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Synoptic temperature structure of the East China and southeastern Japan/East Seas

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Abstract

Air-deployed expendable bathythermograph (AXBT) surveys are used to investigate the synoptic temperature structure of the East China Sea (ECS), southern Yellow Sea, and southeastern Japan/East Sea (JES) from 1992–1995, in the depth range 0–400 m. The main results of this study are as follows. The regional winter mixed layer is shallow along the paths of the Kuroshio and Polar Front due to strong advection of warm water, which suppresses vertical mixing. The region where mixing is to the bottom is generally northwest of the 100-m isobath in the ECS and in the Tsushima Strait. Two September surveys reveal two different Kuroshio Front positions: in 1992 this front was far on-shelf of its mean position, preventing the formation of eddies at Mien Hwa Canyon; in 1993, the Kuroshio Front had migrated off-shelf, and eddies along the front had formed. The Kuroshio Current Branch West of Kyushu is not seen in summer at 60 m depth, only winter and spring; however, there is evidence of this branch current in all seasons at 100 m depth. Along the entire length of the ECS in all surveys except winter (where wind mixing had homogenized the water column), cross sections show that cold water (< 18 °C) inshore of the Kuroshio reached westward of the 200-m isobath, onto the shelf, and as shallow as 60 m. From 1992–1995, the Nearshore Branch is present in all surveys, and the East Korean Warm Current is generally present in spring–fall, and strongest in each May survey.

1. Introduction

The Tsushima Warm Current (TWC) originates in the East China Sea (ECS) and is the sole oceanic supplier of heat and salt to the Japan/East Sea (JES). The source of the TWC in the ECS and its pathway(s) once it travels from the ECS, through the Tsushima Strait (TS), into the JES, are still debated (See Ichikawa and Beardsley (2002) and Preller and Hogan (1998) for overviews of the regional oceanography of the ECS and JES, respectively.)

The ECS is bounded by the Izu Island Chain to the east, and includes the narrow and deep (2100 m maximum depth) Okinawa Trough, which rises steeply to the northwest, onto a broad and shallow (< 200 m) shelf bounded by China to the west and

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Korea to the north (Fig. 1). The Kuroshio enters the ECS northeast of Taiwan through the East Taiwan Strait, flows northeastward along the edge of the continental shelf west of the Izu Islands, and leaves the East China Sea through the Tokara Strait, south of Kyushu, Japan. Volume transports have been estimated at a maximum of 24 Sv (minimum of 20 Sv) through the East Taiwan Strait (Lee et al., 2000) in summer (fall); similarly, the Kuroshio outflow through the Tokara Strait has maximum volume transport in summer and minimum in fall (Kawabe, 1988), with a mean of 24 Sv (Ichikawa and Beardsley, 1993). The Taiwan Current flows through the Taiwan Strait west of Taiwan, northeastward along the continental shelf in the ECS, towards the TS. Volume transport of the Taiwan Current is estimated as 1.0 Sv in winter and 3.1 Sv in summer (Fang et al., 1991). Another input to the ECS is the freshwater discharge of the Changjiang River (0.01/0.05 Sv in winter/summer) (Yanagi, 1994), which modifies the ECS current properties. Transport of the TWC has been estimated to have an annual mean transport of about 2.7 Sv (Takikawa et al., 2001) with a maximum in autumn and minimum in winter. Whether the TWC is fed mainly by a branching of the Kuroshio west of Kyushu (e.g., Lie et al., 1998) or mainly by the Taiwan-Tsushima Warm Current System (TTWCS) (e.g. Fang et al., 1991) is still in question. (Refer to Katoh et al. (1996) for figures illustrating the competing views.) It is also thought that the Kuroshio could both influence the TTWCS and sometimes be the sole source of the TWC (Lie et al., 1998; Isobe, 1999a, b), and that this shift is seasonal, and dependent on the position of the Kuroshio against the continental shelf north of Taiwan.

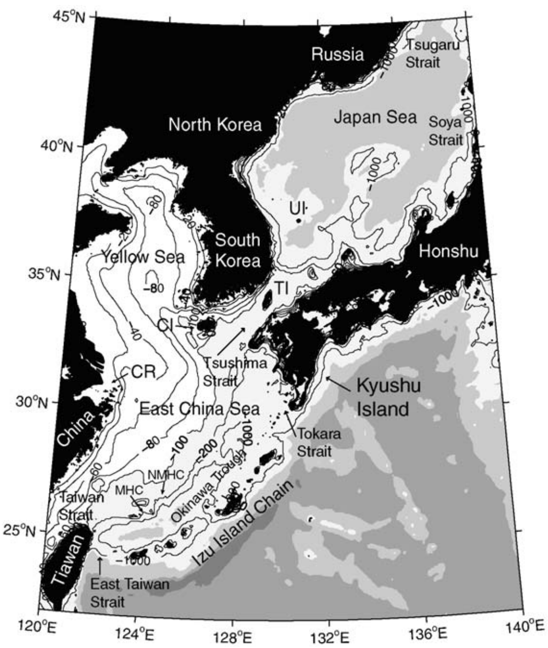


Fig. 1. Reference map of study region. ETOPO2 bathymetry is contoured at every 20 m down to 100 m, at 200 and 1000 m, and shaded at 1000 m intervals. MHC is Mien Hwa Canyon; NMHC is North Mien Hwa Canyon; TI is Tsushima Island; UI is Ulleung Island; CI is Cheju Island; CR is Changjiang River.

Once the TWC travels through the shallow (<200 m deep) TS, it enters the JES, a deep (3700 m maximum depth) semi-enclosed sea. Here, the TWC pathway is contested. The TWC has been thought to split into three branches, the East Korean Warm Current to the west along the coast of South Korea, the Nearshore Branch (NB) to the east following the shelf break west of Honshu, and the Offshore Branch (OB), located in the middle of the two, and flowing generally northward. It is also argued that the TWC, upon entering the JES, follows looping meanders towards the northeast. (Refer to Katoh (1994) for triple-branch or single-meander-path schematics of the TWC.) No matter the path, the TWC works its way north until it combines with the southward flowing Liman Current at about 40°N, turns east and creates the Polar Front, which generally divides the basin along latitude 40°N into cold (northern) and warm (southern) regimes. The outflow of the TWC is through shallow (<200 m) Tsugaru and Soya Straits to the northeast. Transports out of the Tsugaru Strait have been summarized as ~2 Sv, with a seasonal variation of ±0.75 Sv, maximum in autumn and minimum in winterspring (Preller and Hogan, 1998). Outflow through the Soya Strait is smaller, and estimated at 1.4 Sv, with seasonal variations (Oshima, 1994). Transport in and out of the JES is subject to relatively large seasonal and interannual variations.

Different conclusions about the origins of the TWC, and its branching structure entering the

JES, may originate with the limits of temporal and spatial coverage of the different studies. These questions may be further clarified with synoptic surveys of the region. In this study, we examine a series of synoptic air-deployed expendable bathythermograph (AXBT) surveys conducted in the ECS and JES during the years 1992–1995 (Table 1). These data have been used in a previous study of intra-thermocline eddies in the JES (Gordon et al., 2002). Here we provide a description of the larger data set, focusing on the origin of the TWC in the ECS and its pathways on entering the JES. We investigate the temporal evolution and the vertical structure of temperature fronts in these regions, and also across the ECS shelf break and within the TS. The synoptic coverage of the surveys allows a unique look at the quasi-seasonal 0–400 m temperature structure of the ECS and JES that has not yet been available for such a broad area. The numerous surveys allow us to identify persistent (and transient) circulation features.

2. Data

A new AXBT data set that has recently become available is used here to describe the temperature properties of the TWC and the surrounding oceanic environment. It has been shown previously that temperatures, below the influence of seasonal heating can be used as a tracer of water masses in this region, including the Kuroshio and Yellow Sea Cold Water (YSCW) (e.g., Kim et al., 1991). Sharp temperature gradients may sometimes be equated to the current pathways of the TWC (e.g., Katoh, 1994) and other regional currents (R. Beardsley, pers. commun.). This set comprises ~5100 AXBT profiles, obtained from the Master Oceanographic Observations Data Set (MOODS) at the US Naval Oceanographic Office (NAVOCEANO) of the Stennis Space Center. The AXBT profiles were obtained for the region 20°–50°N, 120°–143°E (ECS, Yellow Sea (YS) and JES). These profiles extend from the sea surface to a nominal depth of 400 m. The accuracy of temperature and depth from the AXBTs is about ±0.2 °C and ±5 m (Boyd, 1986).

Out of 30 possible AXBT surveys, 11 were selected for this study for (a) broad coverage of the ECS and southeast JES (specifically, south of 44°N, encompassing the Polar Front, and east of the North Korean air space), (b) high-resolution coverage of TS–southern JES region, or (c) coverage of the P–N line (a repeat survey line conducted from 1972-present by the Nagasaki Marine Observatory of the Japan Meteorological Agency). See Table 1 for exact dates and regions of each survey. The remaining 19 surveys were discounted because the station plan covered a limited region not of interest to this study, e.g. a Topex-Poseidon satellite ground track, or was of coarse resolution. Nominal station spacing for all chosen surveys was 35 km. In addition to the quality control imposed by NAVOCEANO, the selected survey data were examined for any questionable data. Suspect data were compared with AVHRR sea surface

Table 1
AXBT survey information

AXBT survey	Dates	Regions covered	Number of casts
September 1992	15–29 September1992	ECS, YS, JES/TS, P–N line	520
February 1993	31 January–14 February 1993	ECS, YS, JES/TS, P–N line	511
May 1993	30 April–14 May 1993	ECS, YS, JES/TS, P–N line	509
September 1993	29 August–10 September 1993	ECS, YS, JES/TS, P–N line	489
November 1993	2–3 November 1993	TS	67
February 1994	2–11 February 1994	TS, P–N line	157
May 1994	26 April–4 May 1994	TS, P–N line	160
August 1994	18–20 August 1994	TS	83
October 1994	24–31 October 1994	TS	193
May 1995	1–10 May 1995	TS	355
August 1995	7–8 August 1995	TS	127

temperature (SST) data, and, if appropriate, were removed. The single bad XBT profile, from the February 1993 survey, was located at 32.80°N 127.52°E and had nearly uniform temperatures ranging from 9.24 °C at the surface to 9.31 °C at the bottom (138 m), about 7 °C colder than surrounding waters. Although there have been cold eddies found at 32°N 126°E in satellite-derived SST, with surface temperatures 5 °C lower than surrounding waters (He et al., 1995), the February 1993 AXBT survey feature does not appear in 8-day composite averages of SST from AVHRR data from the same time. The offending cast was therefore removed.

Wind speed and direction (at 10 m) were used to help understand the environmental context in which the surveys were taken. Daily wind speed data from the MMR website were a part of the Special Sensor Microwave/Imager (SSM/I) products available from Remote Sensing Systems as a part of NASA's Pathfinder Program. The rms accuracy of the wind speed is 1 m/s (Wentz, 1997). Surface wind vectors were derived from ECMWF and SMM/I data (Atlas et al., 1996). Serial oceanographic data from the Korea Oceanographic Data Center (KODC) were used to help confirm the presence or absence of the East Korean Warm Current during the AXBT survey periods.

3. Results

3.1. Atmospheric context and mixed layer depth

The four large-scale regional surveys, each conducted within a 15-day period, make up a quasi-seasonal time series: September 1992, January–February, April–May and August–September 1993. Hereafter, we will refer to the 1993 surveys as February, May and September 1993 (see Table 1 for exact dates). Regional winds are strong and north–northwesterly from October through April and southerly and weak from May through September (Preller and Hogan, 1998). Wind stress in the ECS and JES is largest in January, coincident with the winter monsoon, and a high-pressure system over Siberia. Net air-sea heat flux is positive (ocean gains heat) from April through August and negative (ocean loses heat) from September through March (Preller and Hogan, 1998). Thus, the September 1992 and September 1993 surveys took place in times of climatologically weak southerly winds, and after months of positive heat flux (late summer). The February 1993 survey occured just after the peak regional wind stress, and negative heat flux (mid-winter). The May 1993 survey occured when winds are again from the south and weak, and heat flux had just become positive (spring).

The regional surveys are presented as horizontal temperature fields at 60 m depth. This depth was chosen as a common depth that fell below the direct influence of seasonal heating, which obscured the structure of the temperature fronts above the thermocline (see below). Mixed layer depth (MLD) for these data was calculated as the shallowest depth at which the subsurface temperature was at least 0.1 °C different from the surface temperature. (The MLD calculation was run with δT up to 0.25 °C, with no qualitative difference in the regional MLD patterns.) The MLD occurs where the mixed layer, the layer with temperature uniform to within 0.1 °C, and the transition layer, the stratified layer that separates the mixed layer from the undisturbed water beneath (Price et al., 1986).

In these data, the September 1992 and 1993 MLDs were shallowest in the JES, the TS, and in the YS, at about 25 m or shallower (Fig. 2A; September 1993 not shown). In the ECS, summer MLDs were generally deeper: 25–50 m in water shallower than 200 m and 50–60 m off-shelf. The deeper MLDs in the ECS compared to the JES in both September surveys may have been caused by strong (>10 m/s) wind events (cyclones)—observed in SMM/I data—that crossed the southeastern ECS 3 days (September 1992) and 8 days (September 1993) before the southern portions of both surveys were taken. No strong wind events occurred prior to the occupation of the northern part of the surveys, which might have deepened the JES/TS mixed layer.

The mixed layer in all regions was deepest in February 1993 (Fig. 2B), where waters were mixed in most areas deeper than 50 m or to the bottom.

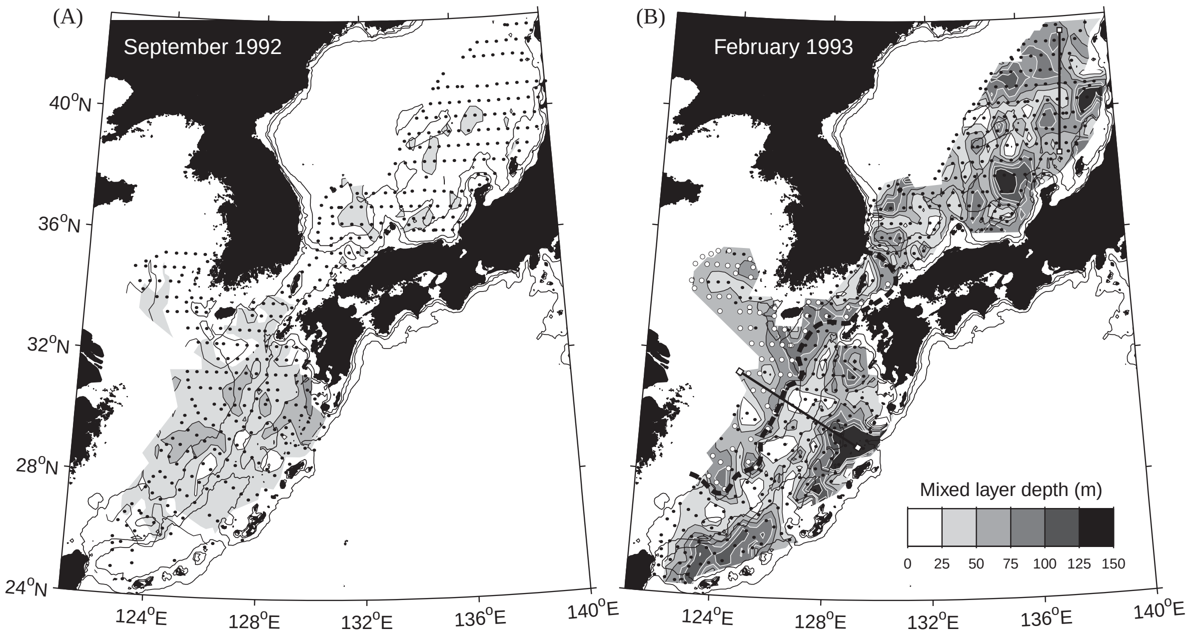


Fig. 2. Mixed layer depth defined as 0.1 °C different from surface temperature. Station locations are marked as black dots, or as white circles. If white circles, then MLD is at bottom; If black dot, then MLD is above bottom. (A) September 1992 survey, representing the summer MLD pattern. (B) February 1993 survey, representing winter mixed layer depths. Also included in (B) is a thick dashed line that separates the region where the water column is mixed to the bottom; black lines capped with white squares show section locations for Fig. 3. The 100-, 200-, and 1000-m isobaths are drawn.

Ten-meter wind speed data indicate that there was more storm activity in January–February 1993 than in August–September 1992, due to the winter monsoons. These strong and sustained winds deepened the mixed layer across the ECS and JES, often to the bottom over the shelf. The thick dashed line in Fig. 2B roughly divides the ECS/YS into regions where water has been mixed to the bottom (stations marked by open circles) or not (stations marked by black dots). In February 1993, most of the YS, the ECS shelf region shallower than 100 m, and the TS were mixed to the bottom. Also present in February 1993 were two 'bands' of shallower MLD: in the ECS, the shallow mixed layer 'band' fell between the 100- and 200-m isobaths, for the length of the sea; in the JES, the shallow mixed layer 'band' lay roughly along 40°N, in the general location of the Polar Front.

Price et al. (1986) modeled the mixed layer as the competing effects of wind strength versus heating and local stratification. Vertical mixing must satisfy the stability requirement $\delta\rho/\delta z \geqslant 0$ (their Eq. (8)). We assume that the wind stress patterns were not anomalously weak in the areas of shallow MLD as compared to regions on either side, and that ocean heat flux is not anomalous in these shallow MLD regions. These assumptions are supported by SMM/I data and by monthly mean (1978–1995) sea surface heat flux maps (Na et al., 1999), respectively. We are then left with the possibility that the vertical density gradient is stronger and shallower in these regions than on either side. Increased $\delta\rho/\delta z$ would act to stabilize the ocean, inhibiting mixing. In winter, salinity acts with temperature to enhance the vertical density gradient along the ECS shelf break (Fujiwara et al., 1987). Across the Polar Front, wintertime mean salinity increases only by ~0.2 ppt with depth to 400 m north and south of the Polar Front at 135°E (Chu et al., 2000), and so density structure would be dominated by temperature structure. Therefore, in winter, an increase in vertical temperature gradient signals an increase in vertical density gradient. Vertical temperature sections perpendicular to the shallow MLD bands (Fig. 3, MLD marked as a solid thick line; transects marked in Fig. 2B) show that where the MLD is shallowest, the vertical temperature gradient is stronger and shallower than on either side.

It seems likely that the advection of warm water along the Kuroshio and along the Polar Front maintains the shallow and strong vertical density gradient in winter in spite of strong wind mixing. The shoreward edge of the Kuroshio is manifested by isotherms that reach towards the surface over the 100- and 200-m isobaths (Fig. 3A), and bring warm water into the ECS. Similarly, the TWC brings in relatively warm water to the JES, and convergence of this current (or branches of this current) with the cold Liman Current maintains the Polar Front, roughly at the latitude at which the shallow mixed layer band is seen (Fig. 3B). Note that strong vertical temperature gradients exist both offshore of the ECS shallow mixed layer band and south of the JES mixed layer band. However, this occurs deeper in the water column off-shelf (ECS) or southwards (JES).

In May 1993, the deep mixed layer (not shown) was still present but less deep and had been capped (as seen in the temperature profiles) by a shallow water layer (<20 m) that was slightly warmer (>0.1 °C) than the mixed layer water temperature. In the following, we chose 60 m as a common display depth for all seasons because this depth fell below the summer heat-stratified layer. The water above the winter MLD, mixed by winter monsoon winds, retains its horizontal temperature structure, unlike water above the summer MLD, which is nearly horizontally uniform (Section 3.4).

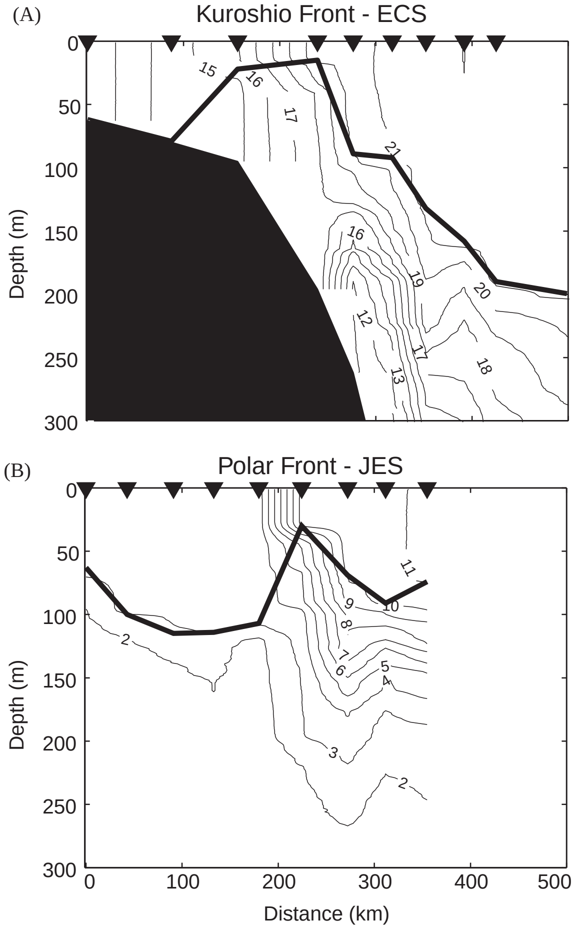


Fig. 3. Vertical temperature structure across the (A) ECS shelfbreak (left is west), and (B) the JES Polar Front (left is north) in February 1993. Triangles mark station locations, transect lines are marked in Fig. 2. The thick black line shows mixed layer depth, as calculated in Fig. 2.

3.2. Temperature structure and water mass identification

In this single year data set (September 1992–September 1993), we describe the temperature changes below the seasonal mixed layer, and relate this to previous water mass identification studies. The warmest water (>25 °C) of this 1-year cycle originates from the Kuroshio north of Taiwan in September 1992 and September 1993 (Figs. 4A and D). By the ECS water mass definitions developed in the T–S cluster analysis of Kim et al. (1991, hereafter K91), upper Kuroshio Water (KW) in summer can be defined as water with $T > 24\,°C$, $S = 34.4$ ppt, at a depth of about 50 m, below the seasonal thermocline of that study (see their Figs. 3 and 4B). We apply their definition to our 60-m depth temperature, also below the seasonal thermocline. By winter, the source of the KW from the Pacific has cooled (Fig. 4B), and is identified as water warmer than

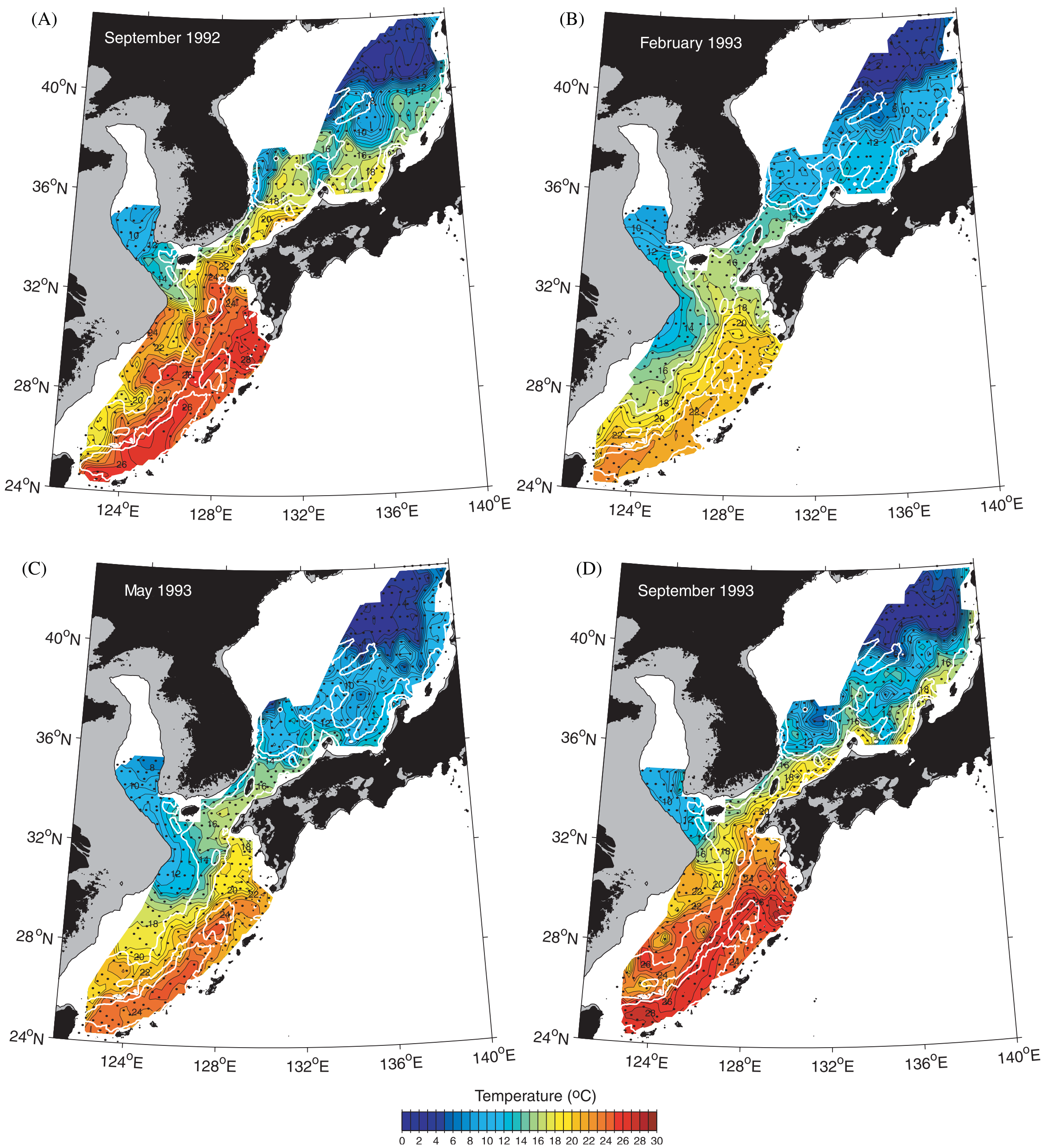


Fig. 4. Horizontal temperature sections at 60 m depth for (A) September 1992, (B) February 1993, (C) May 1993, and (D) September 1993. Black dots mark station locations; temperature contour interval is 1 °C; and the 100-, 200-, and 1000-m isobaths are drawn in white. The bathymetry from 0 to 60 m is masked in gray.

18 °C in this season (K91, their Fig. 3). The K91 study was conducted in July and in January, and thus the temperatures defining the KW in these data will likely be different. In summer and winter in these surveys, the isotherm that marks the shoreward KW extent is generally found between

the 100- and 200-m isobaths in the ECS, closer to the 100-m isobath in the south and gradually moving closer to the 200-m isobath traveling north. The isotherm turns eastward off the 200-m isobath between 29.5 and 31°N and continues eastward to the Tokara Strait. Two exceptions are (a) KW found in water westward of the 100-m isobath in the central ECS (north of 28°N) and westward of the 200-m isobath in the northern ECS in September 1992; and (b) KW found westward of the 100-m isobath south of 29°N in September 1993. In summer and winter, the northern limit of water that can be directly traced to the Kuroshio is about 32°N (farthest northward extent occurs in September 1993). Water mass definitions do not exist for the spring season, but water in the Kuroshio region is warmer overall by about 2 °C (Fig. 4C), and the 21 °C isotherm follows the general pattern described above.

Modified KW (MKW), defined as water that is a mixture of KW and East China Sea Water (ECSW), is identified as having temperatures 17–24 °C in summer (K91), though this water mass is not identified in winter in the K91 study. In both these summer surveys, MKW fills the rest of the ECS up to the mouth of the YS, and continues through the TS, setting the properties of the Tsushima Current. Water warmer than 17 °C in summer is found along the western Honshu coast, and as far north as 37.5°N in September 1992, and to 39°N in September 1993.

In all seasons, K91 define ECSW as having temperatures between 12 and 16.5 °C, with 33.5 ppt $< S <$ 34.6 ppt. This is similar to the water mass defined as the YSCold W extension by (Isobe, 1999b; his temperature range was 10–16 °C). By this definition, in summer, ECSW extends from the mouth of the YS to ~200 km into the YS, and makes up the remaining water entering the TS from the northwest. In winter, ECSW makes up all the water entering the TS and extends from the KW boundary up to approximately the same location as in summer in the YS. Water with $T < 12$ °C is also found just off the 60-m isobath (gray-shaded region in Fig. 4) from about 30–31°N, and extends from the up-shelf (shown in surface plot, below). Again, no springtime water definitions exist, but water within the ECSW temperature range occupies a belt beginning in the 30–31°N band, and following an S-shaped curve northwards towards the TS, and is the primary water mass entering the TS. In spring, water whose temperature falls between 16.5 and 21 °C, which we will consider here as MKW, only extends past 32°N in a narrow band to the southeast in the TS, and does not extend past Tsushima Island. YSCW, defined as water with $T < 10$ °C in all seasons (K91), only just meets the survey boundary in the central YS in these four surveys.

The source for the warm water in the JES is clearly from the ECS, and therefore the TTWCS and/or the Kuroshio. Once in the JES, the water quickly cools, and isotherms reveal complex patterns of branches and eddies. In summer 1992 and 1993, water in the southeastern JES south of Polar Front ranges from about 22 to 14 °C, south to north. The strong Polar Front can be seen at 40°N with a temperature gradient of about 10 °C over 40 km, and cold water (<4 °C) north of that. Within the JES in winter 1993, waters are cooler and more homogenous south of the Polar Front, ranging from about 13 °C in the south to 9 °C at the southern side of the front. The front itself has a weaker gradient, falling about 6 °C over 50 km. North of the Front, waters are about 2–4 °C. In May 1993, the temperature field has a slightly more complicated structure than in February within the southeastern JES; water is slightly warmer, and the Polar Front gradient is slightly stronger. May temperatures range from 14 to 10 °C south of the Front, fall about 6 °C over about 40 km, and are still 2–4 °C north of the Front.

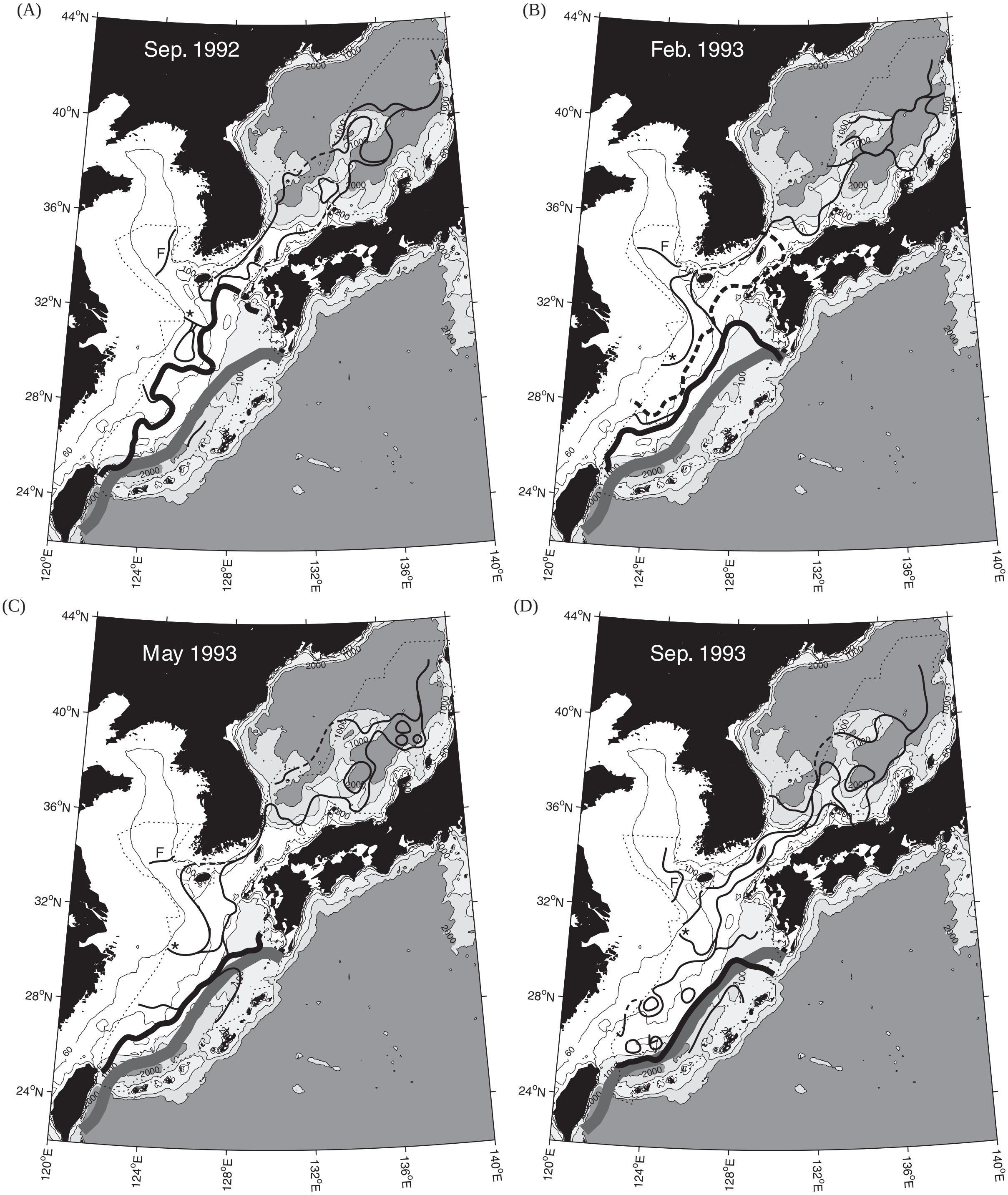
3.3. Seasonal evolution of temperature fronts

The water mass boundaries identified in the previous section are in most cases coincident with temperature fronts, where isotherms converge. These fronts sometimes identify current pathways and current boundaries in this region: i.e., the Kuroshio Front (after Hickox et al., 2000), which defines the shoreward boundary of the Kuroshio as its warm water converges with the cooler ECS shelf water. The synoptic AXBT surveys allow us to investigate the seasonal evolution of the position of these fronts.

The synoptic front structure at 60 m depth in each survey is illustrated in Fig. 5, where schematic lines define temperature gradients of at least 2 °C within ~35 km width, roughly the distance between two survey stations. The shoreward Kuroshio temperature front has been made bold; all other fronts have equal line weight, regardless of intensity of the gradient. The mean surface current pathway of the Kuroshio (from geomagnetic electrokinetograph data, 1953–1977), taken from Sun and Su (1994), is presented as a wide gray band in these schematics for reference. Based on the conclusions of James et al. (1999), who found the Kuroshio in the ECS to oscillate with the 11–12 day period, with a wavelength of 210 km, and a downstream phase velocity of 18–20 km/day, the temperature structure of the Kuroshio may be considered nearly synoptic. Though the surveys took an average of 15 days to complete, the ECS/YS/TS portion of the survey took 5 days, with no more than three days to sample the ECS. We also assume that other fronts in the ECS, YS, TS, and JES will not alter significantly in structure over the few days time it took to survey the region (e.g., inverted echo-sounder data moored at the entrance of the JES show that the TWC takes several weeks to change pathway positions, D. Mitchell, pers. commun.).

In each of the four surveys, the shoreward Kuroshio Front falls west of the mean pathway of the Kuroshio Current, east of Taiwan, as expected. In the two summer surveys (Fig. 5A and D) this front turns immediately due east, whereas in winter (Fig. 5B) and spring (Fig. 5C), the same front is directed first north, bringing KW over the shelf, before it turns eastward about 100 km north of the summertime turning position. The pathway of the September 1993 Kuroshio Front is based on the 25–27 °C isotherms, slightly warmer that the July KW definition of K91. In September 1992, the Kuroshio Front is cooler, 23–25 °C, as there is no obvious front in the warmer isotherms. The Kuroshio northeast of Taiwan has been shown to migrate seasonally on-shelf in winter and spring, and off-shelf in summer and fall (Tang et al., 2000). (And has been shown to follow a similar migration within the entire ECS (Isobe 1999a).) According to the results of Tang et al. (2000), the off-shelf migration of the Kuroshio in summer allows cold water to upwell at the Mien Hwa Canyon and North Mien Hwa Canyon (see Fig. 1 for locations), forming cold eddies up on the shelf of the ECS. This process will be described in greater detail in Section 3.5. The onshore position of the Kuroshio Front in winter and spring prevents eddies from forming at these canyons. The February 1993, May 1993 and September 1993 surveys conform to this theory. Eddies do not form in winter and spring, and have formed in summer, when the Kuroshio Front is off-shelf. (Another cold water 'plug' in September 1993 exists north of the MHC and NMHC at 28.3°N 126.0°E: in cross section, this does not have eddy characteristics, but rather appears as cooler water with temperature signature traceable to the deep water of the Okinawa Trough.) In the September 1992 survey, the Kuroshio Front, after turning due east on entering the ECS, is diverted northward; thus, no eddies have formed. The Kuroshio Front remains far on-shelf (as compared to September 1993) through the ECS until it leaves through the Tokara Strait. The meander lengths of the September 1992 Kuroshio Front are about 100 km, which agrees well with that found by James et al. (1999).

The Taiwan Current flows out of the Taiwan Strait, and proceeds northeastward shoreward of the 100-m isobath (Ichikawa and Beardsley, 2002; hereafter IB02). Most of this region in the southwest ECS is outside the boundaries of these survey data. If we judge Kuroshio-derived water by the water mass definitions of K91, however, we might conclude that the colder waters (<24 °C in summer and <18 °C in winter), if not originating from beneath the warm upper KWs, may originate from the Taiwan Strait, and therefore the Taiwan Current. In September 1992, there appears to be Taiwan Current Water (TCW) to the north of the Kuroshio inflow but this cooler water is blocked downstream at this depth, pushed shoreward of the survey boundary by the warmer Kuroshio intrusion (Fig. 4A), located at about 28°N 125°E. A similar, but less intense 'blocking pattern' appears in September 1993 (Fig. 4D), in the same


(A)
Sep. 1992
(B)
Feb. 1993
(C)
May 1993
(D)
Sep. 1993
44°N
40°N
36°N
32°N
28°N
24°N
120°E
124°E
128°E
132°E
136°E
140°E
F
*
60
100
1000
2000

location. There is evidence of what may be the Taiwan Current in the winter, spring and latter summer surveys. In winter and spring, the cooler gradient (17–19 °C in winter, 19–21 °C in spring) joins with the strong Kuroshio Front at about 28°N. In September 1993, the cooler gradient associated with the Taiwan Current or TTWCS (21 °C–24 °C) runs parallel to the Kuroshio Front, along the 100-m isobath, through the ECS, and into the JES. This pattern (September 1993) is consistent with the January through September schematic developed by Isobe (1999a) in which the TTWCS parallels the Kuroshio but they do not meet, and it is only the TTWCS that enters the TS. The same volume transport modeling study showed the Kuroshio branching into the TWC from October through December. In contrast, in these data, the temperature fronts suggest that the Kuroshio is directly linked to the TWC at this depth in all surveys except for September 1993.

The strong gradient that marks the convergence of the YSCW extension/ECSW with the modified KW or KW (marked by an asterisk in each survey in Fig. 5) migrates seasonally from the north in summer, to its greatest southward extent in winter, and back. The easternmost position of this front occurs in spring. The southeastward push of this cold water is coincident with the northwest monsoon winds. This temperature front is the same as was identified in Hickox et al. (2000) in SST data, and referred to by them as the Yangtze Bank Ring Front. The seasonal movement of this front is better seen in these sub-surface data because this front disappears in their surface study in summer. The heat transport pathway of the TTWCS follows the edge of this cold-water nose (Isobe, 1999b), while the cold water modifies the TTWCS on its way to the TS.

The weak YS front is marked by an 'F' in each survey of Fig. 5. Because we do not have data that covers the breath of the YS, it is not possible to identify that the Yellow Sea Warm Current exists in these 60-m data. The axis of the YS front changes seasonally from northeast to southwest in summer and northwest to southeast in winter, and nearly west to east in spring. Warmer water resides in the east of the YS entrance in summer, and in the west in winter. The summer front is farther up into the YS in September 1992 than 1993, perhaps due to the anomalously shoreward position of the Kuroshio Front.

The Kuroshio, as it turns due eastward to leave the ECS, forms a branch current that continues northward in the ECS, known as the Kuroshio Branch Current to the West of Kyushu (KBCWK; after IB02). The temperature signature of the KBCWK can be clearly seen in the winter and spring surveys in the 17–19 °C isotherms. The separation locations 127.5°E, 30.5°N and 127.5°E, 29.5°N agree very well with that found in surface drifter data by Lie et al. (1998), at 127.5°E, 29.5°N. The KBCWK is not found in either summer survey at this depth, but evidence of it is found deeper in the water columnin the next section. The existence of the KBCWK in February and May contradicts Isobe (1999a), who finds the KBCWK from October to December only. In contrast, Wanxian (1994) finds the same seasonal timing: the KBCWK is the source of the TWC in winter and the 'continental shelf water' is the source of the TWC in summer.

There are weak fronts to the east of the Kuroshio in the ECS present in spring and summer. Similar temperature fronts in the ECS have been interpreted as southward return flow of the Kuroshio (Kondo, 1985). Instead, these temperature gradients may be the expression of weaker flow along the eastern edge of the Kuroshio, similar to the temperature signature seen in the Gulf Stream (R. Watts, pers. commun.).

Despite the difference in the Kuroshio Front position in both summer surveys in the northern

Fig. 5. Temperature front schematic at 60 m depth for (A) September 1992, (B) February 1993, (C) May 1993, and (D) September 1993. The mean surface Kuroshio path (taken from Sun and Su, 1994) is shown as a wide gray line along the Okinawa Trough. Bathymetry drawn as in Fig. 4, shaded every 1000 m. Dashed lines connect front lines that fall outside the survey boundaries; they are not meant to imply pathway, but connect fronts with identical temperature ranges. Dotted lines mark survey boundaries. The thick dashed line in (B) outlines the region (to the west) where water is mixed to the bottom (from Fig. 2b). See text for further description.

ECS, temperature fronts entering and within the TS exhibit a similar pattern. In this season, two fronts enter the TS south of Cheju Island, though in September 1992 the fronts are pushed northward towards Cheju relative to the next September's front positions. In winter, both the KBCWK front and the northeastward front associated with the convergence of the YSCW and the ECSW (IB02) enter the TS north of Cheju. In spring, the KBCWK enters south of Cheju, while the northeastward front remains north of Cheju. The seasonal frontal pattern is consistent with the SST frontal analysis of Hickox et al. (2000). Their 'Eastern Chejudo Front' and 'Western Chejudo Front', which fall along the Korean coast to the east and west of Cheju Island (their Fig. 2), exhibit a similar seasonal cycle: the eastern front develops is summer and fall, and the western front appears in the fall and winter. In the spring the eastern front strengthens, while the western front disappears. This is consistent with the subsurface thermal structure, where the fronts to the west of Cheju Island appear only in winter and spring. Within the TS, in winter and spring, the strongest temperature front at 60 m is found in the western channel. In both summer surveys, two fronts exist, the warmer one in the eastern channel, and cooler one in the western channel.

On exiting the TS, all fronts cross over from west to east and approximately parallel the 200-m isobath off the west coast of Honshu, except in September 1992, where one front continues northward from the western channel. It is possible that this may be due to the onshore position of the Kuroshio in that season (high flow volume?). It is difficult to determine the existence of the EKWC, because this current may flow inshore of the survey boundaries near Korea. Additionally, the Eastern Branch of the TWC may fall shoreward of the eastern survey boundaries. The temperature front structure on leaving the TS will be discussed in more detail, below.

Temperature gradients of the Polar Front are much stronger in summer than winter, due to the warm water influence from the ECS. In September 1992, a very large meander in the Polar Front is centered at 39°N 135.5°E, with a diameter of about 250 km. The Polar Front is oriented along 40°N, and turns sharply northward at 139°E, heading for the Soya Strait. In February 1993, the Polar Front is oriented at a 45° angle from the southwest to northeast towards the Tsugaru Strait region, and a branch continues northward to the Soya Strait. In May 1993, the Polar Front is oriented west to east along 39°N, with a sharp 90° turn to the north at about 139°E, and in September 1993 meanders along 39°–40°N, and again turns sharply northward at 139°E. Temperature front positions in the JES are variable through the 1992–1993 time span of these surveys, exhibiting no obvious seasonal pattern within these survey boundaries.

3.4. *Comparison of mid-depth to surface and deep temperature fields*

To illustrate the changes of the ECS temperature fields with depth and season, we examine the four surveys at the surface, 100, and 200 m (Fig. 6, only the 100-m temperature fields are shown). The 100-m level was chosen because it shows different characteristics from the 60-m summer surveys previously shown, and so that we may compare ECS to the smaller scale surveys of the TWC branching structure, which are also presented at 100 m (Section 3.7).

3.4.1. *Surface layer*

The dominant feature of the surface temperature fields (not shown) is the masking of the subsurface temperature structure within the ECS and JES in the two September surveys. In contrast, the February and May surface temperature fields are approximately the same in structure as the 60-m counterparts (Fig. 4B and C). In September 1992 and 1993, the ECS is blanketed with a relatively warm (~24–28 °C) layer. Variability in temperature of 2–3 °C can be seen in the YS, but this, too has been greatly damped by surface heating (compared to the same surveys at 60 m, Fig. 4A and D). The southeastern JES is similarly masked in summer. This emphasizes the need for subsurface in situ observations in this season.

In February, the isotherm pattern is nearly identical to the 60-m pattern described in the previous section. This reflects the deep mixed layer

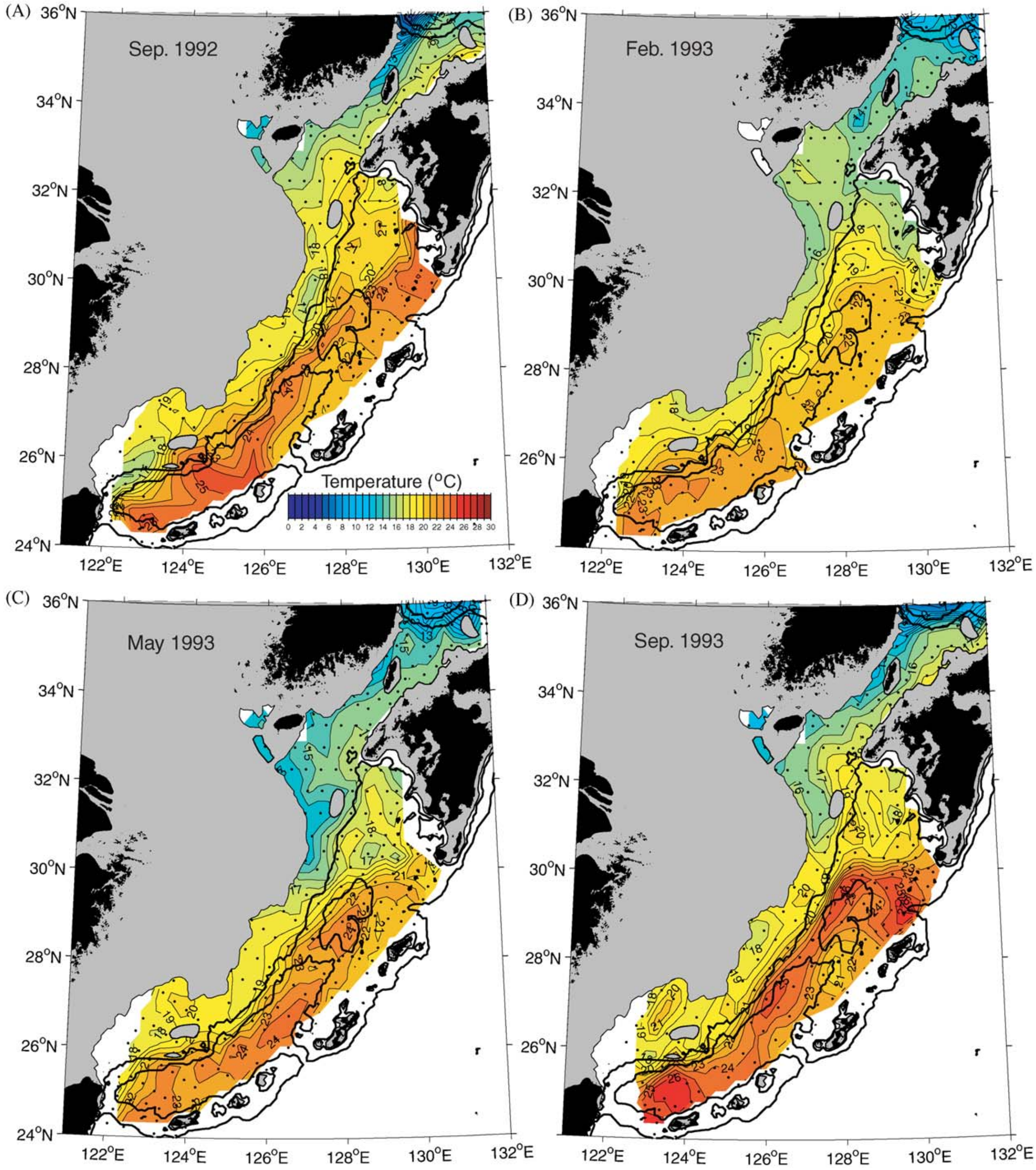


Fig. 6. Temperature at 100 m depth for the East China Sea for (A) September 1992, (B) February 1993, (C) May 1993, and (D) September 1993. Stations and bathymetry drawn as in Fig. 4. The bathymetry from 0 to 100 m is masked in gray.

of winter (Fig. 2B). It is important to note here that the highly stratified ocean in September is vertically well mixed by February, and this mixing is one cause of the weaker horizontal temperature gradients and reduced mesoscale structure. One difference in the February 1993 surface field can be seen east of Taiwan, where water warmer than 20 °C extends to the western edge of the survey. It is clear from the 60-m plot that these isotherms bend to the south with depth, and originate with the Kuroshio. At the surface, the data domain covers a larger area, and at this level a tongue of relatively warm water (10–14 °C) extends NW into the YS to at least 34.5°N 122.5°E— the survey's north-westernmost edge. This tongue had been previously interpreted as the YSWC (e.g., Kondo, 1985), but as noted by IB02, this tongue may be due to tidal mixing or episodic wind events.

In May, the surface waters have warmed, and the surface plot is generally everywhere warmer than the 60-m temperature field. The isotherms north of Taiwan exhibit a similar change with depth as was described in winter. The cold "nose" from the YSCW extension/ECSW does not extend as far east at the surface, consistent with cross sections showing the cold water as a wedge that reaches eastward at the bottom, with warm water above reaching towards the YS (Isobe, 1999b). The YS warm water tongue has diminished and is now oriented N–S and extends only to Cheju Island at 33.5°N 125°E.

3.4.2. 100 m

Much of the shelf of the ECS and all of the YS are shallower than 100 m, so a 200-km wide path connects the deep ECS to the JES through the TS. (The southern JES at 100 m will be discussed in Section 3.7.) The Kuroshio is seen clearly at this depth in summer (Fig. 6A and D) and spring (Fig. 6C) as a band of warm water entering the ECS north of Taiwan, and leaving south of Kyushu. This band breaks down in the February survey (Fig. 6B), where 23 °C water only reaches to 26°N at this depth (and at the surface and 60 m). The Kuroshio Front falls farther off-shelf in the summer and spring surveys at 100-m depth (Figs. 6A, C and D) than at 60 m (Figs. 4A, C and D), reflecting the tilting isotherms of the eastern Kuroshio Front. In contrast, the winter front is in almost the same location with depth (Figs. 4B and 6B), evidence of strong wind mixing. It is notable that the two summer surveys are much more similar in structure at this depth than at 60 m.

Unlike at 60 m, at 100 m evidence of the KBCWK is present in all four surveys, and is located at about 30°N 128°E. In summer, the KCBWK isotherms are 18–20 °C, in winter and spring, 17–19 °C. This separation location appears in approximately the same position from the surface to 100 m in winter and spring. Water in the TS does not seem to be directly from the KCBWK, but a modified version of this water, as it is slightly cooler.

In summer, isotherms (in the 14– 17 °C range) that run generally parallel from the ECS through the TS appear to originate from a combination of the KBCWK and water from the shallow bank to the west at 32°N. In winter, the water through the TS seems to originate from the same two sources, but the cooler water originating up-shelf has migrated southward, and is the deep expression of the front marked with an asterisk in the 60-m front schematic (Fig. 5). Cross sections across the ECS side of the TS are presented below and better illustrate source water to the TS, and therefore the TWC. In the winter survey, where waters have been well mixed by winds from the surface, the temperature is nearly uniform through the strait. In May, this is also true. By summer, the temperature gradient across the strait had increased, with warm water along the eastern channel, similar to the 60-m level.

3.4.3. 200 m

At 200 m (not shown), the JES and ECS are isolated from each other. In the JES in all seasons, temperature structure consists of eddy-like patched of warm water (> 7 °C) with surrounding water < 4 °C. These eddies are confined to the south of the Polar Front, and have been previously described from this data in Gordon et al. (2002), as intra-thermocline eddies, subducted under the Polar Front. In the ECS, the temperature front associated with the Kuroshio is about 15–18 °C in all seasons, with warmer water to the southeast.

The coldest water (< 13 °C) is pooled in the northwest canyon of the Okinawa Trough. Interestingly, the warmest KW is found in February (21 °C), whereas in September 1992, the water temperature only reaches 19 °C. This is likely due to the deep winter mixing, which brings warmer water deeper into the water column than do heating, mixing, or advection in other seasons.

3.5. Vertical temperature structure across the ECS shelf break

3.5.1. Mien Hwu Canyon

At the very southwest of the survey, near MHC, the Kuroshio Branch Current North of Taiwan (KBCNT, after IB02) (Fig. 4A) sometimes forms when the Kuroshio is off-shelf. This is a branch of the Kuroshio that turns westward at the North Mien Hwa Canyon (Isobe, 1999b), recirculates cyclonically to the east, then south-east at Mien Hwa Canyon (MHC), sometimes clipping off the cooler upwelled water, forming cyclonic eddies (Tang et al., 2000). Examples of these eddies were shown in Figs. 4D and 5D. Cross sections of the temperature data perpendicular to the shelf break (Fig. 7) show the development of one MHC eddy. In September 1992, the turning location of the Kuroshio Front is nearly 100 km westward of its September 1993 position, and a plug of cool (< 18 °C) water is surrounded by warmer water (Fig. 7A). In September 1992, an eddy has not formed, probably because the Kuroshio is not off-shelf. The cooler water may have its source from the Taiwan Strait, though the Taiwan Current is usually found shoreward of the 100-m isobath (IB02), or this cooler water may have its origin from the deep Okinawa Trough. The 100-m temperature section (Fig. 6A) does suggest that the KBCNT has formed in September 1992, as the 18–20 °C water forms a cyclonic branch as described by Isobe (1999b). By winter (Fig. 7B), the Kuroshio thermal front structure is much weaker and cooler, with the mixed layer depths shallowest where the Kuroshio Front reaches towards the surface. No. 18 °C water resides on the shelf, probably because it has been mixed with warmer water from shallower in the water column. By May 1993 (Fig. 7C), 18 °C water is again present on the shelf, and may again be a manifestation of the KBCNT (see Figs. 4C and 5C), and the Kuroshio Front temperature gradient has strengthened. In September 1993 (Fig. 7D), the Kuroshio front is farther off-shelf compared to the other surveys, and an eddy can be seen between the 100- and 200-m isobaths. The eddy is about 80 m in height, with a diameter of about 100 m, with a temperature difference between the eddy center and surrounding water of 3–4 °C. These eddy characteristics agree well with those found by Tang et al. (2000).

3.5.2. P–N line

Fig. 8 presents a two-year time series of the vertical temperature structure along the P–N line (two other AXBT surveys have been used (see Table 1) to create this series). In both September surveys (Figs. 8A and D), cool water ($T < 19$ °C) is present along the shelf break between the 100- and 200-m isobaths; its source appears to be the deep Okinawa Trough. By winter in both years (Figs. 8B and E), vertical structure across the P–N line is more homogenous. The cooler water from the trough has modified the ECSW, but the cold water present higher up on-shelf (shallower than the 100-m isobath) originates in the YS (Isobe, 1999b). In each September (Figs. 8A and D) and May (Figs. 8C and F) survey, the seaward temperature front of the Kuroshio is weaker than the inshore front. This compares well with the mean state along the P–N Line (Fujiwara et al., 1987), though the synoptic survey data reveals greater structure in all seasons (e.g. the secondary V-shaped jetto the west in September 1993; the different widths of the main temperature core of the Kuroshio from one May to the next).

The cold water between the 100- and 200-m isobaths originating from the deep trough occurs at almost every cross section perpendicular to the shelf break in the ECS in these September and May surveys, and in some February sections as well, with similar characteristics as the P–N cross sections. This 18 °C water is isolated from the cold YS source water by warmer water between the two. In some cases, as in the cold water 'plug' located at 28.3°N 126.0°E (described briefly above), this cold water domes up as shallow as

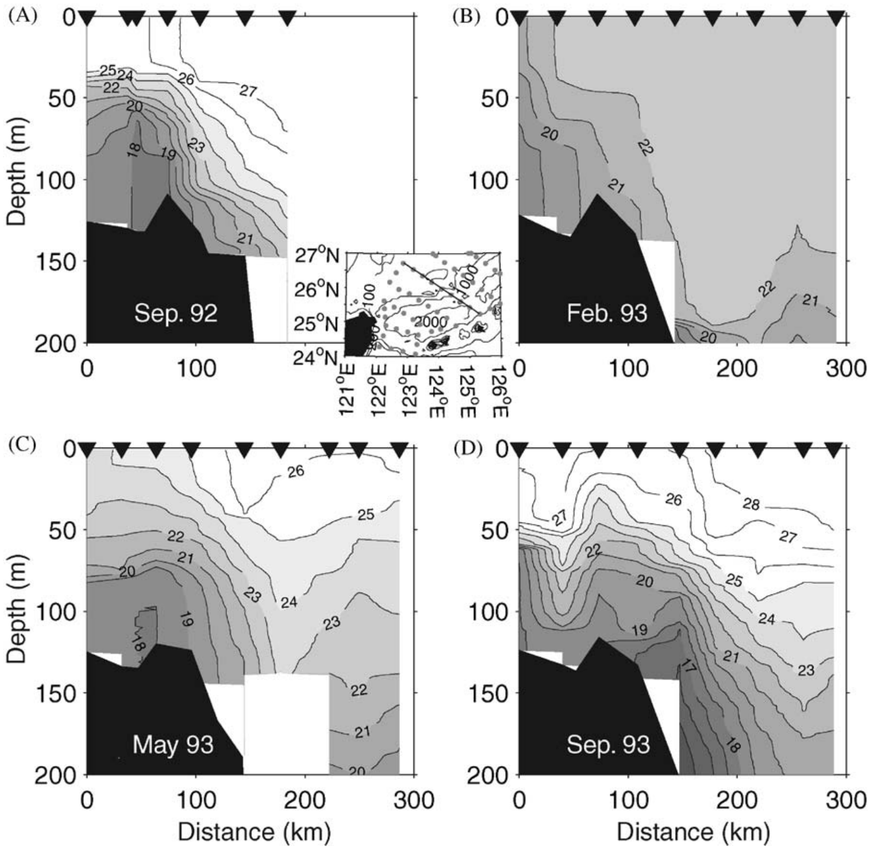


Fig. 7. Vertical cross sections along station lines perpendicular to the continental shelf at Mien Hwa Canyon, showing eddy development in (A) September 1992, (B) February 1993, (C) May 1993, and (D) September 1993. Temperature is shaded and contoured every 1 °C; bathymetry shaded as a black patch, and stations are marked along the top as black triangles. The inset map shows the location of the section, with bathymetry and stations presented as in Fig. 4.

60 m depth, though does not reach shoreward of the 100-m isobath. The extent of the cold water is also visible when comparing the 60- and 100-m horizontal summer (Figs. 4A and D and Figs. 6A and D) and spring (Figs. 4C and 6C) sections. Warm water blankets the shelf from the Kuroshio over the 100–200 m isobaths, but 40 m deeper in the water column, at 100 m, colder water appears inshore of the Kuroshio Front for the length of the ECS. The source of this colder water is most often from the deep trough, and it appears that the water from the deep trough may be another source of cold water to the ECS shelf. It is unclear what mechanism brings the water onto the shelf, though it has been suggested that internal waves along the shelf break may play a role in cross-shelf flow (Han et al., 2001).

Although mean properties across the P-N line below 200 m do not vary significantly with season (IB02), there is significant variation in these synoptic data with season and year. With season, the water is warmer below 200 m in winter and spring than in summer (see 18 °C isotherm). This is likely due to the vertical extent of winter mixing, as mentioned in the previous section. Interannual temperature structure changes between the 2 years are best seen in the February surveys. In February 1993, the coldest water is <9 °C at about 350 m depth, whereas in February 1994, the vertical and horizontal front is not as sharp, and the coldest

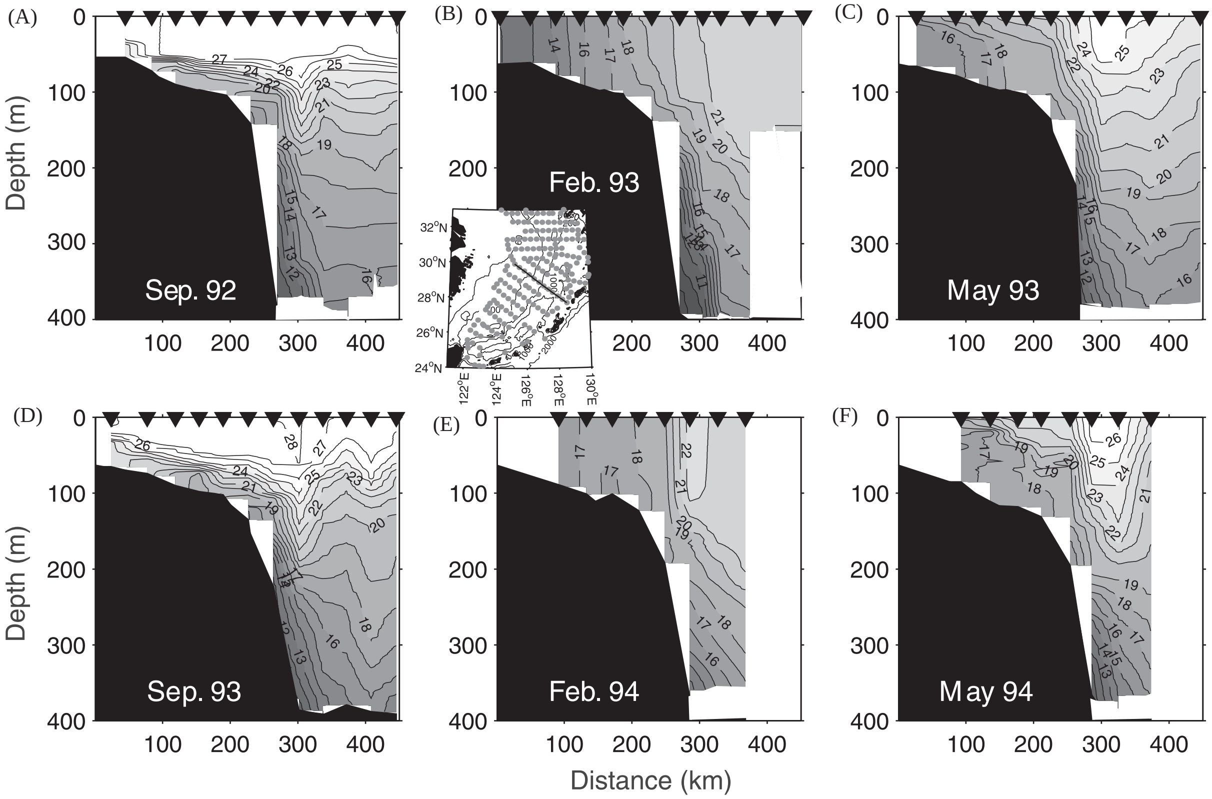


Fig. 8. Cross sections along station lines perpendicular to the ECS shelf break that fall along the P–N line (see text). Vertical temperature fields, bathymetry, and inset map are drawn as in Fig. 7.

water is only 13 °C. The colder isotherms are most likely inshore, but the stronger temperature gradients in 1993 suggest stronger current flow.

3.6. Seasonal evolution of water properties within the TS

Temperature structures across the TS (Fig. 9) generally show that warmer water is found to the east in the TS, and isotherms stretch from the upper water column to the west, diagonally to the bottom at the central or eastern strait. Cold water is to the west and in the deeper water. This is most obvious in the summer surveys (Fig. 9A and D) and also in spring (Fig. 9C), since in winter (Fig. 9B) the water column is vertically well mixed. Water within the strait is warmer deeper in the water column in September 1992 than 1993 by about 1 °C, possibly due to the anomalous westward and northward extent of the upper Kuroshio seen in the 60-m section (Figs. 4A and 5A), which may have brought warmer water into the strait. The coldest water (<13 °C) in the TS occurs in February 1993 (Fig. 9B).

On the ECS end of the strait (Fig. 9, left column), it appears that the warm water source to the TS originates in the ECS, specifically from the KBCWK, or waters modified by this Kuroshio source. The colder water that remains in the western channel of the TS appears to originate from west of Cheju Island, and therefore waters from the YS, or from up-shelf on the western ECS bank. Waters of similar cold temperature are present on the ECS side of the entrance, but these waters appear confined to the east of the 150-m isobath and in water depth below 100 m.

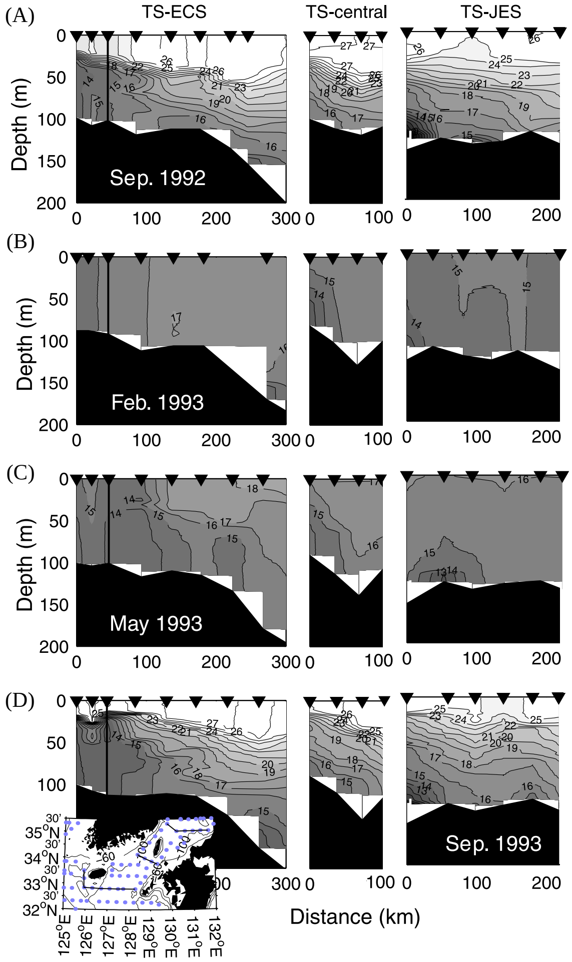


Fig. 9. Vertical sections across the entrance of the Tsushima Strait (TS-ECS, column 1), within the strait south of Tsushima Island (TS-central, column 2), and at the exit of the strait (TS-JES, column 3). Each cross section is presented with west on the left hand side and east to the right. Data and inset map are drawn as in Fig. 7. Rows are (A) September 1992, (B) February 1993, (C) May 1993 and (D) September 1993. The solid vertical line that cuts through the data in column 1 marks the turn from a N–S section to a W–E section.

At the JES end of the strait (Fig. 9, right column), waters with temperatures similar to those within the TS are generally above 150 m, which is the depth of the central strait. In both September surveys, cold water ($<6\,^{\circ}$C) can be seen to the west above 150 m, and is the East Korean Cold Bottom Water (EKCBW) originating from the north side of Korea, and entering the west side of the TS (Cho and Kim, 1999). The EKCBW has been observed to flow out of the JES through the TS only in summer, and to be blocked by the TWC in winter (Cho and Kim, 1999), and this appears true in 1992–1993 as well. Along-strait sections (not shown) show that this water extends to the southern tip of Tsushima Island, and below 100 met depth, except at the exit of the strait, where it shoals to about 75 m depth. The cold temperature signature from the Okinawa Trough is limited in extent to about the southern tip of Tsushima Island in the eastern channel in these data.

3.7. Branching of the TWC in the southern JES

The TWC has two usual branches, the western one which becomes the East Korean Warm Current, which flows northward along the Korean coast, then turns eastward and joins the Liman Current at ~40°N, and the eastern NB, which travels along the 100-m isobath through the Yamato Basin to join the Polar Front at ~40°N (Katoh, 1994). The OB periodically forms as a branch of the EKWC, and flows from the TS to the JES perpendicular to the shelf break (Katoh, 1994). In the temperature fields, regions of high gradient can be interpreted as the branches of the TWC as it travels into the JES. (Hase et al. (1999) show temperature maps at 60–70 m and ADCP data overlaid, which demonstrate this point.) 100 m is the historical depth for observing the TWC branching – e.g. Ichiye and Takano, 1988; Katoh, 1994. We therefore investigate temperature at 100 m for 11 surveys taken from September 1992 through May 1995 (see Table 1 for survey details). The ECWK and NB are sometimes outside the survey boundaries; we therefore use KODC repeat survey sections along latitudes 36.0°N, 36.5°N, and 37.0°N from the Korean coast east to about 131.5°E to determine the presence of the EKWC during these periods. Following the definitions prescribed by Katoh (1994), we define the NB as a single or multiple isotherm(s) oriented west-east along the 100-m isobath off the coast of Honshu. The OB is defined as isotherms that follow out from the TS and travel across isobaths. The EKWC is defined as isotherms that are oriented parallel to the 100-m isobath off the east coast of South Korea. Fig. 10 presents sections that best represent the three characteristic patterns for the 100-m temperature field.

Over the $2\frac{1}{2}$ year period from September 1992 to May 1995, the warmest water (>17 °C) entering the JES is seen in the September, October and November surveys. The coldest source water is in February and May, as was seen in the 60-m sections (Fig. 4). Overall, these surveys seem to fall into three 'modes'. In the first mode (Fig. 10A; February 1993; September 1993–February 1994), the EKWC was not present (confirmed with KODC data), and a single strong gradient (in the range of 8–16 °C) travels from west to east across the mouth of the strait, and will be considered the NB. In the second mode (Fig. 10B; May 1993, May 1994, and May 1995–August 1995), the Ulleung Island eddy is present south of or near Ulleung Island, and two branches can be seen or inferred, EKWC flowing north with a 5–10 °C thermal gradient, and the NB flowing eastward in the 10–15 °C range. In the third mode (Fig. 10C; September 1992; August 1994–October 1994), the axis of the warm water branch that is 'usually' north to south, falling in line with Ulleung Island and along the Korean coast, is displaced eastward, so that the axis of the warm arm is about 30° eastward of Ulleung Island. In this third mode, two branches are present, with the 10–16 °C NB along the Honshu coast and the 6–10 °C branch northeastward of Ulleung Island on leaving the TS. By the definitions of Katoh (1994), we may call this displaced branch the OB, but from its temperature signature and the fact that there is no additional EKWC, it seems possible that this branch is a displaced EKWC.

From 1992 to 1995, the EKWC is strongest and closest to the Korean coast in May. In each August, September and October (except for September 1993), the EKWC is present but offshore of its May position, and east of Ulleung Island (and could be considered the OB). The EKWC is not present in either February survey, and is not present for the period September 1993 through February 1994. In no survey were three branches observed, and in each survey, the NB was present. Comparing these seasonal patterns to Cho and Kim (1999), these surveys generally confirm their hypothesis of branching in summer and non-branching in winter. These data (along with the KODC data) show, however, that this is not always the case (September 1993).

In the four surveys where we can trace the TWC back into the TS, the temperature gradient that makes up the TWC resides in the western channel in February 1993 and May 1993, the cooler temperature gradient in the western channel and the warmer in the eastern channel in September 1992 and 1993. Though in September

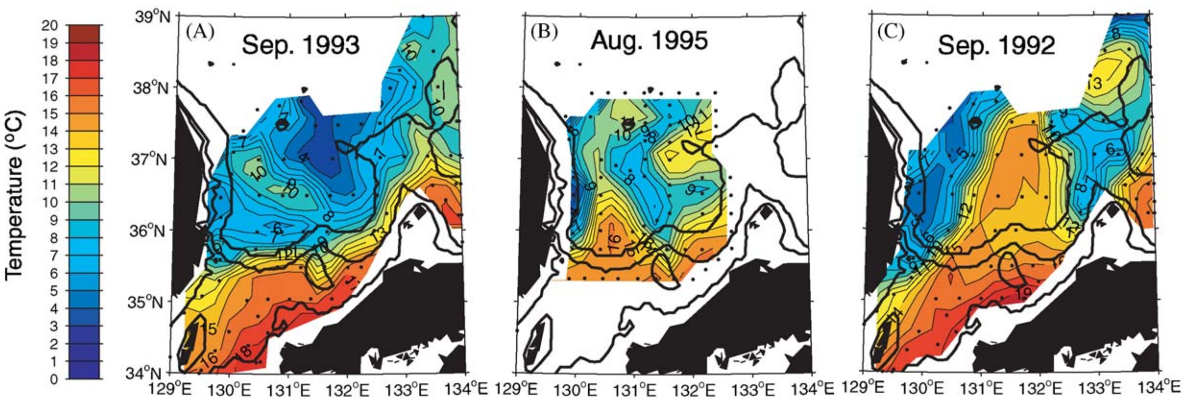


Fig. 10. Three temperature surveys in the Tsushima Strait — southeastern Japan/East Sea, plotted at 100 m depth, (A) September 1993, (B) August 1995, and (C) September 1992. Data presentation is similar to Fig. 4.

1992 (Fig. 10C) the temperature gradient splits on leaving the TS, in September 1993 (Fig. 10A) the temperature gradients both cross to the east, disrupting the seasonal pattern suggested in this short time series. The upstream conditions for the September 1992 and 1993 may support, however, the theory that the presence of the OB may be linked to when volume transport is highest through the western channel of the TS (Kawabe, 1982a). The onshore position of the September 1992 Kuroshio Front possibly indicates high flow volume, and the downstream presence of the OB (or displaced EKWC) supports this. It is interesting, though, that the September 1992 position of the Kuroshio Front is anomalous in the ECS compared to other studies (e.g., Isobe, 1999a, b), whereas downstream, it is the September 1993 survey that is anomalous in the branching region of the JES compared to other studies (Cho and Kim, 1999). This suggests that the TS buffers the JES from the ECS, and that local oceanographic conditions may have more of an effect on TWC branching than upstream conditions in the ECS.

4. Summary

We have used historical AXBT data from the Naval Oceanographic Office MOODS database to investigate the synoptic temperature structure of the ECS, southern YS, and southeastern JES regions. The AXBT data sets have been particularly valuable for understanding the synoptic water mass structure in this region over a very large area, a view usually reserved for remote sensing studies. We focused specifically on temperature evolution with depth and season, and concentrated on the source of the TWC in the ECS, and the TWC branching in the southeastern JES. Previous studies have identified seasonal cycles of these two currents, the on-shelf off-shelf migration of the Kuroshio (Isobe, 1999a; Tang et al., 2000), the seasonality of the KCBWK (Isobe, 1999a, b) and of the TWC branching (Cho and Kim, 1999) from long-term data sets, or from modeling studies. These AXBT data reveal that though the mean seasonality of each region is in general supported by these synoptic data, there are significant exceptions, e.g., the difference in the position of the Kuroshio Front between September 1992 and September 1993. Although we cannot directly assess current structure without complementary salinity data, current structure can often be inferred from temperature fronts in these regions.

Mixed layer depths across the ECS–YS–JES region reveal that the mixed layer is generally uniform and shallower than 25 m in summer, and much deeper (up to 200 m) and patchier in winter due to local wind mixing. Winter shallow mixed layer bands occur where the isotherms of the Kuroshio and Polar Front reach towards the surface in accordance with the local balance of wind forcing and vertical density gradient. The region where winter mixing is to the bottom is generally northwest of the 100-m isobath in the ECS and through the TS. The regional September surveys reveal two extremes of the eastern Kuroshio Front position: in 1992 this front is far on-shelf, preventing the formation of eddies at Mien Hwa Canyon and changing the front structure throughout the ECS; in September 1993, the Kuroshio Front has migrated off-shelf, eddies have formed, following a more canonical pathway. By 100 m depth, these extreme differences in the September fronts have vanished, though the two are not identical. KCBWK is seen in winter and spring, but not in summer at 60 m depth; however, there is evidence of this current branch in all seasons at 100 m depth, though this branching is not directly linked in temperature to the TS. In winter in the ECS, water at 200 m depth is generally warmer by 2 °C, due to the deep wind mixing in this season.

Vertical sections across the ECS shelf break show that synoptic temperature structure below 200 m varies significantly seasonally, and between one year and the next, unlike the seasonal mean (IB02). Along the entire length of the ECS in all surveys except winter (where wind mixing has homogenized the water column), cross sections show that cold water ($<18\,^{\circ}$C) inshore of the Kuroshio reached westward of the 200-m isobath, onto the shelf, and is as shallow as 60 m. This cold water may be an important source for setting the

TWC properties in the ECS, and warrants further investigation. Fronts in the JES do not exhibit a clear seasonal pattern from 1992 to 1993, although the branching of the TWC does over the longer period from 1992 to 1995. The NB is present in all surveys, and the East Korean Warm Current is generally present in spring–fall, and strongest in each May survey.

The regional synoptic surveys reveal that anomalous positions of the Fronts in the ECS in September 1992 occur when temperature fronts in the southeastern JES follow the mean seasonal pattern described by Cho and Kim (1999); and a more canonical front structure in the ECS in September 1993 (following the mean seasonal pattern developed by Isobe, 1999a) occurs when branching in the southeastern JES is disrupted. We surmise that the upstream conditions do not necessarily dictate downstream conditions, that the TS may act to mitigate upstream anomalies, and that local oceanographic conditions may play a more important role in the TWC branching than upstream conditions in the ECS.

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