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ORIGINAL ARTICLE

Evolution and decay of a warm-core ring within the western subarctic gyre of the North Pacific, as observed by profiling floats

Sachihiko Itoh · Yugo Shimizu · Shin-ichi Ito · Ichiro Yasuda

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Abstract This study investigated temporal variations in the vertical structure and water properties of a warm-core ring that migrated into the western subarctic gyre of the North Pacific, based on analyses of temperature and salinity data derived from two profiling floats, together with shipboard and satellite observation data. The floats were initially deployed into cold and fresh Oyashio water in September 2003, and were entrained into a warm-core ring in October 2003, remaining within the ring until detrainment in December 2004. Drastic cooling and freshening of the upper core water of the ring were observed during the above entrainment of the floats with cold and fresh water into the ring, whereas moderate variations in structure and water properties were observed during a quasi-isolated phase from November 2003 to November 2004 when the ring did not experience major interactions with ambient hydrographic features. The upper part of the core water (upper core), with relatively warm/saline water above 26.6 σ_θ, was under the influence of the atmosphere in winter via the formation of a deep mixed layer exceeding 300 dB, and had a prominent pycnostad below the seasonal pycnocline from spring to autumn. In contrast, the lower core, with relatively cold and fresh water below 26.6 σ_θ, was not ventilated throughout the observation period. Isopycnal surfaces showed a shoaling trend of about 50 dB/year during the quasi-isolated phase, suggesting viscous decay over a timescale of several years. Markedly cold and thick water was also frequently observed within the ring, indicating the intrusion of water from the Sea of Okhotsk.

S. Itoh (✉) · I. Yasuda
Atmosphere and Ocean Research Institute,
The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa,
Chiba 277-8564, Japan
e-mail: itohsach@aori.u-tokyo.ac.jp

Y. Shimizu · S. Ito
Tohoku National Fisheries Research Institute,
Fisheries Research Agency, 3-27-5 Shinhama-cho,
Shiogama, Miyagi 985-0001, Japan

1 Introduction

In the northwestern part of the North Pacific, anticyclonic warm-core rings are detached from the Kuroshio Extension and move poleward along the western boundary into the western subarctic gyre (Yasuda et al. 1992; Itoh and Sugimoto 2001). Using sea surface height anomaly (SSHA) maps compiled from satellite altimetry data, Itoh and Yasuda (2010a) identified anticyclonic eddies in this region and tracked their northeastward propagation along the Kuril–Kamchatka Trench, revealing a mean speed of 1–2 cm s^{-1}. Whereas the results presented by Itoh and Yasuda (2010a) were based solely on SSHA data, combined analyses using vertical temperature and salinity profiles have revealed the distributions of anticyclonic eddies with warm and/or cold cores, as well as their detailed structure (Itoh and Yasuda 2010b). The major portion of anticyclonic eddies in the western boundary region of the subarctic North Pacific has vertically aligned double-core waters in the upper (often outcropped to the surface) and intermediate layers (around 26.7 σ_θ), with warm/saline and cold/fresh anomalies on isopycnal surfaces from the climatology, respectively. Itoh and Yasuda (2010b) attributed this double-core structure to a vertical coupling process called alignment (Polvani 1991) between a warm anticyclonic eddy in the upper layer, which originated from the Kuroshio Extension, and a cold anticyclonic eddy in the intermediate layer, which originated from the Sea of Okhotsk. These two types of core waters, both of which are thick compared to the climatology, are hereinafter referred to as the upper core and the lower core, respectively. Temperature and salinity in both the upper and lower cores are high in the south and low in the north.

The above latitudinal contrast in core water properties was suggested to be caused by wintertime convection in the upper layer and the lateral entrainment of cold and fresh water in the intermediate layer, which originated from the Sea of Okhotsk (Yasuda et al. 1992). Intensive hydrographic observations of a large warm-core ring for more than 3 years showed that the upper core was remarkably homogeneous, and that temperature and salinity showed a marked drop during the winter season (Yasuda et al. 1992). The temperature and salinity of the upper core decreased from 16.2 to 10.6°C and from 34.8 to 34.3 psu, respectively, during the first winter, and from about 10 to 6–7°C and from 34.3 to 34.0 psu during the second winter. Yasuda et al. (1992) suggested that these decreases in temperature and salinity were caused not only by convection during winter, but also by mixing with cold and fresh ambient water.

Although the above observations were limited to a single warm-core ring, a temperature decrease of about 5–6°C after the first winter has also been reported in previous studies (Hata 1974; Tomosada 1986). However, because warm-core rings experience rapid interactions with other warm eddies and ambient cold waters that are basically completed within 1 month, which is shorter than the typical period of previous hydrographic observations (1–2 months; Yasuda et al. 1992), observations with higher time resolution are required to enable a more thorough description of the evolution and decay of warm-core rings. High-frequency observations are also effective in examining the nature of modification of the cold and fresh core in the intermediate layer, which has yet to be studied.

Because intense rings trap water in their core (Flierl 1981), floating instruments such as profiling floats may remain in a single warm-core ring for long periods, measuring continuous profiles within the ring. Yoshida and Hoshimoto (2006) deployed a profiling float designed to measure profiles down to 400 dB at a time interval of 35 h, and reported fluctuations in the properties of a surface mixed layer of a warm-core ring located east of Japan at around 40–41°N, from July to December of 1999. Because the ring initially had a homogeneous core in the upper 400 dB, with temperature and salinity of about 11°C and 34.3 psu, respectively, they considered that the ring had experienced one winter season since being shed from the Kuroshio Extension. Yoshida and Hoshimoto (2006) found that variations in the heat content of the mixed layer were consistent with the net surface heat flux, although evolutions of general characteristics of the ring, including changes in the properties of the core water were unexamined.

Continuous observations of a single warm-core ring were also made for more than 1 year by two profiling floats deployed in September 2003. The two floats were originally deployed into the cold and fresh area under the influence of the Oyashio (the western boundary current of the western subarctic gyre) (Shimizu et al. 2009), but were soon entrained within a northward-propagating warm-core ring (Fig. 1), as described in part by Itoh and Yasuda (2010b). Because this ring was tracked for more than 3 years since September 2001, the authors considered it to be a long-lived eddy. Although short-term behavior of the two floats was complex, probably due to anticyclonic swirling flows, they showed general northeastward movements along the Kuril–Kamchatka Trench for more than 1 year, over a distance exceeding 400 km.

To clarify how the changes in structure and water properties of warm-core rings change occur, detached from the subtropical gyre, in the present study, we analyze the profile data obtained by these two floats, together with other shipboard and satellite observation data. Detailed specifications of these data and the analytical methods are given in Sect. 2. Various aspects of the structure and evolution of the ring, such as propagation, entrainment of ambient water, and changes in core water properties, directly derived from the above data are presented in Sect. 3. Then, in Sect. 4, these results are integrated into a comprehensive description of the evolution of the ring, and the relevant processes are discussed, as are the implications for the distribution of upper-layer pycnostads in the western subarctic gyre.

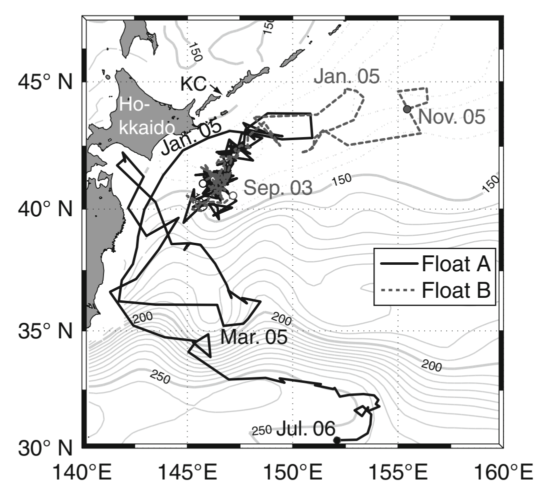


Fig. 1 Trajectories of floats A and B overlain on Rio05 mean dynamic height (MDH) (in centimeters) relative to 1500 dB (Rio and Hernandez 2004). MDH distributions in the range above and below 150 cm are shown with *solid* and *dashed contour lines* (interval of 5 cm), respectively, and the 150-, 200-, and 250-cm contour lines are emphasized as *thick gray lines*. *KC* Kunashiri Channel

2 Data and methods

The two floats (A and B) were deployed at 41°00.0′N, 145°44.7′E during the research cruise WK0309 (aboard the R/V *Wakataka-maru* in September 2003) conducted by the Tohoku National Research Fisheries Research Institute, Fisheries Agency of Japan. The detailed specifications of the floats are listed in Table 1. Floats A and B, assigned World Meteorological Organization (WMO)-IDs of 2900334 and 2900333, respectively, were designed to park at potential densities of 26.8 and 27.2 σ_θ, respectively, and to measure temperature and salinity profiles down to 1000 and 1500 dB every 5 and 10 days, respectively.

The observed temperature and salinity data, with vertical resolutions of 5–15 dB (float A) and 5–50 dB (float B), were interpolated to 5-dB-interval levels from 5 to 1000 dB (float A) and to 1500 dB (float B); the data were then filtered using a three-point median filter and a third-order Butterworth lowpass filter with a half-power width of 50 dB to remove small-scale noise. From these data on temperature and salinity S with respect to pressure, we calculated potential temperature θ and potential density σ_θ at a pressure of 0 dB. The mixed layer depth was defined as the depth at which σ_θ drops by 0.125 kg m^{-3} from the value at 5-dB depth (shallowest available depth) (Ohno et al. 2004). To investigate the structure of the warm-core ring in detail, we also calculated the planetary contribution of potential vorticity, defined as

$$Q = -\frac{f}{\rho}\frac{\partial \sigma_\theta}{\partial z}, \qquad (1)$$

where f is the Coriolis parameter.

Time variations in the profiles of θ and S were analyzed together with sea surface height (SSH) and sea surface temperature (SST) maps compiled from satellite data. We used weekly absolute SSH maps, as produced by Segment Sol Multimissions d'alimétrie, d'Orbitographie et de Localization Precise/Data Unification and Altimeter Combination System (Ssalto/Duacs) and distributed by Archiving, Validation and Interpretation of Satellites Oceanographic data (AVISO), with support from the Centre National d'Etudes Spatiales (CNES). High-resolution daily SST maps used in the present study were compiled by the New Generation Sea Surface Temperature Development Group of Tohoku University, Japan (Kawai et al. 2006).

During the observation period of the profiling floats, two series of hydrographic observations were conducted near the floats. One series of observations was made during the WK0309 cruise, when the floats were deployed, along a liner transect from a coastal point east of Hokkaido toward the offshore area observed by Fisheries Research Agency (FRA) of Japan (the A-line; FRA 2003). The second series of observations was made 8 months later, in May 2004, during cruise KH0404 by the R/V *Kofu-maru* of the Japan Meteorological Agency (JMA), along a line located slightly northeast of the A-line (the JMA line; JMA 2004). To examine the evolution of the warm-core ring, we compiled and examined cross sections of θ, S, σ_θ, Q, and dissolved oxygen, processed using the same filter as that employed for the profile data.

Table 1 Specifications of the deployed floats

	Float A	Float B
WMO ID	2900334	2900333
Parking depth	26.8 σ_θ	27.2 σ_θ
Profile depth	1000 dB	1500 dB
Profile interval	5 days	10 days
Deployment date	17 Sept. 2003	17 Sept. 2003
Deployment latitude	41°00′N	41°00′N
Deployment longitude	145°44.7′E	145°44.7′E

3 Results

3.1 Movement of the floats

The two floats were initially deployed into the Oyashio, distant from any anticyclonic eddies, but were both entrained into an eddy by October 2003 (Fig. 2). As shown below, this eddy had a warm core in the upper layer, referred to herein as a warm-core ring (or simply "the ring"). During the period from October 2003 to November 2004, the floats were trapped within this ring, gradually moving northeastward with propagation of the ring. Deviations of the latitudes and longitudes from this quasi-steady propagation, indicating radial distances of the floats from the center of the ring, were basically within 0.6° latitude and 0.7° longitude, and did not show an increasing or decreasing trend. In December 2004, the ring became strongly deformed east of the Kunashiri Channel east of Hokkaido, and both floats became detrained from the ring.

To examine the events of entrainment and detrainment of waters to and from the ring, SST profiles were overlain on weekly SSH fields (Figs. 3, 4). As seen in Fig. 3a, the position of the float deployments on 17 September 2003 was within the Oyashio water, with low SSH and SST. On 24 September, the ring located around 40°N, 147°E began to entrain the cold Oyashio water together with the two floats into its core (Fig. 3b), and both floats were found within the ring on 1 October (Fig. 3c). The entrainment event was completed by 22 October (Fig. 3c–f), when the surface water of the ring had cooled by about 4°C compared with the temperature on 17 September.

Thirteen months later, in November 2004, the center of the warm-core ring was recognized at around 43°N, 148°E

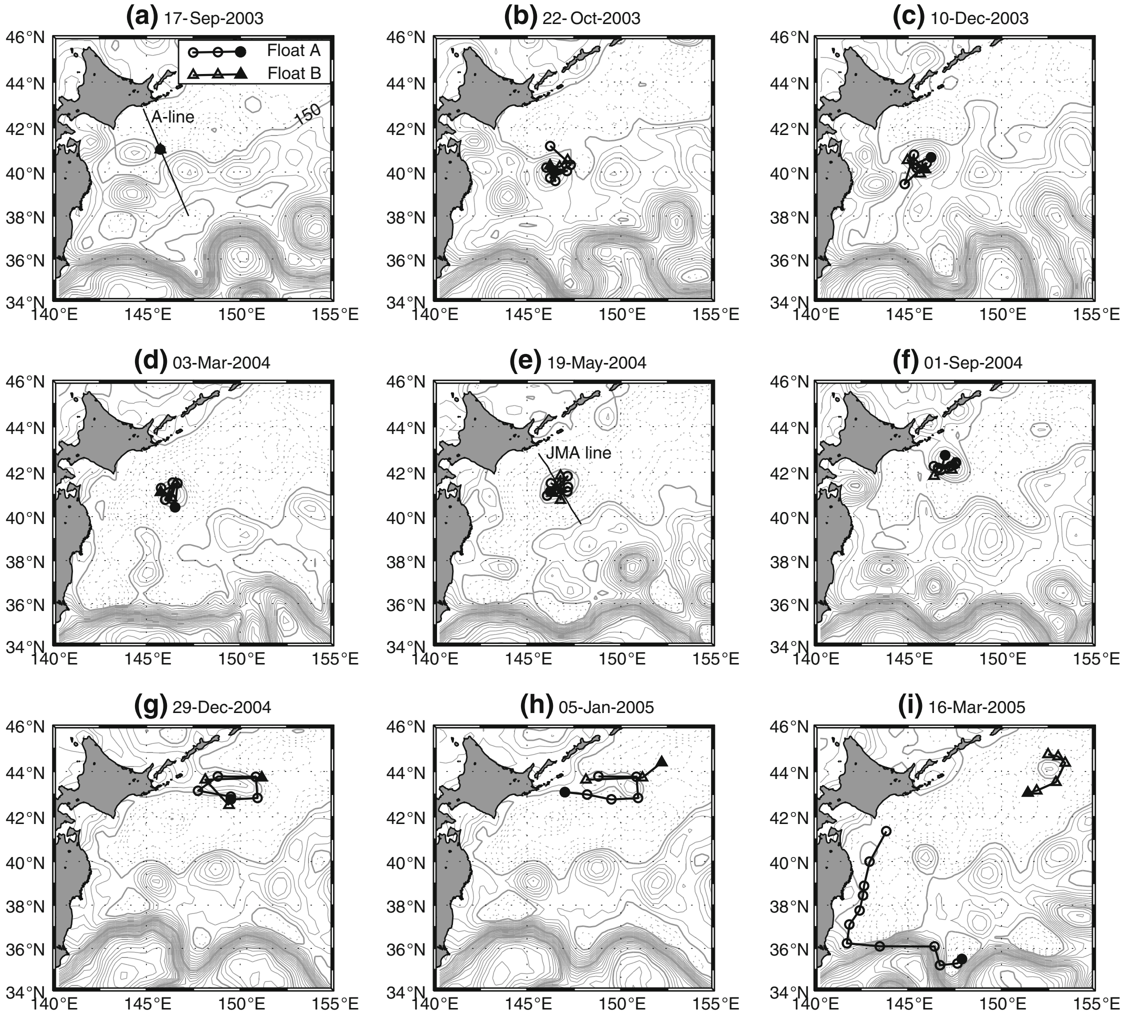


Fig. 2 Positions of the floats on sea surface height (SSH) maps at various time points. The *top*, *middle*, and *bottom rows* basically correspond to the period of float entrainment into a warm-core ring, the period when the floats moved steadily northeastward with the ring, and the period of float detrainment from the ring, respectively. *Solid* and *open symbols* denote float positions on the same days as those represented in SSH maps and those of the past back to 30 days (back to 60 days for Fig. 2i), respectively. Contour intervals for SSH are the same as those for mean dynamic height in Fig. 1

(Fig. 4a), and the connection of the 150-cm SSH contour to the Kunashiri Channel indicates that the ring was influenced by water from the Sea of Okhotsk. This influence became more pronounced in December 2004 (Fig. 4b–f), when the positive SSH and SST anomalies of the ring showed a clearer connection with the Sea of Okhotsk, through the Kunashiri Channel. The shape of the closed SSH contours was elongated in an east–west direction under the influence of the Sea of Okhotsk, and the two floats were detrained from the core of the ring on 22 December (Fig. 4e).

The two floats show quasi-steady movements from October 2003 to November 2004, as mentioned above, with mean eastward and northward propagation speeds of 0.53 and 0.83 cm s^{-1}, respectively (Fig. 5a, b). The rapid entrainment and detrainment processes of the floats (and hence waters to and from the ring) are indicated by a rapid increase and decrease in SSH at the end of September 2003 and at the end of December 2004, respectively (Fig. 5c). Although there was an increasing trend in SSH from March 2004 to November 2004, it is not caused by the enhancement of the eddy structure, as depths of isopycnal surfaces shoaled in this period as presented later in Fig. 9. As the specific volume anomaly of the upper layer typically above 150 dB increased in this period (not shown), we attribute this trend to the seasonal heating.

3.2 Hydrographic cross sections

Positions of the floats at the times of the deployments and the northeastward propagation with respect to the water mass distributions are recognized in the two hydrographic cross sections (Fig. 6) As mentioned above, the two floats were deployed into water of the Oyashio. θ at 100 dB

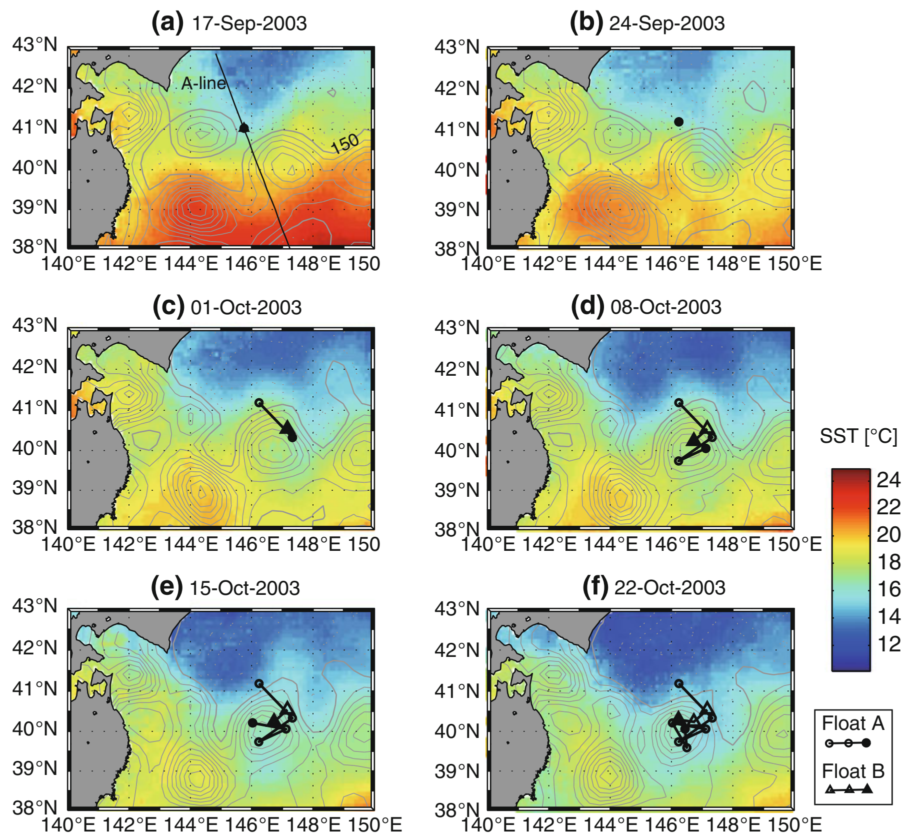


Fig. 3 As for the top row in Fig. 2, but maps of sea surface height are drawn weekly with sea surface temperature (SST) profiles, showing detailed processes related to entrainment of the floats into the ring

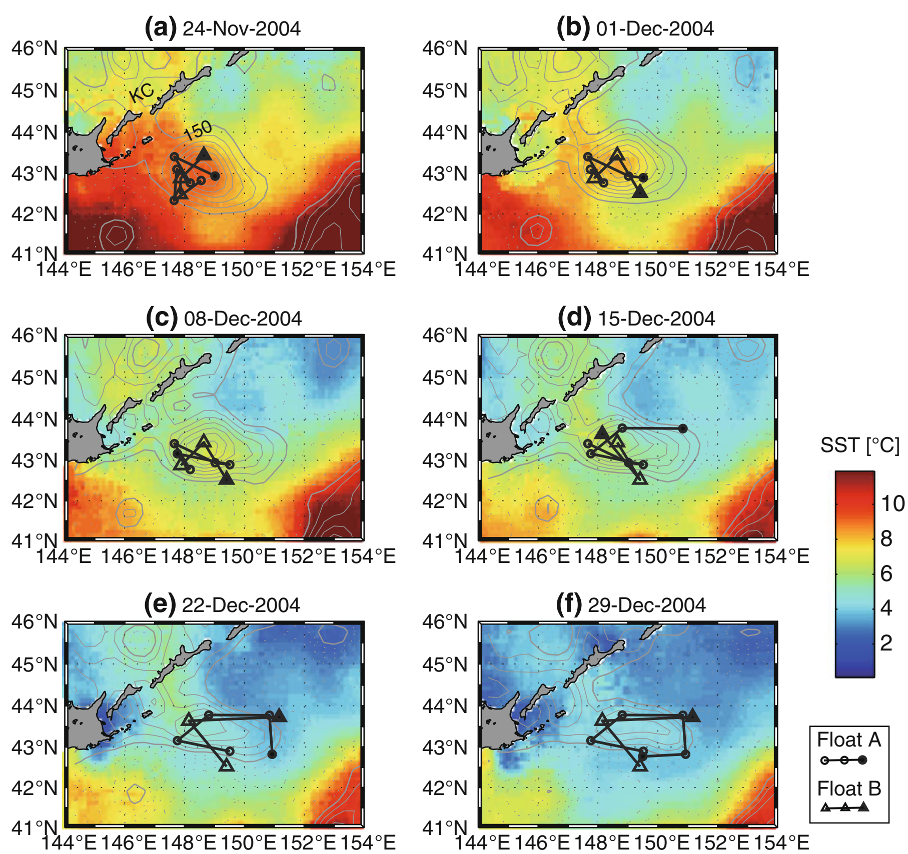


Fig. 4 As for Fig. 3, but for detrainment of the floats from the ring

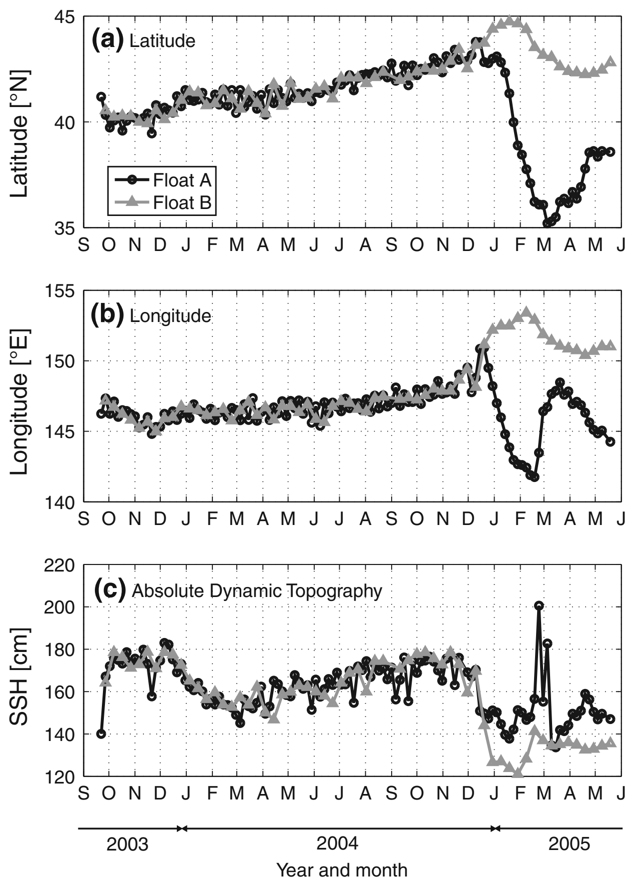


Fig. 5 Time series of **a** latitude, **b** longitude, and **c** sea surface height of the two floats for the period from deployment to complete detrainment

(similar to the temperature at 100 m) at the deployment point was 3°C (Fig. 6a), lower than the indicative temperature of the Subarctic Front (SAF) of 4°C (Favorite et al. 1976). Although the depth of 26.8 σ_θ, indicating the upper part of the pycnocline, was shallow at the deployment point, the lower layer thickness between 26.8 and 27.2 σ_θ was relatively large, as indicated by relatively low values of Q (Fig. 6g). At this time, the ring that would later entrain the floats was found southeast of the deployment point, around 40°N. Although the center of the ring around 40°N was not captured on this transect (Fig. 3), warm/saline and cold/fresh waters were recognized in layers above 26.6 σ_θ and between 26.6 and 26.8 σ_θ, respectively (Fig. 6a, c, around 39°N). The θ value of the upper water of the ring was 15.0°C at 100 dB and 10.9°C at 200 dB, warmer than subarctic water (4°C at 100 m) and colder than the Kuroshio Extension (14°C at 200 m; Kawai 1969); however, for these warm and cold waters, values of Q were not clearly lower than those of the ambient water (i.e., compared with values obtained within the ring, as shown in Figs. 6g, 7g, h), which is expected to be low as the lower core of the ring (Itoh and Yasuda 2010b); this is probably

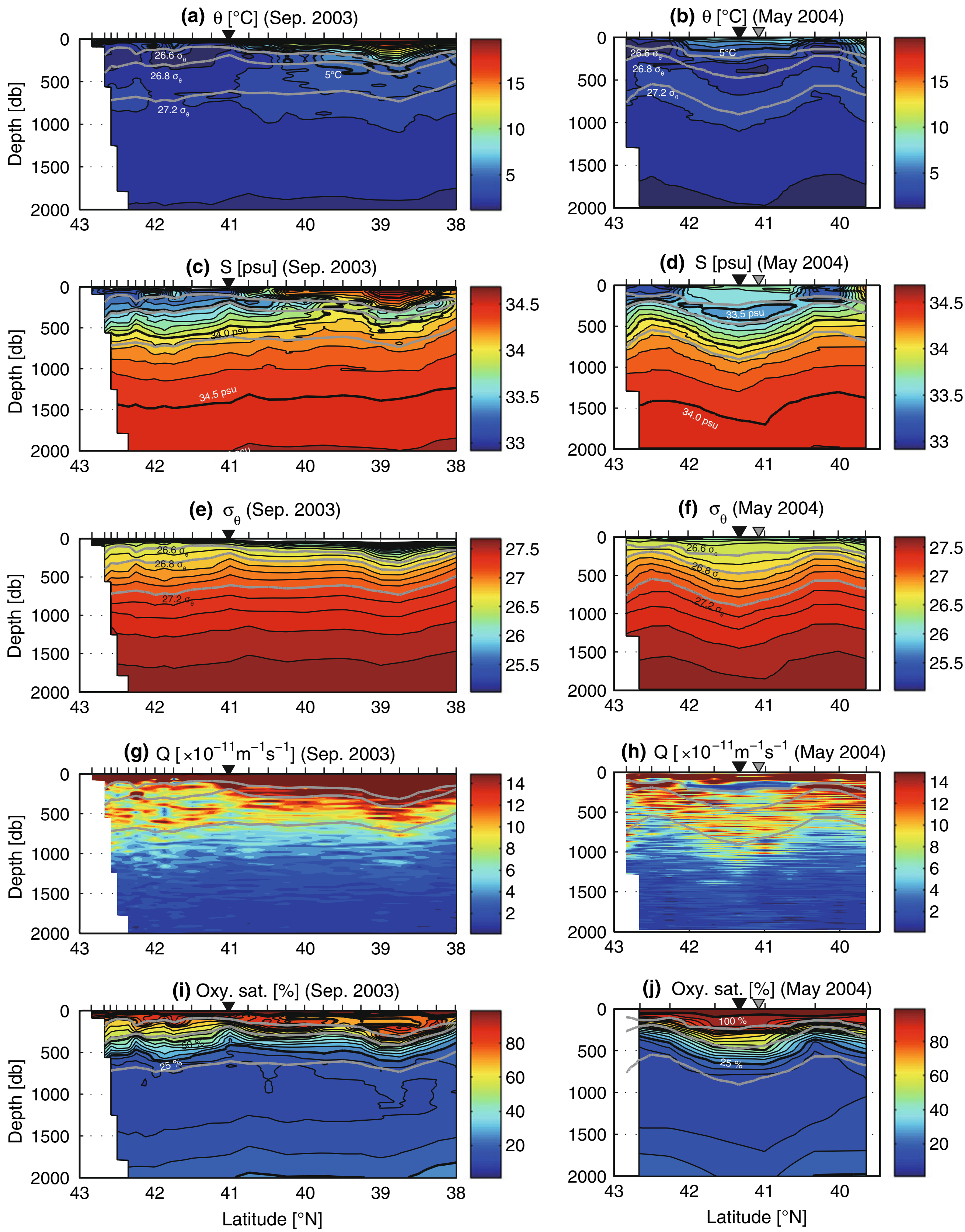
Fig. 6 Hydrographic cross sections along the A-line in September 2003 (*left column*) and along the JMA-line in May 2004 (*right column*). Potential temperature θ, salinity S, potential density σ_θ, planetary contribution of potential vorticity Q, and oxygen saturation level are shown in rows from *top* to *bottom*. Contour lines of σ_θ = 26.6, 26.8, and 27.2 are shown by *gray lines*. The positions of floats A and B during the hydrographic observations are shown by *black* and *gray triangles* at the top of each panel, respectively. *Small vertical lines* on the top of the panels indicate observation points ▶

because the profiles were not obtained near the center of the ring. The oxygen saturation level was relatively high in both the upper and lower cores of the ring, compared with ambient water at the same depth. In contrast, the minimum vertical saturation level was less than 75% within the upper core, where high-salinity water was observed (Fig. 6i).

In May 2004, the upper core was remarkably cooled, freshened, and homogenized following the winter season and after interaction with cold ambient water (Fig. 6b, d, h); however, θ was 5.3–6.4°C at 100 dB, still warmer than typical subarctic waters. While the warm/saline upper core was surrounded by cold/fresh subarctic water, the lower core, centered around 300–500 dB at the center of the ring, was colder and fresher than ambient water at the same depth. The lower core also showed low Q values ($5 \times 10^{-11} \leq Q \leq 10 \times 10^{-11}$ m^{-1} s^{-1}), although the value was moderate compared with that of the upper core ($Q \leq 5 \times 10^{-11}$ m^{-1} s^{-1}; Fig. 6h). Although the θ and S values of the lower core were not clearly colder or fresher than the subarctic water around the ring on isopycnal surfaces centered at 26.7 σ_θ, a difference was recognized between the center and periphery of the ring at the same depth, with colder and fresher water near the center. The oxygen saturation level exceeded 75% within the entire upper core above 26.6 σ_θ, and the minimum in the vertical oxygen saturation level was no longer found within the core (Fig. 6j). Depressions of isopycnal surfaces are recognized at least at 2000 m and 27.5 σ_θ, indicating the penetration of vortex structure below the main pycnocline and the intermediate layer.

3.3 Time evolution of vertical structure within the ring

During the period from October 2003 to November 2004, when the floats were trapped within the ring, the main pycnocline was deeper than during December 2004, after detrainment: the depth of 26.8 σ_θ, indicating the upper part of the pycnocline, was observed at around 500 and 200–300 dB inside and outside the ring, respectively (Fig. 7). The relatively deep isopycnal surfaces, one of the characteristics of surface-intensified anticyclonic eddies, were recognized at least at 27.5 σ_θ (Fig. 7e). This deep pycnocline within the ring was apparently related to the thickening of the isopycnal layer of 26.5–26.8 σ_θ; the


(a) θ [°C] (Sep. 2003)
(b) θ [°C] (May 2004)
(c) S [psu] (Sep. 2003)
(d) S [psu] (May 2004)
(e) σθ (Sep. 2003)
(f) σθ (May 2004)
(g) Q [×10−11m−1s−1] (Sep. 2003)
(h) Q [×10−11m−1s−1] (May 2004)
(i) Oxy. sat. [%] (Sep. 2003)
(j) Oxy. sat. [%] (May 2004)
Depth [db]
Latitude [°N]
26.6 σθ
26.8 σθ
27.2 σθ
5°C
34.0 psu
34.5 psu
33.5 psu
50 %
25 %
100 %

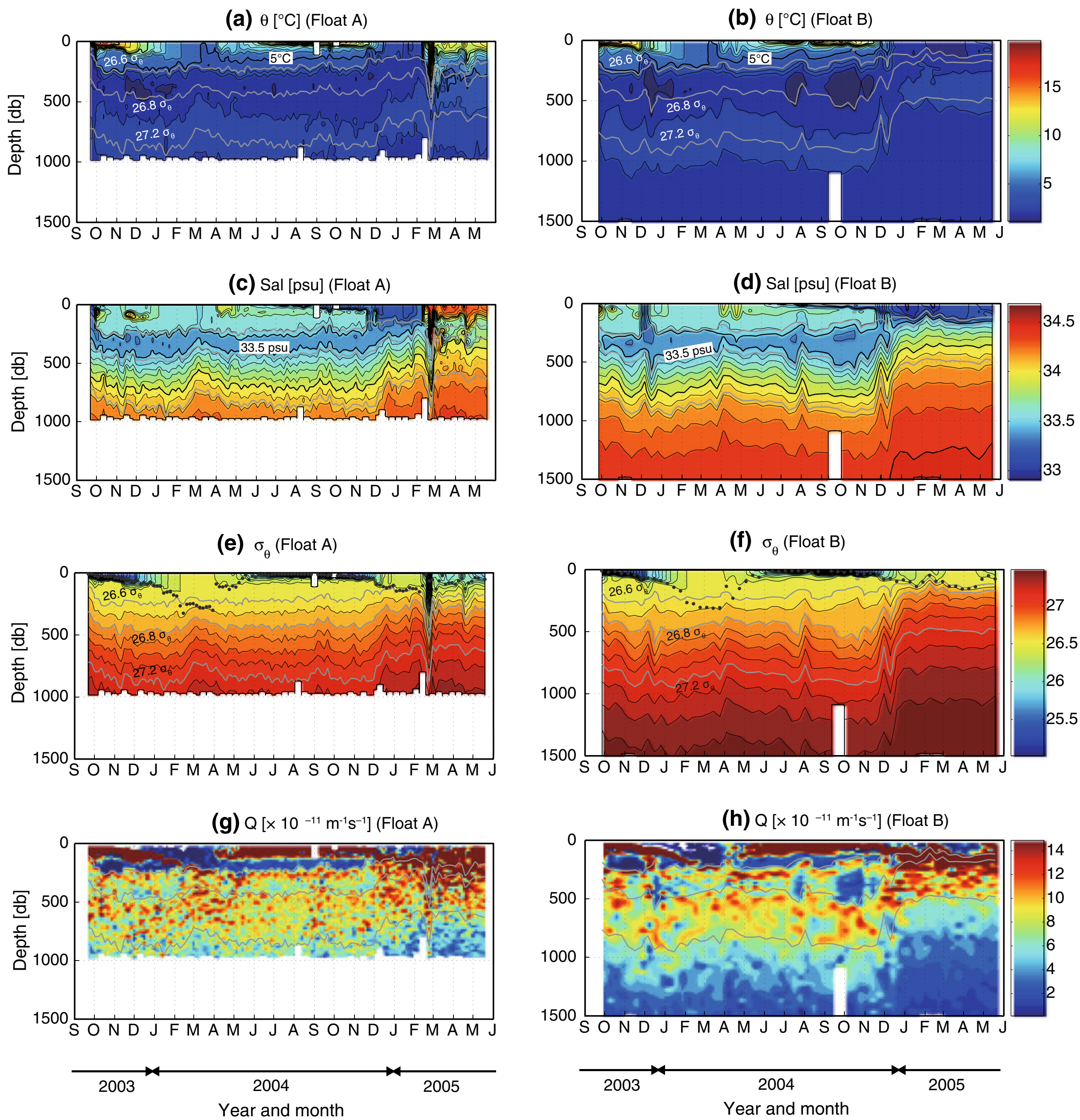


Fig. 7 Time series of profiles measured by float A (*left column*) and float B (*right column*). Evolutions of potential temperature θ, salinity S, potential density σ_θ, and planetary contribution of potential voriticty Q are shown in rows from *top* to *bottom*. Contour lines of $\sigma_\theta = 26.6$, 26.8, and 27.2 are shown by *gray lines*. *Black dots* (in panels showing potential density) indicate the mixed layer depth

layers below 26.8 σ_θ were clearly not as thick as those outside the ring. The upper part of this layer, 26.5–26.6 σ_θ, was observed as a prominent subsurface pycnostad (around 100–300 dB) in spring–summer and as a surface mixed layer (from the surface to about 300 dB) in winter (Fig. 7e, f).

Given that θ and S in the upper 200 dB were higher inside than outside the ring (in Fig. 7a–d, compare the data collected before and after December 2004), the pycnostad of the 26.5- to 26.6-σ_θ layer was considered to be the upper core of the ring, which has positive θ and S anomalies compared with the ambient water at the same depth (Itoh and Yasuda 2010b). Although the vertical gradient in σ_θ was higher (i.e., higher values of Q) in 26.6–26.8 σ_θ than in 26.5–26.6 σ_θ, the thickness difference compared with subarctic water (e.g., that observed in January 2005) was more pronounced in 26.6–26.8 σ_θ, indicating a significant

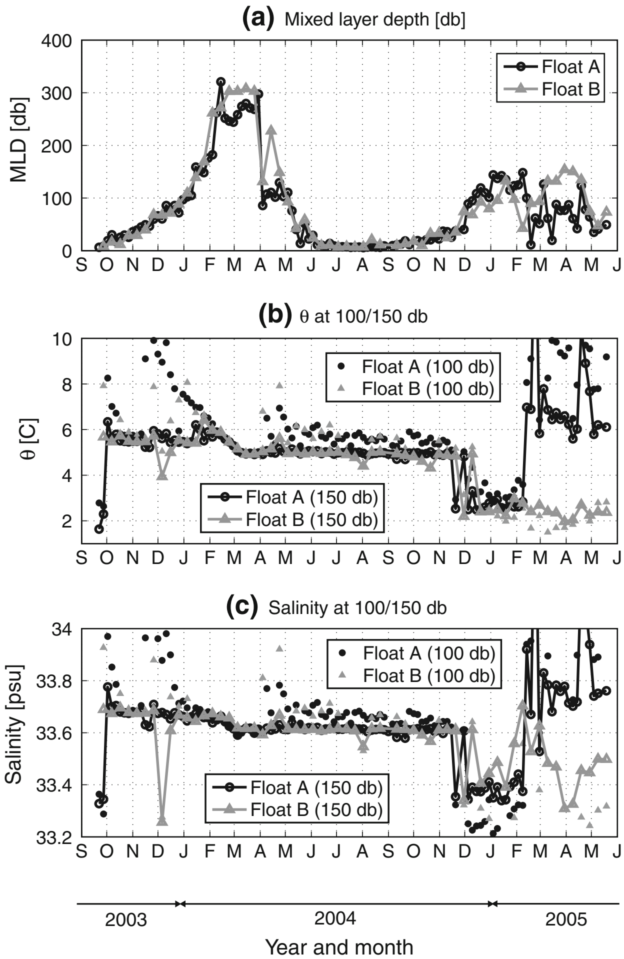


Fig. 8 Time series of **a** mixed layer depth, **b** potential temperature at 100 and 150 dB, and **c** salinity at 100 and 150 dB, observed by the two floats

contribution to depression of the 26.6- to 26.8-σ_θ layer near the center of the ring. Within the ring, this layer corresponded to the vertical minima of θ and S; considering the low values of Q, θ, and S, we regard the 26.6- to 26.8-σ_θ layer as the lower core of the ring, which occurred below the upper core with negative θ and S anomalies (Itoh and Yasuda 2010b).

Data collected by float B show short-term thickening of the layer of 26.6–26.8 σ_θ in December 2003, July 2004, and September–October 2004 (Fig. 7f), associated with occurrences of cold and fresh water (Fig. 7b, d). In contrast, short-term thinning of the 26.6- to 26.8-σ_θ layer was associated with shoaling of the deeper layer of 26.8–27.5 σ_θ, as recorded by float A in March and September of 2004 (Fig. 7e), and as recorded by float B in April, August, and December of 2004 (Fig. 7f).

The mixed layer was remarkably deep within the ring during the winter of 2003/2004, exceeding 300 dB in February, whereas it was less than 150 dB outside the ring during the winter of 2004/2005 (Fig. 8a). θ at 100 dB was generally 5–10°C within the ring, which was higher than the indicative temperature of SAF at 100 m (4°C) and within the range of warm anticyclonic eddies in a subarctic area (Itoh and Yasuda 2010b; denoted as group IIw eddies) (Fig. 8b). S at 100 dB was 33.6–34.2 psu within the ring, except for spike-like variations, dropping to 33.2 psu once the floats had detrained from the ring (Fig. 8c). θ and S of the upper core below the seasonal pycnocline, as indicated by the values at 150 dB, were largely in the ranges of 5–6°C and 33.6–33.7 psu, respectively. During February 2004, when the upper core outcropped at the surface and the mixed layer was deepening, θ and S of the upper core showed slight decreases, by about 0.5°C and 0.05 psu, respectively (Fig. 8b, c), changing potential density approximately from 26.50 to 26.55 σ_θ.

The amplitude of variations in θ and S profiles was moderate below 26.6 σ_θ, compared with seasonal variations in the surface layer, which was not ventilated during the observational period. However, a detailed analysis revealed gradual variations in the structure and water properties of the ring. A marked shoaling trend was found for the depth of 26.6 σ_θ, from approximately 250 dB in October 2003 to approximately 200 dB in November 2004 (Fig. 9a); however, this shoaling did not indicate the complete decay of the ring (i.e., isopycnal surfaces were still deeper than ambient water), as the 26.6-σ_θ depth further decreased to about 100–150 dB in December 2004, when the floats were detrained from the ring. Although a similar shoaling trend was observed by float A for the depth of 26.8 σ_θ, from approximately 450 dB in October 2003 to approximately 400 dB in November 2004, the trend was not significant for the profiles observed by float B, due to short-term thickening of the 26.6- to 26.8-σ_θ layer, as mentioned in the previous paragraph (Fig. 9b). The contrasting isopycnal depth of 26.8 σ_θ inside and outside the ring was clearer than that for 26.6 σ_θ, with differences of 200–300 dB in December 2004. The shoaling trend was less clear for 27.2 σ_θ because of short-term rises in the deep isopycnal surfaces, such as those in March 2004; however, variations were prominent during the detrainment event, with the amplitude exceeding 200 dB (Fig. 9c).

To examine changes in water mass properties, variations in θ on isopycnal surfaces are extracted for 26.7 σ_θ (representing the intermediate layer) and 27.2 σ_θ (representing layers below the main pycnocline) (Fig. 10). On the 26.7-σ_θ surface, θ was largely within 2–3°C, consistent with the mean value of 2.6°C estimated for warm anticyclonic eddies in a subarctic area (denoted as group IIw eddies; Itoh and Yasuda 2010b). Frequent occurrences of waters colder than 2°C corresponds to the thickening of 26.6- to 26.8-σ_θ layer as overviewed in Fig. 7. As shown in Fig. 11,

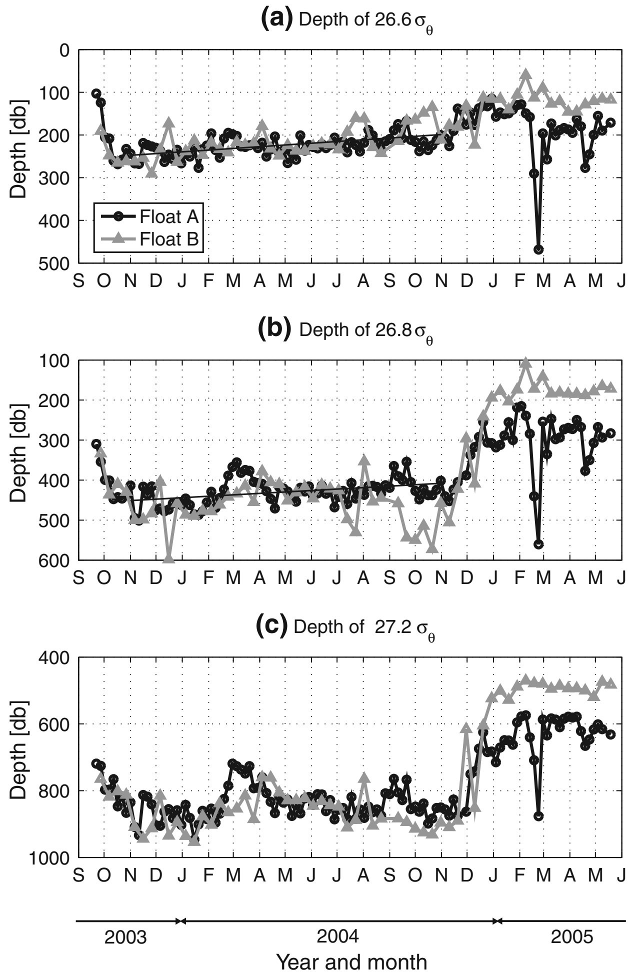


Fig. 9 Depths of isopycnal surfaces of **a** 26.6 σ_θ, **b** 26.8 σ_θ, and **c** 27.2 σ_θ

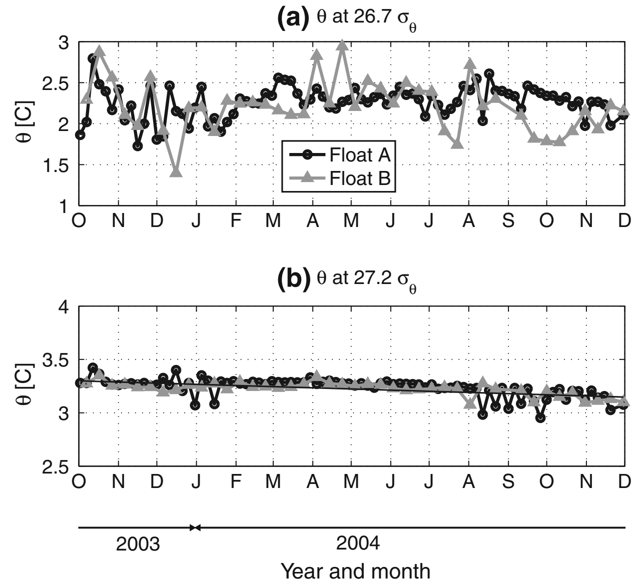


Fig. 10 Potential temperature θ on isopycnal surfaces of **a** 26.7 σ_θ and **b** 27.2 σ_θ

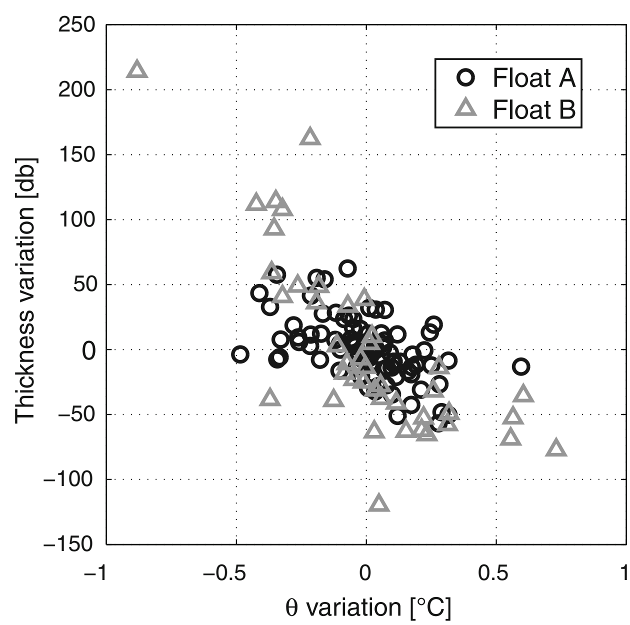


Fig. 11 Relationship between variations in potential temperature θ on 26.7 σ_θ and layer thickness of 26.6–26.8 σ_θ from October 2003 to November 2004

the relationship between variations in θ on 26.7 σ_θ and layer thickness of 26.6–26.8 σ_θ (linear trends were removed) was found to be significant both for floats A ($r = -0.53$, $p < 0.01$, t test) and B ($r = -0.77$, $p < 0.01$); however, as seen in the difference in the correlation coefficients, the relationship was stronger for the data obtained from float B, which observed markedly cold, fresh, and thick water in the layer of 26.6–26.8 σ_θ. Isopycnal temperature on 27.2 σ_θ showed little variation, except for a slight decreasing trend and small fluctuations during August and September of 2004, as observed by float A.

4 Discussion

4.1 Evolution and decay of warm-core rings in the subarctic gyre

We analyzed θ and S profiles of a warm-core ring observed by two profiling floats, together with shipboard and satellite observation data. On the basis of these high-temporal-resolution data (collected at intervals of less than 5 days) collected within the ring for more than 1 year, we presented detailed descriptions of the evolution and decay of the ring that presumably originated from the Kuroshio Extension and propagated poleward into the subarctic gyre.

We recognized two phases in the evolution of the warm-core ring: an interaction phase (September–October 2003 and December 2004), characterized by vigorous interactions with ambient waters, and a quasi-isolated phase (November 2003 to November 2004), without major interactions. During the interaction phase, the ring was under the strong influence of subarctic water, including the Oyashio water and waters from the Sea of Okhotsk. The former was observed in October 2003, when the two floats deployed into the Oyashio water were entrained into the ring. Satellite and hydrographic data revealed drastic cooling and freshening of the core water. A prominent interaction was observed between the ring and warm water from the Sea of Okhotsk through the Kunashiri Channel in December 2004, which caused a marked elongation of the ring and subsequent detrainment of the floats. On the basis of the results of a previous numerical experiment in the region around the Sea of Okhotsk (Uchimoto et al. 2007), we suggest that this warm water originated from the Soya Warm Current.

The magnitude of changes in the structure and water properties of the upper and lower cores during the quasi-isolated phase was much smaller than during the interaction phase, except for variations in the seasonal pycnocline above the upper core. The primary cause of variations in the upper core, typically distributed around 26.5–26.6 σ_θ, was ventilation and convection in winter, which was associated with decreases in θ of about 5.5–5.0°C, and in S of about 33.65–33.60 psu in February 2004. The small magnitude of the decreases in temperature and salinity compared with those reported in previous studies (Tomosada 1986; Yasuda et al. 1992) mainly reflects the fact that the upper core of the ring had already been cooled and freshened before winter, due to interaction with the Oyashio water. Consequently, the vertical entrainment of cold and fresh subsurface water into the mixed layer had less of an impact on this cooled ring than it would have had on a new ring with a warmer and more saline upper core. However, weak convective overturning resulting from the development of cooled and freshened surface water could further suppress the decreases in temperature and salinity, because this would have caused a reduction in the horizontal entrainment of cold and fresh ambient water—a process that changes the salinity of the upper core water, as suggested by Yasuda et al. (1992).

Unlike the upper core, the lower core distributed at around 26.6–26.8 σ_θ and the underlying layers did not outcrop to the surface, and variations in θ and S were well described via isopycnal properties. Note that this differs from the pattern of variability around SAF, where the winter mixed layer sometimes erodes a layer below 26.6 σ_θ (Masujima and Yasuda 2009). Although the pycnostad of the lower core was less prominent than that of the upper core, the thickness difference (compared with ambient subarctic water) was clearer and made a major contribution to depression of the isopycnal surfaces within the ring. The yearlong profiles within the ring revealed shoaling trends for a depth of 26.6 σ_θ observed by both floats and for 26.8 σ_θ observed by float A, from approximately 250–200 dB and about 450–400 dB, respectively. Spin-down caused by viscosity (Flierl and Mied 1985) is thought to have contributed to shoaling of the isopycnal surfaces. Given that the depths of the 26.6-σ_θ and 26.8-σ_θ surfaces in the surrounding water, as observed at the beginning of January 2005 after detrainment of the floats from the ring, were 150–200 and 200–300 dB, respectively, the ring would have sustained relatively deep pycnoclines for at least another year. Thus, the timescale of viscous spin-down of warm-core rings within the western subarctic gyre is suggested to be several years.

However, fluctuations in the lower core and deeper layers were more complex than the simple viscous decay described above. As typically observed by float B, cold, fresh, and low-Q waters often occurred in the lower core. Given that the extremely cold water on 26.7 σ_θ was also observed within the cold-core anticyclonic eddies that originated from the Sea of Okhotsk (Yasuda et al. 2000; Itoh and Yasuda 2010b), we suggest that the cold and fresh intermediate water of the Sea of Okhotsk directly intruded into the layer of 26.6–26.8 σ_θ. The properties of the cold and fresh water indicate an origin as outflow from passages located north of the Kunashiri Channel, such as Bussol' Strait (Katsumata et al. 2004). The markedly cold water was observed only by float B because of differences in the parking depths of the two floats: given that float A was parked at 26.8 σ_θ within the ring, it had fewer occasions (compared with float B, parked at 27.2 σ_θ) on which to encounter the outside intrusions into the 26.6- to 26.8-σ_θ layer of the ring, due to the Lagrangian nature of the floats.

Although Itoh and Yasuda (2010b) suggested the significant contribution of cold anticyclonic eddies from the Sea of Okhotsk to the properties of the lower core of the ring, via coupling of the two eddies in different layers (a process referred to as alignment; Polvani 1991), the observed influence of the intrusions was only seen in short periods of 1–2 months and the associated changes in the properties of the core water did not exceed this period. We presume that complete alignment did not occur for these cases, although a cold anticyclonic eddy with core water in 26.6–26.8 σ_θ was possibly located horizontally close to the warm-core ring and was possibly detected by a float. This situation of non-alignment despite the close horizontal distance between two nonlinear anticyclonic eddies has been reported by Nof and Dewar (1994), based on the results of a numerical experiment in which eddies (with diameters of 150 km and separated by 80 km) failed to align.

4.2 Implications for the distribution of the upper-layer pycnostad

As stated above, warm-core rings that originate from the Kuroshio Extension tend to propagate poleward with a warm/saline upper core and a cold/fresh lower core, even within the western subarctic gyre. Although the upper core water undergoes cooling and freshening due to fluxes from the atmosphere and the horizontal/vertical entrainment of ambient water, the positive anomalies in θ and S (compared with ambient subarctic water) may be maintained for several years.

Because of the deep pycnocline and high salinity, warm-core rings in the western subarctic gyre generally develop a remarkably deep mixed layer. Seasonal variations in the development and decay of the upper pycnostad, as observed by the two profiling floats in the present study, were similar in part to those of North Pacific Subtropical Mode Water (STMW) observed in its formation region—recirculation gyres of the Kuroshio Extension (Qiu et al. 2006). However, the pycnostad of the upper core within the ring was different from STMW in that it was trapped within quasi-isolated mesoscale warm-core rings that propagated far more freely than did recirculation gyres. Because the ring spends a long period located far from the Kuroshio Extension, the properties of the core water show a marked change before and after the winter season; consequently, temperature of the upper-layer pycnostad within warm-core rings north of the Kuroshio Extension, generated by wintertime convection, were observed to range from 5°C (present study) to more than 10°C (Tomosada 1986; Yasuda et al. 1992; Yoshida and Hoshimoto 2006).

This is in contrast to STMW, for which the temperature lies within the narrow range within a prominent mode at 16.5°C, distributed around 150–170°E south of the Kuroshio Extension (Masuzawa 1969); although STMW is warm in the west and cold in the east in and around the recirculation gyre, and several modes corresponding to the difference in the areas of the occurrence were found on the basis of recent profiling float observations (e.g., Oka 2009), these modes were mostly found within the range of 2°C: modes were detected at 17.1–17.3, 17.5–17.7, 17.8–17.9, and 17.9–18.6°C in Oka (2009).

Given that a sequence of propagating eddies and their interactions cause wider horizontal distributions of the pycnostad around the upper-core potential density range of 26.5–26.6 σ_θ, we presume that northeastward-propagating warm-core rings from the Kuroshio Extension, either along the Japan and Kuril–Kamchatka trenches or SAF (Itoh and Yasuda 2010a), has direct or indirect relationships with various mode waters with wide ranges of water properties distributed in subtropical–subarctic transition and subarctic areas of the western North Pacific, such as the lighter and denser varieties of Central Mode Water (Oka and Suga 2005; Oka et al. 2011) and Transition Region Mode Water (Saito et al. 2007).

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