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Impact of Haida Eddies on chlorophyll distribution in the Eastern Gulf of Alaska

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Abstract

Mesoscale Haida eddies influence the distribution of surface phytoplankton in the eastern Gulf of Alaska through two processes: enhanced productivity in central eddy water, and seaward advection of highly productive coastal waters in the outer rings of eddies. These two processes were observed in a sequence of monthly images over five years, for which images of SeaWiFS-derived chlorophyll distributions were overlaid by contours of mesoscale sea-surface height anomaly derived from TOPEX and ERS-2 satellite observations. Satellite measurements were supplemented with ship-based chlorophyll observations through one of the eddies. Haida eddies are deep, anticyclonic, mesoscale vortices that normally form in winter and early spring near the southwest coast of the Queen Charlotte Islands. High levels of chlorophyll observed in eddy centres indicated that they supported phytoplankton blooms in spring of their natal years, with timing of these blooms varying from year to year and exceeding in magnitude the chlorophyll concentrations of surrounding water. Elevated chlorophyll levels also were observed in eddy centres in late summer and early autumn of their natal year. Enhanced chlorophyll biomass is attributed to higher levels of macro-nutrients and higher levels of iron enclosed within eddies than in surface, deep-ocean water. By late spring and summer, when coastal water supported higher chlorophyll biomass than did oceanic offshore regions, eddies that straddled the continental margin entrained high chlorophyll coastal water into their outer rings and carried it several hundred kilometres into the Gulf of Alaska along their southern sides. On some occasions a deep-ocean eddy would entrain chlorophyll from an adjacent eddy located closer to the coast, forming a conveyor-belt transport process to inject coastal biota into the deep-sea region of the gulf. This process extended the coastal region of high-chlorophyll surface water (and therefore, phytoplankton-rich water) several hundred kilometres seaward and dominated the shelf-to-deep-ocean exchange of chlorophyll from late winter to the following autumn.

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1. Introduction

The Haida eddy region lies west of the Queen Charlotte Islands of northern British Columbia, Canada (Fig. 1), extending from 51°N to 54.5°N. Most Haida eddies form as anticyclones near Cape St. James at the southern tip of these islands (Crawford and Whitney, 1999; Crawford et al. 2002; Di Lorenzo et al., 2005) and carry fresh, warm, high-nitrate, coastal water of winter far into the Gulf of Alaska (Whitney and Robert, 2002; Crawford, 2002). They persist for several years, during which their unique waters are likely to influence the biological productivity of the regions through which they pass. Isopycnals depress in centres of Haida eddies below 150 m depth, and often dome slightly above 150 m, especially in summer. Isopycnal depression extends to 1000 m or more below surface, and dominates the baroclinic structure so that the surface waters of large Haida eddies rise by 30 cm or so above surrounding waters (Crawford, 2002). Geostrophic adjustment to this central high sea level sets up the clockwise, anticyclonic currents around all Haida eddies.

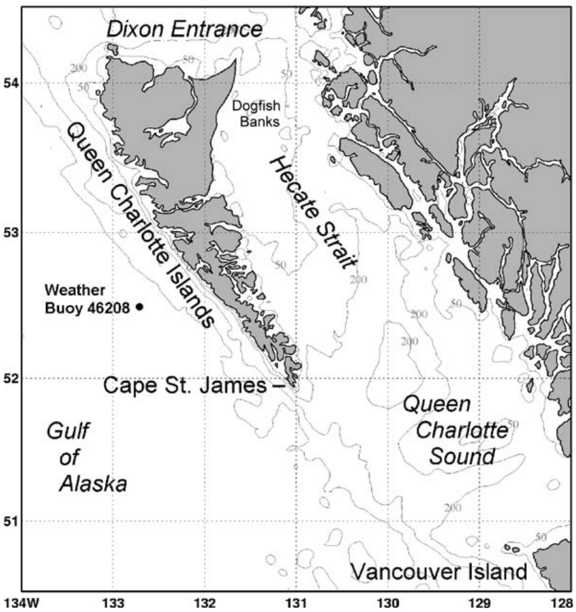

Fig. 1. Geographical Region. Depth contours are in metres.

Heavy cloud cover of the Gulf of Alaska blocks most visible and infrared radiation emitted upward from the ocean surface, allowing few images of surface ocean temperature or chlorophyll *a*. (Hereafter, we denote chlorophyll *a* as chlorophyll.) However, a composite of all clear regions available to satellites in a month provides useful information on mesoscale features, due to their relatively slow movement and evolution. Radar signals are able to penetrate clouds, enabling satellites with active radar systems to measure accurately the sea-surface height anomaly (SSHA). We combine remotely sensed composite images of ocean colour and SSHA images to examine the impact of Haida eddies on chlorophyll distributions over their entire domain.

A few studies have applied single-day ocean colour images to a qualitative treatment of this topic. Crawford et al. (2002) present a *Sea*-viewing *Wi*de *F*ield-of-View *S*ensor (SeaWiFS) image of chlorophyll concentrations on 4 March 1998 showing higher chlorophyll concentrations in a Haida eddy. This eddy had entrained surrounding waters into its outer rings, swirling high-chlorophyll waters from coastal regions and low chlorophyll, deep-sea waters into adjacent, nearly concentric rings in the eddy. An April 1979 image by the Coastal Zone Color Scanner (CZCS) presented by Denman and Powell (1984) also shows such swirling in two Haida eddies west of the Charlottes. Batten and Crawford (2005) present an account of combined zooplankton sampling, altimetry and a few individual SeaWiFS images along the eastern gulf in the spring of 2000 and 2001.

We extend these analyses to include 1998–2002 SeaWiFS observations, presented as monthly composites between March and October of each year, with an additional single-day image captured during the spring of 2002 that also includes Sitka eddies, which are similar vortices formed to the north of the Haida region. Quantitative chlorophyll concentrations are determined along tracks of four eddies and ship-based profiles are presented over a 16-month period through one eddy.

Our objectives are to

- document the role of Haida eddies as agents that redistribute or enhance coastal and oceanic chlorophyll over the continental margin and deep water of the Gulf of Alaska,

- compare and contrast temporal patterns observed inside the eddies with patterns in surrounding deep ocean water and those originating on the productive shelf,
- compare the remotely sensed data with available in situ data from research cruises.

2. Observations

We overlay contours of SSHA onto 39 images of monthly chlorophyll concentrations in surface water measured by SeaWiFS satellite (Fig. 2). SSHA are plotted at 4-cm intervals, with solid lines denoting zero or positive anomalies and dashed lines denoting negative anomalies. SSHA contours were computed by an Internet site maintained by Robert Leben (personal communication, 2002) of the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado, Boulder, using ERS-2 and TOPEX altimetry observations (Leben et al., 2002). SSHAs were determined relative to a multi-year average, and all data were passed through spatial and temporal filters to remove basin-wide and seasonal signals prior to plotting at the Internet site. In addition, inverse barometer effect, tides, ocean swell, and wind waves have all been removed from the signal prior to plotting. Resulting SSHA contours, therefore, highlight mesoscale oceanic features such as Haida Eddies.

The TOPEX/POSEIDON (T/P) and ERS-2 orbits repeat every 9.95 and 35.0 days, respectively. The CCAR Internet site updates SSHA images at three-day intervals using TOPEX data from previous days. We selected images between the 22nd and 25th day of each month to represent SSHA for mid-month.

SeaWiFS detects eight spectral bands of outgoing oceanic electromagnetic radiation in visible and infrared wavelengths, with coverage every two days in the northeast Pacific. Daily global-area-coverage SeaWiFS chlorophyll data produced with standard NASA global coefficients (OC4, version 4, O'Reilly, et al., 2000) are retrieved from the Distributed Active Archive Center (DAAC) at Goddard Space Flight Center. These data were sub-sampled over the study area (Fig. 2) and re-gridded to a cylindrical equidistant projection at 4-km resolution. Scenes from the same day were reformed into a single image to produce a daily time series. Variability is examined by forming 8-day and monthly composites from the daily images, resulting in a sequence of images from 1998 to 2002.

Monthly composite images are not presented from November to February inclusive. They normally reveal few features, due to low-light levels, shorter days and more clouds in winter. The number of cloud-free images contributing to each monthly average is weather-dependent and spatially and temporally variable. Turbid waters very close to shore (<10 km) in the vicinity of shallow bays and river outlets can result in erroneously high chlorophyll values because near-infrared radiances present in these conditions may violate assumptions of the OC4v.4 algorithm (e.g., Dogfish Banks). These regions were masked when clearly present, and sampling was restricted to more than 10 km from shore.

Chlorophyll concentration within Haida eddies and their surrounding waters are calculated using two methods. Monthly composite images are sampled with a 20×20 km box average, (5×5 pixels) positioned over eddy centres as determined by the combined altimetry and SeaWiFS imagery. (We apply the term "*eddy centre*" to the middle of the eddy at the ocean surface and the term "*eddy core*" to the portion of the eddy, often subsurface, with maximum or minimum levels of temperatures or other parameters.) Uncertainty in chlorophyll concentrations is typically ±0.1 mg m^{-3}. A similar analysis is applied at 8-day intervals to the SeaWiFS imagery, to determine time series of chlorophyll levels in the centre waters of eddies as they track away from the continental margin into deep water of the gulf. In this latter case, however, the ocean colour and SSHA data are used to define the eddy interior, ring, and representative non-eddy water and then sampled, respectively. Results from this subjective regional analysis do not differ significantly from sampling a standard-sized box area and allow for circumferential averaging within the eddy rings. Sampling avoided mid-winter days between 15 November and 15 January due to low solar zenith angle.

A dilation operation with a 3×3 kernel was employed to slightly enlarge the cloud-masked regions and remove cloud ringing present in some images. Cloud ringing results from transient detector saturation when scanning cloud tops, which have very high radiance. The saturation can contaminate the next pixel or two in the scan line and bias the chlorophyll retrievals. Dilation is a standard method in image processing (usually operating on binary or greyscale images, such as here) used to enlarge the masking area around known cloud locations and eliminate the ringing effects.

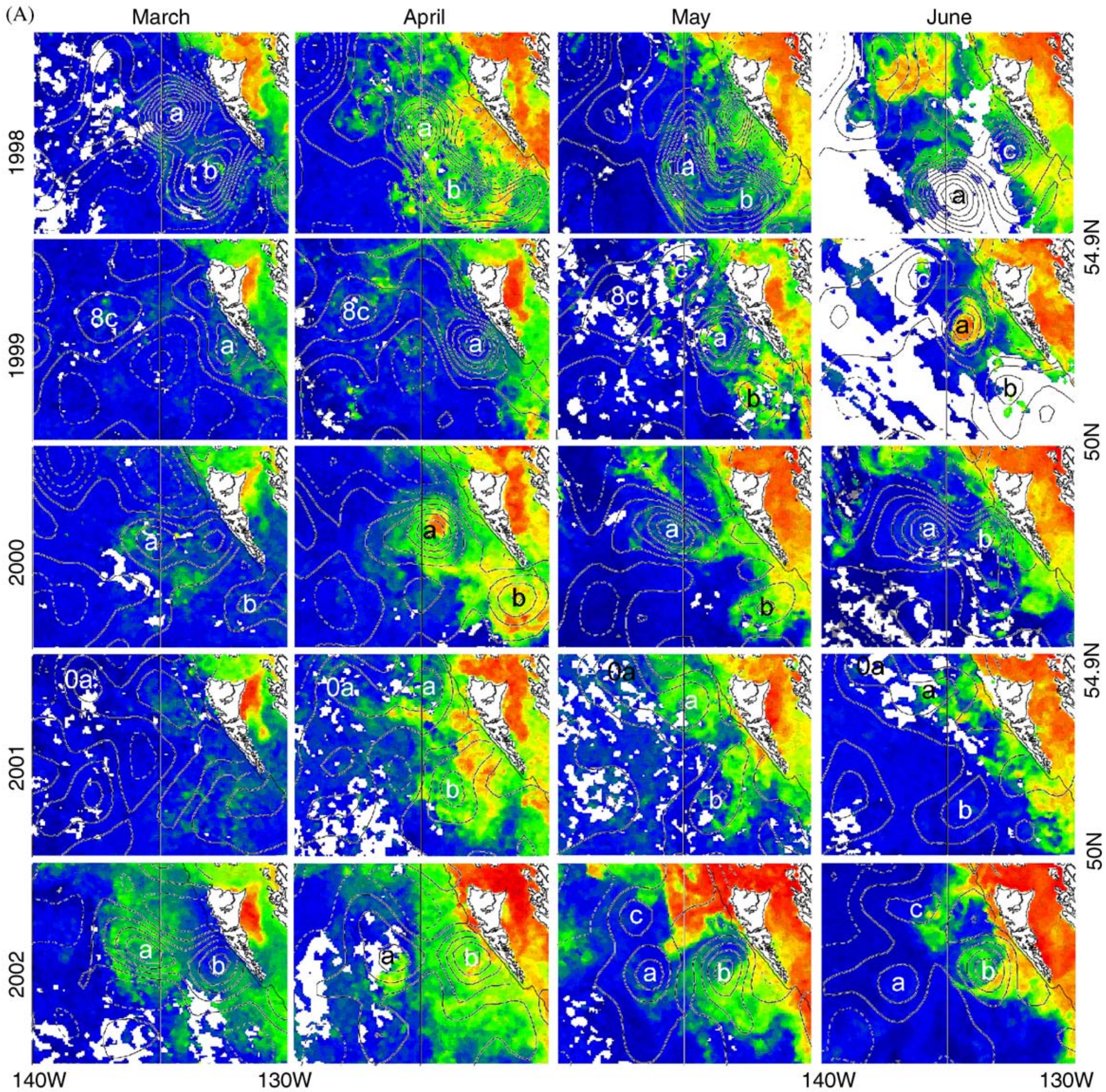

Fig. 2. Monthly composite images of chlorophyll concentrations based on SeaWiFS measurements, overlaid by contours of mesoscale sea-surface height anomaly, from March 1998 to September 2002. SeaWiFS contours are logarithmically scaled, in units of mg chl m^{-3}. Altimetry contours are plotted at 4 cm intervals, and are referenced to a multi-year mean with seasonal and basin-scale variability removed to enhance mesoscale features.

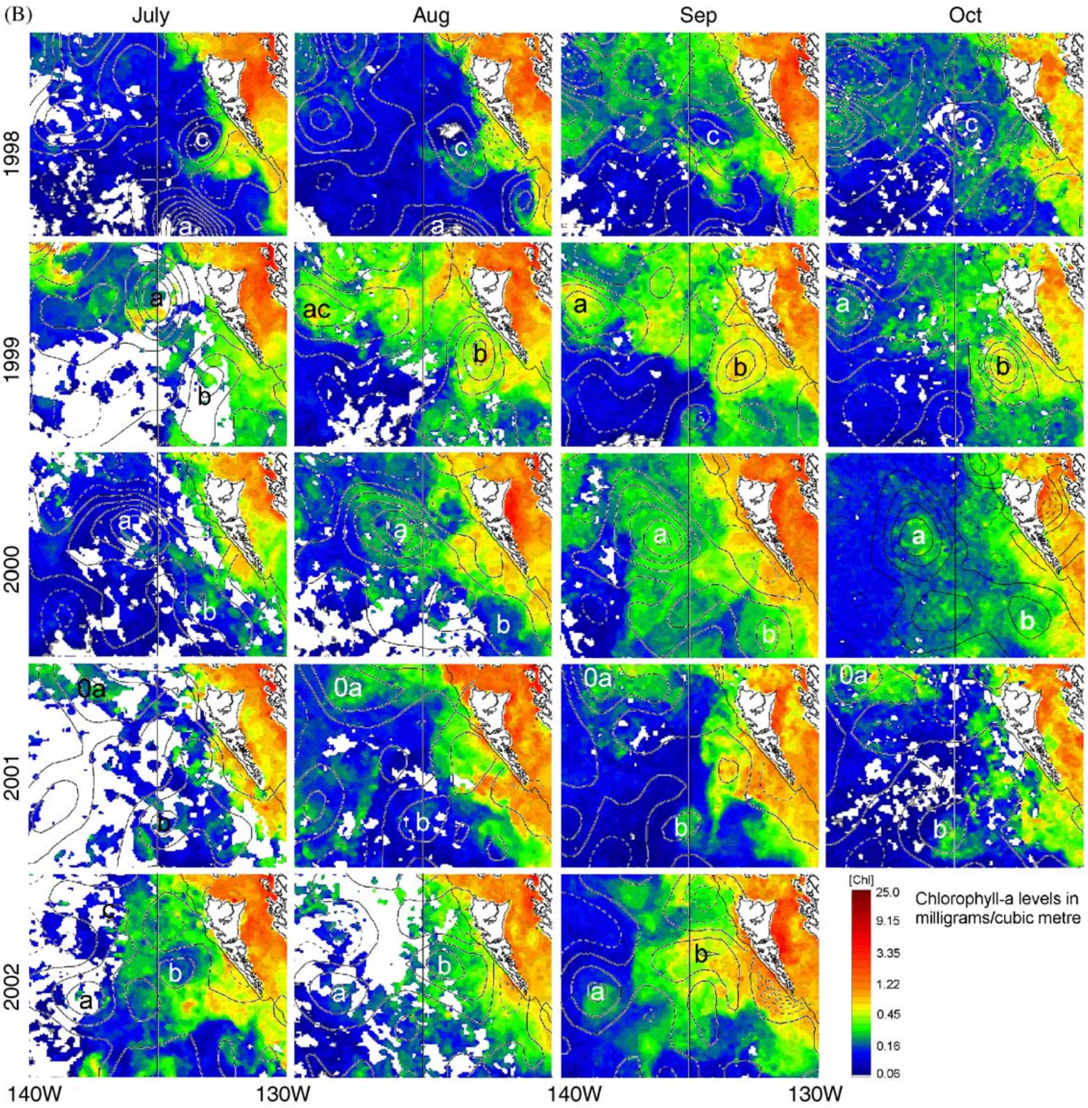

Fig. 2. (*Continued*)

The Haida-2000 eddy was tracked on its westward path from its formation location to its position after 20 months and sampled repeatedly over this time by scientists on board the Canadian Coast Guard Ship (CCGS) *John P. Tully*. Conductivity-Temperature-Depth (CTD) profiles were generated at 10 stations across the eddy using a Seabird CTD probe attached to a rosette frame for June and September cruises. Transects were conducted in a south-to-north direction for all cruises except September 2001, where inclement weather prevented such a sampling scheme. Instead, one detailed S–N half-transect was performed as well as one full transect from southwest to northeast with coarser station spacing. All contours are plotted along a transect increasing in latitude. For September 2001, the longitudinal component is neglected, and we assume that the chlorophyll distribution from centre-to-northeast is roughly equal to that of the centre-to-north radius of the eddy. At each station fluorescence and transmissivity profiles were generated from in situ fluorometer and transmissometer units mounted on the CTD/rosette frame. This transect together with near-real-time altimetry defined the eddy centre and edge, after which detailed chemical and biological sampling was conducted at three stations, one at the eddy centre, one at the edge, and one at a reference station outside.

Samples for chlorophyll were collected either in 10-l acid-cleaned GO-FLO bottles attached to Kevlar® line or from 10-l Niskin bottles mounted to a rosette frame. Sampling depths corresponded to 100, 55, 30, 10, 3, and 1% of near-surface irradiance (measured at 2 m depth) in spring and summer in order to coincide with sampling for primary productivity. Chlorophyll concentrations at fixed depths (0, 10, 30, 50, 75, 100 m) also were determined for cruises in September 2000 and for all cruises in 2001. Light depths were calculated following a cast to determine photosynthetically active radiation (PAR) using a LiCor 2-pi sensor calibrated using external standards.

Chlorophyll and phaeopigments were extracted using 90% v/v acetone (Parsons et al., 1984). Concentrations were measured on board using a Turner Designs™ 10-AU Fluorometer (for cruises conducted in 2000) and Turner Designs™ 10-A Analog Fluorometer (for cruises conducted in 2001) calibrated with chlorophyll (*Anacystis nidulans*, Sigma-Aldrich Chemicals®), the concentration of which had been verified spectrophotometrically. Duplicate chlorophyll samples on one of these cruises suggested an accuracy of about $\pm 0.005\,\mu g/l$ for these measurements. Extracted chlorophyll concentrations are presented for three cruises (September 2000, June 2001, September 2001).

Extracted chlorophyll concentrations were only determined for three stations in June 2000—centre, edge, and a reference site. For other stations along the eddy transect chlorophyll was estimated from relative fluorescence using a calibration curve generated from the extracted chlorophyll and fluorescence values measured from the three stations mentioned above. Fluorescence values were calibrated with acetone-extracted chlorophyll for all measurements taken in 2000. The average R^2 for the regression of estimated chlorophyll on extracted chlorophyll was >0.75 when all samples were pooled and >0.80 for station-specific comparisons. Integrated chlorophyll concentrations were determined by trapezoidal integration over the 1% light depth, typically ca. 50 m.

3. Results

3.1. Monthly composite images

Fig. 2 displays 39 images of chlorophyll concentrations for the months of March to October of the years 1998–2001, plus March to September 2002. An apparent high-chlorophyll region appears in Hecate Strait along the northeast coast of the Charlottes in each of the five March images. This region is Dogfish Banks, with shallow depths, rapid coastal erosion, and high sediment levels. We attribute these apparent high winter chlorophyll concentrations to the presence of sediments, coloured dissolved organic matter (CDOM), as well as phytoplankton. This same region in Hecate Strait has the highest tidal range of all shelf waters in British Columbia. Tides here are poorly resolved in the global tidal models used by CCAR to de-tide the altimetry data (Foreman et al., 2000; Cherniawsky et al. 2001). The SSHA contours are inaccurate in this region and are omitted from Fig. 2.

The two Haida eddies that formed in early 1998, Haida-1998a and Haida-1998b, began to merge in May 1998 to form Haida-1998, and reached the highest SSHA observed to date in any Haida eddy (Crawford, 2002), as well as the warmest and freshest (Crawford, 2005). Images of these two eddies in March 1998 in Fig. 2 (labelled **a** and **b**, respectively) reveal a patchy increase in chlorophyll within the eddies as compared to outside water. Average chlorophyll values within eddy centres were 0.5 and 0.6 $mg\,m^{-3}$ for both Haida-1998a and b, respectively. Surrounding water averaged less than 0.3 $mg\,m^{-3}$. It is unclear from the monthly composite images alone if the eddy itself had promoted these enhanced concentrations or if the eddies have advected high-chlorophyll water out of phytoplankton-rich regions during formation.

By April 1998, chlorophyll concentrations in the two eddies were higher than in deeper water to the west, but lower than observed in coastal regions near the Charlottes. The central chlorophyll concentrations were 0.6 and 0.8 $mg\,m^{-3}$ in May 1998 when the eddies began to merge. By June 1998, having merged into a single large eddy, only the far outer rings revealed enhanced chlorophyll concentrations, but much of this eddy was obscured by clouds. Chlorophyll concentrations dropped further in July in centre and ring water to the very low values of deep-sea regions, and the concentration in northern arcs remained very low through the summer as the eddy drifted south of 50°N and out of this SeaWiFS image.

Haida-1998c revealed depressed chlorophyll concentrations in its interior relative to surrounding water. It formed in June 1998 about 100 km or more to the north of Cape St. James. Its chlorophyll minimum extended from June 1998 (0.5 $mg\,m^{-3}$) to September 1998 (0.4 $mg\,m^{-3}$) and into October. We attribute low chlorophyll in its centre to the formation time and location. Upwelling winds in these waters normally do not begin before the month of July, and the formation region of Haida-1998c is far north of the intense tidal mixing at Cape St. James that stirs nutrients to the surface. From July 1998 onwards, it appeared to carry high-chlorophyll coastal waters offshore towards the west around its southern flank.

In contrast, Haida eddies that formed in the following years reveal high chlorophyll biomass with strong spring maxima in central eddy waters. This pattern is found in May and June 1999, April and May 2000, and to a lesser degree in May 2001 and April 2002. Lack of spring blooms in 1998 is likely related to larger-scale ocean processes associated with the 1997/98 ENSO, as described by Brickley and Thomas (2004).

Mid-eddy surface chlorophyll levels had dropped below 0.4 $mg\,m^{-3}$ by June 2000 and 2001, when sampled by CCGS *John P. Tully*. Low-surface chlorophyll concentrations are seen in July both inside and outside many eddies. (Note that the high-nitrate, low-chlorophyll (HNLC) surface waters of the Gulf of Alaska are found farther offshore than these eddies had drifted in their first summer.) Fig. 2 reveals that only Haida-1999a supported high chlorophyll levels through July, possibly a direct consequence of elevated chlorophyll in June persisting into the next month.

One pattern displayed in Fig. 2 is a chlorophyll maximum found in many eddies in late summer and early autumn. Haida-2001b displayed a clear example of this behaviour, beginning with a low-chlorophyll centre (0.6 $mg\,m^{-3}$) in May surrounded by higher chlorophyll water (1.2 $mg\,m^{-3}$). By early September the centre of the eddy had a local chlorophyll maximum of 0.5 $mg\,m^{-3}$, which increased through October to 0.9 $mg\,m^{-3}$. Haida-1999b gained chlorophyll in August and September, experiencing a one-month increase in the centre from 0.9 to 2.2 $mg\,m^{-3}$. Haida-2000a showed an April peak of 3.6 $mg\,m^{-3}$ in the eddy centre, lost most of its chlorophyll by July, but gained chlorophyll in August (0.6 $mg\,m^{-3}$). Its central chlorophyll concentrations in September nearly tripled from those of July, rising from 0.3 to 0.8 $mg\,m^{-3}$, but the rise of chlorophyll in surrounding coastal water in September exceeded the eddy growth rate. Chlorophyll concentrations generally diminished from September to October, both inside and outside eddies.

In summary, absolute chlorophyll values in almost all Haida eddies rose from July to September, and the existence of a relative chlorophyll maximum in eddy centres most likely depended on the relative phytoplankton growth rates within and outside the eddies. Eddies farthest from coastal influence in late summer normally displayed central maxima at least double the concentration of surrounding water.

3.2. *Chlorophyll biomass along eddy tracks*

We next present time series of chlorophyll concentrations in four individual eddies through the year, based on successive 8-day composites of SeaWiFS observations over this region. Each data point is the cumulative-average value over one of three variable-sized regions defined for each eddy:

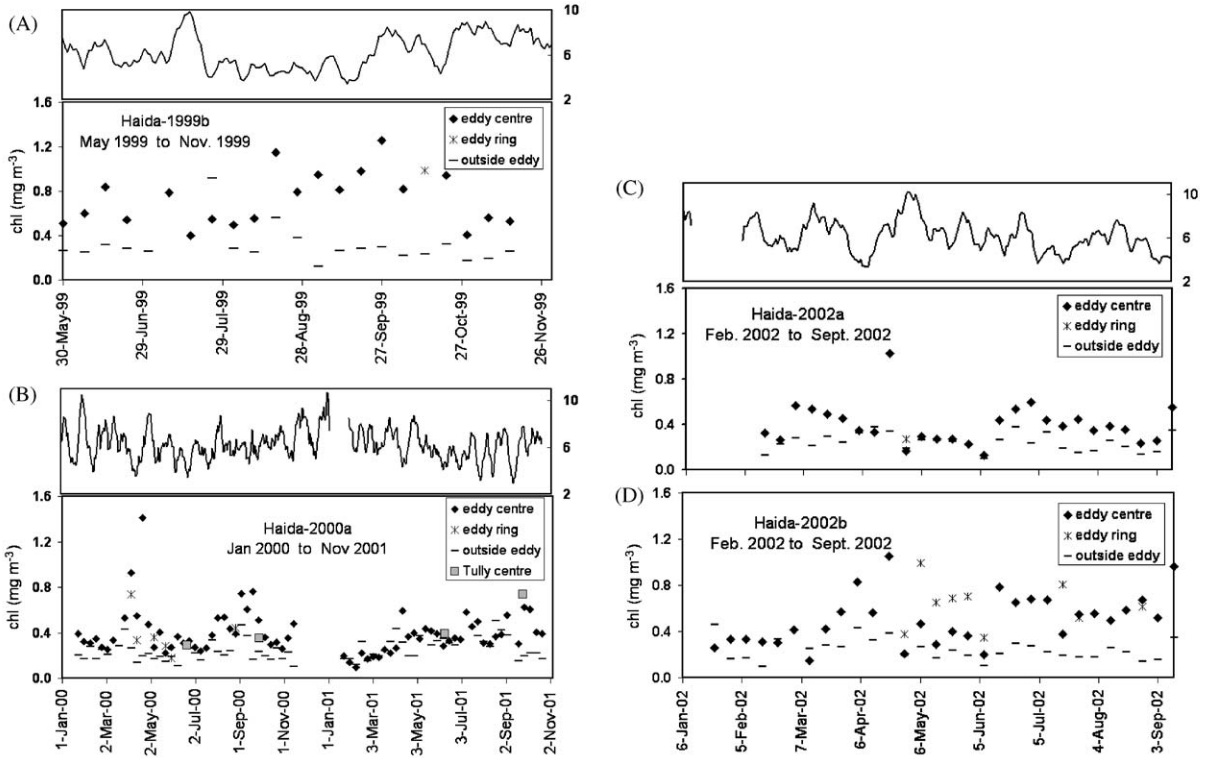

Fig. 3. Time series of chlorophyll measured by SeaWiFS and sampled in successive 8-day intervals: (A) Haida-1999b; (B) Haida-2000a; (C) Haida-2002a; (D) Haida-2002b. Each symbol represents the average of available observations in a 5×5 pixel region of ocean, in each of three zones of Haida eddies: centre, outside, and outer ring. Surface measurements from CCGS *John P. Tully* also are included. Top graphs in (A), (B) and (C) show 8-day average wind speed at Weather Buoy 46208, in $m\,s^{-1}$.

inside the eddy, outside the eddy, and in the outer rings (where these are very obvious). Selection of each region was guided by both the ocean colour images and by the SSHA contours.

Fig. 3 presents these time series plots. Haida-2000a (panel B) provided the longest time series, beginning with its formation in mid-January 2000 and continuing for 22 months except for the winter gap due to low solar angles. High chlorophyll was observed first in late March 2000, with peak values reaching $1.3\,mg\,m^{-3}$ in April 2000 and falling to background (outside eddy) values of $0.3\,mg\,m^{-3}$ by June 2000. A few of the 8-day composites reveal the same high chlorophyll levels in an outer ring of Haida-2000a that were noted in Fig. 2 for April and May, 2000. Chlorophyll in the outer ring appeared to be a distinct patch from the one in the centre and was advecting seaward along the southern edge. Outside waters displayed no concurrent chlorophyll increase, rising above $0.4\,mg\,m^{-3}$ only once between January 2000 and June 2000. Chlorophyll concentrations inside Haida-2000a remained between 0.3 and $0.4\,mg\,m^{-3}$ in June.

The SeaWiFS-based chlorophyll concentrations in Haida-2000a rose to $0.7\,mg\,m^{-3}$ in September and dropped back below $0.4\,mg\,m^{-3}$ in October 2000. The maxima in April and September were noted in the previous section. Low chlorophyll concentrations in June were coincident with low wind speeds; rising chlorophyll from July to September might be attributed to the rising, strong, episodic winds through these months. This late-summer increase maintained levels of chlorophyll above $0.5\,mg\,m^{-3}$, with maximum increase during periods of decreasing wind speeds.

Observations in 2001 reveal a weaker spring maximum, summer minimum, and late summer rise.

The time series for Haida-1999b (panel A) reveals chlorophyll levels in the eddy centre to exceed those in outside, deep-ocean water throughout most of May through mid-November. Peak concentrations of $1.2\,\mathrm{mg\,m^{-3}}$ occurred in September 1999 during a period of increasing winds. Chlorophyll remained above $0.8\,\mathrm{mg\,m^{-3}}$ throughout the following month, while wind speeds diminished in strength. Centres of both Haida-2002a and 2002b (panels C and D) maintained higher chlorophyll concentrations than found in outside deep-ocean water over almost all 8-day intervals between winter and September. Haida-2002a, being farther offshore than its neighbour, displayed less chlorophyll variability from one 8-day interval to the next, perhaps due to less interaction with coastal waters.

The time series for Haida-2002b suggests the centre of this eddy had higher chlorophyll than outside water in late winter and very early spring. However, it appears that the high chlorophyll levels attributed to the centre in April might have been advected offshore by the eddy in rings, rather than grown locally, since the spatial separation of centre and inner ring here is small and difficult to distinguish accurately. The interior concentrations declined in mid-spring to values similar to non-eddy regions. Through late spring and early summer (mid-April to end of May) the interior concentrations remained low, but grew relatively high in the ring as the eddy entrained high chlorophyll from the nearby shelf. In late summer and early fall there was a steady increase in interior chlorophyll relative to the surrounding deep-ocean, coincident with the decay in height of this eddy. We speculate that waters from the outer ring may have been stirred into the centre as this eddy decayed in strength.

3.3. Comparison to ship-based observations in Haida-2000a

Haida-2000a was well studied by scientists on CCGS *John P. Tully*. It began life near Cape St. James in early 2000, drifted north-westward during the spring of 2000, and stalled near 136°W between June and September 2000. By March 2001 this eddy could still be identified in SSHA contours of Fig. 2, labelled **0a** near 54°N, 138°W. Between April and May 2001 a weak maximum in chlorophyll relative to non-eddy waters appears in Fig. 3B, but is not easily discerned in Fig. 2, perhaps owing to the longer averaging period applied to the images in Fig. 2. During these two months Haida-2000a might have entrained high-chlorophyll surface water from Haida-2001a (water entrained clockwise from south has chlorophyll concentrations of $1.6\,\mathrm{mg\,m^{-3}}$). Peterson et al. (2005, denoted PWH hereafter) arrive at a similar conclusion based on ship-board observations. It appears that these two eddies formed a conveyor-belt advection to carry coastal water into mid-gulf. In July 2001 these two eddies merged and drifted north-westward with the label **0a** in Fig. 2.

3.3.1. February to June, 2000

SeaWiFS images show that surface chlorophyll levels in Haida-200a dropped from a local maximum in April ($3.6\,\mathrm{mg\,m^{-3}}$) to very low levels in July ($0.3\,\mathrm{mg\,m^{-3}}$). Whitney et al. (2005a), denoted WCY03 hereafter) and PWH note that surface nitrate and silicic acid concentrations were higher in the centre of Haida-2000a in February 2000 than observed outside the eddy, but were lower in the eddy centre in June 2000 than in surrounding water. Drawdown of silicic acid was much greater than drawdown of nitrate in the eddy centre, indicating diatom growth. Chierici et al. (2005) undertook ship-based measurements, and observed of Haida-2000a that the greatest loss of nitrate and total inorganic carbon occurred in the centre of Haida-2000 during the first year between February and June 2000. They concluded that the highest biological production of carbon (ΔC^{bio}), as derived from integrated nitrate loss in the surface water, was also during in this period.

Measurements in Haida-2001b while it was forming in February 2001 revealed much higher iron levels than in surrounding non-eddy water (Johnson et al., 2005). Higher iron concentrations in young eddies in late winter are attributed to their formation process, when coastal water from Hecate Strait and Queen Charlotte Sound flows offshore to form these eddies (Crawford et al., 2002; Di Lorenzo et al., 2005). These coastal waters acquire nutrients in winter by river runoff and by turbulent mixing from below due to storm winds and tidal currents, processes that inject high levels of all macro- and micro-nutrients. Silicic acid and iron concentrations are generally higher in coastal waters that have strong river input or exposure to bottom sediments (Whitney et al., 2005b). Deep-ocean waters in winter experience only near-surface wind-mixing and, therefore, achieve lower levels of silicate and iron than normally derive from sediments and river flow. In light of these observations, we believe similar conditions were present in Haida-2000a and in other forming Haida eddies in winter. Therefore, we expect that the high chlorophyll concentrations observed in Haida-2000a in the April 2000 SeaWiFS image were closely correlated with higher levels of both macro- and micro-nutrients. The subsequent low levels of macro-nutrients observed in June in Haida-2000a compared to surrounding water (PWH) may have been a direct result of rapid depletion the previous month by a community of phytoplankton supported, in part, by higher in situ iron concentrations than were found in the surrounding region.

3.3.2. June 2000 to September 2001

Fig. 4 presents plots of vertical distributions of chlorophyll in the top 100 m along S–N sections through Haida-2000a, based on measurements from CCGS *John P. Tully* during some of the sampling dates noted in Table 1, beginning in June 2000. The location of the eddy centre, edge and exterior are based on major trends in hydrographic profiles at the indicated stations determined on the initial CTD/rosette survey transect through the eddy. Centre and edge station locations are indicated in Fig. 4.

The vertical distribution of chlorophyll was likely associated with the mixed-layer concentrations of silicic acid and nitrate during eddy evolution. In June 2000, silicic acid and nitrate concentrations in the mixed layer were very low (PWH), and the chlorophyll concentrations were small for the eddy centre and edge stations, especially near surface. The chlorophyll estimates made from fluorescence measurements slightly underestimated chlorophyll concentrations for June 2000, particularly in deeper waters at the eddy centre. At 56 m the extracted chlorophyll concentration was $0.51\,\mathrm{mg\,m^{-3}}$ rather than $0.31\,\mathrm{mg\,m^{-3}}$ at 50 m as estimated by the fluorescence. In September 2000, the surface chlorophyll concentrations were somewhat higher at the edge stations than measured in June 2000. Both cruises found sub-surface maxima in chlorophyll concentrations. Interestingly, highest concentrations in June 2000 were near 50-m depth outside the eddy (to the north). In June of the second year, when mixed-layer nutrient concentrations were higher, chlorophyll concentrations were also higher than in the previous June, perhaps due to sampling earlier in the year in 2001, or a delayed phytoplankton bloom in 2001. Either factor could have delayed the draw down of nutrients and decrease in phytoplankton concentrations. Chlorophyll concentrations were relatively high just below the mixed layer at the centre station in June, 2001, and high all through the mixed layer at the centre station in September, 2001. Although nutrient concentrations were lower within the mixed layer in September 2001 compared to the reference station (PWH), nitrate was 3.5 times higher at the eddy centre than measured the previous September, and silicic acid was 2 times higher, perhaps due to vertical mixing by high winds.

Total chlorophyll integrated from 2-m below surface to the depth of 1% light level showed a tendency to be elevated at the eddy centre in June 2000 relative to water outside the eddy, as listed in Table 2. Centre concentrations were lower than outside in September 2000, but the difference in concentrations is smaller and might not be significant. Relative to outside stations, centre concentrations in 2001 were comparable in June and higher in September.

4. Discussion

To investigate the influence of mesoscale eddies on chlorophyll concentrations in surface waters of the Haida Eddy region, we have presented a series of 39 monthly images in Fig. 2. These images show

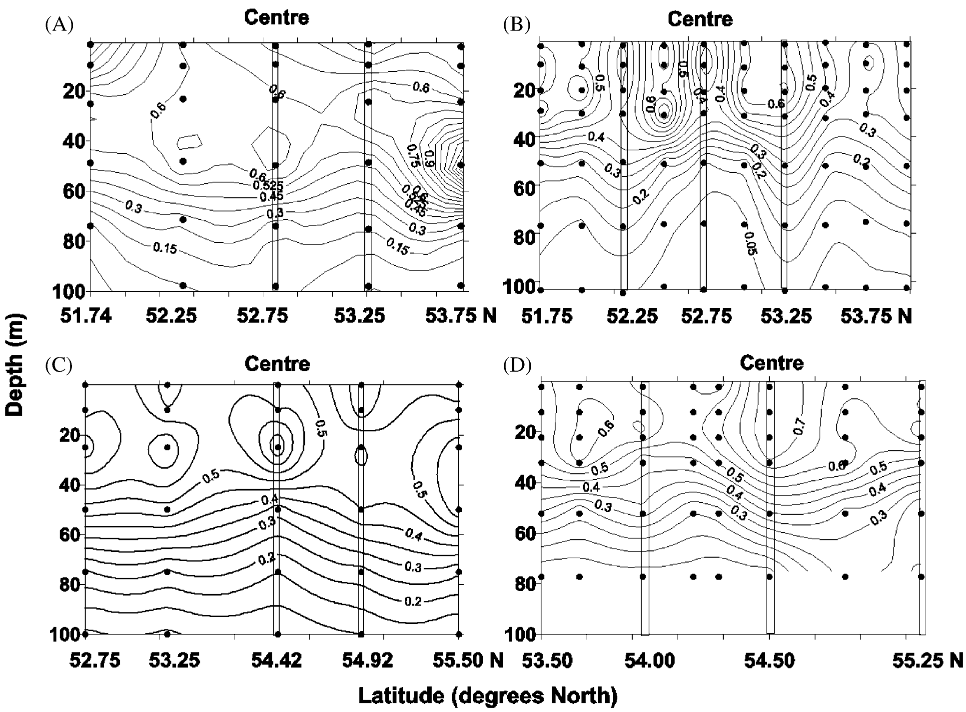

Fig. 4. Contour plots of chlorophyll concentrations across Haida-2000 and vicinity in (A) June 2000, (B) September 2000, (C) June 2001, and (D) September 2001. June 2000 chlorophyll concentrations (top left) are based on relative fluorescence measurements, and are somewhat lower than direct chlorophyll measurements in the deeper waters (1% surface irradiance, 56 m). Dots denote sample points. Centre stations are labelled and denoted by vertical lines. Edge stations are denoted by vertical lines only.

Table 1
Sampling dates of Haida-2000a by CCGS John P. Tully

Central eddy station position	Eddy sample dates
52° 19.93′N 134° 00.09′W	14–16 February 2000
52° 45.10′N 135° 49.86′W	18–21 June 2000
52° 44.92′N 136° 09.98′W	26–29 September 2000
53° 47.92′N 137° 29.80′W	16–18 February 2001
54° 24.78′N 138° 10.09′W	8–11 June 2001
54° 30.02′N 138° 20.03′W	22–26 September 2001

agreement between chlorophyll features observed by SeaWiFS and mesoscale sea-surface height anomalies observed by satellites. This result agrees with observations by Doney et al. (2003) that the spatial scale of variability observed globally in SeaWiFS observations matches the scales found in altimetry measurements. They find SeaWiFS scales of 100–150 km at latitudes of Haida eddies, in the mid-range of typical diameters of these eddies.

From March to October of most years, chlorophyll concentrations are high in coastal regions ($>1\,\mathrm{mg\,m^{-3}}$, but typically higher) of Hecate Strait, Queen Charlotte Sound, and Cape St. James, but decrease seaward toward the HNLC region of the Gulf of Alaska (typically $0.3\,\mathrm{mg\,m^{-3}}$). High concentrations of surface macro- and micronutrients in coastal areas contribute to this high-chlorophyll signal. Nutrients reach the ocean surface through several mechanisms: river flow, tidal mixing, relaxation of winter coastal downwelling, and summer coastal upwelling along the eastern sides of Hecate Strait and Queen Charlotte Sound and the West Coast of the Charlottes. (Whitney et al., 2005b) discuss the relative contributions of these processes to individual nutrient levels.) Haida eddies carry this coastal

Table 2
Chlorophyll concentration ($mg\,m^{-3}$) at surface, and vertically integrated concentration ($mg\,m^{-2}$) from 2 m below surface to depth of the 1% light level

Month and year of sampling	Eddy	Station	Integration depth (m)	Surface chl *a* ($mg\,m^{-3}$)	Vertically integrated Chl.-*a* ($mg\,m^{-2}$)
June 2000		Outside	65	0.33	19
	H-2000a	Centre	56	0.33	29
	H-2000a	Edge	54	0.32	17
Sept 2000		Outside	52	0.62	31
	H-2000a	Centre	52	0.45	26
	H-2000a	Edge	54	0.40	20
June 2001		Outside	53	0.58	17
	H-2000a	Centre	47	0.51	18
	H-2000a	Edge	51	0.38	22
Sept 2001		Outside	53	0.32	15
	H-2000a	Centre	54	0.80	25
	H-2000a	Edge	45	0.57	22

Edge stations in 2000 were to the south of the eddy centre, and to the north in 2001.

water, with its high nutrient and chlorophyll loads, westward into the Gulf of Alaska through two distinct processes: advection in the core and advection in outer rings, as described below.

4.1. Advection in core

Eddy cores contain nutrient-rich coastal water formed in winter and carry these nutrients westward into the gulf. Anticyclonic eddy rotation forms a deep reservoir of warm, fresh, nutrient-rich water in mid-eddy. With the addition of sufficient light, this situation leads to high spring chlorophyll biomass and is observed in centres of Haida Eddies in all years between 1999 and 2002. Detailed ship-based measurements in Haida-2000a in June 2000 revealed that this spring chlorophyll bloom drew down macro-nutrients to lower levels than observed outside eddy cores, likely due to enhanced iron levels during the spring bloom within the eddy that allowed higher plankton productivity (WCY03). By early summer the phytoplankton bloom in mid-eddy would have consumed almost all micro- and macro-nutrients. An increase in phytoplankton biomass that followed thereafter was probably the result of inflow of nutrients from the sides or from the reservoir of nutrient-rich water below the surface mixed layer (PWH; WCY03; Johnson et al., 2005) that upwelled as the eddy rotation rate decreased during eddy decay (Mackas et al., 2005).

4.2. Advection in outer rings

The second process takes place between spring and autumn, once eddies have drifted westward and straddle the transition zone of coastal and deep-ocean water. Eddies entrain these water masses into their outer rings and swirl them through large arcs, hundreds of kilometres long across the continental margin. On some occasions (e.g. Haida-2000a and Haida-2001a) a deep-ocean eddy would entrain chlorophyll from an adjacent eddy located closer to the coast, forming a conveyor-belt transport process to inject coastal biota into deep-sea region of the gulf. By winter the eddies are usually too far west to entrain coastal water, and plankton productivity has declined everywhere due to low-light levels and deep mixing. Okkonen et al. (2003) reported advection in outer rings by a Sitka eddy along the north-western Gulf of Alaska near Kodiak Island. They demonstrate how near-surface shelf water was swept seaward by the eddy as it deflected the surface coastal current offshore. Brickley and Thomas (2004) also note the impact of eddies on chlorophyll distribution in the margin of the Gulf of Alaska.

The seaward transport by outer rings can be swift. The speed of this transport can be evaluated using drifter measurements in Haida-2001b in June and July 2001, which revealed speeds of $0.25\,\mathrm{m\,s^{-1}}$ at 50 km from the centre, in the outer rings of the eddy (Yelland and Crawford, 2005). At this speed, entrained coastal water could be carried through one-half cycle and 100 km seaward in just six days, within the lifetime of zooplankton and eggs and larvae, and within a few lifetimes of phytoplankton. Mackas and Galbraith (2002) and Batten and Crawford (2005) have observed coastal zooplankton in Haida eddies far offshore, and Perry (personal communication, 2002) has observed fish larvae of coastal origin in a Haida eddy. Clearly, one can expect Haida eddies to carry live coastal species to Bowie Seamount (53°18′N, 135°37′W) and nearby seamounts through spring to autumn, and possibly into winter, although our coverage here does not include winter months.

Fig. 5 presents a single-swath SeaWiFS image for 13 June 2002 that illustrates advective processes well. This figure presents a sub-region of the largest cloud-free SeaWiFS image of many years, no doubt due to a massive high-pressure system over the eastern gulf at that time. On this day the central regions of both Haida-2002a and Sitka-2002 again contained higher chlorophyll levels than found in nearby deep-ocean water. This second spring maximum in chlorophyll can be found in time series of Figs. 3c and 3d. These Haida and Sitka eddies straddled the transition region between relatively low-chlorophyll oceanic water and higher-chlorophyll coastal water. Several offshore-directed jets (labelled **j**) are visible in this image. The jet near Sitka-2002 distorted the eddy along its eastern side and carried some high-chlorophyll eddy water away in its associated clockwise (**c**) and anticlockwise (**a**) eddies. Both the jet and Sitka-2002 carried high-chlorophyll surface waters, and their interaction stirred these waters through the region. One jet flowed offshore to the south of Haida-2002a and could be the major source of high chlorophyll in Haida-2002a in late spring. Another type of eddy-jet interaction is found in Haida-2002c. This relatively weak anticyclonic flow had pushed the jet to the south and distorted its cyclonic and anticyclonic eddies.

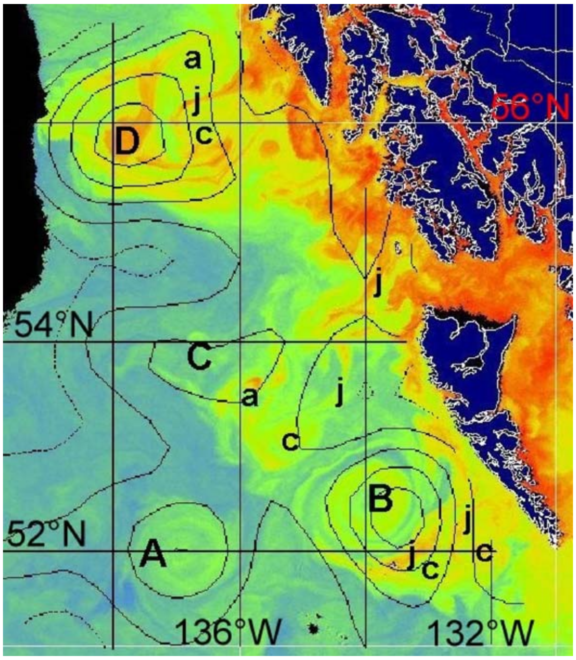

Fig. 5. SeaWiFS image of ocean colour near the Queen Charlotte Islands on 13 June 2002 with overlain black SSHA contours at 4 cm intervals. Features in the colour image denoted **a** and **c** are smaller cyclonic and anticyclonic eddies respectively, associated with jets **j** directed away from shelf waters. Eddies in image: (**A**): Haida-2002a; (**B**): Haida-2002b; (**C**): Haida-2002c; (**D**): Sitka-2002. Colours have been adjusted to bring out flow features and do not correspond to the chlorophyll-a scale in Fig. 2. Black regions denote clouds or regions with no data.

4.3. Mixing and advection up into eddy centre

By late summer all surface nutrients in eddy centres are low (PWH), but within the eddy core below the surface mixed layer exist sufficient micro- and macro-nutrients needed to begin and sustain an autumn phytoplankton bloom caused by mixed layer deepening during storms. Mid-gulf surface waters outside eddies often lack sufficient iron to sustain such a bloom. Therefore, one expects isolated phytoplankton blooms in eddy centres in September if eddies are far offshore, beyond the reach of advection by the outer rings of neighbouring, near-shore eddies. Examples are provided by Haida-2002a in September 2002 and Haida-2001b in September and October 2001. Both are offshore of any chlorophyll-rich filaments of coastal water. Alternatively, this high-nutrient reservoir may be tapped by relaxation of isopycnal depression as eddies spin down or by upwelling of nutrients along steeply sloping isopycnals in the periphery of the eddy, similar to the mechanisms proposed by Franks et al. (1986) and Yentsch and Phinney (1985) for Gulf Stream warm-core rings. Whitney and Robert (2002) observed a Haida eddy in early September 1998 about 130 km southwest of its formation region. They found a region of high biomass in its outer ring between 40 and 70 m below surface, which they suggest could be due to phytoplankton whose growth was enhanced by nutrients that advected upward and outward along upward-sloping isopycnals.

In addition to advecting high-chlorophyll coastal water into the gulf, Haida eddies sometimes advect low-chlorophyll deep-sea water shorewards. Often, both coastal and deep-sea waters are intertwined in Haida eddies, creating a series of rings of alternating low- and high-chlorophyll waters in the outer rings of the eddies. Such rings were observed in the early satellite observations by the CZCS in April 1979 (Denman and Powell, 1984). We speculate that if this stirring creates turbulence that mixes these two water masses together at microscale levels near surface, the iron from the eddy water and nitrate from the outside ocean water will both be together at molecular scales to sustain higher productivity than possible in the separate water masses. High chlorophyll levels in Haida-2002a in September 2002 might be attributed to this stirring. Interleaving is clearly observed in the 13 June 2002 image of Fig. 5, and the August 2000 and October 2001 panels in Fig. 2 also show the eddy holding both high- and low-chlorophyll waters. Enhanced winds in autumn would mix these water masses at molecular levels, bringing all nutrients to plankton and sustaining the bloom observed in September.

Finally, the westward extent of Haida eddies (and also Sitka eddies) likely pushes westward the average location of the NW boundary of HNLC water of the Gulf of Alaska. These eddies carry coastal water westward into the gulf and are able to inject upward their higher levels of iron into the mid-gulf upper mixed layer. Once at surface, enhanced iron levels may stimulate phytoplankton to draw down nitrate below levels defined as HNLC.

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