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A synoptic survey of young mesoscale eddies in the Eastern Gulf of Alaska

Carol Ladd [a,*], William R. Crawford [b], Colleen E. Harpold [c], W. Keith Johnson [b], Nancy B. Kachel [d], Phyllis J. Stabeno [a], Frank Whitney [b]

[a] Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way, Seattle, WA 98115-6349, USA
[b] Institute of Ocean Sciences, Fisheries and Oceans Canada, P.O. Box 6000, Sidney, BC, Canada V8L 4B2
[c] Alaska Fisheries Science Center, NOAA, 7600 Sand Point Way, Seattle, WA 98115-6349, USA
[d] Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Box 357941, Seattle, WA 98195, USA

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ABSTRACT

Eddies in the Gulf of Alaska are important sources of coastal water and associated nutrients, iron, and biota to the high-nutrient, low-chlorophyll central Gulf of Alaska. Three primary eddy formation regions along the eastern boundary of the gulf have been identified, (from south to north, Haida, Sitka, and Yakutat). In the spring of 2005, three eddies (one of each type) were sampled soon after their formation. The subsurface eddy core water in all three eddies was defined by high iron concentrations and low dissolved oxygen compared with surrounding basin water. The Sitka and Yakutat core waters also exhibited a subsurface temperature maximum (mesothermal water) coincident in depth with the iron maximum, suggesting that eddies may play a role in the formation of temperature inversions observed throughout the Gulf of Alaska. The data suggest different formation regions, with the Yakutat eddy forming in shallow shelf water with riverine input, while the Sitka and Haida eddies appear to form in deeper water.

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1. Introduction

The circulation in the Gulf of Alaska (GOA), located in the northeast corner of the subarctic North Pacific, is dominated by the cyclonic Alaska Gyre. The gyre is bounded on the south by the eastward North Pacific Current, which bifurcates near the coast of North America to feed the southward flowing California Current and the northward flowing Alaska Current. The broad, variable Alaska Current forms the eastern boundary current of the Alaska Gyre. The western boundary current, the Alaskan Stream, flows southwestward along the continental slope (Fig. 1).

The eastern boundary of the GOA spawns numerous, anti-cyclonic eddies that can persist for years. These eddies influence physical and chemical water properties and biota in the GOA. Three groups of eddies (Haida, Sitka, and Yakutat eddies) are primarily distinguished by their formation regions (Gower, 1989; Gower and Tabata, 1993; Okkonen et al., 2001). These three eddy groups share many common features, including anticyclonic rotation, ~200 km diameter, formation along the eastern and northern boundary of the GOA, and westward translation.

Haida eddies usually form at Cape St. James, the southern tip of the Queen Charlotte Islands, British Columbia (Crawford et al., 2002; Di Lorenzo et al., 2005). Formation of these eddies is associated with the advection of warmer, fresher watermasses from the outflow of Hecate Strait. These buoyant watermasses generate small anticyclonic eddies west of Cape St. James. When the flow is strong, typically in the winter, several of these small eddies can merge to form a larger Haida eddy. The center of the Haida eddy generally includes mixed-layer water from Hecate Strait, Queen Charlotte Sound, and the continental shelf off northern Vancouver Island (Di Lorenzo et al., 2005). For example, Crawford (2002) noted that the temperature of Haida eddies in summer at 150 m depth matched surface temperatures at Cape St. James in the preceding winter.

Sitka eddies were first described by Tabata (1982) and form near Baranof Island, Alaska at approximately 57°N, 138°W. Model studies suggest that Sitka eddies are formed via baroclinic instabilities in the northward flowing currents along the continental slope, forced by Kelvin waves and southerly winter winds (Melsom et al., 1999; Murray et al., 2001). The formation location appears to be due to interactions with the local topography (Swaters and Mysak, 1985).

Gower (1989) identified a third GOA eddy formation region near Yakutat, Alaska. The shelf in this region is much wider (~100 km) than those near the Sitka and Haida eddy formation regions. Yakutat eddies generally stay close to the shelf-break as they move westward around the boundary of the GOA (Ladd et al., 2005a). They have been observed to carry excess heat, salinity, and nutrients in their subsurface core waters that can be distinguished from the surrounding basin water at least a year after formation (Ladd et al., 2007).

* Corresponding author. Tel.: +1 206 526 6024; fax: +1 206 526 6485.
E-mail address: carol.ladd@noaa.gov (C. Ladd).

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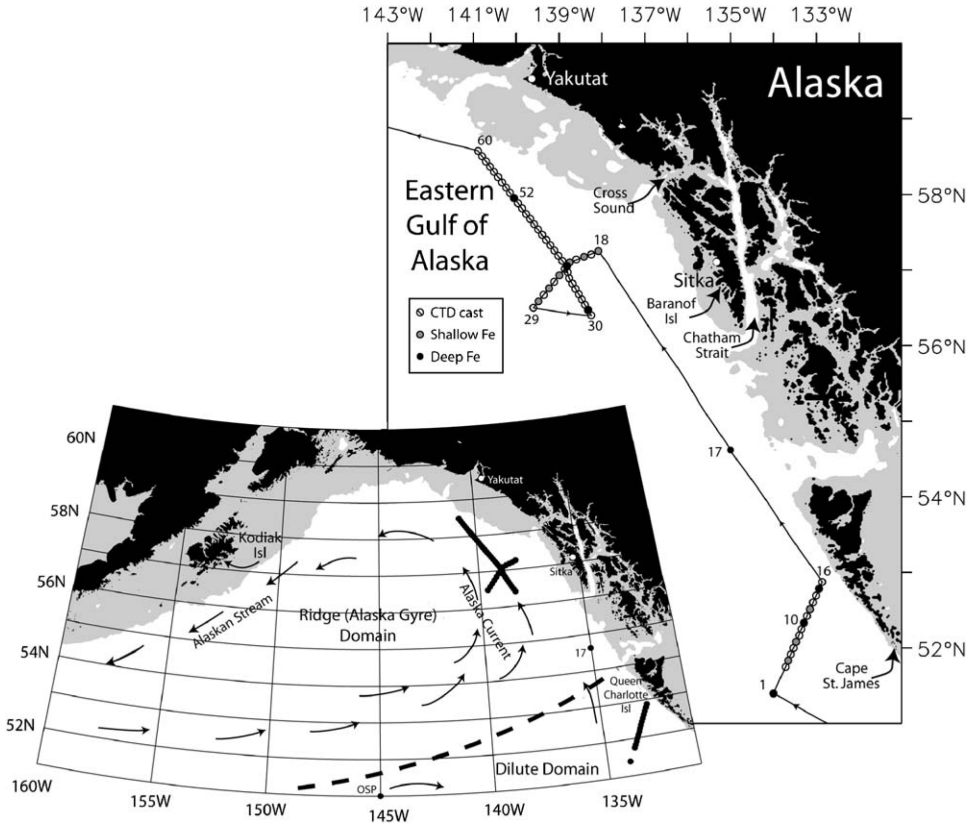

Fig. 1. Schematic of Alaska Gyre circulation. Black dots show locations of CTD stations. Dashed line shows approximate boundary of dilute domain. Shelf region (depth < 200 m) shown with gray shading. Inset shows location of stations and ship track in the eastern GOA. CTD casts were taken at each station. Select cast numbers are noted. Black filled circles show locations of deep Fe casts. Gray filled circles show locations of shallow Fe casts.

Based on water properties, Favorite et al. (1976) described the Dilute and the Ridge Domains in the GOA. The Dilute Domain is indicated by salinity <33.0 at 100 m and extends seaward from the coast of North America to roughly 160°W (Fig. 1). The Ridge Domain, north of the Dilute Domain, is defined as the region of bowed-up isopycnals associated with the center of the Alaskan Gyre. Haida eddies form and stay in the Dilute Domain, while Sitka and Yakutat eddies form in the broad Alaska Current, often translating into the Ridge Domain.

Westward propagation of mesoscale eddies in deep-sea waters is attributed to planetary beta effects, whereby the change in magnitude of Coriolis force with latitude pushes eddies westward at all latitudes. Haida and Sitka eddies form where the continental margin is oriented mainly NNW to SSE and propagate into deep-sea waters within months of formation. Yakutat eddies form closer to the east–west oriented margin, and stray little from this margin during their westward propagation.

Temperature inversions, with a temperature minimum above a deeper temperature maximum, occur throughout the subarctic North Pacific Ocean (Roden, 1964; Uda, 1963). The temperature maximum and minimum have been called the mesothermal and dichothermal waters, respectively (Uda, 1963). The warm and saline mesothermal water is related to the circulation and ventilation of North Pacific Intermediate Water (Ueno and Yasuda, 2001, 2003). However, formation processes contributing to temperature inversions in the North Pacific have been found to vary regionally. Seasonal cooling of the dichothermal layer as well as advection of heat and salinity into the mesothermal layer have both been found to be of importance in maintaining the temperature inversion structure (Musgrave et al., 1992; Ueno et al., 2007; Ueno and Yasuda, 2000, 2005). By transporting excess heat and salinity into the basin (Ladd et al., 2007), Yakutat eddies may be important in the maintenance of mesothermal waters in the GOA (Onishi et al., 2000; Ueno and Yasuda, 2005).

The central GOA is described as high-nitrate low-chlorophyll and the role of iron in controlling primary productivity has been widely accepted (Boyd et al., 2004, 1998; Martin et al., 1989; Martin and Gordon, 1988). Eddies have been suggested as one mechanism that may enhance cross-shelf exchange (Crawford and Whitney, 1999; Ladd et al., 2005b; Okkonen et al., 2003; Stabeno et al., 2004) influencing nutrient limitation in the GOA. Haida eddies carry shelf-derived nutrients (Whitney and Robert, 2002) and biota (Mackas and Galbraith, 2002) westward into the basin. In the Haida eddy region, observations show low nitrate versus salinity at a coastal upwelling station, high nitrate versus salinity in basin water (Ocean Station P, OSP; 50°N, 145°W), with eddy waters in between (Peterson et al., 2005). In the first study of iron transport via GOA eddies, Johnson et al. (2005) showed that young Haida eddies contain dissolved iron concentrations almost two orders of magnitude higher than is typically observed at OSP. In addition, 16 months after its formation, one Haida eddy still contained 1.5–2 times more iron than surrounding water.

This paper reports on the first multidisciplinary set of observations of all three eddy types (Haida, Sitka, and Yakutat) in a single year soon after their formation. Due to ongoing observations along Line P, Haida eddies have been well sampled (e.g. Crawford, 2002; Crawford et al., 2002; Mackas and Galbraith, 2002; Whitney and Robert, 2002). However, only a few directed eddy studies have been accomplished in the two northern eddy types (Ladd et al., 2005a, 2007) and they were accomplished in older eddies (offshore of Kodiak Island in the western GOA). In addition, while one study has examined iron concentrations in Haida eddies (Johnson et al., 2005), the two northern eddy types have not previously been sampled for iron.

2. Methods

The bulk of the data to be discussed here is from a research cruise (Fig. 1) on the R/V *Thomas G. Thompson* in the spring of 2005 (April 26–May 8). This cruise was a multidisciplinary, international investigation of the influence of eddies in the eastern Gulf of Alaska. Three eddies were sampled (from south to north, Haida, Sitka, and Yakutat eddies) for temperature and salinity, macronutrients, iron, chlorophyll and zooplankton (as well as other data not discussed here). The emphasis of this paper will be on data from the Haida transect (casts 1–16) and the long northward transect across the Sitka and Yakutat eddies (casts 30–60). The east–west transect across the Sitka eddy (casts 18–29) was primarily to deploy two drifters to more accurately estimate the location of the center before intensive sampling. During this east–west transect, 12 CTD (conductivity, temperature, and depth) casts were made to only 600 m. These data will not be discussed further.

Additional data used to help characterize Alaska Gyre waters and evolution of eddies were collected onboard the R/V *John P. Tully* in June 2005. Procedures were similar to those used on the *Thompson* survey.

2.1. CTD data

A SeaBird 911 plus CTD was equipped with dual temperature and conductivity sensors, a fluorometer, an SBE43 dissolved oxygen sensor, and a transmissometer. On each cast, salinity, chlorophyll and nutrient samples were taken from 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 several months before extracting in 90% acetone for 24 h. Fluorometric determination of chlorophyll concentration (acidification method (Lorenzen, 1966)) was made using a Turner Designs TD700 fluorometer calibrated with pure chlorophyll-*a*. Nutrient samples were analyzed aboard ship (see Section 2.2). Salinity samples were taken on every cast to calibrate the CTD salinity measurements.

2.2. Nutrient and oxygen sampling

Water samples for dissolved inorganic nutrients (NO_3 plus NO_2, PO_4, and SiO_4) were drawn from CTD rosette casts, GO-FLO casts, and the underway, uncontaminated seawater supply into acid-cleaned polycarbonate test tubes and stored up to 12 h before being analyzed. All samples were analyzed onboard ship using a Technicon AutoAnalyzer II following procedures in Barwell-Clarke and Whitney (1996). Since NO_2 is a trivial portion of the NO_3 plus NO_2 analysis, these data will be subsequently referred to as NO_3 or nitrate.

Nutrient samples were collected from the surface bottle of every CTD cast and from the following sampling depths of approximately every other CTD cast: 0, 10, 20, 30, 40, 50, 60, 75, 100, 120, 150, 200, 250, 300, 400, 600, 800, 1000, 1250, 1500, 1750, and 2000 m for a total of 680 samples. Nutrients were also sampled from 16 Go-Flo casts (see Section 2.3).

On the cruise in June 2005, oxygen samples were analyzed on an automated Winkler titration system following the procedures of Carpenter (1965). A Brinkmann model 665 Dosimat and model PC910 Colorimeter is controlled by a Visual-Basic program to titrate the oxygen samples.

2.3. Iron data

Iron is ubiquitous as a contaminant during sampling and analytical procedures, making accurate measurement extremely difficult. Thus, great care must be taken in all phases of shipboard sampling, handling, and analysis. A detailed description of sampling and analysis methodology is included in Johnson et al. (2005) and will not be repeated here.

Sampling was initiated on 28 April at a "reference" station (station 1; Fig. 1) in an area with low surface chlorophyll concentrations according to concurrent satellite ocean-color data. Surface sampling was conducted away from the *Thompson* from the ship's Zodiac/Hurricane rigid hull inflatable using wide mouth bottles (1 l and 500 ml).

The shallower depths of 10, 20, 30, and 40 m were sampled using an air-driven, double bellows, all plastic/Teflon Asti pump and Teflon lined PVC half-inch ID tubing. These samples were filtered in the on-deck HEPA hood in the staging bay. For greater depths (50, 75, 100, 150, 200, 300, 400, 600, and 800 m), 12 l General Oceanic (GO) GO-FLOs or X-Niskins were used and subsampled in the wet lab using bell jar dust covers and 0.22 μm Opticap cartridge filters. As noted above, nutrient samples were also collected from the Go-Flo sample bottles. All samples were processed inside a plastic clean tent constructed in the ship's main lab. A class 100 HEPA filter maintained a clean environment and positive pressure inside the tent for processing and handling reagents, standards, and samples. Of the four sub-samples collected for iron, one filtered (dissolved) and one unfiltered (labile) were analyzed onboard by FIA chemiluminescence in the clean tent. The other two were acidified to pH 1.7 with 1 ml of 6 N HCL per 125 ml seawater for later analysis of total dissolved iron and total iron. In this paper, we only discuss the labile and total iron concentrations.

Profile data (to 800 m) for iron and nutrients were collected for the reference station (cast 1), Haida eddy center (cast 10), Haida edge (cast 15), a reference station outside Dixon Entrance (cast 17), Sitka eddy edge (cast 31), Sitka center (cast 39), and Yakutat eddy center (cast 52) (Fig. 1, filled circles). All profiles were sampled identically except for the Yakutat eddy center station, which did not have a surface iron sample. In addition to the 800 m profiles, shallower samples were collected as follows. For the Haida eddy, samples were collected from 10 and 40 m for three stations. For the Sitka eddy, samples from 10 and 100 m were collected at six stations on the east–west line (Fig. 1, gray filled circles).

2.4. Zooplankton data

Zooplankton samples were collected using paired bongo frames (60 and 20 cm diameter) with 333- and 153-μm mesh nets, respectively. Nets were equipped with calibrated flowmeters, a real-time depth sensor and were towed obliquely to about 10 m off bottom or 300 m whichever was shallower (Incze et al., 1997). Samples were preserved in 5% buffered formalin, and were identified and sorted by the Polish Plankton Sorting and Identification Center (ZSIOP) in Sczcecin, Poland.

The software package Primer was used to perform the statistical analyses. The taxa rarely encountered in the samples (occurring at <8% of stations) were eliminated from the first round of analyses, except for barnacle larvae which were included because of their potential to identify water of nearshore origin. During a subsequent statistical analysis, adult copepods from under-represented families that potentially had warm-temperate origins were included.

2.5. Drifter data

Satellite-tracked drifter data were used to increase the precision of eddy center location estimates in order to direct the *in situ* sampling, to estimate the location of the *in situ* sampling relative to the eddy center, and to provide information regarding flow patterns, speeds, and residence times in and around the eddies. A total of eight satellite-tracked drifters (Table 1), drogued at 40 m with "holey sock" drogues, were deployed in the three eddies. One drifter (53319) was deployed in the Haida eddy in early March. Two other drifters (53309 and 53312) were deployed approximately one week prior to the *Thompson* cruise. These three initial drifters helped locate the center of the Haida eddy without the need for a preliminary transect. An additional drifter (53310) was deployed at the estimated center location from the *Thompson*. Two drifters each were deployed in the Sitka (53321 and 53308) and Haida (53304 and 53306) eddies resulting in a total of five drifters deployed from the R/V *Thomas G. Thompson* (Table 1). Center locations were calculated using data from one full circuit around the eddy bracketing the time period of interest. The location of the center of the circuit was calculated as an average of latitude and longitude over the full circuit.

2.6. Satellite data

Gridded sea surface height anomalies (SSHA) were downloaded from Aviso. The "ref merged" dataset (obtained from http://www.jason.oceanobs.com) consists of delayed mode, merged data from two satellite missions, Jason-1 and Envisat. This dataset has stable sampling in time (SSALTO/DUACS, 2006). The optimal interpolation methodology used by Aviso to merge data from multiple altimeters is described by Le Traon et al. (1998). The mapped altimetry dataset includes one map every 7 days with a 1/3° spatial resolution on a Mercator grid (Ducet et al., 2000; Le Traon and Dibarboure, 1999). Merging data from multiple satellites with differing spatial and temporal resolution helps resolve mesoscale features allowing for a better description of eddy activity (Ducet et al., 2000; Le Traon and Dibarboure, 2004).

Science-quality chlorophyll-*a* concentration data at the ocean surface from MODIS on the Aqua satellite (downloaded from http://coastwatch.pfeg.noaa.gov) are used to show the spatial context within which our *in situ* observations were made. NASA's Goddard Space Flight Center receives the raw satellite data. Processing is accomplished using the SeaWiFS Data Analysis System (SeaDAS) software (Fu et al., 1998). An atmospheric correction is applied to the data to yield a measurement of water leaving radiance (Gordon and Wang, 1994; Shettle and Fenn, 1979). These radiances are processed to chlorophyll-*a* concentration using the NASA developed OC3M algorithm (described in O'Reilly et al., 2000). This algorithm is analogous to the OC4v4 algorithm used in the processing of SeaWiFS data, but adjusted for the specific bands available on the MODIS sensor. The chlorophyll-*a* data are best used for feature identification and tracking. The actual value of the chlorophyll-*a* is somewhat controversial due to major differences when compared with that of the SeaWiFS sensor on Orbview-2. Both can differ substantially from high-quality *in situ* measurements.

Table 1
Drifters deployed in the three eddies.

Drifter number	Eddy deployed in	Date deployed	Ship deployed from
53319	Haida	13 March 2005	*CCGS* W.E. *Ricker*
53309	Haida	23 April 2005	*CCGS* W.E. *Ricker*
53312	Haida	23 April 2005	*CCGS* W.E. *Ricker*
53310	Haida	30 April 2005	R/V *Thomas G. Thompson*
53308	Sitka	3 May 2005	R/V *Thomas G. Thompson*
53321	Sitka	3 May 2005	R/V *Thomas G. Thompson*
53304	Yakutat	6 May 2005	R/V *Thomas G. Thompson*
53306	Yakutat	6 May 2005	R/V *Thomas G. Thompson*

3. Results

3.1. Formation and translation

Anticyclonic eddies have a positive SSHA signature. Thus, altimetric SSHA were used to track the formation of the eddies before the cruise. The Sitka eddy appeared first around 15 December 2004, followed almost a month later (12 January 2005) by the Haida eddy (Fig. 2, note that the dates shown are slightly later than the first evidence of the eddies in order to show the eddies at sufficient strength). The Yakutat eddy was first observed off-shelf in the altimetry record on 16 March 2005. However, positive SSH anomalies were present on the relatively wide shelf near Yakutat for 2 weeks prior, providing evidence for formation on the shelf. The Yakutat eddy was the youngest, at only 1.5 months, of the three eddies sampled (Table 2). While the Sitka and Haida eddies first appeared in the altimetry record in deep water off the narrow continental shelves of their formation regions, altimetry data provided evidence that the Yakutat eddy formed on the wider shelf north of Cross Sound and subsequently translated into deeper water.

The Haida eddy was sampled from 28 April to 1 May 2005, when the eddy was ~3.5 months old. The center station (cast 10; 52.33°N, 133.29°W) was occupied on 30 April 2005. As noted in Section 2.5, the deployment of drifters in the eddy allowed a precise estimate of the location of the center of the eddy prior to conducting the transect. The location of the center of the eddy derived from drifter trajectories was 52.35°N, 133.30°W, a distance of <3 km from cast 10. The Haida eddy continued to drift slowly toward the northwest, disappearing from the altimetry record in January 2006. During this time, the eddy moved less than 300 km from where it was sampled in spring 2005.

Drifters were not deployed in the Sitka or Yakutat eddies prior to the cruise. Prior to sampling these eddies, the center location of the Sitka eddy was estimated from altimetry and ocean-color data. The ship conducted a transect from east of the Sitka eddy toward the southwest to deploy two drifters to more accurately estimate the location of the center before intensive sampling. By the time the ship was on location at the southern end of the northward transect across the two eddies, data from the two drifters allowed a more precise estimate of the center location of the Sitka eddy. The center of the Sitka eddy was sampled (cast 39) on 5 May 2005 at a distance of <3 km from the center derived from drifter measurements.

Due to time constraints, a cross-section of the Yakutat eddy was not possible prior to intensive sampling. Based on drifter data from drifters deployed during the ship's only transect, the center of the Yakutat eddy was 57.90°N, 139.85°W. The closest CTD cast (cast 51) was ~7 km away while the nearest nutrient and iron data were sampled at cast 52, ~13 km from the center.

During sampling, the centers of the Sitka and Yakutat eddies were only 114 km apart. The radius of the Sitka eddy was ~40 km, based on where the isopycnal slope changed sign, while the radius of the Yakutat eddy was ~ 75 km. Both the Sitka and the Yakutat

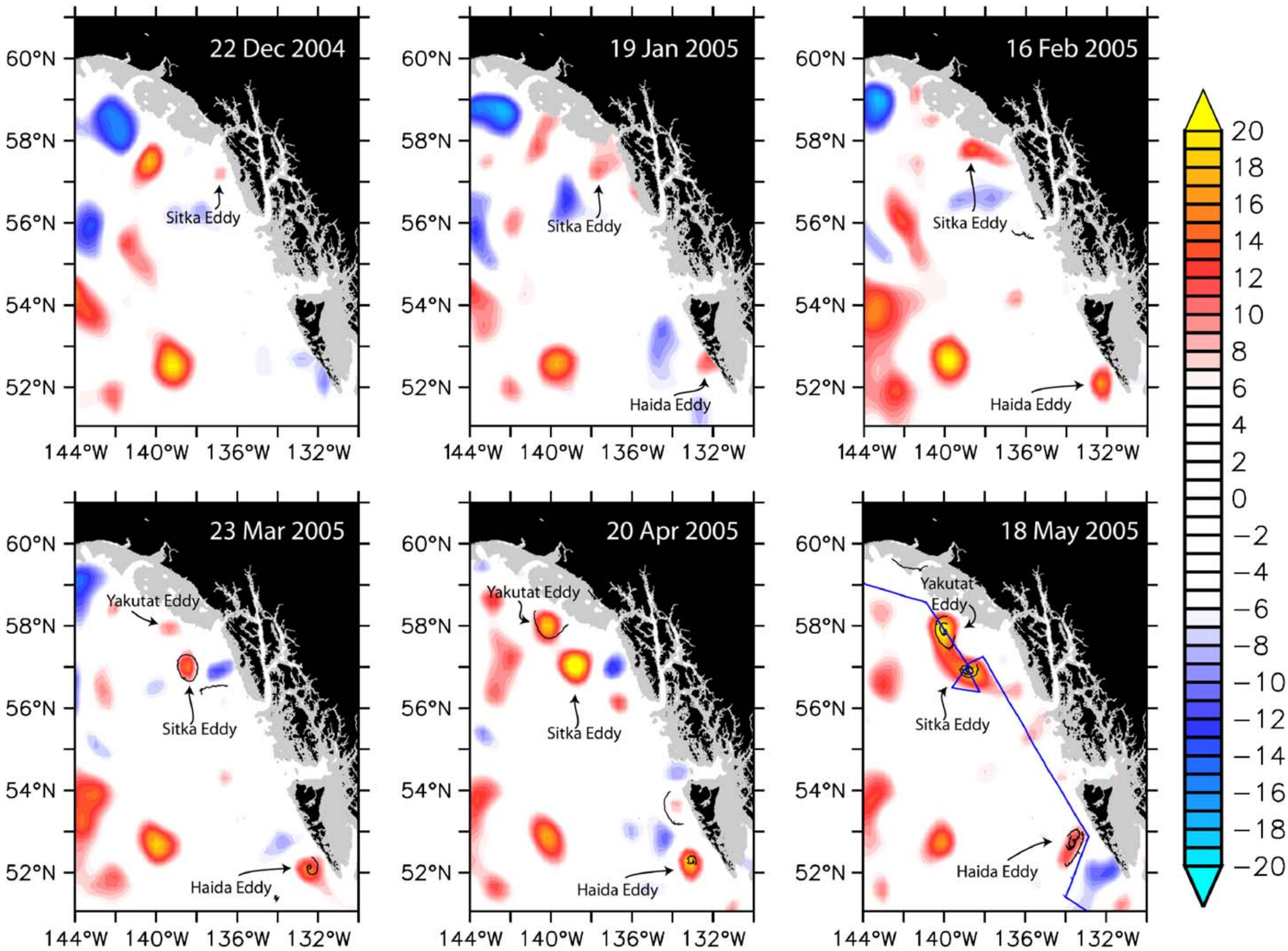

Fig. 2. Altimeter SSHA data in cm (color) and drifter trajectories (5-day tails: black lines). Drifters travel clockwise around these anticyclonic eddies. Blue line in final panel shows cruise track (26 April–8 May 2005). Note that timing of cruise is not exactly coincident with altimetry data shown. In particular, by 18 May, the Haida eddy had moved north from where it was sampled.

Table 2
Eddy formation dates and age when sampled.

	Eddy formation date from altimetry	Dates sampled	Age of eddy when sampled (months)
Haida	10 January 2005	28 April–1 May 2005	3.5
Sitka	22 December 2004	2–5 May 2005	4.5
Yakutat	23 March 2005	6–7 May 2005	1.5

eddies retained their respective two drifters until ~15 June 2005 when the eddies merged. At this point, the four drifters began circling one larger merged eddy. Two of the drifters stayed with the merged eddy until mid-November 2005 when they both exited the eddy almost simultaneously.

3.2. *Temperature and salinity*

The temperature and salinity observed in the three eddies (Fig. 3) reflect the different domains in which they form. Below the mixed layer, the Haida eddy exhibits warmer and saltier water than the two more northern eddies (Table 3) reflecting its more southern location and the greater influence of subtropical waters (see Section 3.4).

The Sitka and Yakutat eddies both exhibited a temperature inversion (Figs. 3 and 9). A similar inversion was observed at the center of the 2003 Yakutat eddy observed in the western GOA (Ladd et al., 2005a). The temperature minimum ($T_{min} < 6.5\,°C$) occurred at depths of approximately 50–100 m, while the temperature maximum ($T_{max} > 6.5$) occurred from 125 to 250 m depth. High levels of iron were coincident with the mesothermal (T_{max}) water (discussed further in Section 3.5). The difference in temperature $\Delta T = T_{max} - T_{min}$ was ~0.5 °C at both the center of the Sitka eddy and the center of the Yakutat eddy. The water properties of the T_{min} and T_{max} within the Sitka and Yakutat eddies are consistent with those found by Ueno and Yasuda (2005) for the eastern Gulf of Alaska. Tabata (1982) notes temperature inversions frequently occur in Sitka eddies. Conversely, the Haida eddy exhibited no temperature inversion, consistent with findings that inversions are infrequent in the area east of 140°W and south of 54°N (Ueno and Yasuda, 2005), although Crawford (2002) notes small temperature inversions in the five Haida eddies he examined. We believe that Haida eddies themselves create subsurface temperature maxima near 150 m depth as they propagate westward and southwestward through increasingly cooler and saltier subsurface waters of the mid-Alaska Gyre.

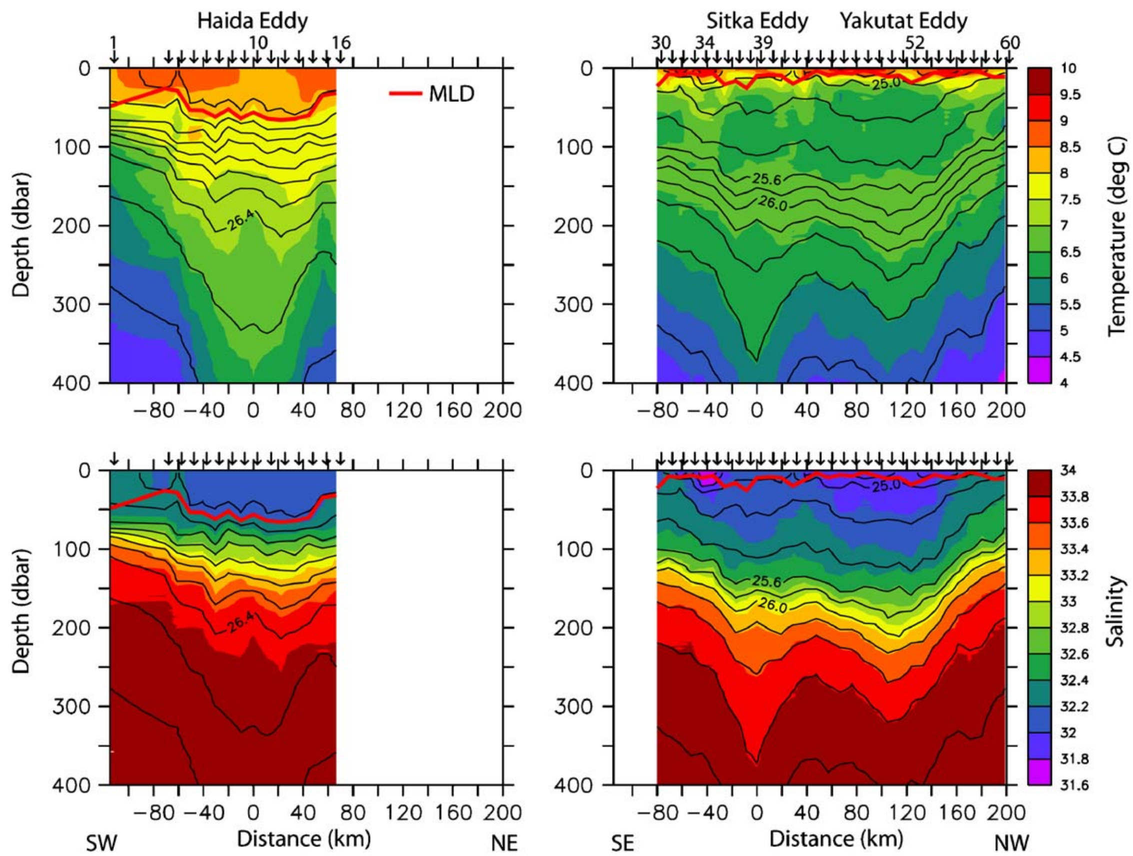

Fig. 3. Temperature (top) and salinity (bottom) observed in the Haida transect (left) and the Sitka/Yakutat transect (right). Density contours overlaid in black. Red line denotes mixed-layer depth. Arrows at the top of the plots show location of stations. Numbers denote cast number. Horizontal axis shows distance (km) from the center of the Haida eddy (left) or the Sitka eddy (right).

Table 3
Eddy core water properties.

	Surface mixed layer			Subsurface core		
	Haida	Sitka	Yakutat	Haida	Sitka	Yakutat
Depth range (m)	0–56	0–10	0–11	100–550	110–550	110–335
Density range (σ_θ)	25.0–25.1	24.9–25.0	24.7–24.9	25.6–26.8	25.4–26.8	25.3–26.7
Temperature (°C)	8.26	8.39	8.74	6.63	6.11	6.44
Salinity	32.14	32.03	31.95	33.79	33.55	33.20
Nitrate (μM)	10.40	6.90	13.95	33.68	31.62	27.30
Silicic acid (μM)	16.89	11.46	27.87	54.13	53.00	42.48
Phosphate (μM)	1.14	0.96	1.36	2.54	2.38	2.13
Total Fe (nM)	0.9	0.5	1.8	14.0	11.5	29.9
Labile Fe (nM)	0.35	0.20	0.77	3.72	2.67	4.56
Chlorophyll ($\mu g\,l^{-1}$)	0.29	1.94	0.47	No data	No data	No data

The freshest water sampled (31.7) occurred on the southern edge of the Sitka eddy (cast 34) (Fig. 3). MODIS chlorophyll data shows a ribbon of high chlorophyll water being pulled away from the shelf and wrapped around the eddy (Fig. 4). The transect through the Sitka eddy crossed this ribbon of high chlorophyll near cast 34. In fact, the highest 10-m chlorophyll concentrations measured on the cruise were observed at cast 34. This suggests that the circulation of the eddy may have actively pulled coastal water, with its low salinity and high chlorophyll, off the shelf and into the basin. Similar advection of coastal chlorophyll off-shelf has been observed in other GOA eddies (Crawford et al., 2005, 2007; Ladd et al., 2005a; Okkonen et al., 2003). Other than this ribbon of low salinity, the lowest salinity sampled during the transects occurred at the surface in the center of the Yakutat eddy (Table 3). This may be due to the surmised on-shelf formation location (trapping fresher coastal water in the center of the Yakutat eddy) or due to the fact that the Yakutat eddy was the youngest of the three eddies and the coastal signature at the center of the eddy had not yet had time to mix away.

Surface mixed-layer depth (defined as the depth where σ_θ is 0.125 denser than the surface) in the Haida eddy was deeper (~50 m) than in the Sitka and Yakutat eddies (5–10 m). The comparison of mixed-layer depths illustrates the dangers of assuming synopticity in a study such as this. The differences in

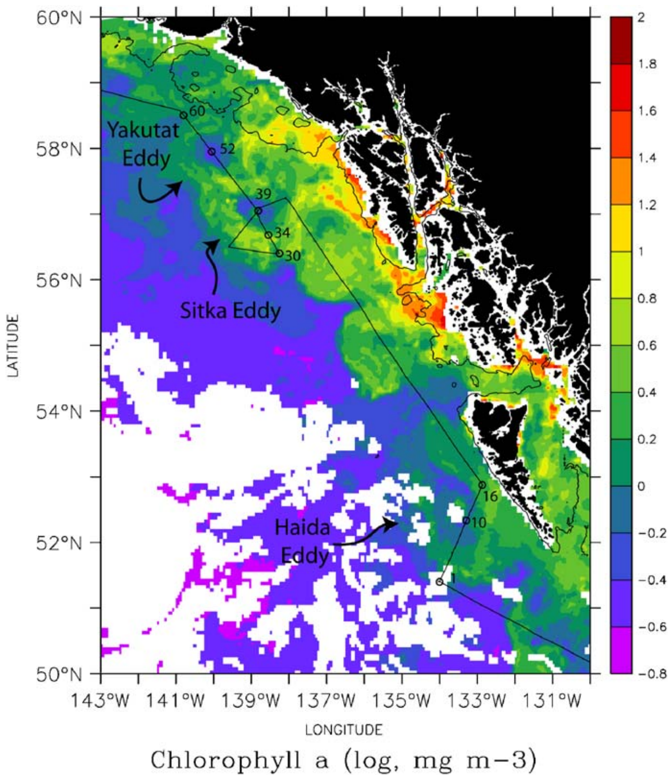

Fig. 4. MODIS chlorophyll data (8-day composite centered on 6 May 2005). Ship track is overlaid (black line). Locations of select casts are denoted by circles and cast numbers.

mixed-layer depth were probably at least partly due to differences in atmospheric forcing prior to sampling each of the eddies. During the 3 days prior to sampling the Haida eddy (28–30 April 2005), wind speed measured by the ship averaged 7.8 m s^{-1} and shortwave radiation averaged 152 W m^{-2}. During the 3 days prior to sampling the Sitka eddy (3–5 May 2005), wind speed and shortwave radiation averaged 2.5 m s^{-1} and 217 W m^{-2}, respectively. The 30% decrease in wind speed and over 40% increase in solar radiation during that time period likely contributed to the shallower mixed layer observed in the northern eddies. The proximity of the eddies to fresh-water sources during formation likely also influenced the depth of the surface mixed layer.

3.3. Macronutrients

Nitrate in the surface 50 m of the Haida eddy was between 5 and 10 μM, except at the center of the eddy where bowed-up, near-surface isopycnals were associated with slightly higher nitrate concentrations (11.7 μM) at 45 m (Fig. 5). Nitrate averaged 10.4 μM over the 56-m-deep mixed layer in the center of the Haida eddy (Table 3). Nitrate in the mixed layer of the 2005 Haida eddy was lower than that measured in the Haida eddy in February 2000 but higher than the same eddy sampled in June 2000 (Peterson et al., 2005). Assuming similar nitrate values in different Haida eddies suggests that nutrient drawdown had already begun when the 2005 Haida eddy was sampled. A weak chlorophyll maximum was observed 20–40 km from the center of the eddy at ~10 m depth.

The Sitka eddy had depleted nitrate in the surface waters at ~40–60 km from the center (casts 34, 35, 45, and 46), indicating that a bloom had already occurred. Below these depleted waters, a subsurface chlorophyll maximum was observed at 10–20 m depth where nitrate was ~5–10 μM. As mentioned in Section 3.2, cast 34 had the lowest salinity and highest 10-m chlorophyll measured on this cruise. The surface mixed layer at the center of the Sitka eddy was also lower in nitrate (and silicic acid and phosphate) and higher in chlorophyll than in the other two eddies (Table 3).

The mixed layer of the Yakutat eddy exhibited lower chlorophyll than the Sitka eddy along with higher nitrate and iron than both the Sitka and Haida eddies (Table 3). With the exception of the casts at the center of the Yakutat eddy (casts 47–54), the silicic acid versus nitrate relationship (Fig. 6) exhibits a strong linear regression ($S = 1.3N+2.9$; $R^2 = 0.95$). Silicic acid appears to be slightly higher per unit nitrate in the Sitka/Yakutat transect than in the Haida transect. This may be due to the higher influence of California Undercurrent (CUC) water (discussed further in Section 3.4) on the Haida eddy core waters (Whitney et al., 2005; Whitney and Welch, 2002). At the center of the Yakutat eddy, silicic acid values in the top 100 m were relatively constant (22 μM< silicic acid <35 μM) and did not conform to the regression equation (Fig. 6). (Phosphate versus nitrate had a tight relationship in all of the eddies; $N = 16.6P–8.6$; $R^2 = 0.98$.) High silicate concentrations in low-salinity waters indicate riverine inputs to the core waters of the eddy (Whitney et al., 2005). It is unclear why the Sitka eddy would have high chlorophyll concentrations and nutrient drawdown while the Yakutat eddy is low in chlorophyll but has plenty of nutrients. It is possible Yakutat surface waters had recently upwelled from below the euphotic layer, pushing aside surface waters previously at the center. This eddy also formed 2 months later than the Sitka and Haida eddies, allowing less time for favorable phytoplankton growth conditions to occur.

Below the mixed layer, nitrate versus salinity was generally higher in the Sitka/Yakutat transect than in the Haida transect (Fig. 7), possibly due to large-scale differences between the Dilute Domain and the Alaska Gyre Domain. (The depth and density ranges of the subsurface core waters in each eddy are noted in Table 3.) In the subsurface core waters ($32.4<S<33.8$), the highest nitrate per unit salinity measured in the entire dataset was at the center of the Sitka eddy. The centers of the Yakutat and the Haida eddies showed levels of nitrate per salinity similar to each other in the subsurface core. These levels were also similar to those observed in a 5-month-old Yakutat eddy in spring 2003 (Ladd et al., 2005a), but 10–20% higher nitrate per salinity than observed in the 2000 Haida eddy (Peterson et al., 2005). Except in the surface waters ($S<32.2$), the center of the Yakutat eddy was not particularly anomalous compared with other data collected on the Sitka/Yakutat transect. On the other hand, the nitrate versus salinity at the center of the Haida eddy was much higher than other observations on the Haida transect. Data from the Haida reference station had the lowest nitrate per unit salinity, indicating that this station consisted of coastal water (Peterson et al., 2005). Patterns of surface chlorophyll (Fig. 4) show high chlorophyll wrapped around the edges of the Haida eddy supporting this conclusion. Patterns of silicic acid and phosphate–salinity relationships were similar (not shown).

3.4. Oxygen and NO

Dissolved oxygen enters the subsurface waters of the subarctic Pacific in ventilation sites along the Asian coast (Whitney et al., 2007). As these waters flow across the Pacific in isolation from the atmosphere, remineralization consumes oxygen and produces nitrate. Oceanic waters in the Alaska Gyre exhibited higher oxygen levels than those of either the three eddies or the shelf waters of Queen Charlotte Sound, especially in the eddy core water density range (σ_θ ~25.4–26.8) (Fig. 8b). Low coastal oxygen levels are the

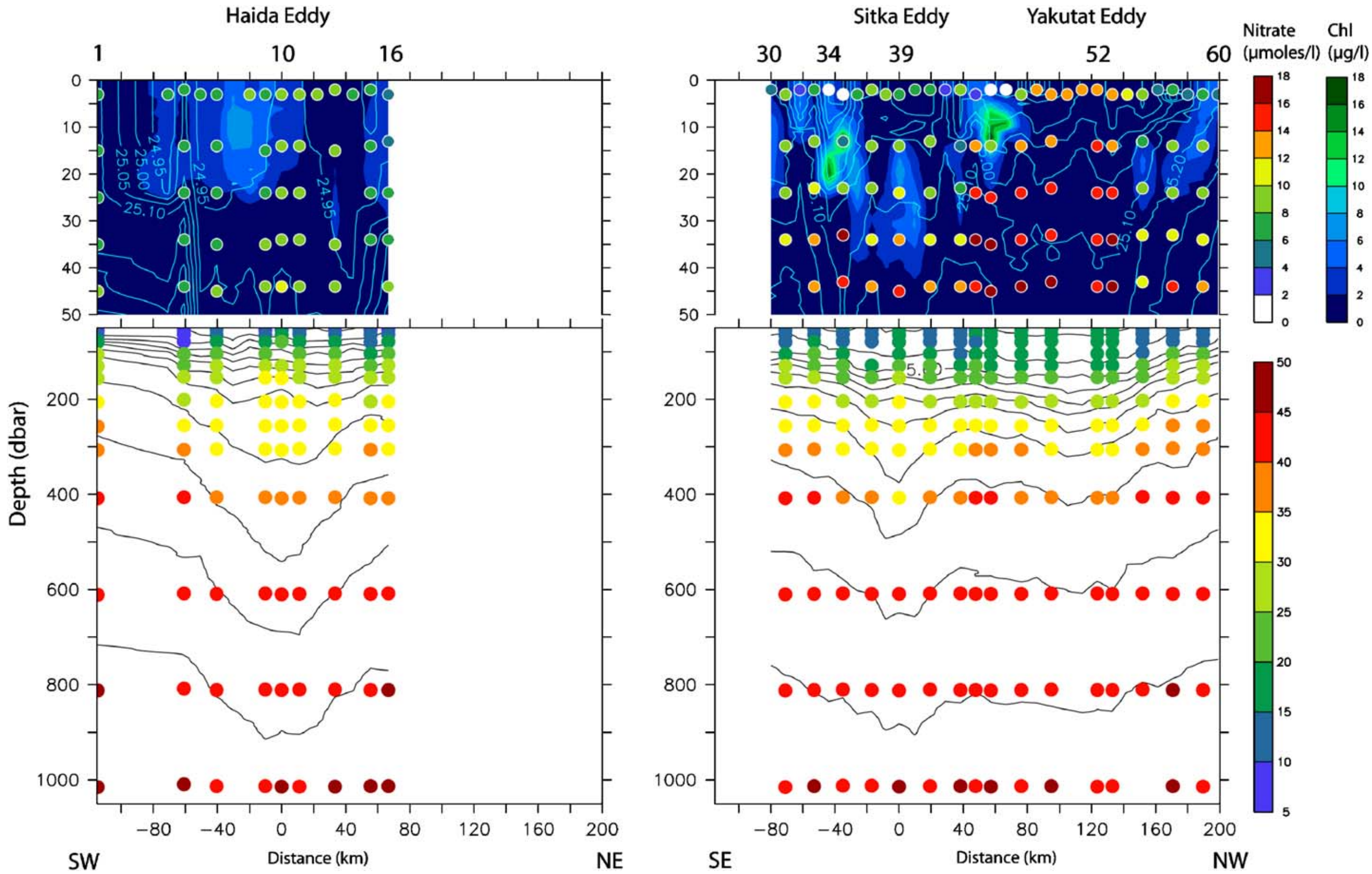

Fig. 5. Background colors (blue/green scale) represent chlorophyll concentrations in the top 50 m. Colored dots represent nitrate. Note that the nitrate color scale for the top 50 m is different from the scale for the deeper water. Density contours overlaid in black.

result of longer isolation from the atmosphere, shelf remineralization processes and the northward transport of subtropical waters via the California Undercurrent (Whitney et al., 2005, 2007). In the eddy core waters, oxygen was slightly higher in the northern eddies than in the Haida eddy. Haida 2005 showed consistent levels of oxygen between the April and June sampling periods. Nitrate, on the other hand, decreased in the Haida eddy from April to June (Fig. 8a). However, in April, nitrate at cast 8 (~10 km from the center cast) was less than nitrate at cast 9 (center) by an amount similar to the difference between April and June. This suggests that the observed decrease between April and June could be explained by slightly different sampling locations within the eddy. The reference station (cast 1) shows a fairly strong coastal influence (lower oxygen) compared with OSP. The spike in oxygen at a density of 26.7 at OSP suggests a ventilation event propagating from the Asian coast into the Alaska Gyre. Oxygen replenishment in the northeast Pacific depends on such periodic events (Whitney et al., 2007).

Broecker (1974) derived a conservative tracer (NO = O_2+9NO_3) based on the preformed levels of nitrate and oxygen in a watermass. Watermasses formed in cold regions with high nitrate levels will have high NO while waters formed in warmer regions with low nitrate will carry a low NO signature. As these waters sink and no longer exchange gases with the atmosphere, remineralization of organic matter consumes oxygen and produces nitrate in a fairly constant ratio as long as oxygen is available. The ratio of oxygen consumption to nitrate production (9.2) is persistent in the interior waters of the Alaska Gyre (Whitney et al., 2007). Thus, following Whitney et al. (2007), we use a slightly modified tracer: NO = O_2+9.2NO_3. Strong regional differences in NO have been observed throughout the North Pacific with minima in the subtropics and in the California Undercurrent (Whitney et al., 2007). Low NO in the CUC is the result of denitrification along the Central American and California coasts (Castro et al., 2001).

NO of slope waters is low in our study region (Fig. 8c, Queen Charlotte Sound), indicating that the dominant source of this water must be the CUC. Using data from Whitney et al. (2007), we estimate the slope and Haida eddy waters on the 26.7 isopycnal to be 85% subtropical in April 2005, based on Alaska Gyre and CUC values of 450 and 380 µmol NO kg^{-1}, respectively. Relatively low NO of CUC origin is found also in each of the eddies at densities greater than ~25.8. However, this southern influence is weaker (higher NO) in the Sitka and Yakutat eddies than in the Haida eddy. The NO of the eddies and the reference stations is fairly constant between 26.4σ_θ and 26.8σ_θ. The Haida eddy in both April and June had values of 390 µmol kg^{-1}, the same as the slope station in Queen Charlotte Sound. Both Sitka and Yakutat core waters were 400 µmol kg^{-1}, compared with 405 µmol kg^{-1} for the Haida reference station and 450 for OSP. Since these differences reflect the contribution to eddies from the subtropics and the Alaska Gyre, they may help explain differences in plankton communities found within them (see Section 3.6).

3.5. Iron

Labile iron at the Haida reference station averaged 0.10 nM in the mixed layer, increasing to a maximum of 1.24 nM at 600 m depth. While the mixed-layer values are typical of Alaskan Gyre

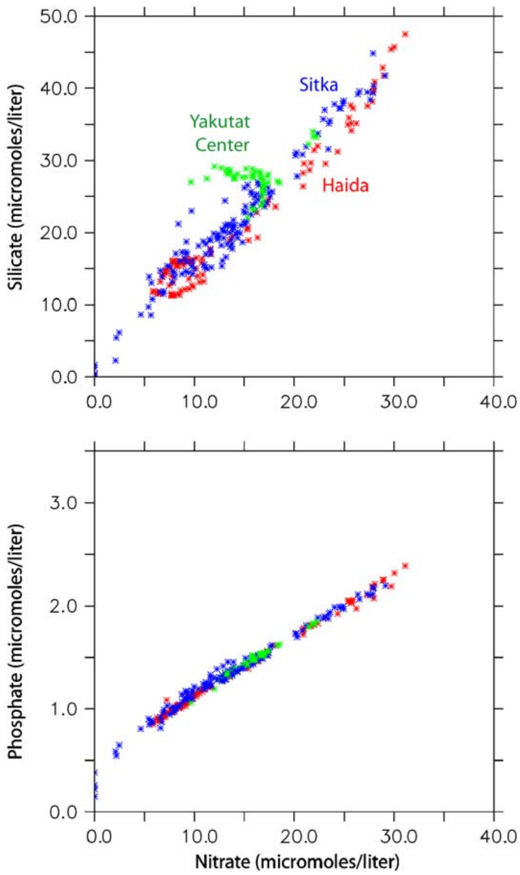

Fig. 6. Silicic acid versus nitrate (top) and phosphate versus nitrate (bottom) for all of the casts (depth = 0–200 m) in the Haida transect (red), and the Sitka/Yakutat transect (blue), except casts 47–54 (center of Yakutat eddy; green).

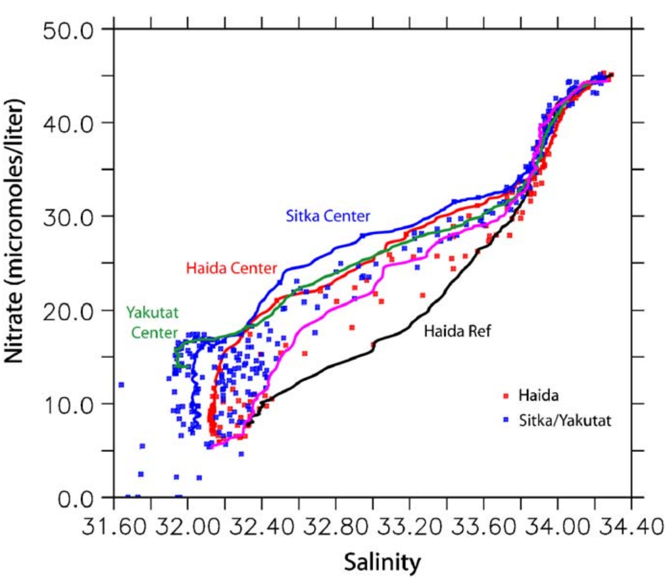

Fig. 7. Nitrate (μM) versus salinity for Haida transect (red symbols) and Sitka/Yakutat transect (blue symbols) (depth = 0–1000 m). Lines represent the cast nearest the center of each eddy (Haida cast 10 = red; Sitka cast 39 = blue; and Yakutat cast 52 = green) and the Reference cast 1 (black).

(i.e. OSP) waters, the deeper values are much higher than typically observed in the open Alaskan Gyre (Johnson et al., 2005), supporting the above conclusion (based on nitrate versus salinity values) that the reference station consisted of coastal water that had advected around the outside of the eddy. However, these values are significantly lower than those measured at the center of the eddies or in an actively forming eddy off the southern Queen Charlotte Islands in February 2001 (Johnson et al., 2005). These differences may indicate that the source of the reference station water is not Hecate Strait (the likely source of Haida eddy core water). Maximum iron (both labile and total) at the center of the Haida eddy occurred at 200 m. The zone of elevated iron (with labile iron levels typical of coastal waters (Johnson et al., 2005)) extended to ~550 m and σ_θ ~26.8 (Fig. 9), the typical depth of Haida eddy core water (Whitney and Robert, 2002). Four-month-old Haida eddies were sampled in June 2000 and 2001 (Johnson et al., 2005). The centers of these two eddies had labile and total iron profiles that were very similar to each other (labile ~2 nM; total ~5 nM at 200 m). The labile and total iron concentrations in the core waters of the 2005 Haida eddy (Table 3) were 2–3 times the concentrations measured in the 4-month-old 2000 and 2001 Haida eddies. Altimetry data suggest that the 2001 eddy was weak (SSHA ~4 cm in June 2001) while the 2000 and 2005 Haida eddies were much stronger (SSHA ~21 cm in June 2000 and ~17 cm in May 2005). The 2005 eddy was sampled approximately one month earlier in the spring than the 2000 and 2001 eddies, suggesting that phytoplankton production had not had as much time to draw down the iron concentrations before our sampling in 2005. Interannual variability in the iron concentration of the source waters also may contribute to the differences between eddies.

While lower than those measured at the center of the Haida eddy, the iron concentrations in the center of the Sitka eddy (Table 3) were still typical of coastal rather than open-basin waters. The vertical distribution, with elevated levels (relative to outside waters) to about 550 m (σ_θ~26.8), was similar to the Haida eddy indicating a core water depth of ~550 m (Fig. 9). The highest total iron concentration measured on the cruise (>60 nM; too high for our measurement techniques), was found at the eastern edge of the Sitka eddy at 100 m. Labile iron at this location was 5.81 nM at 100 m and 1.07 nM at 10 m. Unfortunately, we only have iron measurements from 10 and 100 m at this station. This station may have been in the path of a tongue of coastal water that was being drawn offshore. The high chlorophyll associated with this tongue can be seen in MODIS data (Fig. 4) and appears to have originated from the shelf off of Baranof Island.

Other than this one station, the highest levels of iron were measured at the center of the Yakutat eddy (Table 3) at 200 m. The total iron concentration at 200 m at the center of the Yakutat eddy was more than twice as high as the maximum iron measured at the center of the other two eddies (Fig. 9). The sharp peak in iron concentration of 41.4 nM at 200 m may reflect a source of iron from the sediments in the eddy formation region. If this is true, it would suggest that the source of the eddy core water was approximately 200 m deep. In contrast, the high iron concentrations in the cores of the Sitka and Haida eddies were more broadly distributed over a deeper depth range, reflecting the deeper (off-shelf) formation regions for these two eddies. Note that while the depth range of the Yakutat eddy core waters was about half the depth range of the other two eddies, the density range was similar (Fig. 9 and Table 3).

The peak in iron concentration (for both the Yakutat and Sitka eddies) is at the same depth as the subsurface temperature maximum (T_{max}). The coincidence of the high iron coastal water signature with the T_{max} suggests that the source of the temperature maximum is coastal, lending support to suggestions (Onishi et al., 2000; Ueno and Yasuda, 2005) that eddies may contribute to the formation of temperature inversions observed in the GOA.

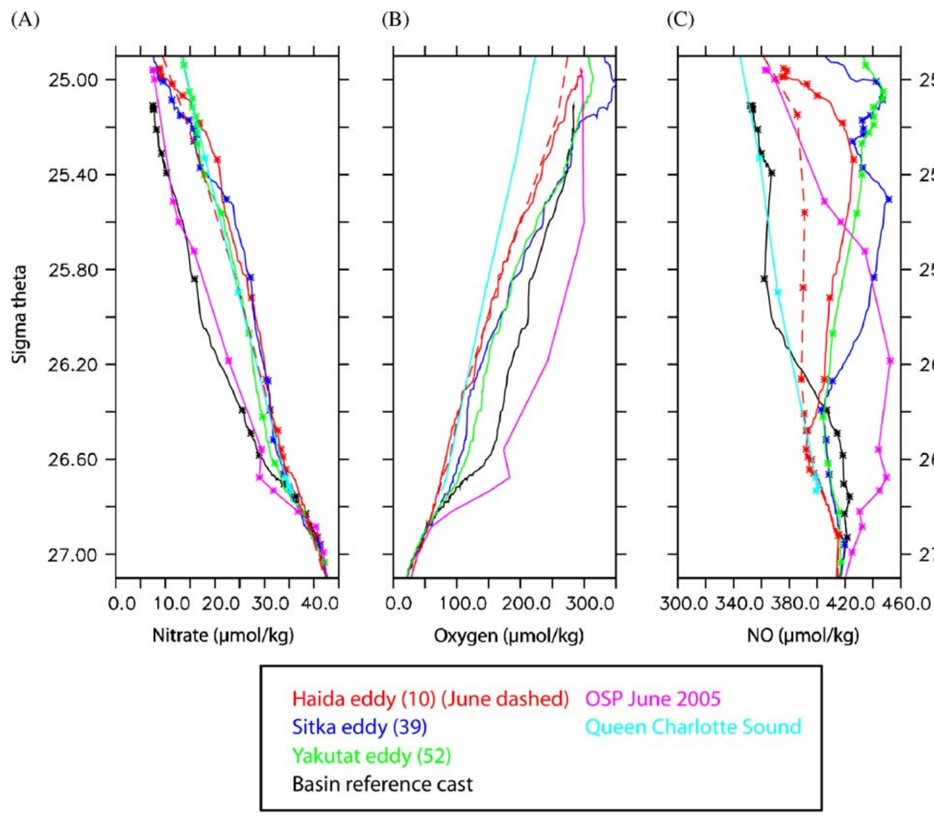

Fig. 8. Data from the center stations of the three eddies in April/May (cast numbers noted in legend) and from the Haida eddy, OSP, and a station in Queen Charlotte Sound in June 2005: (A) nitrate, (B) dissolved oxygen, and (C) NO.

3.6. Zooplankton

Zooplankton data were analyzed to examine differences between eddy center and edge stations and differences between the three different eddies. There was no statistically significant difference detected ($P = 0.659$) in zooplankton assemblages between edge and center stations when data from all eddies were pooled. There was a statistically significant difference between the zooplankton assemblages in the Haida and Sitka eddies ($P = 0.008$), but not the Sitka and Yakutat ($P = 0.301$) or Yakutat and Haida eddies ($P = 0.188$), as determined by ANOSIM tests (analysis of similarity). A series of pairwise SIMPER tests (similarity percentages) was conducted to learn which species were contributing to the difference. ANOSIM and SIMPER tests are multivariate, nonparametric permutation procedures used in ecology research (Clarke, 1993). In general, the difference was due to higher abundances of members of the assemblage in the Sitka eddy than in the Haida eddy, not to the presence or absence of particular taxa in one or the other eddy. Sometimes the differences in abundance were on the order of 10-fold (Table 4). The notable differences in abundance between the two eddies were for the groups: euphausiid developmental stages, larvaceans and several taxa of copepods (*Acartia* spp., *Oithona* spp., *Neocalanus* spp.). Thecosomata (pteropods) were more abundant in the Haida eddy than in the Sitka eddy.

4. Discussion

This paper presents the first directed observations in young Sitka and Yakutat eddies near their formation regions, whereas Haida eddies have been well studied through their evolution (e.g. Crawford, 2002; Johnson et al., 2005; Whitney and Robert, 2002). Previous published work on Sitka and Yakutat eddies has examined historical data for evidence of eddies (Tabata, 1982) or examined older eddies near Kodiak Island in the northwestern GOA (Ladd et al., 2005a, 2007). Synoptic sampling shows that the temperature and salinity of the Sitka and Yakutat eddy core waters were very similar to each other and colder than the Haida eddy. This is not surprising in that the Sitka and Yakutat eddies were close together (centers ~115 km apart) and form farther north where the influence of the California Undercurrent is weaker. Additionally, the T/S properties in the cores of these eddies are not significantly different from the surrounding waters outside the eddies. However, Ladd et al. (2007) showed that after leaving the eastern GOA, these eddies carry anomalous heat and salt along constant σ_θ surfaces into the western GOA.

The nutrient signatures of the three eddies were quite different from each other, suggesting differing biological activity and/or differing formation regions and source waters. The 2005 Yakutat eddy had significantly higher nutrient content (including iron) in the surface waters than the Sitka and Haida eddies (Table 3). High silicic acid and low salinity suggest that the source of the Yakutat eddy surface waters is strongly influenced by river runoff (Whitney et al., 2005). Unfortunately, few winter data from this shelf region exists with which to compare.

While iron in Haida eddies has been previously sampled (Johnson et al., 2005), the current work presents the first observations showing that the Sitka and Yakutat eddies also supply excess iron to the basin. In fact, iron concentrations measured in the Yakutat eddy were higher than any previous Haida eddy measurements (Johnson et al., 2005), including

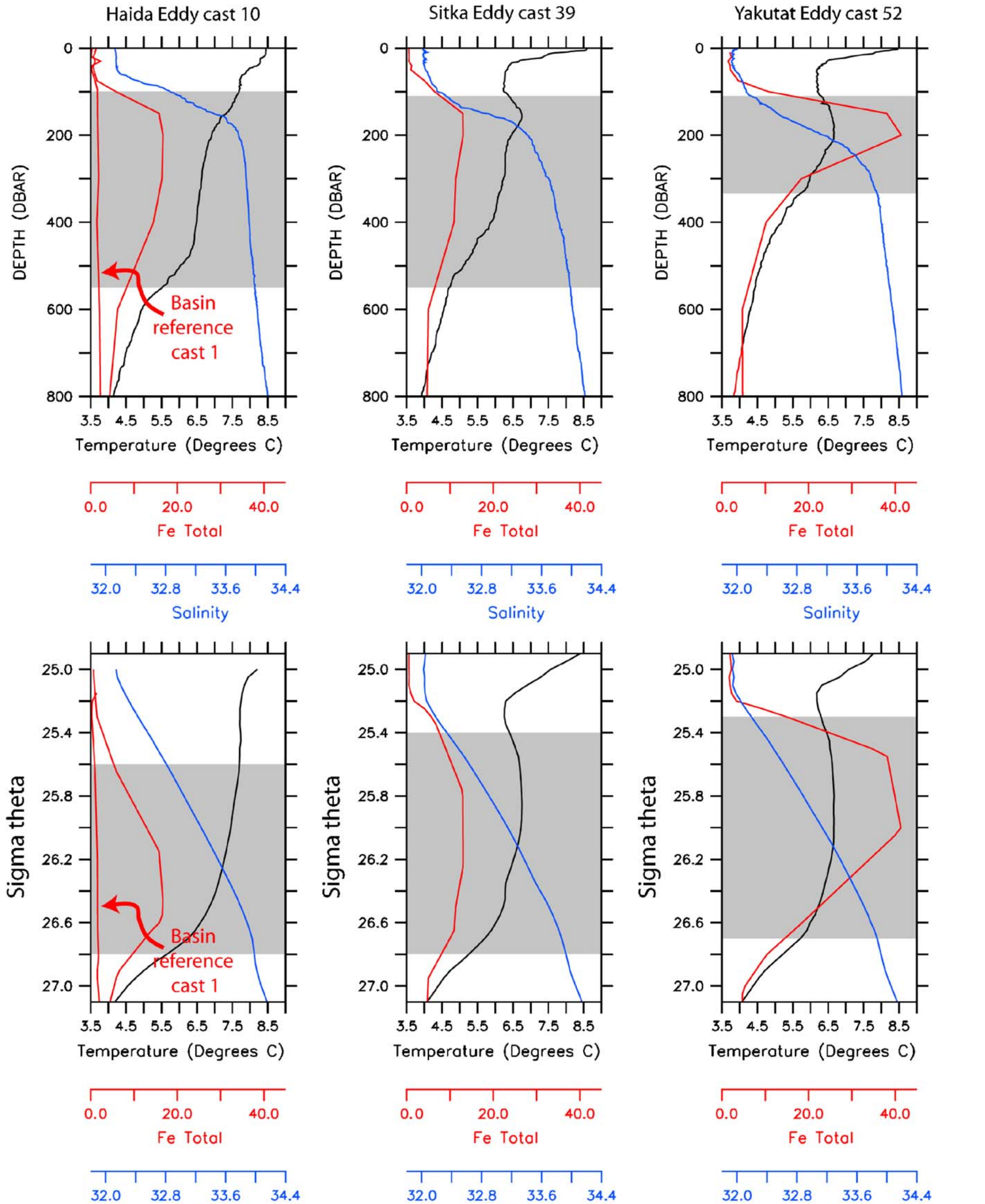

Fig. 9. Profiles of temperature (°C; black), salinity (blue), and total iron content (nM; red) for the casts nearest the center of the three eddies. Iron content at the reference cast (cast 1) is also shown in Haida plots and noted with arrow. Bottom plots are same data with density (σ_0) as the vertical axis. Gray shading illustrates the depth (density) range of the eddy core waters (Table 3). Note that the iron measurements were taken separately from the temperature and salinity casts so the data in each plot were not obtained concurrently. However data in each plot are from the same location and obtained within ~1 day of each other.

Table 4
SIMPER analysis.

Species group	Haida eddy	Sitka eddy	Contribution to dissimilarity (%)
Euphausiid calyptopes, nauplii and furcilia	8.43	79.82	10.88
Acartia spp. (adult)	4.17	23.34	7.62
Thecosomata	212.15	165.62	7.24
Larvacea	12.00	24.63	6.91
Oithona spp. (CV+CVI)	248.91	412.13	6.68
Neocalanus plumchrus/flemingeri (CII—adult)	15.03	54.07	5.99
Siphonophora	10.36	10.25	5.71
Pseudocalanus spp. (CI—adult)	172.86	102.96	5.49
Cnidarian medusa	0.48	1.06	4.60
Eucalanus bungii (CI—adult)	5.78	13.69	4.06
Teleost larvae	0.18	0.30	3.82
Hyperiidea	0.61	0.06	3.77
Cirripedia	0.73	1.47	3.56
Calanus marshallae (CII—adult)	2.34	4.72	3.50
Euphausia pacifica (adult+juvenile)	0.16	0.02	3.19
Calanus pacificus (CIV—adult)	0.47	0.06	3.14
Ostracoda	19.30	14.68	2.89
Metridia pacifica/lucens (CIV—adult)	54.03	77.84	2.75

Average zooplankton abundance (estimated number m^{-3}) in the Sitka and Haida eddies.
Average dissimilarity = 17.36.

measurements from a forming eddy where biological drawdown had presumably not yet occurred. In the surface mixed layer, the Yakutat eddy exhibited twice as much iron (both total and labile) as that measured in the Haida eddy (Table 3), probably because phytoplankton production had not yet utilized this nutrient. Integrated iron values of excess eddy iron (calculated as the amount greater than the reference station) were similar in the Haida and Yakutat eddies. Perhaps shelf iron in the Haida eddy was initially found in a more concentrated shallow layer, but iron was scavenged and distributed to greater depth following spring phytoplankton growth. The Sitka eddy, on the other hand, exhibited less iron than the other two eddies. The center of the Yakutat eddy appeared to be pre-bloom, with plenty of nutrients and iron in the surface layer and relatively little chlorophyll. This may account for the high iron values in the surface waters, while iron in the surface waters of the other two eddies had already been utilized by phytoplankton production. The deeper core waters of the Yakutat eddy were also significantly higher in iron than the Sitka and Haida eddies, possibly due to the shallow formation region and the influence of iron input from the sediments. The iron maximum at 200 m and $\sigma_\theta \sim 26.0$ suggests eddy formation in approximately 200 m deep water with bottom densities of $\sigma_\theta \sim 26.0$. Thus, eddies formed on the shelf north of Cross Sound may be quite important to providing iron to the GOA basin.

Our ability to detect real differences between the zooplankton assemblages from the center and edge of eddies may have been hampered by our low number of samples, and the inherent variability in the composition and abundance of species. Real differences may have existed, but our sampling was inadequate to detect them.

We anticipated detecting differences between the zooplankton assemblages in the Haida and Yakutat and the Sitka and Yakutat eddies. The Yakutat eddies form over shallow water with substantial riverine input, and we expected to see a higher abundance of species groups indicative of that water source. Marine cladocera, often associated with nearshore water (Cooney, 1976), were absent from all the samples analyzed. Barnacle larvae also can be an indicator of nearshore water, but they were only present at two stations at this time of year (one in the Sitka eddy and one in the Haida eddy) and were in relatively low abundance.

It is interesting that we detected a significant difference between the zooplankton assemblages of the Haida and Sitka eddies. Both of these eddies form over deep water and were similar in age. The main difference we found in the zooplankton was that the abundances of several zooplankton groups were much higher in the Sitka eddy than in the Haida eddy. Samples obtained from the Sitka eddy were assumed to be "post bloom" as indicated by chlorophyll-*a* and nutrient concentrations, while water samples from the Haida eddy contained measurable nitrate and an average chlorophyll-*a* value of 0.29 $\mu g\, l^{-1}$ in the surface mixed layer. It could not be determined from this sampling whether or not the production and zooplankton abundance in the eddies was determined by founder effects, bottom-up or top-down processes.

The taxa that accounted for most of the difference between the zooplankton assemblages in the Sitka and Haida eddies are common groups, encountered frequently throughout the study area. Zooplankton communities in Gulf of Alaska eddies are usually made up of a mixture of oceanic and coastal species (Mackas and Galbraith, 2002); however, our sample analyses (i.e. the number and type of taxa identified to species) may have been insufficient to detect the existing differences. Most of the zooplankton taxa accounting for the statistical difference between the Haida and Sitka eddies were not identified to species (euphausiid developmental stages, thecosomata, larvaceans, *Oithona* spp. and *Acartia* spp.), only to general taxonomic group. These groups contain both oceanic and coastal species (Mackas et al., 2005). For example *Acartia longiremis* has been used as an indicator of coastal water influence in Gulf of Alaska eddies (Batten and Crawford, 2005; Mackas and Galbraith, 2002). The adult *Acartia* spp. found in our samples would need to be identified to species to see if the species composition of this group indicated watermass origin. Other species considered to indicate coastal water were not found in high abundances in either eddy (e.g. *Calanus marshallae* (Mackas and Galbraith, 2002)) (Table 4). Our *Neocalanus* spp. group (*Neocalanus plumchrus* and *Neocalanus flemingeri*), are known as part of the oceanic species complex common in Gulf of Alaska eddies (Mackas and Galbraith, 2002), but are also common in coastal fjords such as the Straits of Georgia and Prince William Sound, Alaska (Coyle and Pinchuk, 2005).

The Haida eddy exhibited greater influence of subtropical California Undercurrent water than the two northern eddies as indicated by differences in NO concentrations. However, zooplankton communities did not reflect this difference. The subtropical taxa *Paracalanus* spp., *Mesocalanus tenuicornis* and *Pleuromamma* spp. (Gardner and Szabo, 1982; Mackas and Galbraith, 2002) were present at a few stations, but in extremely low abundances, and did not appear to be restricted to the Haida eddy. The copepod species *Eucalanus bungii*, *Calanus pacificus*, and *Metridia pacifica/lucens*, characterized as subarctic by Mackas et al. (2005), were present in both Sitka and Haida eddies (Table 4). *C. pacificus* had an extremely low abundance in both eddies, but was slightly more abundant in the Haida eddy. *E. bungii* was in low abundance in both eddies (average concentration: Haida 5.78 m^{-3}; Sitka 13.69 m^{-3}), but was more abundant in the Sitka eddy. *M. pacifica/lucens* was in moderate abundance in both eddies, but was also more abundant in the Sitka eddy. *C. pacificus*, *E. bungii* and *M. pacifica/lucens* contributed just less than 10% to the dissimilarity of the zooplankton assemblages in the two eddies (Haida and Sitka) (Table 4). It is unclear if the higher abundance of these two subarctic species is an indication of an increased subarctic water influence in the Sitka eddy, or just reflective of the Sitka eddy's higher average zooplankton abundance.

The coincidence of T_{max} water with the high iron core water of the Sitka and Yakutat eddies has interesting implications. By providing a source of T_{max} water, these eddies may contribute to the formation of temperature inversions in the GOA. Because iron is so difficult to measure, the coincidence of T_{max} water with high iron (if it holds up throughout the region) could give information regarding the distribution (vertical and horizontal) of high iron waters in the GOA. Using Argo profiling float data, Ueno et al. (2007) examined distribution and interannual variability of temperature inversions in the North Pacific. They found that, in the northern GOA, the T_{min} water overlying the T_{max} outcropped in 2002 and 2004, but not in 2003. If winter mixing is deep enough to ventilate the T_{max} layer and its associated high iron, the iron can be mixed to the euphotic zone, resulting in higher iron availability to phytoplankton. Thus, interannual variability of ventilation may influence iron sources to the surface waters. In addition, interannual variability in eddy formation and pathways (Crawford et al., 2007; Henson and Thomas, 2008; Ladd, 2007) suggests that iron input to the GOA via eddies may have strong interannual variability, which could influence productivity. Modeling studies show that the formation and magnitude of eddies in the eastern GOA are forced by wind anomalies associated with El Niño/Southern Oscillation and Pacific Decadal Oscillation cycles (Combes and Di Lorenzo, 2007; Melsom et al., 1999). Thus, eastern GOA eddies and their associated iron transport may provide a link between indices of large-scale climate variability and productivity in the GOA.

Satellite data (chlorophyll and SSHA) support the *in situ* evidence that the Sitka eddy forms in deeper water while the Yakutat eddy forms on the wider shelf north of Cross Sound (Fig. 2). Source waters for the two eddies appear to be different, with coastal water from Chatham Strait (south of Baranof Island) influencing the Sitka eddy while water from Cross Sound and the shelf north of Cross Sound influences the Yakutat eddy. NO suggests that the subsurface core waters of all three eddies (but especially the Haida eddy) are also influenced by waters of subtropical origin via the California Undercurrent.

All three eddies had anomalously high levels of macronutrients and iron in their core waters compared with surrounding basin waters. Additionally, satellite ocean-color data show all three eddies pulling streamers of coastal chlorophyll off-shelf while they were close to the shelf-break. Properties of the Yakutat eddy are consistent with an on-shelf formation in relatively shallow water (~200 m) while Haida and Sitka eddies appear to form in deeper water (~600 m). The on-shelf formation and influence from the sediments may account for the high levels of iron in the core of the Yakutat eddy, while river input at the surface may account for the high levels of silicic acid. Because this is the first study of Sitka and Yakutat eddies near their formation region, it is unclear how typical these properties might be.

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