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큐슈서방에서 쿠로시오의 분기에 대하여
- 위성추적부이 자료분석 -

On the Separation of the Kuroshio west of Kyushu
- Analysis of Trajectories of Satellite-tracked Surface Drifters

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提 出 文

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本 報告書를 "큐슈서방에서 쿠로시오의 분기에 대하여 - 위성 추적부이 자료분석-" 사업의 硏究報告書로 提出합니다.

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요 약 문

1988~1995년 조사한 위성추적부이의 이동궤적 자료와 1993년 12월과 1995년 4월 하순-5월 상순 동중국해 동부해역에서 조사한 CTD 자료를 분석하여 큐슈서방에서 쿠로시오의 분리와 동중국해 대륙붕으로의 유입을 연구하였다. 약 170 여대의 위성추적부이의 합성 궤적은 북동류인 쿠로시오가 큐슈 남서방 깊은 골의 서쪽 입구에서 분리된다는 사실이 직접 확인된다. 즉, 토까라 해협쪽으로 동진하는 쿠로시오의 주류와 골 좌측 대륙사면을 가로질러 대륙붕으로 유입하는 북향류인 지류로 갈라진다. CTD 자료와 동시에 조사된 위성추적부이의 궤적은 소위 대마난류가 쿠로시오로부터 분리되기 바로 전 상류 (upstream)에서는 쿠로시오의 연안쪽 가장자리였음을 보인다. 관측기간동안 분리되는 쿠로시오의 연안쪽 가장자리는 대륙붕단을 따라 북으로 관입하고, 깊은 골의 대륙사면을 비스듬히 가로질러 대륙붕으로 유입한다. 대륙붕으로 유입된 쿠로시오수는 계속 대한해협으로 북상하는데 그 주축은 쿠로시오의 연안쪽 가장자리에 위치한 해수가 특징적으로 갖는 고염에 의해 확실하게 드러난다. 관측된 CTD 자료에 역계산법을 적용하면 쿠로시오의 분리와 유입이 또한 확인되며 북향류가 두 관측에 대해 4.0 x 10^6 m^3/sec의 체적수송량을 갖고 있음을 보인다. 쿠로시오의 연안쪽 가장자리가 분리되는 것은 쿠로시오 주축의 방향전환과 깊은 관련이 있으며, 깊은 골의 급격히 변하는 해저수심과 쿠로시오의 동으로의 방향전환에 따른 와도조정 (vorticity adjustment)의 복합된 영향에 의해 발생되는 것으로 판단된다.

ABSTRACT

The separation of Kuroshio water west of Kyushu and its penetration onto the continental shelf of the East China Sea were investigated by analyzing trajectories of satellite-tracked surface drifters deployed during 1988-1995 and conductivity, temperature, and depth (CTD) data collected in the eastern East China Sea during December 1993 and late April - early May 1995. A composite trajectories of about 170 drifters gave a direct evidence for the separation of the northeastward flowing Kuroshio into two parts at the western mouth of the deep trough southwest of Kyushu; the Kuroshio main stream turning to the east toward the Tokara Strait and a northward flowing branch current penetrating onto the shelf across the continental slope west of the trough. Analysis of the CTD data and drifter trajectories, concurrently observed, shows that the branch current, known as the Tsushima Warm Current, was part of the inshore Kuroshio, just upstream before its separation. During the periods of observations, the separated, inshore Kuroshio water intruded northward along the shelf break of the trough and penetrated onto the shelf after crossing obliquely the western continental slope of the trough. The penetrated water onto the shelf continued to flow northward toward the Korea Strait, the main path of which was obviously traced by high salinity characterized by the inshore Kuroshio water. Application of an inverse method to the observed CTD data also supports the separation and penetration of the Kuroshio and figures the volume transport of the northward branch to be about 4.0 x 10^6 m^3/sec for the two different surveys. The separation of the inshore Kuroshio water may take place in close association with the eastward turning of the Kuroshio main stream and it might be caused by a joint effect of the shoaling bottom topography at the mouth of the trough and the vorticity adjustment created by the eastward turning of the Kuroshio.

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머 릿 말

우리나라 주변해역인 동해, 황해, 남해에 유입되는 고온·고염의 난류수는 대마난류에 의해 수송되며 대마난류수의 시·공간분포가 주변해역의 해황분포에 큰 영향을 미치게 된다. 대마난류수의 기원은 쿠로시오가 수송하는 북태평양 열대수의 변형된 수계로 쿠로시오가 동중국해 대륙사면을 따라 동진하면서 그 일부가 동중국해로 유입되는 것으로 지금까지 알려져 있다. 동중국해의 대륙붕으로 유입된 쿠로시오수계는 북상하면서 부분적으로 비교적 저염의 대륙붕수와 혼합되어 원래의 해수의 물리특성이 약간 변형되게 된다.

한편, 고온·고염인 대마난류수의 기원에 대하여 몇가지 가설 혹은 이론이 제시되었다. Uda [1934]가 최초로 동중국해의 개략적 해류모식도를 제시하였다. 그의 모식도에 의하면 쿠로시로로부터 분리된 대마난류가 고염·고온수를 동중국해로 수송하고 황해난류가 제주도 동남방에서 분리되어 황해로 유입한다. 이후, Nitani [1972]는 수온과 염분, 그리고 GEK 자료를 이용하여 해류모식도를 작성하였는데 기본골격은 Uda의 모식도와 같으며, 대마난류가 북위 30도 30분, 동경 129도 부근에서 쿠로시오로부터 분기되며 큐슈서방 깊은 골 왼쪽사면으로 유입한다고 보다 구체적으로 제시하였고, 또한 황해난류가 대마난류로부터 분기되어 황해로 유입하는 것으로 보고하였다. 한편, 1953년부터 1984년까지의 GEK 자료를 분석하여 작성한 Qiu와 Imasato [1990]의 표층해류도에서는 동중국해 대륙사면에 평행한 쿠로시오의 유로는 잘 나타내나 대마난류에 해당하는 큐슈서방에서 동중국해로 유입하는 해류의 분기는 보이지 않는다. 이외에 여러 사람들이 [Huh, 1982; Muneyama et al., 1984; Qiu et al., 1990; Chen et al., 1992] NOAA적외선 영상자료를 분석하여 큐슈서방에서 쿠로시오에서 고온수가 분리되는 것을 보고하였다.

Nitani [1972]와 같은 모식도와는 사뭇 다른 이론이 제시되었는데 대마난류는 대만해협을 통해 동중국해로 빠져나가는 해류의 연장이라는 설이다 [Beardsley et al., 1985; Fang et al., 1991]. 이 설에 의하면 대만해협을 통과한 고온·고염수는 동중국해의 50-100m 등수심선을 따라 북동쪽으로 흘러 대한해협으로 유입하며, 특히, Beardsley 등 [1985]은 황해난류

가 제주도 서쪽에서 분리되는 것으로 제시하였다. 한편, 여러 해수순환 수치모델 역시 유선이 (streamline of transport) 가시적으로는 대만해협으로부터 대한해협으로 바로 연결되는 결과를 대만난류가 동중국해 대륙붕을 가로질러 대한해협으로 유입하는 것으로 해석하고 있다 [Seung and Nam, 1992; Yanagi and Takahashi, 1993]. 그러나, 수치실험 결과는 동중국해 해수순환을 결정짓는 주요 요소인 여름철 담수 유입, 바람장의 공간변동, 해수의 계절변동에 의한 밀도변화를 적절히 반영하지 못하는데 기인한다고 볼 수 있다. Lie and Cho [1994]는 늦겨울-초봄을 제외하고는 대한해협에서 나타나는 고염수가 연중 대만해협의 고염수보다 염분이 높다는 사실을 확인하였고, 대만해협을 통과한 고염수가 저염수가 지배하는 동중국해 대륙붕을 지나면서 고염화될 수 없기 때문에 대마난류가 대만해협을 통과한 해수가 아니라는 결론을 내렸다.

Lie와 Cho [1994]는 1991-1992년사이 3회에 걸쳐 조사한 위성추적부이실험과 동시관측한 CTD자료를 분석하여 대한해협에서 출현하는 고염수의 기원은 큐슈 남서방에서 쿠로시오로부터 분기되어 북상하는 대마난류가 수송한 해수이며, 대마난류의 분기는 큐수서방 깊은 골 좌측입구일 것이라고 추정하였다. 한편, 동중국해는 세계 최고의 황금어장의 하나로 조업활동이 연중 활발하여 계류에 의한 유속관측의 안전성이 확보되지 못한 관계로 시계열 정점유속 관측자료는 대단히 귀하며, 그나마 대부분의 자료가 짧은 기간동안 관측되었기에 조류와 같은 단주기성 성분을 효과적으로 제거할 만한 이용가능한 해류자료는 더욱 드물다. 동중국해에서 적합한 해류관측방법은 계류에 의한 관측보다는 관측수심, 시간변동성 규명 등 몇 가지 문제점이 있기는 하지만 끌개를 이용하는 라그랑지언 방법이라고 판단된다. 대마난류의 분기역을 찾아내고 어떤 과정을 통해 분기가 이루어지는가를 조사하기 위하여 깊은 골 입구역에서 CTD 및 위성추적부이 실험이 특정연구과제인 쿠로시오 및 동중국해의 해수순환 연구를 통해 1993년부터 집중적으로 실시되고 있다. 또한, 세계해양대순환실험인 WOCE (World Ocean Circulation Experiment)의 한 프로그램인 표층류프로그램 (Surface Velocity Programme)에서 인공위성추적부이를 이용한 전지구적 해류관측을 최근 5년에 걸쳐 집중적으로 실시하였고 그중 상당수의 위성추적부이가 동중국해 대륙사면을 통과하였다. 따라서 본 보고서에서는 한국해양연구소의 위성추적부이자료와 세계해양대순환실험을

통해 투하된 위성자료를 합하여 동중국해 표층해류장을 작성하고 CTD 자료를 분석하여 대마난류수가 쿠로시오로부터 어떻게 분리되어 동중국해 대륙붕으로 유입하는지 검토하였다.

본 보고서는 이용가능한 모든 자료를 분석하여 얻은 주요결과를 해양물리분야의 세계 최고수준의 학술지인 Journal of Geophysical Research 에 1996년 4월에 투고한 원고를 수록한 것임을 밝힌다.

INTRODUCTION

The Kuroshio flowing northeast along the continental shelf slope of the East China Sea (hereafter ECS) has been known to have two branch currents; the Tsushima Warm Current (TWC) in the southeastern ECS, west of Kyushu and the Taiwan Current in the southwestern ECS, northeast of Taiwan. The branch currents transport warm, saline Kuroshio waters and oceanic materials not only for the ECS through its shelf edge, but also for the Yellow Sea and East Sea (often called Japan Sea), located to the north. The Kuroshio water intruded onto the shelf northeast of Taiwan forms a Γ-shaped front with surrounding fresher shelf water and its major portion returns back to the Kuroshio with its physical properties modified due to mixing with the shelf water [Chern and Wang, 1992]. However, the penetration of Kuroshio water onto the eastern ECS shelf remain relatively unclear to date, mainly due to the lack of sufficient direct current measurements and hydrographic data. The origin of TWC carrying the penetrated Kuroshio water to the northern ECS has long been debated since Uda [1934] first suggested its branching from the Kuroshio southwest of Kyushu.

The branching of TWC from the Kuroshio and the northward penetration of the warm, saline Kuroshio water into the eastern ECS are of great importance for understanding the circulation of ECS, Yellow Sea, and East Sea since the TWC is the main supplier of heat and salt for the marginal seas. The warm, saline waters in the eastern ECS, often referred to as the TWC water, have been classified as a mixture of ECS shelf water and Kuroshio water by Sawara and Hanzawa [1979] and Song et al. [1991]. Huh [1982] suggested episodic intrusions of Kuroshio waters into mixed waters occupying the deep trough west of Kyushu, using NOAA satellite images taken during the spring. Guo et al. [1991] proposed that the Kuroshio warm filament observed at the shelf break of the trough was the main source of TWC water. Recently, Lie and Cho [1994] observed a persistent northward flow near the western shelf edge of the deep north-south trough west of Kyushu, transporting saline Kuroshio water, on the basis of trajectories of satellite-tracked drifters and conductivity-temperature-depth (CTD) data collected in 1991-1992. They have suggested that part of the weak inshore fringe of Kuroshio separates from the Kuroshio near the continental slope at the mouth of the trough. Hsueh et al. [1996] applied a theoretical model of the bifurcation of a baroclinic current incident upon step rise in bottom topography to the turning and branching of the Kuroshio west of Kyushu.

Observations of the previous studies could hardly provide concrete, direct evidence for the separation and penetration of the Kuroshio in the eastern ECS since hydrographic stations were too sparse to effectively resolve different water types and current measurements were made sporadically and for a very short period. Three fundamental questions relevant to the TWC can be raised; 1) where does the separation of TWC from the Kuroshio take place ? 2) how does the separated water penetrate onto the ECS shelf ? 3) what route does the penetrated TWC follow ? To answer the questions and to elucidate oceanographic processes related to TWC, the Korea Ocean Research and Development Institute (KORDI) launched the first phase of a survey-oriented interdisciplinary project entitled 'Coastal Ocean Processes Experiment of the East China Sea (COPEX-ECS)' in 1993. Major observational items of the physical oceanography are tracking of satellite-tracked surface drifters, CTD casts, and current measurements by a ship-borne Acoustic Doppler Current Profiler (ADCP). The surface drifter experiment is the Korean contribution to the World Ocean Circulation Experiment/Surface Velocity Programme (WOCE/ SVP).

In general, physical structures of the eastern ECS during the cold season are much simpler than during the warm season and representative water types such as shelf water and Kuroshio water can be more readily identified, so data of COPEX-ECS collected in December 1993 and late April - early May 1995 were subject to analyses, focusing on the separation of TWC at the mouth of the deep trough and its northward penetration onto the shelf across the continental slope. Also available WOCE drifter data, mostly collected through the Taiwan-USA joint SVP program, were combined with the KORDI data to construct a surface current field and to detect the turning and separation of the Kuroshio. Thus, the present study is a Korea-USA-Taiwan joint contribution to the WOCE/SVP. Finally, we estimated the volume transport of TWC by applying an inverse method to the observed CTD data and sketched a schematic surface circulation of the eastern ECS for the cold season when the vertical stratification on shelf is weak or broken, mainly due to surface cooling and vertical mixing.

EXPERIMENTS AND DATA PROCESSING

Figure 1 presents CTD stations and release points of drifters for the two COPEX-ECS surveys in early December 1993 (hereafter, winter cruise) and late April-early May 1995 (spring cruise). Intensive CTD castings were made on the western shelf and slope of the deep trough, elongated in the north-south direction. The deep trough is the northeastern cul-de-sac of the Okinawa Trough. The separation of TWC from the Kuroshio has been proposed to take place at the western mouth of the trough [Lie and Cho, 1994]. The CTD sections in the intensive survey area are approximately normal to isobaths and marked by thick dashed line in Figure 1. Spacing of

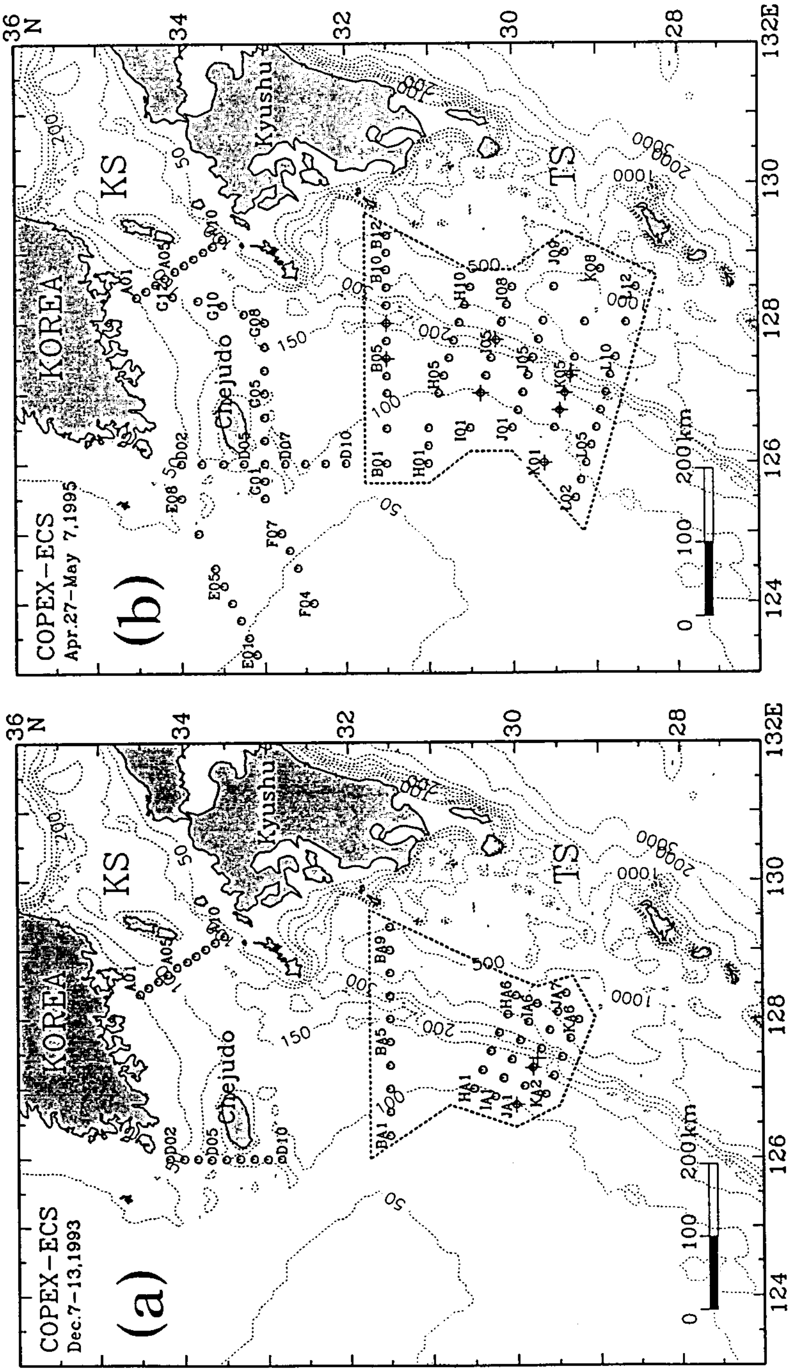

Fig. 1. Study area indicating CTD stations (open circles) and release points of satellite-tracked surface drifters (crosses).
(a) December 1993 and (b) May 1995. Bottom topography is in meters. KS and TS denote the Korea Strait and the Tokara Strait, respectively. The thick dashed lines indicate intensive CTD survey areas for the two surveys.

stations were chosen to be narrow enough to identify different water types passing through the sections. Satellite-tracked surface drifters were deployed during the CTD surveys and release points adequate to trace the penetrated Kuroshio water were effectively selected on board, in consulting vertical sections of temperature and salinity, together with trajectories of drifters deployed by KORDI and WOCE in the past.

During the winter survey, CTD casts in the intensive survey area were made only at 35 stations on five sections, due to rough sea state caused by passage of a storm, though about 50 stations were originally scheduled. During the spring survey, CTD data were collected at 58 stations on six sections as scheduled and the sections extended further inward to the shelf and outward to the southeast to see spatial distribution of the two representative water types of shelf and Kuroshio waters over a relatively larger area. We used a Neil Brown CTD Mark V for the winter cruise and a Sea Bird CTD 911 for the spring cruise. Observed temperature (T) and salinity (S) were resampled every 1 m by depth averaging over 1 m after removing spiked data.

The surface drifters used were the standard WOCE/SVP type equipped with a sea surface temperature sensor and holey sock drogue 644 cm long [Sybrandy and Niiler, 1991]. Most drifters were drogued at 15 m below sea surface and release points are denoted by '+' symbol in Figure 1. For the winter survey, three drifters were released on December 9, 1993 along section JA; at stations JA1, JA3, and near station JA4. One drifter released at JA3 was drogued at 45 m. For the spring survey, nine drifters were released along three sections B, I, and K; two at stations B5 and B7 on April 27, two at stations I2 and I5 on April 30, five at stations K1, K3, K4, K5, and near station K5 on May 3. Two drifters released at I5 and K5 were drogued at 50 m and one at K4 failed to transmit signals, due to unknown cause. A large number of WOCE drifters were released east of Taiwan, jointly by the Scripps Institution of Oceanography and Taiwan Ocean University. Thus, all available WOCE drifter data, collected in the ECS during 1988-September 1994, were combined with the KORDI data archived during 1991-1995. The combined dataset of about 170 trajectories were used to construct a composite map of trajectories and the surface Lagrangian current field for the separation of TWC from the Kuroshio.

TURNING AND SEPARATION OF THE KUROSHIO

The separation of TWC from the Kuroshio at the southern mouth of the trough, along with the eastward turning of the Kuroshio toward the Tokara Strait are examined using the comprehensive drifter trajectories since it has not been evidenced by direct current observations. Figure 2 is a composite map of trajectories constructed from all available drifters released during 1988-1995. Open circles denote release points of KORDI drifters deployed in the eastern ECS during 1991-1995.

Trajectories are densely distributed off the east coast of Taiwan, along the ECS continental slope, and the Okinawa Trough west of the Tokara Strait. The dense trajectories are in good agreement with the main path of the Kuroshio, traced from historical hydrographic and Geoelectrokinetograph (GEK) data [Nitani, 1972; Qiu and Imasato, 1990]. The Kuroshio path in the ECS is again confirmed to be largely controlled by the steep bottom topography of the ECS. The trajectories show clockwise meander motion northeast of Taiwan and at the mouth of the deep trough southwest of Kyushu where the bottom topography is very complicated. A small number of trajectories in both areas are not parallel to isobaths, crossing the continental slope. Northeast of Taiwan, many drifters moving in from the south

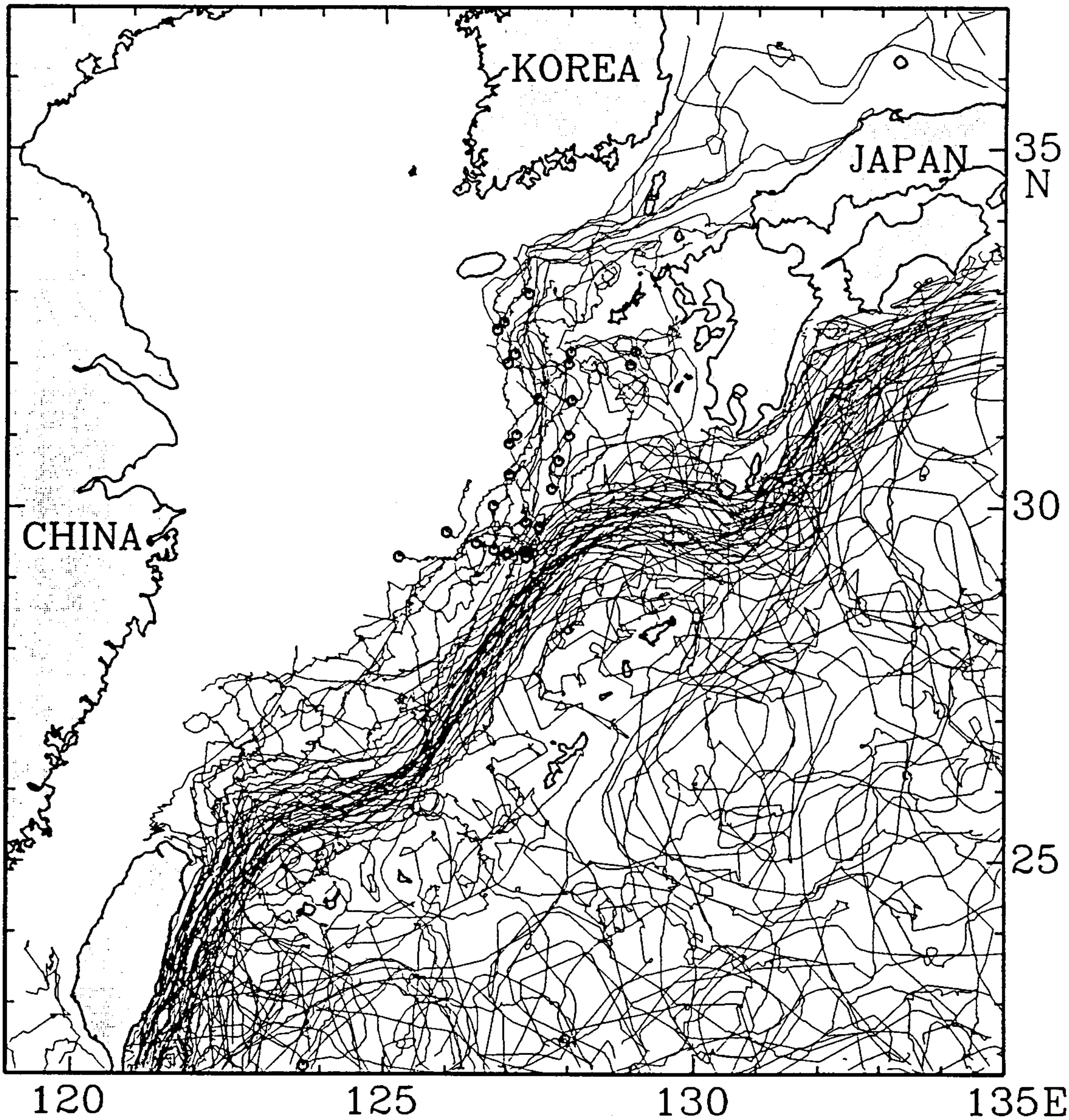

Fig. 2. A composite map of trajectories of satellite-tracked surface drifters conducted by the WOCE/SVP during 1988-September 1994 and by the KORDI during 1991 -1995. Open circles are release points of KORDI drifters deployed west of Kyushu.

entered the shallow shelf area across the continental slope and then returned back to the main path of Kuroshio, eventually forming a clockwise circulation near the shelf edge. The general pattern of trajectories northeast of Taiwan is well consistent with the observed intrusion of the Kuroshio into the shelf and clockwise circulation northeast of Taiwan [Chern and Wang, 1992; Chuang and Liang, 1994; Hsueh et al., 1992].

On the other hand, trajectories southwest of Kyushu are divergent toward the north, very indicative of a separation of the Kuroshio into two parts. Most drifters, following the northeastward flowing Kuroshio, turned their moving direction to the east around 29° N, 127° 30′ E, near the western mouth of the deep trough and crossed the trough to pass through the Tokara Strait located south of Kyushu. However, in the neighborhood of the turning point of the Kuroshio, some drifters on the inshore side of the Kuroshio were displaced away from the Kuroshio and crossed obliquely the continental slope. Other drifters, released on shelf and near the western shelf edge of the trough, moved northward along the 100-200 m isobaths. Most drifters on shelf continued to move northward and entered the Korea Strait, while a few drifters turned clockwise in the northern trough and finally joined the Kuroshio. Thus, the ensemble of trajectories demonstrate the eastward turning of the Kuroshio main stream toward the Tokara Strait, more clearly and comprehensively than the previous study [e.g., Nitani, 1972] and provide for the first time direct evidence for the separation of a northward branch current, TWC, from the Kuroshio around the turning point.

An average surface current pattern of the eastern and southern ECS was computed by applying 20′ by 20′ box-averaging to the trajectories (Figure 3). Arrow vectors are daily mean Lagrangian velocity obtained from three or more drifters passing through each box. Isobaths of 100, 200, 500, and 1000 m are marked by thick solid lines in Figure 3. The main axis of the Kuroshio with high speed is

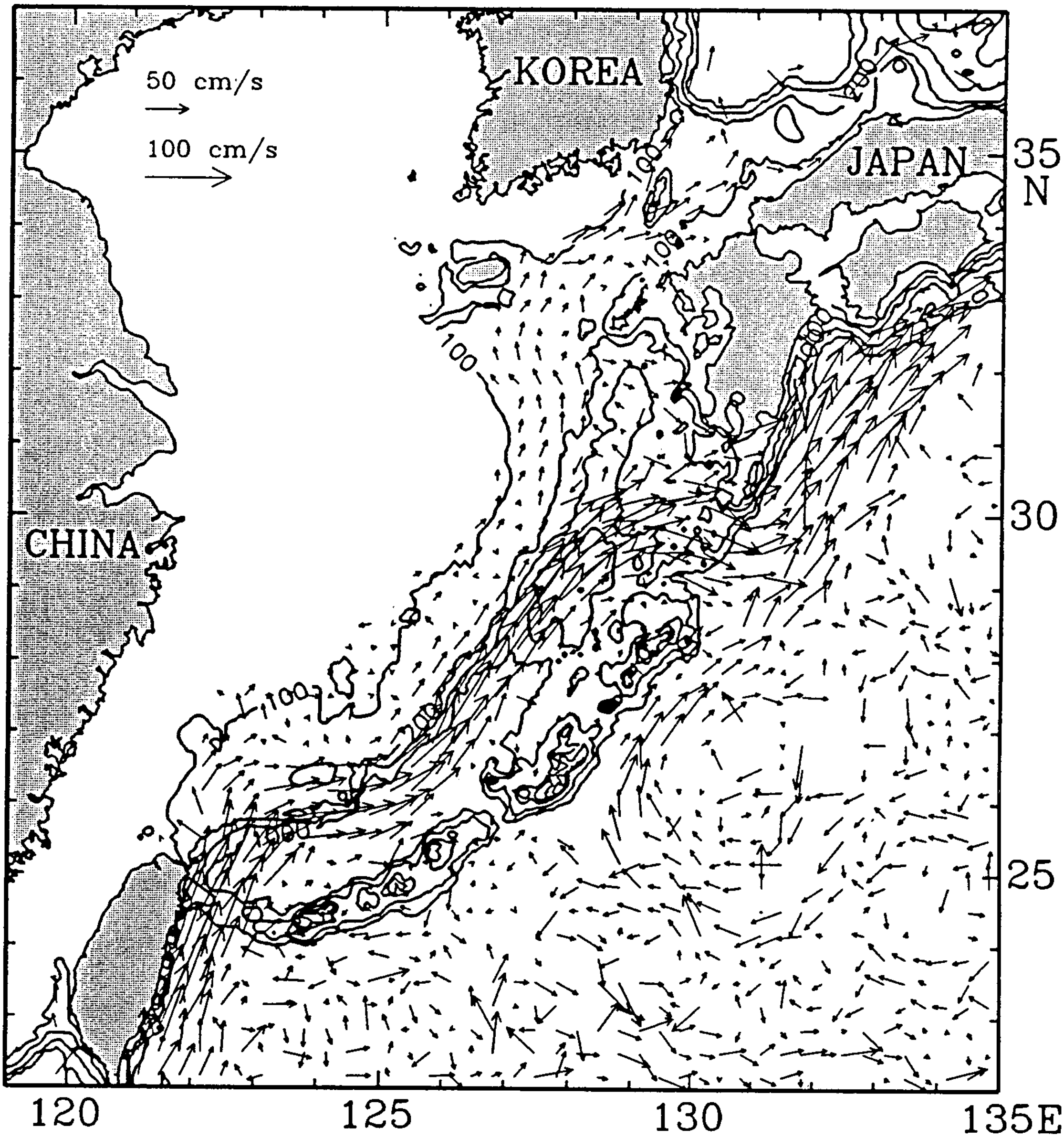

Fig. 3. Surface current fields derived from the drifter trajectories in Figure 1 by 20′ by 20′ box averaging. Current vectors were computed using equal to or more than three drifters passing through corresponding boxes. Vector scales are on the upper left panel and isobaths of 100, 200, 500, and 1000 m are marked by thick continuous lines.

coincident with location of the dense trajectories in Figure 2. A northward current prevails on the 100-200 m shelf west of the trough, but in the area south of 29° N, the shelf current is not unidirectional even though the Kuroshio touches the shelf edge. The northward shelf current separates from the Kuroshio main stream near the continental slope at the western mouth of the trough. After separation, it continues northward nearly along the western shelf edge of the trough between 29.5° and 33.5° N. Figures 2 and 3 reveal that the branch current corresponds to the inshore part of the Kuroshio, immediately before the separation. The separation takes place near 29° 30′ N, 127° 30′ E, in the neighborhood of the turning point of the Kuroshio main stream, as suggested by Lie and Cho [1994].

A large anticyclonic eddy is seen in the northern trough west of Kyushu. The existence of a large warm eddy in the trough has been also detected on infrared imagery in spring 1986 [Qiu et al., 1990], on absolute geostrophic current field estimated from ADCP and CTD data in January 1986 [Chen et al., 1992], and on mean surface currents for autumn derived from GEK data for the period of 1971-87 [Hsueh et al., 1996]. Lie and Cho [1994] also observed a large warm eddy by drifter trajectories from November 1992 to January 1993. A drifter released on the western slope of the trough made a clockwise rotating loop trajectory in the northern trough. Chen et al. [1992] suggested a relation between the eddy and a countercurrent of the Kuroshio in the trough. Lie and Cho [1994] pointed out a bifurcation of the northward flow near the northwestern corner of the trough into a northward continuing flow and an eastward flow along the northern wall of the trough, the latter forming the clockwise eddy in the northern trough. Thus, the formation of a large anticyclonic warm eddy in the trough is one of the major circulation features, frequently detected during the cold season.

SEPARATION OF KUROSHIO WATER AND ITS PENETRATION ONTO SHELF

The Lagrangian surface current field revealed the separation of the Kuroshio into the eastward Kuroshio main stream and the northward flow in the neighborhood of the turning point of the Kuroshio southwest of Kyushu. Detailed structures of the separation and penetration are examined in this section by analyzing the CTD data and drifter trajectories observed in the intensive survey area for the two surveys. The Kuroshio and shelf waters of the ECS have an important seasonality in T and S, mainly due to seasonal heating and cooling, and heavy precipitation and flooding in summer. The Kuroshio water is characterized by high T and S throughout the year, while the ECS shelf water is fresher and colder (warm) during the cold (warm) season. Furthermore, hydrographic structures during the cold season are much simpler than those during the warm season when various mixed waters of the Kuroshio and shelf waters coexist. T and S can be used to trace the separation of the Kuroshio water and its northward penetration onto the shelf and we examine CTD data collected during the two cold seasons. In general, drifters move following water parcel in which the drifters are deployed, so a combination of hydrography and drifter trajectories help us to locate the separation of the Kuroshio water and to trace its northward penetration route more reasonably. We present horizontal maps of T, S, and sigma-t at a depth of 50 m for the two surveys on which daily mean Lagrangian velocity estimated from drifter trajectories are marked as arrows. Though drifters were drogued at 15 m or at a deeper depth around 50 m, hydrographic structures at 15 m were very similar to those at 50 m, mainly due to strong vertical mixing. The velocity vectors are plotted only for the first 15 days or a shorter period after release of drifters since the Kuroshio front, developed especially in spring [e.g., Chen et al., 1992; Qiu et al., 1990], fluctuates with characteristic scales of 14-20 days in time and of 100-150 km in length. The Kuroshio water can be more readily identified by S than T in the survey area for the two observation periods since T is much more sensitive to the surface cooling. Therefore, only vertical sections of S are presented to examine how the inshore part of the Kuroshio water penetrates onto the shelf from the south to the north.

1. Winter Survey

Figure 4 presents T, S, and sigma-t at 50 m in December 1993. In the southern intensive survey area, isotherms and isopycnals diverged toward the north, and Kuroshio water of T > 22.5 °C, S > 34.7 psu, and sigma-t < 24.0 occupied the southeastern survey area. The radial pattern of isolines of high T and S implies the eastward turning of the Kuroshio main stream. According to surface currents measured by a ship-born ADCP during the CTD casts [KORDI, 1994], the Kuroshio main stream located approximately in the Kuroshio water of maximum T > 22.5 °C and S >34.8 psu. On the other hand, water of 21.5-22.5 °C and 34.5-34.8 psu intruded into the shelf across the continental slope and isolines of 22.0-23.0 °C and 34.75-34.85 psu extended to the north in a tongue-shape, displaced away from the Kuroshio main stream. Three drifters, deployed in the expected separation area, moved northward almost along the 34.3-34.75 psu isolines. The northward movement suggests a northward penetration of the saline Kuroshio water onto the shelf. In particular, a drifter, released at the shelf edge, crossed the continental slope obliquely in the northwest direction parallel to isolines in the neighborhood of the release point. The similarity of the northward and northwestward trajectories and the isolines is direct proof of the penetration of saline Kuroshio water onto the shelf. The penetrated

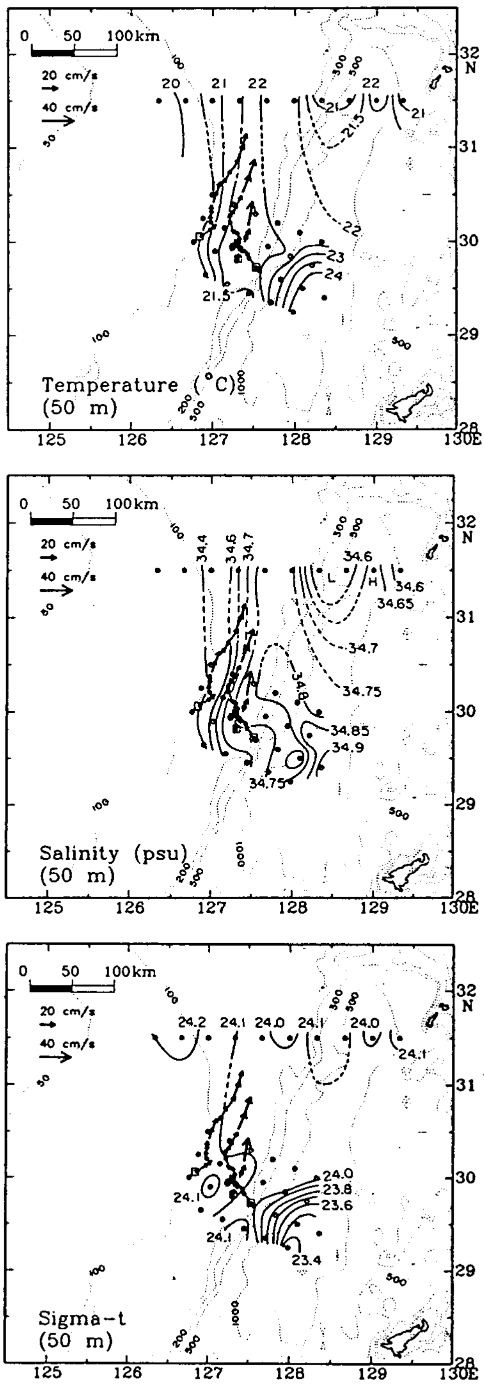

Fig. 4. Temperature, salinity, and sigma-t at the 50 m depth in December 1993, with daily mean current vectors derived from drifter trajectories during the first 15 days after release. The scale of arrow vectors is shown on the upper left corner.

Kuroshio water lay on the cyclonic side of the Kuroshio water just before its separation and its S was slightly lower than the maximum S of the Kuroshio core water, reflecting that the penetrated water was the inshore Kuroshio water.

Vertical sections of S at five CTD lines in Figure 5 demonstrate how the inshore Kuroshio water intruded into the shelf across the slope during the winter survey. Water column on the shelf was vertically well mixed, mainly due to surface cooling and stirring by the strong northerly wind, so T and S were vertically homogeneous, except for the near-bottom layer near the shelf edge. In the surface mixed layer 80-100 m thick, S increased from the shelf toward the offshore and a strong salinity front on shelf separated shelf water of low T and S from Kuroshio water of higher T and S. For convenience, surface S equal to 34.5 psu is taken as a reference value indicating the shelf front. At the southernmost line KA, the inshore boundary of saline Kuroshio water (S equal to 34.6 psu is here referred to as a lower limit value) was located at KA3, just near the shelf edge. The Kuroshio core water of S > 34.7 psu was distributed in a wedge shape in the upper layer, with its forehead extending upto the shelf edge. At line JA, 27 km distant from line KA, the inshore boundary moved to the outer shelf by about 35 km from the edge and the wedge became thinner and wider. At line IA, isohalines of 34.6-34.7 psu moved farther inward and the Kuroshio core water was much thinner, so the Kuroshio main stream already turned to the east in the survey area south of this line. At line HA, the inshore boundary advanced farther inward, about 45 km distant from the edge and a S maximum appeared at station H3 at the shelf edge. At line BA, 75 km far from line HA to the north, the salt wedge existed no longer, but two high salinity cores (>34.6 psu) were observed at stations BA4 - BA7 on the shelf and at station BA9 located in the central through. The S core on the shelf is about 100 m thick and 90 km wide. A similar hydrographic structure with the two S cores

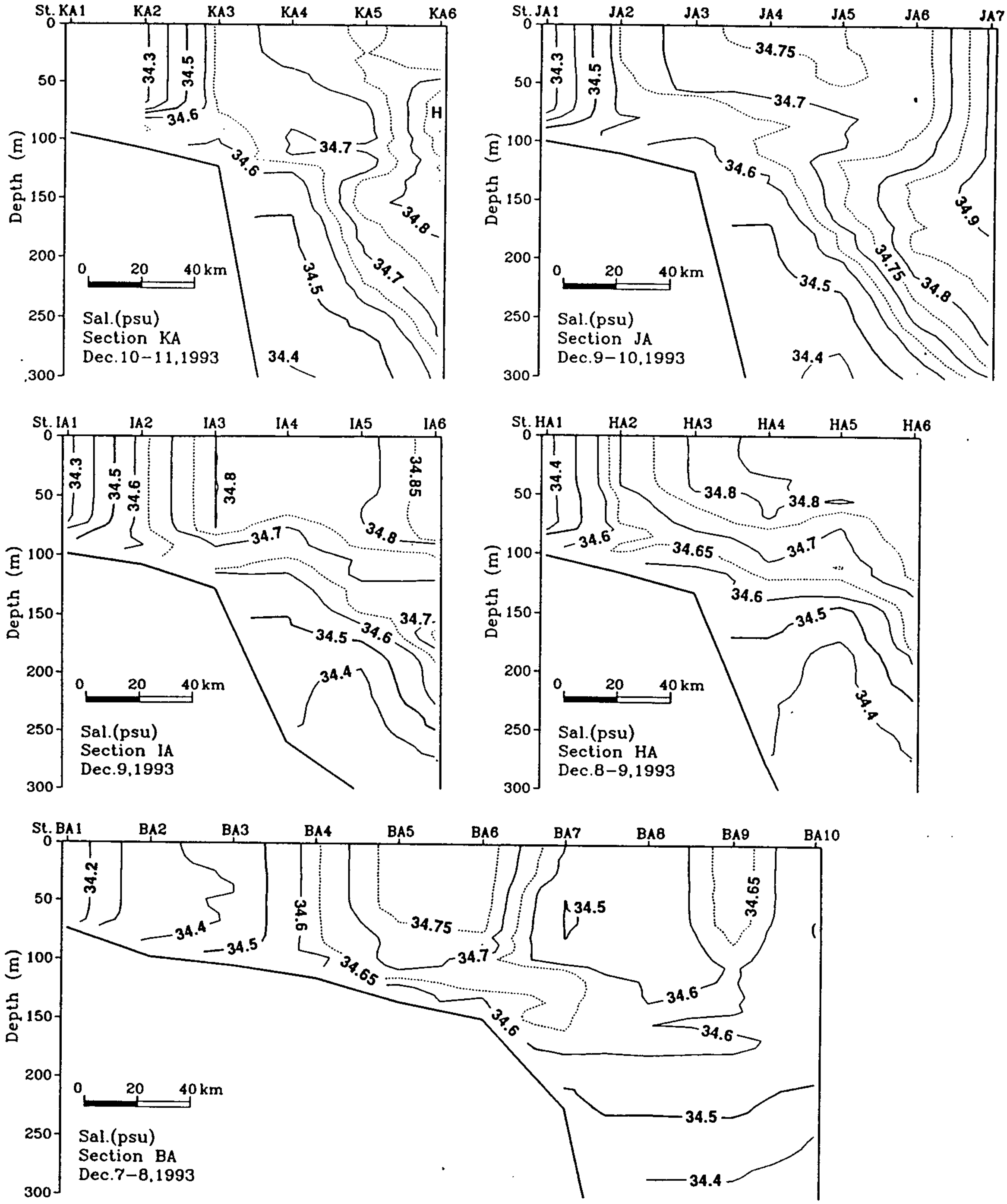

Fig. 5. Vertical sections of salinity at lines KA to BA for December 1993. Stations are marked in Figure 1a.

were observed in November 1992 and the saline water, flowing northward on the shelf, was suggested to be splitted into two parts: one flowing into the Korea Strait and another one turning clockwise in the northern trough [Lie and Cho, 1994]. Thus, the S core in the trough during the winter survey is thought to be a part splitted from the penetrated Kuroshio water onto the shelf.

From the wintertime hydrographic structure and drifter trajectories, it is concluded that part of the inshore Kuroshio separated from the Kuroshio main stream near the continental slope at the western mouth of the trough and then penetrated onto the shelf across the western shelf edge of the trough.

2. Spring Survey

Figure 6 is T, S, and sigma-t at 50 m observed in April-May 1995. During the spring cruise, the eastward turning of the Kuroshio main stream at the mouth of the trough was clearly detected on the surface current measured by an ADCP (not shown here). The Kuroshio core water with maximum T (>23 °C) and S (>34.70 psu) at 50 m was consistent with the main axis of the Kuroshio. Inshore boundary of the Kuroshio water is referred to as S of 34.6 psu and T of 18 oC as was for the winter cruise. It is noteworthy to see that the Kuroshio core water having the highest T (> 23 °C) does not necessarily the highest S and that shelf water was colder and fresher than for the winter cruise. Tongue-shaped isolines of high T and S show that part of the Kuroshio water was detached from the Kuroshio main stream near the continental slope at 29° 30′N, 128° N, almost in the same area observed as for the winter survey. The separated inshore Kuroshio water intruded northward along the western shelf break of the trough and extended to the shelf across the shelf edge north of line I. Furthermore, two drifters, released at

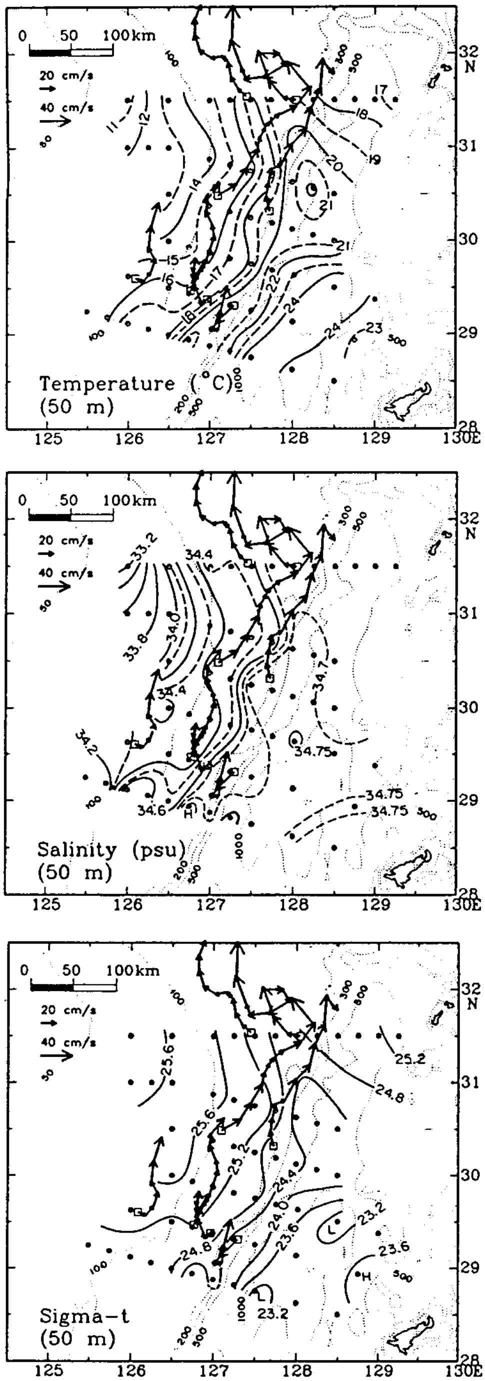

Fig. 6. Temperature, salinity, and sigma-t at 50 m in late April-early May 1995, with daily mean current vectors derived from drifter trajectories during the first 10 days after release. The scale of arrow vectors is shown on the upper left corner.

line B, moved northwestward nearly along the isolines, approximately normal to the 200-500 m isobaths. Thus, the intruded inshore Kuroshio water penetrated mainly onto the shelf across the northwestern trough north of line I. On the other hand, mixed water of S of 34.3 - 34.5 psu occupied a narrow band on the shelf and located between the 100 m isobath and the inshore Kuroshio water. The band gradually widened from line K to line B, due to lateral mixing between fresher shelf water and the inshore Kuroshio water coming from the south.

Of four drifters deployed at line K, two on shelf moved northward almost along isolines, but two near the shelf edge moved southward for the first several days after release and then moved north in a small eddy-like trajectory. This suggests large spatio-temporal variability of surface current in the southern intensive survey area covering lines J-L, which might be related to existence of frontal meander or eddy during the survey as was frequently observed in spring [Chen et al., 1992; Guo et al., 1991; Qiu et al., 1990]. Two drifters, released at line I, followed roughly isolines for the first several days between lines I and H and continued in the same direction, apparently crossing isolines between lines B and H. CTD observations at the lines B and H were made a few days before the two drifters passed the lines. The misalignment of the trajectories with the isolines might be caused by a frontal meander. The northwest movement of drifters and distribution of isolines across the continental slope north of line H imply that the inshore Kuroshio water penetrated mainly onto the shelf across the northwestern trough.

Vertical sections of S at six lines in Figure 7 also reveal separation of the inshore Kuroshio water from the Kuroshio main stream and its penetration onto the shelf across the slope at the northern intensive survey area. Water column on shelf was stratified at the southern lines J-L, but vertically homogeneous at the northern

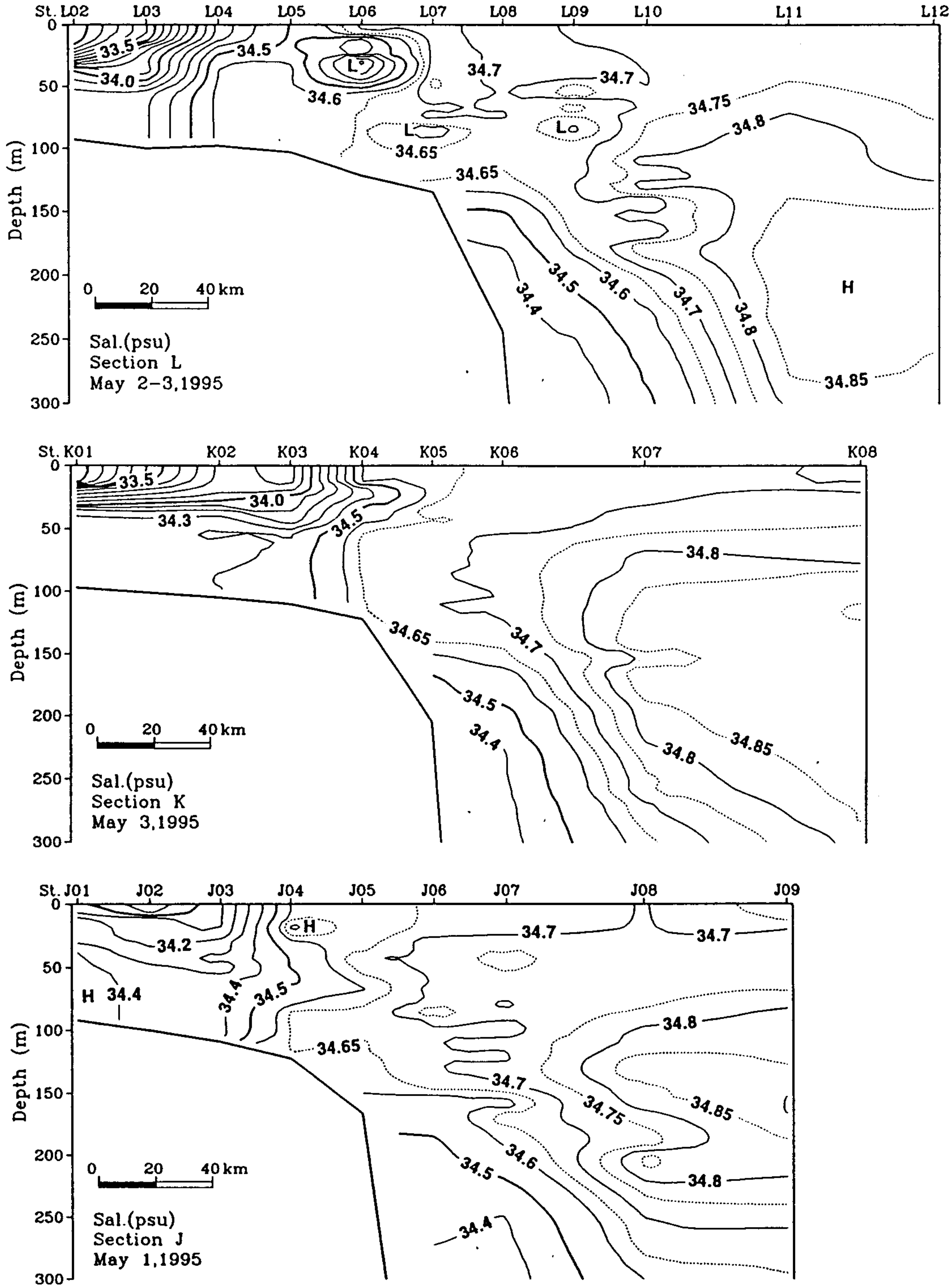

Fig. 7. Vertical sections of salinity at lines L to B for late April - early May 1995. Stations are marked in Figure 1b.

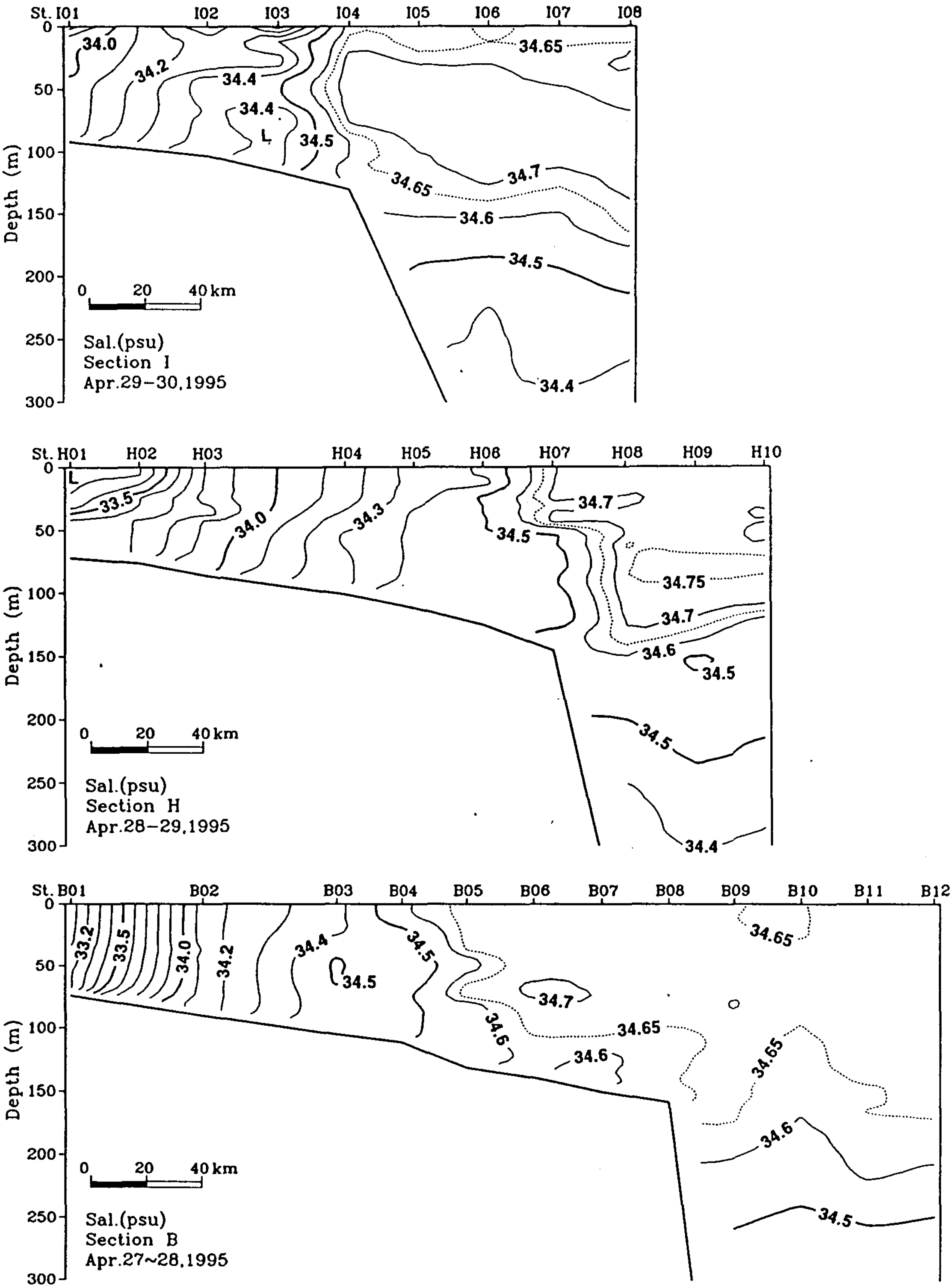

Fig. 7. (Continued)

lines B-I. The Kuroshio core water was a few hundred m thick in the central trough of the southern three lines J to L, but much thinner at the northern lines. This is considered as a consequence of the eastward turning of the Kuroshio main stream in the southern survey area as seen in Figure 6. At the southernmost line L, a very strong front formed near station L4 on the shelf and the inshore boundary of the core water was located at station L9. The inshore Kuroshio water of S of 34.6-34.7 psu occupied the outer shelf area about 80 km wide east of the front and the upper layer of the slope area. At line K, the front moved outward to station K4 near the shelf edge, while the core water approached to the shelf edge. Thus, the inshore Kuroshio water shrank largely in sectional volume at line K, when compared to that at line L. Two drifters on shelf at line K moved northward along the isolines with different speeds, but two, deployed near the shelf edge in the inshore Kuroshio water, moved southwestward for the first few days after release and then moved northward. This suggests that the decrease in sectional volume of the inshore Kuroshio water at line K may be related to the southwestward movement of the two drifters, possibly due to a frontal meander or eddy during the survey. At line J, the vertical structure was similar to line K, but the gradient of S across the front was much weaker. Disappearance of saline water of $S > 34.8$ psu north of line J indicates that the major portion of Kuroshio core water turned eastward south of this line. At two northern lines I and H, the inshore Kuroshio core water approached to the shelf edge in a salt wedge 80-100 m thick in the upper layer. This implies that the inshore Kuroshio water was completely detached from the Kuroshio main stream and intruded northward along the shelf edge. At line B, the front moved farther to the inner shelf, about 80 km from the shelf edge and the wide shelf area was occupied by the inshore Kuroshio water. The inshore Kuroshio water near the shelf edge was warmer and slightly saltier than in the central trough, with isolines crossing the shelf edge.

The vertical sections of S and the trajectories during the spring cruise also show that the inshore Kuroshio water separated from the Kuroshio main stream near the continental slope of the western mouth of the trough as observed for the winter survey and the intruded Kuroshio water along the shelf edge of the trough penetrated onto the shelf, mainly across the northwestern trough and partly in the neighborhood of its separation.

VOLUME TRANSPORT BY INVERSE METHOD

Volume transport for the two different surveys in the intensive survey area is estimated by applying an inverse method to the observed CTD data. ADCP data are not used for the calculation because the ship-born ADCP covers only the upper 300 m layer and strong tidal components contained in the one time surveyed data are not effectively filtered out. In this section, we present shortly the outline of the method and some results related to the separation of the Kuroshio. More details will be prepared and presented separately somewhere.

T and S data along the boundaries marked by solid lines in Figure 8 were used as input data for estimating volume transport in the three dimensional region. The vertical was divided into five layers by four isopycnal interfaces. The sigma-t values of interfaces are 24.4, 25.9, 26.5 and 27.0, respectively, which were chosen on the basis of water mass analysis. The upper three layers correspond to the Kuroshio waters and the lower two represent the intermediate layer of S minimum and the deep water layer of low T. Each layer has a different horizontal boundary on the shallow shelf and the continental slope region. We assume no vertical transport across the elected

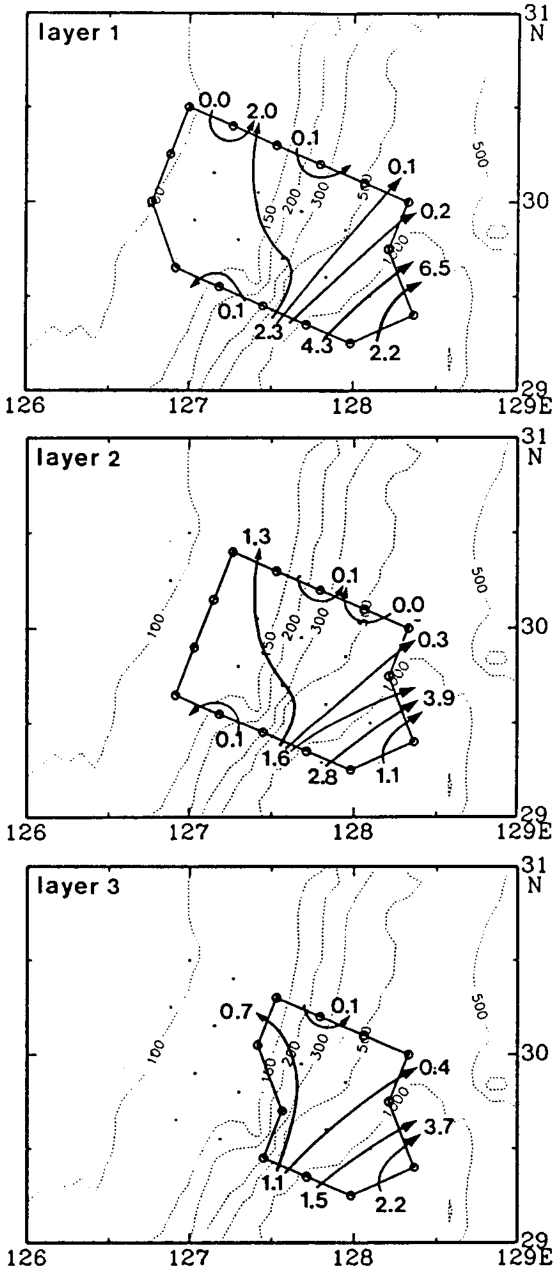

Fig. 8. Contours of transport for the upper three layers estimated by an inverse calculation. (a) December 1993 and (b) April-May 1995. The solid lines indicate lateral boundaries to compute the geostrophic velocity.

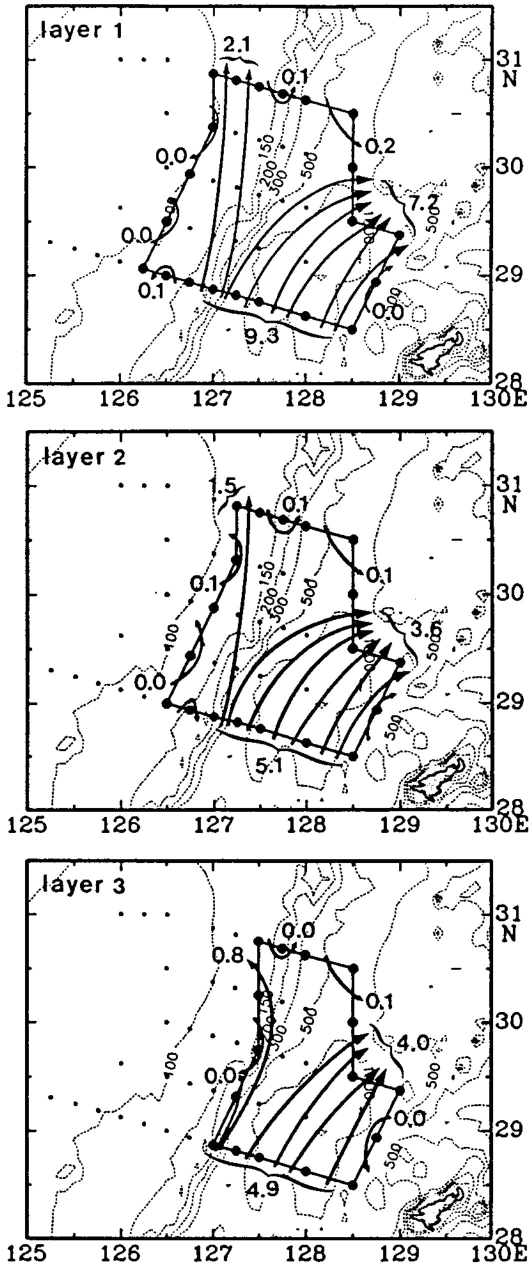

Fig. 8. (Continued)

density interfaces, so the total volume flux in each layer should be conserved.

With assumption of the hydrostatic and geostrophic balances, the thermal wind equations yield the velocity relative to a reference level. However, the mass flux based on the relative velocity is not conserved for a layer considered. The imbalance of mass is due to the reference (or barotropic) velocity. This means that the conservation of total volume flux can be used to determine the reference velocity [Veronis, 1986]. That is, the inverse analysis allows us to estimate the absolute velocity. We denote the reference velocities between pairs of stations in the study area as elements of an unknown vector m and we take the coefficients of the unknown elements in the matrix **G**. The problem can be expressed as a linear algebraic system **Gm**=**d**, where **d** contains components given by the baroclinic transport. The system of inverse model here is highly underdetermined. Solutions can be obtained by a method of singular value decomposition.

Contours of volume transport in each layer are constructed from results of the inverse calculations and most of transport is concentrated in the upper three layers. Figures 8a and 8b are contours of volume transport in the upper three layers for the two surveys, respectively. The contours have a pattern similar to the divergent trajectories in the intensive survey area and contours of large transport in the trough are consistent with the Kuroshio main path. The total volume transport of inflow through the southern section is estimated 20.6 x 10^6 and 19.3 x 10^6 m^3/sec for the winter and spring cruises, respectively. The observation line in the trough for the spring cruise is longer than for the winter cruise, so the Kuroshio transport might be larger in December 1993 than in May 1995, implying a seasonal variation of the Kuroshio transport. The transport values are a little smaller than those of Yuan et al. [1990] and Nakano et al. [1994] across the Tokara Strait. They estimated

23.3 x 10^6 and 28.0 x 10^6 m^3/sec, respectively, by applying inverse methods to the same data observed in the fall of 1987. Part of contours near the slope region extend northward to the outer shelf west of the trough, not along the Kuroshio main path. This remarkable feature strongly supports the separation of the Kuroshio at the western mouth of the trough and its penetration onto the shelf west of the trough as discussed in the previous sections. The northward transport is estimated 4.0 x 10^6 and 4.4 x 10^6 m^3/sec for the winter and spring cruises, respectively, which are about twice larger than the transport across the Korea Strait [e.g., Yi, 1966].

SCHEMATIC SURFACE CIRCULATION AND MAIN ROUTE OF TWC

Figure 9 is a schematic surface circulation pattern of the eastern ECS during the cold season, together with the main route of the TWC. The pattern was constructed from the data collected during the two surveys, the comprehensive WOCE drifter data, and other available CTD data of KORDI observed in the northern ECS during 1986-1993. The Kuroshio flowing northeast along the continental slope of ECS turns to the east toward the Tokara Strait near 29° N, 127° 30′ E, and inshore Kuroshio separates from the Kuroshio main stream in the neighborhood of the eastward turning point of the Kuroshio. The separated Kuroshio water intrudes northward along the western shelf edge of the trough as clearly marked by the tongue-shaped isolines of high T and S, and light density in Figures 4 and 6. The intruded Kuroshio water of S > 34.6 psu is referred to as the TWC water in order to make difference from mixed waters on shelf. The TWC is splitted into two parts near the northwestern trough; a northward continuing TWC after penetration onto the shelf

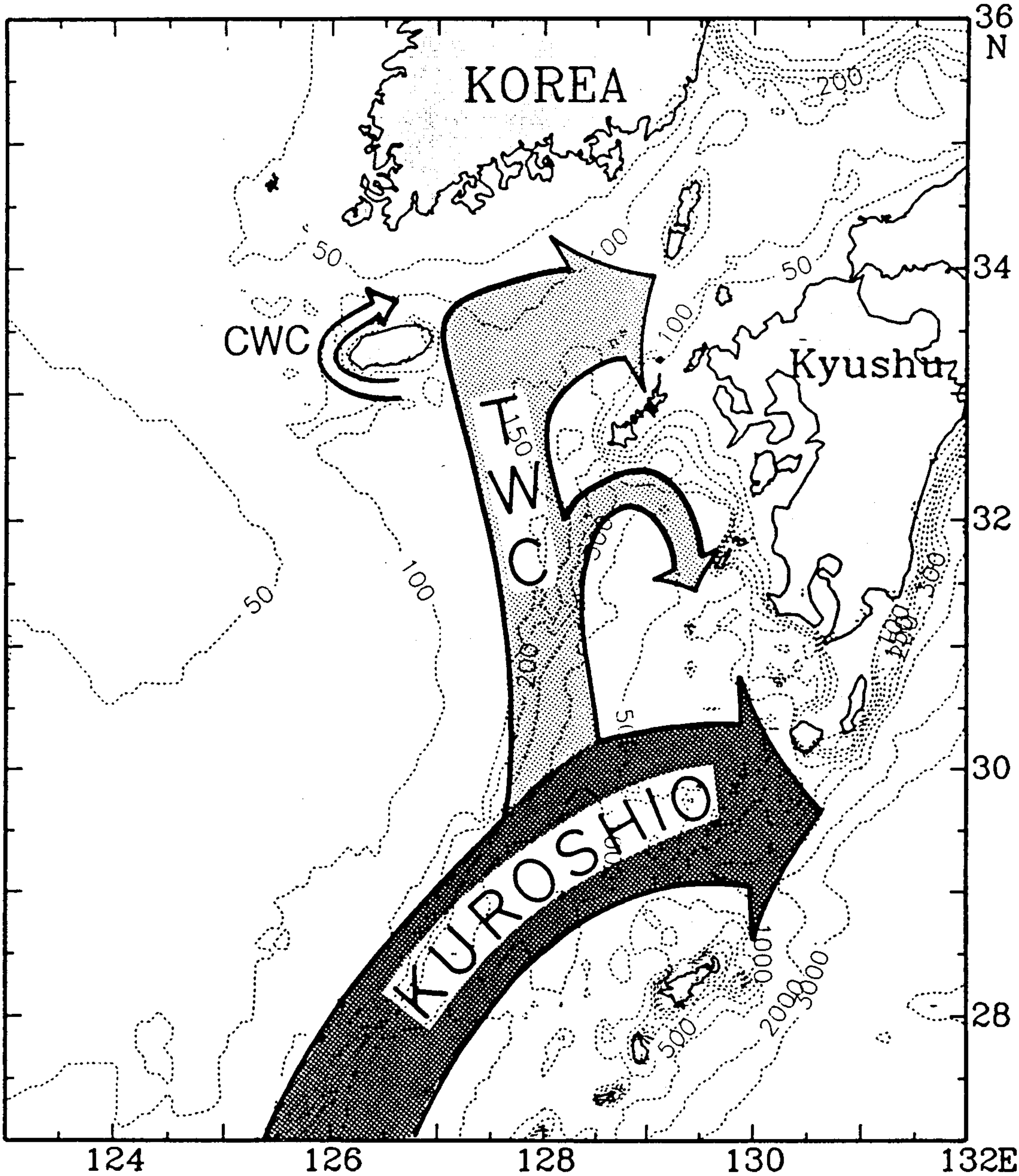

Fig. 9. A schematic surface circulation pattern in the eastern East China Sea and main path of the Tsushima Warm Current (TWC) during the cold season. The pattern was constructed from the drifter trajectories and the salinity distribution. The clockwise circulation around Chejudo is denoted by CWC (Cheju Warm Current) in order to avoid confusion with part of the YSWC entering the Yellow Sea.

and an eastward turning TWC along the northern wall of the trough. The penetration of TWC onto the shelf takes place mainly across the northwestern trough and the TWC on the shelf continues northward upto 33° 30′ N, east of Chejudo. On the other hand, the TWC in the northern trough turns clockwise, forming an anticyclonic warm eddy of order 100 km in diameter in the northern trough and eventually joins the Kuroshio [Lie and Cho, 1994].

During the cold season, a strong surface to bottom front forms nearly along the 100 m isobath, approximately parallel to a line connecting Chejudo and Tsushima Island in the Korea Strait as pointed out by Lie and Cho [1994]. The TWC water is generally bounded to the north by the front, though the front moves back and forth during the cold season. The front running west to east has been frequently seen [e.g., KORDI, 1994] and drifters following the TWC water scarcely entered the fresher coastal water across the front. North of 33° 30′ N, drifters turned to the northeast and moved toward the Korea Strait. A mixed water of S of 34.4-34.6 between fresher shelf water and the TWC water was found to exist on the inner shelf west of the TWC and its width widened toward the north.

The Yellow Sea Warm Current (YSWC) has long been believed to separate from the TWC between Chejudo and Kyushu and to flow into the eastern Yellow Sea, even though the different origin of the TWC has been suggested [Uda, 1934; Nitani, 1972; Chen et al., 1994]. Analysis of historical hydrographic data has shown the existence of a mixed water with $S > 33.0$ psu throughout the year west of Chejudo [Lie, 1985] and relatively saline mixed water with $S > 34.0$ psu, lying in a narrow band close to the west coast of Chejudo, is found to turn clockwise around Chejudo [Lie, 1986; Kim et al., 1991]. However, branching of the YSWC from the TWC is not seen on the drifter trajectories in Figure 2. Only CTD data around Chejudo during the cold season show that the saline mixed water close to the southern Chejudo infiltrated partly into the southwestern coastal area of

Chejudo and its large portion tended to turn clockwise around Chejudo. This suggests that the YSWC water may not separate directly from the TWC water and it may be a northwest infiltration of the mixed water just south of Chejudo. The clockwise circulation around Chejudo is denoted as the Cheju Warm Current in Figure 9 in order to avoid confusion with part of the YSWC entering the Yellow Sea.

During the winter survey, the drifters, released near or in the inshore Kuroshio water moved northward at a daily mean speed of 5-10 cm/s near the separation area and at a faster speed up to 15 cm/s north of line IA. During the spring survey, the drifters moved northward with about 10-15 cm/s in the neighborhood of separation and more than 20 cm/s north of line I. The intruded Kuroshio water in the trough located in the surface layer of the stratified water column, but the penetrated TWC water onto the shelf occupied almost the whole water column on the shelf. This suggests that TWC in the trough was characteristic of a baroclinic flow in the trough, but of a barotropic flow on the shelf after its penetration onto the shelf. The transition from a baroclinic flow to a barotropic one has been pointed out by Hsueh et al. [1996].

SUMMARY AND CONCLUSIONS

The separation of the inshore Kuroshio water from the Kuroshio main stream southwest of Kyushu and its penetration onto the shelf have been evidenced for the first time by all available drifter trajectories of KORDI and WOCE, and CTD data collected twice during the cold seasons, December 1993 and April-May 1995. The separation took place in the western mouth of the deep trough, elongated south-north west of Kyushu, where the northeast Kuroshio main stream made a detour to the east. The separated branch current, TWC, transported the inshore Kuroshio water, just upstream before the separation. The TWC water penetrated onto the shelf mainly across the western flank of the trough and partly the continental slope in the neighborhood of the turning point of the Kuroshio. The penetrated TWC onto the shelf continued northward and east of Chejudo and turned to the northeast toward the Korea Strait, bounded to the north by a strong surface to bottom front. The application of an inverse model to the CTD data also supported the separation and penetration of the Kuroshio. The estimated volume transport of the Kuroshio flowing in the study area is about 20 10^6 m^3/sec and the northward transport by the TWC is about one fifths of the inflow.

The separation of the TWC at the western mouth of the trough may be closely associated with the eastward turning of the Kuroshio main stream toward the Tokara Strait. Lie and Cho [1994] have suggested that while the Kuroshio main stream overshoots the mouth of the trough, the inshore Kuroshio does not leave the shelf edge and might change its direction toward the north, following isobaths of the western trough. Hsueh et al. [1995] have demonstrated that a baroclinic current incident upon a step-rise in bottom topography is bifurcated into a deflected main stream to the right to follow the step and a barotropic branch current to the left of the main stream that enters the shelf. The model is qualitatively in agreement with the observed separation at the mouth of the trough. However, the observed results of a tongue-shaped intrusion of the inshore Kuroshio water into the surface layer of the trough and its penetration onto the shelf across the isobaths cannot be satisfactorily explained by the above two simplified suggestions. The branch current in the trough is still a baroclinic flow with a large vertical shear when the geostrophic velocity is estimated and it does not follow the same isobaths.

The vorticity adjustment created by the eastward turning of the Kuroshio may be a candidate responsible for the intrusion and penetration of TWC. We consider fluid parcel with maximum speed and no shear on the main axis of a jet. The parcel acquires anticyclonic vorticity when it turns to the right and the anticyclonic vorticity is compensated by a cyclonic vorticity of the same magnitude, so the parcel must be displaced leftward with respect to the main axis. The curvature vorticity to the planetary vorticity in the southern trough is estimated to be of the order 0.1 for the mean path of the Kuroshio during January 1986 [Chen et al., 1992]. Furthermore, the Kuroshio is not horizontally uniform in speed, with a large shear across the stream. Upstream of the Kuroshio, fluid parcel on the cyclonic side of the Kuroshio possesses a significant cyclonic shear vorticity and downstream of the Kuroshio where it turns to the east, the parcel acquires additional shear vorticity due to the eastward turning of the Kuroshio. Consequently, the parcel can be displaced farther leftward to the shelf edge, away from the Kuroshio main stream. The tongue-shaped isotherms and isohalines extending to the shelf (see Figures 4 and 6) can be considered as a result of leftward displacement of inshore Kuroshio water by the combined cyclonic vorticity. The shoaling bottom topography of the trough and the incidence of the Kuroshio upon the trough are also responsible to some extent for the separation of TWC, so a joint effect of the topography, incidence, and vorticity adjustment might be the major candidates for the separation of the Kuroshio and its penetration. The joint effect of the three candidates should be investigated to better understand the Kuroshio and TWC, and related oceanic processes in the eastern ECS.

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