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Japan/East Sea Intrathermocline Eddies

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ABSTRACT

Intrathermocline eddies (ITE) with diameters of 100 km and of thickness greater than 100 m are observed within each of the three quasi-stationary meanders of the Tsushima Current of the Japan/East Sea. Within the ITE homogenous, anticyclonic flowing core, the temperature is near 10°C with a salinity of 34.12 psu. Because of compensatory baroclinicity of the upper and lower boundaries of the ITE core, the ITE has minor sea level expression. The ITE core displays positive oxygen and negative salinity anomalies in comparison to the surrounding thermocline water, indicative of formation from winter mixed layer water along the southern side of the Japan/East Sea subpolar front. The winter mixing layer is then overridden, or slips below, the regional upper thermocline stratification with its characteristic salinity maximum layer. The winter mixed layer off the coast of Korea closely matches the ITE core characteristics, and is considered as a potential source region. Other sources may be present along the southern boundary of the subpolar front, including a frequently observed warm eddy over the western side of Yamato Rise.

1. Introduction Return to TOC

A special class of ocean eddies, called intrathermocline eddies (ITE: a term introduced by Dugan et al. 1982), has been detected in numerous regions of the ocean (Kostianoy and Belkin 1991). ITE are characterized by a subsurface lens of relatively homogeneous water, 10 to 100 km in diameter, on the order of 100 m in vertical extent. The normal thermocline stratification is divided by the lens, with the upper thermocline forming a dome over the top of the lens and the lower thermocline forming a bowl defining the base of the lens. The temperature and salinity properties of the ITE are often distinct from those of the regional thermocline, suggesting a remote origin.

ITE were observed in the Japan/East Sea (Fig. 1) by CTD data obtained during various cruises in 1999 and 2000. They are also present in archived hydrographic and air-deployed expendable bathythermograph (AXBT) data. In this study we describe the characteristics, location, and possible origin of the Japan/East Sea ITE features. A theoretical treatment of the Japan/East Sea ITE is presented by Ou and Gordon (2002).

2. Background Return to TOC

South of the Japan/East Sea subpolar front, which lies between 38° and 40°N, there is a relatively warm saline surface layer (Fig. 2) over a shallow thermocline [see Preller and Hogan (1998) for an overview of the Japan/East Sea oceanography and Chu et al. (2001) for a presentation Japan/East Sea upper 400 m climatology]. At the base of the thermocline near 300 m is the low salinity (3°C, 34.0 psu) Japan/East Sea intermediate water (Kim and Chung 1984; Senjyu and Sudo 1994). The warm surface waters and thermocline occupy only 5% of the Japan/East Sea volume, but represent about 40% of the surface area (Kitani 1987). The thermocline of the southern Japan/East Sea is maintained by the import of water through Tsushima/Korea Strait near 35°N between Japan and Korea (Fig. 1). The surface water is exposed to strong winter cooling that converts a portion of Japan/East Sea inflow into the colder water composing the remaining 95% volume of the Japan/East Sea. The warm surface layer is characterized by abundant transient circulation features, such as warm and cold eddies, clearly observed in satellite infrared images of sea surface temperature (Ichiye and Takano 1988; Isoda 1994; Isoda and Saitoh 1993; Toba et al. 1984), by sea surface height anomalies detected by satellite altimeter, and by drifters trajectories (Jacobs et al. 1999; Morimoto et al. 2000; Lee et al. 2000).

The Tsushima/Korea Strait is composed of two channels: the eastern (Tsushima) channel with a sill depth of 115 m, and the western (Korean) channel with a sill depth of 204 m (Preller and Hogan 1998). Together they transfer on average 2 to 3 Sv (Sv 10^6 m^3 s^{-1}) of water from the East China Sea into the Japan/East Sea, with significant seasonal and interannual fluctuations (Katoh 1994; Preller and Hogan 1998). The Korean channel carries the bulk of this transport. Balancing the inflow are outflows of cold water through the Tsugaru and Soya Straits, the former carrying most of the export. The inflow forms the Tsushima Current composed of two or three branches within the Japan/East Seas (Isoda and Saitoh 1993; Kawabe 1982; Katoh 1994). The main branch is associated with the East Korean Warm Current, entering the Japan/East Sea through the Korean channel. It extends northward along the Korean coast to between 37° and 39°N, where it encounters the southward flowing Liman Cold Current. After confluence these waters flow eastward forming the Japan/East Sea subpolar front. The subpolar front is observed in the sea surface temperature pattern throughout the year, with maximum horizontal gradients of 16°C/100 km in winter (Chu et al. 2001). In the coldest month (February) the central isotherm at the sea surface of the subpolar front is 5°C, in the warmest month (August) the central isotherm is 24°C. The subpolar front meanders around the northern side of the Yamato Rise (Isoda et al. 1991). A second branch, referred to as the Tsushima Current, enters through the Tsushima channel and flows along the Japan/East Sea coast of Honshu. Occasionally, a third branch is present, which enters the Japan/East Sea through the Korean channel. It represents an offshore contribution to the Tsushima Current (Hase et al. 1999). The latter is highly variable, perhaps seasonal, suggesting frequent merging of the western two branches.

In contrast to the three branch concept is a single meander-path view (Katoh 1994; see Fig. 15.19 of Preller and Hogan 1998). In that view, quasi-stationary meanders (axis oriented north–south) form near 130°–131°E, 133°–134°E, and 136°–137°E. These meanders may be a consequence of coastal features, as the Tsushima Current is disturbed by two promontories: at the Oki Spur near 36°–37°N, 133°E and at the Noto Peninsula near 37°–38°N, 137°E (see Fig. 19 of Hase et al. 1999).

Isoda and Saitoh (1993) describe a warm eddy that develops yearly along the coast of Korea. It results in a large (diameter 100 km) warm eddy in the autumn near 38°N. The seasonality may be driven by the presence of thicker winter surface layers (Cho and Kim 2000). The warm eddy core with sea surface temperature approximately 10°C is observed into the early winter months (their Fig. 3). The eddy dissipates later in winter. The warm eddy described by Isoda and Saitoh (1993) is probably the same feature as the Ulleung Warm Eddy discussed by Ichiye and Takano (1988) and Kim et al. (1991). Isoda et al. (1992a) describe a "stably located" warm core eddy in summer 1989 over the western side of the Yamato Rise, with a core temperature of 8° to 9°C and a salinity of 34.3 psu, surrounded by a ring of warmer water. In winter the eddy structure becomes ambiguous. Isoda et al. (1992b) describe a similar trapped warm eddy in summer 1988, with a colder core temperature between 5° and 7°C and salinity between 34.1 and 34.2 psu. Isoda and Nishihara (1991) find that warm eddies are frequently found off the Korean coast, over the western side of Yamato Rise, and north of Oki Spur and Noto Peninsula. Isoda (1994) describes warm eddies generated at Oki Spur and Noto Peninsula as drifting eastward eventually to merge with the Tsushima Current east of Noto Peninsula. Although the author describes the "core temperatures" vary from 6° to 9°C, it is likely that the term "core temperatures" denote the eddy temperature at 200 m depth. Isoda (1996) presents a section east of Noto Peninsula in which an eddy with a relatively homogeneous layer (which is more traditionally called the core temperature) between 14° and 17°C from 50 to 150 m, is shown coalescing with the Tsushima Current.

3. Description Return to TOC

Intrathermocline eddies within the Tsushima Current are evident in the CTD data obtained by the RV *Revelle* cruises in May–July 1999 and in January–February 2000, and during a RV *Hakuho-Maru* cruise by the Ocean Research Institute, University of Tokyo, in October 1999.

a. *Hakuho-Maru*, October 1999

Potential temperature (Fig. 3a), salinity (Fig. 3b), and sigma-θ density (Fig. 3c) distribution observed during the *Hakuho-Maru* cruise reveal a relatively homogeneous lens of 9.8° to 10.0°C water of 34.12 to 34.13 psu salinity extending from 100 to 240 m. The geostrophic flow relative to a deep reference level (Fig. 3c) is anticyclonic, as characteristic of ITE (Kostianoy and Belkin 1991), with compensatory geostrophic shear within the lower and upper boundaries of the ITE. The highest geostrophic speeds of 30–40 cm s^{-1} occur at the edges of the ITE near 150 db. Sea surface geostrophic speeds are less than 10 cm s^{-1}.

The ITE core is observed at five sequential stations (505–509) covering a distance of 84 km. The thickest part is observed at stations 507 and 508, centered at 37°54′N and 133°36′E (close to the site that Isoda et al. 1992a find a 9° to 10°C eddy in September 1989; see their Fig. 1). Including the peripheral stations of 504 and 510, the lens dimension along the ship track is about 120 km. Of course, this need not be the average diameter of the ITE as the *Hakuho-Maru* probably did not pass across the central diameter of the feature, nor may the ITE be circularly symmetric. The maximum Rossby number (using the radius for the scale length, roughly 50 km) is 0.08, signifying approximate geostrophic balance.

The ITE is capped with a dome of warm upper thermocline water, containing the subtropical salinity maximum (S_{max}) layer. The S_{max} core, which is advected into the Japan/East Sea through the Tsushima/Korea Strait, falls within the 13° to 14°C isotherms. If the homogeneous lens were the product of winter mixing layer, as is likely, it has been overridden by, or it has slipped below, the regional upper thermocline stratification. The presence of the S_{max} indicates that the ITE is not the remnant of a simple one-dimensional process. The lower thermocline marking the base of the ITE displays a salinity minimum near the 3°C isotherm. This is the Japan/East Sea intermediate water, which forms by sinking of subpolar water immediately north of the subpolar front (Senjyu and Sudo 1994; Yoshikawa et al. 1999). As the ITE is warmer (less dense) than the intermediate water, its source region must be south of the region of intermediate water formation. As the subpolar front central isotherm at the sea surface in winter is 5°C (Isoda et al. 1991), the ITE source region along the southern half of the subpolar front is suggested.

The group of profiles of potential temperature and salinity (Fig. 4a) clearly reveal the contrast of ITE stratification with regional stratification. marks the thermostad and halostad defining the main ITE lens. A thinner, 40 m, homogeneous layer, labeled , of 7.9° to 8.0°C is observed at station 505, suggesting a family of ITE may be present within the Japan/East Sea thermocline. The θ/S structure (Fig. 4b) within both the and stads display a small negative salinity anomaly in comparison to adjacent thermocline stratification. In θ/oxy space (Fig. 4c) the lens displays positive oxygen anomalies. The 93% saturation of the and features is about 5 percentage points above that of the regional oxygen saturation of similar density. Elevated oxygen concentrations are indicative of ventilation during the cold periods, presumably as part of a winter mixed layer.

Remnant winter mixed layers isolated from the parent water mass often display anomalous properties relative to those of the parent. For example, the winter mixed layer within detached warm core rings from a western boundary current often display positive oxygen anomalies and positive salinity anomalies (Gordon 1981; Olson et al. 1992). The most likely source of the high oxygen is contact with the atmosphere. The high salinity is induced by latent heat loss to the winter atmosphere. However, low salinity anomalies within the Japan/East Sea ITEs requires freshwater addition. The negative salinity anomaly is less than 0.1 relative to the regional values at similar density. Were it not for introduction of freshwater, one may expect a positive salinity anomalies of 0.1, similar to that found within the core of warm core eddies spun off from the Gulf Stream or Brazil Current. Development of an anomaly of 0.1 to 0.2 requires an introduction of a 0.3 to 0.6 m thick layer of freshwater to the sea surface. While this is feasible, it is perhaps more likely that the lowered salinity is derived at least in part by incorporation of low salinity Japan/East Sea subpolar water, injected into the subpolar front at the confluence of the East Korean Warm Current and the Liman Cold Current.

b. *Revelle* cruises, May–July 1999

In May, 1999 the R/V *Revelle* obtained several high-resolution, quasi-synoptic sections across an ITE. A towed, undulating vehicle (SeaSoar) collected measurements of temperature, salinity and a suite of bio-optical variables. At typical tow speeds of 8 knots, SeaSoar provided along-track horizontal resolution of approximately 3 km while profiling between the surface and approximately 400 m.

The SeaSoar crossed a 10°C ITE (9.8°C, 34.1) at approximately the same location and depth as that observed by the *Hakuho-Maru* 5 months later (Figs. 5a,b; 6), implying the ships sampled the same feature. The May sea surface temperature of 16°C is about 5°C cooler than those observed in October, a result of summer heating. A trough, 20 km wide and 100 m deep, of high upper layer salinity water ($S > 34.3$) follows the western edge of the ITE (133°15′E, Fig. 5b). Additional meridional and zonal sections across the ITE (not shown) indicate that this is a filament of the Tsushima Current that extends northward from near the Japanese coast and wraps, in an anticyclonic sense, around the edge of the lens. The water within the filament exhibit water mass properties consistent with those found in the branch of the Tsushima Current flowing along the Japanese coast.

While the May 1999 data reveal a nearly continuous salinity minimum layer at the ITE base, the S_{max} layer in the upper thermocline is nonexistent or only weakly developed. Two months after the May SeaSoar measurements, a broad CTD survey of the Japan/East Sea was obtained by the RV *Revelle* (Fig. 6). A feature presumed to be the same ITE was sampled. The few profiles obtained within the feature all show a well formed S_{max} above the ITE core, suggesting that local thermocline waters have overriding the 10°C lens since the May cruise.

The May 1999 section (Fig. 5b) also transverses a subsurface homogeneous lens of water adjacent to the Korean coast, roughly from 130° to 131°E. The lens core is between 10.3° and 10.6°C, with salinity between 34.1 to 34.2 psu, slightly warmer than the ITE observed farther east. As it too displays a domed upper thermocline lid it can also be classified as an ITE feature. The location of this western ITE is within the western meander of the Tsushima Current. It may be part of the Ulleung Warm Eddy (Ichiye and Takano 1988; Isoda and Saitoh 1993; Preller and Hogan 1998).

c. *Revelle* cruise, January 2000

The January 2000 SeaSoar cruise reoccupied several of the May 1999 sections, including the 37°45′N section (Fig. 5). The winter section reveals an ITE near 133.5°E, perhaps the same feature sampled in May, July, and October 1999, shifted eastward by about 30 km from positions estimated from earlier cruises. Both the upper thermocline and mixed layer have cooled and freshened, and the 10°C isotherm that marks the ITE has deepened by nearly 100 m. Mixed layer temperatures above the ITE are near 13°C, suggesting that wintertime overturning has entrained the 13°–14°C salinity maximum layer observed during the previous summer and fall. The stratification and *T*–*S* properties of the ITE remain distinct, indicating that convective mixing has not penetrated to the lens core.

The western ITE has disappeared, replaced by a deep surface mixed layer of 13.3°C, about 3° warmer than the ITE core observed the previous May, though with similar salinity, 34.1 psu. The disappearance of the 10°C homogeneous feature in the winter period is consistent with the Isoda and Saitoh (1993) findings that the warm eddy formed off the Korean coast dissipates in winter. As the eddy core is warmer and less dense in winter (sigma-θ of 26.2 in May vs 25.8 in January) modification of the 10°C lens by winter convection is unlikely. It is surmised that the ITE has shifted position, rather than dissipated.

d. 1999 Summer/fall ITE distribution

The May to October 1999 dataset represented by the *Hakuho-Maru* CTD and the *Revelle* SeaSoar and larger-scale CTD station data are combined into a map view of the thickness of the layer from the 8° to 11°C isotherms (Fig. 6). Three 10°C ITE are found with approximate centers (to the extend resolved by the station distribution): 37°45′N, 130° 30′E; 38°N, 133°45′E; and 38°45′N, 137°35′E. Two meridional and three zonal SeaSoar sections sampled the ITE at 133°45′E over a span of 2 days, providing a synoptic snapshot of this feature. It appears as an ellipse, the major axis oriented in the north–south azimuth. The negative salinity anomaly is greater in the eastern sites than in the western sites. The sparse station distribution does not allow for the calculation of the translation velocity of the central ITE to a high degree of certainty, but it appears to be small, on the order of 1 cm s^{-1}. Each quasi-stationary meander of the warm regime displays an ITE.

e. Sea level above the ITE

Sea level over the ITE lens is higher than the surrounding regions, but only slightly so. Generally, sea level follows approximately a linearly relationship of the depth of the lower thermocline, for example, the 6°C isotherm (Fig. 7). However, over the ITE the baroclinic shear below the lens is compensated somewhat by the shear above the lens, so the sea level expression of the intrathermocline eddies is weaker than expected from the thermocline relief. Based on the regional relationship of the depth of the 6°C isotherm to the sea surface dynamic topography relative to the 500-db level, sea level over the ITE is 10 cm less than would be expected from the regional linear relationship of thermocline to sea level.

f. Archive hydrographic stations

The archived hydrographic data provide some climatic prospective on ITE occurrences in the Japan/East Sea (Fig. 8). We inspected 29 653 stations obtained from 1926 to 1999 for evidence of ITEs, as revealed by separation of the 8° to 11°C isotherms by more than 80 m. The highest percentage of occurrence is at 38°N, 131°E; 38°N, 134°E; 38°N, 136°E; and along the Japan coast east of the Noto Peninsula. The three peaks of occurrences along 38°N coincide with the positions of the three meanders in the single meander-path view of the Tsushima Current.

A high occurrence of 8° to 11°C spacing greater than 80 m is found along the Japan coast east of the Noto Peninsula. This is also is observed in the *Revelle* summer 1999 data (Fig. 6) and in the AXBT data (Fig. 9) discussed in the next section. The winter sea surface temperature and salinity in this region is 9° to 10°C, 33.8 to 34.0 psu (Chu et al.

2001). This is slightly fresher than the water within the ITE cores. The depth of the 6°C isotherm within this feature follows the regional trend with 0–500 m dynamic height anomaly shown in Fig. 7, rather than that of the ITE. Additionally, it is not likely that the coastal waters east of Noto Peninsula move towards the west. Inspection of hydrographic sections in the region indicate the 8°–11°C thickening is a product of a relaxed vertical temperature gradient closer to 11°C, and at warmer temperatures. Isoda (1996) shows a section east of Noto Peninsula with relatively homogeneous layer between 14° and 17°C from 50 to 150 m. Hase et al. (1999) sections show a relatively thick layer from 13° to 15°C.

g. Air deployed expendable bathythermograph (AXBT)

The AXBT dataset provides a more synoptic view of the Japan/East Sea thermocline structure. Comprehensive AXBT surveys were obtained in September 1992, 1993; May 1993, 1995; and in February 1993 (Fig. 9). Regions of great separation of the 8° and 11°C isotherms marking ITE features are evident. Not counting the profiles for which the 11°C isotherm reaches the sea surface (open circles), an 8°–11°C separation greater than 100 m is observed in May 1993, 1995 between 37° and 39°N at 131°E, 133°E, and 136°–137°E, and along the Japanese coast east of Noto Peninsula. This is in agreement with the percentage of occurrences seen in the archive hydrographic data and further supports the ITE positioning within the three meanders of the Tsushima Current. In September 1992 and 1993, the 8°–11°C separation is smaller than observed in May, not exceeding 100 m. However the positions are consistent with the meander positions.

In February 1993 (Fig. 9) the AXBT survey coincided with a fine grid of hydrographic stations off the Korean coast (Fig. 10). A thick mixed layer of between 10° and 12°C, with 80% to 100% oxygen saturation, matching the ITE properties is observed off the Korean coast. This feature may lie within the warm eddy near 38°N described by Isoda and Saitoh (1993).

4. Conclusions Return to TOC

In the Japan/East Sea, lenses of homogeneous water are observed within the thermocline. These intrathermocline eddies (ITE) are approximately 100 km in diameter with thickness greater than 100 m. The anticyclonic ITE is in approximate geostrophic equilibrium with rim speeds of 30–40 cm s^{-1}. The upper-thermocline dome capping the ITE and the lower thermocline depression marking the ITE base, produce compensatory baroclinic shear, attenuating the sea level expression of the ITE relative to the regional thermocline depth to sea level height relationship. ITE features are observed within the three quasi-stationary meanders of the Tsushima Current near 130°–131°E, 133°–134°E, and at 136°–137°E. Minor movement of these features is suggested during the 1999 to 2000 periods of observations described above.

The ITE core properties of near 10°C with salinity of 34.12 psu are cooler and less saline than those of the local winter surface water, implying that the ITE are drawn from a more northern source. Positive oxygen anomaly within the ITE lens relative to the oxygen levels of the surrounding thermocline water is indicative of an origin involving winter exposure to the atmosphere. The negative salinity anomaly within the ITE lens is likely a consequence of addition of freshwater by precipitation and/or admixture with lower salinity waters from the winter mixed layer at the subpolar front.

The dome of upper thermocline water in summer and autumn incorporates the regional S_{max}, near the 13° to 14°C isotherms. The S_{max} core develops during the course of spring and summer as regional upper thermocline water overflows the ITE lens or as the ITE slips below the regional stratification. The S_{max} is weakened or removed the following winter by the thickening mixed layer, but this convection does not penetrate into the ITE core. The ITE base is marked by the salinity minimum of the Japan/East Seas intermediate water formed along the northern edge of the subpolar front.

Winter mixed layer waters along the southern edge of the subpolar front may provide the source for ITE cores. Water mass characteristics found within wintertime mixed layers off the Korean coast (Fig. 10) closely match those found in the ITEs. These waters may be subducted into the midthermocline and subsequently advected eastward along the front. The SeaSoar surveys of the subpolar front indicate that ITE properties may also occur at the winter sea surface at other points along the front, closer to the locations at which eddies are observed. Data obtained in January 2000 near 39°45′N, 134°26′E (along the southern edge of the subpolar front) reveal a winter mixed layer 60 m thick with temperature between 9.5° and 10°C and salinity 34.12 psu (Fig. 11). These θ–S properties coincide with those found within the ITE 175 km to the south sampled during the May 1999 SeaSoar cruise (Fig. 11). Thus surface waters found along the southern edge of the wintertime subpolar front may provide a local source for the ITE. The ITEs may form through frontal convergence and subduction (Ou and Gordon 2002) at the subpolar front near the poleward ends of the distinct, northward Tsushima Current meanders. The warm core eddy observed over the western side of the Yamato Rise near 39°N, 133°–134°E (Isoda et al. 1992a,b) provides another example. This feature is similar to the ITE described above at a position south of Yamato Rise, with a core temperature of 8° to 9°C, salinity of 34.3 psu, and depth range of 100 to 200 m. The February (coldest month) sea surface temperature and sea surface salinity maps of Chu et al. (2001) show an extensive area of 9° to 10°C, 34.1 to 34.2 psu surface water within a 150-km band south of the subpolar front.

Ou and Gordon (2002) investigate the dynamics of formation of the Japan/East Seas ITE features by subduction along the subpolar front. However, many other questions should be addressed in future research, for example, what is the relationship of the ITE to the pattern of the various streams and meanders of the Tsushima Current?

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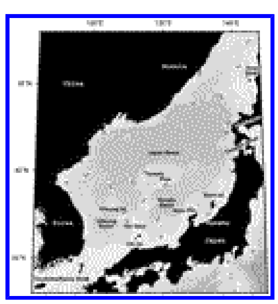

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FIG. 1. The Japan/East Sea (JES). Isobaths are in meters

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FIG. 2. Feb 1999 and Oct 1999 sea surface temperature maps. The data shown are for a monthly average of the daily sea surface temperature data analysis from the Japan Meteorological Agency. The analysis has a resolution of a quarter degree and combines sea surface observations by NOAA with in situ observations by ships and buoys. The data was obtained from the NEAR-GOOS Regional Delayed Mode Data Base operated by the Japan Oceanographic Data Center

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FIG. 3. *Hakuho-Maru* section, obtained in Oct 1999, showing the ITE; potential temperature (a), salinity (b), and sigma-θ density (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

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FIG. 4. The potential temperature and salinity profiles (a), potential temperature vs salinity (b), and potential temperature vs oxygen (c). The stations 505–509 defining the ITEs are shown in blue

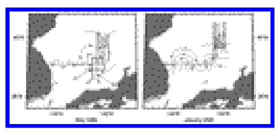

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FIG. 5a. Map of SeaSoar sections in May 1999 and Jan 2000 obtained by the RV *Revelle*. The contours are of the 12°C isotherm depth

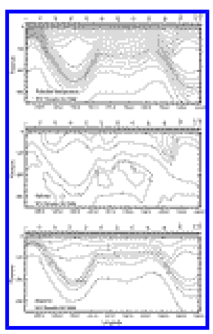

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FIG. 5b. May 1999 *Revelle* section of potential temperature, salinity and sigma-θ along 37°45′N

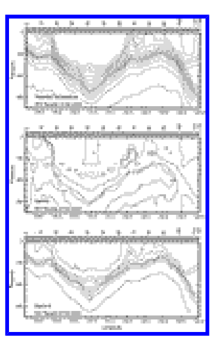

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FIG. 5c. Jan 2000 *Revelle* section of potential temperature, salinity, and sigma-θ along 37°45′N

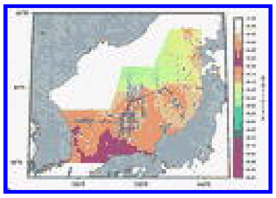

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FIG. 6. Map of the layer thickness (m) between the 8° and 11°C isotherms as observed during the *Revelle* cruises of May–Jul 1999 and Jan–Feb 2000, and from the *Hakuho-Maru* in Oct 1999. The color coding shows mean salinity within this temperature interval. Jul *Revelle* stations are shown as red dots; *Hakuho-Maru* are shown as black dots; the SeaSoar lines of the May and Jan *Revelle* cruises are shown as dotted lines

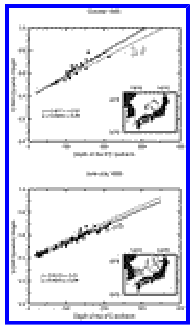

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FIG. 7. Relation of depth of the 6°C isotherm to 0/500 dynamic height anomaly for the *Revelle* Jun/Jul 1999 data and for the *Hakuho-Maru* in Oct 1999 data. Solid circles all data, open circles are within ITE (when the distance between the 11° and 8° isotherms is greater than 80 m). Insert maps show location of the ITEs. The regressions are calculated for all the Japan Meteorological Agency data

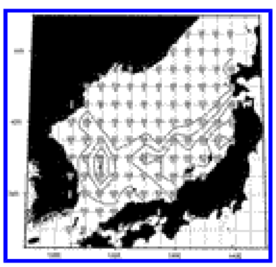

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FIG. 8. Percentage of occurrence of profiles displaying ITE characteristics as denoted by more than 80 m separation between the 8° and 11°C isotherms. The total number of stations inspected was 29 653, drawn from the 1926–94 NODC dataset, the 1995–97 (Japan Meteorological Agency) archive, and the 1999 *Revelle* and *Hakuho-Maru* data. The data is binned in 1° lat by 1° lon boxes. For each box the upper value is the total number of stations inspected, and the number below that value is the percentage displaying ITE characteristics. The values are positioned in the center of their lat/lon box

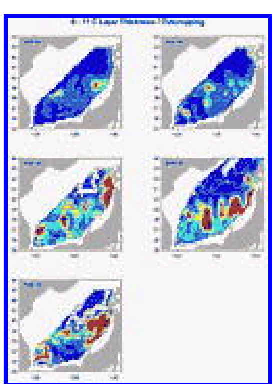

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FIG. 9. Distance (in m) between the 8° and 11°C isotherms as seen in five comprehensive surveys by AXBT Sep 1992, 1993; May 1993, 1995; and Feb 1993. Open circles are profiles where the sea surface temperature is colder than 11°C

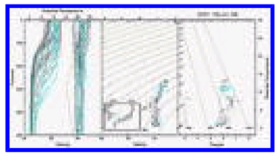

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FIG. 10. The potential temperature and salinity profiles (a) and potential temperature vs salinity (b) and oxygen (c) obtained at stations off the Korean coast, Feb 1993 (NODC dataset). Stations displaying thick surface layers with characteristics similar to those of the ITE are shown as thicker lines or larger dots

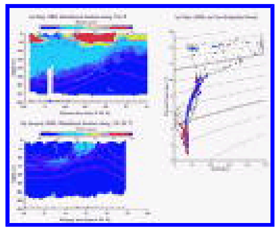

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FIG. 11. Meridional sections of potential temperature (contours) and salinity (color) (a) along approximately 134°E occupied in May 1999 and (b) along 134°26′E occupied in Jan 2000. The horizontal axis (in km) is relative to 39°30′N with inverted triangles marking profile locations. The Jan section extends to the subpolar front, while the May section displays only the region around the ITE. Colored (blue/Mar, red/Jan) triangles mark the profiles displayed in the potential temperature–salinity diagram (c). Waters within the winter mixed layer along the southern edge of the subpolar front (red) and within the ITE (blue) have temperatures between 8° and 11°C and salinity near 34.12 psu

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