Modification of a Kenai eddy along the Alaskan Stream

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[1] A Kenai eddy was studied through analyses of satellite altimeter data and hydrographic data from shipboard and Argo float observations. This eddy formed in December 2006 south of the Kenai Peninsula and propagated southwestward along the Alaskan Stream. The eddy held horizontally uniform warm core water in January 2007. In late winter 2007, this core water was cooled from the top and a subsurface temperature maximum was formed around $26.5\sigma_\theta$. Two years later in summer 2009, warm and low-dissolved-oxygen (low-DO) water characterized by a temperature maximum around $26.5\sigma_\theta$ was observed again in the eddy core and was likely the remnant of original core water. At the same time, cold and high-DO water intrusions occurred in the eddy core, suggesting that strong modification of core water was ongoing. After summer 2009, the core water was fully changed through interaction with another eddy.

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1. Introduction

[2] In the subarctic North Pacific, mesoscale eddies have significant impacts on the heat, freshwater, macro- and micro-nutrient, and biota exchanges between shelf and offshore regions and thus play an important role in the productivity of the offshore region [*Johnson et al.*, 2005; *Whitney et al.*, 2005; *Crawford et al.*, 2007; *Ueno et al.*, 2010; *Ikenoue et al.*, 2012]. For example, Haida, Sitka, Yakutat, and Alaskan Stream eddies affect water exchanges between the shelf and offshore regions by trapping coastal water in their interiors and propagating offshore. These eddies also interfere with the slope circulation and result in cross-shelf flow [*Okkonen et al.*, 2003; *Crawford*, 2005; *Ladd et al.*, 2005; *Janout et al.*, 2009; *Ueno et al.*, 2009].

[3] *Rovegno et al.* [2009] observed an anticyclonic eddy southwest of Kodiak Island in September 2007 and reported that this eddy contained warm core water with relatively uniform temperature-salinity (TS) relations near the eddy center. Their analysis of satellite altimeter data as well as hydrographic data indicated that this eddy originated near the Kenai Peninsula and propagated southwestward along the Alaskan Stream. They thus called it a Kenai eddy. The formation region of Kenai eddies (~150°W) is between the formation regions of Yakutat (~143°W) and Alaskan Stream (~160°W) eddies. A more recent study [*Lippiatt et al.*, 2011] investigated macro- and micro-nutrients in and around a Kenai eddy based on the data obtained in September 2007 [*Rovegno et al.*, 2009] and indicated that the Kenai eddy drove biological productivity in the western Gulf of Alaska via water exchange between the shelf region and the offshore region.

[4] In summer 2009, we observed the same eddy as the one observed in September 2007 by *Rovegno et al.* [2009]. Observations were made on board the T/S Oshoro-maru and the R/V Hakuho-maru and by two Argo floats deployed near the center of the eddy at different times. In this paper, we discuss the propagation and modification of the Kenai eddy through analysis of satellite altimeter data and hydrographic data obtained by the Oshoro-maru, Hakuho-maru, and Argo floats.

2. Data and Method

[5] We used temperature and salinity data obtained by the T/S Oshoro-maru in June 2009 (Figure 1a) and temperature, salinity, and oxygen data obtained by R/V Hakuho-maru in August 2009 (Figure 1b). Observations by the Oshoro-maru were performed with a conductivity-temperature-depth profiler (CTD) and an expendable CTD (XCTD), and observations by the Hakuho-maru were performed with a CTD and a CTD-dissolved-oxygen sensor (CTDO). CTD observations by the Hakuho-maru include observations using a moving-vessel profiler (MVP), which obtains hydrographic data with fine horizontal resolution. Since there was a bias in MVP salinity data, we corrected the data using ship-based CTDO data, which were calibrated with IAPSO standard seawater. DO data obtained by the CTDO on board the Hakuho-maru were calibrated with bottle-sampled data. All CTD, CTDO,

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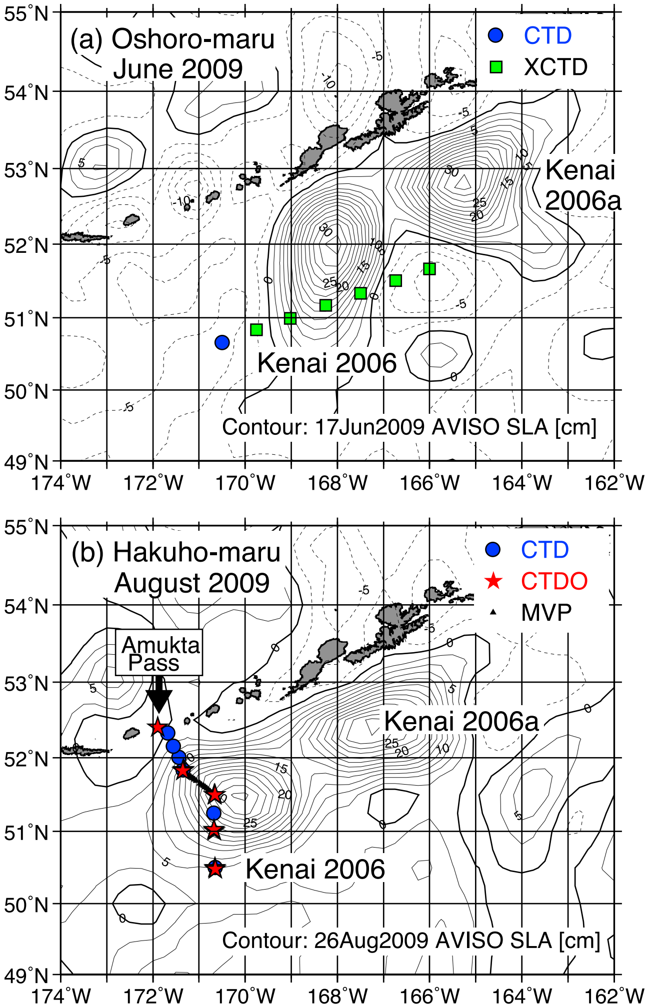

Figure 1. Locations of CTD, XCTD, CTDO, and MVP observations by the (a) T/S Oshoro-maru and (b) R/V Hakuho-maru overlaid on satellite sea level anomaly data around the date of ship observation (contours).

and XCTD data were analyzed after 10-m box-averaging in the vertical direction to remove small-scale fluctuations.

[6] In addition to Oshoro-maru and Hakuho-maru data, we used temperature and salinity profiles recorded by Argo floats [*Argo Science Team*, 2001] around the Alaskan Stream from December 2006 to July 2011 (five Argo floats, see Figure 2). The real-time quality-controlled float data were downloaded from the FTP site of the Argo Global Data Assembly Center. From these data, defective temperature and salinity profiles, such as those with measurements flagged as bad and those lacking intermediate layers for certain depths, were eliminated following the procedures of *Oka et al.* [2007].

[7] We also used delayed-time maps of sea level anomalies (SLA) of a merged-altimeter satellite product distributed at 7-day intervals by AVISO [*Collecte Localisation Satellites*, 2011]. The spatial resolution of the SLA data was 1/4° × 1/4°, and we used the data for the period December 2006 to July 2011. The weekly spatial mean state of the subarctic North Pacific north of 45°N, except for the marginal seas, was removed from each weekly map of the SLA to compensate for seasonal steric effects.

[8] Eddy tracking was performed using the Okubo-Weiss parameter W [*Okubo*, 1970; *Weiss*, 1991] calculated from SLA data assuming geostrophy. We defined the area of $W < -2 \times 10^{-12}$ s^{-2} as an eddy area following *Chelton et al.* [2007] and tracked the eddy in the same manner as *Henson and Thomas* [2008] and *Inatsu* [2009]. To determine the relative locations of Argo float observations in and around the eddy, we evaluated the radius of the eddy (R_{eddy}) assuming a radially symmetrical eddy whose area corresponded to the eddy area. The eddy centers were calculated as the geometrical mean of the eddy area. We defined the same three regions as used by *Ueno et al.* [2010]: (1) inner-eddy ($D < 0.5\ R_{eddy}$), (2) outer-eddy ($0.5\ R_{eddy} < D < R_{eddy}$), and (3) periphery of eddy ($R_{eddy} < D < 2R_{eddy}$), where D is the distance from the eddy center. Note that center locations estimated from altimeter data can give errors of >50 km due to data resolution and eddy propagation [*Ladd et al.*, 2005, 2007].

3. Propagation and Modification of a Kenai Eddy: Satellite Altimeter Data Analyses

[9] Using the Okubo-Weiss parameter, we tracked the eddy observed on board the Oshoro-maru and Hakuho-maru in summer 2009 (Figure 3a). We found that the eddy formed at 57.8°N, 148.2°W south of the Kenai Peninsula in the end of 2006. Therefore, we called the eddy Kenai 2006. Kenai 2006 propagated southwestward along the Alaskan Stream and was observed by *Rovegno et al.* [2009] around 155°W in summer 2007. The eddy split into two (Kenai 2006 and Kenai 2006a) around 163°W in February 2009 (Figure 3) before observations by the Oshoro-maru and Hakuho-maru. Kenai 2006 propagated westward along the Alaskan Stream and was absorbed by a large anticyclonic eddy (an Aleutian eddy formed south of the Aleutian Islands [*Rogachev et al.*, 2007]) around 175°E in July 2010. Meanwhile, Kenai 2006a was detached from the Alaskan Stream around 170°W in January 2010. Just before and during the detachment, Kenai 2006a was located next to Kenai 2006, and some SLA contours encircled both eddies (Figure 4), suggesting that eddy-eddy interaction between Kenai 2006 and Kenai 2006a induced detachment of Kenai 2006a from the Alaskan Stream. After detachment, Kenai 2006a propagated southward away from the Aleutian Islands and decayed in June 2011. Hereafter, we focus on the main part of the eddy (Kenai 2006).

[10] Figure 5 shows time series of longitude, westward propagation speed, SLA, and area of Kenai 2006. Westward propagation speed ranged from −0.8 to 5.0 km day^{-1} and was 1.8 km day^{-1} on average, which is similar to the propagation speeds of the Sitka, Yakutat, and Alaskan Stream eddies along the Alaskan Stream ranging from −0.5 to 7.0 km day^{-1} with an average of 2.0 km day^{-1} [*Ueno et al.*, 2009]. *Ueno et al.* [2009] compared westward eddy propagation speeds in the Alaskan Stream with the bottom slope, Alaskan Stream velocity, and SLA. They found that bottom slope effects dominated, with faster propagation over steeper slopes. Since Kenai 2006 propagated in a similar route and with similar speed to eddies studied by *Ueno et al.* [2009], bottom slope likely also accounted for the propagation speed of Kenai 2006. Figures 5b and 5c further show that Kenai

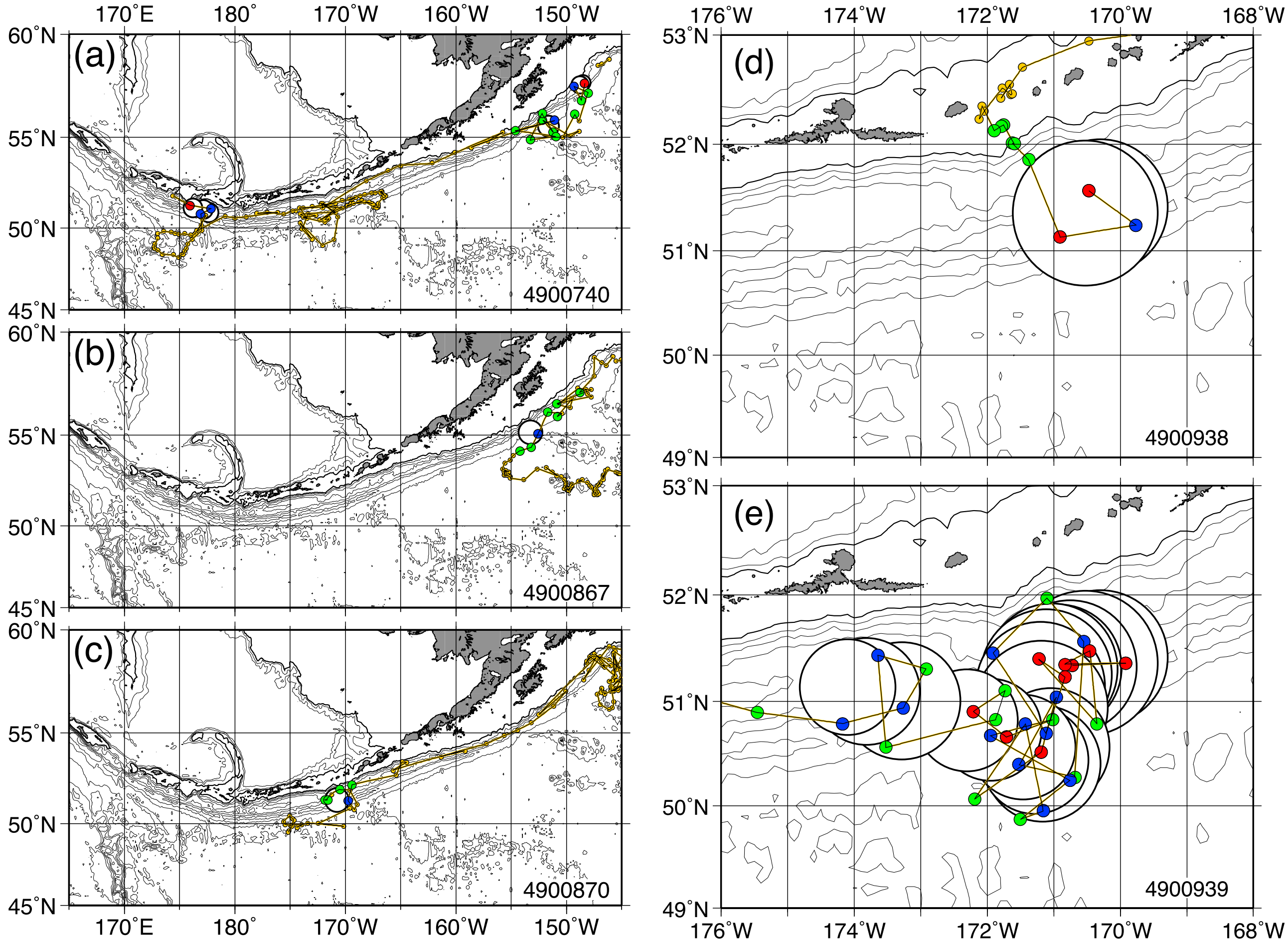

Figure 2. Trajectories of Argo floats (WMO IDs: (a) 4900740, (b) 4900867, (c) 4900870, (d) 4900938, and (e) 4900939) which observed inner-eddy (red circles) or outer-eddy (blue circles) areas of Kenai 2006 from December 2006 to July 2010. Observations located in the periphery of Kenai 2006 and outside the periphery of Kenai 2006 are shown by green circles and orange dots, respectively. Large white circles indicate the location of Kenai 2006 (see caption of Figure 3a for details) when its inner-eddy or outer-eddy area was observed.

2006 stopped propagating around 155°W for three months (October–December 2007), and SLA suddenly increased in February 2008 after this stop. This might be related to eddy intensification due to low-salinity surface water outflow from Shelikof Strait around 155°W [*Reed et al.*, 1986, 1987; *Stabeno and Hermann*, 1996; *Stabeno et al.*, 2004] as discussed by *Ueno et al.* [2009].

[11] Figures 5c and 5d indicate that Kenai 2006 intensified in the first three months (SLA) and five months (area). After that, SLA decreased with fluctuations to a minimum (20–25 cm) from November 2007 to January 2008. It then suddenly increased in February 2008 as mentioned in the previous paragraph. After January 2008, SLA was mostly constant for a year, gradually decreased in 2009, increased in the early half of 2010, and rapidly decreased in July 2010. SLA increase in the early half of 2010 occurred near 170°W, where eddies sometimes intensified possibly due to outflow of low potential vorticity water from the Bering Sea [*Ueno et al.*, 2009]. On the other hand, eddy area was relatively high (15,000 km^2) from June 2007 to September 2009 and low (10,000 km^2) after October 2009, and finally decreased to 6000 km^2 in July 2010.

[12] As suggested by Figure 5, the propagation speed, SLA, and area of Kenai 2006 largely changed around the end of 2009 when Kenai 2006 was located next to Kenai 2006a and some SLA contours encircled both eddies. These results suggest that eddy-eddy interaction occurred around the end of 2009 and influenced the propagation speed, SLA, and area of Kenai 2006. Changes in water mass in Kenai 2006 during this period will be discussed in Section 4.3.

4. Modification of the Kenai Eddy: Hydrographic Data Analyses

4.1. Observations in 2007: Argo Float Data Analysis

[13] Two Argo floats (WMO ID: 4900740 and 4900867, hereafter Argo floats (a) and (b), respectively) observed Kenai 2006 in the first half of 2007 (Figures 2a and 2b). Fortunately, Argo float (a) was located in the inner-eddy area of Kenai 2006 on 1 January 2007 (red circles in Figures 2a and 6a), within a week of the first evidence of the eddy in

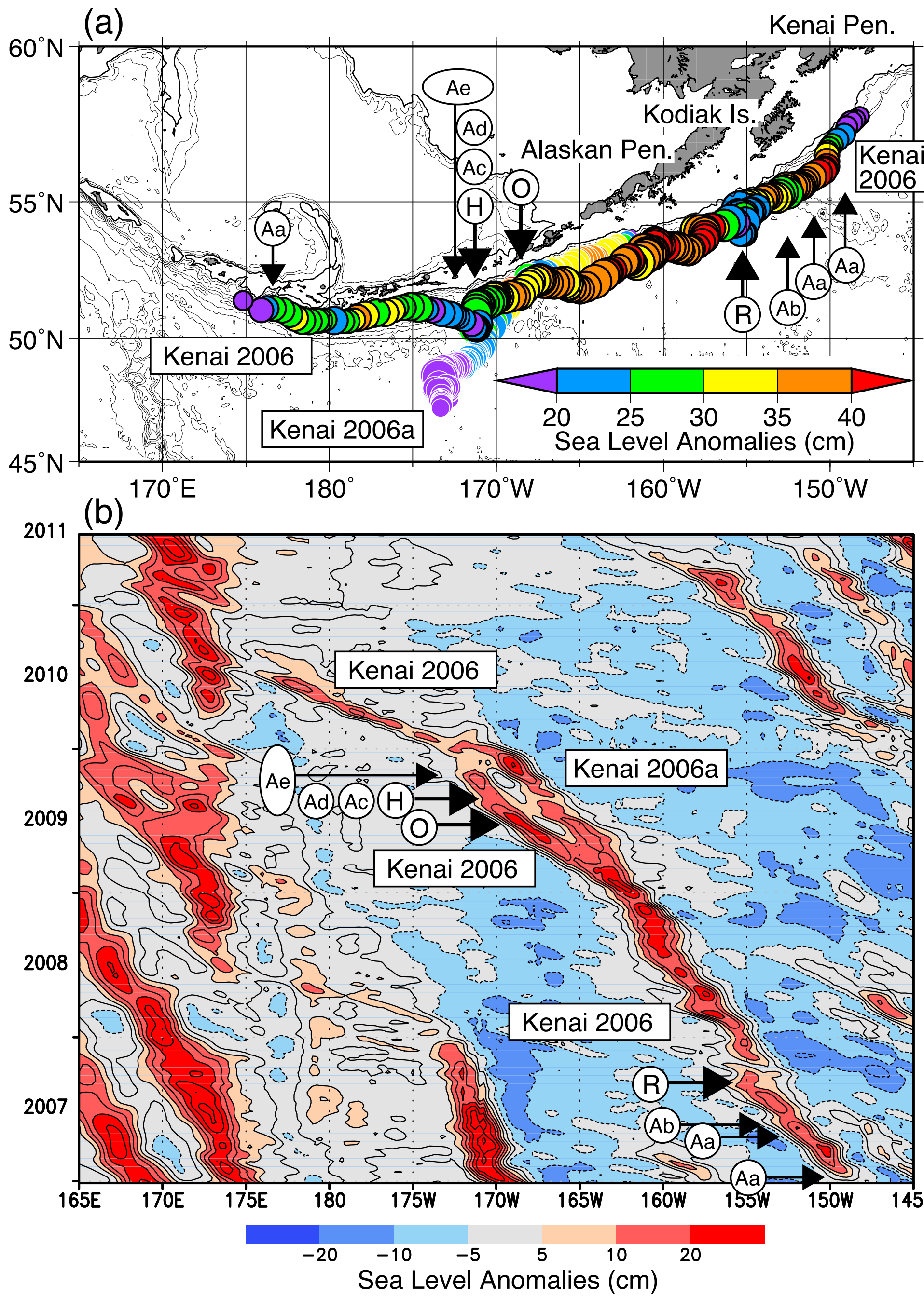

Figure 3. (a) Trajectories of Kenai 2006 and Kenai 2006a. Colors represent SLA (cm) at the eddy and the radius of each circle in the map mostly corresponds to an Okubo-Weiss radius (R_{eddy}). Bathymetric contours are depicted every 1000 m, with a thicker contour at 1000 m depth. (b) Longitude-time diagram of SLA along the northern boundary of the Pacific Ocean. SLA was averaged within 2° south of the 1000 m depth contour. Arrows represent the rough location (Figure 3a) and date (Figure 3b) of each observation. R indicates *Rovegno et al.* [2009], O represents the Oshoro-maru, H represents the Hakuho-maru, and Aa, Ab, Ac, Ad, and Ae are the Argo floats shown in Figures 2a, 2b, 2c, 2d, and 2e, respectively.

altimeter data. This observation revealed that Kenai 2006 held water warmer than 6°C in the density range of 25.8–26.5σ_θ near the eddy center just after its formation (Figure 6a). Similar TS profiles were observed in the outer-eddy area on 11 January 2007 (blue triangles in Figure 6a), suggesting that relatively uniform warm water was distributed in the eddy area as defined using the Okubo-Weiss parameter. This water, which would be the original core water that Kenai 2006 gained at formation, was warmer than the core water observed by *Rovegno et al.* [2009] in September 2007, which was characterized by a subsurface temperature maximum (Tmax) of 5.5–5.8°C at 26.4–26.6σ_θ.

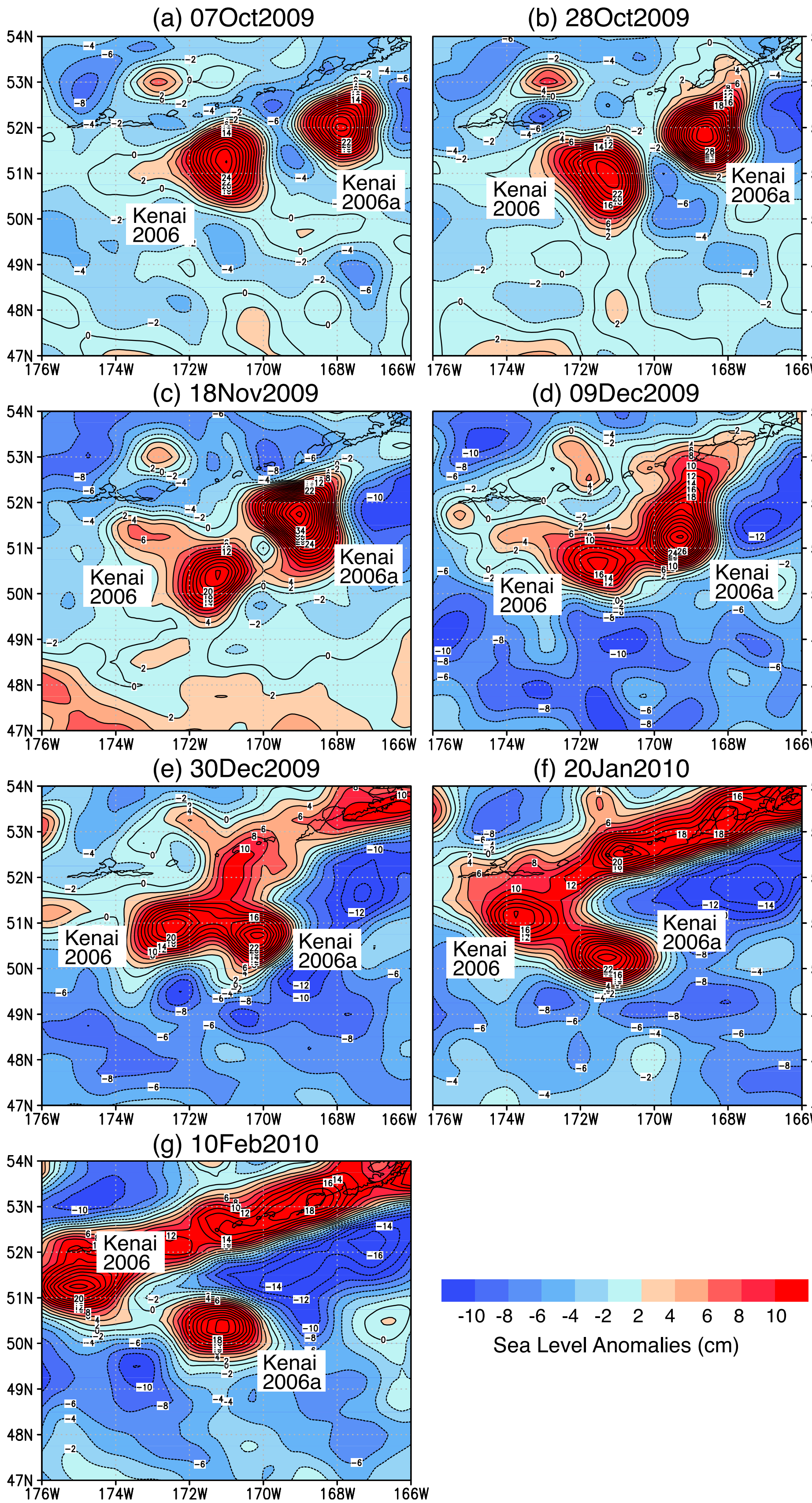

Figure 4. SLA (cm) distributions in (a) 7 October 2009, (b) 28 October 2009, (c) 18 November 2009, (d) 9 December 2009, (e) 30 December 2009, (f) 20 January 2010, and (g) 10 February 2010. The contour interval is 2 cm.

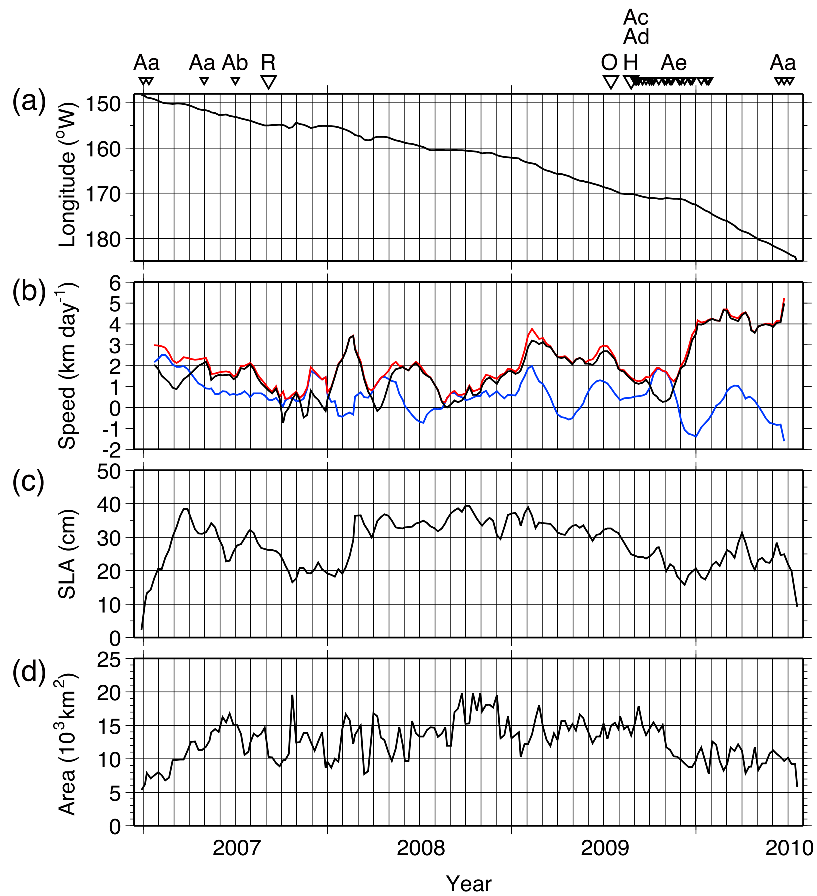

Figure 5. Time series of Kenai 2006 (a) longitude (°W), (b) westward propagation speed (black), southward propagation speed (blue) and propagation speed (red) (km day^{-1}), (c) SLA (cm) averaged in the 0.5° × 0.5° area around the geometrical mean of the eddy area, and (d) area (10^3 km^2). Triangles located at the top represent the rough location of each observation (see caption of Figure 3 for the meaning of Aa, etc.)

[14] Kenai 2006 was not observed by Argo floats from February to April 2007. The observation restarted on 1 May 2007 around 177°E (Figure 2a) by Argo float (a) and indicated that a strong temperature inversion formed between 25.9σ_θ and 26.5σ_θ in the outer-eddy area (blue triangles with plots of 4.0°C at 25.9σ_θ and >5.5°C at 26.5σ_θ in Figure 6b). The Tmin density of 25.9σ_θ corresponded to the climatological winter-mixed-layer density in the northwestern Gulf of Alaska [*Suga et al.*, 2004], indicating that the strong temperature inversion was formed by surface cooling in late winter 2007. The TS relations observed by the Argo floats in May–July 2007 in the eddy area (blue triangles in Figure 6b) were almost the same as those observed in the eddy core in September 2007 by *Rovegno et al.* [2009]. Between October 2007 and August 2009, Argo floats did not observe Kenai 2006 and thus float data to describe the modification of the eddy were unavailable.

[15] Properties in the periphery of Kenai 2006 in May–July 2007 varied from those similar to eddy core water (dots with Tmax warmer than 5.5°C in Figure 6b) to those similar to basin water (dots with Tmax colder than 5.5°C in Figure 6b). This is probably because of uncertainty in eddy location determination from satellite altimeter data [*Ladd et al.*, 2005, 2007]. The trajectories of Argo floats (a) and (b) show a kind of eddy-like feature (Figures 2a and 2b). However, it was difficult to estimate eddy location from these trajectories because their resolutions were low compared with the eddy scale. The parking depth (1000 dbar) of Argo floats (a) and (b) might also make it difficult to estimate the eddy location from the trajectory data.

4.2. Observations in Summer 2009

4.2.1. Oshoro-maru Data Analysis

[16] Figure 7a shows an east-west potential temperature section of Kenai 2006 obtained by the Oshoro-maru in June 2009 (see Figure 1a). At 168.25°W (red open circle in Figure 7), a subsurface temperature maximum (Tmax) of 5.4°C was observed at 170 m depth and 26.5σ_θ. This Tmax water was similar to that in the eddy core in September 2007 (5.5–5.8°C at 26.4–26.6σ_θ) [*Rovegno et al.*, 2009], suggesting that the Oshoro-maru cruise captured the Kenai 2006 core water at 168.25°W.

[17] At 168.25°W, a strong temperature inversion was observed between 25.7σ_θ (3.6°C) and 26.5σ_θ (5.4°C). The subsurface temperature minimum (Tmin) of 3.6°C at 25.7σ_θ was colder than that in the eddy core in September 2007 (about 4.9°C) [*Rovegno et al.*, 2009]. Tmin was formed by winter surface cooling in the northern Gulf of Alaska [*Ueno and Yasuda*, 2000; *Ueno et al.*, 2005], suggesting that

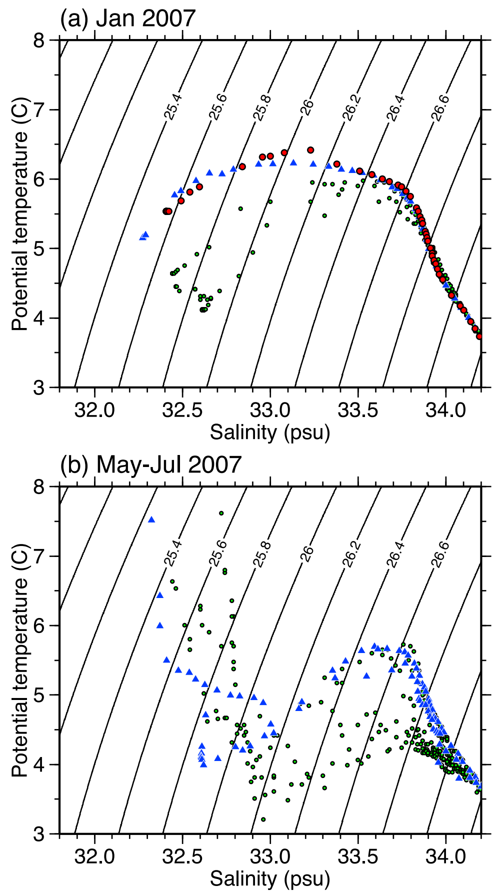

Figure 6. TS relations in (a) January 2007 and (b) May–July 2007 obtained by Argo floats located in the inner-eddy (red circles), outer-eddy (blue triangles), and periphery of the eddy (green dots).

surface cooling in the winters of 2008 and 2009 cooled subsurface Tmin and strengthened the temperature inversion. This result is consistent with findings that the climatological winter-mixed-layer density and temperature around the observation areas of *Rovegno et al.* [2009] and the Oshoro-maru were 26.0–26.2σ_θ and 3–4°C, respectively, and were denser and colder to the west. On the other hand, the Tmax water at 168.25°W was similar to that in September 2007 as mentioned above. This indicates that winter surface cooling hardly modified the Kenai 2006 core water characterized by Tmax.

[18] The Oshoro-maru cruise also observed a hydrographic structure that was different from that found by *Rovegno et al.* [2009]. At 169°W (blue open triangles in Figure 7), temperature decreased by 1.5°C from 26.5 to 26.7σ_θ, forming a Tmin around 26.7σ_θ. Since the Tmin formed by winter surface cooling was located at 26.1σ_θ, we propose that the observed hydrography was created by other mechanisms, such as lateral intrusion of cold water. Since TS relations at 169° and 169.8°W were similar at the densities of cold water intrusion, we speculate that this cold water originated from the basin water outside the eddy (e.g., water at 169.8°W, black open squares, with cold Tmin of 3.1°C at 26.7σ_θ). The basin water is probably influenced by waters in the Western Subarctic Gyre [see, e.g., *Ueno and Yasuda*, 2005].

[19] TS relations at stations east of 168°W, which were similar to one another, were between those of the core water (red open circles, 168.25°W) and the basin water (black open squares, 169.8°W) and were similar to the TS relation of the transitional water indicated by *Rovegno et al.* [2009], with water properties between those of the Kenai core water and the basin water. Therefore, we considered the water east of 168°W to be the transitional water. The TS relation of the transitional water was similar to that of the Alaskan Stream water [e.g., *Favorite et al.*, 1976, Figure 48], suggesting that the waters east of 168°W were influenced by the Alaskan Stream flowing along the southern rim of Kenai 2006. In addition, water east of 168°W could be influenced by the small cyclonic eddy (around 51.5°N and 166°W) indicated by the altimeter contours in Figure 1a.

4.2.2. Hakuho-maru Data Analysis

[20] The Hakuho-maru observed Kenai 2006 in more detail using CTD, CTDO, and MVP. Along the observation

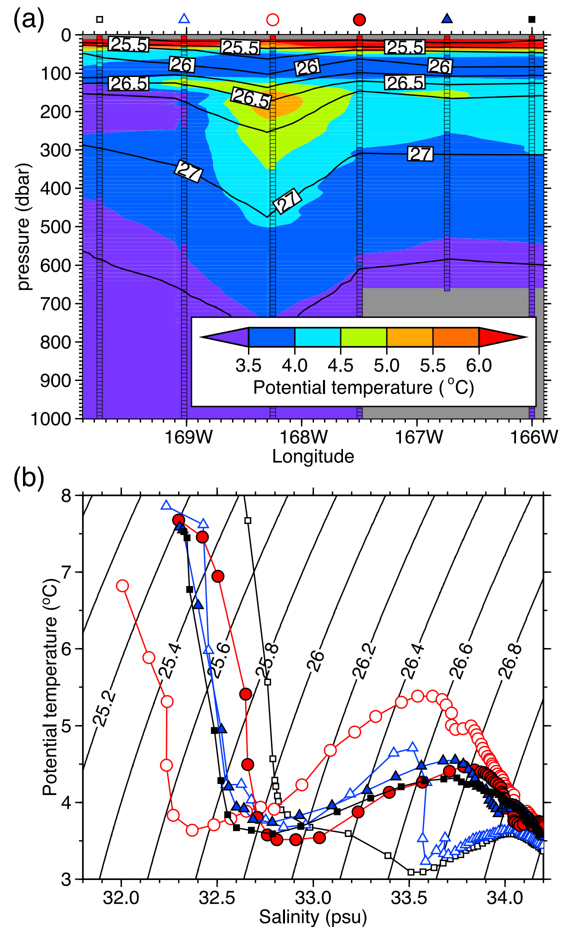

Figure 7. (a) Potential temperature distribution (°C, colors) superimposed by the density distribution (σ_θ, contours) and (b) TS relations along the east-west section of the Oshoro-maru cruise (Figure 1a). Colored squares with black outlines in Figure 7a represent potential temperature observed by XCTD, and background colors and contours in Figure 7a denote potential temperature horizontally box-averaged with a width of 0.8° in longitude. Symbols drawn at the top of Figure 7a represent the location of the profile drawn in Figure 7b.

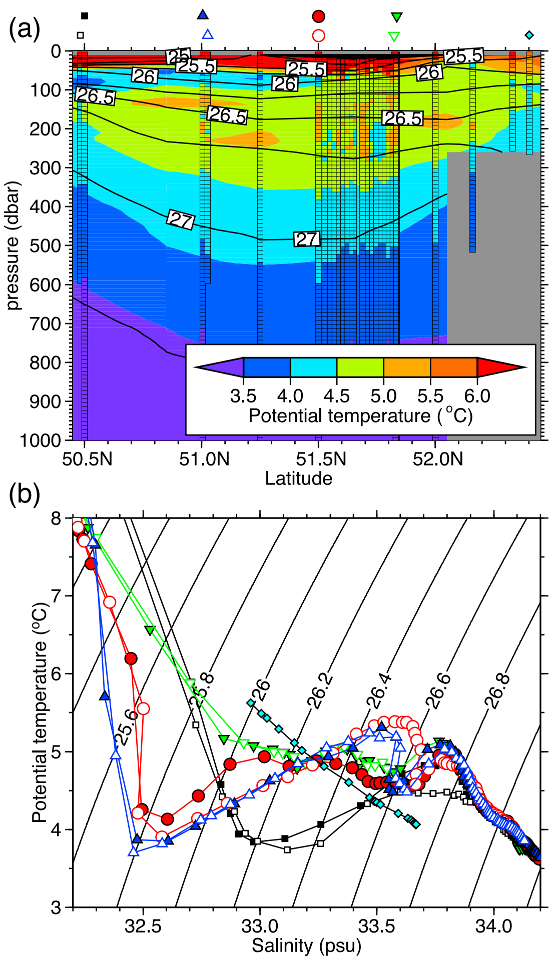

Figure 8. (a) Potential temperature distribution (°C, colors) superimposed by the density distribution (σ_θ, contours) and (b) TS relations along the Hakuho-maru cruise (Figure 1b). Colored squares with black outlines in Figure 8a represent potential temperature observed by CTD/CTDO/MVP, and background colors and contours in Figure 8a denote potential temperature horizontally box-averaged with a width of 0.4° in latitude. Symbols at the top of Figure 8a represent the location of the profile in Figure 8b; solid and open symbols correspond to deep and shallow CTDO casts, respectively.

line, Tmax water warmer than 5°C, which corresponded to the core water of Kenai 2006, was observed in the wide area of 51°–52°N (Figure 8). This is probably because the Hakuho-maru observation line was closer than the Oshoro-maru observation line to the center of Kenai 2006 (Figure 1). In the eddy core area of 51°–52°N, waters warmer than 5°C and colder than 4.5°C were patchily observed, suggesting the modification of core water as described below.

[21] During the Hakuho-maru cruise, CTDO observation was conducted twice at an observation station, with a deep cast (0–2000 dbar: solid symbols in Figures 8 and 9) and a shallow cast (0–600 dbar: open symbols in Figures 8 and 9), to obtain vertically high-resolution bottle-sampled data. TS relations of deep and shallow casts at each station were mostly similar, but those at 51.5°N (red open and solid circles) were significantly different at densities of 26.4–26.6σ_θ even though the horizontal distance between the two casts was just 1.5 km. Whereas a Tmax layer of 5.2–5.4°C was observed in the shallow cast (open red circles), a Tmin layer of 4.6–4.7°C was observed in the deep cast (solid red circles). Such non-uniformity in water properties near the eddy center differs from the observation in 2007, when the TS relation was relatively uniform among eight casts near the eddy center [*Rovegno et al.*, 2009]. The eddy core water likely lost its uniformity between 2007 and 2009.

[22] A strong Tmin layer was also observed by the Hakuho-maru and Oshoro-maru at the intermediate depth where winter surface cooling was unlikely to have formed the Tmin layer. At the 51.5°N shallow cast (red open circles in Figure 8), temperature decreased from 5.2°C (26.60σ_θ and 220 m) to 4.6°C (26.66σ_θ and 250 m) and increased to 4.9°C (26.72σ_θ and 270 m), suggesting lateral intrusion of cold water. A strong Tmin layer was also observed at the 51°N shallow and deep casts (blue open and solid triangles) around the 26.6σ_θ isopycnal surface. The temperature and salinity of the Tmin water were similar to those at 50.5°N (black open and solid squares), whose TS relation resembled that of transitional water discussed in Section 4.2.1. This finding suggests that the transitional water influenced by the Alaskan Stream modified the eddy core through lateral intrusions.

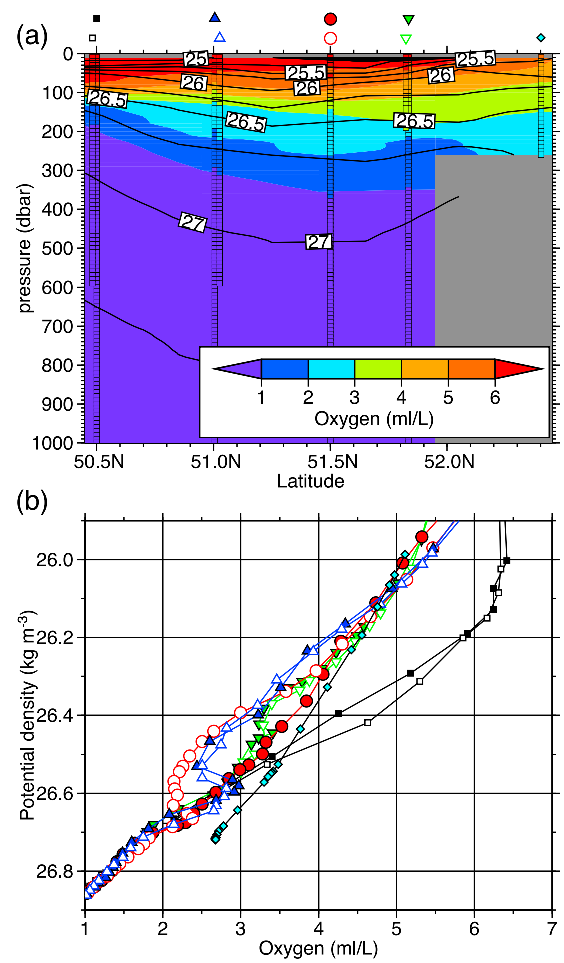

Figure 9. Same as Figure 8 but for the (a) dissolved oxygen distribution (ml l^{-1}) and (b) dissolved oxygen profiles in density coordinates.

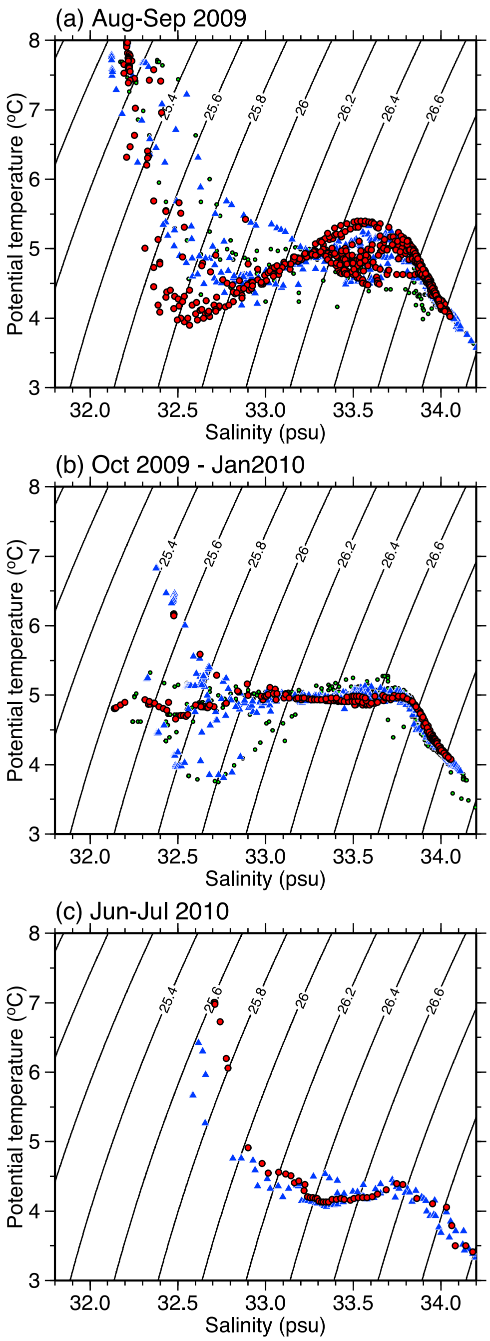

Figure 10. Same as Figure 6 but for (a) August–September 2009, (b) October 2009–January 2010, and (c) June–July 2010.

[23] Kenai 2006 core water was also detected by dissolved-oxygen (DO) data (Figure 9). Previous research found that DO in the coastal region of the Gulf of Alaska, where Kenai 2006 formed, was lower than that in the deep-sea region of the subarctic North Pacific [*Whitney et al.*, 2007]. We examined the DO data obtained by the Hakuho-maru (Figure 9) and found that DO values obtained at the 51.5°N shallow cast (red open circle) and the 51.0°N shallow and deep casts (blue triangles) were lower than values obtained at the other CTDO casts at densities of 26.4–26.6σ_θ. This low-DO layer corresponds to the Tmax layer, which suggests that warm and low-DO original core water was carried from south of the Kenai Peninsula to south of the Aleutian Islands along the Alaskan Stream for two and a half years.

[24] In addition to the transport of original core water, modification of the core water was also indicated by the DO data. At the 51.5°N shallow cast (red open circle) and the 51.0°N shallow and deep casts (blue triangles), high-DO water intrusion was observed at densities of 26.65σ_θ and 26.6σ_θ, respectively. The DO value of this high-DO intrusion was almost the same as the DO values at 50.5°N, indicating that water surrounding the eddy core intruded to the eddy core. This intrusion corresponds to the cold Tmin water intrusion noted in the previous paragraph, supporting the hypothesis obtained by TS relation analysis that water in the southern rim of the eddy influenced by the Alaskan Stream modified the eddy core through lateral intrusions.

4.2.3. Argo Data Analysis

[25] In August 2009, we deployed two Argo floats (WMO ID: 4900938, Argo float (d), and 4900939, Argo float (e), see Figures 2d and 2e, respectively) from the Hakuho-maru. In addition, Argo float (a) also observed the outer-eddy area of Kenai 2006 in September 2009 (Figure 2a). These three Argo floats obtained many profiles in Kenai 2006 during August–September 2009 (Figure 10a). During this period, two types of profiles were observed simultaneously in the inner-eddy area: profiles with Tmax warmer than 5°C and those with Tmin colder than 5°C around 26.5σ_θ (red circles in Figure 10a). Such non-uniform TS profiles near the eddy center correspond to the results from the Oshoro-maru and Hakuho-maru observations that lateral intrusion of cold and high-DO water occurred actively in Kenai 2006.

4.3. Observations After September 2009: Argo Float Data Analysis

[26] Observations by Argo floats from October 2009 to January 2010 show a relatively uniform TS relation with ~5°C water at densities of 26.0–26.7σ_θ in Kenai 2006. This TS relation without marked Tmin and Tmax was completely different from the relations observed in Kenai 2006 before October 2009. Altimeter data suggested that eddy-eddy interaction occurred between Kenai 2006 and Kenai 2006a during this period (Figure 4). Therefore, the water mass in Kenai 2006 might have been fully changed by water exchange or mixing due to eddy-eddy interaction around the end of 2009.

[27] In June–July 2010, when Kenai 2006 became weak and just before Kenai 2006 was absorbed by an Aleutian eddy, Argo float (a) obtained hydrographic data in Kenai 2006 (Figures 2a and 10c). Water in Kenai 2006 in June–July 2010 was colder than that observed from October 2009 to January 2010 at densities between 26.0σ_θ and 27.0σ_θ (Figures 10b and 10c). Winter surface cooling would account for cooling at densities shallower than 26.4σ_θ (the climatological winter mixed layer density in this area) [*Suga et al.*, 2004]. Cooling at densities deeper than 26.4σ_θ suggests strong mixing or water exchange in Kenai 2006 due to eddy decay during this period. However, it is also possible that this cooling was a result of errors in the determination of eddy

location from altimeter data, since only three profiles were obtained in Kenai 2006 during this period.

5. Summary

[28] We investigated the propagation and modification of a Kenai eddy (Kenai 2006) through analysis of satellite altimeter data and hydrographic data obtained by the Oshoro-maru, Hakuho-maru, and Argo floats. Kenai 2006 formed in the area south of the Kenai Peninsula in December 2006 and propagated southwestward along the Alaskan Stream, splitting into two around 163°W in February 2009. The main part propagated westward along the Alaskan Stream and finally was absorbed by an Aleutian eddy around 175°E in July 2010. The other part was detached from the Alaskan Stream around 170°W in January 2009, propagated southward away from the Aleutian Islands, and decayed in June 2011. The two eddies were located close to one another around the end of 2009, and the occurrence of eddy-eddy interaction was suggested during the period.

[29] Kenai 2006 held horizontally uniform core water warmer than 6°C near the eddy center in January 2007, just after its formation. This core water was cooled by surface cooling in late winter 2007, and strong temperature inversion was formed around 26.0–26.5σ_θ. This cooling in late winter 2007 did not break the uniformity of the eddy core, as demonstrated by *Rovegno et al.* [2009]. Two years later, in June–September 2009, Kenai 2006 carried warm and low-DO water characterized by Tmax of around 26.5σ_θ in the eddy core in the area south of the Aleutian Islands. This warm and low-DO water was suggested to be the remnant of the original eddy-core water obtained at the eddy formation area. Cold and high-DO water intrusions into the eddy core were also observed, which suggest that strong modification of the eddy-core water was ongoing in summer 2009. Around the end of 2009, Kenai 2006 core water was fully changed, probably because of eddy-eddy interaction between Kenai 2006 and Kenai 2006a.

[30] Although water mass modification of a Kenai eddy was investigated for the first time in this study, water mass changes in other eddies formed in the Gulf of Alaska have been studied. *Chierici et al.* [2005] studied changes in water properties of a Haida eddy for a year and indicated that the TS relation of the eddy showed little temporal change in waters below 100 m in the eddy center during its first year. *Ladd et al.* [2007] investigated water property change in a Sitka eddy for one and one half years and indicated that heat and salinity anomalies became less than half in a year and less than one third in a year and a half. Although a cold-water intrusion was not observed in the Haida eddy [*Chierici et al.*, 2005], fluctuation in the TS relation, which was similar to that in Kenai 2006, was observed in the Sitka eddy [*Ladd et al.*, 2007], suggesting that Sitka core water was modified by mechanisms similar to those in Kenai 2006. However, a more comprehensive study is necessary for detailed understanding of core water modifications in eddies formed in the Gulf of Alaska.

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