 1981).

Water masses in the study area

At least six water masses take part in the mixing processes (CHEN, 1988a); the Kuroshio Surface Water (SW), Kuroshio Tropical Water (TW), Kuroshio Intermediate Water (IW), East China Sea Water (ECSW), Coastal Water (CW), and the Taiwan Strait Water (TSW). SW is depleted in nutrient and normalized alkalinity ($\text{NTA} = \text{alkalinity} \times 35/S$) but has the highest temperature and pH of all these waters (Fig. 2). The salinity is also high, albeit somewhat lower than TW mainly because of precipitation and mixing with fresher shelf and coastal waters (Fig. 3). A prism of fresher surface water extending offshore is underlain by the shelfward intrusion of deeper and more saline offshore waters (Fig. 3). The layer immediately beneath SW is TW which has relatively high temperature, and the highest salinity of all waters. The salinity maximum in the Kuroshio is usually between 100 and 300 m deep, shallower in winter and deeper in summer with a large interannual variability. TW is clearly recognizable as a salinity maximum near the shelf break. The temperature, salinity and density stratifications are stronger in summer than in winter (CHEN, 1988a; Figs 2–4).

Topographically induced upwelling at the shelf break is evident as indicated by the shelfward- and upward-tilting isotherms, isohalines, and isopycnals which extend over the shelf break (Figs 2–4). At the shelfward edge of the upwelling water, the isotherms, isohalines and isopycnals formed a bulge. The frequently detected bulge has a dimension of a few tens of kilometers. It may be caused by strong upwelling or else may represent eddies, filaments, or meandering of the Kuroshio (WONG *et al.*, 1991).

The above mentioned bulge of subsurface upwelling water is also evident in the apparent oxygen utilization (AOU, calculated based on the equation of CHEN, 1981), nitrate, phosphate, silicate and pH cross-sections (Figs 5–9). In the surface waters, the AOU is near zero, the nutrients are all low but the pH is high. The upwelling water has high AOU and nutrients but has low pH. Subsurface waters on the shelf show much variability, but in general, the vertical gradients are larger on the shelf than offshore.

IW is located between 400 and 600 m beneath TW, and is characterized by a salinity minimum (Fig. 3), high nutrient content and alkalinity, but low pH and oxygen (Figs 5–9). The minimum salinity core does not upwell onto the shelf (Fig. 3). Only isopleths saltier than 34.45, warmer than 14°C, contain more than 3.4 ml l⁻¹ O₂, and shallower than 450 m in the Kuroshio (saltier than 34.50, warmer than 15°C, contain more than 3.6 ml l⁻¹ O₂, and shallower than 350 m in summer) seem to extend onto the shelf (CHEN, 1988a). Four of the above mentioned major water types can be seen on the *T-S* diagrams for the December cruise (Fig. 10).

ECSW is low in salinity, temperature and nutrients, but high in oxygen and NTA. Coastal water has a wide temperature and salinity range. Since we are not studying the mixing of river waters and seawater, we choose a salinity of 28 to represent CW. CW has low salinity and nutrient contents but is high in NTA.

Taiwan Strait Water moves mainly northward year round, except that some surface water may move southward in winter (we exclude from this study the coastal water flowing southward along the Fukien coast). TSW is generally depleted in nutrients. The characteristics of the above mentioned waters are listed in Table 1 (WANG, 1988; CHEN, 1988a).

Fig. 2. Cross-section of temperature in (a) September 1988 and (b) December 1989.

Fig. 4. Cross-section of σ_T in (a) September 1988 and in (b) December 1989.

Fig. 5. Cross-section of apparent oxygen utilization in (a) September 1988 and in (b) December 1989.

Fig. 6. Cross-section of nitrate in (a) September 1988 and in (b) December 1989.

Fig. 7. Cross-section of phosphate in (a) September 1988 and in (b) December 1989.

Fig. 8. Cross-section of silicate in (a) September 1988 and in (b) December 1989.

Fig. 9. Cross-section of pH in (a) September 1988 and in (b) December 1989.

Fig. 10. Diagram representing mixing of four water masses. The CTD data for Stas 2, 4, 6, 8, 10, 12 and 14 of the September cruise are also plotted.

Table 1. Typical salinity, temperature, oxygen, pH, normalized alkalinity, nitrate, phosphate and silicate for SW, TW, IW, ECSW, CW and TSW

	S	T, °C	O ₂ (ml l ⁻¹)	pH	NTA (mmol kg ⁻¹)	NO ₃ (μmol kg ⁻¹)	PO ₄ (μmol kg ⁻¹)	SiO ₂ (μmol kg ⁻¹)
SW	34.30–34.70	24.5–29.0	4.20–4.80	8.00–8.30	2.30–2.32	0.2–2.7	0–1.2	2–8
TW	34.85–34.90	20.0–23.4	4.00–4.34	8.10–8.20	2.30–2.32	0.6–2.5	0.5–1.1	2–14
IW	34.25–34.30	6.6–8.0	2.10–2.80	7.50–7.80	2.36–2.41	20–30	1.6–2.3	40–80
ECSW	30.50–33.50	8.6–20.0	3.00–4.80	8.10–8.30	2.37–2.57	0–10	0–0.6	15–40
CW	28	13.0–25.0	5.20–6.80	8.10–8.50	2.37–2.57	0–20	0–0.5	15–40
TSW	33.70–34.60	19.0–28.0	4.00–5.20	8.00–8.30	2.28–2.32	0–2	0–1.5	0–15

The traditional T - S method is useful for describing surface and shelf waters (MAO *et al.*, 1964; CHEN, 1985; CHEN *et al.*, 1985), but the uncertainty is large because neither T nor S is strictly conservative. Oxygen, % oxygen saturation or AOU are subject to the same limitations because of air-sea exchange, biological activities and temperature variations (which affect percentage oxygen saturation and AOU). These properties are less useful in summer but are more useful in winter when mixing becomes relatively more important relative to biological activities. Nutrients, total carbon dioxide (TCO₂) or pH are subject to similar problems as oxygen (CHEN, 1985, 1988b, 1993; CHEN *et al.*, 1985).

Calcium and alkalinity are more conservative on a shelf, especially when normalized to the same salinity (CHEN, 1985; WANG, 1988). Chinese coastal waters also have higher normalized calcium (N_{Ca}) and normalized alkalinity (N_{TA}) than Kuroshio waters because river waters generally have high N_{Ca} and N_{TA} values (CHEN *et al.*, 1985; SUI, 1986).

Typical salinity, temperature, oxygen, pH, normalized alkalinity, nitrate, phosphate and silicate for SW, TW, IW, ECSW, CW and TSW are given in Table 1 based on data from the following reports: UDA, 1941; CHU, 1963; CSK, 1966, 1968, 1969, 1970; NITANI, 1972; HUANG *et al.*, 1983; LIMBURNER *et al.*, 1983; WENG and WANG, 1985; SUI, 1986; WANG, 1988; RUO, 1989; and WONG *et al.*, 1989a,b, 1991.

Method for calculating the mixing percentages for a four component mixing

We have made an initial attempt to quantify the mixing percentages of four major water masses based on data collected on R.V. *Ocean Researcher I* (RUO, 1989; WONG *et al.*, 1989a,b, 1991; CHEN *et al.*, 1991). Because there are insufficient data, ECSW, CW and TSW have been grouped together as the Shelf Surface Water (SSW; $S = 33.1$, $T = 28^\circ\text{C}$, $\text{NO}_3 = 0.2 \mu\text{mol kg}^{-1}$, $\text{PO}_4 = 0 \mu\text{mol kg}^{-1}$ and $\text{pH} = 8.3$ in September 1988; $S = 33.8$, $T = 19^\circ\text{C}$, $\text{NO}_3 = 2 \mu\text{mol kg}^{-1}$, $\text{PO}_4 = 0 \mu\text{mol kg}^{-1}$ and $\text{pH} = 8.2$ in December 1989). The four major water types, SSW, SW, TW and IW are marked on Fig. 3(a). SSW is mostly not present near the study area in winter thus only SW, TW and IW are marked on Fig. 3(b).

Assuming that a water mass P is a mixture of four water masses A , B , C , and D (Fig. 10). By drawing perpendicular lines from P to the four sides of the tetragonal we obtain four intercepts, P_1 , P_2 , P_3 and P_4 . The length between P and P_1 is represented as PP_1 . Likewise the lengths between: P and $P_2 = PP_2$; P and $P_3 = PP_3$; P and $P_4 = PP_4$; P_1 and $A = X_{A1}$; P_1 and $B = X_{B1}$; P_2 and $B = X_{B2}$; P_2 and $C = X_{C1}$; P_3 and $C = X_{C2}$; P_3 and $D = X_{D1}$; P_4 and $D = X_{D2}$; P_4 and $A = X_{A2}$.

Let f_A , f_B , f_C and f_D be the fractions of A , B , C , D in P :

$$f_A + f_B + f_C + f_D = 1. \quad (1)$$

Likewise we can let f_{P1} , f_{P2} , f_{P3} and f_{P4} be the fractions of P_1 , P_2 , P_3 and P_4 in P :

$$f_{P1} + f_{P2} + f_{P3} + f_{P4} = 1.$$

In other words, T and S of P can now be calculated from the T and S of P_1 , P_2 , P_3 and P_4 . The T and S of P_1 can be calculated from f_{A1} , f_{B1} , X_{A1} and X_{B1} where f_{A1} and f_{B1} are the fractions of A and B , respectively, involved in forming P_1 . The objective now is to solve for f_{A1} , f_{A2} , f_{B1} , f_{B2} , f_{C1} , f_{C2} , f_{D1} , f_{D2} .

Water mass A also contributes f_{A2} to mix with water mass D to form water mass P_4 . Thus A contributes f_{A1} and f_{A2} altogether to form P . Similarly the contributions of B , C and D can also be subdivided into two parts. Equation (1) now becomes:

$$f_{A1} + f_{A2} + f_{B1} + f_{B2} + f_{C1} + f_{C2} + f_{D1} + f_{D2} = 1. \quad (2)$$

Further, PP_1 is inversely proportional to $f_{A1} + f_{B1}$ giving the following equation:

$$PP_1 \cdot (f_{A1} + f_{B1}) = PP_2 \cdot (f_{B2} + f_{C1}) = PP_3 \cdot (f_{C2} + f_{D1}) = PP_4 \cdot (f_{D2} + f_{A2}). \quad (3)$$

On the four sides of the tetragonal:

$$f_{A1} \cdot X_{A1} = f_{B1} \cdot X_{B1}, \quad f_{B2} \cdot X_{B2} = f_{C1} \cdot X_{C1}, \quad f_{C2} \cdot X_{C2} = f_{D1} \cdot X_{D1}, \quad f_{D2} \cdot X_{D2} = f_{A2} \cdot X_{A2} \quad (4)$$

By solving equations (2)–(4), we obtain:

$$\begin{aligned} f_{A1} &= \frac{X_{B1}}{AB \cdot PP_1} \left(\sum_4 \frac{1}{PP_i} \right)^{-1} & f_{A2} &= \frac{X_{D2}}{DA \cdot PP_4} \left(\sum_4 \frac{1}{PP_i} \right)^{-1} \\ f_{B1} &= \frac{X_{A1}}{AB \cdot PP_1} \left(\sum_4 \frac{1}{PP_i} \right)^{-1} & f_{B2} &= \frac{X_{C1}}{BC \cdot PP_2} \left(\sum_4 \frac{1}{PP_i} \right)^{-1} \\ f_{C1} &= \frac{X_{B2}}{BC \cdot PP_2} \left(\sum_4 \frac{1}{PP_i} \right)^{-1} & f_{C2} &= \frac{X_{D1}}{CD \cdot PP_3} \left(\sum_4 \frac{1}{PP_i} \right)^{-1} \\ f_{D1} &= \frac{X_{C2}}{CD \cdot PP_3} \left(\sum_4 \frac{1}{PP_i} \right)^{-1} & f_{D2} &= \frac{X_{A2}}{DA \cdot PP_4} \left(\sum_4 \frac{1}{PP_i} \right)^{-1}, \end{aligned}$$

where

$$\sum_4 \frac{1}{PP_i} = \frac{1}{PP_1} + \frac{1}{PP_2} + \frac{1}{PP_3} + \frac{1}{PP_4}.$$

It is now possible to calculate the mixing percentages in the study area (MAO, 1964; RUO, 1989; CHEN *et al.*, 1990). Strictly speaking, however, T and S are not conservative properties near surface, but neither are any of the parameters that we measured. We tried to make the calculation using T – S , NO_3 – S , PO_4 – S and pH – S pairs and found little difference (Table 2). We thus decided to use T – S as these data are the most reliable.

RESULTS AND DISCUSSION

Figure 11(a) and (b) show the percentages of shelf water in September 1988 and December 1989, respectively. In September, the shelf water dominates on the shelf, but only in the surface layer. The percentage reduces to below 50% below 60 m. The shelf water spreads out off the shelf break and the shelf water percentage reduces rapidly to 1% before reaching Sta. 14. In December the picture is quite different [Fig. 11(b)]. The shelf water makes up only 20% of the surface water on the shelf, reflecting reduced river flow from the continent and stronger Kuroshio intrusion in winter.

Figure 12(a) and (b) show the percentages of Kuroshio Surface Water, which dominates off the shelf break. The percentage is higher than 90% in September in the Kuroshio region, slightly lower in December. The dome-like structure at the shelf break reflects upwelling of deeper waters. The Kuroshio Surface Water contributes approximately 30% of the water on the shelf in September, and up to 70% in December when the continental fresh water outflow is low.

Figure 13(a) and (b) show the mixing ratio of the Kuroshio Tropical Water in September and December, respectively. The core of the Tropical Water is near the salinity maximum at about 150 m in September, slightly deeper in December. The Tropical Water does not

Table 2. Mixing ratios based on T-S, NO_3^- -S, PO_4^{3-} -S and pH-S pairs for cruise 179

Method	<i>T-S</i>				NO_3^- - <i>S</i>				PO_4^{3-} - <i>S</i>				<i>pH-S</i>			
Sta. 10																
Depth (m)	SSW	SW	TW	IW	SSW	SW	TW	IW	SSW	SW	TW	IW	SSW	SW	TW	IW
50	13	71	15	1	11	67	13	9	6	76	17	11	6	71	14	9
75	7	44	38	11	6	46	35	13	5	50	33	12	6	58	28	8
100	2	18	66	14	3	15	61	21	2	13	66	19	2	16	71	11
150	0	0	55	45	0	0	61	39	0	0	56	44	0	0	52	38
200	0	0	41	59	0	0	43	57	0	0	49	51	0	0	41	59
400	0	0	7	93	0	0	9	91	0	0	8	92	0	0	9	91
Sta. 12																
Depth(m)																
50	0	82	18	0	0	80	20	0	0	84	16	0	0	85	15	0
75	6	50	34	10	9	43	41	7	0	76	24	0	0	75	25	0
100	0	20	66	14	1	15	71	13	0	22	73	5	0	22	70	8
200	0	0	54	46	0	0	56	44	0	0	52	38	0	0	57	43
400	0	0	5	95	0	0	8	92	0	0	12	88	0	0	10	90
Sta. 13																
Depth (m)																
50	0	78	22	0	0	80	20	0	0	85	15	0	0	84	16	0
75	0	48	52	0	0	42	58	0	0	48	52	0	0	50	50	0
100	0	0	100	0	0	0	100	0	0	8	92	0	0	13	87	0
200	0	0	58	42	0	0	65	35	0	0	69	31	0	0	79	21
400	0	0	10	90	0	0	6	94	0	0	11	89	0	0	12	88

get to the surface but shows its influence at the shelf break and near the bottom on the shelf, making up as much as 50% on the bottom in September, lower in December.

Figure 14(a) and (b) show the mixing ratio of the Kuroshio Intermediate Water in September and December, respectively. The Intermediate Water contributes to the upwelled water at the shelf break and makes up 30% of the bottom water on the shelf in September, less in December.

Overall, the largest September–December contrast occurs on the shelf. The original “Shelf Water” component makes up 70–80% of the surface shelf water in September, only 20% in December. The bottom shelf waters contain only 10% of the original “Shelf Water” in September and little or no original “Shelf Water” in December. They are composed of 10% Kuroshio Surface Water, 50% Kuroshio Tropical Water and 30% Kuroshio Intermediate Water in September, 30–50% Kuroshio Surface Water, 30% Kuroshio Tropical Water and 10–30% Kuroshio Intermediate Water in December.

There are regions on Fig. 10, say a point P' at Sta. 6 where perpendicular lines can not be drawn to all four sides. Such points are near one of the four sides thus are mainly a mixture of two water masses. For instance, point P' is mainly a mixture of SW and SSW. The contribution of IW diminishes from the point P to P' until IW becomes zero. After that, P' can simply be calculated as a mixture of SSW, SW and TW.

CONCLUSION

We have calculated the mixing ratios of Shelf Water, Kuroshio Surface Water, Kuroshio Tropical Water and Kuroshio Intermediate Water in an area northeast of Taiwan. In

Fig. 11. Cross-section of SSW percentage in (a) September 1988 and in (b) December 1989.

Fig. 12. Cross-section of SW percentage in (a) September 1988 and in (b) December 1989.

Fig. 13. Cross-section of TW percentage in (a) September 1988 and in (b) December 1989.

Fig. 14. Cross-section of IW percentage in (a) September 1988 and in (b) December 1989.

September 1988, surface shelf water in the study area was affected by the Kuroshio Surface Water. The bottom waters on the shelf contained only 10% of the original "Shelf Water". The rest came from the Kuroshio Surface Water (10%), Kuroshio Tropical Water (50%) and the Kuroshio Intermediate Water (30%).

In December 1989, the original "Shelf Water" constituted only 20% of the surface water on the shelf. Intrusion of the Kuroshio Surface Water dominated (>70%). The original "Shelf Water" was almost nonexistent near bottom where Kuroshio Surface Water (30–50%), Kuroshio Tropical Water (30%) and Kuroshio Intermediate Water (10–30%) dominated. The mixing ratios offshore are also calculated and they do not show large temporal variations.

Although it is not apparent on Figs 2–8, Kuroshio Intermediate Water also participated in the upwelling and cross shelf mixing by a higher percentage [>30% near bottom; Fig. 12(a)] in summer than in winter [less than 10%; Fig. 12(b)].

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