Observations from a Yakutat eddy in the northern Gulf of Alaska

C. Ladd, N. B. Kachel, and C. W. Mordy
Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, Washington, USA

P. J. Stabeno
Pacific Marine Environmental Laboratory, NOAA, Seattle, Washington, USA

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[1] The impingement of deep basin eddies on the shelf in the Gulf of Alaska has been implicated as an important mechanism for cross-shelf exchange. The influence of eddies on biological processes has been confirmed with data from the Sea-viewing Wide Field-of-view Sensor showing elevated chlorophyll associated with eddies. Altimetry data suggest that an eddy formed in the winter of 2003 near Yakutat, Alaska, and propagated along the shelf break, reaching the head of the gulf by spring. This eddy was sampled during May and September of 2003. The eddy core water was warm, salty, and high in nitrate relative to basin water of the same density but was similar to historical water properties from the shelf near Yakutat. This suggests a shelf origin for the eddy core water.

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1. Introduction

[2] Although the predominance of downwelling winds in the Gulf of Alaska (GOA) limits the supply of nutrients to the shelf, it is a highly productive region. On the other hand, the basin of the GOA has been described as a high-nutrient, low-chlorophyll environment. Winter mixing and advection provide nutrients to the basin, but due to iron limitation [*Boyd et al.*, 1995, 2004; *Martin et al.*, 1989], chlorophyll concentrations remain low throughout the year [*Wong et al.*, 1995]. Eddies have been hypothesized as one mechanism that may contribute to the cross-shelf exchange of iron and nutrients supporting the GOA ecosystems [e.g., *Johnson et al.*, 2005; *Ladd et al.*, 2005; *Okkonen et al.*, 2003; *Stabeno et al.*, 2004; *Whitney and Robert*, 2002].

[3] Three groups of GOA eddies have been identified (Haida, Sitka, and Yakutat eddies) and are primarily distinguished by their formation region [*Gower*, 1989; *Okkonen et al.*, 2001]. These three eddy groups share many common features, including anticyclonic rotation, ~200 km diameter, formation along the eastern boundary of the GOA, and westward propagation.

[4] Haida eddies are formed during winter off the west coast of the Queen Charlotte Islands (named Haida Gwaii by the local Haida people) [*Crawford*, 2002]. These eddies carry warm, fresh, nutrient-rich coastal water into the basin [*Crawford*, 2002; *Whitney and Robert*, 2002] and can persist for several years. Haida eddies have been observed to carry shelf-origin zooplankton species into the basin, potentially providing "seed populations" to isolated offshore seamounts [*Mackas and Galbraith*, 2002]. Data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) show that Haida eddies influence phytoplankton distributions both through local processes (resulting from higher nutrient levels within the eddies) and through the entrainment of chlorophyll and iron from the shelf and subsequent transport into the basin [*Crawford et al.*, 2005; *Johnson et al.*, 2005].

[5] Sitka eddies, formed near Sitka, Alaska, were first discussed by *Tabata* [1982]. Without the benefit of satellite altimetry, *Tabata* [1982] was not able to determine propagation pathways or lifetimes, but did suggest that these eddies can persist for longer than 10 months. The advent of satellite altimetry measurements has facilitated greater understanding of eddy pathways and speeds. Sitka eddies generally move away from the shelf with a heading between 240° and 280° and average speeds of 1.3 cm s^{-1} [*Gower*, 1989; *Matthews et al.*, 1992]. However, altimetry suggests that some eddies formed near Sitka move toward the northwest to become imbedded in the Alaskan Stream [*Crawford et al.*, 2000], following a path more like that of the Yakutat eddy (described below). Mechanisms that may be important to the formation of Sitka eddies include the reflection of atmospherically forced planetary waves [*Willmott and Mysak*, 1980], the interaction between the Alaska Current and the underlying topography [*Swaters and Mysak*, 1985], and/or abrupt reversals of the prevailing southerly winds [*Thomson and Gower*, 1998]. Many studies have suggested a link between the interannual variability of Sitka eddies and the El Niño-Southern Oscillation (ENSO). Downwelling coastal Kelvin waves excited by ENSO [*Melsom et al.*, 1999; *Murray et al.*, 2001] as well as atmospheric teleconnections with the tropics [*Melsom et al.*, 2003, 1999; *Okkonen et al.*, 2001] contribute to interannual mesoscale variability in the eastern GOA.

[6] Yakutat eddies have the northernmost formation region of the three GOA eddy types. While *Gower* [1989] and *Gower and Tabata* [1993] suggested a distinct formation region near Yakutat, Alaska (141°–144°W), satellite

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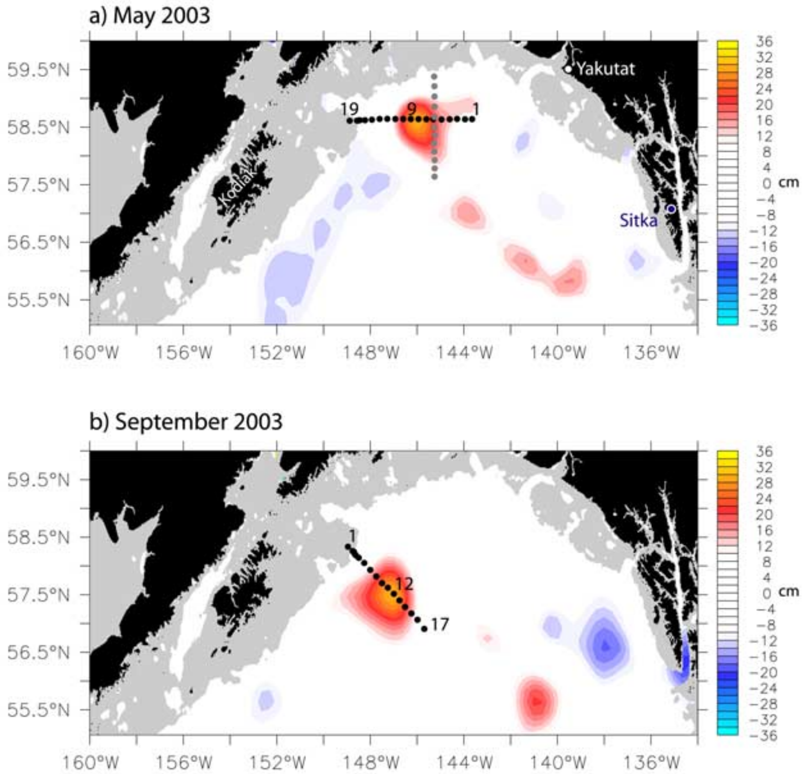

Figure 1. Location of conductivity-temperature-depth (CTD) casts (black and gray dots) overlaid on altimetry data (color) from merged altimetry in (a) May 2003 and (b) September 2003.

altimetry data suggest that in some cases these eddies may form near Sitka and propagate toward Yakutat. Yakutat eddies tend to stay relatively close to the shelf as they propagate westward [*Crawford et al.*, 2000; *Okkonen et al.*, 2001]. In contrast, Haida and Sitka eddies tend to move away from the shelf into the deep basin [*Crawford*, 2002; *Gower and Tabata*, 1993; *Whitney and Robert*, 2002]. Thus Yakutat eddies may influence cross-shelf exchange over a larger portion of their lifecycles than their more southern counterparts. *Okkonen et al.* [2003] reported on hydrographic measurements in spring 1999 that fortuitously sampled the edge of a Yakutat eddy where it impinged on the shelf break. They used TOPEX altimetry and SeaWiFS chlorophyll to put the in situ observations into a larger spatial and temporal context and documented evidence of cross-shelf exchange due to Yakutat eddies near Kodiak Island. We expand on their results by reporting on a directed set of measurements from hydrographic transects crossing a Yakutat eddy in spring and fall of 2003. Using near-real-time satellite altimetry data along with satellite-tracked drifter trajectories (drogued at 40 m), we were able to pinpoint the location of the center of the eddy prior to conducting the transects, providing a well-defined characterization of the hydrographic structure of the eddy and in particular the unique core water.

2. Methods

2.1. In Situ

[7] To document the physical and biological influence of Yakutat eddies on the waters of the GOA, transects bisecting an eddy near Kodiak Island were occupied in May and September 2003 on the *R/V Kilo Moana*. On 12–13 May 2003, a transect was occupied from north to south through the eastern edge of the eddy (Figure 1). During this transect, two satellite-tracked drifters, drogued at 40 m with "holey sock" drogues, were deployed. The hydrography collected on this transect, combined with the drifter trajectories and near-real-time satellite altimetry data from the Colorado Center for Astrodynamics Research (http://www-ccar.colorado.edu/~realtime/welcome) allowed a precise estimate of the location of the center of the eddy. The second transect through the eddy on 14–16 May 2003 consisted of 19 conductivity-temperature-depth (CTD) casts extending ~300 km, from the deep basin (3520 m depth) onto the shelf (117 m depth).

[8] One of the drifters deployed in May was still circling the eddy in September (Figure 2) allowing for an estimate of the position of the eddy center before conducting the September transect. The September 2003 transect (17 CTD casts) extended ~250 km, from the shelf (126 m depth) to deep water (3890 m depth) (Figure 1).

[9] In both May and September, CTD casts were taken with a Seabird SBE-911 Plus system. Salinity calibration samples were taken on all casts and analyzed on a laboratory salinometer. Chlorophyll fluorescence was measured with a Seapoint chlorophyll fluorometer mounted on the CTD cage. Water samples for dissolved inorganic nutrients (NO_3^-, NO_2^-, HPO_4^{-2}, and $Si(OH)_4$) and chlorophyll were collected using 5 L Niskin bottles. Chlorophyll samples were filtered through Osmonics glass fiber filters (nominal pore size 0.7 μm), and stored in the dark at −80°C for

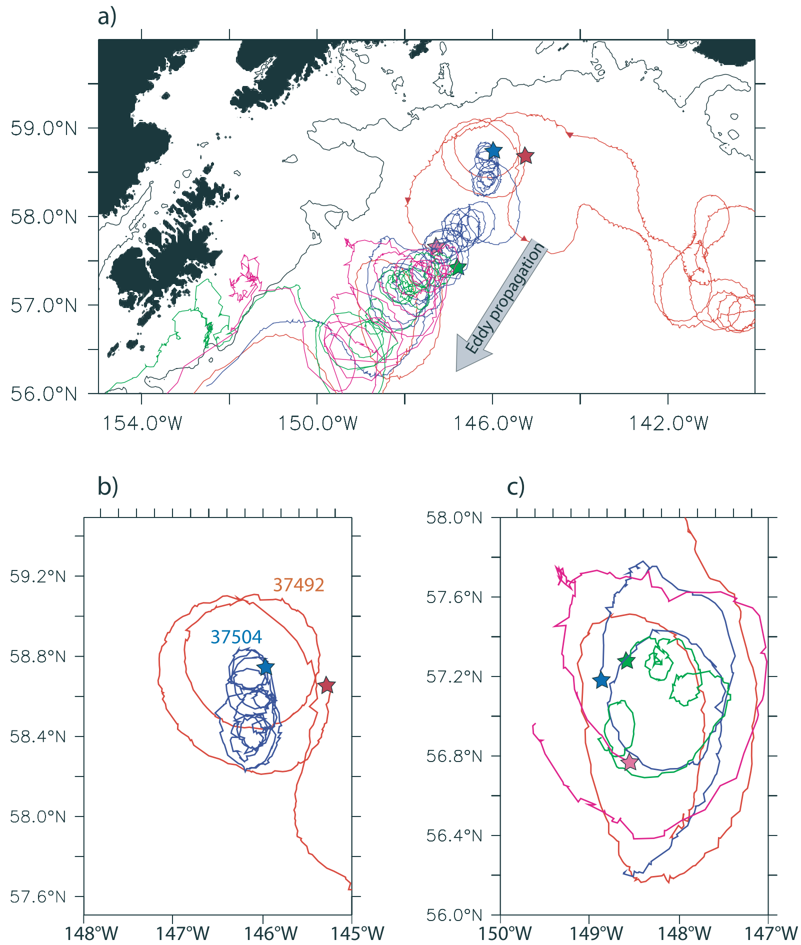

Figure 2. Trajectories from four drifters deployed in the 2003 Yakutat eddy: drifter 37492 (red), 37504 (blue), 37499 (green), and 37516 (purple). Stars indicate the start of the trajectory. (a) Entire trajectory in region. (b) Trajectories from deployment until 30 June 2003. (c) Trajectories during the period 16 November–16 December 2003.

several months before extracting in 90% acetone for 24 hours. Fluorometric determination of chlorophyll concentration (acidification method [*Lorenzen*, 1966]) was made using a Turner Designs TD700 fluorometer calibrated with pure chlorophyll *a*. Nutrient analysis was performed aboard ship using the World Ocean Circulation Experiment (WOCE)/Joint Global Ocean Flux Study (JGOFS) protocol [*Gordon et al.*, 1994].

2.2. Satellite

[10] Gridded sea level anomalies (with respect to a 7 year mean) computed by merging data from the Jason-1 and ENVISAT satellites were downloaded from Aviso (http://www.aviso.oceanobs.com). These data were merged into a single map using optimal interpolation as described by *Le Traon et al.* [1998]. The mapped altimetry data set includes one map every 7 days with a spatial resolution of 1/3° in both latitude and longitude [*Ducet et al.*, 2000; *Le Traon and Dibarboure*, 1999]. Merging data from multiple satellites helps resolve the mesoscale allowing for a better description of eddy activity [*Ducet et al.*, 2000; *Le Traon and Dibarboure*, 2004].

[11] Data from SeaWiFS were used to create images of chlorophyll concentration. Level 1A SeaWiFS files, using the OC4 algorithm [*O'Reilly et al.*, 2000], were distributed by the Distributed Active Archive Center (DAAC) of Goddard Space Flight Center and were processed using SeaDAS (SeaWiFS Data Analysis System), which is maintained and distributed by the Goddard Space Flight Center.

3. Results

[12] The 2003 Yakutat eddy was first observed in the altimetry data in early January 2003 offshore of Yakutat, Alaska. Between its formation and the September 2003 observations, the maximum sea surface height anomaly (SSHA) associated with this eddy was approximately 40 cm and occurred in early February. The location of the center of the eddy, estimated from the maximum SSHA, remained roughly 100 km offshore of the 200 m isobath (approximate location of the shelf break) as it propagated around the head of the GOA at ~1.5 km day^{-1} (similar to the propagation speed computed for the 2000 Yakutat eddy [*Okkonen et al.*, 2003]).

3.1. May 2003

[13] In mid-May 2003, the R/V *Kilo Moana* conducted a survey of the shelf around Kodiak Island and the Kenai

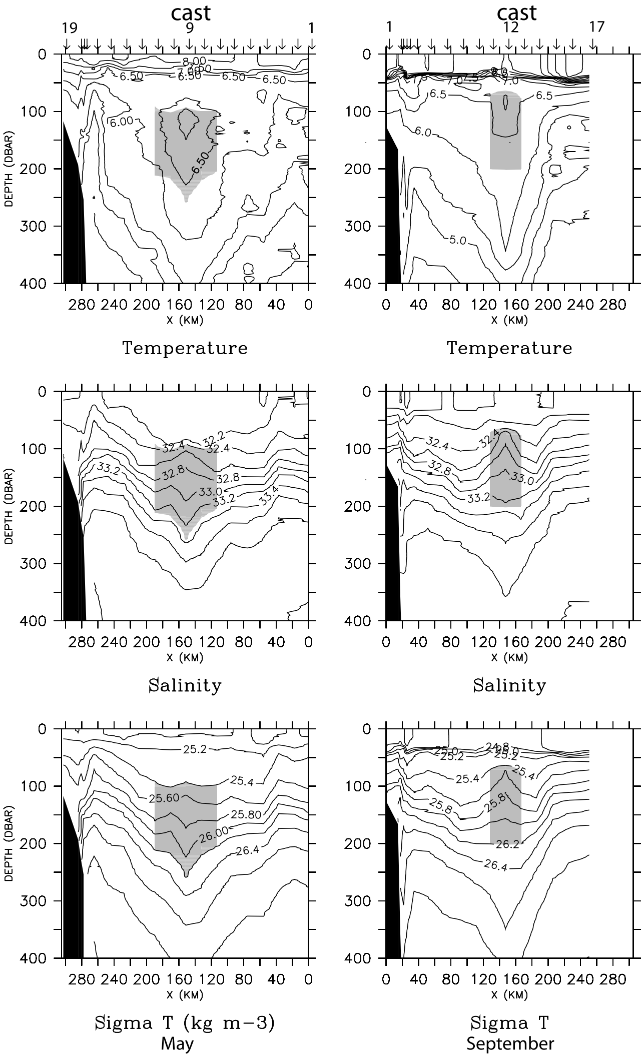

Figure 3. (top) Temperature (°C), (middle) salinity (psu), and (bottom) density (σ_t kg m^{-3}) from the (left) May and (right) September transects across the eddy. The location of CTD casts is denoted by arrows in the top two panels (temperature) and by black dots in Figure 1. Shading denotes the core water defined by 25.4 kg m^{-3} < σ_t < 26.2 kg m^{-3}; 7 < casts < 11 (May), 11 < casts < 13 (September).

Peninsula. On 11 May 2003, the ship moved off-shelf to study the eddy. As noted previously, two satellite-tracked drifters were deployed during the first (north-south) transect through the eddy (Figure 1). The trajectories of these drifters, combined with the results of the first transect, allowed a more precise estimate of the location of the center of the eddy than that obtainable from altimetry. The first drifter deployed (37492) made two full circuits around the eddy at a distance of 40–50 km from the center before exiting the eddy in early June (Figure 2). The first full circuit was traced between 12 May and 24 May and its center was located at 58.66°N, 146.20°W. The north-south transect crossed the eddy approximately 55 km east of this location (Figure 1). Isopycnals were depressed at the center of the transect (with isopycnal displacements observed as deep as 2000 m) illustrating the anticyclonic nature of the eddy (not shown). However, at 55 km from the center, this transect did not sample the core water of the eddy as discussed below.

[14] Between 15 May and 20 May 2003, drifter 37504 made one rotation around the eddy. The center of the rotation was at 58.62°N, 146.15°W, and the distance of the drifter from the center was ~13.8 km. By fitting a circle to this rotation, we smooth out the high-frequency current oscillations and position noise to compute an azimuthal speed (24 cm s^{-1}). Between May and December, this drifter made at least 22 circuits of the eddy with a mean radius of ~19 km and mean azimuthal speed of ~20 cm s^{-1}. The drifter exited the eddy around 20 December 2003 (Figure 2).

[15] The data from the first transect and from the drifter trajectories allowed refinement of the cruise track for the second transect (westward from deeper water across the center of the eddy toward the shelf: Figure 1). We estimate that this transect came within 8 km of the eddy center, with cast 9 sampling nearest the center of the eddy. The dynamic height relative to 1500 m was approximately 26 cm at the center of the eddy, while dynamic height relative to 2400 m was ~30 cm, an increase of more than 15%. For comparison, *Crawford* [2002] estimated that dynamic height differences below 1500 m contributed a 10% increase in the Haida 1998 eddy.

[16] Isopycnals in the center of the transect were depressed from ~150 m (Figure 3) to as deep as 3000 m (the deepest CTD casts taken on the transect). The bottom depth along the transect ranged from 117 m at cast 19 to over 4600 m at cast 9. Just to the west of the large-scale structure of the anticyclonic eddy, a shelf break front, with southward geostrophic velocities, was apparent at ~280 km from the start of the transect (abscissa of Figure 3). Below the seasonal thermocline at ~30 m depth, a low-stratification remnant of the previous winter mixed layer reached to about 100 m throughout most of the transect (Figure 3). For comparison, *Suga et al.* [2004] estimated climatological late winter mixed layer depths between 75 and 100 m in the northern GOA. Water shallower than the depth of winter mixing would not be expected to retain its original water properties over the winter. At the center of the transect, a subsurface temperature maximum was observed directly below the remnant mixed layer. A local temperature maximum of 7.25°C was recorded at 113 m depth at 151.4 km (cast 9) near the center of the eddy. This temperature maximum was approximately 1.5°C warmer than water at the same depth outside the eddy.

[17] Doming of isopycnals (and isohalines since density is primarily determined by salinity at these temperatures) was observed shallower than ~150 m. At this depth, the water in the center of the eddy was approximately the same salinity and density as the water at the same depth outside the eddy. Deeper than 150 m, however, the water at the center of the eddy was fresher and less dense than outside the eddy. For example, at 200 m, the center of the eddy was ~33.0 psu compared with 33.7 psu at the eastern end of the transect (cast 1). The warm, fresh core with doming isopycnals at the top is similar to the observed structure of Haida and Sitka eddies [*Crawford*, 2002; *Tabata*, 1982].

[18] The nitrate distribution in the eddy shows similar features to those exhibited by temperature, salinity and density with domed isopleths shallower than 150 m

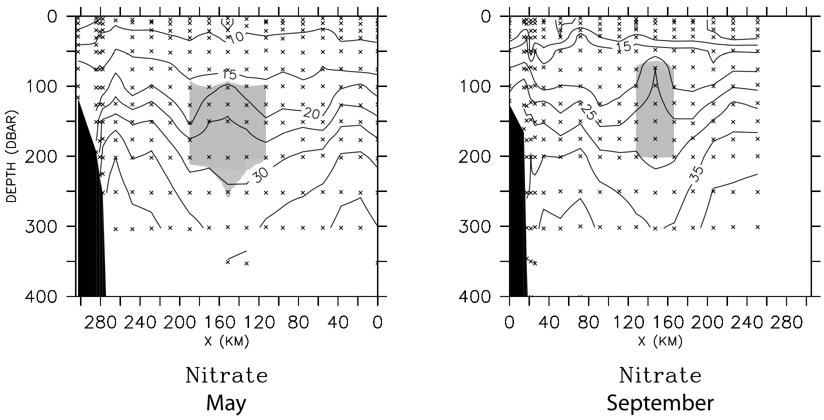

Figure 4. Nitrate concentration (μM) from the (left) May and (right) September transects. Crosses denote measurement locations. Shading is as in Figure 3.

(Figure 4). Core water of the eddy had higher nitrate concentrations by ∼5.9 μM than basin water of the same density (Table 1). At the surface, nitrate concentrations were low over the shelf (<1 μM) and at the center (<4 μM; cast 9) while the remainder of the casts showed surface concentrations >5 μM. The regions of lower nitrate content corresponded to regions of higher chlorophyll (Figure 5).

[19] The temperature/salinity (T/S) relationship illustrates how unique the water at the center of the eddy was in May (Figure 6). In the density range 25.4 kg m^{-3} < σ_t < 26.2 kg m^{-3}, the three casts in the center of the eddy (casts 8–10) were distinct from the water properties of all of the other casts taken on this cruise. (The 267 stations occupied on the cruise included locations on the shelf near Kodiak Island and the Kenai Peninsula and those off-shelf locations shown in Figure 1.) We define the eddy "core water" as this unique water mass (defined by the density range 25.4 kg m^{-3} < σ_t < 26.2 kg m^{-3} in casts 8–10). Table 1 summarizes the water properties of the core water. The thickness of this layer averaged 143 m over the three casts (with a maximum thickness of 167 m at cast 9). The casts were separated by 19 km suggesting that the radius of the unique core water mass was 19 km < r < 38 km. There was no indication of the unique core water on the north-south transect, located ∼55 km from the center.

[20] Assuming the core water in cast 9 is pure coastal water and the cast at the basin end of the section (cast 1) is pure basin water and using the average salinity in the layer as two end members, we estimate the volume of coastal water comprising the core water. Using this method, we estimate that the 25.4 kg m^{-3} < σ_t < 26.2 kg m^{-3} layer is 81% coastal water for cast 8, 44% for cast 7, 31% for cast 6, and 28% for both casts 5 and 4. Farther from the center, the percent was close to zero and noisy. The fraction of coastal water multiplied by the thickness of the layer gives the amount of coastal water observed at each cast. By adding the volume of coastal water included in concentric cylinders defined by the CTD stations, we estimate the volume of coastal water trapped in the eddy core. In May, this volume was ∼1,600 km^3. For comparison, *Whitney and Robert* [2002] calculated that the Haida 1998 eddy contained 5000–6000 km^3 of coastal water when sampled in September 1998. However, their estimate included the entire layer from the surface to 500 m while we included only the density layer with anomalous water properties (maximum thickness = 167 m).

[21] In an attempt to pinpoint the formation region of the 2003 eddy, we searched the archives of the National Oceanographic Data Center (NODC) for data from the shelf region of the eastern GOA. Unfortunately, few data (particularly recent data) from this region were available and they represent only autumn (September–November) and early spring (April–May) months. The early spring data were generally colder (by >1°C) and fresher than the eddy core water at the same density (not shown). However, autumn water properties from the eastern GOA shelf were similar to those of the eddy core water. Temperature/salinity data from three different years (1980, 1983, and 1999) and from three different locations on the shelf show the range of water properties that have been observed in this region in autumn (Figure 7). Of the archived data we examined, observations taken from the shelf south of Yakutat during October–November 1980 exhibited water properties most like those of the 2003 eddy core. Water farther south was warmer than the eddy core water while the water observed farther north was colder. The similarity in water properties near Yakutat is consistent with the hypothesis that the 2003 eddy was formed in the winter near the Yakutat shelf, trapping shelf water inside the eddy and propagating toward Kodiak Island.

[22] This small sampling of data gives little information about the interannual variability or seasonal cycle of water

Table 1. Description of Eddy Core Water

	May 2003	September 2003
Density range (σ_t), kg m^{-3}	25.4–26.2	25.4–26.2
Average salinity,[a] psu	33.0 (+0.3)	33.0 (+0.2)
Average temperature,[a] °C	6.8 (+0.8)	6.6 (+0.7)
Average nitrate,[a] μM	25.9 (+5.9)	26.8 (+5.4)
Depth range at center cast, m	92–259	64–202
Thickness, m	167 (+57)	139 (+73)
Volume of coastal water, km^3	1610	380

[a]Averaged over density range at center cast (cast 9 in May; cast 12 in September). Quantity in parentheses is difference from ambient basin water (averaged over the same density range) as represented by the cast at the basin end of the respective transect.

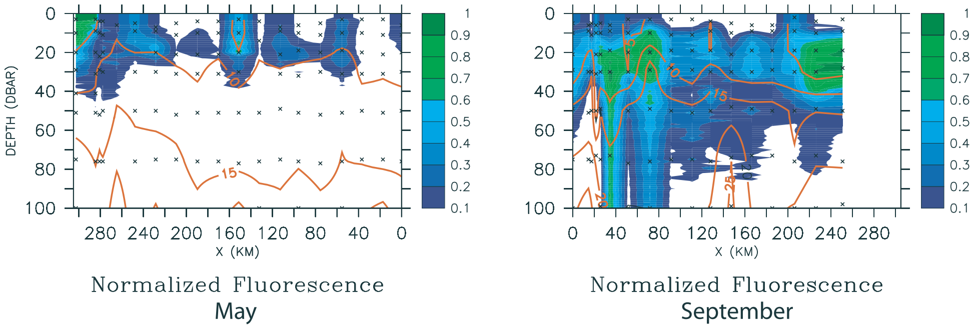

Figure 5. Chlorophyll fluorescence (color) normalized by the highest fluorescence observed in each section. Contours of nitrate concentration (red) are overlaid.

properties in this region. Thus the possibility that the 2003 Yakutat eddy was formed farther south (near Sitka) cannot be dismissed. Note that water properties in the center of the Sitka eddy observed in 1961 [*Tabata*, 1982] were similar to the core water properties of the 2003 eddy. While Sitka eddies have been described as propagating primarily southwestward into the basin [*Crawford*, 2002; *Crawford and Whitney*, 1999], some eddies formed near Sitka have been observed to propagate northwestward along the shelf break, eventually interacting with the Alaskan Stream [*Crawford et al.*, 2000]. However, as mentioned above, the Yakutat formation region is supported by altimetry data, which suggests that the eddy was first observed off the shelf near Yakutat in January 2003.

[23] After leaving the shelf, the water within the eddy was modified during its journey toward Kodiak Island. The shallow layer (surface to ~100 m) was cooled and mixed during the winter, which explains the remnant mixed layer observed in May (Figure 3). The core water below 100 m probably was not substantially modified between eddy formation (and exiting the shelf) in late autumn/early winter and our observations in May near Kodiak Island.

[24] Excluding data from cast 9, a significant linear relationship (r^2 = 0.95) was observed between nitrate and salinity at depths shallower than 400m (Figure 8). In the core water, nitrate was significantly higher than would be expected from the nitrate/salinity relationship. In the salinity range 32.4 psu < salinity < 33.0 psu, almost all of the points that fall above the one standard deviation envelope are from casts 8–10. In May, nitrate at the surface of cast 9 was drawn down, probably due to the bloom observed both in SeaWiFS data at the center of the eddy in late April (Figure 9) and in chlorophyll fluorescence data collected in May (Figure 5).

[25] Nitrate data from the eastern GOA (WOCE P17N; casts 147–148; ~56.8°N, 136°W) taken in June 1993 [*Tsuchiya and Talley*, 1996] also show a surplus of nitrate (~5 μM) in the same salinity range as the eddy core water (Figure 8) consistent with the hypothesized formation region discussed above.

3.2. September 2003

[26] In September 2003, the R/V *Kilo Moana* once again had an opportunity to sample the same eddy. By mid-September, the center of the eddy had moved ~136 km toward the southwest from the time when it was sampled in mid-May, a propagation speed of 1 km day^{-1}. The September transect began on the shelf northeast of Kodiak Island and proceeded southeast, crossing the center of the eddy (cast 12) at approximately 57.52°N, 147.01°W on 26 September 2003 (Figure 1b). Drifter 37504 was still in the eddy in September and from 23 September to 1 October, was tracing a circle centered at 57.52°N, 147.04°W (<2 km from cast 12). The azimuthal speed calculated from the drifter trajectory (22.3 km from the center) was 19.3 cm s^{-1}.

[27] The density section across the eddy in September exhibited a 35-m-deep mixed layer (approximately the same mixed layer depth observed in May) (Figure 3). However, the seasonal pycnocline at the base of the mixed layer was stronger than that observed in May reflecting the input of heat at the surface over the summer. Apparently, a storm the day prior to the eddy transect did not result in mixing deeper than ~35 m.

[28] In September, in the depth range 50 m < depth < 300 m, water at the center of the eddy was denser (at the same depth) than in May. The base of the core water (σ_t = 26.2 kg m^{-3}) shoaled almost 60 m (from 259 m to 202 m) between May and September. Outside the eddy, this density surface appeared at ~150 m in May and 130 m in

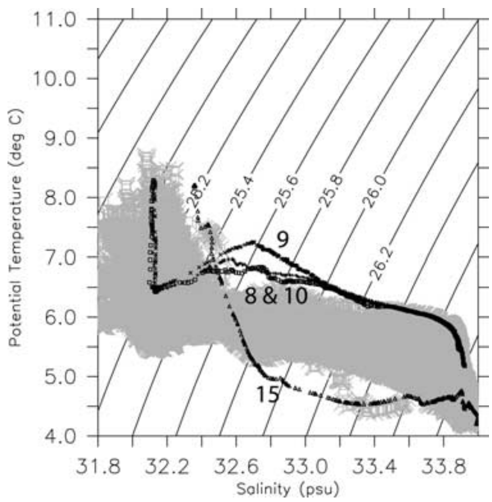

Figure 6. Temperature/salinity relationship from surface to 400 m from all 267 CTD stations taken during the May 2003 Kilo Moana cruise. Bold curves are from the three casts near the center of the eddy and cast 15 at the shelf break.

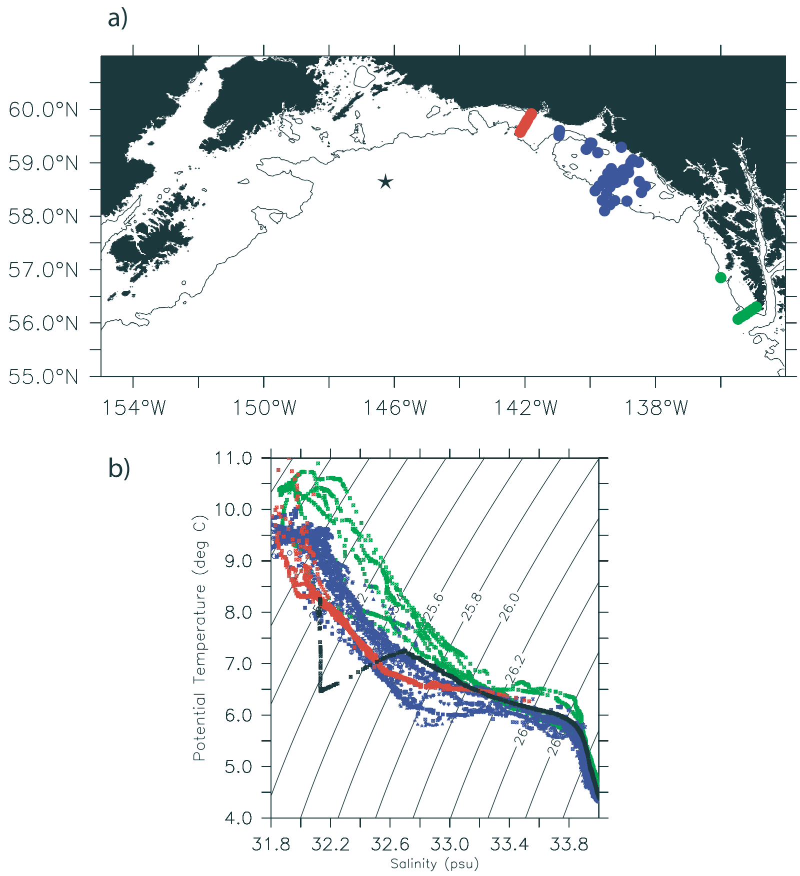

Figure 7. (a) Map showing color-coded locations of data. (b) Temperature/salinity relationship from September to October 1999 (green), October to November 1980 (blue), and September 1983 (red) overlaid with the *T*/*S* relationship from the cast at the center of the eddy in May 2003 (black).

September. The depth of deeper isopycnal surfaces (i.e., σ_t = 27.2 kg m^{-3}) did not change much between May and September and the SSHA from the altimetry data was still greater than 25 cm in September. Altimetry data show that this eddy continued to exist at similar SSHA magnitude until at least December 2004 (when this manuscript was completed), a lifetime of at least 24 months.

[29] The subsurface temperature maximum that defined the shallow core water in May had shoaled to about 85 m by September. In addition, the temperature anomaly was not as strong in September as in May. The temperature at 85 m in the center of the eddy (7.1°C) was only 1.2°C warmer than at the seaward end of the section (recall that the difference was 1.5°C in May). In addition, the average temperature of the core water decreased from 6.8°C in May to 6.6°C in September (Table 1).

[30] Nitrate concentrations in the eddy core water increased slightly from May to September (Table 1; Figure 4). Spreading of nitrate isopleths was again observed in September corresponding to the core water. Shoaling of the core water from May to September was reflected in shoaling of the nitrate dome. For example, nitrate increased from 13.7 μM at 78 m (cast 9) in May to 24.9 μM at 75 m (cast 12) in September. In addition, nitrate was drawn down in the surface water on the basin side of the transect and not over the shelf as was seen in May. While chlorophyll maxima (colocated with nitrate minima) were observed at

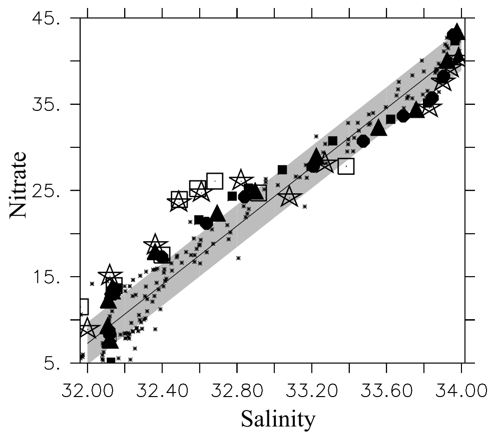

Figure 8. Salinity versus nitrate from the May 2003 transect across the eddy and from World Ocean Circulation Experiment (WOCE) P17N casts 147–148. The black line represents a least squares fit, and the shading shows the one standard deviation envelope around the fitted line. Solid triangles, squares, and circles show data from casts 8, 9, and 10, respectively. Open stars and squares show data from P17N, cast 147 and 148, respectively.

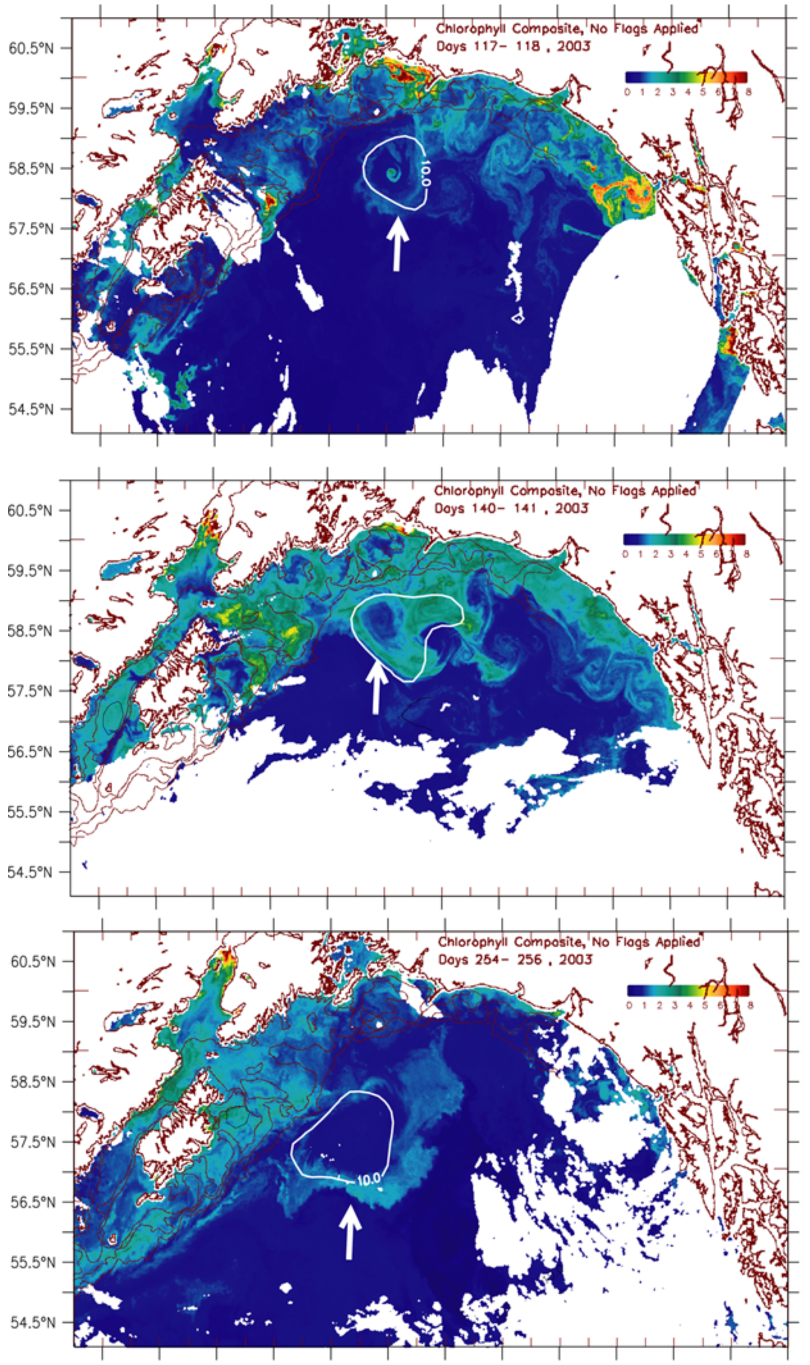

Figure 9. Composites of chlorophyll concentrations observed by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite averaged over (top) 27–28 April 2003, (middle) 20–21 May 2003, and (bottom) 11–13 September 2003. The white contour shows 10 cm altimeter sea surface height anomaly near the date of the SeaWIFS image. The white arrow shows the location of the eddy.

the surface in May, maxima in chlorophyll were observed at the eddy edges at >20 m depth in September (Figure 5). Subsurface chlorophyll maxima are not uncommon around eddies [e.g., *Whitney and Robert*, 2002]. In order to illustrate the spatial patterns in both May and September, fluorescence values in Figure 5 were normalized by dividing the voltages obtained from the Seapoint fluorometer by the maximum voltage obtained during the transect. The maximum chlorophyll *a* values measured from water samples on these transects were 6.5 μg L^{-1} in May and 1.4 μg L^{-1} in September.

[31] The temperature/salinity plot from the September transect (Figure 10) shows that the water properties of the core water at the center of the eddy were still distinct from the surrounding water. However, the distinct core water signature was only seen at the centermost cast (cast 12) suggesting a smaller core water radius (<19 km). Recall that in May, the center *three* casts were distinct from the

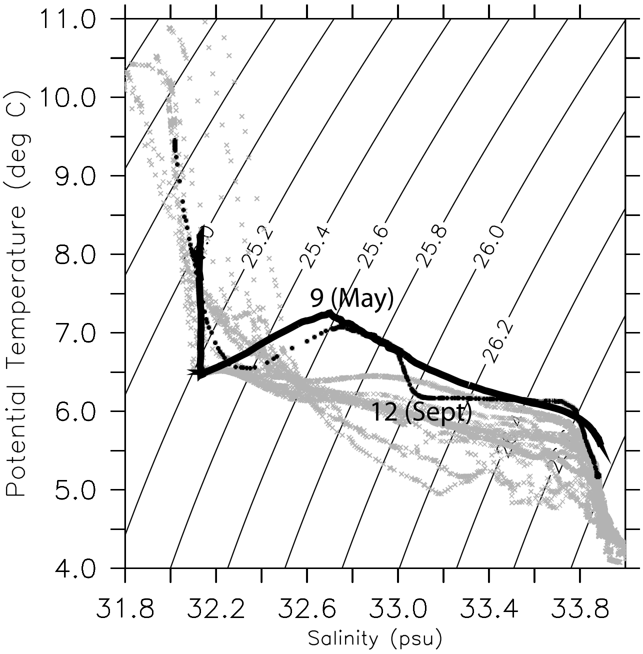

Figure 10. Temperature/salinity relationship from surface to 400 m from the September 2003 eddy transect. Bold symbols are from the cast at the center of the eddy. The solid line is from the May 2003 cast at the center of the eddy.

surrounding water. In September, the average thickness of the core water layer (25.4 kg m^{-3} < σ_t < 26.2 kg m^{-3}) was ~139 m (~83% of the May layer thickness). The water properties at σ_t ~ 26.0 kg m^{-3} changed the most from May to September, becoming more similar to the surrounding water. In fact, the layer thickness of the core water in the density range 25.95 kg m^{-3} < σ_t < 26.05 kg m^{-3} more than doubled from May to September while the layer thickness of the remainder of the core water layer decreased. This suggests an input of noncore water in the 25.95 kg m^{-3} < σ_t < 26.05 kg m^{-3} density range, diluting the unique core water properties. The mechanisms responsible for the preferential exchange of water at this density range are unclear. A density front, including the σ_t = 26.0 kg m^{-3} isopycnal surface, was impinging on the bottom topography near the shelf break (Figure 3). *Barth et al.* [1998] and *Houghton and Visbeck* [1998] present evidence for upwelling from the bottom boundary layer into the interior along a shelf break front. Thus interaction with the bottom may have been responsible for enhancing exchange in this density range.

[32] Assuming as before that the water observed on the center cast in May in the density range 25.4 kg m^{-3} < σ_t < 26.2 kg m^{-3} was pure coastal water, we estimate how much coastal water remained in the eddy in September. The average salinity in the core density range at cast 12 (center of the eddy) in September was 32.97 psu (compared to 32.95 psu at cast 9 in May). Thus we assume that the center cast (12) remained 100% coastal water. Using the same methodology described for the May data, we estimate that the eddy retained ~380 km^3 of coastal water in September, 24% of the volume calculated for May (Table 1). The difference was primarily due to a much smaller radius over which unique salinities were observed. In May, at a radius of ~100 km from the center, the core water density range contained 28% coastal water; while in September, at a radius of 40 km, the proportion of coastal water had dropped to only 4%.

4. Discussion

[33] Temperature/salinity and nitrate/salinity relationships from data collected within a Yakutat eddy in spring and autumn 2003, suggest that the core water of the eddy was distinct from the surrounding water. Water properties were consistent with the hypothesis that the eddy formed on the eastern GOA shelf near Yakutat, Alaska, isolating the shelf-derived core water from mixing with the surrounding water as the eddy propagated westward along the shelf break.

[34] The basin water in the GOA has been characterized as a high-nutrient, low-chlorophyll environment where production is limited by a lack of iron [*Boyd et al.*, 1995, 2004; *Martin et al.*, 1989]. Phytoplankton have been found to be iron stressed in the basin interior but not in the coastal water or the transitional water between the basin and the shelf [*La Roche et al.*, 1996]. Thus by transporting shelf water into the basin, Yakutat eddies may provide a source of iron to the iron-depleted water of the basin. A supply of iron from the core water may explain the high chlorophyll sometimes observed by SeaWiFS at the center of GOA eddies. A small eddy center bloom observed in SeaWiFS data in late April likely resulted in the nitrate drawdown observed in the surface water in the center of the eddy in May.

[35] *Whitney and Robert* [2002] showed that Haida eddies contain anomalous temperature and nitrate signals to a salinity of 33.9 psu while the Yakutat eddy contains anomalous water properties to a salinity of only 33.2 psu. Haida eddies form from the flow out of Hecate Strait where depths in the outflow region can be greater than 400 m deep. Salinities less than 33.2 psu occur shallower than ~200 m on the eastern GOA shelf suggesting that Yakutat eddies must form in shallower shelf regions. Thus differences in core water properties and volume may be due to the depth where the eddies were formed. This suggests that Yakutat eddies transport less shelf water offshore in their core than Haida eddies. However, Yakutat eddies may be more important in contributing to cross-shelf exchange of nutrients, iron, and biomass along their edges because they follow the slope.

[36] Interactions with the shelf break circulation can contribute to cross-shelf exchange. The 2003 Yakutat eddy remained within ~100 km of the shelf break from its formation in January 2003 until at least December 2004. *Ladd et al.* [2005] showed evidence from a shipboard ADCP that the eddy was interacting with the Alaskan Stream resulting in onshore flow southwest of the eddy and offshore flow northeast of the eddy. *Okkonen et al.* [2003] also noted the role of eddies in the exchange of water between the shelf and the basin in this region. SeaWiFS data often shows ribbons of chlorophyll apparently being transported off-shelf and wrapping around the edge of eddies (Figure 9). The coastal biomass may be transported on the order of 200 km off-shelf (the diameter of these eddies). However, it is unclear how much of the signal observed by

SeaWiFS (Figure 9) is due to transport versus local processes. Haida eddies have also been observed to pull ribbons of high chlorophyll off the shelf [*Crawford et al.*, 2005]. Because Yakutat eddies typically stay close to the shelf break during their entire life cycles, they are more likely to influence cross-shelf exchange in this way than Haida or Sitka eddies.

[37] In addition to the influence of cross-shelf exchange on nutrient dynamics, eddies can also influence nutrient concentrations through vertical processes within the eddy. *Martin and Richards* [2001] showed that ageostrophic upwelling due to perturbations to the circular flow of an eddy, coupled with wind-induced Ekman pumping can produce significant fluxes of deep nutrients to the surface waters of an anticyclonic eddy. However, in the presence of a large-scale horizontal gradient in the nutrient field (such as the shelf/basin gradient in the Gulf of Alaska), it has been shown that horizontal transport by eddies likely dominates over vertical processes [*Lévy*, 2003].

[38] From SeaWiFS imagery, it is obvious that GOA eddies influence phytoplankton distributions. This influence on the base of the food chain should effect distributions at higher trophic levels. Haida and Sitka eddies have been found to transport shelf- and slope-origin species to offshore regions [*Mackas and Galbraith*, 2002]. Anecdotal evidence from our cruises suggests that the 2003 Yakutat eddy may also influence species distributions. During the May cruise, numerous jellyfish up to ~0.5 m in diameter were observed at the eastern edge of the eddy while none were noticed near the eddy center. *Graham et al.* [2001] note that accumulations of jellyfish within frontal features is probably the most commonly reported type of jellyfish patchiness in the ocean. The mechanisms responsible for concentrating jellyfish at fronts are unclear, but may include convergences or behavioral responses to current shear or physical gradients [*Graham et al.*, 2001]. In September, zooplankton were sampled at four sites along the eddy transect using MARMAP bongo tows: one site at the shelf edge, one over the slope, and two near the center of the eddy. A dramatic visual difference in the quantity and type of zooplankton was observed at the center of the eddy compared with the other sites. However, these data have not yet been processed and details are reserved for future work.

[39] *Okkonen et al.* [2003] showed that between 1993 and 2001, anticyclonic eddies were present in the spring over the continental slope near 148°W every year except 1998. Thus they probably influence this region each year. Interannual variability in their formation region, water properties, amplitude, etc. may have important implications for the ecosystems around Kodiak Island.

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N. B. Kachel, C. Ladd, and C. W. Mordy, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, 7600 Sand Point Way NE, Seattle, WA 98115, USA. (nkachel@ocean.washington.edu; carol.ladd@noaa.gov; mordy@pmel.noaa.gov)

P. J. Stabeno, Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115, USA. (stabeno@pmel.noaa.gov)