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The Exchange of Kuroshio and East China Sea Shelf Water

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A detailed hydrographic study of the East China Sea shelf edge north of Taiwan revealed an intense cold eddy on the shelf break and a large low-salinity filament at the slope. The cold eddy which is induced by the upwelling of the subsurface Kuroshio water has been repeatedly documented in previous studies. The filament which is made of the mixed shelf and subsurface Kuroshio water, on the other hand, has not been recognized before. The shelf edge upwelling appears to be associated with the sharp bending of the Kuroshio north of Taiwan, while the outpouring of shelf water appears to be associated with the northeasterly storms. Both the eddy and the filament consist of large fractions of the subsurface Kuroshio water, and they may be important to the salt and nutrient budget on the East China Sea shelf.

INTRODUCTION

The Kuroshio Current originates from east of the Philippines and flows north along the east coast of Taiwan. After leaving Taiwan the Kuroshio turns northeast along the edge of the East China Sea before eventually turning east near Kyushu Island. The Kuroshio meanders over the continental edge and frequently intrudes the East China Sea. Some striking examples of the Kuroshio intrusion are the permanent (year-round) flows through the Taiwan Strait [*Chuang*, 1986] and the Korea Strait [*Milta and Ogawa*, 1984]; the transports are of the order of 1 Sv (10^6 m^3/s). In addition, during the stratified season the cold and high-salinity subsurface Kuroshio water is found on the shelf, sometimes extending up the mouth of the Changjiang (Yangtze River) [*Su and Pan*, 1987]. Because of the massive onshore intrusion of the Kuroshio, the mean salinity on the East China Sea is only slightly less than that of the oceanic water. This is rather interesting, considering that the East China Sea has a broad (about 400 km wide) shelf and also receives large river runoff (about 40,000 m^3/s in summer).

The subsurface Kuroshio water on the East China Sea shelf is believed to have originated from the inflow through the Taiwan Strait and the upwelling on the shelf edge northeast of Taiwan [*Guan*, 1984]. However, recent studies indicated that the Kuroshio water is significantly warmed and therefore has lost its temperature-salinity (T-S) characteristic upon passing through the shallow Taiwan Strait [*Wang and Chern*, 1988]. This leaves the shelf edge upwelling as the only major source for the observed cold subsurface Kuroshio water on the shelf. In this study we describe the structure of an upwelling center northeast of Taiwan, based on a well-sampled hydrographic study. The hydrographic survey, which was conducted immediately after passage of two typhoons (hurricanes), also found a large filament of low-salinity shelf water on the slope. Our analysis suggests that the offshore transport of the shelf water is driven by the northerly storms.

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CHRONOLOGY OF TYPHOONS GERALD AND FREDA

Typhoons are very common in the South and East China seas during the summer season. In 1987, six typhoons directly affected the Taiwan area. Typhoon Gerald was formed on September 6 about 500 km east of Luzon Island. By September 8 it was about 500 km southeast of Taiwan and moving northwestward at about 15 km/h; its low-pressure center was about 950 mbar (Figure 1*a*). Gerald passed through Bashi Channel on September 9 and crossed Taiwan Strait on September 10 before landfall (Figure 1*b*). Gerald also had intensified with its low-pressure center dropping to less than 900 mbar. By then, typhoon Freda had developed about 1800 km east of Taiwan and was traveling eastward towards Taiwan (Figure 1*b*). However, facing a high-pressure weather system over the continent, Freda turned north on September 12 and never directly threatened Taiwan (Figure 1*c*). Nevertheless, between the high-pressure center and typhoon Freda, strong northeasterly winds persisted over the East China Sea during the earlier part of our hydrographic survey (Figure 1*d*). In fact, Freda marked the year's transition from the southwest to the northeast monsoon season.

HYDROGRAPHIC OBSERVATION

The hydrographic survey was conducted on board the R/V *Ocean Research I*, between September 14 and 19, 1987, when the sea state was still much influenced by typhoon Freda. A total of 57 stations were occupied over the shelf/slope area around northeastern Taiwan (Figure 2). Temperature and salinity data were obtained at each station with a Neil Brown Instrument Systems conductivity-temperature-depth (CTD) meter. Figures 3*a* and 3*b* show temperature and salinity distribution at 50 m depth. The surface Kuroshio water is warm (> 26°C), has high salinity (> 34.5 ppt), and is separated from the slope water by a steep front. While the Kuroshio front is essentially a temperature front, its location is better indicated by the salinity gradient. Next to the Kuroshio there was a distinct cold and high-salinity eddy on the shelf edge with minimum temperatures < 19°C and maximum salinities > 34.6 ppt. This cold eddy has been

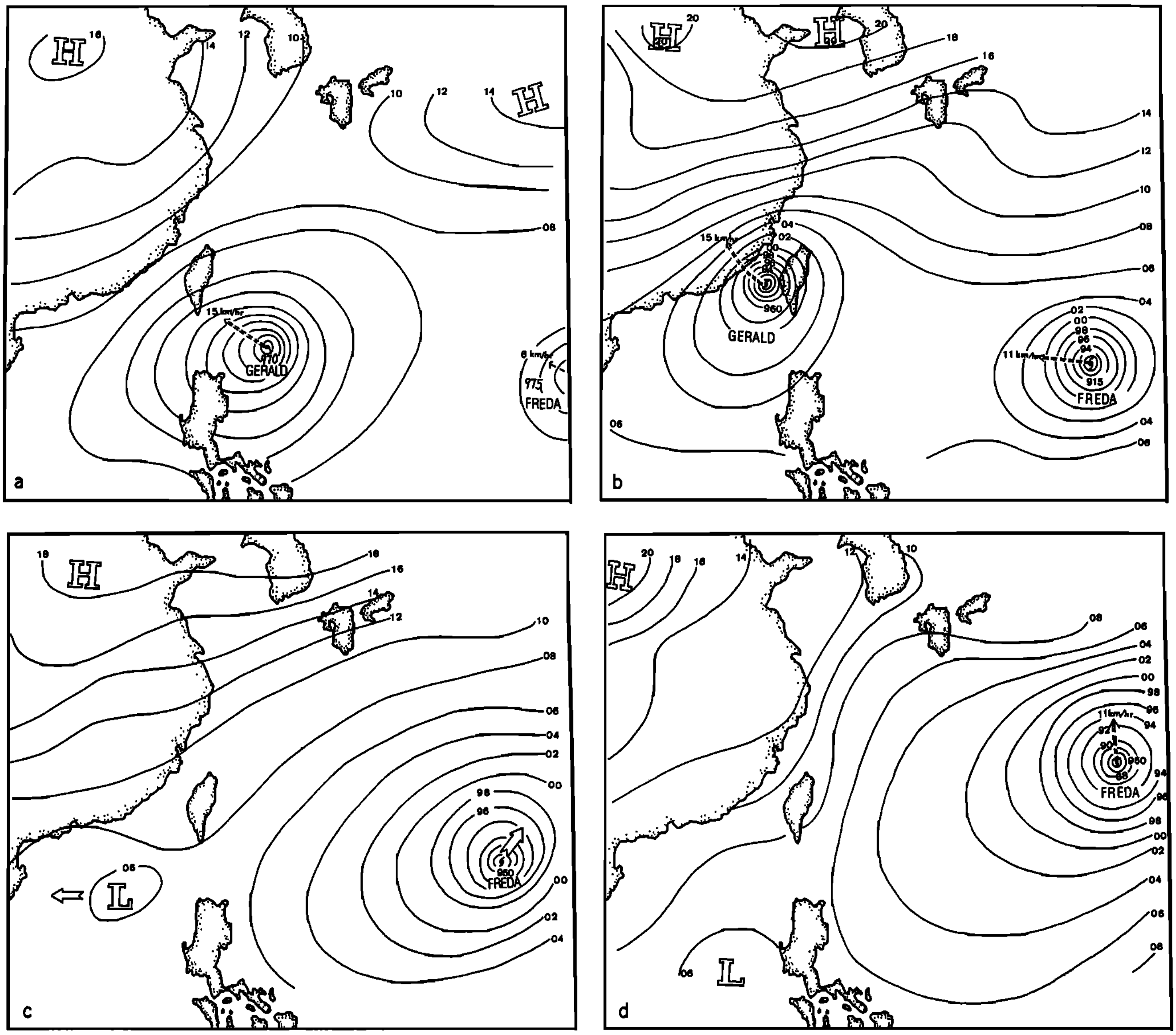

Fig. 1. The surface weather maps (surface pressure in millibars) during the two hurricanes: (*a*) September 8, (*b*) September 10, (*c*) September 12, and (*d*) September 14, 1987.

documented in many early studies and apparently is a permanent upwelling center [*Uda and Kishi*, 1974; *Fan*, 1980; *Liu and Pai*, 1987]. In water depth < 100 m the shelf water is warm (> 24°C) and has low salinity (< 34.2 ppt). On the outer shelf, however, the low-salinity water stretched out between the eddy and the Kuroshio, forming a funnel-shaped filament. Unlike the homogeneous inner-shelf water, the filament has strong temperature gradient, suggesting that the filament is a mixed-water type.

Figures 4*a* and 4*b* show temperature and salinity transects along line A across the center of the eddy, and Figures 5*a* and 5*b* show transects along line B across the shelf (both lines are marked in Figure 2). The warm, low-salinity shelf water is well mixed. West of the low-salinity column the shelf water is stratified, marked by warm and relatively high-salinity water at the bottom (Figure 4). This bottom water is part of the Taiwan Strait water which originated from the intrusion of open ocean (Kuroshio and South China Sea) water southeast of Taiwan [*Wang and Chern*, 1988]. East of the low-salinity column the cold, high-salinity eddy domes above the shelf edge. The eddy is formed by upwelling of the subsurface Kuroshio water. The high-salinity (> 34.7 ppt) core in the eddy is located above the bottom, indicating that the source water spans beyond the salinity maximum layer (Figure 5). Off the slope the Kuroshio is marked by a steep warm front and a well-mixed upper layer. Because of the strong surface heating the mixed layer normally is nonexistent during the stratified season [*Liu and Pai*, 1987]. The storms must have generated a rapid erosion of the surface layer.

A pocket of relatively low salinity water is located above the Kuroshio front (Figure 5*b*). This low-salinity water, which covered a large area, was identified earlier with the funnel-shaped filament (Figure 3*b*). The source of the filament water can be traced from the T-S diagram (Figure 6). The Kuroshio water is marked by high salinity, the inner-shelf water by low salinity, and the Taiwan Strait water by intermediate salinity. In addition, there are two distinct

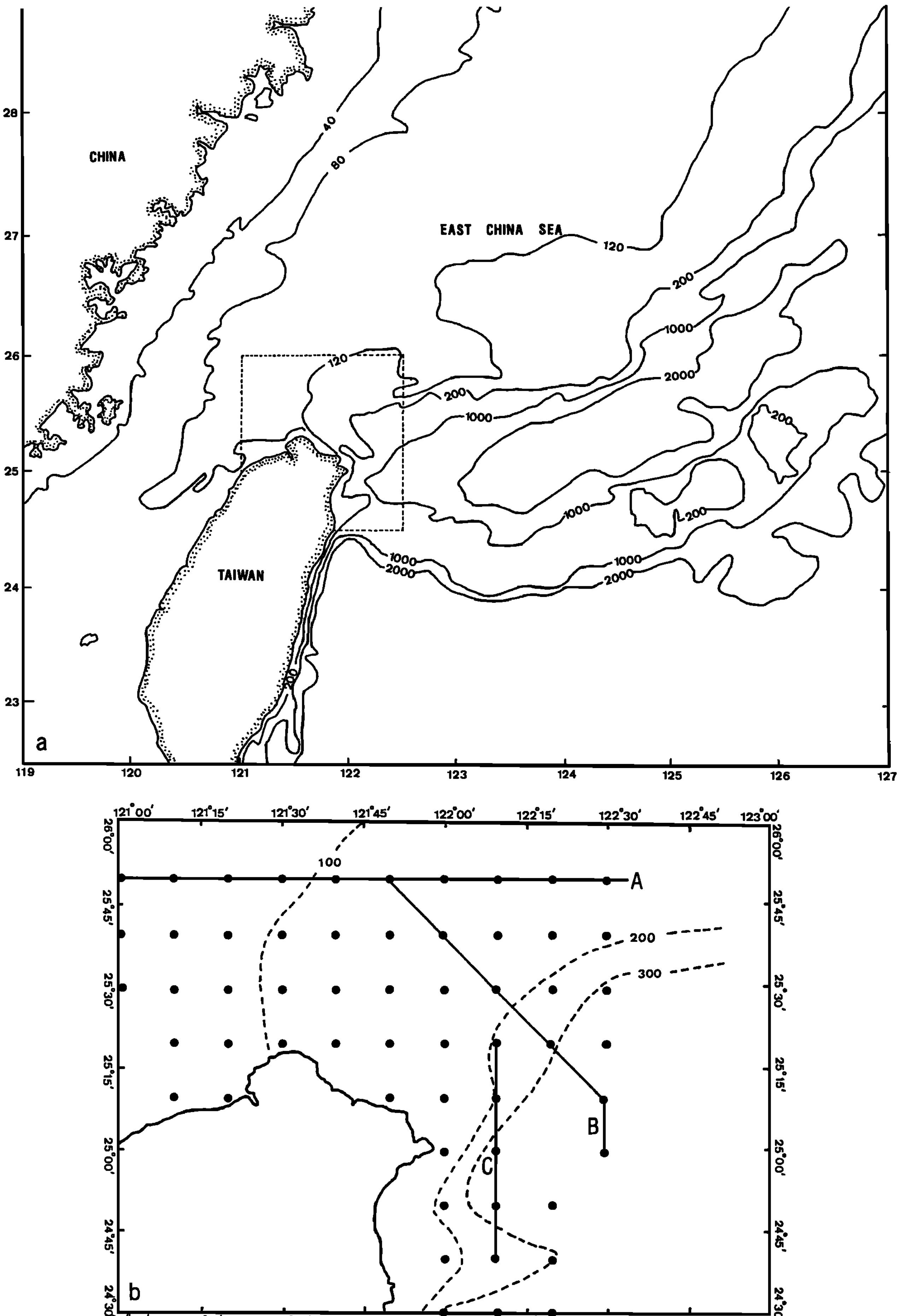

Fig. 2. (*a*) The bathymetric map (in meters) of Taiwan and East China Sea area. (*b*) Hydrographic station locations of dashed box area shown in Figure 2*a*.

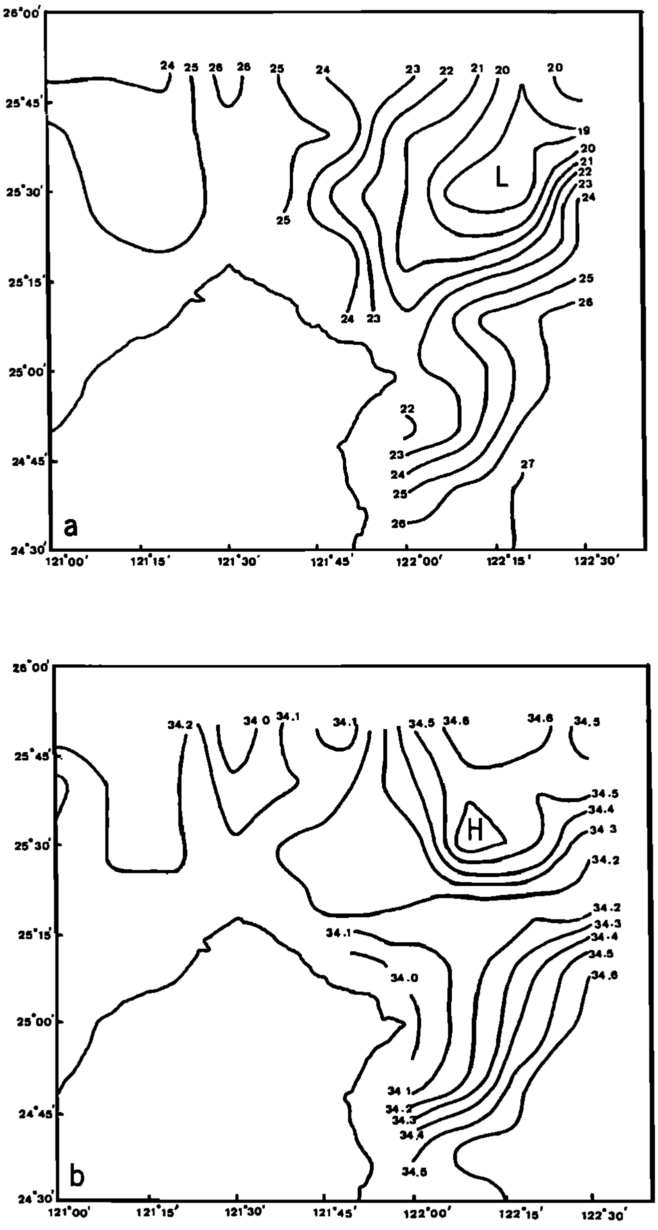

Fig. 3. Horizontal distribution of (*a*) temperature (in degrees Celsius) and (*b*) salinity (in parts per thousand) at 50 m.

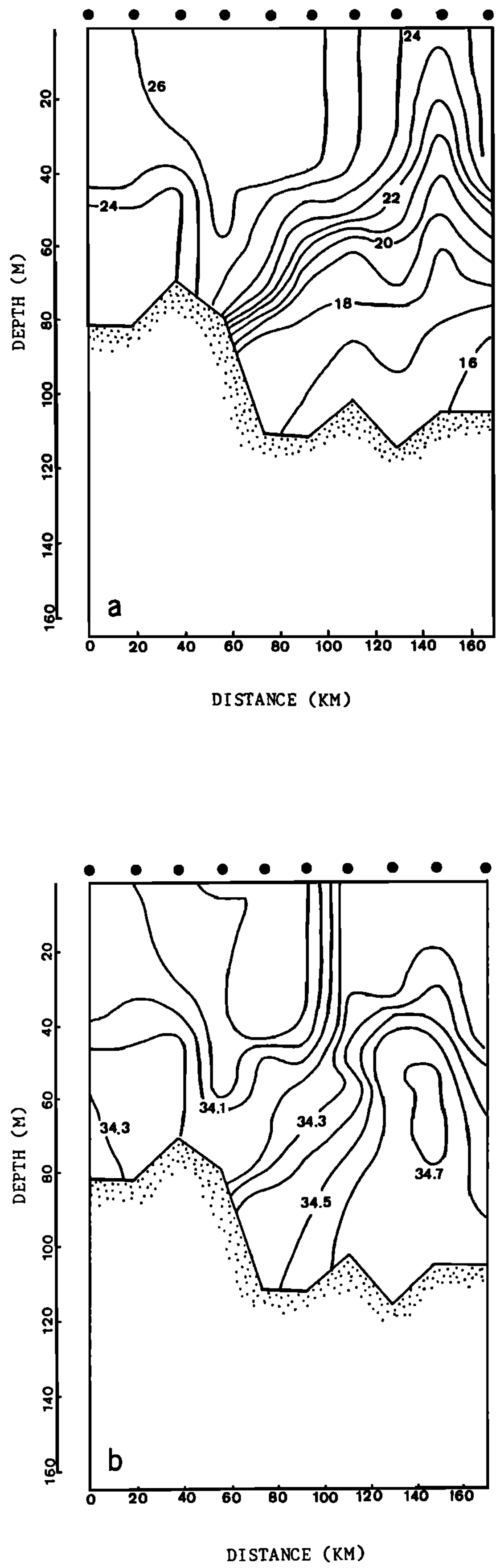

Fig. 4. East-west transect of (*a*) temperature (in degrees Celsius) and (*b*) salinity (in parts per thousand) along line A. (The distance is measured from the easternmost station; see Figure 2.)

mixing lines in the T-S diagram. The cold eddy falls into one mixing line consisting of the slightly diluted, subsurface Kuroshio water. This water mass structure is consistent with the cold eddy being a newly upwelled Kuroshio water. The filament, on the other hand, falls into a different line consisting of mixed shelf and Kuroshio water. It is interesting to note that the source of the filament also is from the subsurface Kuroshio water. In other words, the filament was made from mixing of the inner-shelf water with the upwelled subsurface Kuroshio water.

Most CTD stations in the filament had multiple salinity inversions. Figures 7*a* and 7*b* show temperature and salinity transects through the filament (line C in Figure 2). In general, a thin salinity inversion layer existed at the base of the surface mixed layer. Since the salinity can be treated as passive tracer, the salinity interleaving suggests strong

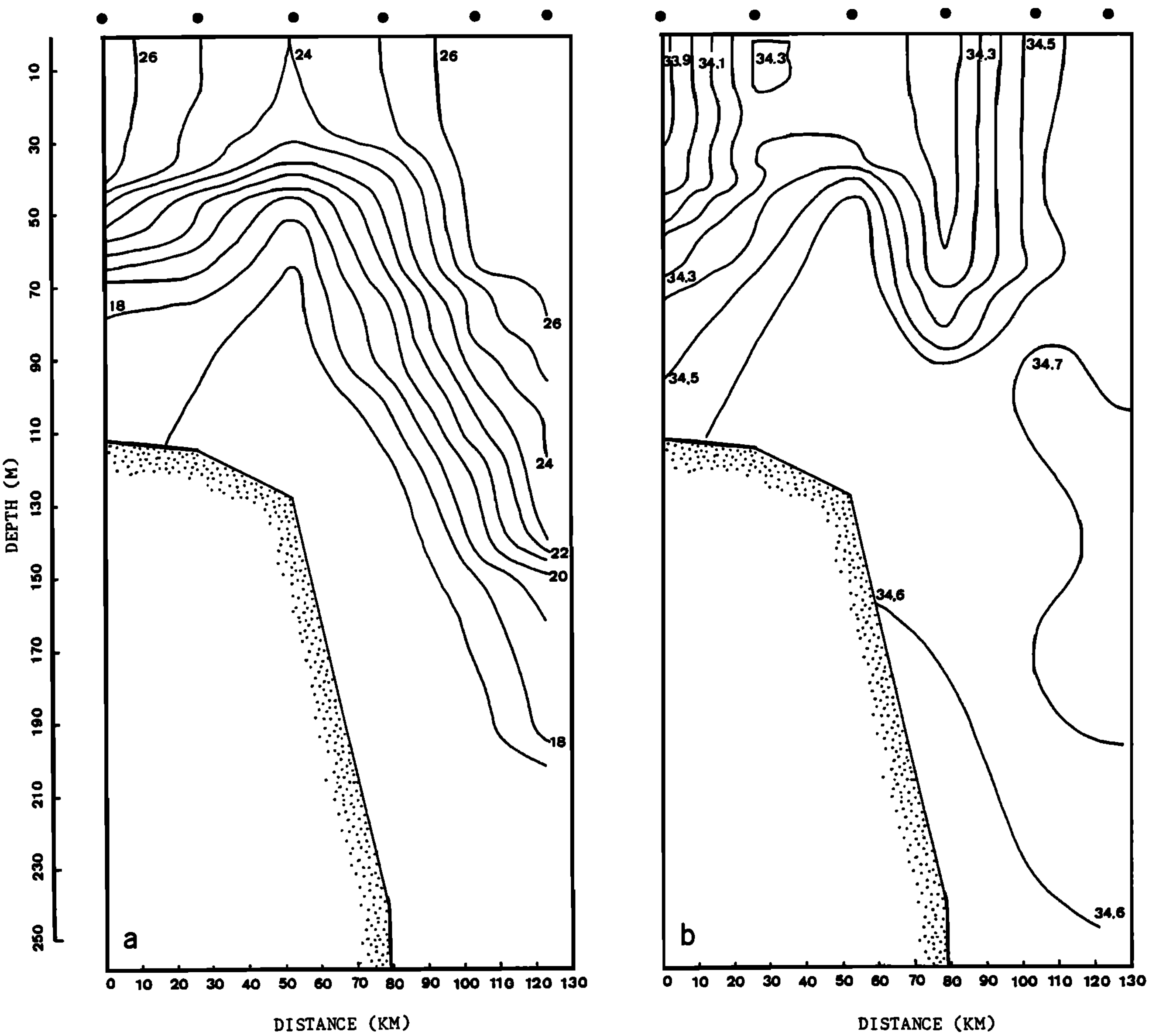

Fig. 5. North-south transect of (*a*) temperature (in degrees Celsius) and (*b*) salinity (in parts per thousand) along line B. (The distance is measured from the northernmost station; see Figure 2.)

sheared motion at the base of the mixed layer. We suspect that these might be inertial motions generated by the storms. At middepth there was a thick layer of anomalously low-salinity water. This low-salinity pool is quite interesting as it appears to cut through the upwelling zone (for example, compare Figure 7*a* with 5*a*). In other words, the outpouring shelf water appears to have mixed directly with the upwelled Kuroshio water.

Since the filament was located within the Kuroshio Current, the amount of shelf water carried by the Kuroshio can be roughly estimated from the geostrophic transport. With a reference level at 300 m the surface geostrophic velocity in the Kuroshio front is about 100 cm/s. The filament is 50 km wide and 100 m thick (Figure 5*b*), and assuming that half of the filament water is shelf water, the total offshore transport of shelf water by the filament is about 1 Sv. This is not a trivial amount of transport; for comparison, *Kupferman and Garfield* [1977] found filaments along the Gulf Stream with transport of only 0.1 Sv.

DISCUSSION

On the East China Sea shelf, intrusion of the subsurface Kuroshio water is mainly through the shelf edge upwelling. The cold eddy which is anchored at the shelf edge is most likely induced by the sharp bending of the Kuroshio northeast of Taiwan. A similar feature is found on the South Atlantic Bight where frontal eddies and bottom intrusion are related to the meandering of the Gulf Stream along the shelf edge [*Atkinson*, 1985]. The upwelled Kuroshio water penetrates well beyond the shelf edge, contributing significantly to the salt budget in the East China Sea. Also, the upwelling

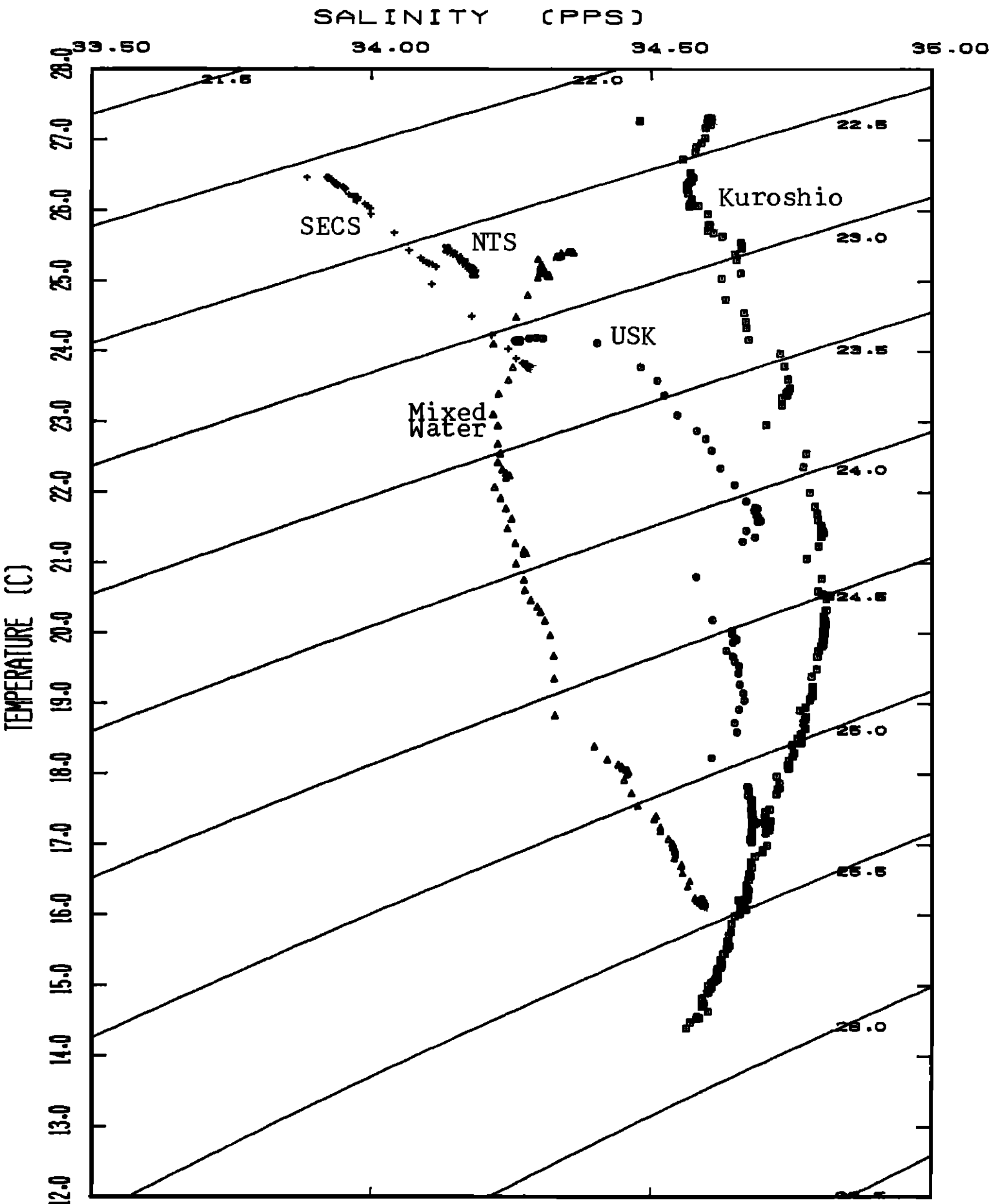

Fig. 6. Temperature-salinity diagram for selected conductivity-temperature-depth stations. (Pluses are SECS, southern East China Sea water; crosses are NTS, northern Taiwan Strait water; triangles are Mixed water, filament water; circles are USK, upwelled subsurface Kuroshio water; squares are Kuroshio, offshore Kuroshio water.)

brings high nutrients to the shelf [*Liu and Pai*, 1987], which may enhance the local productivity. Similarly, the filament which entrains the nutrient-rich subsurface Kuroshio water may be an important nutrient source for the otherwise barren surface Kuroshio water [*Liu et al.*, 1988].

Unlike the cold eddy which has been well documented, the filament was not recognized in early studies. The filament might be associated with the cyclonic circulation around the cold eddy; satellite images suggest entrainment of shelf water by cyclonic eddies at the Gulf Stream edge [*Churchill et al.*, 1989]. The filament might also be induced by the preceding storms, which may explain why large filaments were not frequently found. During typhoons Gerald and Freda, winds were predominantly from the northeast. A northeasterly wind will raise sea levels on the coast and drive southward transport down the Taiwan Strait. However, since the mean flow through the strait is northward [*Chuang*, 1986; *Wang and Chern*, 1988], the southward wind-driven flow must turn to the east and offshore, and the sea levels will also rise along the Taiwan coast. This relationship was confirmed by *Chern* [1982], who found high coherence between northerly wind, coastal sea level rise, and eastward current during the winter monsoon season. Thus the observed offshore transport of shelf water could be caused by the northerly wind associated with the typhoons. *Hsueh* [1988] proposed a similar mechanism for the onshore intrusion of the Kuroshio water in the Yellow Sea trough during winter northerly storms.

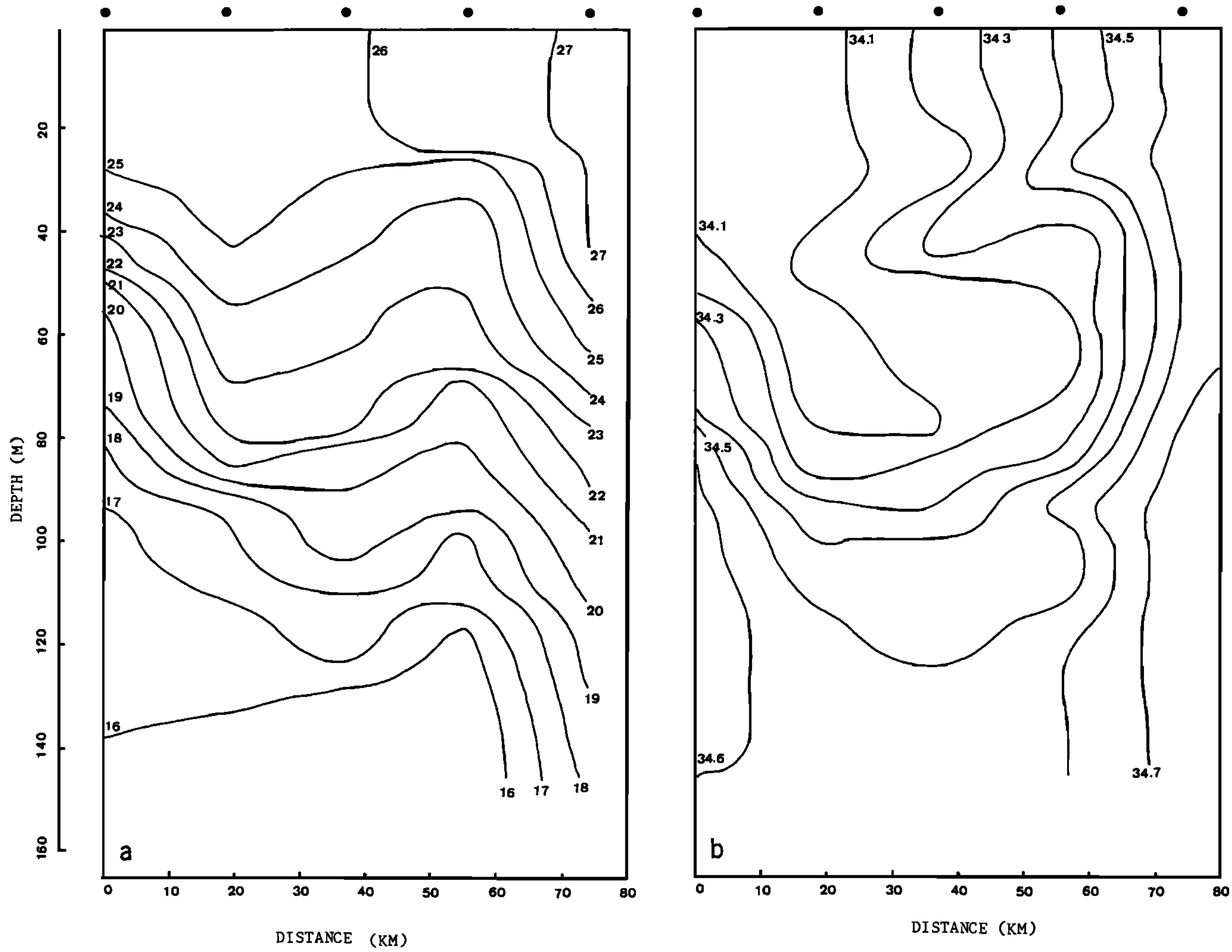

Fig. 7. North-south transect of (*a*) temperature (in degrees Celsius) and (*b*) salinity (in parts per thousand) along line C. (The distance is measured from the northernmost station; see Figure 2.)

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REFERENCES

Atkinson, L. P., Hydrography and nutrients of the southeastern U.S. continental shelf, in *Oceanography of the Southeastern U.S. Continental Shelf, Coastal Estuarine Ser.*, vol. 2, edited by L. P. Atkinson, D. W. Menzel, and K. A. Bush, pp. 77–92, AGU, Washington, D. C., 1985.

Chern, C.-S., A preliminary study on the response of Taiwan Strait to winter monsoon, *Acta Oceanogr. Taiwan.*, *13*, 124–139, 1982.

Chuang, W.-S., A note on the driving mechanisms of current in the Taiwan Strait, *J. Oceanogr. Soc. Jpn.*, *42*, 355–361, 1986.

Churchill, J. H., P. C. Cornillon, and P. Hamilton, Velocity and hydrographic structure of subsurface shelf water at the Gulf Stream's edge, *J. Geophys. Res.*, *94*, 10,791–10,800, 1989.

Fan, K. L., On upwelling off northeastern shore of Taiwan, *Acta Oceanogr. Taiwan.*, *11*, 105–117, 1980.

Guan, B. X., Major features of the shallow hydrography in the East China Sea and Huanghai Sea, in *Ocean Hydrodynamics of the Japan and East China Sea*, edited by T. Ichiye, pp. 1–13, Elsevier, New York, 1984.

Hsueh, Y., Recent current observations in the eastern Yellow Sea, *J. Geophys. Res.*, 6875–6884, 1988.

Kupferman, S. L., and N. Garfield, Transport of low-salinity water at the slope water–Gulf Stream boundary, *J. Geophys. Res.*, *82*, 3481–3486, 1977.

Milta, T., and Y. Ogawa, Tsushima currents measured with current meters and drifters, in *Ocean Hydrodynamics of the Japan and East China Sea*, edited by T. Ichiye, pp. 67–76, Elsevier, New York, 1984.

Liu, C.-T., and S.-C. Pai, As Kuroshio turns, II, The oceanic front north of Taiwan, *Acta Oceanogr. Taiwan.*, *18*, 49–61, 1987.

Liu, K.-K., S.-C. Pai, and C.-T. Liu, Temperature-nutrient relationships in the Kuroshio and adjacent waters near Taiwan, *Acta Oceanogr. Taiwan.*, *21*, 1–17, 1988.

Su, J., and Y. Pan, On the shelf circulation north of Taiwan, *Acta Oceanol. Sin.*, *6*, suppl. 1, 1–20, 1987.

Wang, J., and C.-S. Chern, On the Kuroshio's branching with Taiwan Strait during winter time, *Prog. Oceanogr.*, *21*, 469–492, 1988.

Uda, M., and A. Kishi, Cyclonic cold eddies along the edge of the Kuroshio current in the relation to the genesis and passage of cyclones, I, Waters north of Taiwan, in *The Kuroshio III, Proceedings of the 3rd Symposium, Bangkok, Thailand, 1972*, pp. 199–218, 1974.

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