ELSEVIER

Deep-Sea Research II 52 (2005) 893–908

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

Heat and fresh water transport by eddies into the Gulf of Alaska

William R. Crawford*

Institute of Ocean Sciences, Fisheries and Oceans Canada, P.O. Box 6000, 9860 West Saanich Road, Sidney, B.C., Canada V8L 4B2

Accepted 7 February 2005
Available online 1 April 2005

Abstract

Anticyclonic mesoscale eddies form in winter along the continental margin of Canada and Southeast Alaska between the latitudes of 51N and 60N and drift westward into the Gulf of Alaska, carrying warmer, fresher water away from the continental margin. Detailed measurements of temperature and salinity between 1995 and 2001 were examined to determine the amount of heat and fresh water transported seaward by several eddies that formed west of the Queen Charlotte Islands. Eddies formed in a typical winter carry about 30×10^{18} J of heat into the gulf, which is about 35% to 60% of the heat transported northward each winter along the continental margin toward this region. The observed range of eddy heat transport is 10^{19} to 10^{20} J. Largest observed eddy heat transport coincided with increased northward heat flow along the continental margin during the El Niño winter of 1997/1998. Fresh-water volume was determined by evaluating the amount of fresh water required to reduce the salinity from a reference level to that observed in eddies. This volume varied from 0 to 70 km^3, and was largest during the 1997/1998 El Niño winter. Eddies formed in a typical winter transport 50 km^3 of fresh water seaward, which is about 15% of the estimated fresh-water input to the continental margin in winter between the Columbia River and 54N attributed to local runoff, plus direct rainfall and flow in major rivers.

1. Introduction

Several papers have described the magnitude and motion of eddies through the Gulf of Alaska, with special treatment of their origin and possible formation mechanisms (Crawford et al., 2002; Melsom et al., 1999) and features shared by this class of eddy (Crawford, 2002; Whitney and Robert, 2002; Mackas and Galbraith, 2002). Their work is extended here to examine the heat excess and salt deficit of these eddies, as well as their offshore transport of heat and fresh water.

Haida eddies share many features with Sitka eddies that form to the north. All rotate anticyclonically. Most form in winter along the western continental margin of the Queen Charlotte Islands in British Columbia and the Alexander

*Tel.: +1 250 363 6369; fax: +1 250 363 6746.
E-mail address: crawfordb@pac.dfo-mpo.gc.ca.

0967-0645/$ - see front matter Crown Copyright © 2005 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.dsr2.2005.02.003

Archipelago in Alaska (Fig. 1) and carry both heat and fresh water seaward. Haida eddies form west of the Queen Charlotte Islands; Sitka eddies west of the Alexander Archipelago. Haida eddies carry the coastal waters and biota of the Queen Charlotte region. Sitka eddies have somewhat lower temperatures and generally keep to more northern regions of the Gulf of Alaska. They occasionally enter the Alaskan Stream where they are carried to the International Date Line (Musgrave et al., 1992; Crawford et al., 2000; Okkonen et al., 2003).

Heavy rain and snow fall in winter all along the British Columbia and Alaska coastline and flow to the ocean in a myriad of small streams. Royer (1982) places the annual average fresh-water input to the Alaskan portion of the gulf at 23,000 $m^3 s^{-1}$, a rate comparable to the flow of the Mississippi River. Additional fresh-water input from major rivers and direct rainfall onto the continental margin also freshen the surface near-shore waters. Surface shelf waters in winter are warmer than waters of mid-gulf due to coastal Ekman downwelling driven by winds of the Aleutian Low Pressure System, and northward-flowing California Undercurrent waters (Freeland, 2002). Haida

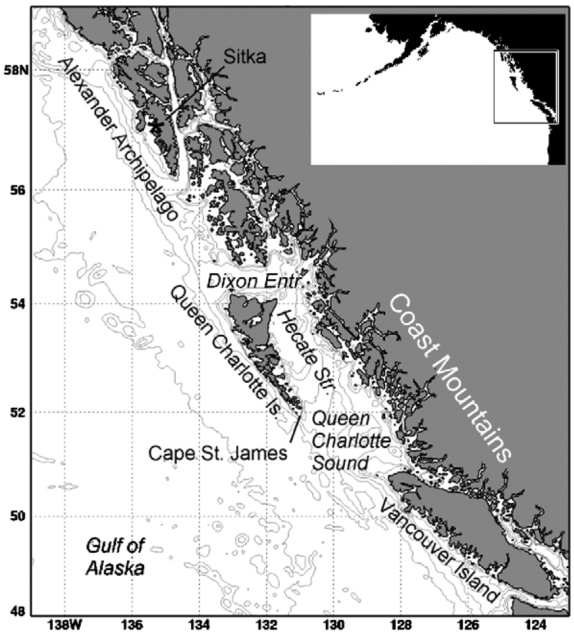

Fig. 1. Geographical region.

and Sitka eddies carry some of this warmer and fresher water away from the shelf.

This paper quantifies these heat and salt fluxes. Flux away from the continental margin clearly reduces the heat, fresh-water content, and buoyancy of coastal currents north of the Sitka and Haida formation regions. This heat flux is strong enough to impact the annual temperature cycle between Skagway and Kodiak Island. Fresh-water and buoyancy impacts are likely high as well, but not known at present.

1.1. Previous studies

Research cruises through these waters prior to 1999 sampled without prior knowledge of the location of eddies, and for many years without knowledge of their existence. Tabata (1982) compiled historical profiles of temperature and salinity, along with images of drifter tracks, and concluded that an anticyclonic gyre is normally present west of the continental margin near the town of Sitka, Alaska, at 56N (Fig. 1). He gave the name "Sitka" to this eddy, and described many of the eddy features later found to be shared between Sitka and Haida eddies: anticyclonic rotation, warm fresh core, nearly uniform-temperature (mesothermal) water in the core from 100 to 200 m depth, and isopycnal depression at depths of 1000 m or more. Thomson and Gower (1998) described a series of anticyclonic Sitka and Haida eddies all along the continental margin northward of Vancouver Island, based on a series of infrared satellite images during a rare cloud-free period in March 1995. However, a full understanding of the motion of eddies through the Gulf of Alaska awaited reliable satellite altimetry. Gower and Tabata (1993) applied Geosat observations to track eddies from continental margin into mid-gulf. Crawford and Whitney (1999) extended this analysis to the TOPEX/POSEIDON era of satellite altimetry, establishing the west coast of the Queen Charlottes as the eddy-forming region for Haida eddies. Crawford et al. (2002), Crawford (2002) and Di Lorenzo et al. (2005) showed how outflow currents past Cape St. James contribute to the formation and growth of Haida eddies and carry coastal waters into the gulf.

Significant Haida and Sitka eddies carry names based on their formation region, year, and order. Haida eddies form west of the Queen Charlotte Islands; Sitka Eddies west of the Alexander Archipelago (Fig. 1). Each is identified by its year of formation (defined by its separation from the continental margin) with an additional letter, if needed, to note its order of birth. For example, Haida-2000a was the first eddy formed west of the Queen Charlotte Islands in the year 2000.

1.2. Scope of present study

This paper examines water property measurements by Canadian research vessels, mainly between 1995 and 2001. Many research cruises during this interval were specifically directed to the eddies by use of satellite altimetry observations that locate eddy cores to within about 15 km. Cruises in 1995 and 1998 sampled to within 15 km of the eddy cores by chance, as determined later by satellite imagery. One series of measurements through an eddy in 1983 is included for comparison, despite lacking knowledge of core location, to show features of a large Haida eddy during formation.

Section 2 describes the observation techniques and features of the eddies and surrounding waters. Section 3 analyses the heat excess and salt deficit of individual eddies, and the rate at which they carry heat and fresh water away from the continental margin and lose heat and fresh water over time. Exceptions to this rule are found and investigated. The Discussion in Section 4 compares the offshore transports to larger scale processes in the Gulf of Alaska.

2. Observations

2.1. Observation programs

Water property profiles were taken along Line-P on most Canadian weathership missions between 1959 and 1981, as the ships transited between home port in Victoria, British Columbia and Ocean Weather Station Papa at 50N, 145W (Fig. 2). Following the elimination of the weathership

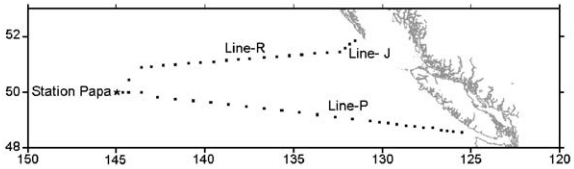

Fig. 2. Location of Station Papa, and Lines P, R, and J in the Gulf of Alaska, as sampled in May 1982 by CSS *Parizeau*.

program at Station Papa in 1981, and continuing to the present, cruises by Canadian research vessels sampled Line-P two to six times a year. For several years in the early 1980s the vessels also sampled along Line-R and Line-J between Station Papa and Cape St. James at the southern tip of the Queen Charlotte Islands (Fig. 2), on the shoreward leg of the trip. These two additional lines of stations were established to look for eddies noticed in the historical records of this region (Tabata, 1982).

In the summers of 1995 and 1998, large Haida eddies drifted southward across Line-P coincident with surveys by the Canadian Coast Guard Ship *John P. Tully*. Beginning in January 1999, the CCGS *John P. Tully* cruises have sought out and sampled Haida eddies, guided to eddies by near-real-time satellite altimetry images posted on the Internet by the Colorado Centre for Astrodynamics Research (CCAR). Several cruises specifically sought to examine biology, chemistry and physics of these features (Whitney and Robert, 2002; Mackas and Galbraith, 2002). Two eddies, Haida-1998 and Haida-2000, were sampled on repeat cruises over periods of 10 and 18 months, respectively.

Each survey sampled across the eddy, with CTD profiles to depths of at least 1000 m, and in some cases to 3000 m or bottom. Profiles from 1995 to present were sampled with a SeaBird SBE911Plus CTD augmented with a secondary temperature sensor and hydro bottles for salinity calibration. The 1983 cruise used a Guildline CTD augmented with hydro bottles and reversing thermometers to 1300 m depth.

2.2. Background ocean conditions

Background ocean properties along Line-R and Line-J are presented in Fig. 3 to show the seasonal change in water properties from deep ocean to continental margin. Upward sloping isotherms in Fig. 3A between the continental margin and deep ocean can be attributed to strong prevailing winds of the Aleutian Low Pressure system in winter, which upwell water in mid-gulf due to Ekman divergence of the ocean surface layer by the wind-stress curl. Close to shore these same winds downwell water, in this case due to Ekman convergence of surface water along a continental margin. Horizontal, along-track, isotherm slope (Fig. 3A) exceeds isohaline slope (Fig. 3B) in the region shown. However, in Hecate Strait and Queen Charlotte Sound (which lie to the east of the region in Fig. 3) the horizontal isohaline gradient increases, due to injection of fresh water at shore in winter as noted earlier.

One eddy is observed in Fig. 3A near 135.5W in May 1982. This feature displays typical traits of Haida eddies: depression of isotherms and isohalines at depths below 150 m, with this depression observed at depths of at least 1000 m.

In addition to the one Haida eddy observed in these four sections along Line-R, one can see in Fig. 3B regions of isohaline elevation in deep waters at 135W and 138.5W in September 1982, and at 136W in November 1982. None of these regions penetrate upward through the halocline. Only the second of these features is clearly present in the plot of isotherms in Fig. 3A. These features might indicate cyclonically rotating waters at depth, from an unknown source, and are not considered further in this paper.

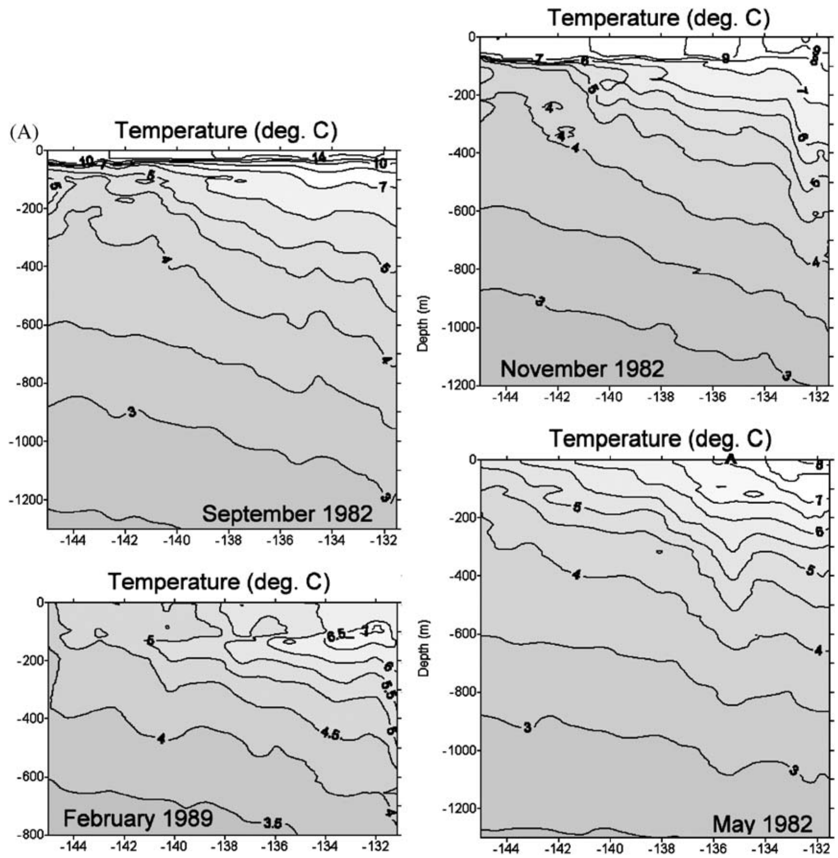

Fig. 3. Isotherms in degrees C (A) and isohalines (B) along Line-R and Line-J from 145W at left to continental margin at right. Bottom axis denotes west longitude. Nominal station spacing is 75 km. Eddy position is denoted by ˆ.

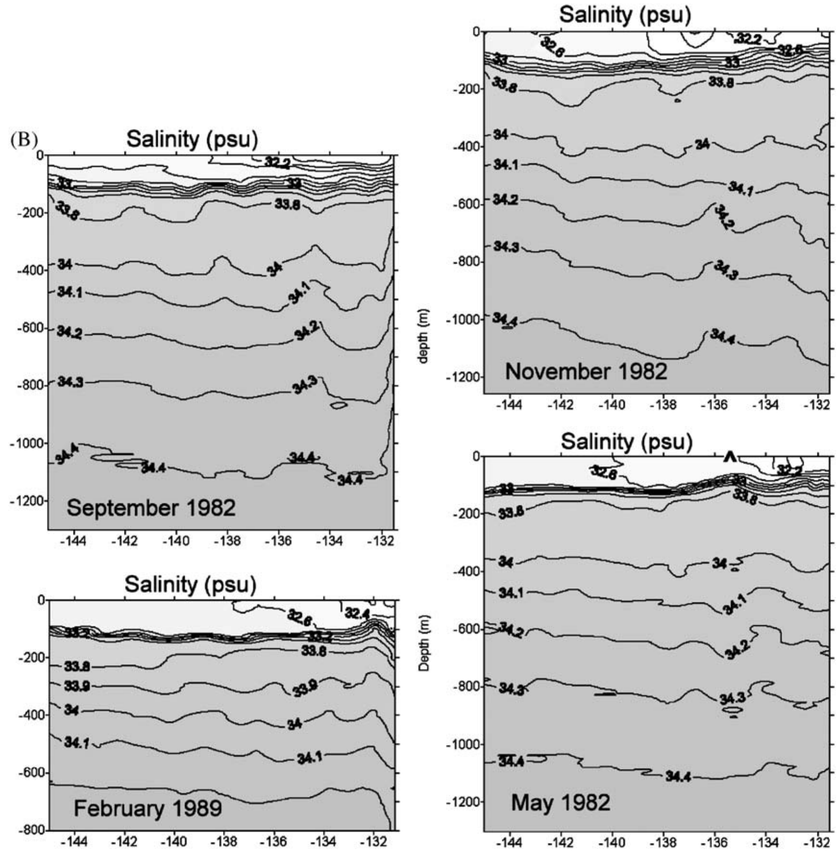

Fig. 3. (*Continued*)

2.3. Depth of eddies

In calculating offshore transport of heat and fresh water, it is necessary to determine the depth penetration of eddies. Fig. 4 displays deep cross-sections of temperature and salinity contours through Haida eddies as measured from the CCGS *John P. Tully* between 1995 and 1999. The August 1998 and January 1999 cruises through Haida-1998 sampled to 1500 below surface. Profiles were taken to 3000 m depth during the August 1995 cruise through Haida-1995. All June 1999 profiles sampled to ocean bottom, with the top 4000 m are plotted here. All sections reveal depression of isotherms and isohalines in eddies at bottom of the plots, although the June 1999 contours are unambiguous to 2300 m depth only. Below this level the depression of June 1999 contours might be attributed to processes at neighbouring stations.

2.4. Eddies selected for this study

In those eddies sampled to 2000 m or more, isotherms and isohalines were depressed at depths as great as 2000 m. Therefore, the calculations will be made at 500-m intervals down to 2000 m depth, or to the nearest 500 m of those casts that stopped short of 2000-m depth. Table 1 lists the eddies selected for this study, together with the positions and dates of ship transits through them.

3. Analyses

CTD profiles collected by scientists of the Institute of Ocean Sciences were used to evaluate average temperature and salinity of each eddy between ocean surface and depths of 500, 1000, 1500 and 2000 m. Warm-core, anticyclonic eddies such as these will usually contain more heat and less salt at these depths than found at the same depth in surrounding waters. By fitting Gaussian profiles to cross-sections of vertically averaged temperature, one can compute excess temperature and heat as described below. The discussion is similar for salt deficit and equivalent fresh-water content, presented later.

3.1. Calculation method

The equation for a Gaussian cross-section of temperature through a cylindrically symmetric eddy, embedded in a background ocean with a uniform, linear horizontal temperature gradient is

$$\Delta T_D(r) = \Delta T_{Do}\exp(-r^2/2R^2) + B + Cx, \quad (1)$$

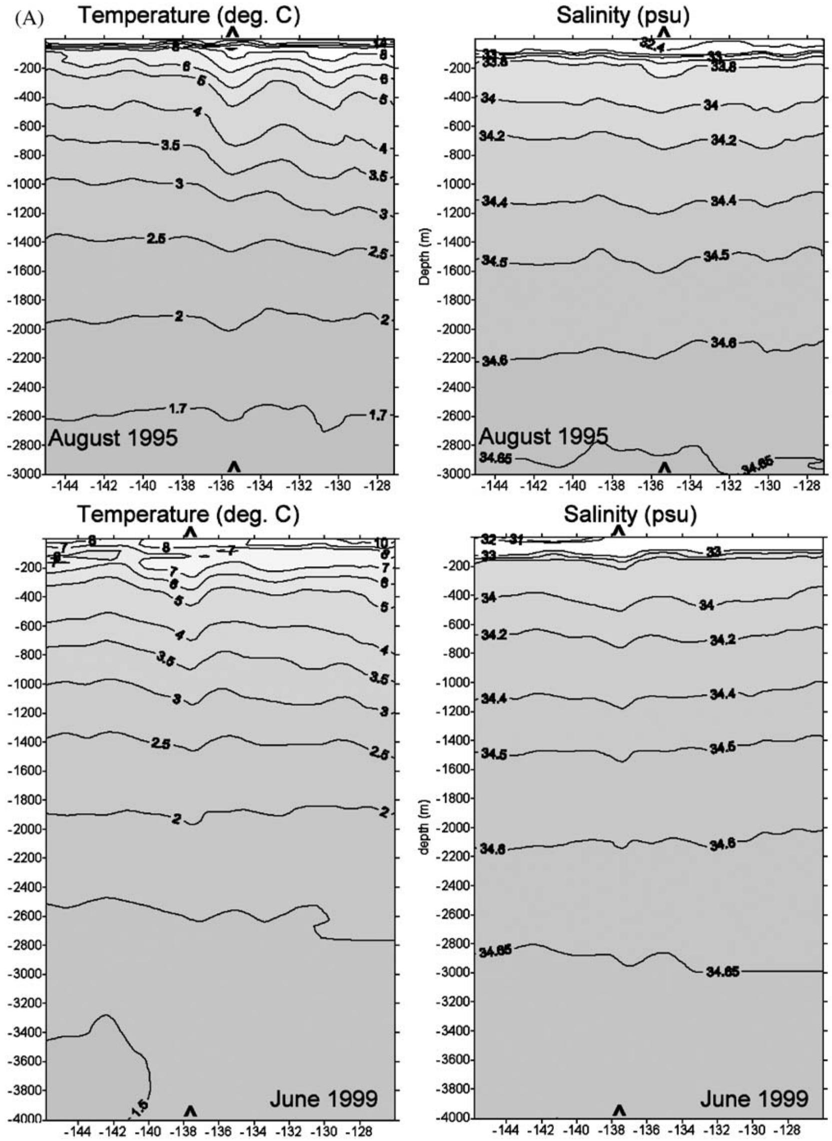

Fig. 4. Isotherms (degrees C) and isohalines (psu) through Haida eddies. Eddy positions are denoted by ˆ. (A) Haida-1995 in August 1995 along Line-P and Haida-1998 in June 1999 along 47N; (B) Haida-1998 in August 1998 along Line-P and Haida-1998 in January 1999 along 47.75N. The eddy centre station in January 1999 lies 55 km north of other stations. Nominal station spacing is 75 km.

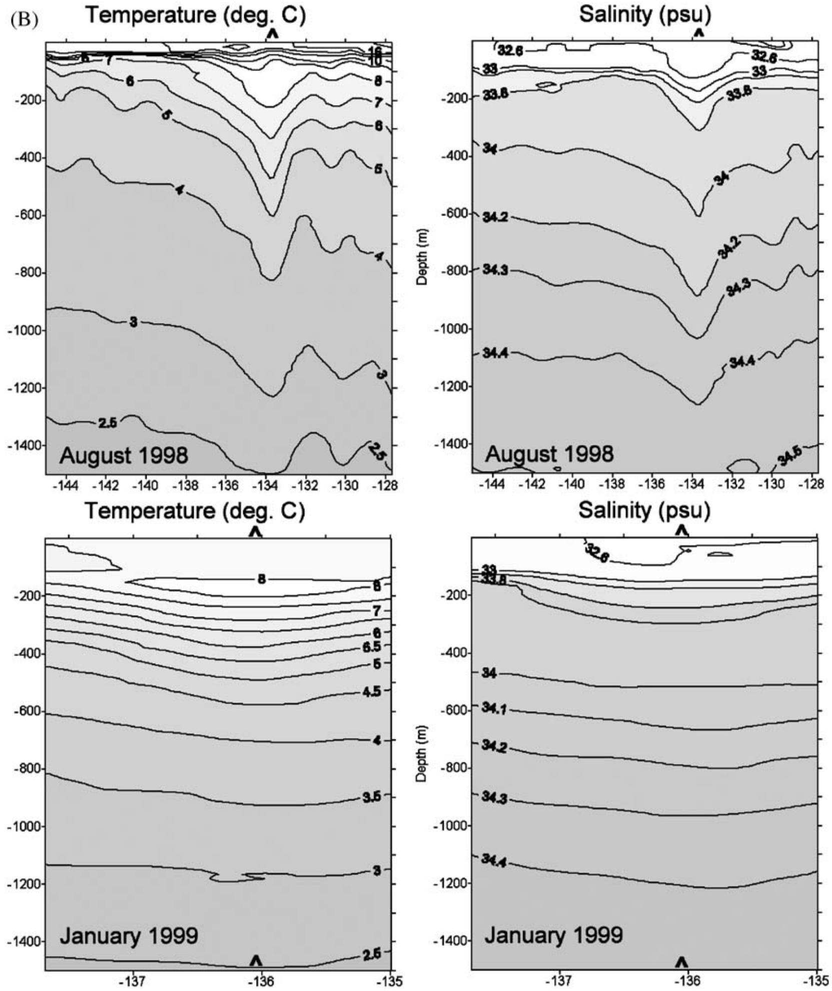

Fig. 4. (*Continued*)

where $\Delta T_D(r)$ represents the vertically averaged temperature between ocean surface and depth D, at radial distance r from the centre, ΔT_{Do} the vertically averaged temperature at the eddy centre, R the Gaussian eddy radius, B a constant background temperature, and C a coefficient of background horizontal temperature gradient in the x-direction along the ship track. B and C represent surrounding ocean conditions between surface and depth D, and the co-ordinate origin ($x = 0$, $r = 0$) lies at eddy centre. This equation assumes sampling along an eddy diameter and no background temperature gradient in the y-direction. The parameters ΔT_{Do}, R, B, and C were determined by fitting (1) by eye to the depth-averaged observations at sampling stations through each eddy.

Fig. 5A displays the fitted Gaussian sections of temperature of four eddy transects along with observed averages at each sampling station computed from ocean surface to depths spaced at 500-m intervals. Not all transects fit a Gaussian shape well, and in some cases the background ocean conditions are fitted poorly by a linear slope. The ship-track passing through Haida-1998 in June 1999 actually passed in a due-west direction along a

Table 1
Details of CTD profiles through station closest to eddy centre. Height of eddy is determined at eddy centre using satellite altimetry

Haida eddy	CTD date	Latitude (North)	Longitude (West)	Height (cm)
1983	24 Mar-83	51°27.5′	132°24.0′	N/A
1995	29 Aug-95	49°20.88′	135°39.91′	18
1998	30 Aug-98	49°13.06′	133°40.00′	30
1998	7 Sept-98	49°11.83′	133°39.77′	30
1998	21 Feb-99	47°45.14′	136°20.07′	23
1998	8 Jun-99	47°31.90′	137°27.61′	16
2000a	16 Feb-00	52°19.93′	134°00.09′	11
2000a	19 Jun-00	52°45.09′	135°49.86′	20
2000a	18 Feb-01	53°47.92′	137°29.80′	9
2000a	9 Jun-01	54°24.78′	138°10.09′	8
2000a	23 Sept-01	54°30.02′	138°20.03′	12
2001a	3 Jun-01	51°14.98′	133°49.99′	8
2001a	5 Jun-01	51°14.99′	133°59.89′	8

No satellite altimetry observations are available for 1983.

southern chord of this eddy, diverting 55 km northward for one sample in the eddy centre. For this eddy, the mathematical fit to a background linear slope in (1) was adjusted to fit an east–west slope along 47N, excluding the eddy-centre station.

The calculation of temperature excess described above applies equally well to salt deficit in the eddies. Fig. 5B displays the fitted Gaussian sections embedded in a background oceanic salinity gradient, for averages of salinity deficit from surface to depth intervals increasing in increments of 500 m.

3.2. Choice of reference temperature and salinity profiles

Any calculation of excess heat requires a reference temperature. To determine excess heat in Haida eddies, historical profiles of temperature and salinity

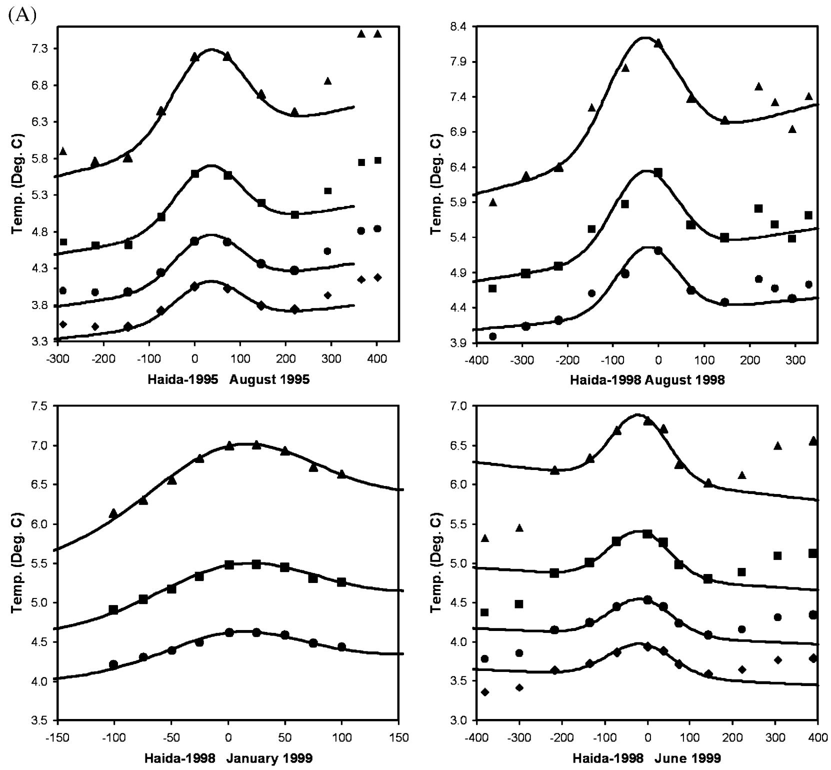

Fig. 5. Vertically averaged temperature (A) and salinity (B) computed for individual profiles in sections through Haida eddies. Solid line represents Gaussian curves fitted to observations. Symbols denote averaging intervals: Triangle 0–500 m, Square 0–1000 m, Circle 0–1500 m, Diamond 0–2000 m. Horizontal axes denote distance in km from a central station near the eddy centre.

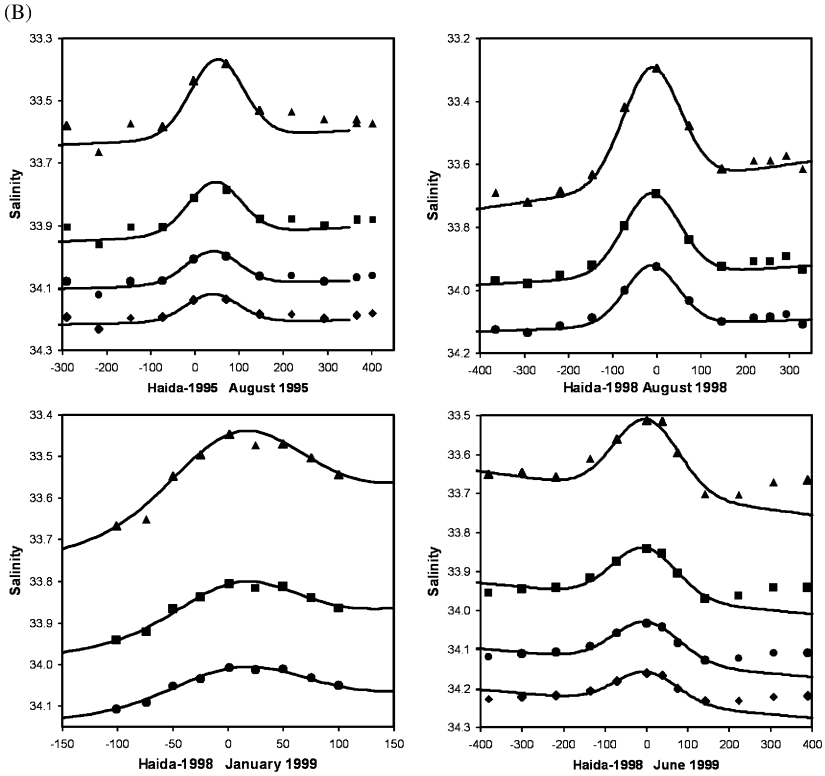

Fig. 5. (*Continued*)

in winter for the waters immediately to the west of Cape St. James were examined to find winter reference conditions in the absence of any eddy. Only a 1982 sample seems to be clearly outside an eddy, and was selected as a reference profile in the upper 1240 m, its deepest extent. No suitable winter CTD profiles below 1240 m were found in the database for the waters near the southwest margin of the Queen Charlotte Islands; instead, a deep profile of June 2001 was selected. The reference profile applied to both the heat excess and salt deficit calculations is based on the 1982 winter profile above 84 m, an average of the 1982 and 2001 profiles from 84 m to bottom of the 1982 cast at 1240 m, and the 2001 profile to 2000 m (Fig. 6).

3.3. Heat anomalies and fresh water content

The integral of a cylindrically symmetrical Gaussian function to an infinite radius is $2\pi H(R^2/2)$, where H is the centre height and R is the Gaussian radius. Therefore, in cylindrically symmetrical eddies the heat excess in any layer of thickness D can be computed as

$$\Delta H_D(r) = (4.2)(2\pi)\rho c_p D(\Delta T_{Do})(R^2/2), \tag{2}$$

where ΔH_D is the excess heat in joules in the slab of thickness D with depth-averaged, excess core temperature ΔT_{Do}, in an eddy of Gaussian radius R. The factor 4.2 converts calories to joules. Specific heat and density of seawater are c_p and ρ, respectively.

Similar calculations apply to salt deficit; however, all calculations are presented as equivalent fresh water content in the eddies, by calculating the amount of fresh water needed to produce the observed salt deficits relative to the reference profile. This number is calculated from the equations

$$S_e V_e = S_r V_r, \tag{3a}$$

$$V_e = V_r + S_r, \tag{3b}$$

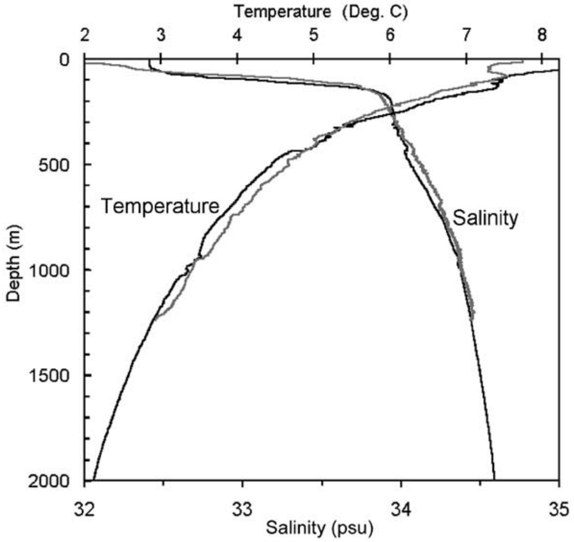

Fig. 6. Salinity and temperature profiles representing reference waters in the formation region of Haida eddies along the outer continental margin west of southern Queen Charlotte Islands. Black line: 2 June 2001 at 50.25N, 133.83W; grey line: 23 March 1982 at 51.45N, 132.40W.

where S denotes salinity, V denotes volume, and the subscripts e, r, and f refer to eddy, reference and fresh water, respectively. The volume of fresh water needed to dilute the reference water to the salinity of the eddy water is

$$V_{\mathrm{f}} = (S_{\mathrm{r}} - S_{\mathrm{e}})V_{\mathrm{e}}/S_{\mathrm{r}}. \quad (4)$$

Table 2 lists the heat excess and fresh water content in the eddies at four depth ranges. Fig. 7 displays results for the top 500 m.

3.4. Growth and decay of anomalies with time

Both Haida-1998 and Haida-2000 lost at least half of their excess heat and fresh water by February of the second year, but the heat decay rates were not uniform, and the time of maximum heat content is poorly known. Haida-2000 gained heat from formation until month 4, and between months 16 and 19. Heat gain in the first 4 months suggests that this eddy was not fully formed when sampled in early February 2000. This conclusion is supported by a satellite image of the region in April 2000 that reveals coastal waters flowing into Haida-2000 (Crawford et al., 2005; Batten and Crawford, 2005). The second period of Haida-2000 growth, from months 16 to 19, was at a time when Haida-2000 merged with one of the two Haida-2001 eddies that formed in the winter of 2001, bringing additional heat into the older eddy. Haida-1998 was not sampled until the seventh month, giving no clues to a heat budget in later winter and spring of its natal year. From month 7 onwards it lost heat steadily.

The fresh-water content of Haida-2000 decayed uniformly in time, but Haida-1998 lost fresh water between months 7 and 11 only. The small increases in fresh-water content of Haida-1998 during the sixth month, and from months 11 to 16 are within the uncertainty of measurement (see below). Haida-1998 carried the greatest quantity of fresh water; however, in contrast to the heat content, three other eddies carried more than half the fresh water found in Haida-1998.

The calculation of heat and fresh water in Haida-1983 should be considered a lower boundary given the absence of altimetry observations to determine distance to the core from the central station identified in CTD profiles. The height of the highest station sampled in this eddy rose to the second highest dynamic height observed in any Haida eddy (Crawford, 2002), and only its small radius placed its heat and fresh-water content well below that of Haida-1998, the highest ever observed.

3.5. Uncertainties in heat anomalies and fresh water content

Uncertainties in these excess heat calculations may be due to asymmetries of eddies, lack of knowledge of background temperature structure of the ocean surrounding eddies, and an imperfect choice of reference temperature profile. These factors are discussed below.

3.5.1. Asymmetries

One assumes cylindrical symmetry when calculating heat content of an eddy based on samples along a diameter. This assumption is examined using two-dimensional images of eddy heights as

Table 2
Details of temperature and excess heat content (a) and salinity and fresh water content (b) of Haida eddies

Natal year of Eddy	Section direction	Month and year	Gaussian radius (km) from surface to depth listed below in metres				Local excess temperature (C) from surface to depth listed below in metres				Excess heat (10^{18} J) from surface to depth listed below in metres			
			500	1000	1500	2000	500	1000	1500	2000	500	1000	1500	2000
Temperature and excess heat content (a)														
1983	SW–NE	Feb-83	40	37			2.30	1.43			24	26		
1995	E–W	Aug-95	78	71	71	71	1.24	0.87	0.68	0.55	55	58	62	65
1998	E–W	Aug-98	77	70	65		1.60	1.20	0.95		95	103	98	
1998	N–S	Sep-98	77	68	65		1.25	1.17	0.95		93	97	98	
1998	W–E	Jan-99	73	67	60		1.06	0.62	0.45		39	41	37	
1998	E–W	Jun-99	67	70	72	75	0.83	0.60	0.47	0.42	25	28	37	53
2000	W–E	Feb-00	38	33	33		0.68	0.54	0.46		8	10	12	
2000	S–N	Jun-00	56	58			1.13	0.96			21	35		
2000	W–E	Feb-01	65	65	70	65	1.89	1.43	1.17	0.82	6	13	21	20
2000	S–N	Jun-01	65	60	60	60	0.58	0.35	0.30	0.27	0	0	2	5
2000	S–N	Sep-01	42	41	44	50	0.53	0.33	0.25	0.24	6	7	9	12
2001	S–N	Jun-01	30	30	30	30	0.59	0.49	0.39	0.33	4	7	8	9
2001	E–W	Jun-01	35	35	34	33	0.78	0.63	0.49	0.39	6	10	11	11
Salinity and fresh water content (b)														
1983	SW–NE	Feb-83	35	50			0.34	0.20			40	28		
1995	E–W	Aug-95	60	60	60	60	0.25	0.17	0.11	0.09	45	62	65	68
1998	E–W	Aug-98	65	65	65		0.17	0.15	0.12		66	95	107	
1998	N–S	Sep-99	65	64	60		0.37	0.26	0.37		69	98	97	
1998	W–E	Jan-99	58	53	58		0.21	0.12	0.1		30	37	49	
1998	E–W	Jun-99	78	77	80	75	0.19	0.13	0.11	0.08	31	65	70	66
2000	W–E	Feb-00	57	42	48		0.38	0.19	0.15		36	27	40	
2000	S–N	Jun-00	55	65			0.28	0.22			29	60		
2000	W–E	Feb-01	100	90	90	90	0.11	0.15	0.15	0.14	9	28	49	62
2000	S–N	Jun-01	60	60	60	65	0.01	0.07	0.05	0.05	–9	13	15	21
2001	S–N	Jun-01	30	40	35	30	0.08	0.06	0.04	0.03	3	4	4	1
2001	E–W	Jun-01	45	45	—	—	0.14	0.10	—	—	–2	0	—	—

A dash indicates an unsatisfactory Gaussian fit to observations.

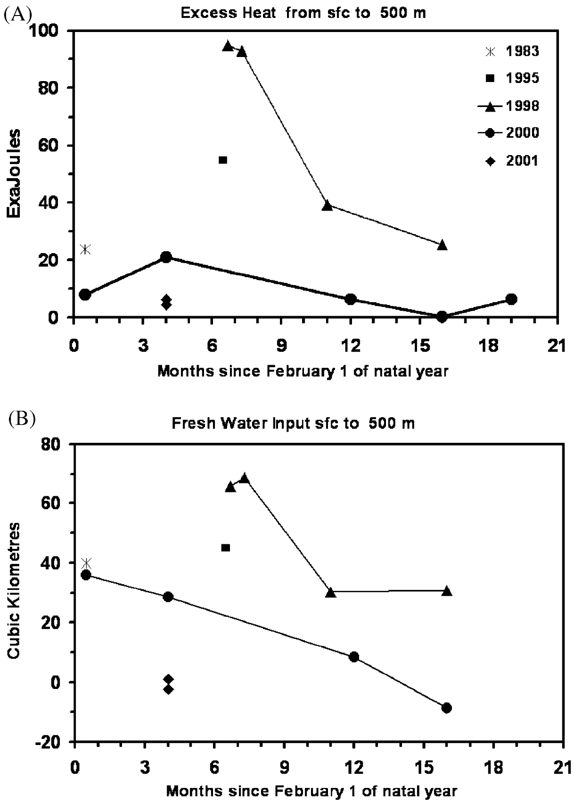

Fig. 7. Excess heat (A) and fresh water (B) in Haida eddies.

measured from space by satellite altimetry. The CCAR Internet site provided images of mesoscale ocean topography from 1995 to 2001, based on TOPEX/POSEIDON and ERS-2 satellites. T/P samples with a repeat cycle of 10 days and about 100 km track separation; ERS-2 every 35 days and about 30-km separation. These images were used to determine possible errors in the excess heat content listed in Table 2, by comparing eddy widths along and across the ship track, based on the diameters of constant height surfaces.

The median error determined by this method was 5% to 10%. The largest errors were 25% for Haida-2000 in February 2000 and 20% for Haida-2001 in early June 2001. These two samples captured the eddies early in their lives and close to shore. The symmetry error in the February 2000 eddy transect was actually much larger than 25%, but was cancelled to a large extent by the ship track missing the eddy centre, and therefore under-sampling the heat content. Both Haida-2000 and Haida-2001 were likely accumulating new water at the time of sampling, which could have contributed to their asymmetry.

3.5.2. Background ocean

It is more difficult to estimate errors due to incomplete knowledge of waters surrounding the eddies. Much of this error may be due to the assumption of uniform background oceanic temperature gradient along the ship track. One extreme case can be seen in Fig. 5A, in the Gaussian temperature fit to Haida-1995. There is clearly a shift in background temperature between the east and west sides of this eddy. The Gaussian section fits reasonably well to the seven central CTD stations, but poorly to the outside stations. An alternate Gaussian profile could fit only the five CTD profiles within 150 km of the $r = 0$ kilometre point. The best fit to these five stations provides an excess heat content 10% greater in the top 1000 m and 30% greater in the top 500 m than does the fit to the seven stations. This range of 10% to 30% provides useful guidelines for such errors.

3.5.3. Choice of reference profile

Haida and Sitka eddies are almost always warmer and fresher than surrounding waters at most depths, from their formation until their disappearance into the background oceanic variability (Crawford, 2002). With this observation as a guideline, the reference temperature profile was selected to be reasonably cool, ensuring positive offshore heat flux for almost all eddies observed. Similarly, the reference salinity profile was selected to be relatively salty. Calculations of heat and fresh water contents plotted in Fig. 7 reveal no negative heat and only two negative fresh water volumes, of small magnitude. Had the reference profiles of temperature and salt been inaccurate by more than 10% or so, a few of the weak eddies would show near-zero values, or significantly negative heat and fresh water contents would be found.

4. Discussion

4.1. Comparison of heat excess with regional heat flux input

Table 2a gives details of Gaussian radii and excess heat content for each cruise section. Eddies sampled prior to 2000 carried almost all of their excess heat in the top 500 m, whereas Haida-2000 carried about one-half its heat in the top 500 m in June 2000 and in February 2001. Haida-2001, sampled only once in June 2001, also carried about one-half its excess heat in the top 500 m.

Fig. 7A presents the calculated heat excess above 500 m for each cruise, plotted with date since February 1 of the natal year along the horizontal axis. Measurements were made through Haida-2000 in September 2000 but failed to observe Gaussian-like cross-section, likely due to wake effects of Bowie Seamount. Table 2a presents no heat excess for this section.

The heat excess of about 100 exajoules (1 exajoule $= 10^{18}$ J) for Haida-1998 in August 1998, listed in Table 2, represents 10^{20} J. Its extreme height can be partly attributed to the high sea levels and heat content in coastal waters during its formation. In addition, it was formed by the merging in June 1998 of the two eddies that formed the previous winter. In normal winters, several eddies form and go their separate ways.

Freeland (2002) computes northward, oceanic heat transport in the upper 500 m across the 10 Line-P stations closest to shore for the period 1997 to 1999, a time interval that includes the 1997/1998 El Niño. Most of the temperature and velocity structure lies in the top 500 m; therefore little transport is expected at greater depths. For the period of November 1997 to February 1998, inclusive, Freeland has determined an average transport of 7 to 15 TW, (1 TW $= 10^{12}$ W). During these 4 months, (roughly 10^7 s) when Haida-1998 was forming along the continental margin north of Line-P, the Freeland (2002) heat flow therefore transported between 70 and 150 exajoules of heat northward across Line-P. At first look, it appears that Haida-1998 had carried almost this quantity of heat offshore, based on August and September 1998 measurements of heat content of about 100 exajoules.

However, the reference sea level and temperature applied by Freeland (2002) in this heat flux calculation are based on an *average* TOPEX/POSEIDON sea level for the period 1992–2000, and *average* water properties over the 44 years of Line-P measurements. His calculation is therefore an attempt to determine the transport *anomaly* relative to an average ocean, and many of his values are negative, even in winter. The reference temperature profile applied here for Haida eddies was placed at a low level, ensuring that offshore eddy heat flow remains positive. If one displaces all of the Freeland fluxes upward, just to the point where all of his individual winter values are positive, the November 1997 to February 1998 northward cumulative heat transport increases to a range of 120 to 200 exajoules, and the remaining values increase to 50 to 80 exajoules. By this measure, Haida-1998 carried offshore of order 50% to 80% of the magnitude of heat transported northward across Line-P during the peak of this El Niño winter. However, build-up of heat along the British Columbia coast began in the spring and summer of 1997, and much of the Freeland winter heat flux across Line-P failed to reach the Northern British Columbia in time to enter the Haida-1998 eddies.

Table 2 shows that Haida-2000, a more typical eddy, transported 21 exajoules of heat northward in the upper 500 m. It was the larger of two eddies that formed that winter. Its value lies between that of Haida-2001 at 4 to 6 exajoules, and Haida-1995 at 55 exajoules. The former is one of two such eddies formed in 2001, a year of very weak eddies, whereas the latter is the larger of two eddies formed in a winter of larger eddies. One might expect, therefore, that eddies of a typical winter would carry about 30 exajoules of heat into the gulf, with transport of 10 and 100 exajoules representing the upper and lower range observed in other years. Typical eddies would therefore carry offshore between 35% and 60% of the Freeland (2002) typical northward heat transport.

One may also compare this heat movement with net surface heat transfer in these waters. Tabata (1958) computed net surface heat flux for coastal waters in eastern Dixon Entrance. His net winter heat loss to atmosphere from ocean is about 250 g-cal/cm^2/day between November and February. Elliott (1965) extended this analysis to most shelf regions of the British Columbia coast, computing a net upward heat flux of 250 g cal/cm^2/day during the cooling season, which is identical to the Tabata (1958) value. This winter heat flux amounts to 70 exajoules over a continental margin of 700 km by 100 km. Therefore, typical Haida eddies transport offshore about one-half as much heat as lost upward through the ocean surface on the Canadian continental margin in a typical winter.

If the Haida eddies of a typical winter carry 30 exajoules of heat seaward in the upper 500 m, their combined offshore heat flux is 6 mW/m of shoreline along 500 km of the coast.

4.2. Comparison of fresh water content with regional fresh water input

Table 2b gives details of Gaussian radii, core salt deficit and equivalent fresh-water content for each cruise section. Fig. 7B presents the calculated fresh-water volumes above 500 m for each cruise, plotted with date since February 1 of the natal year along the horizontal axis. Salinity measurements through Haida-2000 in September 2001 and Haida-2001 in June 2001 revealed two salinity maxima in a cross-section of the eddy that did not fit a Gaussian distribution. Table 2 presents no results for these cruises.

The range of fresh water content among the 1995, 1998 and 2000 eddies is smaller than the relative range of heat excess. The increased northward flow of California Undercurrent waters in winters of major El Niño carries warmer and saltier water (Freeland and Denman, 1982). As the Aleutian Low Pressure system strengthens during typical El Niño winters, it also carries warmer waters, but not necessarily fresher waters. Therefore, the very large Haida-1998 eddy, attributed to El Niño processes, likely gained most of its extreme volume and potential energy from warm water rather than fresh.

Haida-2000 carried 29–36 km^3 of fresh water. Assuming that it represents a typical year, and that it carried about 60% of the total winter eddy transport, as was done for heat flux, then eddies in a typical winter will carry about 50 km^3 of fresh water into the gulf. The range of observed transport varies from 0 to 70 km^3.

One can compare this input to fresh-water runoff from the continental margin and direct rainfall. LeBlond et al. (1983) have compiled weekly runoff rates for the Washington State and British Columbia coasts for the period 1950–1978. Summary details are presented in Table 3, for the West Coast between the Columbia River and northern Queen Charlotte Islands omitting Dixon Entrance, and also for the Puget–Georgia–Fuca Basin. Their flow rate for the Columbia River is derived from NOAA tables. Rainfall input to continental shelf west of Vancouver Island and Washington State is estimated from neighbouring regions. This rainfall requires a 4-month input of 1.2 m, spread uniformly over these waters. This rate far exceeds the rainfall rate of 0.2 m in these four winter months measured at Station Papa, reported by Tabata (1965).

Assuming the fresh-water input to the Puget–Georgia–Fuca Basin is available to the continental shelf by the end of February, these numbers add

Table 3
Fresh water input to ocean from river runoff and direct rainfall, for November–February inclusive, for West Coast between Columbia River and northern Queen Charlotte Islands

Runoff to Pacific Ocean	
Queen Charlotte Sound	2500
Queen Charlotte Strait	1200
West Coast Van Island	2500
Washington State	8000
Columbia River	3000
Total	17,200
Runoff to Georgia–Fuca–Puget basin	
Juan de Fuca Strait	700
Puget Sound	2600
Strait of Georgia	3500
Total	6800
Direct rainfall on ocean	
Queen Charlotte Islands area	2500
Hecate Strait	2500
Queen Charlotte Sound	1900
WC Van. Is. + Wash State shelves (est.)	2100
Total	9000

All units are m^3 s^{-1}.

to 33,000 $m^3 s^{-1}$. Over a 4-month period of 1 November to 28 February this input is 340 km^3. Therefore, the typical Haida eddy with 50 km^3 of fresh water carries offshore about 15% of the fresh water input to the shelf between November and February inclusive, with an observed range of 0% to 25%.

4.3. Comparison with Sitka eddies

Sitka eddies also carry heat and fresh water into mid-gulf, away from the shelf. These eddies are of similar size to Haida eddies (Tabata, 1982; Crawford, 2002), although slightly cooler due to their more northern origin. No detailed calculations are provided here of heat and fresh water transport by Sitka eddies, due to poor information on co-location of eddy centres and historical ship-based observations. However, both classes of eddies share many properties, and one can expect the magnitude of Sitka ddy transport to be of similar magnitude to that of Haida eddies. Together, they carry westward much of the fresh water and heat that accumulates in winter, and deflect offshore the northward flow of heat and freshwater that would otherwise continue to flow in the Alaskan Current and eventually in the Alaskan Stream.

5. Conclusions

Sitka and Haida eddies that form in winter along the British Columbia and Alaska continental margin carry significant heat and fresh water seaward, into the Gulf of Alaska, with major interannual variability. Detailed surveys through Haida eddies between 1995 and 2001 enable calculations of heat and fresh-water content and transport rates.

Offshore transport in the top 500 m by Haida eddies is about 30 exajoules in a typical winter with a range of 10–100 exajoules observed in other winters. This heat flow compares with northward transport rates of 50–80 exajoules in the top 500 m in a typical winter (November–February), and 120–200 exajoules in 1997–1998, a winter of very strong northward heat flow, based on calculations by Freeland (2002). In comparison, Tabata (1958) and Elliott (1965) compute the net upward heat flux from ocean to atmosphere in these months to be 70 exajoules over the entire Canadian continental margin.

Offshore transport of fresh water by Haida eddies is about 50 km^3 in typical winters with a range of 0–70 km^3. By comparison, estimates of fresh-water input along the entire B.C. and Washington State coast is about 300 km^3 between November and February. Therefore, the top 500 m of typical Haida eddies typically transport seaward about 15% of this fresh-water input, with a range of 0–25%.

Both excess heat and fresh-water content in eddies decrease in time and pass the 50% level within 12 months of eddy formation. In some cases, especially near the continental margin, eddies appear to gain heat by merging with younger eddies.

Acknowledgements

I am grateful for the insight and persistence of scientists, officers and crew of the Canadian Coast Guard Ship *John P. Tully*, especially: S. Tabata, F. Whitney, P. Boyd, M. Robert, R. Perkin, D. Mackas. I also recognise the insight and efforts of my colleague Dr. Susumu Tabata, who has led scientific studies of the Gulf of Alaska over the past 50 years. Robert Leben of the Colorado Center for Astrodynamics Research provided the Web site with images of eddy height contours. Thanks to Lisa Miller, Mike Foreman, Richard Thomson, Susumu Tabata, Frank Whitney and Howard Freeland for critical comments on this manuscript. Funding for CCGS *John P. Tully* cruises and analysis was provided by Fisheries and Oceans Canada.

References

Batten, S.D., Crawford, W.R., 2005. The influence of coastal origin eddies on oceanic plankton distributions in the eastern Gulf of Alaska. Deep-Sea Research Part II, this issue [doi:10.1016/j.dsr2.2005.02.009].

Crawford, W.R., 2002. Physical characteristics of Haida eddies. Journal of Oceanography (Issue on Physics and Biology of Eddies, Meanders and Rings in the PICES Region) 58 (5), 703–713.

Crawford, W.R., Whitney, F.A., 1999. Mesoscale eddy aswirl with data in Gulf of Alaska. Eos Transactions of the American Geophysical Union 80 (33), 365.

Crawford, W.R., Cherniawsky, J.Y., Foreman, M.G.G., 2000. Multi-year meanders and eddies in the Alaskan Stream as observed by TOPEX/Poseidon altimeter. Geophysical Research Letters 27 (7), 1025–1028.

Crawford, W.R., Cherniawsky, J.Y., Foreman, M.G.G., Gower, J.F.R., 2002. Formation of the Haida-1998 oceanic eddy. Journal of Geophysical Research (Oceans) 107 (C7) [doi:10.1029/2001JC000876].

Di Lorenzo, E., Foreman, M.G.G., Crawford, W.R., 2005. Modelling the generation of Haida Eddies. Deep-Sea Research Part II, this issue [doi:10.1016/j.dsr2.2005.02.007].

Elliott, J.A., 1965. A study of heat budget components for the British Columbia and S.E. Alaska Coast. Manuscript Report Number 18. Institute of Oceanography, University of British Columbia, Vancouver, B.C., Canada, 101 pp.

Freeland, H., 2002. The heat flux across Line-P 1996 to 1999. Atmosphere-Ocean 40, 81–89.

Freeland, H.J., Denman, K.L., 1982. A topographically controlled upwelling center off southern Vancouver Island. Journal of Marine Research 40, 1069–1093.

Gower, J.F.R., Tabata, S., 1993. Measurement of eddy motion in the north–east Pacific using the Geosat altimeter. In: Jones, I.S.F., Sugimori, Y., Stewart, R.W. (Eds.), Satellite Remote Sensing of the Oceanic Environment. Seibutsu Kenkyusha, Tokyo, pp. 375–382.

LeBlond, P.H., Dyck, K., Perry, K., Cumming, D., 1983. Runoff and precipitation time series for the coasts of British Columbia and Washington State. Manuscript Report Number 39, Department of Oceanography, University of British Columbia, Vancouver, 133 pp.

Mackas, D.L., Galbraith, M.D., 2002. Zooplankton distribution and dynamics in a North Pacific eddy of coastal origin: I. Transport and loss of continental margin species. Journal of Oceanography (Issue on Physics and Biology of Eddies, Meanders and Rings in the PICES Region) 58 (5), 725–738.

Melsom, A., Meyers, S.D., Hurlburt, H.E., Metzger, E.J., O'Brien, J.J., 1999. ENSO effects on Gulf of Alaska eddies. Earth Interactions 3. Available online at http://EarthInteractions.org

Musgrave, D.L., Weingartner, T.J., Royer, T.C., 1992. Circulation and hydrography in the northwestern Gulf of Alaska. Deep-Sea Research 39, 1499–1519.

Okkonen, S.R., Weingartner, T.J., Danielson, S.L., Musgrave, D.L., 2003. Satellite and hydrographic observations of eddy-induced shelf-slope exchange in the northwestern Gulf of Alaska. Journal of Geophysical Research 108 (C2) [doi:10.1029/2002JC001342].

Royer, T.C., 1982. Coastal freshwater discharge in the Northeast Pacific. Journal of Geophysical Research 87 (C3), 2017–2021.

Tabata, S., 1958. Heat budget of the water in the vicinity of Triple Island, British Columbia. Journal of the Fisheries Research Board of Canada 15, 429–451.

Tabata, S., 1965. Variability of oceanographic conditions at Ocean Station "P" in the northeast Pacific Ocean. Transactions of the Royal Society of Canada, Volume III: Series IV, Proceedings of a symposium on "Time Series Measurements in Canada", June 1965.

Tabata, S., 1982. The anticyclonic, baroclinic eddy off Sitka, Alaska, in the northeast Pacific Ocean. Journal of Physical Oceanography 12, 1260–1282.

Thomson, R.E., Gower, J.F.R., 1998. A basin-scale oceanic instability event in the Gulf of Alaska. Journal of Geophysical Research 103 (C2), 3033–3040.

Whitney, F., Robert, M., 2002. Structure of Haida eddies and their transport of nutrient from coastal margins into the NE Pacific Ocean. Journal of Oceanography (Issue on Physics and Biology of Eddies, Meanders and Rings in the PICES Region) 58 (5), 715–723.