Pergamon

Continental Shelf Research, Vol. 14, No. 7/8, pp. 909–929, 1994

0278–4343/94 $7.00+0.00

Comparison of winter and summer hydrographic observations in the Yellow and East China Seas and adjacent Kuroshio during 1986

CHANGSHENG CHEN,* ROBERT C. BEARDSLEY,† RICHARD LIMEBURNER† and KUH KIM‡

(*Received* 23 *March* 1992; *accepted* 5 *May* 1992)

Abstract—Two regional hydrographic surveys conducted in January and July 1986, aboard the R.V. *Thompson* and R.V. *Washington* illustrate the seasonal change in water properties from winter to summer in the Yellow and East China Seas (YECS) and adjacent Kuroshio. In January 1986, water over the shelf in the YECS was locally well mixed in the vertical, and the horizontal distribution of water properties was dominated by a large tongue or plume of relatively fresh Yellow Sea Cold Water (YSCW) flowing southeastward along the Chinese margin into the East China Sea. To the east of this plume, along the Korean margin, was found the more saline Yellow Sea Warm Water (YSWW). The Kuroshio front in the East China Sea was located at the shelf break, separating the warmer, more saline Kuroshio water from the relatively well-mixed cooler, less saline coastal water. Evidence of mixing between these two water masses was observed but limited to near the shelf break. In July 1986, water over the shelf in the YECS was strongly stratified everywhere except within tidally mixed areas near the coast. The surface water distribution in the YECS was dominated by a bubble or lens of Changjiang dilute water located to the northeast of the Changjiang mouth, and the bottom YSCW intensified and extended southward to the shelf break. The relatively fresh coastal water from the East China Sea shelf extended far past the shelf break over the Kuroshio near the surface, and in turn, Kuroshio water intruded onto the shelf near the bottom. Mixing between the Kuroshio and coastal water was found over much of the mid- and outer shelf and upper slope, spanning a cross-stream distance of 75 km. The seasonal freshening due to the Changjiang discharge contributed directly to the summer increase in freshwater transport in the upper Kuroshio. In addition, evidence of deep vertical mixing within the Kuroshio itself was found near 32.0°N, 128.2°E, most likely due to a mesoscale eddy found near there and internal tidal mixing over the slope.

1. INTRODUCTION

THE Yellow Sea is a shallow, marginal sea bounded to the west and north by the east coast of China and to the east by Korea (see Fig. 1). To the south of the Yellow Sea is the East China Sea which starts at the Taiwan Strait at about 25°N and extends northeast toward the Korea Strait and west of Kyushu. A line running northeastward from the mouth of the Changjiang to the southwestern tip of Korea separates the Yellow Sea to the north from

*MIT/WHOI Joint Program, Woods Hole, MA 02543, U.S.A.
†Physical Oceanography Department, WHOI, Woods Hole, MA 02543, U.S.A.
‡Seoul National University, Seoul 151–742, Korea.

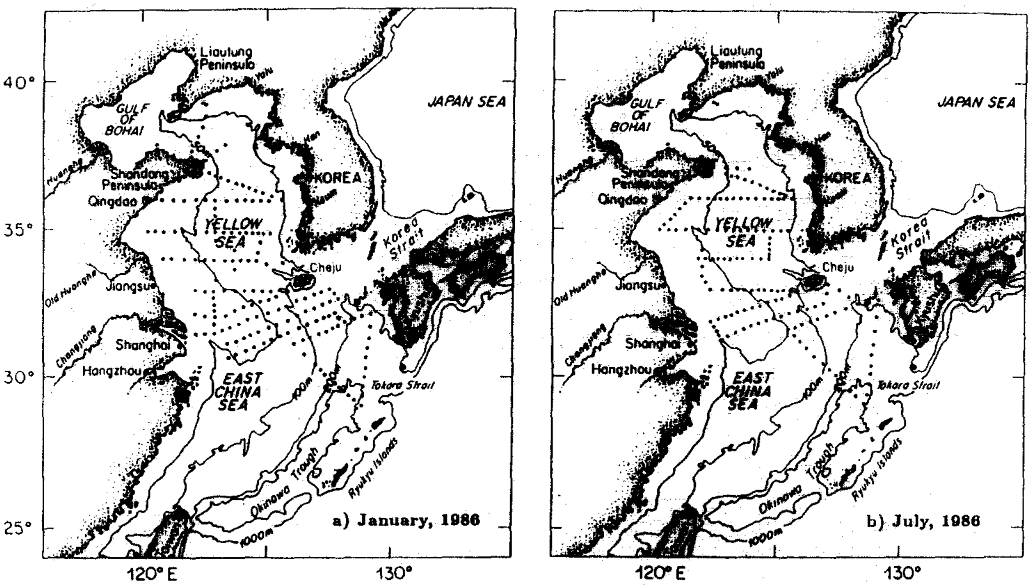

Fig. 1. CTD stations made during the (a) R.V. *Thompson* cruise, 8 January–1 February 1986, and the (b) R.V. *Washington* cruise, 4–20 July 1986.

the East China Sea to the south. The Ryukyu Island chain forms the southeastern boundary of the East China Sea so that the Yellow and East China Seas (YECS) region includes the broad, relatively flat, continental shelf and the deep Okinawa Trough.

The distribution and variability of water properties in the YECS region are strongly influenced by river discharge, air–sea interaction, tidal mixing and the Kuroshio. The YECS is surrounded by the largest rivers in Asia, the Huangho (Yellow River) and Changjiang (Yangtze River) along the east coast of China, and by three relatively small rivers, the Yalu, Han and Keum, along the north coast of China and west coast of Korea. The seasonal cycle of freshwater discharge from these rivers dominates the surface distribution of water properties in the YECS, especially in summer when the river output is largest (BEARDSLEY *et al.*, 1985). Air–sea interaction is responsible for the vertical stratification of water masses in the YECS where the water is mixed vertically by strong surface cooling and wind mixing during winter and re-stratified by strong surface heating during summer (NAKAO, 1977; BEARDSLEY *et al.*, 1985). Strong semidiurnal tidal currents occur in much of the YECS (CHOI, 1984). Non-linear interaction between tidal currents over the bottom in the shallower regions can cause both strong tidal mixing and generate subtidal residual flow, which contribute to water property distribution and sediment movement near the coast. It is well known that the Kuroshio enters the East China Sea east of Taiwan, flows northeastward along the edge of the continental shelf along the 200 m isobath, and then leaves the East China Sea through the Tokaro Strait southwest of Kyushu (Fig. 2). The water exchange between the coastal and Kuroshio waters tends to form a strong frontal zone between the warm and high salinity Kuroshio water and the low salinity coastal East China Sea water at the shelf break. This front exhibits eddies due to baroclinic instability (QIU and IMASATO, 1988).

There were few direct hydrographic measurements made in the YECS on a basin-wide

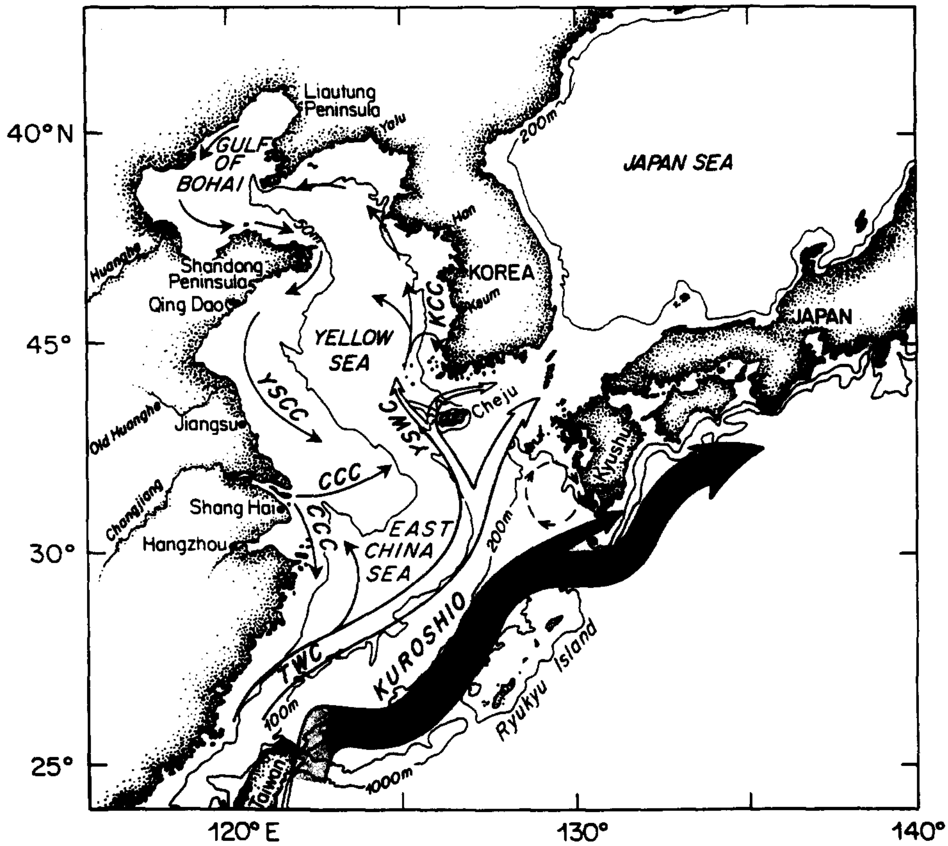

Fig. 2. Regional circulation pattern in the Yellow and East China Sea. The various currents are denoted as the Yellow Sea Cold Current (YSCC), the Yellow Sea Warm Current (YSWC), the Korean Coastal Current (KCC), the Changjiang Coastal Current (CCC) and the Taiwan Warm Current (TWC).

scale before 1986. Previous surveys conducted separately by Chinese, Korean and Japanese scientists were seriously limited by territorial restrictions. An international collaboration among American, Chinese and Korean scientists resulted in two successful regional hydrographic surveys in the YECS and adjacent Kuroshio region during 8 January–1 February 1986, aboard the R.V. *Thompson* [Fig. 1(a)] and 4–20 July 1986, aboard the R.V. *Washington* [Fig. 1(b)]. These surveys were conducted with Neil Brown Instrument Systems Mark III CTD equipped with a 25 cm light transmissometer and provided quasi-synoptic, high vertical and horizontal resolution snapshots of the distribution of water properties in the YECS and adjacent Kuroshio. Based on these two surveys plus some concurrent Japanese hydrographic data, we will describe here the winter–summer variation of water properties and mixing processes in the YECS and adjacent Kuroshio. To begin, the regional circulation and sources of fresh water are reviewed in Section 2. In Section 3, the horizontal distribution of water properties and their winter–summer change are described in more detail. Then the cross-stream water structure, including the classification of water masses, horizontal mixing near the Kuroshio front, and vertical mixing within the Kuroshio, are discussed in Sections 4 and 5. Conclusions are given in Section 6.

It should be pointed out that the derived salinity data obtained during the R.V. *Thompson* January 1986 survey exhibited some scatter and horizontal deviation from station to station in the Kuroshio which we have attributed to noise and drift in the conductivity sensor. To correct for these problems, the salinity data were first smoothed at each station as a function of depth with a symmetrical low-pass filter (frequency cutoff is 0.08 cpm), and then the smoothed salinity data were compared with concurrent Japanese Meteorological Agency deep bottle data from the Kuroshio and adjacent region to minimize horizontal deviations error (see CHEN, 1989, for a detailed discussion of this editing procedure). The resulting salinity data are believed good within a total measurement error of ±0.02‰.

2. REGIONAL CIRCULATION AND SOURCES OF FRESH WATER

Circulation

A schematic of the general circulation in the Yellow and East China Seas is shown in Fig. 2: this composite is based on the circulation patterns suggested by NITANI (1972) and BEARDSLEY *et al.* (1985) and modified using recent GEK (QIU and IMASATO, 1990), satellite-tracked drifter (BEARDSLEY *et al.*, 1992) and ADCP (CHEN *et al.*, 1992) measurements. The Kuroshio enters the ECS through the passage east of Taiwan at 24°30′N, 123°20′E, and flows northeastward along the 200 m isobath. The Kuroshio may split around a tall seamount into two branches southwest of Kyushu (CHEN *et al.*, 1992) before it leaves the East China Sea and flows along the south coast of Japan. Inshore of the Kuroshio, a warm saline current called the Taiwan Warm Current (TWC) also flows northeastward, but unlike the Kuroshio, the TWC directly flows over the continental shelf of the East China Sea and provides the relatively saline water front there (CHEN *et al.*, 1992). Although the branches of the TWC are not clearly documented near Cheju Island, some studies suggest that part of the TWC may flow into the Japan Sea through both passages of the Korea Strait between Korea and Japan as the Tsushima Current (BEARDSLEY *et al.*, 1992), while another part of the TWC flows intermittently northward into the Yellow Sea (HSUEH, 1988; BEARDSLEY *et al.*, 1992).

The semi-enclosed Yellow Sea is characterized by a slow intermittent northward inflow of saline water along the Korean side of the basin (the Yellow Sea Warm Current or YSWC) and outflow of less saline water along the northeast coast of China (the Yellow Sea Cold Current or YSCC). The Changjiang Coastal Current (CCC), associated with the Changjiang discharge, tends to flow southward along the Chinese coast or more offshore in a southeastward direction in winter and to flow east and northeastward in summer (BEARDSLEY *et al.*, 1983, 1985). A northwestward inflow of relatively saline TWC water is generally found in the submerged river valley located just offshore of the Changjiang mouth. This inflow is believed to be the source of the near bottom saline water found in the outer Changjiang estuary (BEARDSLEY *et al.*, 1985).

Circulation in the YECS exhibits a seasonal variation due to large seasonal changes in the freshwater input by rivers and surface forcing by the East Asian monsoon. The spring and summer discharge of the Changjiang is large enough to form a surface plume of

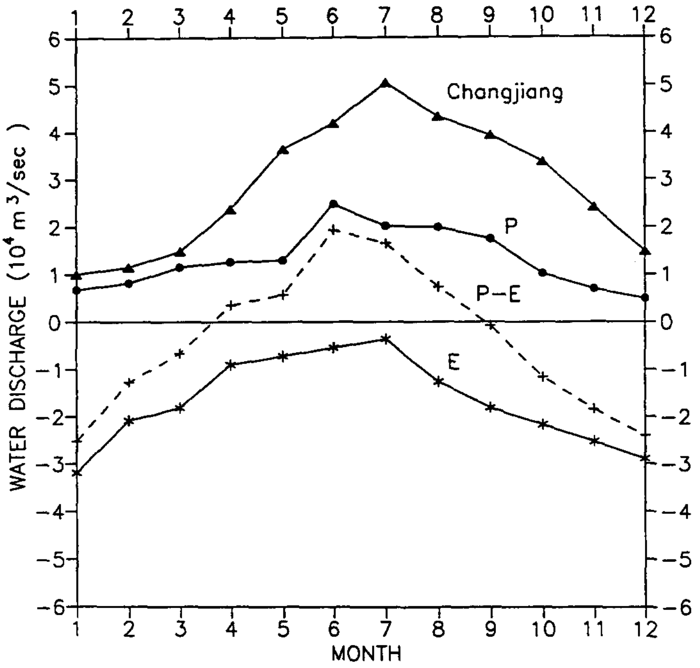

Fig. 3. Average monthly discharge of Changjiang measured at Datong (from YANG *et al.*, 1983). Monthly average precipitation (*P*) at Shanghai from 1912 to 1972 (WERNSTEDT, 1972), evaporation (*E*) from 1947 to 1960 in the East China Sea (WYRTKI, 1966), and *P*−*E* (dashed line).

relatively fresh water which can extend at least 300 km out over the shelf and also increase the southward along-coast flow of the CCC (BEARDSLEY *et al.*, 1983; 1985). In contrast, the much weaker Changjiang discharge in winter is generally confined to flow primarily southward in a narrow band along the Chinese coast. The seasonal variation of TWC flow is not known, but it is probably much stronger in summer than in winter due to the strong northeast monsoon in winter. We will identify next the major sources of freshwater input into the YECS.

Sources of fresh water

Local sources of fresh water in the YECS include river discharge and the net precipitation minus evaporation balance. The Changjiang originates in the Tibetan high plateau and flows more than 6000 km through ten provinces of China before draining into the East China Sea near Shanghai. In terms of volume discharge, the Changjiang is the largest river in Asia and the fifth largest in the world, while the other major rivers which drain into the YECS are one or two orders of magnitude smaller (see Table 1). Therefore, the Changjiang is the single most important river source of freshwater discharge into the YECS.

The seasonal variation of Changjiang discharge measured at Datong, 400 km upstream from the Changjiang mouth, is shown in Fig. 3. The mean monthly Changjiang discharge ranges from about 1.0×10^4 m^3 s^{-1} in winter to more than 5.0×10^4 m^3 s^{-1} in summer. The maximum monthly discharge occurs in July and minimum in January. Such an annual

Table 1. Freshwater discharge statistics for the five largest rivers flowing into the YECS. Values represent annual monthly averages and units are 10^3 m^3 s^{-1}

River	Annual mean	Minimum	Maximum	Reference
Changjiang	20.0	10.0 (January)	50.0 (July)	YANG *et al.* (1983)
Yalu	1.1	0.6 (April)	1.6 (July)	SCHUBEL *et al.* (1984)
Huangho	0.9	0.5 (February)	2.0 (September)	QIN and LI (1983)
Han	0.8	0.1 (January)	3.2 (July)	SCHUBEL *et al.* (1984)
Keum	0.2	0.03 (January)	0.5 (June)	SCHUBEL *et al.* (1984)

discharge variation is due to the monsoonal climate over eastern China where rainfall increases during the summer and, to a lesser degree, to the spring melting of the winter snow pack.

An estimate of the net influx of fresh water due to rainfall in the YECS can be made by subtracting evaporation from precipitation. WYRTKI (1966) calculated the mean heat exchange at the surface of the Pacific Ocean based on ship weather reports from 1947 to 1960. Using his monthly mean evaporation maps, we estimate that the mean monthly evaporation rate in the East China Sea varies from about 0.4×10^4 m^3 s^{-1} in July to 3.2×10^4 m^3 s^{-1} in January* (see Fig. 3). The mean annual evaporation is about 5.3×10^{11} m^3 $year^{-1}$ (~1.5 m $year^{-1}$). There are few direct observations of precipitation over the East China Sea. Since the contours of equal frequency of rainfall are almost parallel to latitude in the region between the east coast of China and Kyushu,† we will use rainfall data from the land weather station at Shanghai to estimate precipitation over the sea. Data from 1912 to 1972 (WERNSTEDT, 1972) show that the mean annual precipitation over the East China Sea is about 4.0×10^{11} m^3 $year^{-1}$ (~1.1 m $year^{-1}$), with a monthly maximum rainfall of about 2.5×10^4 m^3 s^{-1} in June, and a minimum value of about 0.49×10^4 m^3 s^{-1} in December (see Fig. 3). The resulting precipitation minus evaporation curve suggests that the summer influx of fresh water from April to September is approximately balanced by excess evaporation in the rest of the year, so that there is no annual net freshwater flux into the East China Sea from rainfall. Even if we consider the mean summer precipitation minus evaporation rate of 2.1×10^4 m^3 s^{-1} from April to August as applying to the entire East China Sea region, this influx amounts to only about 30% of the Changjiang discharge during the same period, so we conclude from these crude calculations that the Changjiang is the single most important source of freshwater input into the East China Sea.

*For comparison with the river discharge, we use a factor of 600×600 km^2 to re-scale the evaporation and precipitation data.

†U.S. Navy Marine Climatic Atlas of the World, Volume 11, North Pacific Ocean.

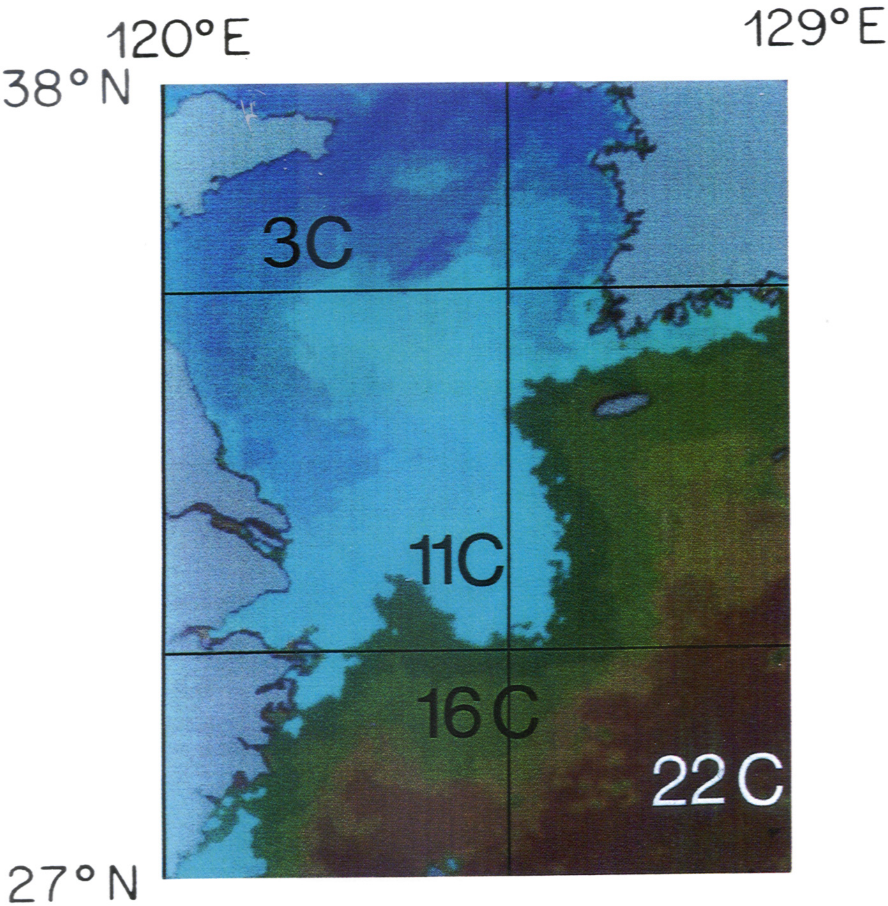

Fig. 6. Sea surface temperature map for 8 March 1986, derived from NOAA-AVHRR data. Note the presence of low-temperature tongue feature in the East China Sea. (This image was kindly supplied by R. Legeckis.)

3. HORIZONTAL DISTRIBUTION OF WATER PROPERTIES

Long CTD sections covering much of the YECS were made along the transects shown in Figs 4 and 5 in January and July, 1986 aboard the research vessels *Thompson* and *Washington*, respectively. Because our surveys did not cover the southwestern East China Sea, bottle data* obtained on the Japanese research vessels *Chofu Maru* and *Ryofu Maru* during January and *Chofu Maru* during July, 1986, have been used to extend our analysis and provide high quality hydrographic measurements in the Taiwan Warm Current and the Kuroshio upstream of our survey area. To illustrate the horizontal distribution of water properties, maps of properties at 4 m (called the surface) and at the bottom or 100 m, whichever is shallower, are described next. The maps of temperature and salinity shown in Fig. 4 reflect a variety of processes such as advection, diffusion, a seasonally and geographically variable surface heat flux and river runoff, tidal mixing, and a spatially and temporally variable wind stress. We will attempt in this paper to identify the dominant physical processes associated with the main hydrographic features observed during the January R.V. *Thompson* and July R.V. *Washington* field surveys.

January 1986

The surface salinity and temperature distributions (see Fig. 4) show that the highest salinities and temperatures (greater than 34.4‰ and 19°C which are characteristic of Kuroshio water) were located in the southeast of the study area. The 34.4‰ isohaline laid roughly along the 200 m isobath so that the inner boundary of the Kuroshio water at the surface was located near the shelf break. Intermediate salinity (33.0‰ $<$ S34.5‰) and temperature (10°C $<T<$16°C) water associated with the TWC and YSWC was found to the northwest of the Kuroshio and to the west of Korea. Based on a statistical cluster analysis of the surface T and S data, KIM *et al.* (1991) suggested defining part of this water characterized by a temperature of 12.5°C$<T<$16.5°C and a salinity of 33.5‰$<S<$34.6‰ as East China Sea Water (ECSW). To the left of the ECSW, the YSCC, characterized by relatively low temperature and salinity, tended to flow southeastward toward the shelf break, forming a relatively cold and less saline tongue-like structure near 32°N and 124°E. This tongue-like structure was also clearly seen in the sea surface temperature map (Fig. 6) obtained on 8 March 1986, 5 weeks after the R.V. *Thompson* survey, indicating that it is a dominant characteristic of water properties in the East China Sea during winter. Similar structures were also found near the bottom in the Yellow Sea where the water was mostly vertically well-mixed due in part to strong wind and tidal mixing and surface cooling (NAKAO, 1977; BEARDSLEY *et al.*, 1985). The water filling the main deep channel running northward into the Yellow Sea was very weakly stratified in January 1986. As noted by HSUEH (1988), the presence of relatively warm, more saline water in this channel implies the existence of the YSWC in winter, albeit as a weak, highly intermittent subsurface current.

July 1986

The surface (4 m) and the bottom (100 m) distributions of temperature and salinity are shown in Fig. 5. The seasonal increase in solar heating resulted in the high surface

*From the data report on Result of Marine Meteorological and Oceanographical Observation No. 78, January–December, 1986, published by the Japan Meteorological Agency.

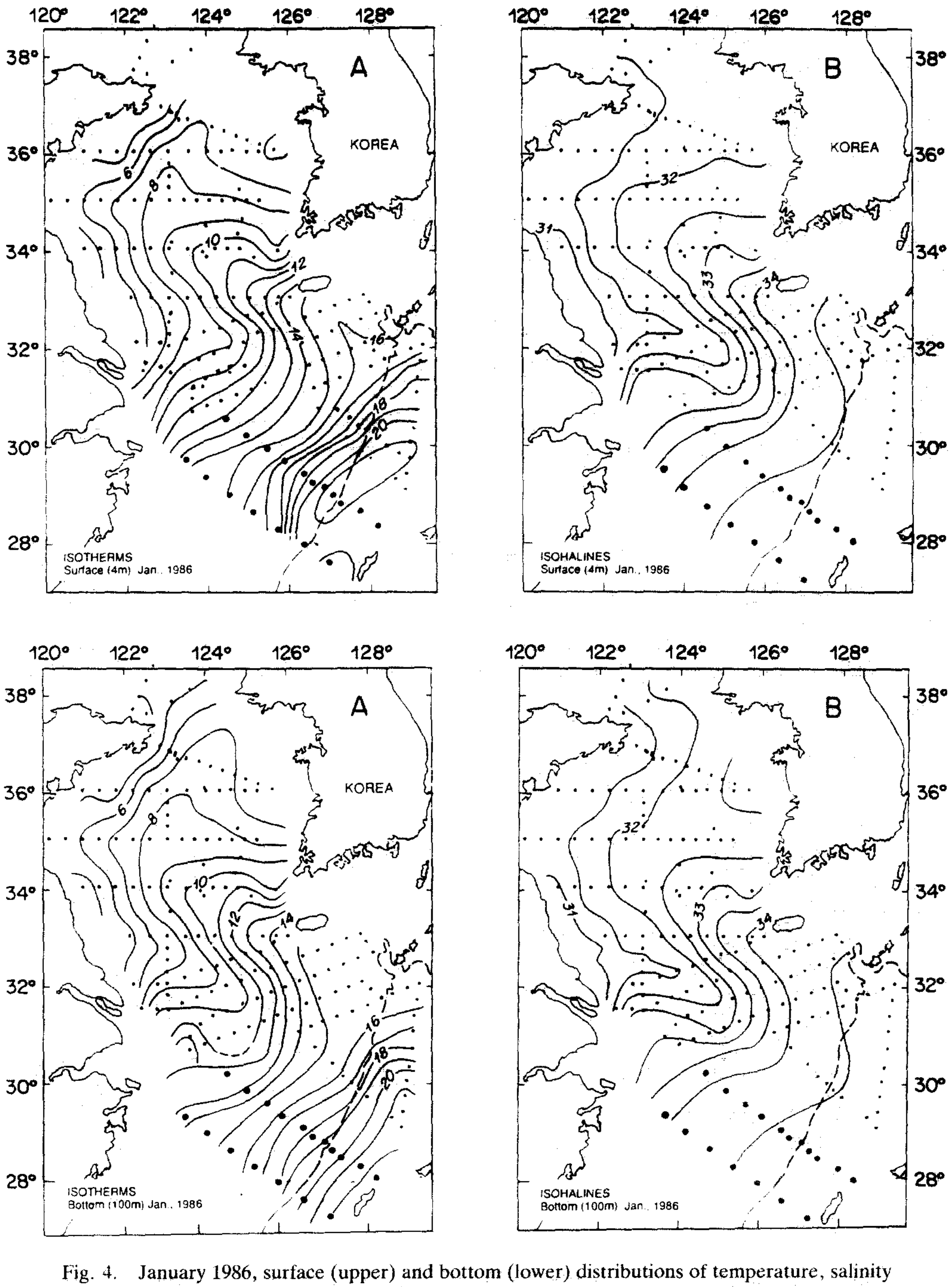

Fig. 4. January 1986, surface (upper) and bottom (lower) distributions of temperature, salinity and sigma-*t*. The surface values are at 4 m and the bottom values are at either 100 m or nearest the bottom (in water less than 100 m deep). The large dots represent Japanese bottle data stations, and the dashed line is the 200 m isobath.

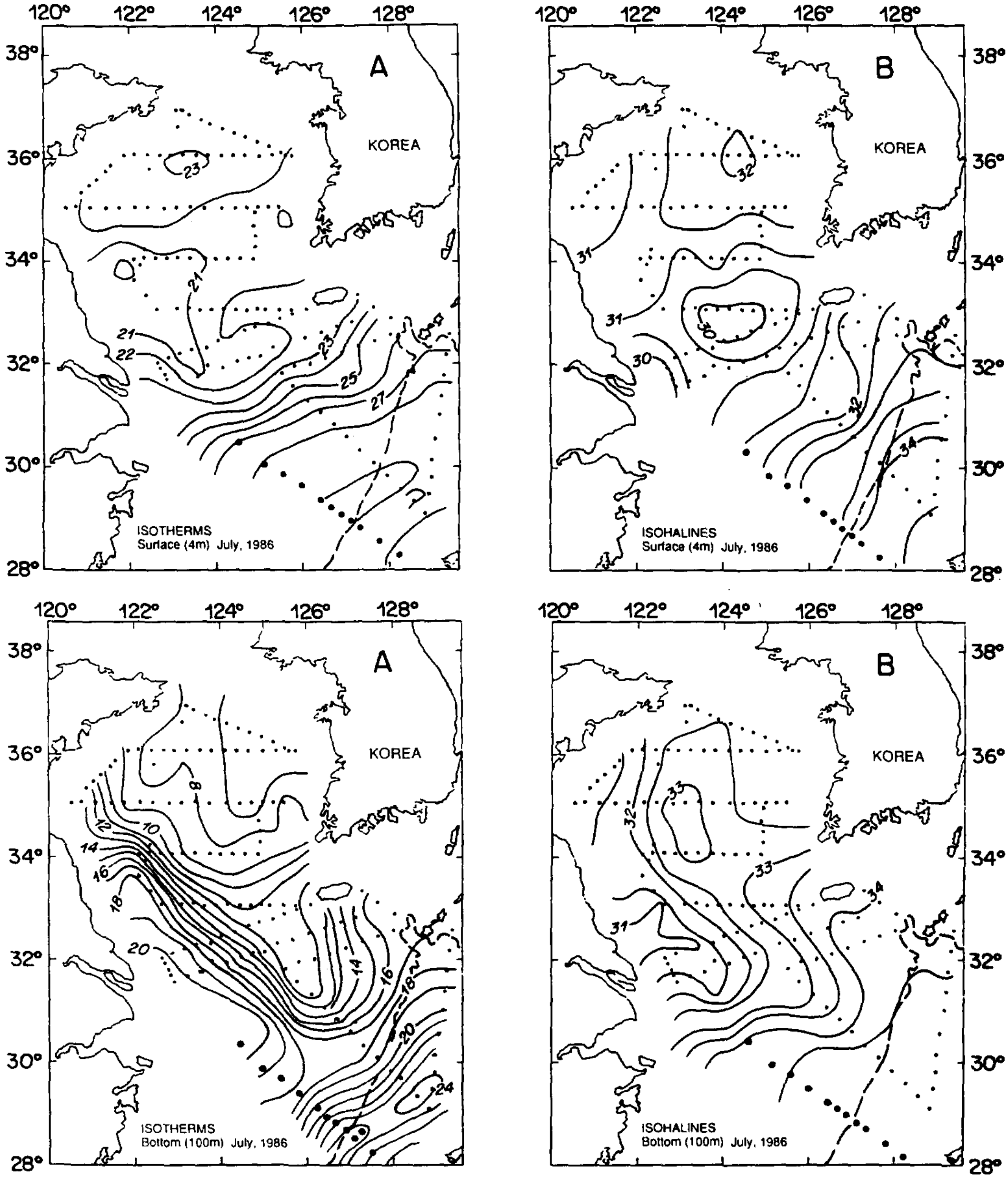

Fig. 6. Sea surface temperature map for 8 March 1986, derived from NOAA-AVHRR data. Note the presence of low-temperature tongue feature in the East China Sea. (This image was kindly supplied by R. Legeckis.)

temperatures during summer. Although the tongue-like structure was distorted near the surface due to surface warming, it remained clear in the bottom distribution of salinity. This fact implies that water properties near the bottom remain stable after winter and are renewed only in the following winter when the strong surface cooling and wind mixing occur. Unlike the previous winter, the YSWC was intensified during summer near the bottom where the salinity core was found to intrude into the northern Yellow Sea. In turn, the relatively fresh and cold YSCC tended to flow southwestward directly onto the shelf break where the Kuroshio is located. The Kuroshio can be clearly recognized by the maximum temperature core near the southern corner of the triangle during summer, and the TWC was identified by the large temperature gradient over the East China Sea shelf southwest of Cheju Island.

There was a big difference in the surface salinity distribution from January to July 1986. Much fresher water was found near the surface south of 33°N during summer, with a salinity minimum near 32.5°N, 124°E between Korea and China, and another salinity minimum near the mouth of the Changjiang along the Chinese coast. This leage spreading of fresher water was due to the increased discharge of the Changjiang, which caused less saline water to flow both northwest toward Cheju Island (which in July 1986 had formed a surface bubble or lens of Changjiang dilute water centered near and 33°N, 125.5°E) and southward along the Chinese coast. This latter flow then turned southwestward to mix with TWC and YSCC over the continental shelf (Limeburner et al., 1983).* A simple scaling argument supports this explanation. From the previous sections, the total discharge of fresh water from the Changjiang from January to July is about 4.8×10^{11} m^3. This amount of discharge would cover the East China Sea (with an area of about 3.6×10^{11} m^2) with a layer of fresh water 1.3 m thick or cause the salinity to be reduced by 1.2‰ if mixed over the top 50 m, as suggested by the summer observations. Since the net precipitation minus evaporation is almost zero during these 7 months, the increased discharge of the Changjiang should cause the observed distribution of surface low salinity water over the shelf and in the Kuroshio in the East China Sea in summer.

4. CROSS-STREAM WATER STRUCTURE IN THE KUROSHIO

January 1986

The vertical distributions of temperature, salinity and sigma-t on the January 1986 western transect across the Kuroshio from Stas 118 to 127 are shown in Fig. 7(a). The corresponding T/S diagram for this transect is given in Fig. 8. Near the surface was found Kuroshio Surface Water (Nakao, 1977), which exhibited considerable scatter in the T/S diagram due to atmospheric variability. Tropical Water, characterized by a salinity maximum, formed at the surface of the subtropical North Pacific by excess evaporation over precipitation in winter and advected northward by the Kuroshio (Masuzawa, 1972), was generally found beneath Kuroshio Surface Water on the T/S diagram. The maximum salinity at the core of the Tropical Water exceeds 34.8‰ at about 250 m depth at Stas 126–127, and the corresponding temperature was about 20°C. Defined by temperature 18–21°C and salinity more than 34.8‰, the core of Tropical Water was about 100 m thick, covering the depth range from 200 to 300 m. In the range from 18 to 10°C and 34.4 to 34.8‰, the T/S relation was nearly linear, and temperature and salinity exhibited local maximums of vertical gradient. This water is called Central Water (Sverdrup et al., 1942) or Thermocline Water (Masuzawa, 1972). The average depth of the Central Water can be defined by

*For convenience, we will use the general name of coastal water in the following discussion to refer to mixtures of YSCC, TWC and CCC.

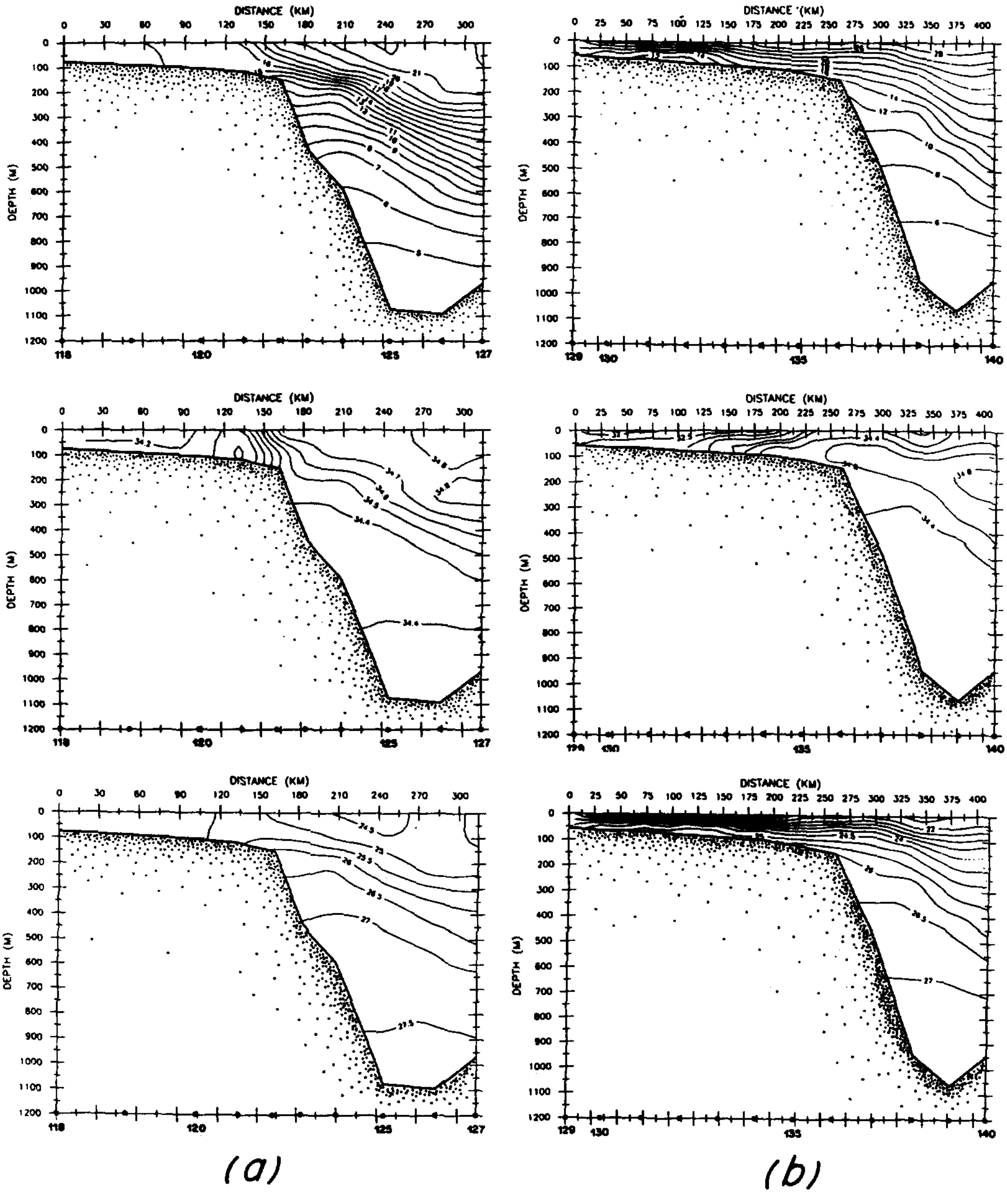

Fig. 7. The vertical structure of temperature (top), salinity (middle) and sigma-*t* (bottom) on the western transect of the triangle for January (left) and July (right), 1986. The January transect occupied Stas 118–127, and the July transect Stas 129–140, respectively.

the axis of maximum vertical gradient of temperature which, in general, increases from the shelf break toward the open ocean. At Stas 126–127, the Central Water was found from 300 to 600 m with an average depth of about 450 m. At Sta. 123 on the upper slope, the average depth was about 150 m and the thickness ranges from 150 to 350 m. Below the

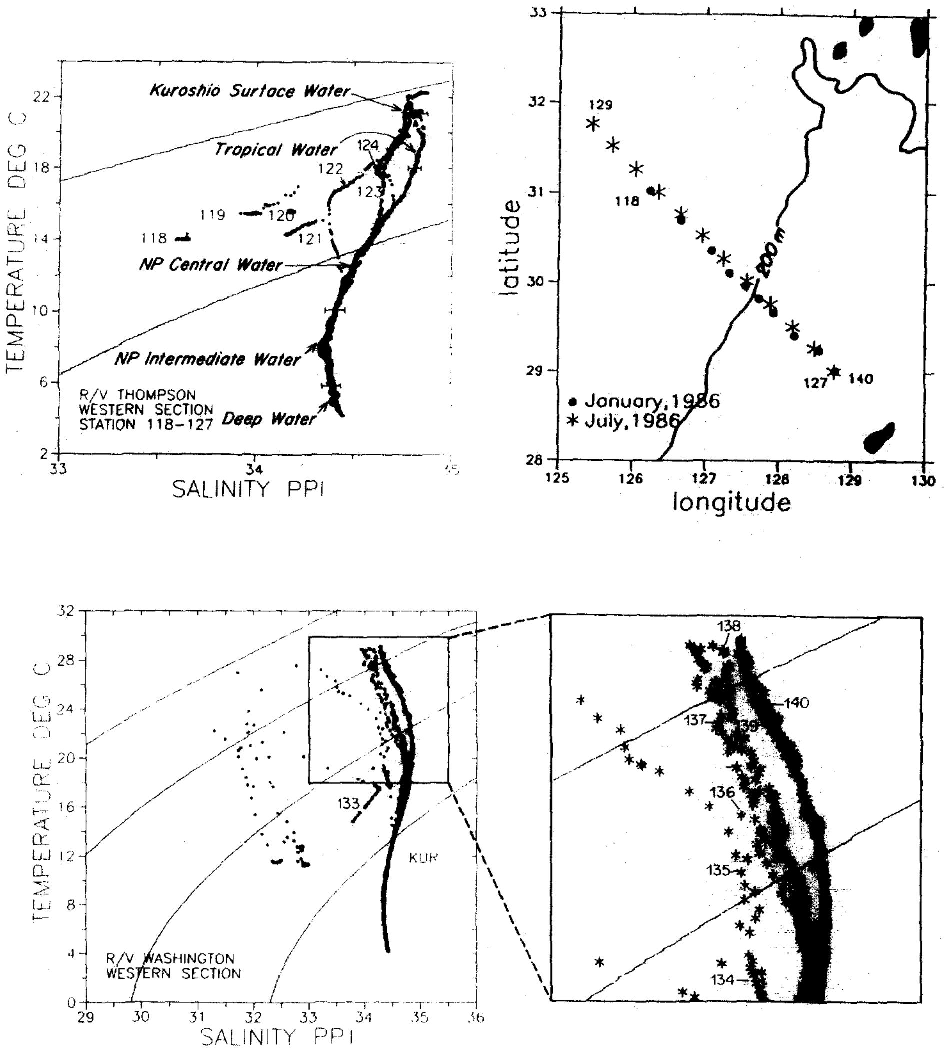

Fig. 8. *T/S* curves for CTD stations on the western transect for January (upper) and July (lower) 1986. The station locations are shown in the upper right panel and an enlargement of the July *T/S* curve is shown in the lower right panel.

Central Water was found North Pacific Intermediate Water, which was formed in subarctic regions (REID, 1965) and identified by its vertical salinity minimum of about 34.36‰ near 8°C. If we define this water to have salinity less than 34.4‰ and temperature between 6 and 10°C, then North Pacific Intermediate Water occupied much of the deep Kuroshio in the East China Sea in January 1986. Near the bottom was found the North Pacific Deep Water (PICKARD, 1979), which was characterized by more uniform properties with depth. As mentioned before, the large scatter in the deeper *T/S* relationship in the North Pacific Central Water, Intermediate Water and Deep Water was due to conductivity noise in the January 1986 CTD data.

July 1986

Vertical sections of temperature, salinity and sigma-*t* on the July 1986, transect across the Kuroshio from Stas 129 to 140 are shown in Fig. 7(b), and the T/S diagram for this transect is shown in Fig. 8. Seasonal increases in solar heating, Changjiang discharge and net precipitation resulted in the highly stratified structure of the upper ocean in July 1986. Kuroshio Surface Water had warmed 6°C from the January survey and contained water of less than 34‰. Tropical Water can be traced by the salinity maximum in the upper ocean at Sta. 140 to the shelf break at Sta 136, with the salinity maximum decreasing from the trough to the shelf break. The core of Tropical Water at Sta. 140, with a salinity of 34.83‰ and a temperature greater than 21°C, was located at a depth of about 200 m, 50 m shallower than in January. At Sta. 136 at the shelf break, the core was located at a depth of 100 m with a maximum salinity of only 34.75‰ and a temperature of 18.8°C. The Central Water, characterized by temperature between 10 and 18°C and salinity from 34.4 to 34.7‰ in July, had intruded onto the shelf. The 34.4‰ isohaline, which was limited to the shelf break in January, reached station 134, 100 km northwest from the slope. The 18°C isothermal surface, which intersected the sea surface on the slope in January, had been overlaid everywhere by seasonal thermocline water in July. The 25.0 isopycnal surface intersected the bottom on the slope rather than the sea surface as in January. In turn, the less saline coastal water extended from the shelf over into the Kuroshio near the surface, helping to create a highly stratified surface layer over the Kuroshio. There was little change in the North Pacific Intermediate Water and Deep Water from January to July since both were too deep to be affected by local atmospheric factors and freshwater runoff.

5. EVIDENCE OF MIXING PROCESSES NEAR THE KUROSHIO FRONT

The seasonal variation of the Kuroshio front is clearly shown on the western transects of temperature and salinity taken in January and July 1986 [Fig. 7(a) and (b)]. During winter, the Kuroshio front was located almost vertically at the shelf break, which separated the warmer, more saline Kuroshio water over the slope from the vertically well-mixed, cooler and less saline coastal water over the shelf. During summer, however, surface coastal water extended far past the shelf break over the Kuroshio region near the surface, and in turn, Kuroshio water intruded onto the shelf near the bottom. A similar structure of the front was also observed in summer by Miyazaki and Abe (1960) west of Kyushu, implying that the frontal structures observed in January and July 1986, may be a regular seasonal feature southwest of Kyushu. Mixing processes over the shelf and slope were very different from winter to summer 1986 because of the seasonal variation of the Kuroshio front. During winter, evidence of horizontal mixing between the Kuroshio and coastal water was observed but was limited to the region near the shelf break. During summer, however, mixing between the Kuroshio and coastal water was found over much of the mid and outer shelf and upper slope, spanning a wide cross-stream region of the Kuroshio. A detailed discussion will be given next based on the *T/S* diagrams.

January 1986

Mixing between the Kuroshio and coastal waters was mainly confined to the shelf break front centered at Sta. 122 where the sharp bend in the *T/S* curve from the surface to bottom was observed. Mixing at Sta. 122 occurred between three different water masses: (1) Kuroshio Surface Water with a salinity greater than 34.74‰ and temperature of about 21.2°C; (2) coastal water with a salinity of 34.36‰ and temperature of 16°C, and (3) Central Water with a salinity greater than 34.43‰ and temperature of about 11.8°C. At Sta. 123, 15 km offshore from the shelf break, mixing was observed between the Kuroshio Surface Water at a salinity of about 34.74‰ near 21°C and Central Water with a salinity of 34.64‰ near 15°C. A similar phenomenon was also seen at Sta. 124, 45 km off the shelf from the shelf break. Small scale bends in the *T/S* curves at Stas 123 and 124 near 34.6‰ and 18°C imply the indirect influence of the mixed water over the shelf break (i.e. at Sta. 122). At Sta. 121, 30 km onto the shelf from the shelf break, the linear *T/S* curve indicated mixing between coastal water with a salinity of 34.13‰ and temperature of 14.2° and the more saline and warmer mixed water at Sta. 122. Over the mid and inner shelf, the coastal water tended to be more well-mixed vertically, and there was no evidence to show any direct influence of the Kuroshio. Since the wintertime overturning due to the strong surface cooling and wind mixing caused a vertically well-mixed density over the continental shelf [see Fig. 7(a)], mixing with the coastal water on the *T/S* curves tended to occur along isopycnal surfaces (see examples at Stas 121 and 122). In contrast, the density was vertically stratified over the slope where some Kuroshio water was located and mixing between the deeper water masses on the *T/S* curves tended to be across isopycnal surfaces (see examples at Stas 123 and 124).

July 1986

Mixing between Kuroshio and coastal waters occurred symmetrically to the shelf break over a distance of 150 km within Stas 134–138 [Figs 7(b) and (8)]. The *T/S* curves at Stas 136–138 from the shelf break to the center of the Okinawa Trough indicate mixing between the less saline and warmer coastal water and Kuroshio Surface Water (S<34.0‰ and T>28°C) and the upper Tropical Water (S<34.8‰ and T>20°C). As a result, the maximum salinity and corresponding temperature of the Tropical Water were reduced to 34.7‰ and 19.6°C, 0.12‰ fresher and 2°C cooler than at Stas 139–140. Over the outer shelf at Sta 135, 37 km onto the shelf from the shelf break, the *T/S* curve showed the minimum salinity core of 34.3‰ and 19.6°C at the depth of about 80 m, with linear segments down to 34.4‰ and 17.8°C and up to 34.5‰ and 23°C, implying mixing among the less saline coastal water, Central Water and Kuroshio Surface Water. Mixing between coastal water and Central Water was still observed at Sta. 134, 75 km onto the shelf from the shelf break. The direct influence of Kuroshio water disappeared at Sta. 133, 113 km inshore from the shelf break where mixing was found between TWC water with a salinity of 34.3‰ and temperature of 17°C and YSCW (S<33.7‰ and T<14.5°C).

The *T/S* curves for the eastern downstream side of the survey triangle (not shown here) were very similar to those on the western transect from Stas 134 to 140, implying that the less saline surface water comes from the mixed Kuroshio and Coastal water. In other words, the relatively fresh coastal water found over the mid and inner shelf (inshore of Sta. 134) did not flow directly to the eastern section. However, the trace of this fresher water was found on the northern transect of the triangle through the similarities of the *T/S* curves on both the western and northern sections. This implies that the mixed coastal water intruded farther north in July 1986. In addition, strong solar heating contributed to the strong vertical density stratification over both shelf and the Okinawa Trough [see

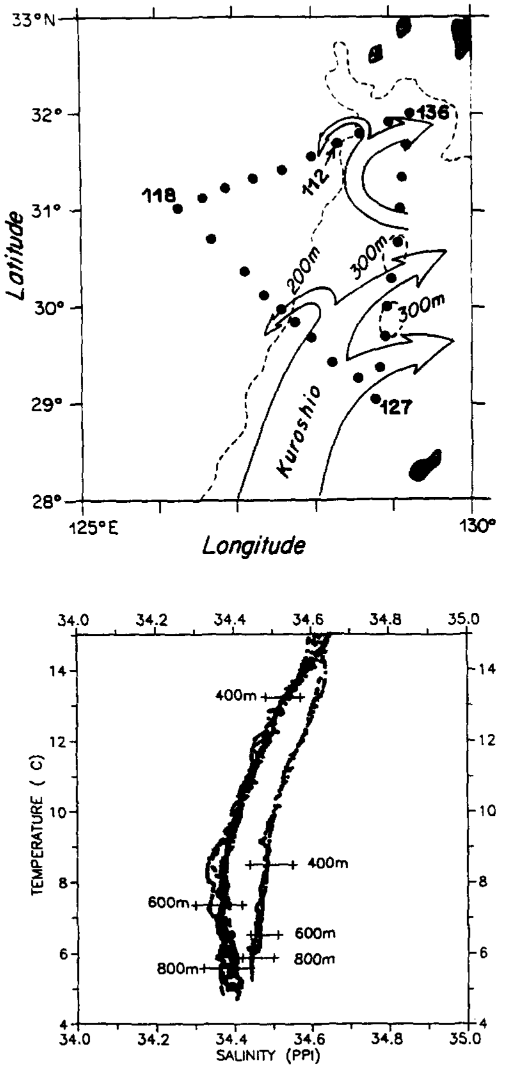

Fig. 9. Schematic of vertically averaged absolute geostrophic current field in triangle region during January 1986 taken from CHEN *et al.* (1992) (upper panel) and *T/S* curves for CTD Stas 127–136 along eastern transect (lower panel). Also shown on the upper panel are 200 and 300 m isobaths taken from the East China Sea Bathymetry Chart (provided by Second National Institute of Oceanography, P. R. China).

Fig. 3(b)],so that mixing between different water masses occurred primarily across isopycnal surfaces everywhere except near the bottom at Sta. 133, where the water density was relatively vertically mixed [Fig. 3(b)].

Vertical mixing in the Kuroshio

Indirect evidence for vertical mixing within the deeper Kuroshio was found in the *T/S* data at Stas 135–137 in January 1986 (see Fig. 9). These stations exhibited nearly straight

T/S curves in the deeper water instead of the more curved T/S relationship characterized by North Pacific Central Water. This nearly linear T/S curve implies mixing of North Pacific Central Water and Intermediate Water over the temperature and salinity ranges 6–14.5°C and 34.4–34.6‰, such that water beneath about 200 m at these stations consisted of this mixture.

What mechanisms do we think can cause or contribute to this vertical mixing? Estimates of the absolute geostrophic currents in the survey area (see Fig. 9, also CHEN *et al.*, 1992) indicate an anticyclonic eddy circulation pattern near the northeastern point of the survey triangle, with mixed water flowing out of the triangle at speeds of about 30 cm s^{-1} between Stas 135 and 137. In the July survey, the Kuroshio was located farther south and no mesoscale eddy was formed in the northeast corner of the survey triangle (CHEN, 1989). The fact that vertical mixing within the deeper Kuroshio occurred in January rather than in July 1986, implies that the mesoscale eddy played an important role in this mixing process. The bottom bathymetry west of Kyushu is quite complex and poorly known, with several tall seamounts indicated on Chinese navigation charts. Water may be trapped by an active eddy over such rough bottom topography, with much subsequent local vertical mixing. The vertically averaged semidiurnal tidal currents* have an approximate amplitude of only 3 cm s^{-1} over the slope, but they may generate vigorous internal waves when the semidiurnal tidal wave propagates up over the slope and onto the shelf (WUNSCH, 1969). Crude estimates of bottom slope and stratification suggest that the bottom slope over the upper slope (700–200 m) in this region is critical with respect to the semidiurnal tidal frequency, so that internal wave mixing caused by small-scale turbulence may also mix water vertically over rough topography. A straightening of the T/S curve also has been observed downstream of several submarine canyons off the Middle Atlantic Bight, where slope water flowing through the canyon has been vertically mixed by internal waves generated within the canyon by semidiurnal tidal currents (HOTCHKISS, 1982), supporting our argument for internal wave mixing. Since it is hard to estimate which mechanism, mixing by internal waves or mesoscale eddies, is dominant in this case, we suggest that both may be important to explain the inferred mixing found near the northeast corner of our survey triangle.

A crude estimate of the magnitude of the effective vertical eddy diffusivity required to cause the inferred mixing can be made using the simple vertical diffusion model shown in Fig. 10. If H is the vertical depth over which mixing occurs, and T is the time required for the T/S curve to straighten, then the effective eddy diffusivity is $K \sim H^2/T\pi^2$. If we estimate T as the time taken for a water parcel to move from CTD Sta. 133 to CTD Stas 135–136 (see Fig. 9) where the distance is about 2×10^5m and velocity* was about 30 cm s^{-1}, then $T \sim 6.7 \times 10^5$s, so that $K \sim 0.05$ m^2 s^{-1}. This is close to the maximum accepted value reported for K of 0.1 m^2 s^{-1} (POND and PICKARD, 1983), indicating that unless our estimate of T is

*Since the semidiurnal co-tidal lines are parallel to the continental slope and the tide propagates from the deep sea onto the shelf (NISHIDA, 1980), we can estimate the tidal current on the slope southwest of Kyushu from the known data on the inner shelf using mass conservation. A typical value of the vertically averaged M_2 tidal current on the 20 m isobath is about 60 cm s^{-1} in the East China Sea (CHOI, 1984), so that the estimated vertically averaged tidal current is about 3 cm s^{-1} at the 400 m isobath on the slope.

*The velocity was estimated by the geostrophic calculation with an averaged ADCP velocity at 60 m as a reference level. For a detailed explanation, see CHEN *et al.*, 1992.

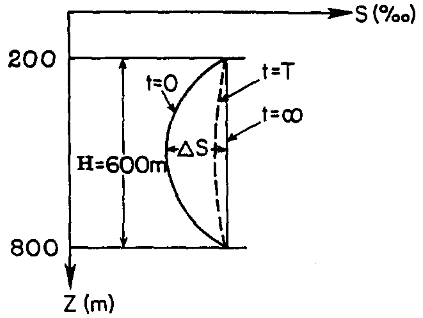

Fig. 10. Model configuration used to estimate the effective vertical eddy diffusivity required for the salinity–depth curve to relax from its initial profile at $t=0$ to the nearly straight profile at $t=T$.

significantly too small, the inferred vertical mixing in the Kuroshio near the northeastern region of the survey triangle must have been very intense.

6. CONCLUSION

Hydrographic data collected on basin-wide CTD surveys in the Yellow and East China Seas and adjacent Kuroshio in January and July 1986 have been used to describe the spatial structure of water properties in this large marginal sea region. In January 1986, the river discharge was weak and water in the shallower inshore regions of the YECS was locally well-mixed in the vertical and the horizontal distribution of water properties dominated by a large tongue or plume of relatively fresh Yellow Sea Cold Water flowing southeastward along the Chinese margin into the East China Sea. To the east of this plume, along the Korean margin, was found the more saline Yellow Sea Warm Water. The Kuroshio front was located at the shelf break, separating the warmer, more saline Kuroshio water from the relatively well-mixed cooler, less saline coastal water. Evidence of mixing between these two water masses was observed but limited to near the shelf break. In July 1986, however, increased solar heating and freshwater discharge from the Changjiang lead to strong vertical stratification within the Yellow and East China Seas. The surface water distribution in the Yellow and East China Seas was dominated by a bubble or lens of Changjiang fresh water located to the northeast of the Changjiang mouth, and the bottom YSCW intensified and extended southward to the shelf break. The relatively fresh coastal water from the East China Sea shelf extended far past the shelf break over the Kuroshio near the surface, and in turn, Kuroshio water intruded onto the shelf near the bottom. Mixing between the Kuroshio and coastal water was found over much of the mid and outer shelf and upper slope, spanning a cross-stream distance of 75 km. The seasonal freshening due to the Changjiang discharge contributed directly to the summer increase in freshwater transport in the upper Kuroshio. In addition, evidence of deep vertical mixing within the Kuroshio itself was found near 32.0°N, 128.2°E, most likely due to a mesoscale eddy found near there and internal tidal mixing over the slope.

Acknowledgements—This research was supported by the National Science Foundation under grants OCE 85–01366, OCE 86–16937, and OCE 91–01034. The CTD data were obtained with the aid of Chinese and Korean scientists as well as C. Alessi, J. Barth, P. Cessi, T. Lehman, R. Sternberg, E. Welsh and T. Wood. Their assistance is greatly appreciated. We also thank David Chapman, Glenn Flierl, Paola Rizzoli and John Toole for their helpful comments and suggestions during the course of this research, and Harry Bryden and Larry Atkinson for their helpful review of an early draft of this manuscript. Finally, we want to thank Richard Legeckis for his help with locating the appropriate satellite images and producing the complete SST map shown here in Fig. 6. The final manuscript was prepared by Anne-Marie Michael with valuable assistance from Barbara Gaffron. This is WHOI contribution No. 7344.

REFERENCES

BEARDSLEY R. C., R. LIMEBURNER, K. LE, D. HU, G. A. CANNON and D. J. PASHINSKI (1983) Structure of the Changjiang plume in the East China Sea during June 1980. In: *Proceedings of the International Symposium on Sedimentation on the Continental Shelf, with Special Reference to the East China Sea, April* 12–16, *Hangzhou, P. R. China*, **1**, China Ocean Press, Beijing, pp. 265–284.

BEARDSLEY R. C., R. LIMEBURNER, K. KIM and J. CANDELA (1992) Lagrangian flow observations in the East China, Yellow and Japan Seas. In: *Proceedings of Japan and East China Sea study (JECSS) workshop* VI. *La Mer*, **30**(3), 297–314.

BEARDSLEY R. C., R. LIMEBURNER, H. YU and G. A. CANNON (1985) Discharge of the Changjiang (Yangtze River) into the East China Sea. *Continental Shelf Research*, **4**, 57–76.

CHEN C. S. (1989) The structure of the Kuroshio west of Kyushu. M.Sc thesis, MIT/WHOI Joint Program, Woods Hole, Massachusetts, 137 pp.

CHEN C. S., R. C. BEARDSLEY and R. LIMEBURNER (1992) The structure of the Kuroshio southwest of Kyushu: velocity, transports and potential vorticity fields. *Deep-Sea Research*, **39**, 245–268.

CHOI B. H. (1984) A three-dimensional model of the Eastern China Sea. In: *Ocean hydrodynamics of the Japan and East China Seas*, Elsevier Oceanography Series, T. ICHIYE, editor, Elsevier, New York, pp. 209–224.

HOTCHKISS F. L. S. (1982) Observed circulation and inferred sediment transport in Hudson submarine canyon. Ph.D thesis, MIT/WHOI Joint Program, Woods Hole, Massachusetts, 224 pp.

HSUEH Y. (1988) Recent current observation in the Eastern Yellow Sea. *Journal of Geophysical Research*, **19**, 612–625.

KIM K., K. R. KIM, T. S. RHEE, H. K. RHO, R. LIMEBURNER and R. C. BEARDSLEY (1991b) Identification of water masses in the Yellow Sea and the East China Sea by cluster analysis. In: *Oceanography of Asian marginal seas*, Elsevier Oceanography Series, K. TAKANO, editor, Elsevier, New York, pp. 253–267.

LIMEBURNER R., R. C. BEARDSLEY and J. ZHAO (1983) Water masses and circulation in the East China Sea. In: *Proceedings of the International Symposium on Sedimentation on the Continental Shelf with Special Reference to the East China Sea, April* 12–16; *Hangzhou, China*, Vol. 1, China Ocean Press, Beijing, pp. 285–294.

MASUZAWA J. (1972) Water characteristics of the North Pacific central region. In: *Kuroshio: its physical aspects*, H. STOMMEL and K. YOSHIDA, editors, University of Washington Press, Seattle, Washington, pp. 95–128.

MIYAZAKI M. and S. ABE (1960) On the water masses in the Tsushima current area. *Journal of the Oceanographic Society of Japan*, **16**, 59–68 [in Japanese with English abstract].

NAKAO T. (1977) Oceanic variability in relations to fisheries in the East China Sea and the Yellow Sea. *Journal of the Faculty of Marine Science and Technology*, Tokai University Spec. No. 11, 362 pp.

NISHIDA H. (1980) Improved tidal charts for the western part of the North Pacific Ocean. *Report of Hydrographic Research*, **15**, 55–70.

NITANI H. (1972) Beginning of the Kuroshio. In: *Kuroshio: its physical aspects*, H. STOMMEL and K. YOSHIDA, editors, University of Washington Press, Washington, pp. 129–163.

PICKARD G. L. (1979) *Descriptive physical oceanography*, 3rd edition. Pergamon Press, New York, 200 pp.

POND S. and G. L. PICKARD (1983) *Introductory dynamical oceanography*, 2nd edition, Pergamon Press, New York, 329 pp.

QIN Y. S. and F. LI (1983) Study of influence of sediment loads discharged from the Hanghai river on sedimentation in the Bohai and the Hanghai Sea. In: *Proceedings of the International Symposium on Sedimentation on the Continental Shelf with special reference to the East China Sea, April* 12–16; *Hangzhou, China*, Vol. 1, China Ocean Press, Beijing, pp. 83–92.

QIU B. and N. IMASATO (1988) Baroclinic instability of buoyancy-driven coastal density currents. *Journal of Geophysical Research*, **93**, 5037–5050.

QIU B. and N. IMASATO (1990) A numerical study on the formation of the Kuroshio counter current and the Kuroshio branch current in the East China Sea. *Continental Shelf Research*, **10**, 165–184.

REID J. L. (1965) Intermediate water of the Pacific Ocean. *The Johns Hopkins Oceanographic Studies*, **2**, 85 pp.
SCHUBEL J. R., H. T. SHEN and M. J. PARK (1984) A comparison of some characteristic sedimentation processes of estuaries entering the Yellow Sea. In: *Marine geology and physical processes of the Yellow Sea, proceedings of Korea–U.S. Seminar and Workshop, June* 19–23, 1984, *Seoul, Korea*, pp. 286–308.
SVERDRUP H. V., M. W. JOHNSON and R. H. FLEMING (1942) *The oceans*. Prentice-Hall, New Jersey, 1087 pp.
WERNSTEDT F. L. (1972) *World climate data*, Climatic Data Press, 522 pp.
WUNSCH C. (1969) Progressive internal waves on slopes. *Journal of Fluid Mechanics*, **35**, 131–144.
WYRTKI K. (1966) *Seasonal variation of heat exchange and surface temperature in the North Pacific Ocean*. Hawaii Institute of Geophysics, University of Hawaii, 80 pp.
YANG Z. S., J. D. MILLIMAN and M. G. FITZGERALD (1983) Transfer of water and sediment from the Yangtze River to the East China Sea, June, 1980. *Canadian Journal of Fisheries and Aquatic Sciences*, **40**, 72–82.