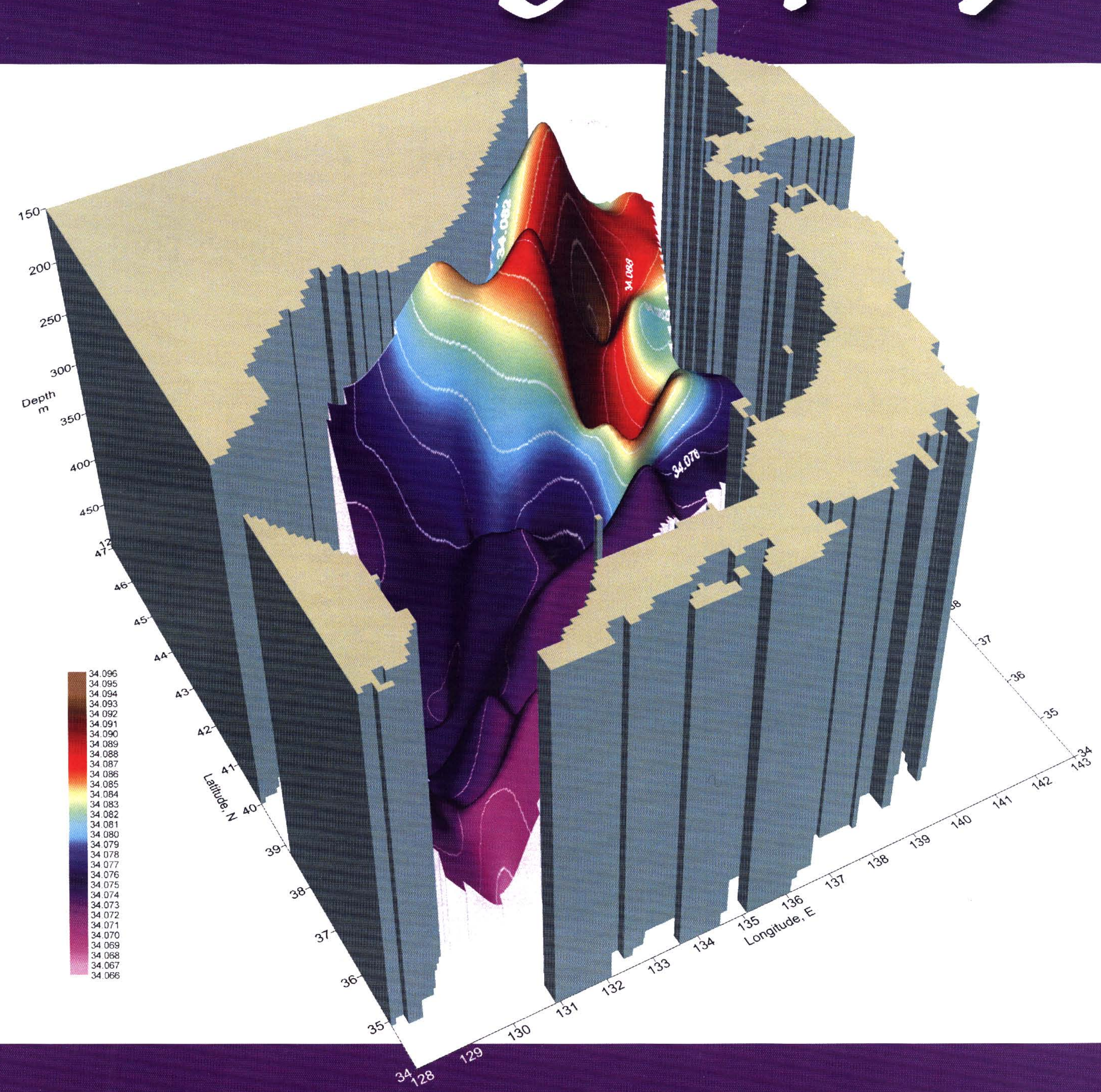
THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

VOL.19, NO.3, SEPTEMBER 2006



SPECIAL ISSUE ON THE JAPAN/EAST SEA

WHY DO INTRATHERMOCLINE EDDIES FORM IN THE JAPAN/EAST SEA?

A Modeling Perspective

BY PATRICK J. HOGAN AND HARLEY E. HURLBURT

Intrathermocline eddies (ITEs) are characterized by a subsurface lens of relatively homogeneous water. By definition, they are situated within the thermocline and therefore split the stratified water column, taking the form of a dome in the upper part of the thermocline and a bowl in the lower part. Observations of ITEs in diverse regions of the world ocean (Kostianoy and Belkin, 1989) indicate typical spatial scales of 10–100 km horizontally and 100 m vertically. In the Japan/East Sea (JES) (Figure 1) there are at least three mechanisms for the formation of ITEs from pre-existing non-ITE eddies based on results from the HYbrid Coordinate Ocean Model (HYCOM). Those mechanisms include advection of the stratified seasonal variations of temperature and salinity through the Tsushima Strait, restratification of the upper water column due to seasonal heating and cooling of the upper ocean, and subduction of ITE water originating from the Tsushima Strait beneath the wintertime Subpolar Front. The formation mechanisms are not mutually exclusive. Indeed, all three are shown to be interactively affecting the formation of an ITE in at least one case.

Gordon et al. (2002) reported the existence of ITEs in the JES based on observations from SeaSoar instrumentation, conductivity-temperature-depth (CTD) sensors, and airborne expendable bathythermographs (AXBTs). Their paper contains extensive analysis and discussion of ITEs in the JES and observational evidence of formation mechanisms based on cruise data collected during 1999–2000 as part of the Office of Naval Research (ONR) JES Departmental Research Initiative (DRI), as well as results from earlier studies. The observed ITEs have diameters of ~100 km, thicknesses of ~100 m, and are characterized by a nearly homogeneous core rotating anticyclonically (clockwise) with temperature ~10°C and salinity ~34.12 psu (Figure 2).

The Gordon et al. (2002) work inspired a numerical-model-ing study to examine whether or not similar features could be simulated. If they could be simulated, could the ocean model be used as a tool to elucidate the formation mechanisms of the ITEs? Here, we use HYCOM to simulate JES ITEs. Eddies are prolific in the JES, and are often associated with quasi-stationary meanders of the East Korea Warm Current (EKWC), Subpolar Front, and the Tsushima Warm Current (TWC) located near the northwestern coast of Japan. The anticyclonic eddies in the JES: (1) can be unstratified from the sea surface down to the thermocline within the eddy (i.e., have a mixed layer throughout the eddy core down to the thermocline), (2) have domed stratification at the top, forming a lens-shaped interior of nearly unstratified water, or (3) can have stably stratified water near the surface without the doming. It is only the middle class of eddies (2) that are considered ITEs in this paper.

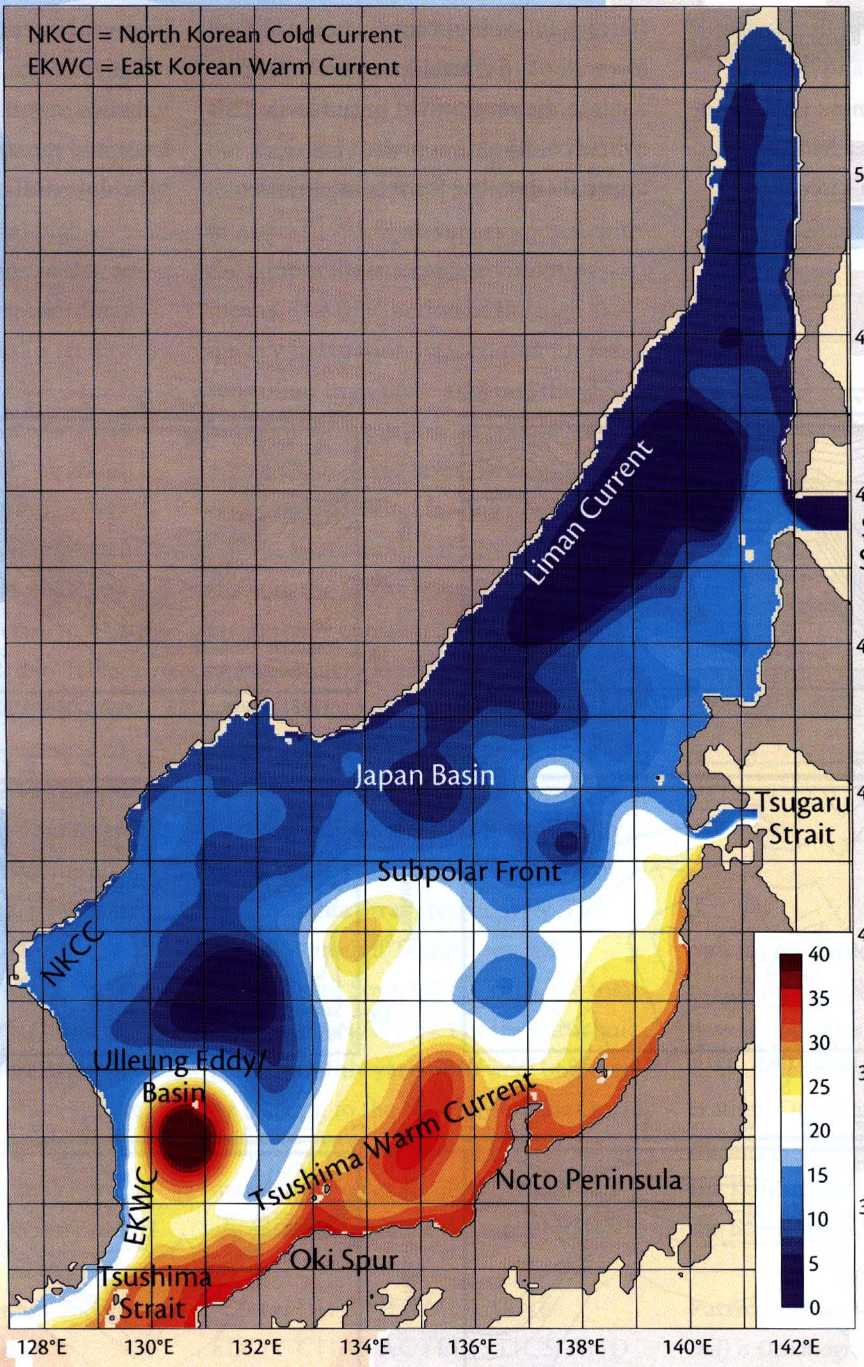


Figure 1. The HYbrid Coordinate Ocean Model (HYCOM) simulates the major circulation features in the Japan/East Sea as depicted here by mean sea surface height from model years 7–10 of the simulation. The names of the circulation features are overlaid as are the names of key geographical features mentioned in the text.

THE NUMERICAL MODEL

HYCOM was developed from the Miami Isopycnal Coordinate Ocean Model (MICOM) using the theoretical foundation set forth in Bleck and Boudra (1981), Bleck and Benjamin (1993), and Bleck (2002). HYCOM is a hydrostatic primitive equation ocean-circulation model that uses isopycnal coordinates in the open stratified ocean, but makes a dynamically smooth transition to sigma (terrain-following) coordinates in shallow water and z-level (pressure) coordinates in the unstratified mixed layer. This hybrid coordinate approach provides unusual capability for accurate transition between the shallow and deep water and allows the use of a sophisticated embedded mixed-layer model. With the isopycnal interior, HYCOM provides an effective design for investigating the interaction among surface flows, the mixed layer, and the stratified ocean below. The hybrid vertical coordinate design also

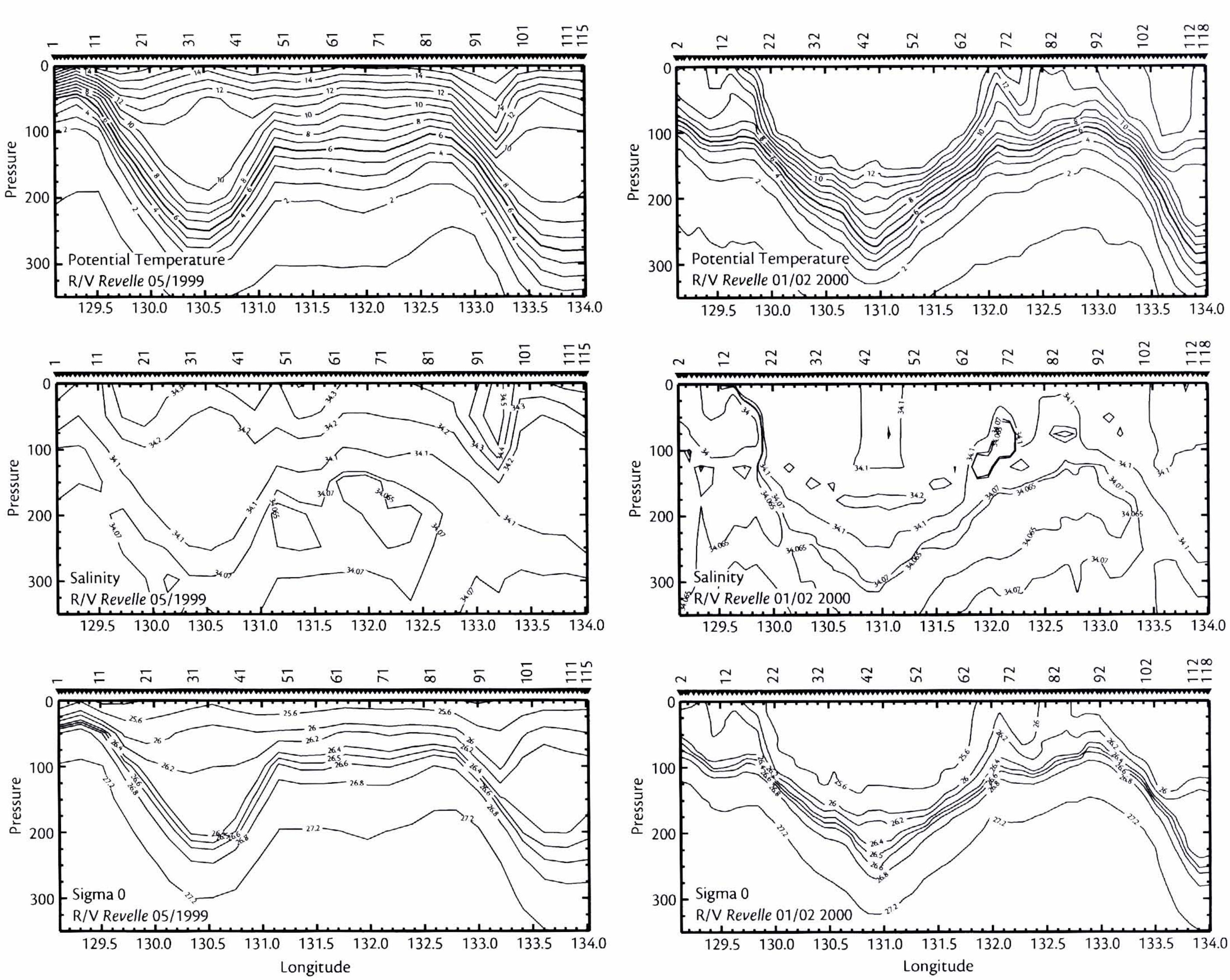


Figure 2. (a) In May 1999 two intrathermocline eddies (ITEs) were seen in observed cross sections of potential temperature, salinity, and density along 37°45' (top to bottom). The ITEs are characterized by a relatively homogeneous interior with a bowl-shaped bottom and a domed top in all three cross sections. (b) When the cross section was repeated during January 2000, the two eddies had lost their domed-shaped tops and could no longer be classified as ITEs. Both (a) and (b) are from Gordon et al. (2002).

retains particular advantages associated with the different vertical coordinate types: (1) the retention of water-mass characteristics for centuries (a characteristic of isopycnal coordinates), (2) high vertical resolution in the surface mixed layer and unstratified or weakly stratified regions of the ocean (a characteristic of z-level coordinates), and (3) high vertical resolution in coastal regions (a characteristic of terrain-following coordinates).

The simulation used in this study covers the JES (127.5°E–143°E, 34.5°N–52°N) (See Figure 1). The horizontal grid resolution is .04° x .04°, or about 3.5 km. Fifteen layers are used in the vertical, with a target density assigned to each layer (based on climatology) ranging from 23.0 σ_θ at the surface to 27.4 σ_θ in the abyssal layer, as noted in Table 1. Target densities are chosen so that the top layer is always a fixed-pressure coordinate, and usually it is the only one present during the stratified summer–fall months. In the winter–spring months, the top six layers are typically at fixed depths, thereby ensuring adequate resolution of the mixed layer when it is deepest. Sigma (terrain-following) coordinates are allowed in this simulation, but are rarely present because there is little shelf area in the JES. For the simulation described here, the K-Profile Parameterization (KPP) turbulence closure model of Large et al. (1997) is used to invoke vertical mixing and determine the surface boundary-layer depth.

There is no assimilation of ocean data in the simulation used here (except weak relaxation to a monthly surface salinity climatology), and the only forcings are surface wind and thermal flux at the ocean surface and flow in through the Tsushima Strait and out through the Tsugaru and Soya Straits. For the surface forcing, a monthly climatology from the European Centre for Medium-Range Weather Forecasts (ECMWF) 10-m reanalysis covering 1979–1993 was used, but six hourly sub-monthly wind fluctuations, derived from September 1994 to August 1995, were superimposed onto the temporally interpolated monthly means. The time period of the high-frequency fluctuations was chosen for reasons other than those affecting the JES, but served the purpose of adequately energizing the mixed layer (which monthly climatological wind forcing does not). For the lateral boundary conditions, flow through the straits was decomposed into an annually constant barotropic (depth-averaged) component and a monthly varying baroclinic component that carried the deviations from the mean in each model layer. For the barotropic part, the inflows were 1.5 Sv and 0.5 Sv in the western and eastern channels of the Tsushima Strait, respectively. The outflow through Tsugaru was 1.3 Sv and through Soya, 0.7 Sv. Thus, the total throughflow was 2 Sv. For the baroclinic parts, monthly variations were obtained by relaxing to the Navy's Modular Ocean Data Assimilation System (MODAS) climatology (Fox et al., 2002), which was also used to initialize the model state.

Table 1. Layer Numbers and Corresponding Target Densities Used in HYCOM to Simulate the ITEs

Layer Number	Target Isopycnal σ_θ
1	23.00
2	23.50
3	24.00
4	24.50
5	25.00
6	25.50
7	26.00
8	26.50
9	26.75
10	26.95
11	27.10
12	27.22
13	27.30
14	27.36
15	27.40

JES INTRATHERMOCLINE EDDY CHARACTERISTICS AND FORMATION MECHANISMS

In earlier work, Hogan and Hurlburt (2000, 2005) performed extensive investigations of JES circulation dynamics, including the roles of wind and straits forcing, flow instabilities, isopycnal outcropping, and the impact of upper ocean-topographical coupling via the flow instabilities on the mean circulation and preferred regions of eddy generation. Of particular interest were the dynamics of EKWC separation from the Korean coast, a topic of relevance to the formation of the semi-permanent

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Ulleung Eddy and its seasonally recurring transformation into the Ulleung ITE. Observationally, the Ulleung Eddy is shown as the western eddy in the right column of Figure 2 and the Ulleung ITE is the westernmost ITE in the left column of Figure 2 and in Figure 3.

Hogan and Hurlburt (2005) found that the choice of wind-forcing product had a large impact on the simulation of the mean strength and location of major JES currents and that only two out of six products resulted in simulation of the Ulleung eddy in the long-term mean, one being the ECMWF 10 m used in forcing HYCOM (their Figure 8). When they performed six interannual simulations using the ECMWF 10-m wind product, which differed only in the time each started from the corresponding climatological simulation, they found that more than 50 percent of the variability in the simulations was not a deterministic response to the atmospheric and straits forcing because of flow instabilities, a form of chaos or turbulence (their Figure 11). Even when means formed over one year (1991) were examined, large differences were evident in these simulations (their Figure 10). However, with

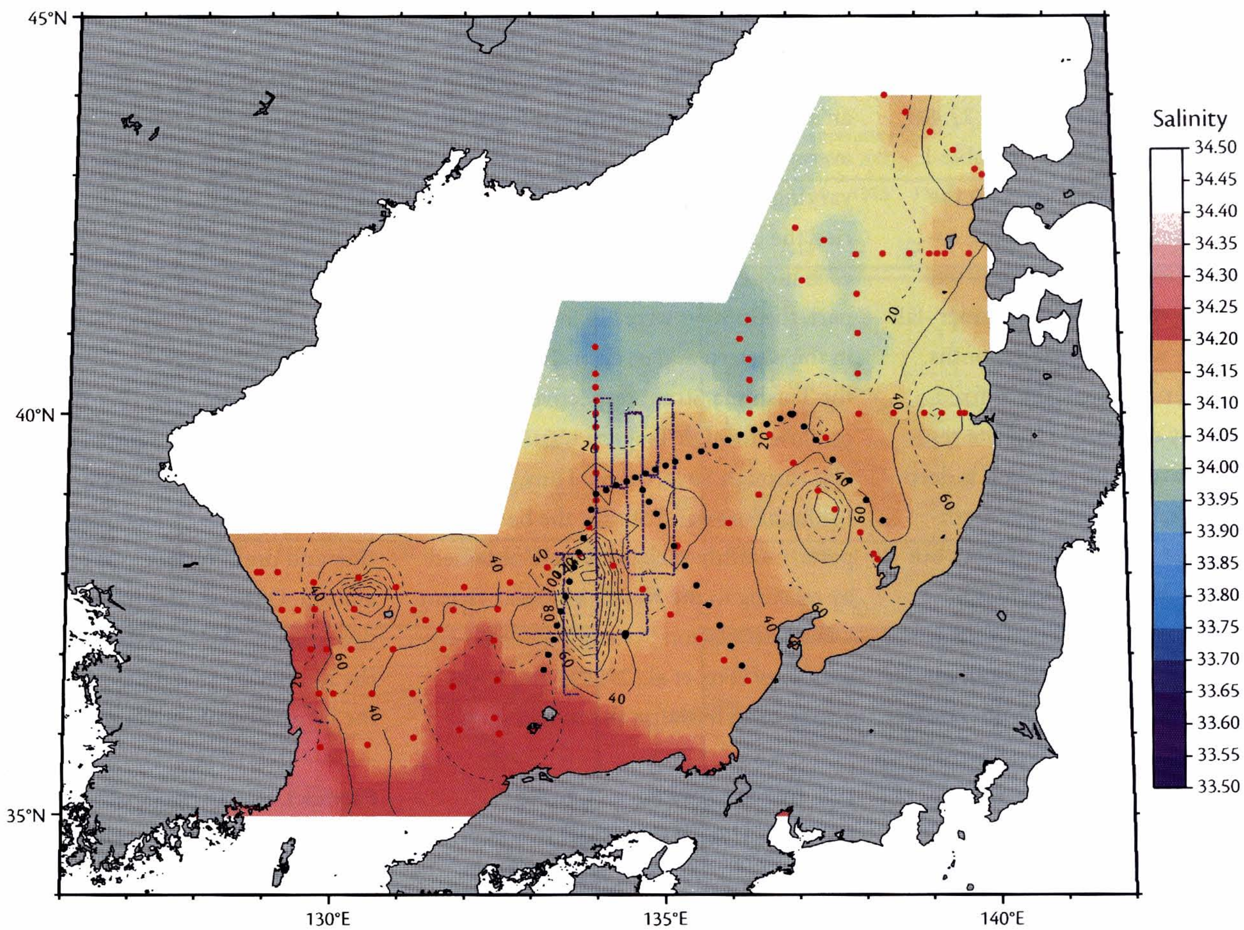


Figure 3. Three ITEs are clearly depicted by mapping the layer thickness (m) between the 8°C and 11°C isotherms (the interior of the ITEs) as observed during the R/V *Revelle* cruises of May–July 1999 and January–February 2000, and from the *Hakuho-Maru* in October 1999. The color coding shows the mean salinity within this temperature interval. July R/V *Revelle* stations are shown as red dots; *Hakuho-Maru* are shown as black dots; SeaSoar tracks of the May and January R/V *Revelle* cruises are shown as dotted lines. From Gordon et al. (2002).

some variation, the Ulleung Eddy was present in five of the six simulations; the same was true to a lesser extent for the other locations where the HYCOM simulation used here shows ITE formation (discussed shortly). As in the HYCOM simulation, all were adjacent to the south side of a major current or front and showed evidence of geographic or topographic constraints. While these results identified realistic preferred locations for persistent, long-lived eddies, they also show that HYCOM cannot be expected to simulate the same ITEs in the same location that they are observed in nature without assimilation of ocean data. For the chosen atmospheric forcing, simulation of the Ulleung Eddy and other representative eddies can be considered a likely occurrence.

The model used by Hogan and Hurlburt (2000, 2005) was not designed to simulate the vertical structure observed in the JES ITEs because it did not include a mixed layer or thermal forcing and it lacked sufficient vertical resolution. In JES-HYCOM, these limitations are removed and there are four primary locations where the ITEs tended to form during the two years they were examined. One location is near the Ulleung basin where the EKWC separates from the Korean coast (~131°E, 37°N), the Ulleung ITE. Another ITE forms at a location east of the Oki Spur (~135°E, 37°N) and a third forms near the western coast of Honshu (~138°E, 39°N). These three ITEs are located close to the ITEs reported by Gordon et al. (2002) based on observations collected during 1999–2000 (Figure 3). Although the ITEs propagate and wobble with time, they are largely associated with topographically controlled quasi-permanent meanders of the major current systems (EKWC and TWC) and as such exhibit a tendency to reform in approximately the same locations over the two years examined here. Unlike the observations during this time frame, JES-HYCOM simulates a fourth ITE near the Yamato Rise at ~40°N, 134°E, a location just south of the Subpolar Front in HYCOM (Figure 1) and near the edge of the region where ITEs have been observed historically (Figure 8 of Gordon et al., 2002). This result is not surprising based on the nondeterministic nature of the JES eddies simulated by Hogan and Hurlburt (2005). In the simulation used here, ITEs are most easily identified during the summer–fall by maps of layer-7 thickness, as this is the layer with the target density (26.0 σ_θ isopycnal layer) that carries the bulk of the ITE characteristic temperature (~10°C) and salinity (~34.1 psu) (Figure 4d–f and Table 1) in close agreement with the observations reported by Gordon et al. (2002). The ITEs are much less discernible in the winter and early spring when the mixed-layer depth typically extends as deep as the ITE water (Figure 5a–c).

During February through April, the JES is subject to significant cold-air outbreaks and the mixed layer south of the Subpolar Front typically extends to ~300-m depth. This deep mixing results in the destratification of many eddies, giving them homogeneous water properties from the surface to the thermocline within the eddy. February through April is also when the coldest and most saline water enters the JES through the Tsushima Strait. Model layer 7 lies above the sill depth of the Tsushima Strait (~204 m; see Preller and Hogan, 1998) from approximately February through August, and is the primary source of higher-salinity water for the subsurface water masses in the JES. During this time, the salinity of the eddies within layer 7 increases via mixing along the isopycnal layer (Figure 5). It decreases when the isopycnal cap is removed by deepening of the mixed layer during winter.

Starting around May, the surface heat flux begins to increase (net heat into the ocean) and the eddies develop a stratified cap (Figure 5c). However, an additional process is required to create an ITE, which has a cap of doming isopycnals. Above model layer 7, doming of the near-surface isopycnals capping an ITE (Figure 5d–f) occurs when advecting plumes of warm saline surface water originating from the Tsushima Strait wrap around the cap of the ITE as illustrated by the layer-6 salinity maps in Figure 4, especially the map for July (Figure 4d). This ITE phenomenon is also seen in observations (e.g., Figure 2) (Gordon et al., 2002). The water in this layer has higher temperature and salinity than the ambient JES water and is advected to the ITEs via the current systems of the JES. During the fall, the ITEs have a clear signature on a map of the thickness of layer 7 (Figure 4). At the locations of the ITEs, layer 7 typically has a central depth of 150–200 m. This layer is always shallower than that north of the Subpolar Front where isopycnal outcropping occurs (Hogan and Hurlburt, 2000).

Interestingly, even north of the Subpolar Front, HYCOM shows evidence of an ITE centered just north of 41°N in Figure 5. It is best seen in the November cross section (Figure 5f) in layers 8

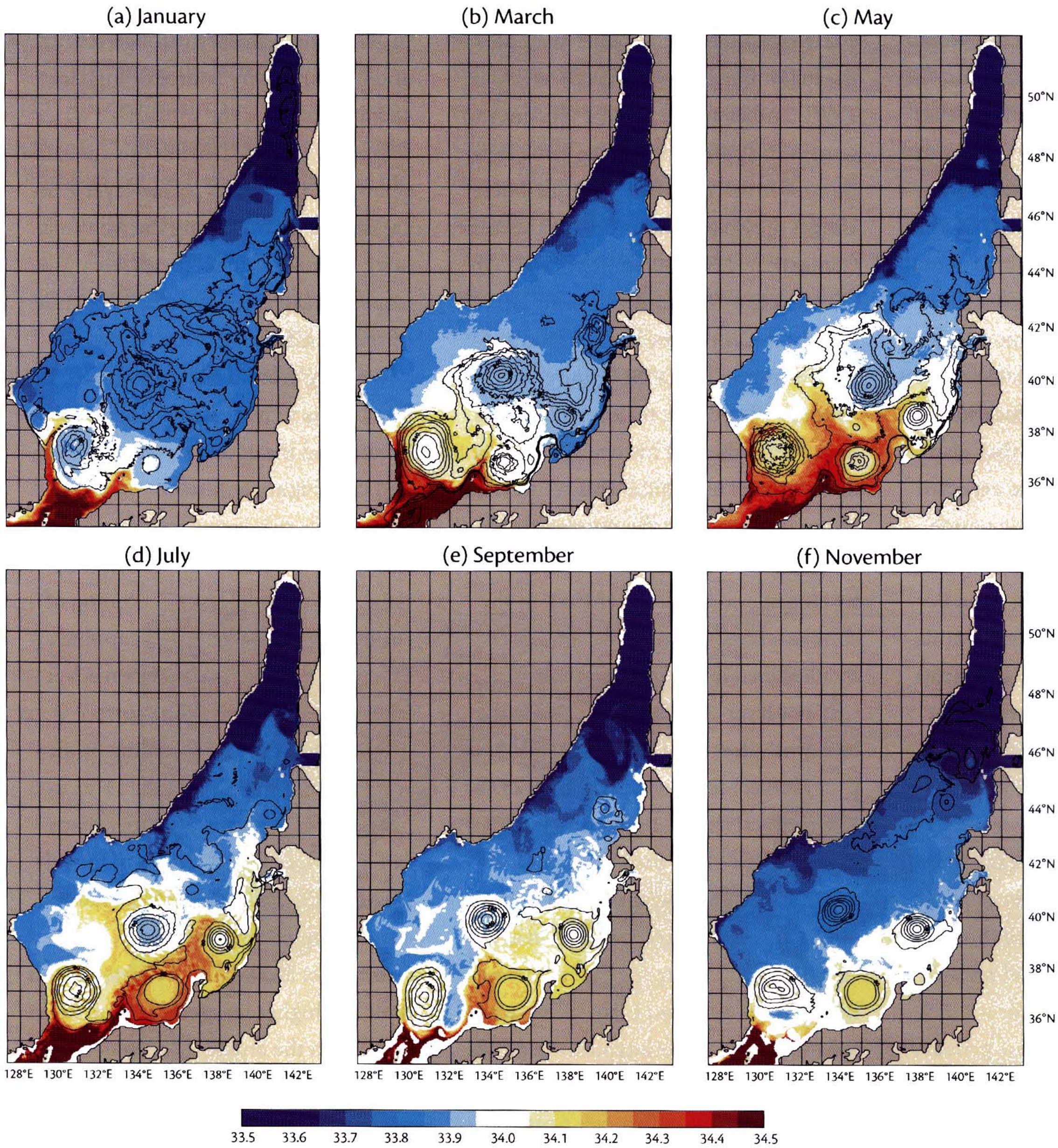


Figure 4. Bi-monthly, one-month means of salinity (color) in model layer 6 (the 25.5 σ_θ isopycnal layer) and the thickness of ITE interiors (line contours) as represented by model layer 7 (the 26.0 σ_θ isopycnal layer). Plumes of high salinity originating from the Tsushima Strait can be seen wrapping around the caps of the ITEs.

(σ_θ=26.5) and 9 (σ_θ=26.75). Talley et al. (2004) report observations of two ITEs north of the Subpolar Front, one close to the location shown in Figure 5, but both with more dense interiors (σ_θ=27.2–27.3).

Subduction at ocean fronts and in oceanic eddies is an efficient process for exchange between surface water in the oceanic mixed layer and the ocean interior where surface water of the same density sinks along an isopycnal often in response to the strengthening of an ocean eddy or frontal meander. Although not required, the process can be enhanced by strong surface cooling. Although the development of the Ulleung ITE (centered near 37°N, 131°E) is generally similar to the other JES ITEs, an additional process is identified in the model development of this ITE during January of both years studied.

Ou and Gordon (2002) used an idealized model to investigate the dynamics of subduction along an oceanic front and its linkage to ITE formation. Their theoretical study attributes the develop-

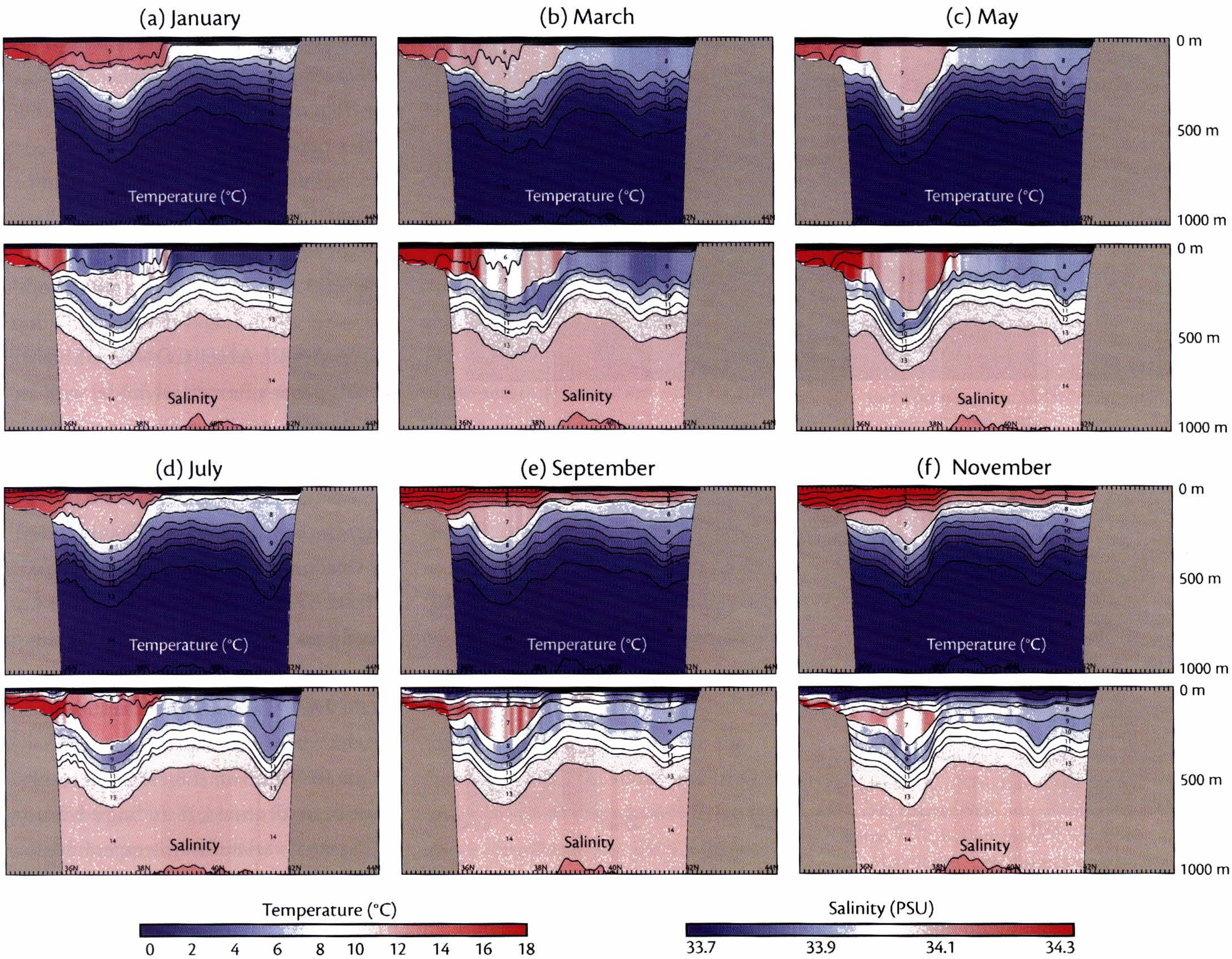
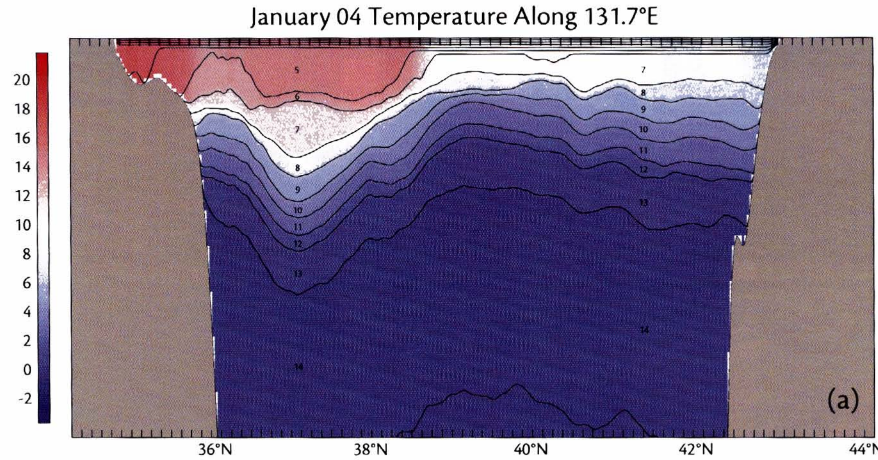
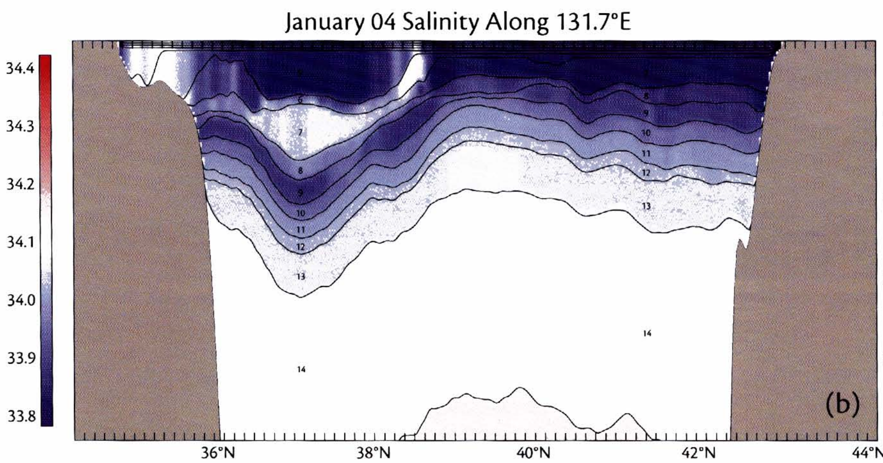


Figure 5. An annual cycle of the Ulleung ITE can be seen in bi-monthly snapshots of cross sections of temperature and salinity along 130.8°E. The model layer interfaces are superimposed as line contours and the layer numbers are linked to their target densities in Table 1. The erosion of the Ulleung ITE cap is most evident in March and the restratification with a domed cap is most evident in November.

ment of ITEs in the JES to a mismatch in potential vorticity across a frontal jet (the Subpolar Front). In JES-HYCOM, the water-mass characteristics of the Ulleung ITE can be maintained by subduction of a similar type of surface water along isopycnal surfaces. This phenomenon is clearly depicted in the cross section of temperature and salinity shown in Figure 6a. Subduction occurs along the Subpolar Frontal boundary, and the water being subducted is formed on the south side of the Subpolar Front, similar to results reported by Lee and Thomas (2005). Although the HYCOM simulation certainly reveals the presence of subduction during winter along the frontal boundary associated with the Ulleung ITE, it is relatively short-lived (< 1 month) and secondary to ITE formation processes discussed earlier. The subduction of ITE-type water is only depicted in the simulations because of the unique occurrence of ITE water entering through the Tsushima Strait, and its advection along the Subpolar Front. The vertical coordinate in HYCOM gives a





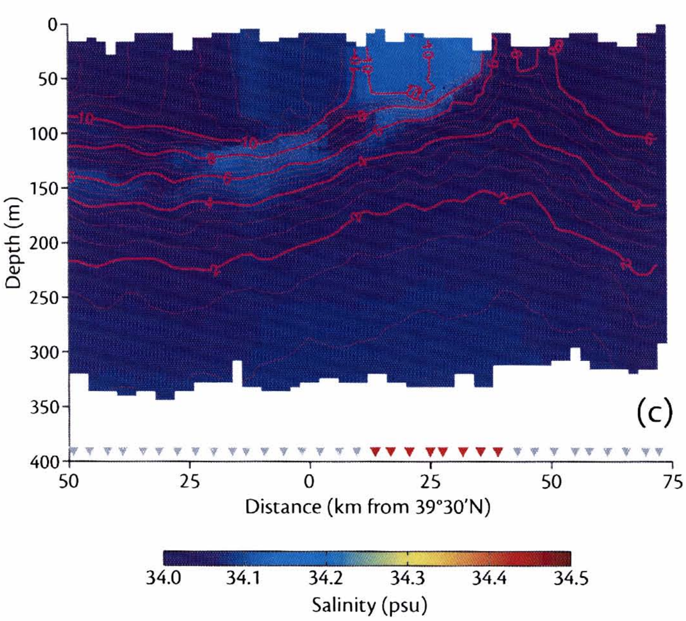


Figure 6. Subduction along the Subpolar Front is evident in salinity and temperature from the model and in a January 2000 cross section of salinity from the observations. Subduction is illustrated by January 4 cross sections of (a) temperature and (b) salinity from the model and in (c) by an observed cross section of salinity (color) and temperature (line contours) from January 2000 (the latter from Gordon et al., 2002). In the model, the subduction feeds into an ITE in layer 7 (σ_θ=26.00).

particularly clear depiction of the subsequent subduction process where (1) water from the surface mixed layer with ITE water-mass characteristics (represented mostly by z-levels) (2) subducts within an isopycnal layer of HYCOM, which (3) depicts an ITE where it is deepest (Figure 5).

SUMMARY AND CONCLUSIONS

In this paper a numerical model with an advanced vertical coordinate design was used to simulate ITEs in the JES. ITEs are unique, poorly understood features, but were observed in the JES as reported by Gordon et al. (2002) and Talley et al. (2004). The locations of the ITEs are largely associated with topographically controlled quasi-permanent meanders of the EKWC and TWC. At least three mechanisms for the formation of ITEs in the JES based on JES-HYCOM results have been identified, including advection of seasonal variations of temperature and salinity (including their variations in vertical structure) through the Tsushima Strait, restratification of the upper water column due to seasonal heating and cooling of the upper ocean, and subduction of ITE water (with an origin of Tsushima Strait inflow) beneath the wintertime Subpolar Front. The advection and restratification mechanisms occurred in all of the simulated ITEs. Subduction along the Subpolar Front was identified (in addition to the other two mechanisms) in the Ulleung ITE. In these simulations, subduction appears to play a minor role in the formation and evolution of the ITEs.

Because the Ulleung ITE demonstrated components from all three of the formation mechanisms, its time evolution is summarized here as follows. In March, the wintertime mixed layer extends to ~300 m, which coincides with the base of the isopycnal layer 7 (σ_θ = 26.00). March also coincides with the onset of relatively high-salinity water (> 34.5 psu) through the Tsushima Strait, although the temperature is still relatively cool. This relatively high-salinity water fills the area of the Ulleung eddy in April and May. By July, warmer, fresher water is flowing into the surface layers of the JES. The water is also more stratified as indicated by the isopycnals in the Tsushima Strait (Figure 5d). This inflow of warm, stratified water and increasing surface heat fluxes result in restratification of the upper water column and initial capping of the eddy. The Ulleung eddy develops the characteristic domed cap of an ITE when a plume of relatively warm, saline water (compared to ambient JES water) advected from the Tsushima Strait wraps around the cap. Stratification of the ITE capping is strongest from September to November. In January, relatively cooler and more saline (i.e., more dense) water flows through the Tsushima Strait, and the isolated ITE is still located at ~ 200–250-m depth. During this time, the relatively more dense water entering the Tsushima Strait has nearly the same water-mass characteristics as the nearly isopycnal interior of the ITE, but is more dense than the water above the ITE. During this time, the role of subduction is evident. The relatively dense water that enters through the Tsushima Strait is advected northward as part of the EKWC, separates from the coast of Korea, and it is subducted along the edge of the Subpolar Front near 38.5°N. This process is seen clearly in the salinity cross section along 131.7°E on January 4 (Figure 6), as well as in the map of salinity on the 26.50 isopycnal surface (Figure 4).

Observations collected by Gordon et al. (2002) and Talley et al. (2004) revealed the existence of ITEs in the JES. Here we have used a state-of-the-art ocean model to elucidate the evolution and formation mechanisms of the ITEs. The simulation allowed the investigation of the seasonal evolution of ITEs and identified seasonal variations of water-mass properties through the Tsushima Strait and restratification of the upper water column as the primary formation mechanism(s). Subduction along the Subpolar Front was shown to be a secondary mechanism in ITE formation.

ACKNOWLEDGMENTS

This paper is a contribution to the Japan/East Sea DRI sponsored by ONR under program element 601153N. It is also a contribution to the 6.2 project Coastal Ocean Nesting Studies and the 6.1 project Global Remote Littoral Forcing via Deep Water Pathways funded by ONR under program elements 602345N and 601153N, respectively. The simulation was performed on the Cray T3E at the Naval Oceanographic Office under a grant of computer time from the Defense Department High Performance Computing Modernization Program. Dr. Alan Wallcraft is recognized for substantial contribution to this effort through his work on model development and his computer expertise.

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