Variability of the Chemical Hydrography at the Frontal Region between the East China Sea and the Kuroshio North-east of Taiwan

George T. F. Wong[a]**, Su-Cheng Pai**[b]**, Kon-Kee Liu**[b,c]
Cho-Teng Liu[b] **and Chen-Tung A. Chen**[d]

[a]*Department of Oceanography, Old Dominion University, Norfolk,
VA 23529-0276, U.S.A.,* [b]*Institute of Oceanography, National Taiwan
University, P.O. Box 23–13, Taipei, Taiwan, R.O.C.,* [c]*Institute of Earth
Science, Academia Sinica, P.O. Box 23–59, Taipei, Taiwan, R.O.C. and*
[d]*Institute of Marine Geology, National Sun Yat-Sen University, Kaohsiung,
Taiwan, R.O.C.*

The hydrography across the frontal region between the East China Sea and the
Okinawa Trough north-east of Taiwan, observed during the summer of 1985 and
1988 and the early spring of 1987, was governed mainly by mixing across the
front and the topographically induced upwelling of the modified Kuroshio water
in the Okinawa Trough during the periodic shelfward migration of the
Kuroshio. The location of the front relative to the shelf break seemed to be
temporally variable. Topographically induced upwelling was evident during the
summer of 1988 and the early spring of 1987 when the front was located close to
the shelf break. It might not have occurred in the summer of 1985 when the front
was further offshore. The end-member composition of the upwelling water was
similar in both seasons. It originated from about 300 m with a temperature and
salinity of 13 °C and 34·4 psu. It was rich in nutrients and poor in oxygen with
concentrations of nitrate, phosphate, silicate and oxygen of 16, 1, 18 and 160 µM
respectively. This upwelling water is potentially a major source of nutrients to
the East China Sea. The deep water in the Okinawa Trough at temperatures
below 15 °C did not participate in cross-shelf mixing. Its chemical characteristics
did not change significantly from year to year.

Introduction

As the Kuroshio travels from the Equatorial to the North Pacific, it passes through a
passage over a ridge between Taiwan and the Yonakunijima and enters the Okinawa
Trough. Because of topographic restrictions, this northward-flowing current in the
Okinawa Trough has to turn eastward, skirt along the seaward edge of the East China Sea
and may interact with this shallow shelf sea before it re-enters the Pacific Ocean south of

Japan through the Tokara Strait (Figure 1). Extensive studies on the interactions between the Gulf Stream and the South Atlantic Bight (Atkinson, 1985; Atkinson & Menzel, 1985; Wong, 1988) have demonstrated that material exchange across the frontal region between a western boundary current and the adjacent shelf waters may act as a major control of the biogeochemical processes in the shelf. Conceivably, the Kuroshio may have similar effects on the chemistry in the East China Sea.

The physical characteristics of the frontal zone between the Kuroshio and the East China Sea north-east of Taiwan has been studied for some time (Yin, 1973; Chu, 1976; Fan, 1980; Liu, 1983; Liu & Pai, 1987; Liu *et al.*, 1989) although data with the appropriate spatial and temporal spacing for studying the exchange processes in the region are still unavailable. Systematic data on the corresponding chemical signatures in the region are sparse (Liu & Pai, 1987; Liu *et al.*, 1989; Wong *et al.*, 1989). In this paper, we report on a comparison of the chemical hydrography in this region in the spring of 1987 and the summer of 1985 and 1988.

Sampling and analytical methods

Study area

The Okinawa Trough is bounded to the north and to the west by the East China Sea which occupies the Tunghai Shelf that extends from the Asian continental mainland to the shelf break at a water depth of about 200 m (Mogi, 1972). To the south and the east, the Okinawa Trough is bounded by the Okinawa Island chain. Our study area straddles the southern part of the East China Sea and the Okinawa Trough north and north-east of Taiwan where the water depth increases abruptly from 100 to 200 m at the shelf break and then even more precipitously to over 2 km at the centre of the Okinawa Trough (Figure 1). The Changjiang, or Yangtze River, empties into the East China Sea and is the major source of freshwater to the study area (Beardsley *et al.*, 1985).

Surveys

Stations were occupied across the frontal region between the East China Sea and the Kuroshio in the Okinawa Trough north-east of Taiwan during three cruises by R/V *Ocean Researcher I*: summer 1985 on 12 to 15 September during cruise CHIPS-2 (Cooperative Hydrographic Investigation of the Philippine Sea); spring 1987 on 29 to 31 March during cruise CHIPS-4; and summer 1988 on 19 to 21 September during cruise KECS-2 (Kuroshio–East China Sea Study). The cruise tracks and the locations of the stations are shown in Figure 1.

Methods

At each station, profiles of temperature and salinity were measured with a Sea-Bird CTD. Discrete samples were collected with Niskin bottles mounted on a rosette sampler for the determination of salinity, dissolved oxygen and phosphate during all three cruises. Nitrate was determined during summer 1985 and summer 1988 while silicate was determined only during summer 1988. Oxygen was measured by the Winkler titrimetric method (Carpenter, 1965). Phosphate was determined by the molybdenum blue method (Murphy & Riley, 1962). Silicate was measured by the silicomolybdenum blue method (Fanning & Pilson, 1973). Nitrate was determined by the azo dye method (Strickland & Parsons, 1972).
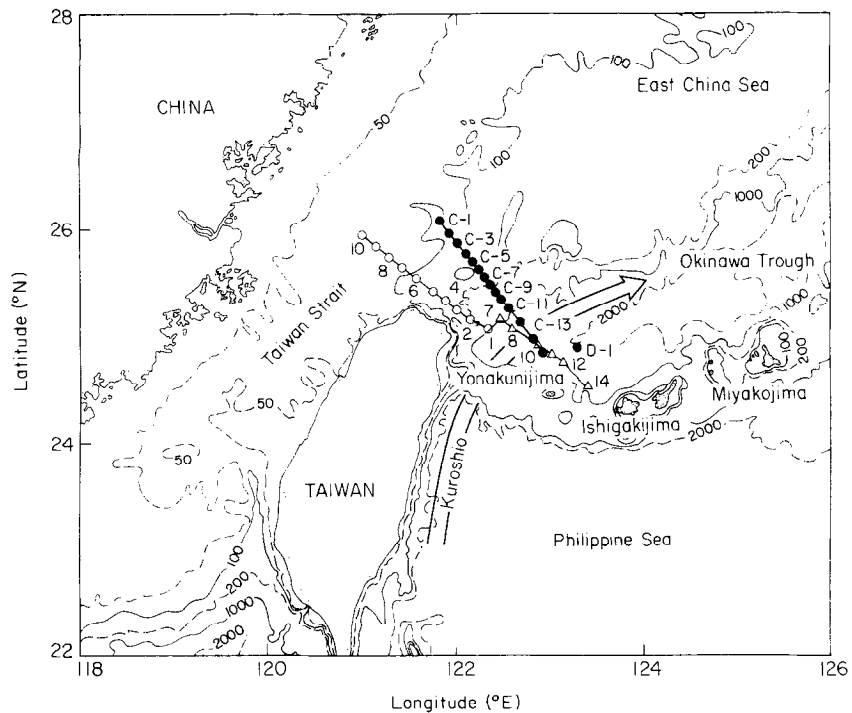
Figure 1. Station locations. △, Summer 1985 (CHIPS-2); ○, spring 1987 (CHIPS-4); ●, summer 1988 (KECS-2).

Results and discussion

Temperature–salinity (T–S) relationships

The T–S relationships in summer 1988 at selected stations are shown in Figure 2(a). The broad salinity maximum between 34·8 and 34·85 psu, 19·5 to 24·5 °C at 75 to 200 m at station C-14 and D-1 represented the core of the Kuroshio (Nitani, 1972; Guan, 1983). At shallower depths, the Kuroshio water mixed with the warmer and fresher surface water. The T–S curves converged to a common point at about 15 °C and 34·5 psu with a sigma-t of 28·5 at about 250 to 350 m. Above 15 °C, the T–S curves fanned out systematically from the station farthest offshelf (station D-1) to the station closest inshelf (station C-1). Along each isopycnal, salinity and depth increased from station C-1 to station D-1. However, reversals from this trend were observed occasionally in the intervening stations suggesting that, aside from cross-shelf mixing between shelf water and Kuroshio water along isopycnal surfaces, upwelling might have occurred resulting in complex mixing processes involving multiple end-members.

Below about 15 °C, temperature was linearly related to salinity down to a broad salinity minimum between 34·3 and 34·35 psu, at 7·5 °C and at 450 to 550 m. This salinity minimum represented the North Pacific Intermediate Water which has been traced from the east of Luzon through the Okinawa Trough to the south-east of Japan (Nitani, 1972; Masuzawa, 1972). The T–S relationships were identical at all stations below 15 °C, indicating that these deeper waters did not participate in the cross-shelf mixing between the East China Sea and the Kuroshio. Its composition was only affected by vertical mixing between Kuroshio water and the North Pacific Intermediate Water. The bottom water in
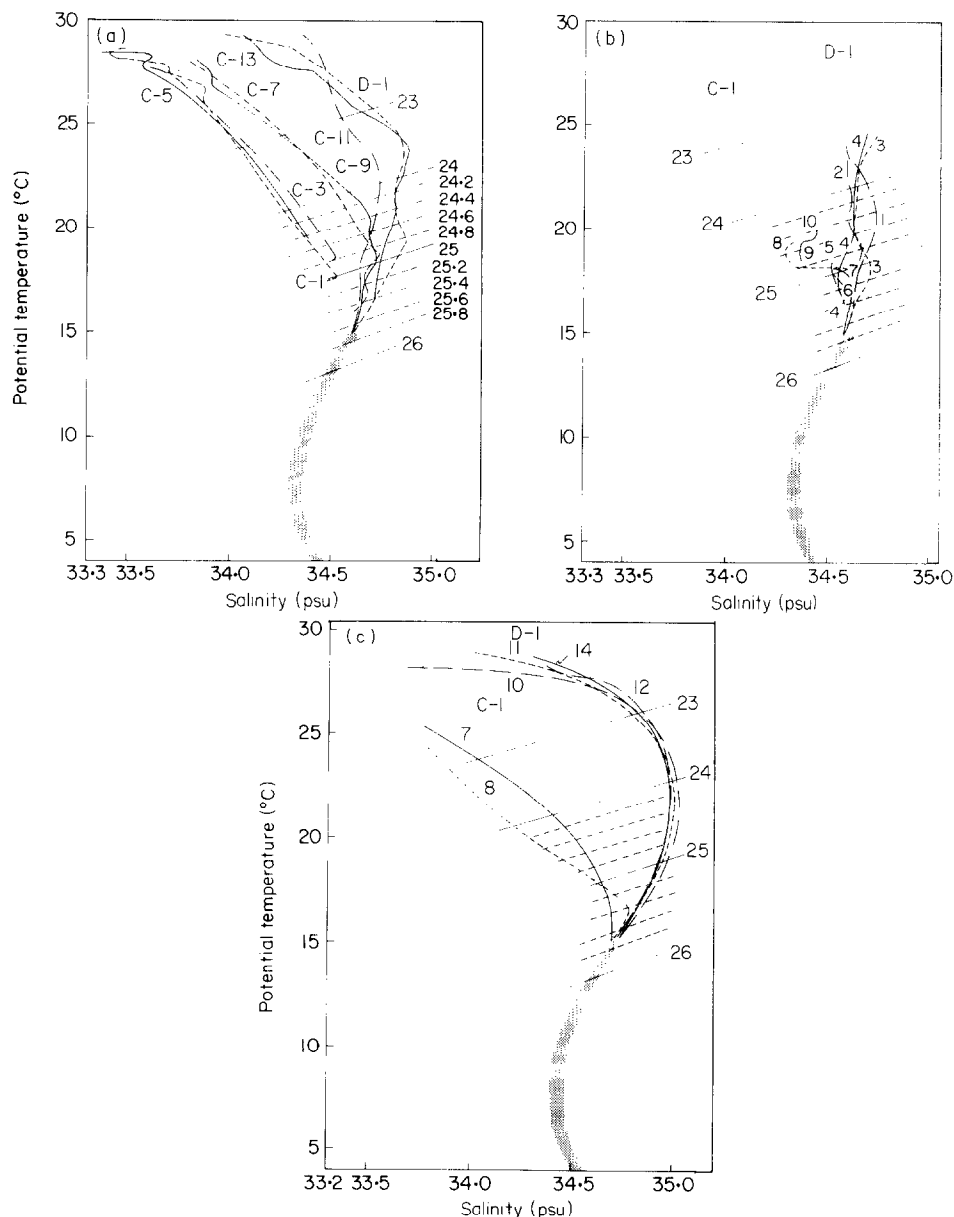
Figure 2. The temperature–salinity relationships (T–S) at selected stations during (a) summer 1988, (b) spring 1987 and (c) summer 1985. Stippled area indicates the T–S field below 15 °C for all three cruises. Dotted lines in (b) and (c) denote the T–S relationship at stations D-1 and C-1 observed during summer 1988.

the Okinawa Trough was represented as a salinity maximum in the T–S curves with temperatures below 5 °C and salinities above 34·39 psu.

During spring 1987, above 15 °C, the T–S relationships fell into three groups [Figure 2(b)]: at stations 8 to 10, 5 to 7 and 1 to 4. The T–S field of the first, the most inshelf, group of stations was limited to a temperature range of 17 to 20 °C and a salinity range of 34·25 to 34·6 psu. The coldest surface water was found further offshelf, in the second group of
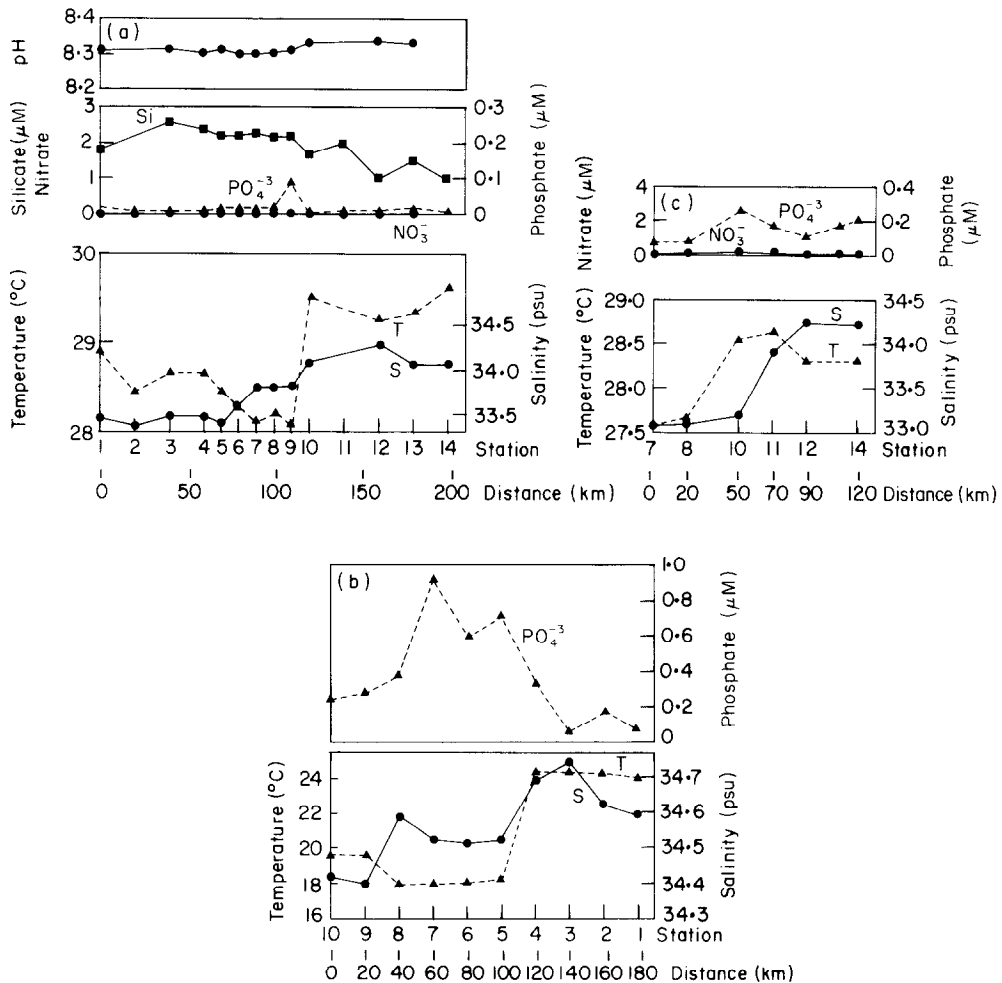
Figure 3. The distribution of temperature (T), salinity (S), phosphate (PO$_4^3$), nitrate (NO$_3$), silicate (Si) and/or pH in the surface waters along the transect during (a) summer 1988, (b) spring 1987 and (c) summer 1985.

stations where the temperature and salinity ranges were 16 to 18·6 °C and 34·5 to 34·6 psu [Figure 3(b)]. In the third group of stations, the surface temperature reached 24·5 °C. The T–S curves tended to converge together as the temperature decreased. The water depth was great enough only at station 1 to include waters colder than 15 °C.

In comparison to the data obtained during summer 1988, the temperature field observed during spring 1987 was, as expected, greatly compressed. In the Okinawa Trough, the East China Sea and around the shelf break, the surface water was about 5, 9 and 10 °C colder respectively [Figure 3(a) and (b)]. The shelf water was also more saline. For example, although station 10, occupied during spring 1987, was further inshelf than station C-1, which was occupied during summer 1988, its surface salinity was about 0·9 psu higher [Figure 3(a) and (b)]. This difference in the surface salinity is probably the result of the temporal variation in the discharge of the Changjiang where the peak discharge occurs from late June to August, while the minimum discharge is found in January to March (Beardsley *et al.*, 1985). In the deep waters at temperatures below 15 °C, the
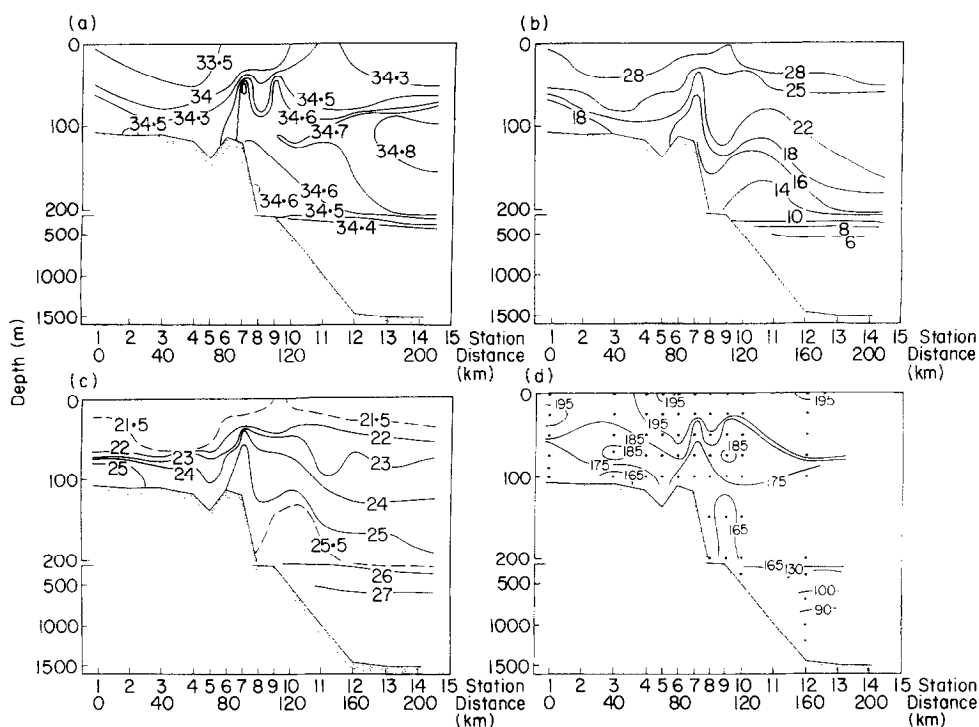
Figure 4. The distribution of (a) salinity (psu) (b) temperature (°C), (c) sigma-*t* and (d) oxygen (μM) along the transect during summer 1988. ●, Locations of discrete samples.

T–S relationship was similar to that observed during summer 1988 suggesting that the composition of the deep water was not affected by seasonal events.

During summer 1985, the T–S relationships below 15 °C were also similar from station to station and to those observed during summer 1988. Above 15 °C, the T–S relationships fell into two groups: stations 7 and 8, and 10 to 12 and 14. In the first group of stations, the T–S relationship resembled those at the most inshelf stations occupied during summer 1988 even though those stations were about 130 km further inshelf. In the second group of stations, the T–S relationship was similar to those in the Okinawa Trough in summer 1988. The T–S relationship changed abruptly between stations 8 and 10 which were only 30 km apart. A transition zone between the shelf water and the Kuroshio water in the Okinawa Trough as indicated by the intermediate T–S relationships observed during summer 1988 was conspicuously absent. Apparently, during summer 1985, the Kuroshio had moved offshelf enough so that the shelf water extended beyond the shelf break into the Okinawa Trough.

Sections of temperature, salinity and sigma-t

The addition of freshwater to the East China Sea, primarily via the Changjiang, resulted in fresher water on the shelf and more saline water further offshelf. Thus, as a first approximation, the distribution of salinity along the transects resembled that of an estuary (Figures 4–6): a prism of fresher surface water extending offshelf was underlain by the shelfward intrusion of deeper and more saline offshelf waters from the Okinawa Trough, resulting in a salinity front that can be detected as a surface expression (Figures 1 and 3).
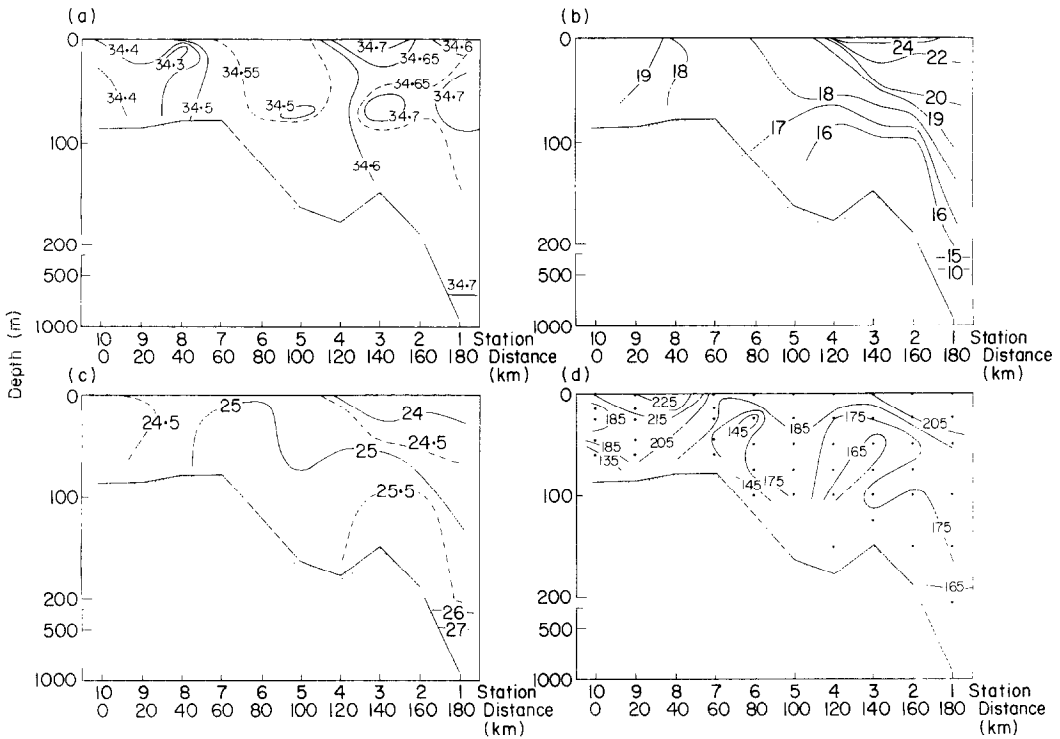
Figure 5. The distribution of (a) salinity (psu) (b) temperature (C), (c) sigma-*t* and (d) oxygen (μM) along the transect during spring 1987.

Superimposed on this pattern was the influence of the Kuroshio which was represented as a subsurface layer of saline water with a maximum salinity exceeding 34·7 psu and a sigma-*t* of about 24·5. The interaction between the shelf water and the Kuroshio water varied from one cruise to another. During summer 1988 and spring 1987, topographically induced upwelling at the shelf break was evident as indicated by the shelfward- and upward-tilting isohalines, isotherms and isopycnals which extended over the shelf break (Figures 4 and 5). For example, the 34·6-psu isohaline which originated from below the salinity maximum, the 18 C isotherm and the isopycnal at a sigma-*t* of 25 climbed by 50 to over 100 m from the Okinawa Trough to the East China Sea and reached the shelf proper. In contrast, during summer 1985, the Kuroshio, as depicted by the isohaline at 34·7 psu, did not reach the shelf and gave rise to a sharp temperature, salinity and density front between stations 8 and 11 at about 70 km from the shelf break (Figure 6). No water with a salinity exceeding 34·7 psu was found further inshelf. Evidently, the core of the Kuroshio was situated further offshelf from the shelf break during summer 1985, and, as a result, topographically induced upwelling of Kuroshio water onto the shelf was less intense, if it occurred at all. Thus, while topographically induced upwelling at the shelf break clearly occurred in both summer 1988 and spring 1987, the situation was much less certain in summer 1985. Since the axis of the Kuroshio in this general area has been observed to fluctuate from its mean position by about 40 km seasonally and inter-annually during the same season (Nitani, 1972), the location of the Kuroshio relative to the shelf break in the study area conceivably may also vary even within a season. Thus, it is unclear whether the observed differences between the two summers reflect inter-annual or intra-seasonal variations.
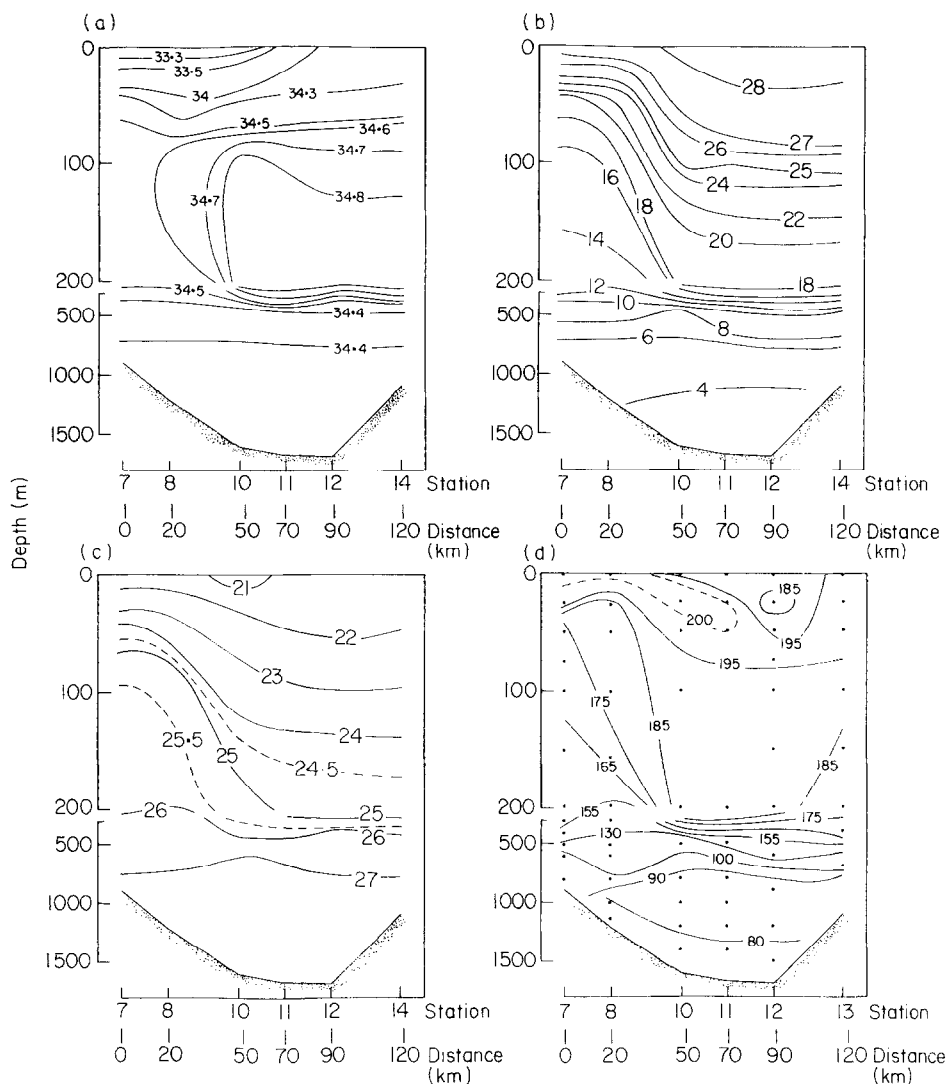
Figure 6. The distribution of (a) salinity, (psu) (b) temperature (C), (c) sigma-*t* and (d) oxygen (μM) along the transect during summer 1985.

The influence of topographically induced upwelling could also be detected as a pool of anomalously cold surface water located at the vicinity of the shelf break [Figure 3(a) and (b)]. Salinity was a less distinct indicator since the salinity of upwelling water was in between those of the waters further inshelf and offshelf (Figures 4 and 5). Although the sigma-*t* at the core of the Kuroshio was about 24·5, isopycnals at higher sigma-*t* and greater depths tilted even more markedly towards shallower depths shelfward. This suggests that the upwelling water was not made up of pure Kuroshio water alone. The influence of the upwelling water on the composition of the shelf water seemed to be more extensive during spring 1987. Although the isohaline at 34·6 psu could be traced across the Okinawa Trough over the shelf break in both spring 1987 and summer 1988, during summer 1988, the Kuroshio was centred around 110 m and the shelfward edge of the
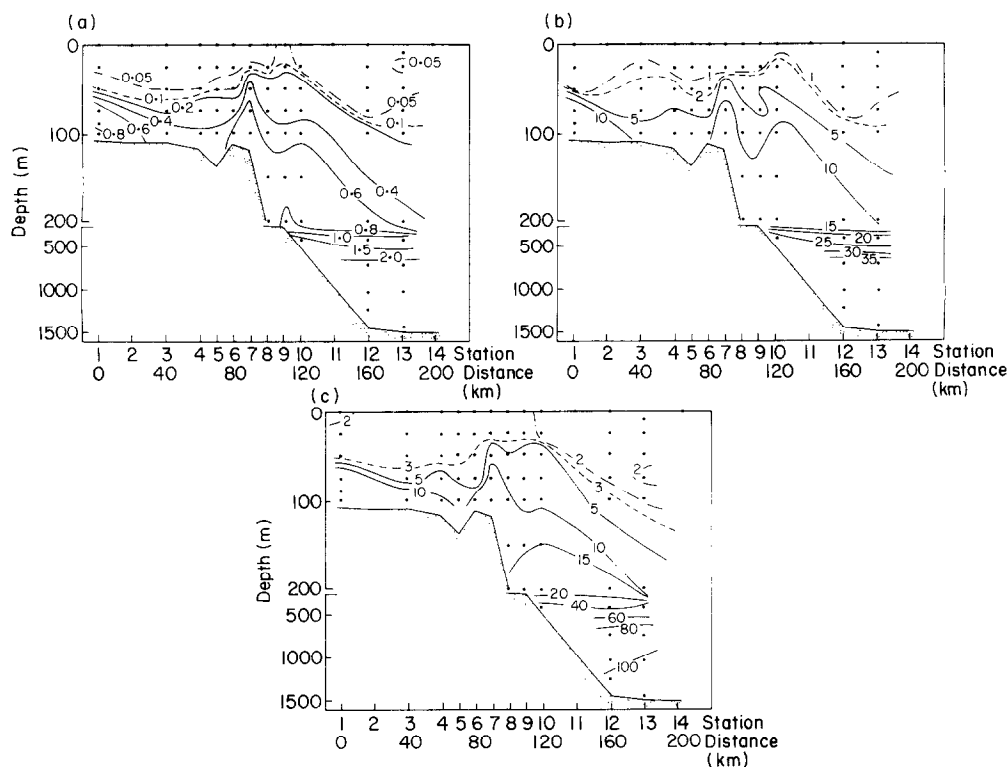
Figure 7. The distribution of (a) phosphate, (b) nitrate and (c) silicate along the transect during summer 1988. All concentrations are µM.

Kuroshio ended as an abrupt subsurface salinity front at the shelf break. During spring 1987, the core of the Kuroshio was located at a shallower depth at about 50 m and the 34·5-psu isohaline reached the sea surface.

Some finer-scale hydrographic features were also observed during summer 1988. A prism of bottom water with high salinity, low temperature and a sigma-*t* exceeding 24·8 was found at the most shelfward stations, C-1 and C-2 (Figure 4). This type of water was found at stations C-6 to C-14 but was absent in the intervening stations C-3 to C-5, suggesting that another branch of upwelling modified Kuroshio water might have found its way to the most shelfward station in the East China Sea possibly, as an eddy, a filament or as a separate branch of upwelling water. At the shelfward edge of the upwelling water, the isohalines, isotherms and isopycnals formed two bulges between stations C-6 to C-12 at 50 to 150 m (Figure 4). Similar structures were also evident during spring 1987 (Figure 5). However, in this case, these structures extended onto the shelf. These bulges, which had dimensions of a few tens of kilometres, may represent eddies or filaments at the shelfward edge of the Kuroshio front or the episodic consecutive inshelf and offshelf meandering of the Kuroshio.

Oxygen, phosphate, nitrate and silicate

During summer 1988, the topographically induced upwelling at the shelf break, the bulges of this subsurface upwelling water at the vicinity of the shelf break and the occurrence of another parcel of offshelf water at the bottom of stations C-1 to C-3 were also evident from the distribution of oxygen, phosphate, nitrate, and silicate (Figures 4 and 7).

In the surface waters, the concentrations of phosphate and nitrate were around the detection limit in the entire transect. The concentration of silicate was also low. However, there was an indication that the concentration of silicate in the East China Sea was higher than that in the Okinawa Trough [Figure 3(a)]. This may be a reflection of the influence of the input of river water, water from Changjiang in this case (Edmond et al., 1985), which is well known for its elevated concentrations of silicate relative to surface seawater (Moore et al., 1986), on the chemical composition of the shelf water. The core of the Kuroshio at 110 m at station C-14 was relatively poor in phosphate, nitrate and silicate with concentrations of 0·13, 2·1 and 1·9 µM respectively. The topographically induced upwelling water was characterized by a low concentration of oxygen, between 160 to 175 µM, and high concentrations of phosphate, nitrate and silicate, between 0·4 and 1, 5 and 16, and 5 and 20 µM respectively. Thus, while the lateral exchange of Kuroshio water with shelf water would have minimal effect on the nutrient budget, the upwelling water can be an important source of nutrient to the East China Sea. The bottom water at station C-1 was also low in oxygen and high in nutrients.

In the Okinawa Trough, the concentrations of nitrate, phosphate and silicate increased monotonically with depth while that of oxygen decreased in the same fashion. A nutrient maximum or an oxygen minimum zone was not found even at 1400 m at station C-14 although such features were found routinely at about 800 to 1000 m in the western Philippine Sea south of the Okinawa Island chain (Yamamoto & Horikoshi, 1979; Liu et al., 1987a; Pai et al., 1987). This difference in the distributions of oxygen and nutrients suggests that the communication between the oxygen-rich deep water in the western Philippine Sea and the oxygen-poor deep water in the Okinawa Trough may have been severely restricted by the Okinawa Island chain (Liu et al., 1987b). As a result, the in situ remineralization of organic matter, the concomitant utilization of oxygen within the water column, the diffusive supply of nutrients from the sediments and the removal of oxygen to the sediments in the Okinawa Trough may be large enough to play a prominent role in regulating the composition of the deep and bottom waters in the basin.

During spring 1987, the concentrations of phosphate and oxygen in the surface waters on the shelf at stations 9 and 10 were about 0·3 and 225 µM (Figures 5 and 8). The corresponding concentrations in the Okinawa Trough at stations 1 to 3 were about 0·1 and 210 µM. Thus, the composition of these surface waters in terms of phosphate and oxygen were quite similar although their temperature and salinity were obviously different from each other. Between stations 3 and 8, there was a plume of nutrient-rich and oxygen-poor (up to 24‰ undersaturated in oxygen at the sea surface), water around the shelf break where the isopleths of the nutrients and oxygen tilted shelfward towards shallower depths. It may represent the transport of water onto the shelf by topographically induced upwelling. The concentrations of phosphate and oxygen in this plume of upwelling water were 0·4 to >0·8 and 150 to 200 µM. Unlike the distributions of nutrients and oxygen observed during summer 1988, the upwelling water was not confined to below the sea surface. Some of the tilted isopleths reached the sea surface (Figure 8). This difference may result from a stronger upwelling event, a weaker stratification in the water column to impede upwelling and/or a reduced level of biological activity to strip off the nutrients from the upwelling water promptly during this time of the year. Thus, distinct nutrient fronts between the upwelling water and the shelf water and between the upwelling water and the water in the Okinawa Trough were observed at the sea surface [Figure 3(b)] and the concentration of phosphate in the surface waters was substantially higher than those observed during summer 1988.
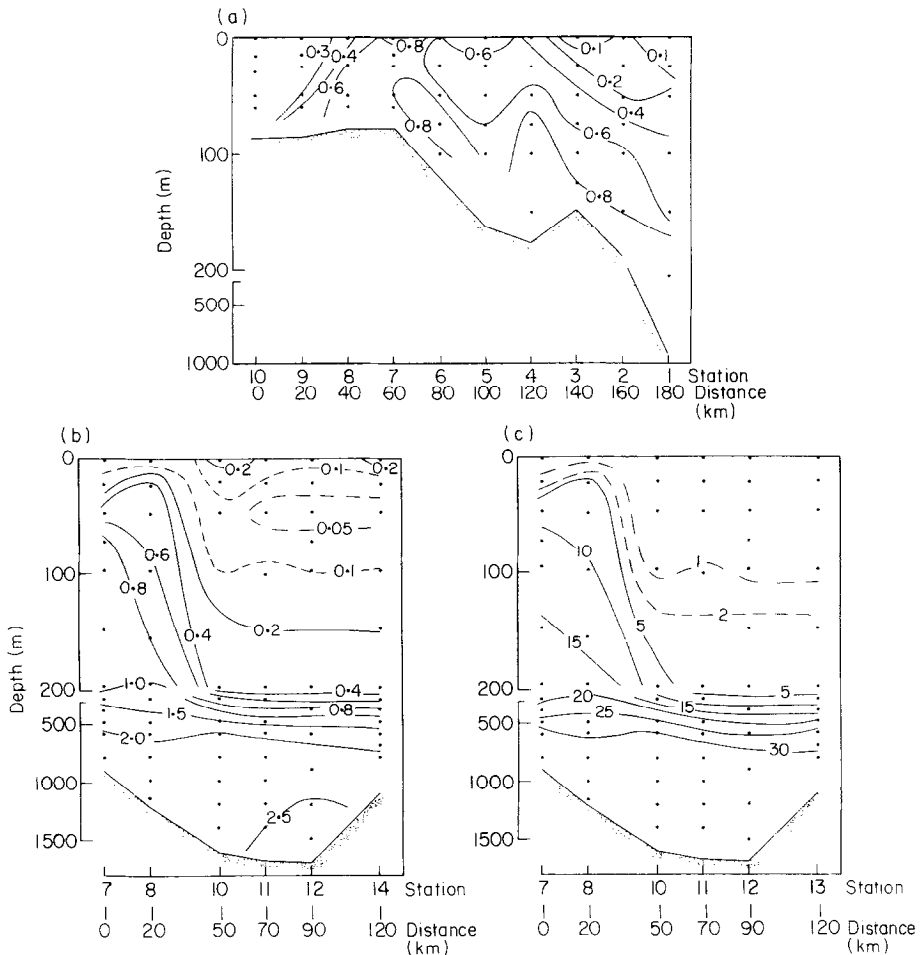
Figure 8. The distribution of (a) phosphate along the transect during spring 1987 and (b) phosphate and (c) nitrate during summer 1985. All concentrations are μM.

During summer 1985, there was no distinct nutrient front at the sea surface [Figure 3(c)]. Both the concentration of nitrate and phosphate hovered around the detection limit in the entire transect. There was only a weak indication of a slightly lower concentration of phosphate at stations 7 and 8. However, in the subsurface water, there were strong fronts in phosphate, nitrate and oxygen in the top 200 m between stations 8 and 10 where their concentrations might change by more than an order of magnitude (Figures 6 and 8). Between 30 and 200 m, the concentrations of phosphate, nitrate and oxygen in the inshelf waters were 0·4 to 1, 7 to 17 and 146 to 182 μM respectively. The corresponding concentrations in the offshelf waters were 0·03 to 0·3, <0·1 to 5 and 180 to 200 μM. These distributions are consistent with the notion that the inshelf waters are richer in nutrients relative to the offshelf waters. However, in the surface waters, during the summer, the biological activity is high enough and the stratification of the water column is strong enough that nutrients can be effectively removed to similar levels in both inshelf and offshelf waters. The concentrations of phosphate, nitrate and oxygen at the centre of the Kuroshio were 0·2, 3 and 185 μM respectively. These concentrations were similar to those
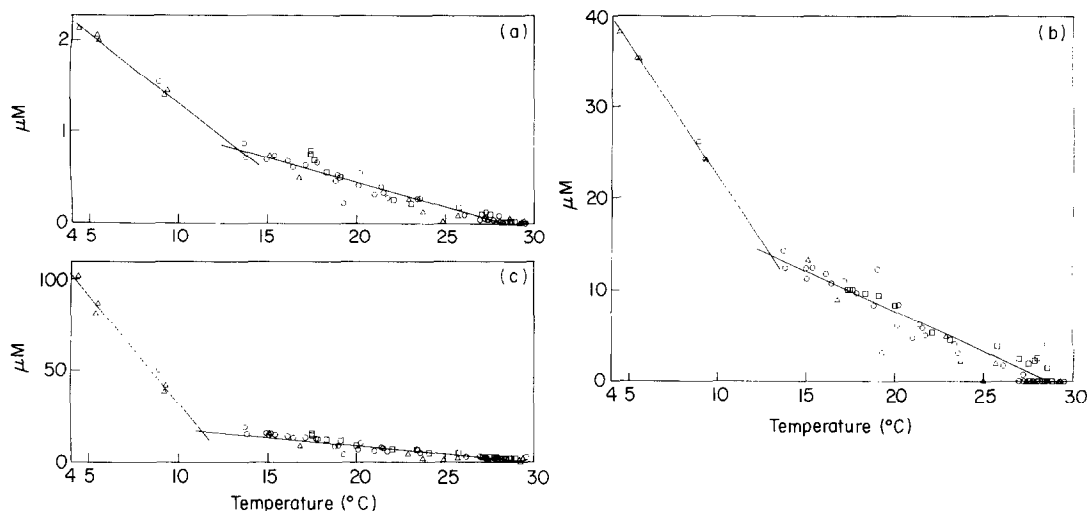
Figure 9. The relationship between (a) phosphate, (b) nitrate, (c) silicate and temperature during summer 1988. □, Stations C-1 to C-5; ○, stations C-6 to C-10; △, stations C-11 to C-14.

observed during summer 1988 and spring 1987 indicating that the composition of the Kuroshio did not vary substantially from season to season or from year to year.

Relationships among the chemical hydrographic parameters

During summer 1988, although there were relatively few data points at temperatures below 15 °C, the relationship between the concentration of nitrate and temperature seems to fall on two linear lines (Figure 9). The point of intersection of these lines was around 12 to 14 °C, the corresponding depths of which were about 200 to 300 m. Above 13 °C, the relationships were

$$[NO_3] = 24\cdot9\,(\pm\;0\cdot8) - 0\cdot87\,(\pm\;0\cdot03)\;T \qquad \text{and}\;r = -\;0\cdot96$$
$$[PO_4] = 1\cdot51\,(\pm\;0\cdot04) - 0\cdot053\,(\pm\;0\cdot002)T \qquad \text{and}\;r = -\;0\cdot96$$
$$[Si] = 28\cdot5\,(\pm\;1\cdot0) - 0\cdot95\,(\pm\;0\cdot04)T \qquad \text{and}\;r = -\;0\cdot95.$$

where $[NO_3]$, $[PO_4]$ and $[Si]$ are the concentrations of nitrate, phosphate and silicate in μM, T is temperature in °C and r is the correlation coefficient. Wong *et al.* (1989) have examined these data in greater detail by subdividing the stations into three groups according to their proximity to the shelf break: stations 1 to 5 (waters on the shelf), stations 6 to 10 (transition zone) and stations 11 to 14 (Kuroshio waters in the Okinawa Trough). The relationships seemed to change systematically from the shelf to the Okinawa Trough. However, the changes were small, in the order of at most 15%, in both the slope and the intercept. These linear relationships suggest that one of the dominating processes governing the composition of the water in the top 200 to 300 m is the mixing of cold, nutrient-rich deeper water with the warm, nutrient-poor surface waters. If these linear relationships can be verified, temperature may be a convenient indicator for estimating exchanges of nutrients between these waters as in the South Atlantic Bight (Dunstan & Atkinson, 1976; Lee *et al.*, 1981; Atkinson *et al.*, 1982, 1983; Lee & Atkinson, 1983). Below 13 °C,

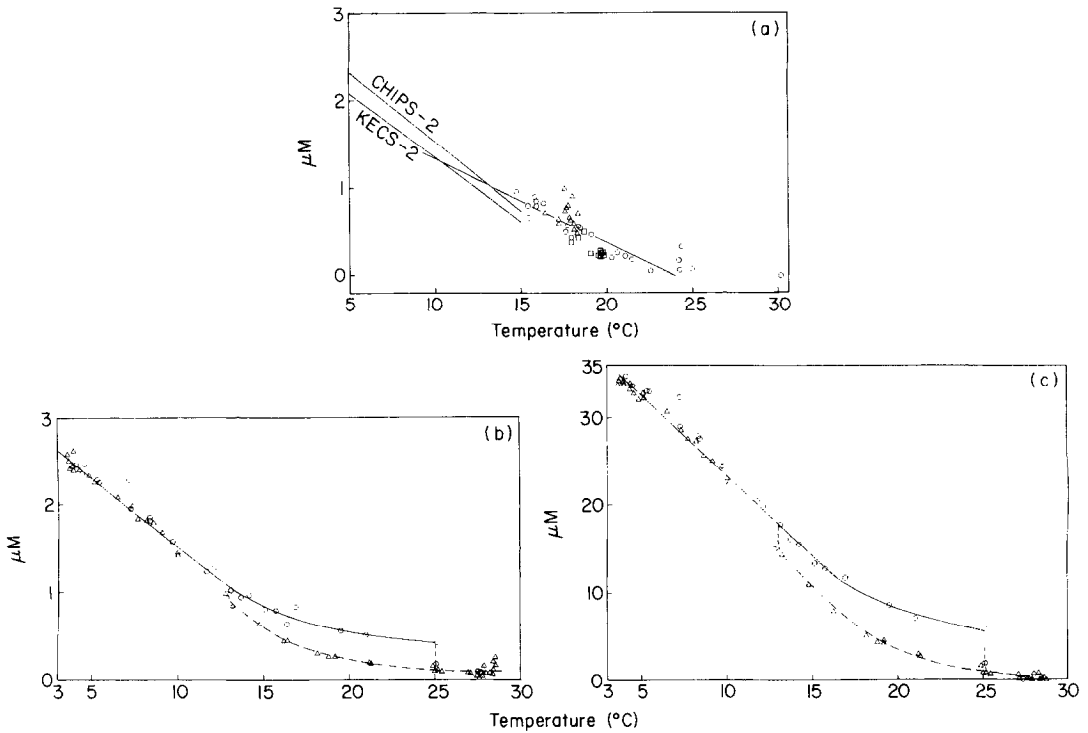$$[NO_3] = 51\cdot2\,(\pm\;0\cdot7) - 2\cdot88\,(\pm\;0\cdot09)T \qquad \text{and}\;r = -\;1\cdot00$$

Figure 10. The relationship between (a) phosphate and temperature during spring 1987 (○, stations 1 to 4; △, stations 5 to 7; □, stations 8 to 10), and (b) phosphate, (c) nitrate and temperature during summer 1985 (○, stations 7 to 8; △, stations 10 to 14).

$$[PO_4] = 2\cdot81 \,(\pm\,0\cdot06) - 0\cdot146 \,(\pm\,0\cdot008)\,T \qquad \text{and } r = -0\cdot99$$
$$[Si] = 148 \,(\pm\,6) - 11\cdot5 \,(\pm\,0\cdot8)\,T \qquad \text{and } r = -0\cdot95.$$

If the point of intersection at 13 °C represents the end-member of the upwelling deep water, it will have a salinity of 34·4 psu and contain about 16 μM of nitrate, 1 μM of phosphate, 18 μM of silicate and 160 μM of oxygen. Some diluted form of this water makes its way onto the shelf where its nitrate and phosphate are stripped to undetectable levels and silicate is reduced to about 2 μM, and it may constitute a significant source of nutrients to the East China Sea.

The relationships between nitrate, phosphate and temperature during summer 1985 are shown in Figure 10. Between 13 and 25 °C, the data points fell into two distinct groups: those from stations 7 and 8 at the inshelf side of the front and stations 10 to 14 at the offshelf side of the front that divided the Kuroshio water from the shelf waters. These abrupt changes reflect the lack of a transition zone between the shelf water and the Kuroshio water during this cruise. The data within this temperature range can be represented by concave curves or by two linear lines with a point of intersection at about 17 °C. The former interpretation suggests that there was a removal, most likely a biological removal, of nutrients in these relatively warm and shallow waters. The latter interpretation would indicate mixing processes involving three end-members. The data from stations 10 to 14 showed more pronounced concavity above 13 °C. At these stations, the thermocline and the nutriclines were considerably deeper than those at stations 7 and 8.

The removal of nutrients by biological processes might have been more important in controlling the concentrations of nutrients in these waters. Above 25 °C, the concentrations of phosphate and nitrate were uniformly low, around the detection limit, in both groups of stations suggesting that biological removal of nutrients in the surface water was almost complete. Below about 13 °C, the relationships were identical at all stations, where,

$$[NO_3] = 41\cdot9\,(\pm\,0\cdot5) - 1\cdot85\,(\pm\,0\cdot08)T \qquad \text{and } r = -0\cdot98$$
$$[PO_4] = 3\cdot11\,(\pm\,0\cdot04) - 0\cdot158\,(\pm\,0\cdot005)T \qquad \text{and } r = -0\cdot98.$$

The relationship between phosphate and temperature was almost identical to that observed during summer 1988. The nitrate–temperature relationship was slightly different. However, within the range of observed temperatures, the difference was probably insignificant relative to the uncertainties involved in this kind of analysis. Thus, the composition of the deep water in the Okinawa Trough does not seem to change perceptibly from season to season or from year to year.

During spring 1987, only waters at temperatures above 15 °C were sampled. The relationship between phosphate and temperature (Figure 10) may be represented by the equation

$$[PO_4] = 2\cdot3\,(\pm\,0\cdot2) - 0\cdot096\,(\pm\,0\cdot009)T \qquad \text{and } r = -0\cdot82.$$

This line intersects the lines that represent the colder deep waters in the Okinawa Trough during summer 1985 and summer 1988 between 10 and 15 °C. This temperature at the point of intersection was similar to those observed during the other two cruises. Liu *et al.* (1989) examined the phosphate–temperature relationship during this cruise in greater detail. They observed that the relationship for the data points from stations 1 to 4, the more offshelf stations, was significantly different from that for stations 5 to 10. By treating stations 1 to 4 separately, they estimated that the end-member of the upwelling water had a temperature of 13·3 °C. The corresponding concentrations of nitrate and phosphate were 14·2 and 0·97 μM. These values are remarkably similar to those estimated here from the data from summer 1988. This similarity suggests that the temporal variations of the composition of the source of the upwelling water was probably small.

Conclusions

The boundary between the East China Sea and the Kuroshio water in the Okinawa Trough north-east of Taiwan was clearly defined by large contrasts in temperature and salinity across the frontal region at the sea surface. The exact location of this boundary relative to the shelf break varies. During the periodical shelfward migration of the Kuroshio, it may get close enough to the shelf break to cause topographically induced upwelling onto the shelf, possibly in any season as observed in summer 1988 and spring 1987. At other times, such as during summer 1985, the Kuroshio can be far away from the shelf break. Under such circumstances, topographically induced upwelling onto the shelf might not have occurred, and, instead, filaments of shelf water could have spun out onto the Kuroshio. The observed chemical hydrography reflects the dynamic, and temporally and spatially variable nature of the mixing processes across the front.

The water at the core of the Kuroshio was nutrient-poor. The topographically induced upwelling water was modified Kuroshio water from about 300 m deep. Its composition seemed to remain rather constant with time with a temperature and salinity of around

13 °C and 34·4 psu respectively. It is enriched with nutrients, concentrations of nitrate, phosphate and silicate being 16, 1 and 18 µM respectively. The upwelling water can be identified as a pool of cold water at the vicinity of the shelf break. Depending on the intensity of the upwelling and the ability of organisms to strip off nutrients from surface waters, the upwelling water may or may not result in nutrient fronts at the sea surface. Such fronts were observed during spring 1987 and were not clearly evident during summer 1988.

The concentrations of the nutrients at temperatures above 13 °C were linearly related to temperature during summer 1988 and spring 1987 when topographically induced upwelling occurred. As a result, it may be possible to estimate the exchange of nutrients between the East China Sea and the Kuroshio in the Okinawa Trough from the corresponding heat exchanges.

The deep water (below about 300 m) in the Okinawa Trough at temperatures below 15 °C did not participate in cross-shelf mixing. Its chemical characteristics were significantly different from those of the deep water at comparable depths in the Philippine Sea.

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