The Upper-Layer Circulation of the Japan Sea: Historical Data Analysis

Dr. Amy S. Bower, PI, and Heather Furey
Department of Physical Oceanography, MS#21
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
(508) 289-2916 / hfurey@whoi.edu
Award #: N00014-98-1-0184

Project Goals:
The circulation of the Japan/East Sea is characterized by significant temporal and spatial variability due to several factors, including seasonal fluctuations in the warm inflow through Tsushima Strait, branching of the Tsushima Warm Current downstream of the strait, and the formation of mesoscale eddies along these branches. The long-range objective of the Japan/East Sea study is to understand the dynamical processes that govern this variability.

Methods:
We used the very large AXBT data set from NAVOCEANO to investigate a) the structure and distribution of intra-thermocline eddies and b) the seasonal variability in the three-dimensional, synoptic temperature structure and circulation in the East China, southern Yellow and southeastern Japan/East Seas in the upper 400 m. The study region is shown in Figure 1. Previously, we converted the vast store of XBT data to dynamic height following the methods of Lagerloef [1994] to address our original objective of describing the spatio-temporal modes of variability in dynamic height and determine the primary sources of this variability. We found that the error estimates were not random scatter, as hoped and as was the result in the Gulf of Alaska (where Lagerloef's study was conducted), but biased due to the profound effect salinity has on density structure in the Japan/East Sea. Therefore, we decided to focus more on the unique AXBT data set provided through NAVOCEANO and investigate the synoptic temperature structure and its variability.

Major Findings:
An inventory of intra-thermocline eddies (ITE) was made in the Japan Sea from five air-deployed XBT surveys from 1992 through 1995 [Gordon et al., 2002]. The eddies, characterized in the XBT data by homogenous cores of greater than 100 meter thickness and mean temperatures of less than 12°C, have also been observed in other data to have a positive oxygen anomaly and negative salinity anomaly compared to surrounding thermocline water (Figure 2). The ITE properties indicate winter formation within the Japan Sea polar front, and subsequent subduction under the thermocline to the south. The AXBT surveys reveal the existence of ITEs throughout the year (Figure 3), between the 8° and 11°C isotherms. The seasonally-repeated synoptic AXBT surveys allow us to see possible formation and follow the movement and water mass modification of the individual ITEs. The AXBT surveys indicate formation can occur in both winter and spring, with complete subduction taking less than three months. The core temperatures of the ITEs can be directly linked to surface temperature at the formation site, and the ITEs appear to translate 1.1 ± 0.4 cm/sec to the south-southwest after formation. These observations confirm the working hypothesis of ITE formation along the polar front.

We also completed a paper detailing the temperature structure and circulation of the East China, southern Yellow, and southeastern Japan/East Seas from AXBT data [Furey and Bower, 2005]. The main focus of the paper is on four unique AXBT surveys that provide high-resolution coverage of these regions, providing the first synoptic view of quasi-seasonal (September, February, and May) surface to 400-meter temperature structure for this region. The 60-meter temperature for the fours surveys is shown in Figure 4. Over the entire region, we focus on mixed layer depth dynamics and temperature front structure at the surface, sub-mixed layer (60 meters) (Figure 5), and deep (100 meters) levels. Surface temperature structure is indicative of deeper temperature structure only in winter, when strong monsoonal winds mix the stratified water column often to the bottom (see heavy dashed line of Figure 5), and spring, before surface heating re-stratifies the water column. The two September surveys illuminate the possible differences in temperature structure. In 1992, the eastern Kuroshio temperature front (Kuroshio Front) is far on-shelf of its usual position between the 200-meter isobath and the mean Kuroshio path [Isobe, 1999a,b], blocking formation of eddies north of Taiwan, and branching into the Tsushima Strait. In 1993, the September Kuroshio Front is found off-shelf of its winter and spring position, and eddies have formed north of Taiwan, bringing cooler deep Kuroshio water onto the shelf [Tang, et al., 2000]. Despite the 1992 Kuroshio Front anomaly, subsurface temperature fronts through the Tsushima Strait exhibit a seasonal pattern that is consistent with SST fronts [Hickox, et al., 2000], where a front develops southeast of Cheju Island in both summers, and migrates north of Cheju Island in winter and spring. Possible downstream affect of the onshore position of the Kuroshio Front may be the off-shelf direction of the front through the western channel of the Tsushima Strait (Figure 5a), whereas in 1993, the September fronts in the eastern and western strait channels followed the Honshu coast once entering the Japan/East Sea (Figure 5d).

In addition to the regional results, we also focused on inflow and outflow of the Tsushima Strait and, using seven other AXBT surveys that cover the Tsushima Strait outflow region in the JES, we describe branching structure of the Tsushima Warm Current for the years 1992-1995. The East Korean Cold Current can be seen in summer only, reaching back into the western strait as far as the southern end of Tsushima Island. There is evidence of previously undocumented cold water entering the strait from the southwest, appearing to originate from upwelled water near the entrance of the strait. Branching patterns are not seasonally dependant, and fall into three categories: a) one front following the Honshu coast, b) two fronts splitting, one following the Honshu coast, and one following the East Korean Coast (the East Korean Warm Current), and c) similar to b), but with the East Korean Warm Current appearing displaced to the east.

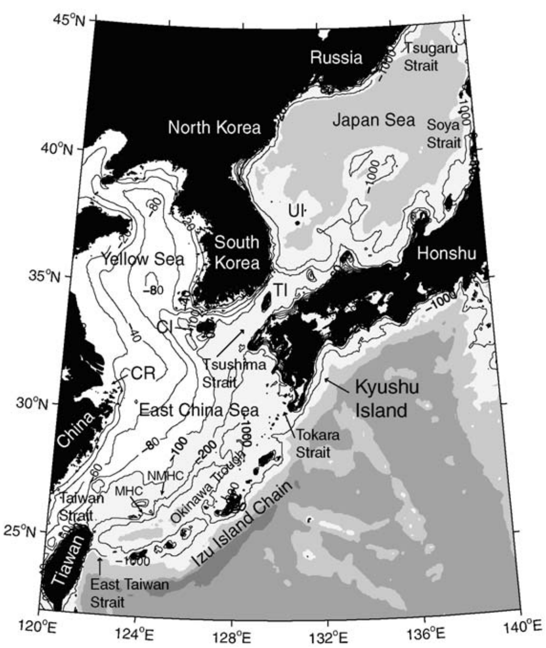

Figure 1. Reference map of the study region. ETOPO2 bathymetry is contoured at every 20 m down to 100 m, at 200 and 1000 m, and shaded at 1000 m intervals. MHC is Mien Hwa Canyon; NMHC is North Mien Hwa Canyon; TI is Tsushima Island; UI is Ulleung Island; CI is Cheju Island; CR is Changjiang River. Figure reproduced from Furey and Bower [2005].

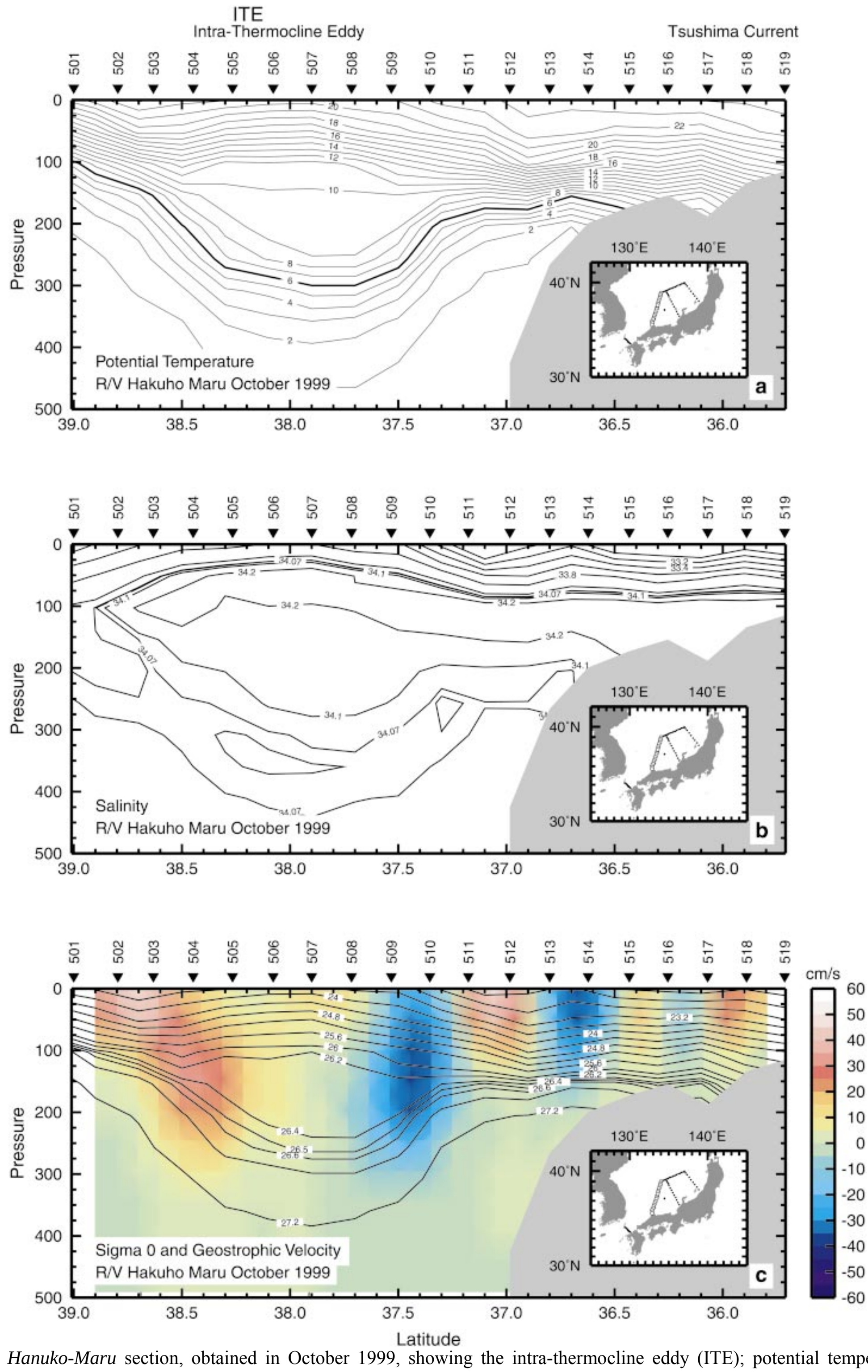

Figure 2. *Hanuko-Maru* section, obtained in October 1999, showing the intra-thermocline eddy (ITE); potential temperature (a), salinity (b), and sigma-θ (c). Superimposed on the sigma-θ section is the geostrophic current normal to the section relative to 1000 db or to the seafloor where shallower than 1000 db. Figure reproduced from Gordon, et al. [2002].

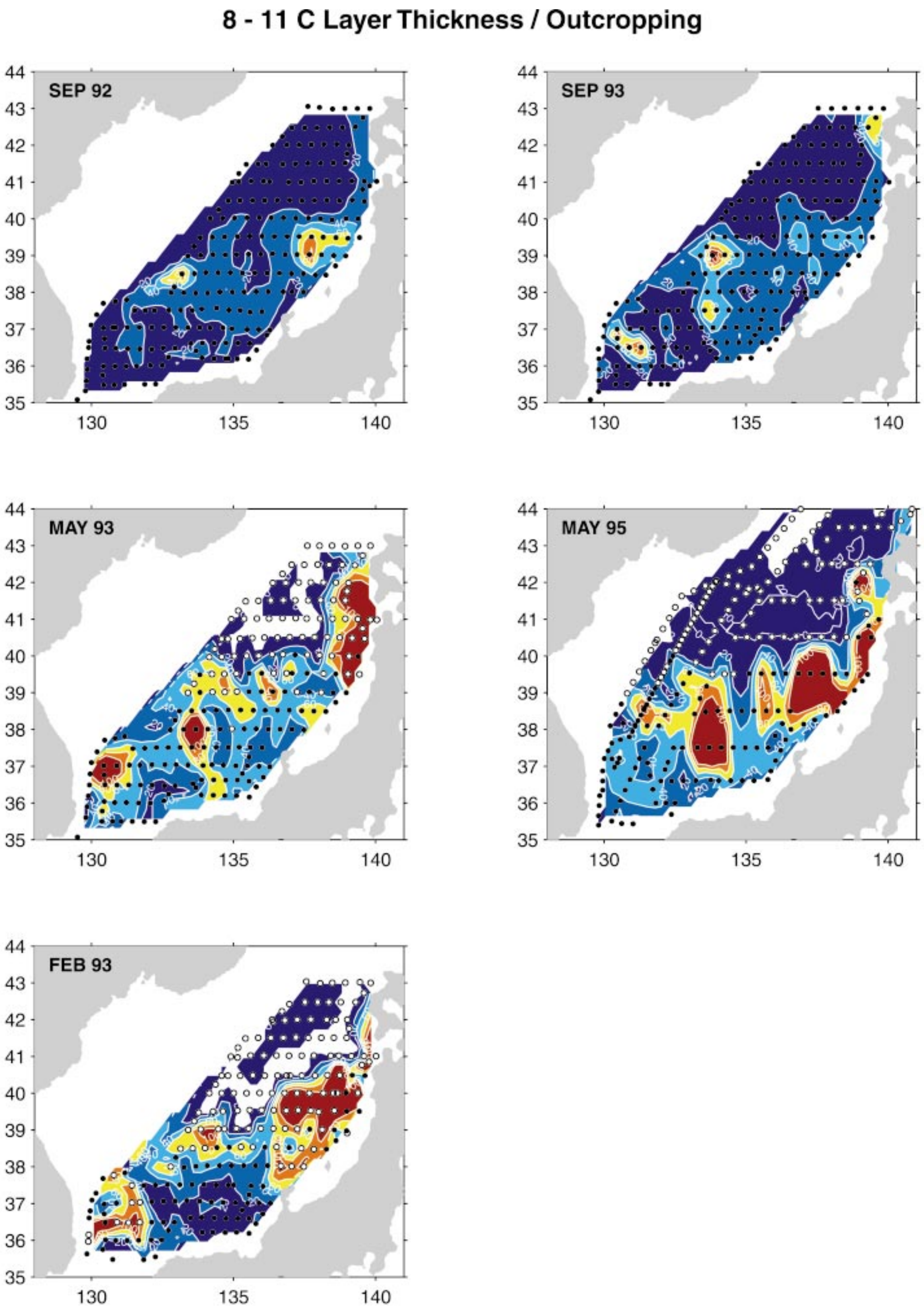

Figure 3: Distance (in meters) between the 8° and 11°C isotherms, the ITE layer, as seen in five comprehensive surveys by AXBT (September 1992, 1993, May 1992, 1995, and February 1993). The station locations are designated by solid or open dots. If a layer is submerged, then the station marker is designated by a black dot. If the upper temperature of the layer has outcropped, then the station is marked with an open circle. For example, in September 1992, no outcropping occurs, and all data represent the layer thickness. In February 1993, some northern stations have outcropped, and those stations represent the depth of the 11°C isotherm. In cases where there is no data, but a station marker exists, the lower isotherm has outcropped as well. Figure reproduced from Gordon, et al. [2002].

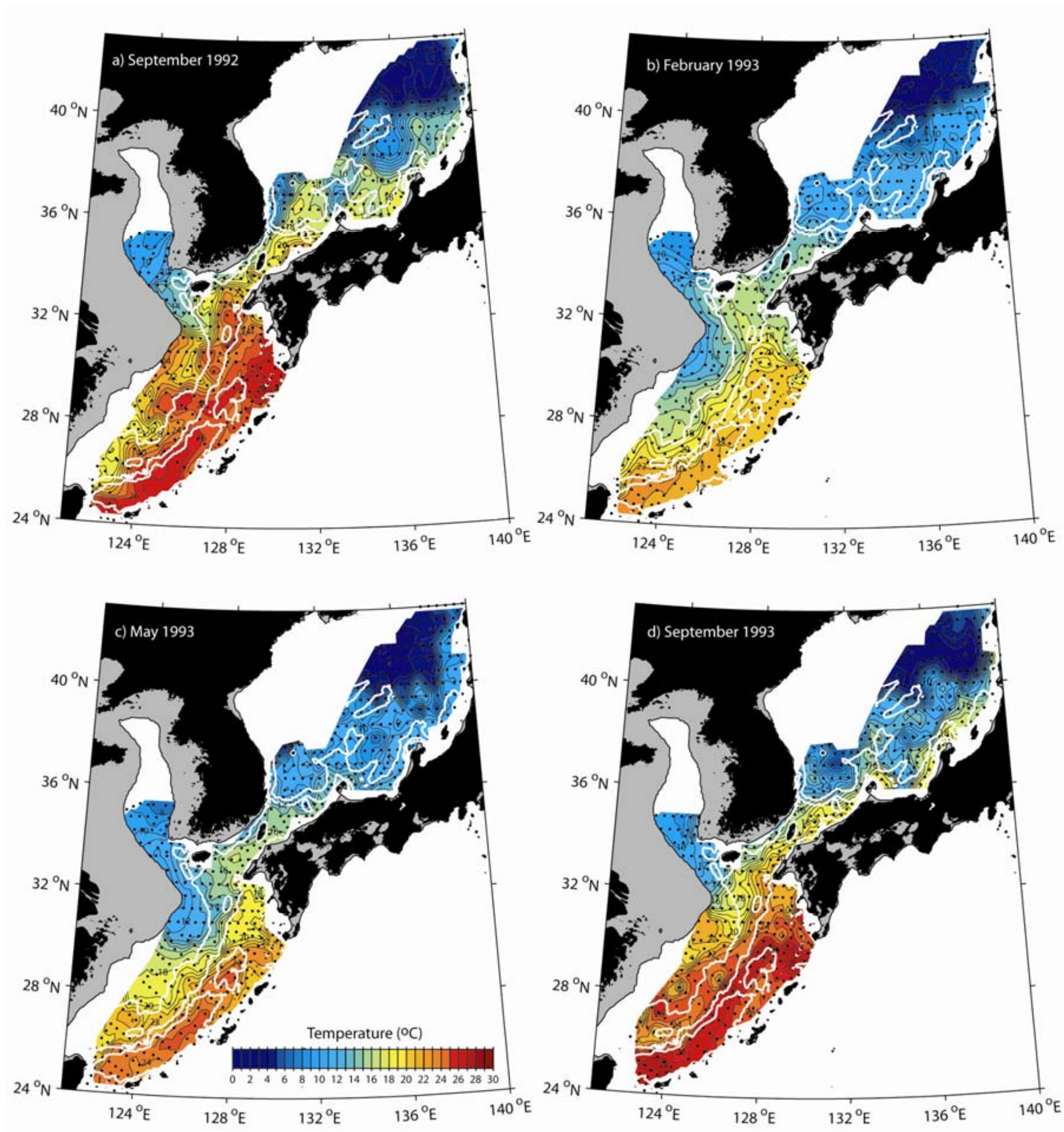

Figure 4. Horizontal temperature sections at 60 m depth for (a) September 1992, (b) February 19933, (c) May 1993, and (d) September 1993. Black dots mark station locations temperature contour interval is 1°C; and the 100-, 200-, and 1000-m isobaths are drawn in white. The bathymetry from 0 to 60 m is masked in gray. The 60-m depth was chosen as that depth below the level of seasonal heating and cooling, described in text. Figure reproduced from Furey and Bower [2005].

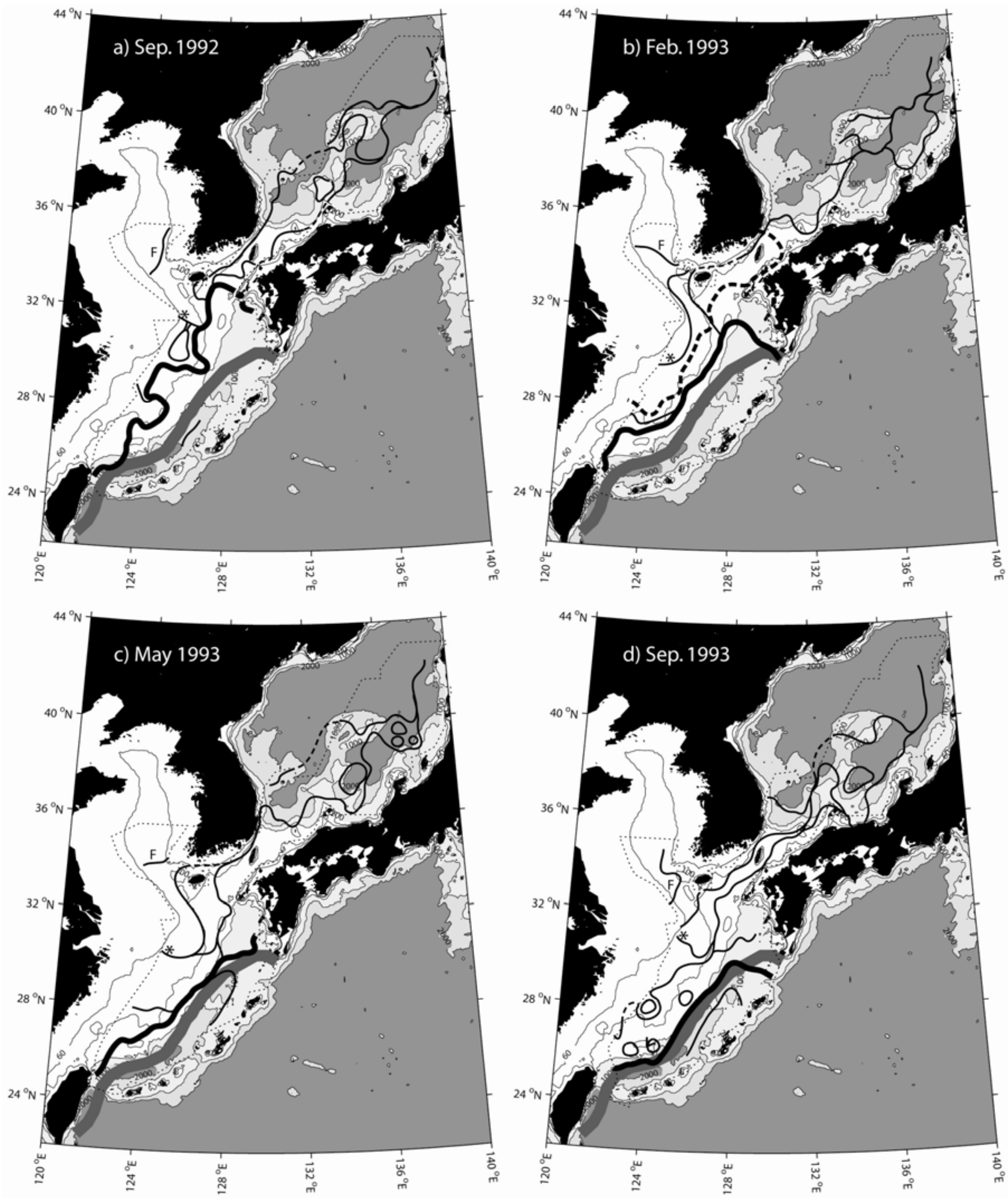

Figure 5. Sixty-meter temperature front structure for (a) September 1992, (b) February 1993, (c) May 1993, and (d) September 1993. Fronts have been defined as ~δT>3°C over 40 km distance (roughly the station spacing). Mean Kuroshio path (taken from Sun and Su, 1994) is shown as a wide gray line. Thin 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. Survey boundaries are drawn as dotted lines. The 100-, 200-, and 1000-meter isobaths are drawn, and bathymetry is shaded every 1000 meters. The thick black dashed line of b) defines the boundary of the region (to the northeast) where the water column in well-mixed (uniform to within 0.1°C) to the bottom. Heavy black line in ECS is the eastern temperature front of the Kuroshio. Figure reproduced from Furey and Bower [2005].

Summary:
Our results provide a better description of the water properties and seasonal variability in the upper-ocean circulation of the East China and Japan/East Seas, and its causes. 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. The intrathermocline eddies described above were heretofore not identified in the extensive AXBT surveys. They may play an important role in the flux of properties across the subpolar front in the Japan Sea. The broad scale AXBT surveys illuminate the difference between surface and sub-mixed layer depth temperature structure, and how this structure evolves seasonally. The two Septembers surveys bring forth the possible difference between sub-mixed layer front structures in the East China Sea, and also how this difference may affect downstream conditions in the Tsushima Strait and southeastern Japan/East Seas. Subsurface synoptic temperature structure aids understanding of previous [e.g., Hickox, et al., 2000] and future remote sensing studies. The large-scale synoptic nature of the surveys provides a context and reference point for future work in these regions.

Publications:

Gordon, A., C. Guilivi, C. Lee, H. Furey, A. Bower, and L. Talley, 2002. Japan/East Sea Intra-thermocline Eddies. *Journal of Physical Oceanography*, **32**, 1960-1974.

Furey, H., and A. S. Bower, 2005. Synoptic temperature structure of the East China and southeastern Japan/East Seas. *Deep Sea Res. II*, **52**, 1421-1442.

References:

Furey, H., and A. S. Bower, 2005. Synoptic temperature structure of the East China and southeastern Japan/East Seas. *Deep Sea Res. II*, **52**, 1421-1442.

Gordon, A., C. Guilivi, C. Lee, H. Furey, A. Bower, and L. Talley, 2002. Japan/East Sea Intra-thermocline Eddies. *Journal of Physical Oceanography*, **32**, 1960-1974.

Hickox, R., I. Belkin, P. Cornillon, and Z. Shan, 2000. Climatology and Seasonal Variability of Ocean Fronts in the East China, Yellow, and Bohai Seas from Satellite SST Data. Geophysical Research Letters, V 27, N. 18, pp. 2945-2948.

Isobe, A., 1999a. On the origin of the Tsushima Warm Current and its seasonality. Cont. Shelf Res. V. 19, pp. 117-133.

Isobe, A., 1999b. The Taiwan-Tsushima Warm Current System: Its Path and the Transformation of the Water Mass in the East China Sea. J. of Oceanography, V. 55, pp.185-195.

Lagerloef , G. S., 1994. An alternate method for estimating dynamic height from XBT profiles using empirical vertical modes. *Journal of Physical Oceanography*, **24**, 205-213.

Sun, X.-P., and Y.-F. Su, 1994. On the variation of the Kuroshio in the East China Sea. D. Zhou, Y.-B. Liang, and C. K. Tseng, Eds., Vol. 1, Kluwer Academic, 49-58.

Tang, T.Y., J.H. Tai, and Y. J. Yang, 2000. The flow pattern north of Taiwan and the migration of the Kuroshio. Cont. Shelf Res., V 20, pp. 349-371.