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Variations in oxygen, nutrient and carbonate fluxes of the Kuroshio Current*

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Abstract: Measured concentrations of dissolved oxygen (DO), phosphate (PO_4), nitrate (NO_3), silicate (SiO_2), total alkalinity (TA) and calculated total CO_2 (TCO_2) in a section (WOCE PR 20 line) off southeast Taiwan across the Kuroshio current have been combined with the geostrophic velocity to estimate the net northward transports of oxygen, nutrients and carbonates. During the four cruises of R/V Ocean Researcher 1: CHIPS-1 (May 1985); OR 257 (Oct. 1990); OR 287 (June 1991) and OR 316 (May 1992) the net northward volume transports across the 121–130°E cross-section at 21°45′ N were 20, 19, 50 and 39 Sv, respectively, above 1000 m. The Kuroshio could be clearly identified in May 1985 and June 1991 when the northward transports were 38 and 53 Sv, respectively, between 121 and 123°E. The segment between 123 and 130°E actually transported respectively, 18 and 3 Sv, southward. In Oct. 1990 and May 1992 the northward transports were more diffusive. The nutrient fluxes indicate a "nutrient stream" below the high velocity core of the Kuroshio current. For oxygen and carbonates, the distributions of flux have similar structures as the velocity field. For each cruise, the net along-stream transports of oxygen, phosphate, nitrate, silicate, alkalinity and total CO_2 between 121 and 130°E were as follows : May, 1985, 3971 (DO), 12 (PO_4), 194 (NO_3), 725 (SiO_2), 62156 (TA) and 63571 (TCO_2)kmol/s; Oct. 1990, 8585(DO), 12 (PO_4), 196(NO_3), 382(SiO_2), 45258(TA) and 41822(TCO_2) kmol/s; June 1991, 8487 (DO), 11 (PO_4), 164 (NO_3), 317 (SiO_2), 82002 (TA) and 71399 (TCO_2) kmol/s; and May, 1992, 6549 (DO), 21 (PO_4), 299 (NO_3), 474 (SiO_2), 89818 (TA) and 77531 (TCO_2) kmol/s. Northward fluxes were concentrated between 121 and 123°E and southward fluxes were more diffusive.

1. Introduction

The Kuroshio (Black Stream), as the western boundary current in the North Pacific Ocean, plays an important role in the meridional transports of mass, momentum, heat and fresh water. It is generally considered to be originated from the area southeast of Taiwan and east of the Bashi Strait as a continuation of the North Equatorial Current. The Kuroshio is characterized by its high speed, narrow width and great depth. It brings a large quantity of warm equatorial seawater while traveling northward along the east coast of Taiwan (NITANI, 1972; PAI, *et al.*, 1987). Because of its characteristic high temperature and salinity, it has important impacts both on the local climate and the marine biological resources. Our interest is to quantitatively estimate the material fluxes carried by the Kuroshio.

Although there are numerous studies on Kuroshio volume transport(e.g. SVERDRUP *et al.*, 1942; WYRTKI, 1961; NITANI, 1972; BINGHAM and TALLEY, 1991, CHEN *et al.*, 1992; ICHIKAWA and BEARDSLEY, 1993), in fact none of these dealt with fluxes of chemical species. The first quantitative estimates of nutrient fluxes for the Pacific was as recent as 1983 (WUNSCH *et al.*). In the Atlantic, the first calculation of nutrient fluxes seems to be that of BREWER and DYRSSEN (1987). They multiplied the average property values by the net meridional transport in each depth class to find the net flux across 24°N. BREWER *et al.* (1989), CSANADY (1990) and RINTOUL and WUNSCH (1991) further extended the flux calculation in the North Atlantic

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Ocean to include nutrients, oxygen and CO_2.

In the North Pacific, ROEMMICH (1989) studied the mass and nutrient fluxes in the southern California coastal waters and ROBBINS *et al.* (1994) covered the entire 24° N cross-section. We are not aware of similar work in the source region of Kuroshio except for our preliminary work based on data collected southeast of Taiwan in May, 1985 (CHEN *et al*, 1994).

In this note, we shall compare our 1985 data with additional data collected in 1990, 1991 and 1992. The fluxes, and the gross and net transports of dissolved oxygen, phosphate, nitrate, silicate, alkalinity and total CO_2 are presented.

2. Sources of data

The hydrographic data used in this note are cited from the data reports of CHIPS-1 (May 1985, LIU *et al.*, 1986, 1987); OR 257 (Oct. 1990, CHEN *et al.*, 1993a); OR 287 (Jun. 1991, LIU *et al.*, 1991; CHEN *et al.*, 1993b), and OR 316 (May 1992, PAI *et al.*, 1992; CHEN *et al.*, 1993c). As is shown in Fig. 1, there were 29 CTD stations between 121 and 130°E, but in general only 21 stations were chosen for chemical analysis. The analytical procedures in determining the dissolved oxygen, phosphate, nitrate, silicate, and total alkalinity were described in PAI *et al.* (1987) and CHEN *et al.* (1993a). Total CO_2 was calculated based on pH and TA data (CHEN, 1984).

3. Results and discussion

Currents

We calculatd geostrophic velocity based on a level of no motion at 1000 dB (Fig. 2a–d). The calculation based on a level of no motion at 2000 dB resulted in a similar pattern above 1000 dB and little or no motion (<5cm/s) below 1000 dB (Fig. 2e). These results agree with that obtained by NITANI (1972) and show various northward and southward bands. There were two rather strong northward current bands west of 123° E and weaker but much wider southward bands in May, 1985 (Fig. 2a). The total northward transport above 1000 m was 65 Sv and the total southward transport was 45 Sv, yielding a net northward flow of 20 Sv (Table 1).

It should be pointed out that the net northward transport was as much as 38 Sv between

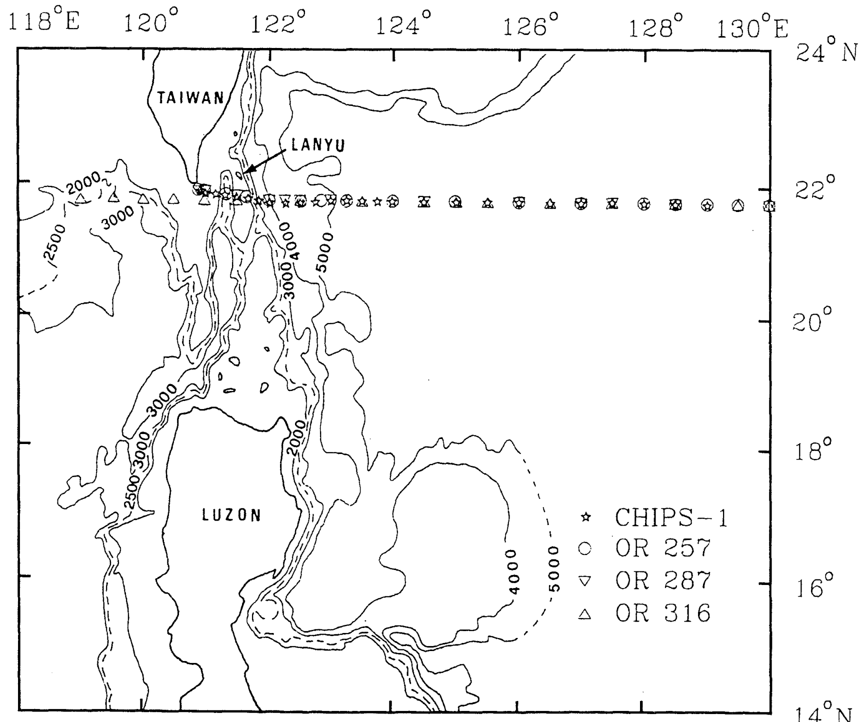


Fig. 1. Study area and station locations.

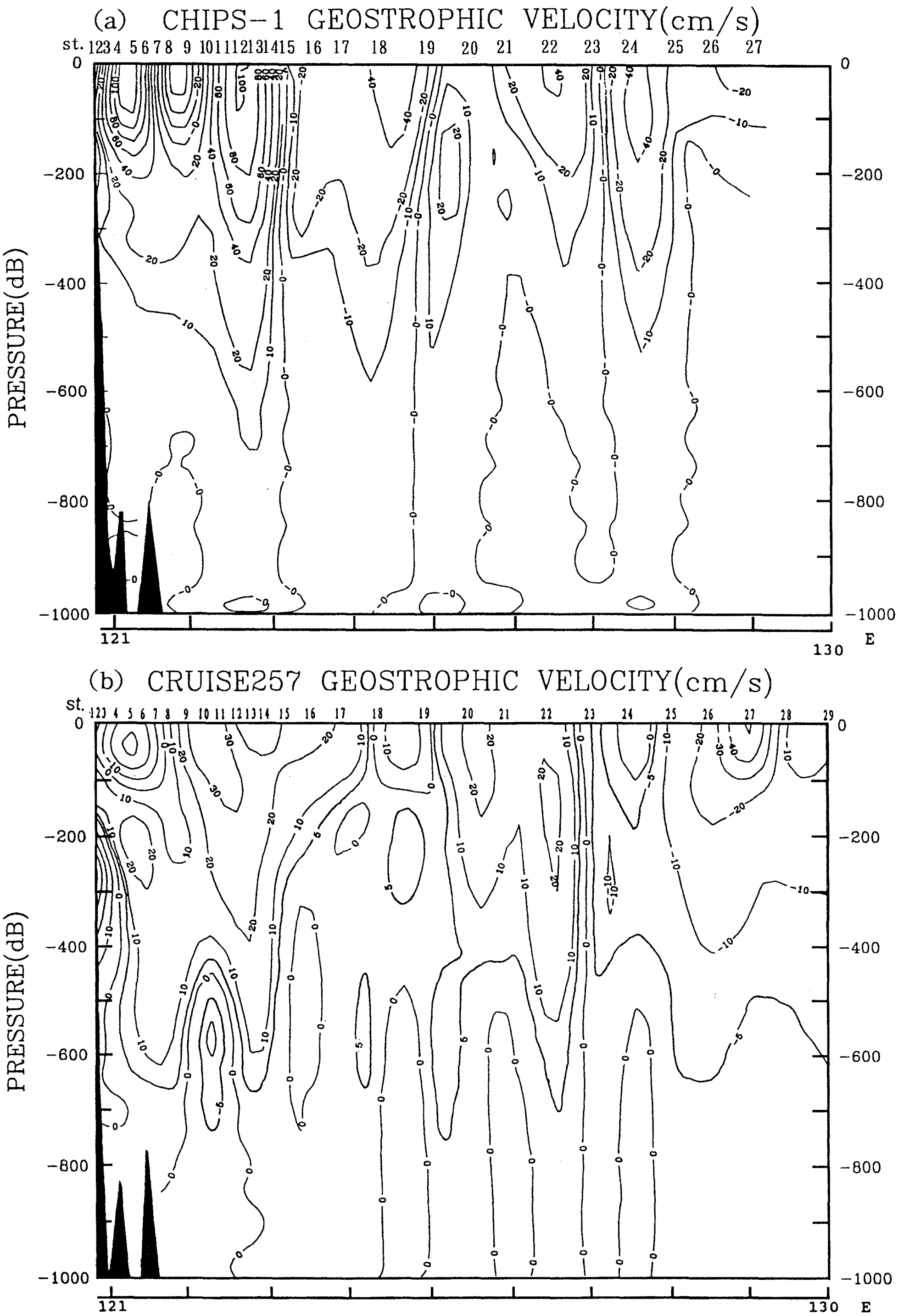


Fig. 2. Geostrophic velocity at the section near 21°45′ N for (a) CHIPS 1, (b) OR 257, (c) OR 287 and (d) OR 316 cruises based on a level of no motion at 1000 dB; and for (e) OR 316 based on a level of no motion at 2000 dB. Contours are in centimeter per second and the positive sign indicates northward flow.

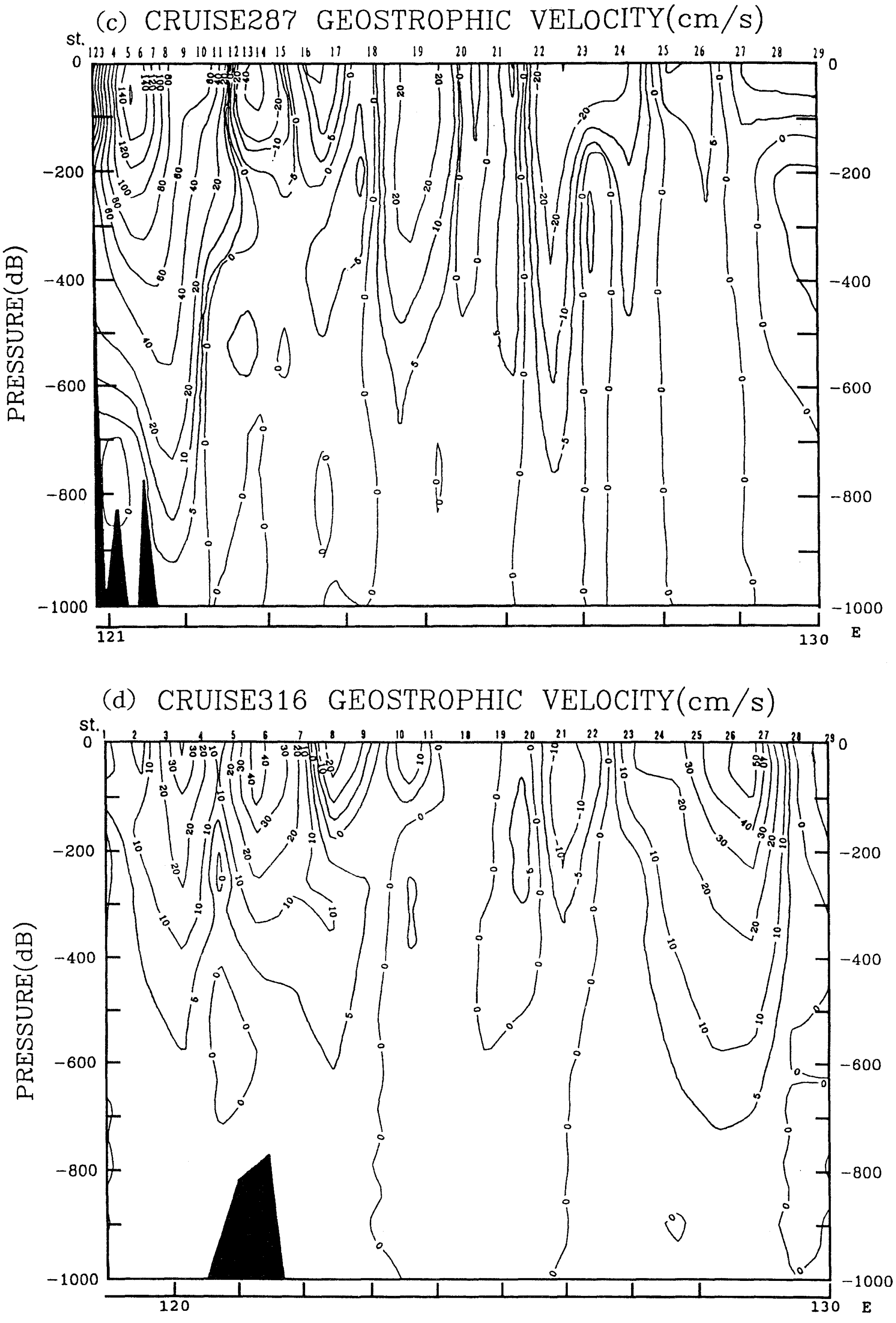


Fig. 2. (Continued)

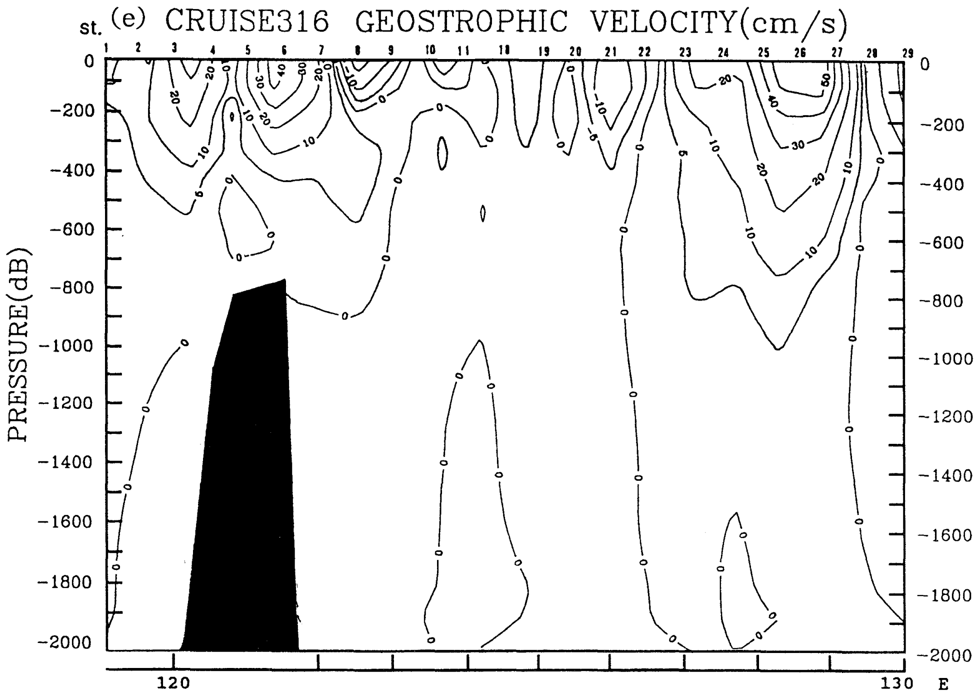


Fig. 2. (Continued)

121 and 123° E (Table 1), which reflects the strong influence of the Kuroshio. The net flow was southward (18 Sv) between 123 and 130°E. Again we discuss only the flow above 1000 m and do not consider the deep southward flow beneath the Kuroshio (CHEN, 1992; NAKANO *et al.*, 1994).

The currents in Oct. 1990 were relatively weak and variable with no dominating bands. The Kuroshio could not be easily identified (Fig. 2b). The northward flow was 49 Sv and the southward flow was 30 Sv, resulting in a net northward flow of 19 Sv. The net northward transport was 15 Sv between 121 and 123° E. The currents between 123 and 130° E contributed 4 Sv to the northward transport (Table 1).

The Kuroshio was rather strong in June, 1991 with a dominating northward flowing current band between 121 and 123° E (Fig. 2c). The northward flow totaled 78 Sv. The net northward flow was as much as 50 Sv after subtracting the southward flow of 28 Sv. Most of the northward transport occurred between 121 and 123°E (53 Sv, Table 1).

Table 1. Volume transports (Sv) at 21°45′ N west of 130° E during CHIPS-1, OR 257, 287 and 316 cruises

	CHIPS-1* May 1985	OR 257 Oct. 1990	OR 287 June 1991	OR 316 May 1992
121–130°E				
Northward	65	49	78	50
Southward	−45	−30	−28	−11
Net	20	19	50	39
121–123°E				
Northward	40	18	56	14
Southward	−2	−3	−3	−2
Net	38	15	53	12

* 121–129°E

The Kuroshio was again weak in May, 1992 after the weak El Nino, but the total northward flow was still as much as 50 Sv. The southward flow was weak, totaling 11 Sv. The net northward flow was 39 Sv between 121 and 130° E and only 12 Sv between 121 and 123° E. This suggests that the northward flow was wide and not concentrated by the Kuroshio.

The fluxes of oxygen, nutrients and carbonates were calculated by multiplying geostrophic velocity by concentration. Integrating these data gives the total fluxes.

Oxygen

The highest dissolved oxygen was always found near the surface layer, with concentration near or slightly above saturation. The minimum was as low as 60 μmol/kg near 1000 m. A typical cross-section (OR 316, May, 1992) is given in Fig. 3a. The contours shoaled westward indicating upwelling. The strong vertical mixing in the South China Sea also tends to lower the oxygen concentration of waters above 1000 m. Because the South China Sea water has a strong influence near the Bashi Channel above 1000 m, the oxygen content was lowered accordingly (CHEN and HUANG, 1995).

As is shown in Fig. 4a, the typical fluxes of dissolved oxygen (OR 316, May 1992) ranged from -58 to 108 mmol/m^2/s (positive sign indicates northward flow), with maxima near St. 5 and 26. Since the flux was dominated by oxygen concetration and current velocity, and both decreased with depth, the flux structure of dissolved oxygen was similar to the velocity structure. The gross flux of oxygen at this section was 7.96 $\times$ 10^6 mol/s northward and 1.42 $\times$ 10^6 mol/s southward, yielding a net flux 6.55 $\times$ 10^6 mol/s down-stream, for this section between 121 and 130°E. The segment between 121 and 123°E contributes 36% to the oxygen flux. In May 1985 and June 1991 the segment between 121 and 123°E contributed 54 and 80% of the northward oxygen flux. Only 30% of the Oct. 1990 flux was between 121 and 123°E. There were large annual variations in oxygen

Table 2. Transports of Dissolved oxygen, Nutrients and Carbonates at 21°45′ N Between 121 and 130°E

	DO 10^6mol/s	PO_4 kmol/s	NO_3 kmol/s	SiO_2 kmol/s	TA 10^6mol/s	TCO_2 10^6mol/s
May 1985*						
Northward	11.542	24	392	1156	122.18	116.42
Southward	−7.571	−12	−198	−431	−60.02	−52.85
Net	3.971	12	194	725	62.16	63.57
Oct. 1990						
Northward	9.533	24	351	672	85.35	77.49
Southward	−0.948	−12	−155	−290	−40.09	−35.67
Net	8.585	12	196	382	45.26	41.82
June 1991						
Northward	11.368	24	329	667	114.79	100.88
Southward	−2.881	−13	−165	−350	−32.78	−29.48
Net	8.487	11	164	317	82.00	71.40
May 1992						
Northward	7.964	24	335	549	103.40	90.57
Southward	−1.415	−3	−36	−75	−13.58	−13.04
Net	6.549	21	299	474	89.82	77.53

* 121–129°E

Table 3. Net Northward Transports of Dissolved Oxygen, Nutrients and Carbonates at 21°45′ N between 121 and 123°E

	DO (10^6mol/s)	PO_4 (kmol/s)	NO_3 (kmol/s)	SiO_2 (kmol/s)	TA (10^6mol/s)	TCO_2 (10^6mol/s)
May 1985	7.305	15	232	730	84.49	79.21
Oct. 1990	2.609	11	162	310	41.70	37.04
June 1991	6.757	13	179	365	65.91	58.87
May 1992	2.378	8	121	180	31.67	29.41

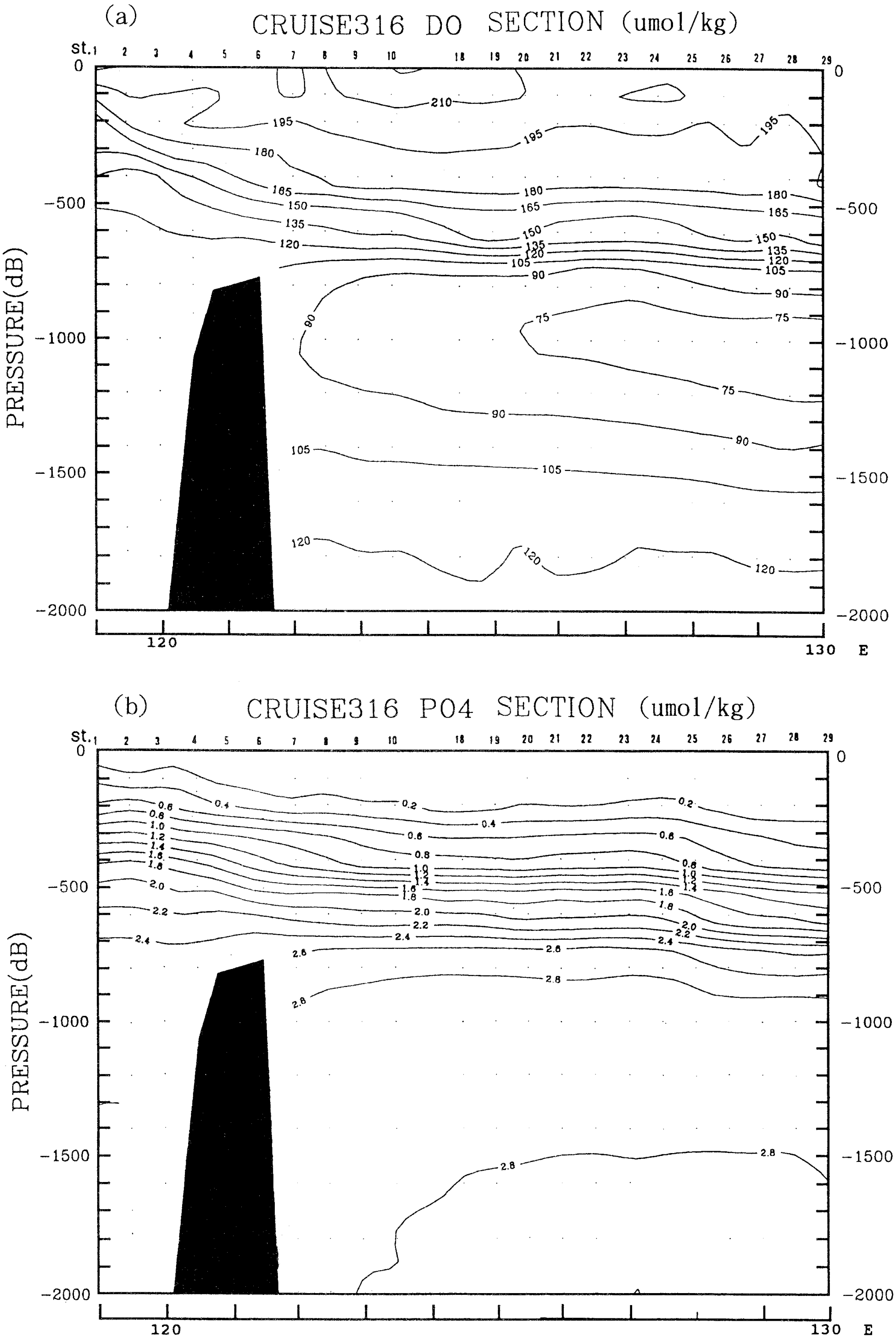
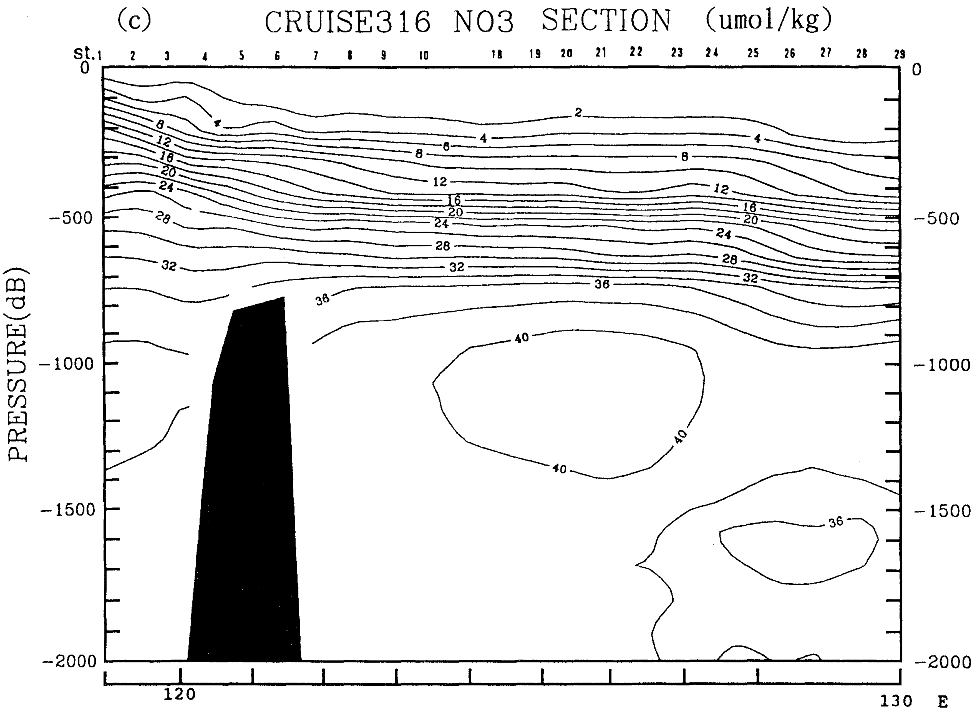


Fig. 3. Cross-section of (a) dissolved oxygen; (b) phosphate; (c) nitrate; (d) silicate; (e) alkalinity and (f) total CO_2 near 21°45′ N for OR 316 cruise.



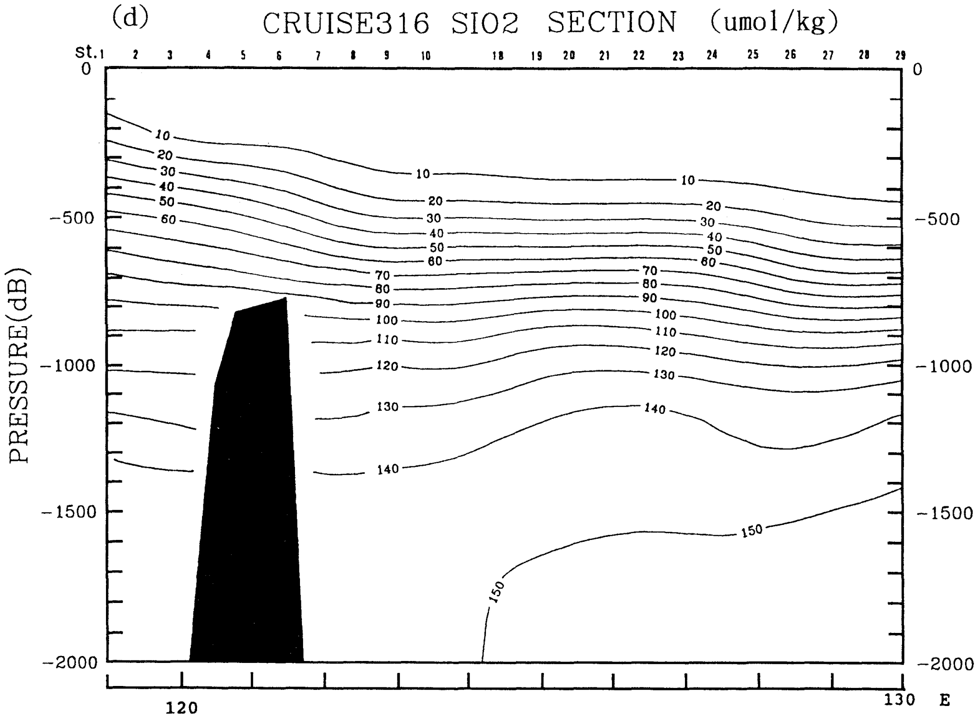
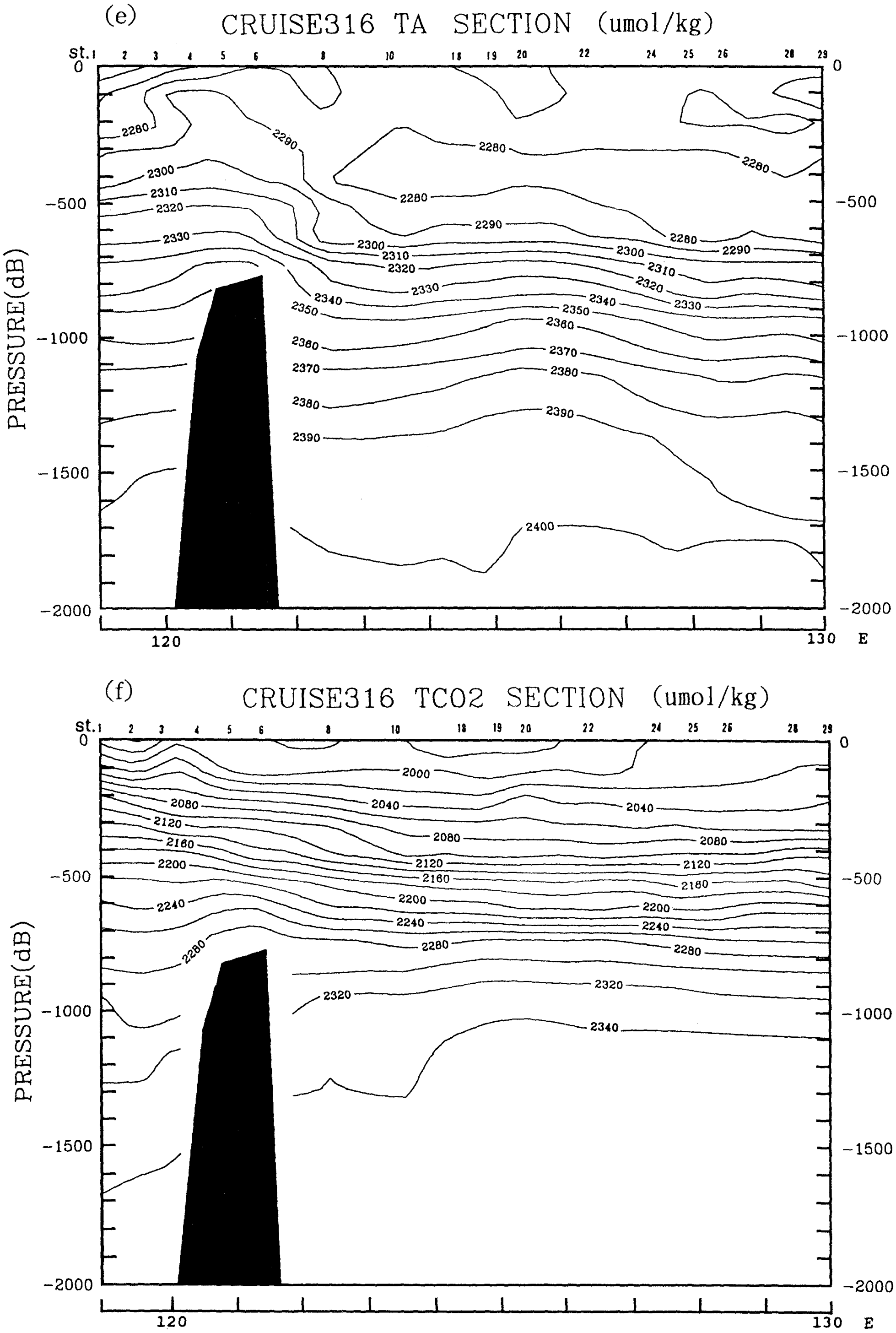


Fig. 3. (Continued)

(e)



(f)

Fig. 3. (Continued)

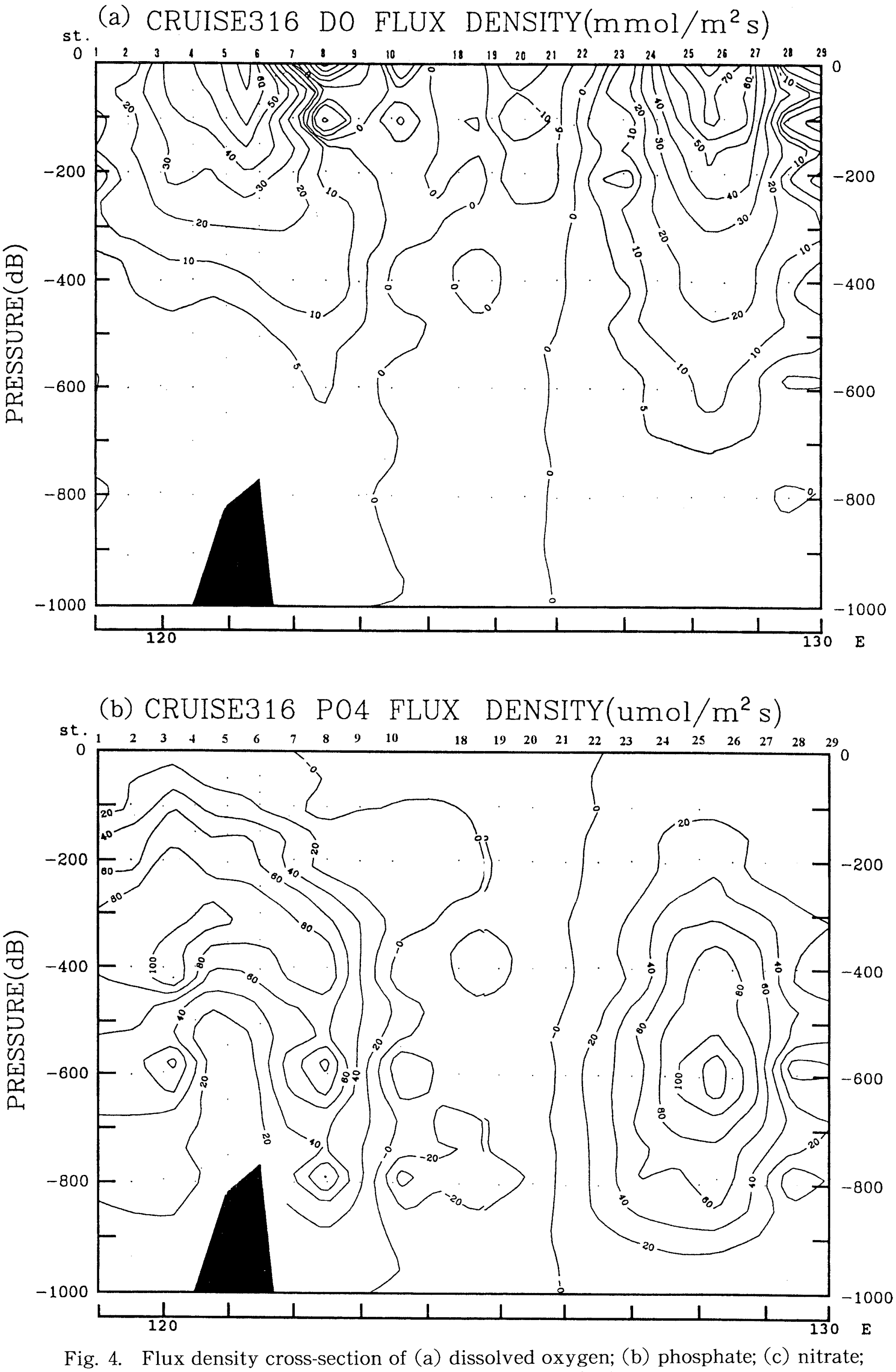
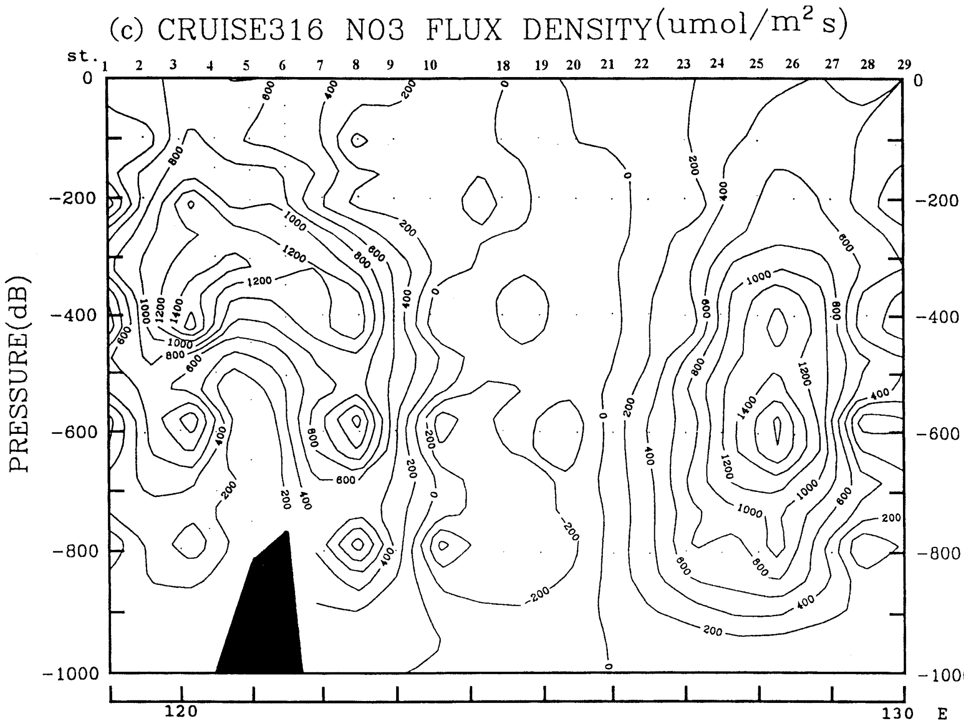


Fig. 4. Flux density cross-section of (a) dissolved oxygen; (b) phosphate; (c) nitrate; (d) silicate; (e) alkalinity and (f) total CO_2 near 21°45′ N for OR 316 cruise.



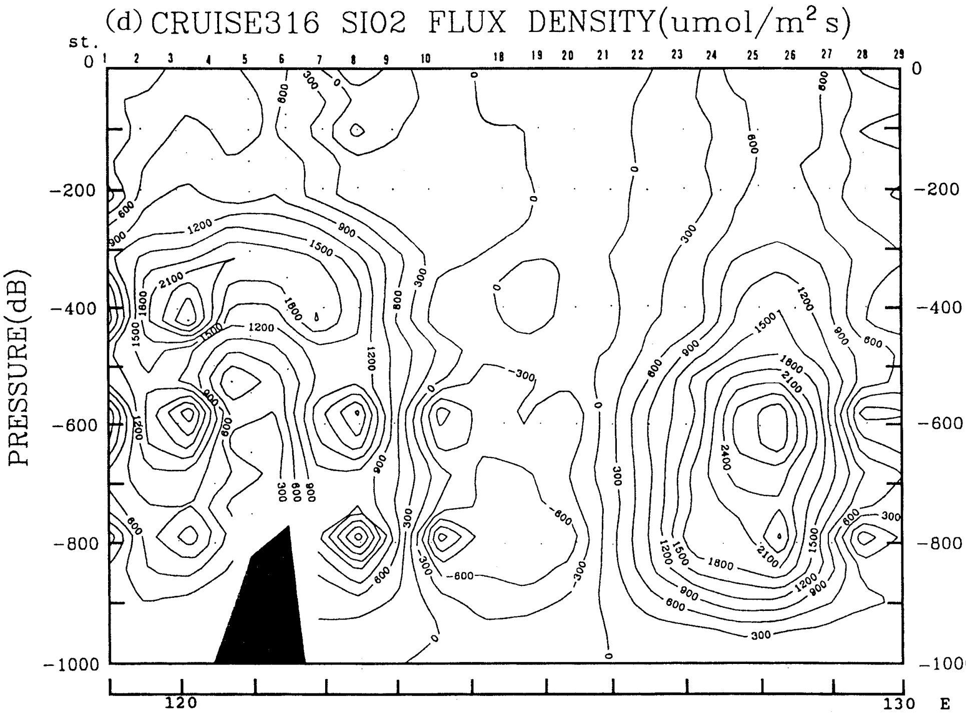
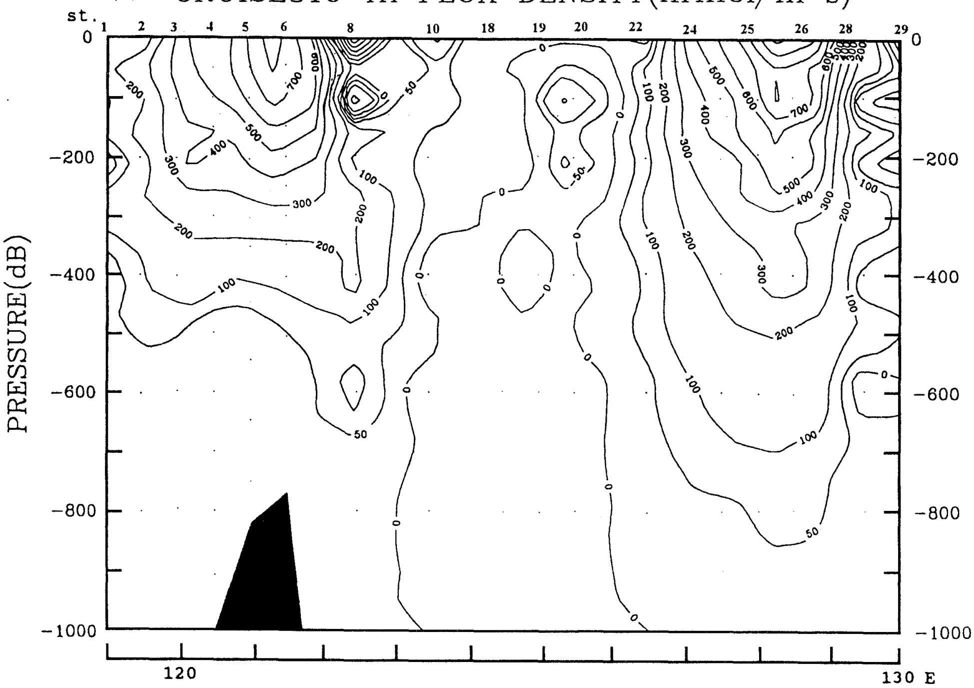


Fig. 4. (Continued)

(e) CRUISE316 TA FLUX DENSITY(mmol/m^2s)



(f) CRUISE316 TCO2 FLUX DENSITY(mmol/m^2s)

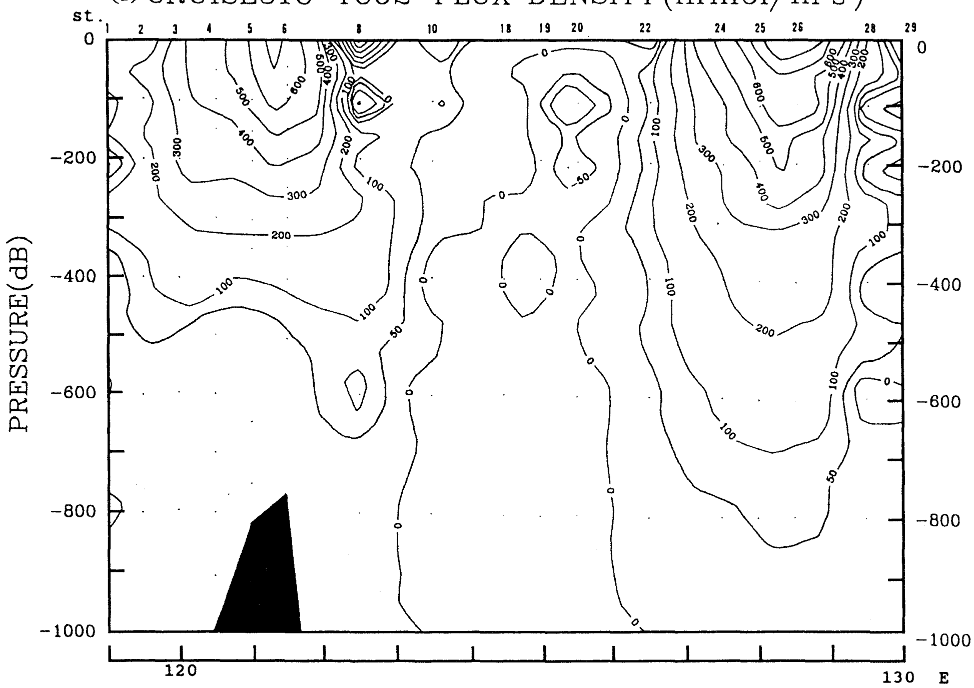


Fig. 4. (Continued)

fluxes, ranging from 3.97×10^6 mol/s for May 1985 to arround 8.5×10^6 mol/s for Oct. 1990 and June 1991 (Table 2).

The annual variations were most apparent between 121 and 123°E (Table 3). The Oct. 1990 and May, 1992 transports were low (2.61 and 2.38×10^6 mol/s, respectively) whereas the May 1985 and June 1991 transports were much higher (7.31 and 6.76×10^6 mol/s, respectively). By way of comparison, BREWER *et al.* (1989) reported an oxygen transport of 4.89×10^6 mol/s above 850 m in the Florida current between Florida and the Bahamas (Nov. 1988).

Phosphate

The phosphate concentration increased with depth, ranging from almost zero near the surface to a maximum of about 3.0 μmol/kg near 1200 m (Fig. 3b).

The typical distribution of the phosphate flux based on OR 316 data in May 1992 is shown in Fig. 4b. The values ranged from −61 to 176 μmol/m^2/s with a maximum near St. 3, 8 and 26. Since the phosphate concentration increased with depth but the current velocity decreased with depth, the maximum phosphate flux was located at 600 m. The Gulf Stream shows a similar pattern (CSANADY, 1990). The total flow of phosphate across this section was 24 kmol/s northward and 3 kmol/s southward, yielding a net northward flow of about 21 kmol/s (Table 2) of which 38% was between 121 and 123°E.

There were large annual variations (Tables 2, 3) ranging from 11 to 21 kmol/s between 121 to 130°E and 8 to 15 kmol/s between 121 and 1 23°E. The segment between 121 and 123°E contributed 15 and 13 kmol/s, respectively, of northward phosphate flow in May 1985 and June 1991 when the Kuroshio was strong. These values were higher than the net northward flow between 121 and 130°E, implying that phosphate was transported southward between 123 and 130°E during these two cruises.

In Oct. 1990 when the Kuroshio was weak, the northward phosphate transport was still concentrated between 121 and 123°E (11 kmol/s) vs. only 1 kmol/s between 123 and 130°E. In May 1992 the northward phosphate flow spreaded out more evenly with 8 kmol/s between 121 and 123°E and 13 kmol/s between 123 and 130°E.

Nitrate

The vertical distribution of nitrate for OR 316 (May 1992) is similar to that of phosphate (Fig. 3c). The concentration varied from near zero at surface to above 42 μmol/kg at the maximum near 1200 m. The flux ranged from −844 to 2572 μmol/m^2/s (Fig. 4c), and also had the same pattern as that of phosphate with a mid-depth maximum. The cores at St. 3, 8, 26 were also apparent. The total northward and southward transports were 335 and 36 kmol/s, respectively (Table 2). The net northward transport between 121 and 130°E was 299 kmol/s which was 14 times the phosphate transport. Large annual variations were found (Table 2) with net northward transports ranging from a low of 164 kmol/s in June 1991, to about 195 kmol/s in May 1985 and Oct. 1990, to a high of 299 kmol/s in May 1992.

When the Kuroshio was strong in May 1985 and June 1991 the section transported 232 and 179 kmol/s, respectively, of nitrate northward between 121 and 123°E (Table 3). Between 123 and 130°E the net transports were 38 and 15 kmol/s, respectively, southward.

In Oct. 1990 the segment between 121 and 123°E transported 83% of the nitrate northward. In May 1992 the percentage was 40%. In both years the segment between 123 and 130°E also transported nitrate northward.

Silicate

The silicate concentration ranged from near zero at surface to above 150 μmol/kg near 2000 m (OR 316, Fig. 3d).

The flux of silicate ranging from −2 to 4.3 mmol/m^2/s is shown in Fig. 4d (OR 316). It shows a silicate stream core at between 400 and 800 m. The negative values between St. 10–21 reflected the southward transport of currents. The total silicate transport was 549 kmol/s northward and 75 kmol/s southward (May 1992). The net northward flow of silicate between 121 and 130°E was 474 kmol/s (Table 2), some 22 times the net phosphate transport and 1.6 times the nitrate transport. Large annual variations were found (Table 2), ranging from

317 kmol/s in June 1991, to 382 kmol/s in Oct. 1990, to 474 kmol/s in May 1992 to a high of 725 kmol/s in May 1985.

Similar to what happened for phosphate and nitrate, the northward silicate flux occurred mostly between 121 and 123°E (Table 3). In May 1985 and June 1991 when the Kuroshio was strong, this segment contributed, respectively, 730 and 365 kmol/s northward. The segment between 123 and 130°E contributed 5 and 48 kmol/s, respectively, southward. Even when the Kuroshio was less concentrated in Oct. 1990 and May 1992, the segment between 121 and 123°E transported 81 and 38%, respectively, of silicate northward.

Alkalinity

The alkalinity ranged from about 2000 μmol/kg near surface to above 2400 μmol/kg near 2000 m (OR 316, Fig. 3e). The calculated alkalinity flux (Fig. 4e) had band structures similar to the geostrophic velocity because the spatial distribution of alkalinity was relatively homogeneous (Fig. 2d). The down-stream maximum flux of alkalinity at this latitude in May 1992 was 1203 mmol/m^2/s near St. 26. The southward maximum flux was 100 mmol/m^2/s at St. 20. The alkalinity (Table 2) transported by the Kuroshio was 103.4 $\times$ 10^6 mol/s northward. The southward transport was 13.6 $\times$ 10^6 mol/s, thus the net alkalinity transport was 89.8 $\times$ 10^6 mol/s, northward between 121 and 130°E.

There were large annual variations (Table 2) ranging from a low of 45.3 $\times$ 10^6 mol/s in Oct. 1990, to 62.2 $\times$ 10^6 mol/s in May 1985, to 82.0 $\times$ 10^6 mol/s in June 1991, to a high of 89.9 $\times$ 10^6 mol/s in May 1992. These values are comparable with the Florida current transport of 71.7 $\times$ 10^6 mol/s in Nov. 1988 (BREWER *et al.*, 1989).

In May 1985 the section transported 84.5 $\times$ 10^6 mol/s of alkalinity northward between 121 and 123°E. By way of comparison, the segment between 123 and 130°E transported 22.3 $\times$ 10^6 mol/s of alkalinity southward. In other years the segment between 121 and 123°E transported northward most of alkalinity, 92% in Oct. 1990, 80% in June 1991 and 35% in May 1992, respectively.

Total CO_2

The distribution of total CO_2 was similar to that of alkalinity, with concentrations ranging from 1.9 mmol/kg near surface to 2.4 mmol/kg near 2000 m (OR 316, Fig 3f).

Total CO_2 flux (Fig. 4f), similar to that of alkalinity, also showed the band structure. In May 1992 the northward maximum flux of about 1039 mmol/m^2/s was located near St. 26, and southward maximum of 100 mmol/m^2/s was located at St. 20. The transports were 90.6 $\times$ 10^6 mol/s northward and 13 $\times$ 10^6 mol/s southward. These values yielded a net northward flow of 77.5 $\times$ 10^6 mol/s between 121 and 130°E. Large annual variations were also found (Table 2) with a pattern similar to that of TA. The lowest value was 41.8 $\times$ 10^6 mol/s in Oct. 1990. BREWER *et al* (1989) reported a transport of 63.9 $\times$ 10^6 mol/s by the Florida current in Nov. 1988.

In May 1985 the transport was 63.6 $\times$ 10^6 mol/s, in June 1991 it was 71.4 $\times$ 10^6 mol/s, and in May 1992 it was 77.5 $\times$ 10^6 mol/s, all northward. Also similar to the pattern for TA, the TCO_2 transport was 79.2 $\times$ 10^6 mol/s northward between 121 and 123°E but was 15.6 $\times$ 10^6 mol/s southward between 123 and 130°E. In other years the 121–123°E segment transported 89%, 82% and 38%, respectively, of the northward TCO_2 flow.

4. Conclusion

1. The Kuroshio could clearly be identified in May 1985 and June 1991 when the northward volume transports above 1000 m were 38 and 53 Sv, respectively, between 121 and 123°E along 21°45′N. Whereas between 123 and 130°E the transports were southward, 18 Sv in May 1985 and 3 Sv in June 1991. In Oct. 1990 the Kuroshio was weak yet the total northward flux of 19 Sv between 121 and 130°E was still mostly concentrated between 121 and 123°E (15 Sv). After the El Nino, the northward volume transport was large (39 Sv) in May 1992 but widely spreaded between 121 and 130°E. The Kuroshio transport between 121 and 123°E was relatively low at 12 Sv.
2. The fluxes of phosphate, nitrate and silicate by the Kuroshio at 21°45′N showed along-

stream cores between 400 and 600 m, below the high-velocity core (between the surface and 200 m) of the Kuroshio current.

3. The distributions of fluxes for dissolved oxygen, alkalinity and total CO_2 were simialr to the velocity structure, indicating that they were dominated by the velocity field.
4. The net northward transports for dissolved oxygen, phosphate, nitrate, silicate, alkalinity and total CO_2 were 4.0–8.6 $\times$ 10^6 mol/s, 11–21 kmol/s, 164–299 kmol/s, 317–725 kmol/s, 45.3–89.8 $\times$ 10^6 mol/s and 41.8–77.5 $\times$ 10^6 mol/s, respectively. These were mostly concentrated between 121 and 123° E except after the 1992 El Nino. The fluxes were frequently southward between 123 and 130° E.

Acknowledgements

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黒潮における酸素，栄養塩および炭酸塩のフラックス

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要旨：酸素，栄養塩類および炭酸塩の真の輸送量を求めるために，台湾東南沖の黒潮を横断する観測線（WOCE PR20）において，地衡流と合わせ溶存酸素（DO），リン酸（PO_4），硝酸（NO_3），珪酸（SiO_2），全アルカリ度（TA），および全炭酸（TCO_2）を測定した。調査船オーシャンリサーチャーによる４航海（CHIPS-1，1985年５月；OR 257，1990年10月；OR 287，1991年６月；OR 316，1992年５月）の間に 21°45′N，121°–130°E 間における 1000m 以浅の北向きの真の体積輸送は，それぞれ 20，19，50 および 39Sv であった。121°–123°E 間の北向きの輸送が 38 および 53Sv であった1985年５月と1991年６月には明らかに黒潮が識別された。123°E と 130°E の間には 18 および 3Sv の輸送量を持つ明らかな南向きの分流が認められた。1990年５月および1992年５月には，北向きの輸送は拡散的であった。黒潮の高速流心部以深では，栄養塩類のフラックスは“栄養塩類の河”の様態を示した。酸素および炭酸塩のフラックス分布は，速度場と同様の構造であった。４回の航海時における 121°–130°E 間の流れに沿った DO，PO_4，NO_3，SIO_2，TA および TCO_2 の真の輸送量は以下の通りであった。1985年５月は，3971(DO)，12(PO_4)，194(NO_3)，725(SIO_2)，62156(TA) および 63571(TCO_2) kmol/s；1990年10月は 8585(DO)，12(PO_4)，196(NO_3)，382(SIO_2)，45285(TA) および 41822(TCO_2)kmol/s；1991年６月は 8487(DO)，11(PO_4)，164(NO_3)，317(SIO_2)，822002(TA) および 71399(TCO_2)kmol/s；1992年５月は 6549(DO)，21(PO_4)，299(NO_3)，474(SIO_2)，89818(TA) および 77531(TCO_2)kmol/s。北向きのフラックスは 121°E および 123°E 間で濃縮され，一方南向きのフラックスはより拡散的であった。