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Progress in Oceanography 75 (2007) 287–303

Progress in Oceanography

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Mesoscale eddies dominate surface phytoplankton in northern Gulf of Alaska

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Abstract

The HNLC waters of the Gulf of Alaska normally receive too little iron for primary productivity to draw down silicate and nitrate in surface waters, even in spring and summer. Our observations of chlorophyll sensed by SeaWiFS north of 54°N in pelagic waters (>500 m depth) of the gulf found that, on average, more than half of all surface chlorophyll was inside the 4 cm contours of anticyclonic mesoscale eddies (the ratio approaches 80% in spring months), yet these contours enclosed only 10% of the total surface area of pelagic waters in the gulf. Therefore, eddies dominate the chlorophyll and phytoplankton distribution in surface pelagic waters. We outline several eddy processes that enhance primary productivity. Eddies near the continental margin entrain nutrient – (and Fe) – rich and chlorophyll-rich coastal waters into their outer rings, advecting these waters into the basin interior to directly increase phytoplankton populations there. In addition, eddies carry excess nutrients and iron in their core waters into pelagic regions as they propagate away from the continental margin. As these anticyclonic eddies decay, their depressed isopycnals relax upward, injecting nutrients up toward the surface layer. We propose that this transport brings iron and macro-nutrients toward the surface mixed layer, where they are available for wind-forced mixing to bring them to surface. These mesoscale eddies decay slowly, but steadily, perhaps providing a relatively regular upward supply of macro-nutrients and iron toward euphotic layers. They might behave as isolated oases of enhanced marine productivity in an otherwise iron-poor basin. We note that much of this productivity might be near or just below the base of the surface mixed layer, and therefore poorly sampled by colour-sensing satellites. It is possible, then, that eddies enrich phytoplankton populations to a greater extent than noted from satellite surface observations only.

Keywords: Mesoscale; Eddies; Phytoplankton; Gulf of Alaska

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1. Introduction

1.1. Background oceanography

The Alaska Gyre lies in the Gulf of Alaska under the cyclonic winds of the Aleutian Low pressure system (Dodimead et al., 1962; Favorite et al., 1976). This gyre and neighbouring currents are illustrated in Fig. 1.

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0079-6611/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.pocean.2007.08.016

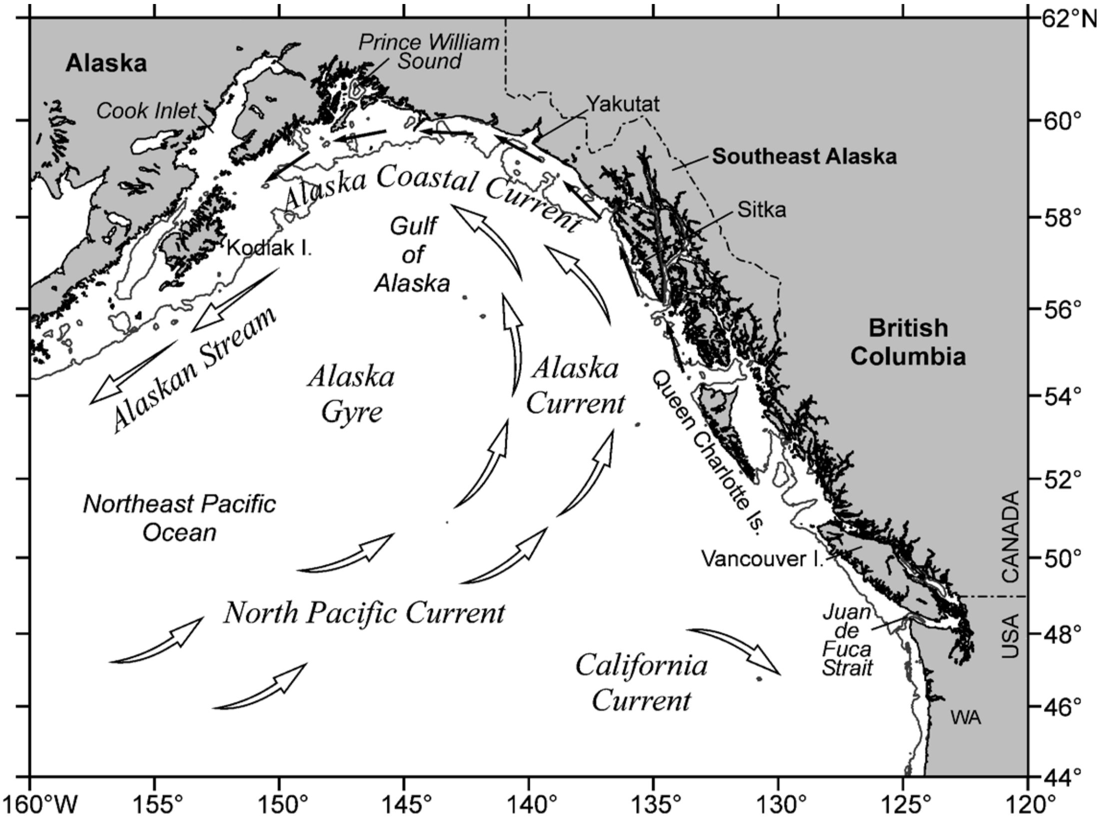

Fig. 1. Geographical features surrounding the Gulf of Alaska and main currents of this basin. The 200 m contour is shown in grey.

The Alaska Gyre reveals itself as a series of connected lows in a map of dynamic topography of the sea surface, as illustrated in Fig. 2, based on our compilation of all archived measurements (1929–2005) of temperature and salinity profiles in the Gulf of Alaska. Low dynamic heights are formed by Ekman surface flow away from the centre of the cyclonic Aleutian Low pressure system. The near-surface upwelled waters in mid-gyre that replace this outflow are cooler and saltier. Gargett (1991) computes an upwelling rate of 30 m/year in mid-gyre, as well as an effective upwelling rate of 8 m/year due to mixing. Central waters of the Alaska Gyre are labelled "High-Nitrate, Low-Chlorophyll" (HNLC) due to the inability of phytoplankton to use all available macro-nutrients in surface waters in summer. High phosphate concentration in the gyre is first noted by Reid (1962) and high nitrate by Anderson et al. (1969).

Various interactions of strong mixing and slow phytoplankton growth were invoked to explain this HNLC condition, however ship-board incubation studies by Martin and Fitzwater (1988) revealed that the central gulf is likely iron limited. The subarctic ecosystem response to iron enrichment experiment (SERIES) in 2002 injected dissolved iron into surface waters at Ocean Station Papa (50°N, 145°W) in July 2002 and stimulated a significant phytoplankton bloom. This program firmly established that iron is the limiting nutrient (Boyd et al., 2004), a feature shared with HNLC regions in the northwest Pacific subarctic gyre, the eastern equatorial Pacific and the Southern Ocean. Surface waters of all these regions receive higher-than-normal input of macro-nutrients due to local, wind-forced upwelling and mixing, but these deep sources of nutrients are too iron-poor to allow phytoplankton to consume all upwelled nitrate. Non-HNLC waters receive sufficient iron in atmospheric dust or riverine and sedimentary minerals to allow nitrate drawdown, either because the input of iron is relatively large, or because the local sources of macro-nutrients are relatively small (Cullen, 1991).

Fig. 3 presents summer, ocean-surface nitrate concentrations in the Gulf of Alaska for the month of August. The high-nitrate waters of the central gulf are clearly present. Surface waters in shelf and slope regions

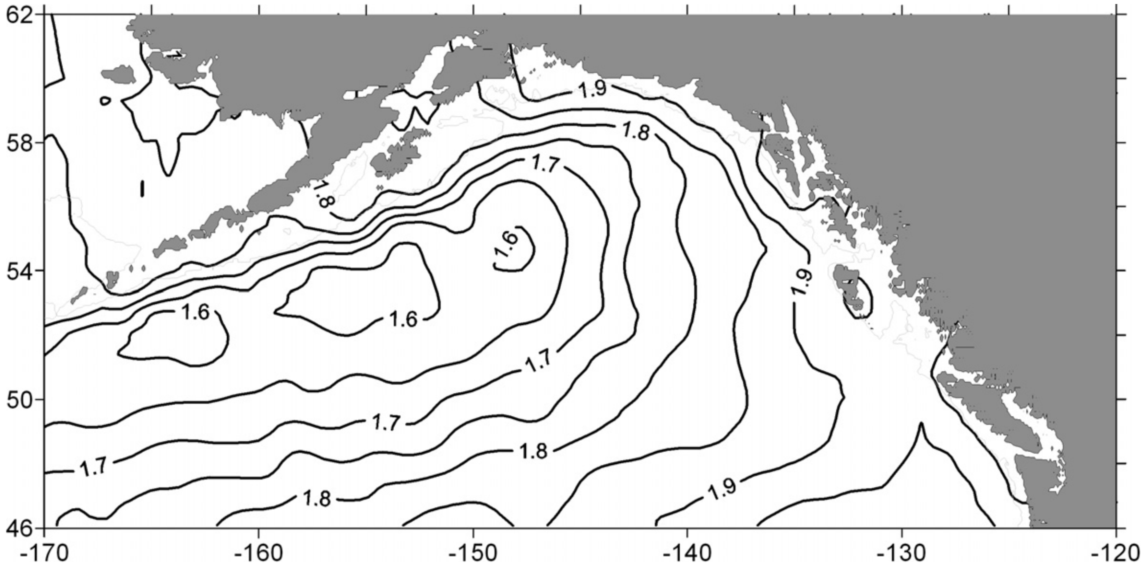

Fig. 2. Dynamic height of ocean surface relative to 1900 dbar pressure surface. (Argo floats profile to a nominal pressure of 2000 dbar. A reference surface of 1900 dbar allows inclusion of all Argo float observations.).

usually receive sufficient iron to prevent it from limiting phytoplankton growth, and may instead become nitrate poor by summer, as illustrated in Fig. 3 along the eastern gulf. These waters are denoted "transition waters" by Whitney and Welch (2002). The HNLC waters of the Alaska Gyre receive too little iron from coastal waters because the cross-gyre flow from iron-enriched peripheral regions is weak. Some studies identified wind-transported Asian dust carried into mid-gyre as the main (although small) source of iron (e.g.

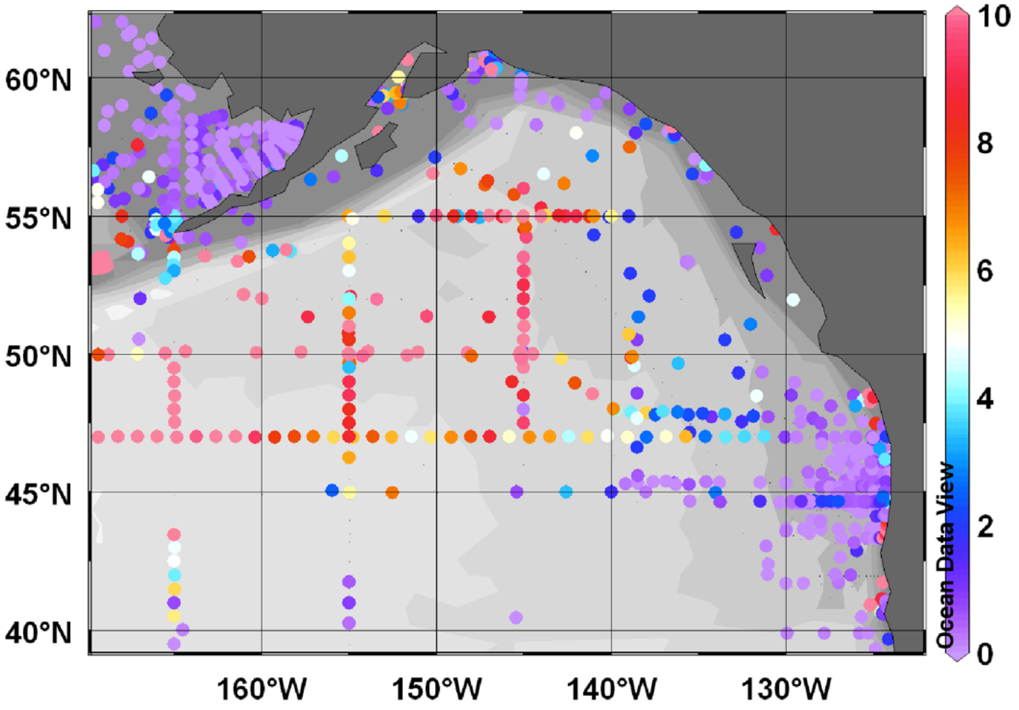

Fig. 3. NO_3 concentration (μmol/l) at ocean surface for August in years 1931–1996. (Data source: NODC archives).

Bishop et al., 2002). However, two recent papers determine that oceanic transport supplies iron from the continental margin of the Gulf of Alaska. Lam et al. (2006) conclude that the iron at Ocean Station Papa (50°N, 145°W) arrives from the Aleutian continental shelf via the Alaska Gyre, based on *in situ* sampling of metals and numerical models of ocean currents. Hongo et al. (2005) identify coastal waters as the primary metal source for subarctic North Pacific waters, based on extensive oceanic sampling of rare earth elements.

Therefore, our premise is that most of the small amount of iron that does arrive in the HNLC region of the central Gulf of Alaska is terrigenous, delivered from the neighbouring continental shelf by anticyclonic mesoscale eddies. Eddy processes enhance input of iron to the euphotic layer, reducing the surface area that is characterized as HNLC, and enhancing the relatively meager supply of iron to regions that are HNLC.

1.2. Anticyclonic eddies

Mesoscale anticyclonic eddies were noticed in early dynamic height and drifter observations of the Gulf of Alaska, and are described and named "Sitka Eddies" by Tabata (1982). (They form offshore of the town of Sitka, Alaska.) Later observations identify these eddies using satellite measurements of ocean temperature (Thomson and Gower, 1998) and ocean surface height (Okkonen, 1992; Gower and Tabata, 1993). Crawford and Whitney (1999) find a second formation region to the south, along the Canadian coast, where eddies denoted as "Haida" also form in winter. A third class, denoted "Yakutat" Eddies, form in the far northern gulf and are sometimes shallower than Sitka and Haida Eddies (Ladd et al., 2005a). Many Yakutat and Sitka Eddies enter the Alaskan Stream where they grow in diameter and height (Crawford et al., 2000). Crawford and Whitney (1999) use altimetry measurements to track the progress of anticyclonic eddies in the period 1992–1998, providing the first census of eddies in the gulf. (All studies to date note that cyclonic eddies contribute much less than anticyclonic eddies to oceanic processes in the gulf.)

Eddies generally form in winter, detaching from the continental margin in late winter and spring. They are baroclinic in structure, with diameters of 150–300 km, centre waters elevated by about 0.1–0.4 m, and mainly propagate westward and south-westward after they detach from the continental margin. Haida Eddies usually form in the outflow of coastal waters past the southern tip of the Queen Charlotte Islands (Crawford et al., 2002; Di Lorenzo et al., 2005). Sitka and Yakutat Eddies are believed to form in instabilities of flow along the continental slope (Melson et al., 1999). Fig. 4 presents the three formation regions and eddy distribution in September 2005, based on satellite altimetry algorithms of the Colorado Center for Astrodynamics Research (Leben et al., 2002). Eddies are denoted by region and year of formation, such that Sitka-2004 (or S4 in Fig. 4)

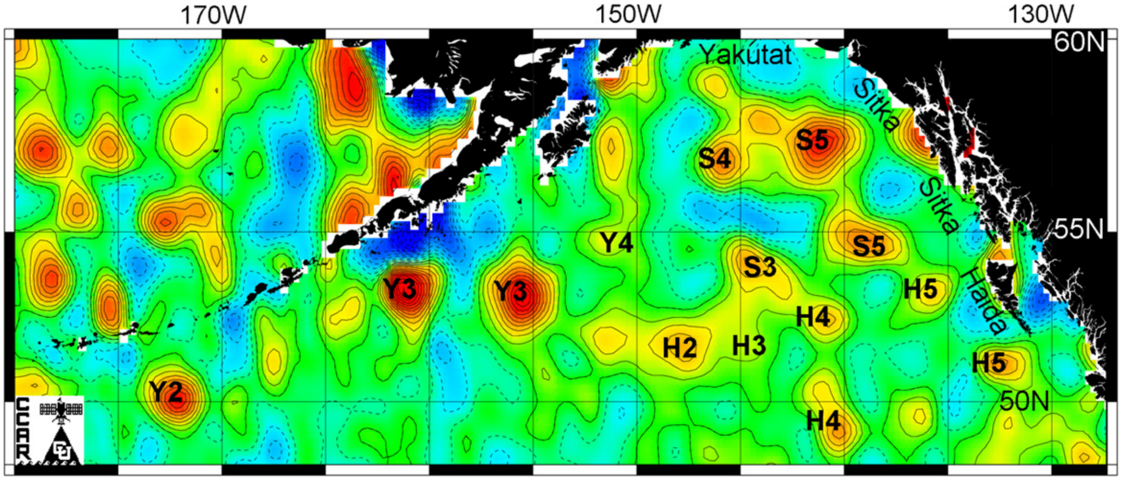

Fig. 4. Mesoscale eddies in the Gulf of Alaska on 5 September 2005. Shading denotes sea surface height anomaly (SSHA), with positive anomalies in red and negative in blue. Contours are at 2 cm intervals. Eddies are denoted in abbreviated format whereby Sitka-2004 is labelled S4. Eddy formation regions are indicated along the coast. Unnamed positive anomalies could not be reasonably tracked to a coastally generated eddy.

is a Sitka Eddy formed in the year 2004. Identification in Fig. 4 has some subjectivity due to merging and splitting of eddies, and occasional disappearance from view when they are between tracks of altimeter satellites.

Haida Eddies carry nutrients (Whitney and Robert, 2002; Whitney et al., 2005), iron (Johnson et al., 2005), phytoplankton (Batten and Crawford, 2005; Crawford et al., 2005) and zooplankton (Mackas and Galbraith, 2002; Mackas et al., 2005), as well as heat and fresh water (Crawford, 2002, 2005) into the gulf from continental shelves along the eastern margins of the gulf. Similar roles for Sitka and Yakutat Eddies are identified by Okkonen et al. (2001), Ladd et al. (2005b), Batten and Crawford (2005), and Keith Johnson, (personal communication, 2006). These previous studies focus on eddies and immediately surrounding waters. In this paper we present their general impact on the pelagic (<500 m depth) HNLC domain of the Gulf of Alaska.

1.3. Organization of paper

This paper is organized as follows. Section 2 describes the satellite and ship-based observation methods applied to this study. Our satellite-based observations of ocean colour and height, presented in Section 3.1, quantify the interaction between surface chlorophyll and eddy area. Sections 3.2 and 3.3 present ocean processes that might account for this eddy dominance of phytoplankton distribution. Conclusions are presented in Section 4.

2. Methods

Contour maps of sea-surface height anomaly (SSHA) at 4 cm intervals were computed and plotted every three days from T/P and ERS-2 altimeter data using the Internet site of the Colorado Center for Astrodynamics Research (CCAR). Inverse barometer effect, tides, ocean swell, and wind waves were all removed from the signal prior to plotting. SSHA values were referenced to multi-year, average sea-surface heights, and all data were low-pass filtered to remove basin-wide and seasonal SSHA signals. Therefore, SSHA contours highlight mesoscale oceanic features such as eddies and suppress long-lived and/or time invariant features such as the Alaskan Stream noted in Fig. 1. Removing the average sea surface slope of the Alaskan Stream may cause some meanders of this stream to appear as anticyclonic eddies.

The sea-viewing wide field-of-view sensor (SeaWiFS) detects chlorophyll using eight spectral bands of water-leaving radiance in visible and infrared wavelengths, with full coverage daily in the northeast Pacific Ocean. Although cloud-cover is a severe hindrance over most of the gulf, multi-day composite images provide better areal coverage (Brickley and Thomas, 2004). Daily global-area-coverage SeaWiFS chlorophyll data produced with standard NASA global coefficients (OC4, version 4) were retrieved from the Distributed Active Archive Center (DAAC) at Goddard Space Flight Center. These data were sub-sampled over the study area 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 was examined by forming 8-day and monthly composites from the daily images, resulting in a sequence of images from 1997 to mid 2003. The months of November to February were excluded from the analysis due to persistent clouds and the low light levels of winter.

We compared SSHA and chlorophyll at monthly and 8-day intervals. For comparison to chlorophyll monthly means, we selected one SSHA contour field for each month. Each SSHA map representing mid-month features for March to October of 2000 and 2001 was re-scaled in latitude and longitude to enable comparison with monthly composite images of surface chlorophyll concentrations.

For comparison of SSHA and chlorophyll images at 8-day intervals, closed contours of SSHA greater than +4 cm were chosen as a threshold level defining eddy sub-regions. These eddy sub-regions were then applied as sampling masks, within which chlorophyll concentrations were sub-sampled from the 8-day composite SeaWiFS images. Features less than 15 km in radius (on the order of the internal Rossby radius) were removed from the masks on SeaWiFS chlorophyll fields using an erosion/dilation operation (Gonzalez and Woods, 1992). We define anticyclonic eddies with radii $\geqslant 15$ km and height $>+4$ cm as “mesoscale” and the region seaward of the bathymetric 500 m contour as “deep-sea” or “pelagic”. These mesoscale eddies are more stable than smaller eddies, persist for months to years and have the potential to impact surface chlorophyll patterns over large regions of the gulf (Brickley and Thomas, 2004). Assuming an SSHA accuracy of ±4 cm, the error in the sub-region area for idealized Gaussian profiles is ±30%. Since the mesoscale eddies evolve and propagate relatively slowly (nominal speed of 1 km d^{-1}), the compositing period of 8-days is a reasonable compromise between increasing the likelihood of valid chlorophyll data in this cloudy region without sacrificing synchrony with mesoscale eddy features. Sub-sampling of chlorophyll concentrations was restricted to pelagic regions off the shelf by masking the shelf and upper slope (shoreward of the 500 m isobath) in each image.

Time series were then formed of the total eddy area, the total chlorophyll found within eddies, and the total chlorophyll outside eddies, summed over the study region. Visual inspection of a number of comparisons suggested that a large portion of surface chlorophyll in eddy waters is circumscribed by the +4 cm SSHA contour. Chlorophyll just outside the eddy peripheries (<4 cm SSHA heights) is not included, resulting in underestimation of eddy-associated chlorophyll. In addition, the altimetry and SeaWiFS measurements were not perfectly coincident in time, leading to small spatial offsets between the chlorophyll and eddy locations. We therefore conclude that the dominant bias in our measurements is interior eddy chlorophyll concentrations that are underestimated, and chlorophyll concentrations exterior to eddies that are likewise slightly overestimated. Nonetheless, combining the SSHA and SeaWiFS imagery provides a useful relationship between eddy area and surface chlorophyll distribution.

Ship-based observations derive from the WOCE program and from observations by scientists on the Canadian Coast Guard Ship *John P. Tully*. WOCE Section P17NE was sampled by the R/V *Thomas G. Thompson* in May–June 1993, with water samples from ocean surface to bottom. Details of the type, sampling intervals and quality of observations are presented by WOCE Internet sites and documents. We extracted the contour plots along this line directly from WOCE site: http://www-pord.ucsd.edu/whp_atlas/pacific/p17ne/sections/printatlas/printatlas.htm. Observations from the CCGS *John P. Tully* are described by Miller et al. (2005) and are available at the internet site: http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/dsr2/default_e.htm.

3. Results and discussion

3.1. Observations of chlorophyll and eddies from space

Studies have revealed higher chlorophyll and/or plankton levels in eddies compared to outside waters, suggesting that eddies provide an enhanced ecosystem in the otherwise lower productivity of the HNLC gulf. Whitney and Robert (2002) observe significantly higher subsurface particulate concentrations in the outer rings of Haida-1998 in its first summer. Crawford et al. (2005) compute consistently higher surface chlorophyll concentrations in eddies than in nearby outside waters in four Haida Eddies tracked for a total of 40 months in SeaWiFS imagery. Johnson et al. (2005) compute upward advection and mixing of iron in Haida Eddies to be a factor of ten greater than rates outside these eddies and attribute the enhanced chlorophyll in eddies to this iron injection. Therefore, the iron-to-chlorophyll link is established for Haida Eddies. Ladd et al. (2005a,b) provide clear evidence of eddy transport of shelf waters into deep-sea regions by Yakutat and Sitka Eddies, with associated advection of warmer and saltier waters along constant density surfaces. Keith. Johnson (personal communication, 2006) has measurements of enhanced iron levels in newly formed Sitka and Yakutat eddies of similar magnitude to those in Haida Eddies.

A time series of eddy surface area over our study period (Fig. 5a) shows that the total surface area of mesoscale eddies ranges from ~0.5 to 2.6×10^5 km^2, with a pronounced annual cycle and strong interannual variability. Maxima are observed early in the year, consistent with Crawford et al. (2000) who show new eddies are usually spawned in late winter and early spring, and some enlarge during spring. Crawford et al. (2002) observe that eddy area is particularly large in 1997–1998, the El Niño period, when unusually warm coastal SST and high coastal sea levels may have led to much larger mesoscale eddies. Interannual differences among post-1998 years are less pronounced, with some decrease in winter of 2001–2002.

Total eddy chlorophyll was sampled from the SeaWiFS image fields, using the SSHA-defined masks over the surface area containing valid, cloud free chlorophyll retrievals. Results over the 5-year study period (Fig. 5b) show mean surface chlorophyll concentrations within eddy interiors are much greater than those of the remaining deep-sea GOA, with the strongest contrast in late spring and summer. A peak in eddy-chlorophyll appears each spring and decays in late summer to non-eddy values, with a brief and typically weak resurgence in chlorophyll in autumn. The weak spring maximum in non-eddy chlorophyll is an artefact of

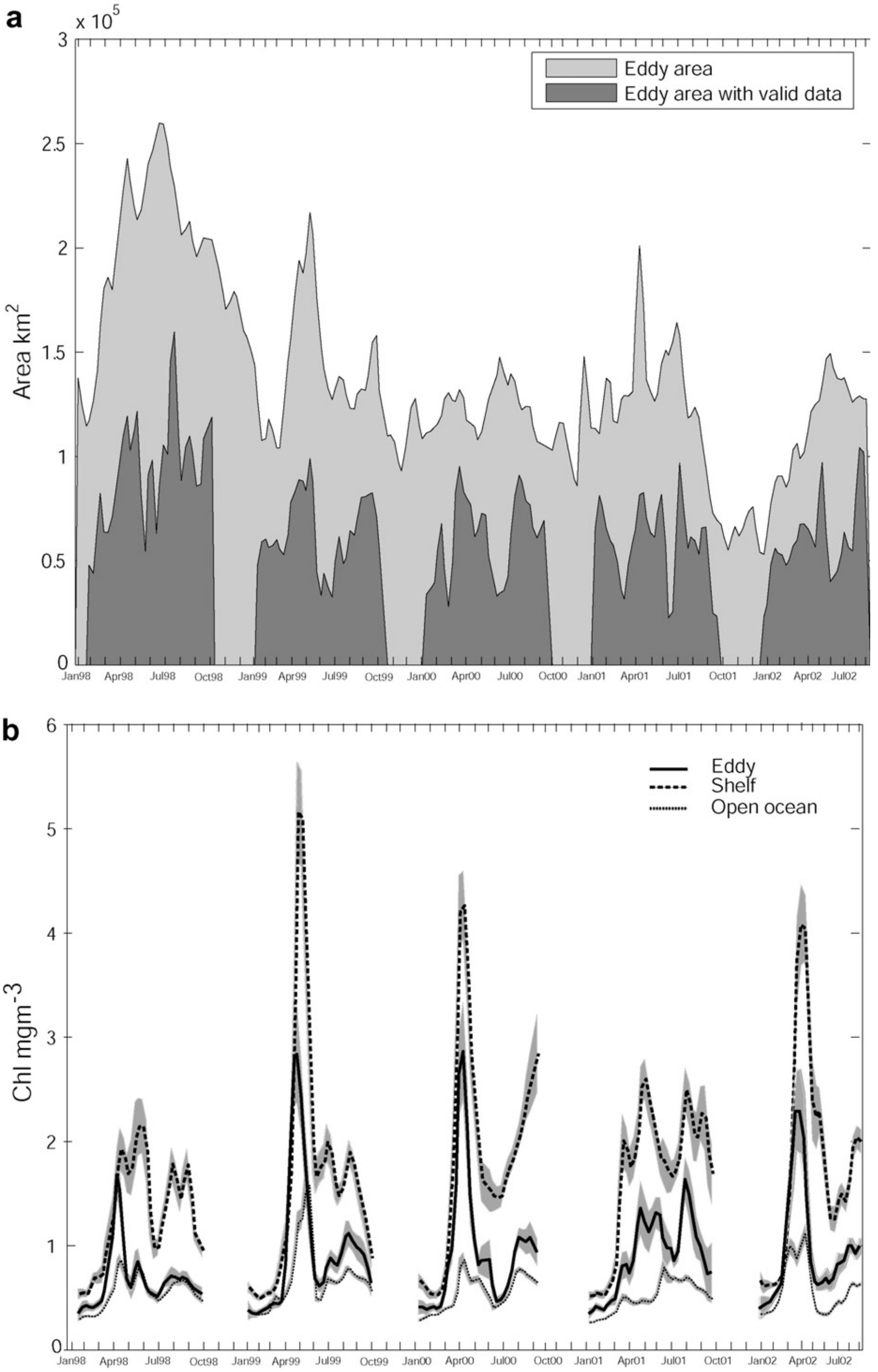

Fig. 5. (a) Total area north of 54°N (km^2) in mesoscale eddies with SSHA greater than +4 cm (light shade) and the sub-area containing valid SeaWiFS data (dark). (b) Average surface chlorophyll concentration north of 54°N on the CGOA shelf (dashed line), within deep-ocean, eddy waters (solid line) and in non-eddy, deep-ocean waters (dotted line with shading). Shading indicates standard deviation of the mean.

our sampling protocol, because shelf chlorophyll is frequently entrained along the eddy peripheries just outside of the 4 cm contour we use to define eddy area. The total area examined for eddies (north of 54°N and seaward of 500 m) is 1.2×10^6 km^2. Interestingly, this analysis shows that the total area of eddies is small compared to the non-eddy area of the northern Gulf, averaging about 1/10 in any given year. Our results show that much of the pelagic chlorophyll, and therefore surface phytoplankton and their associated variance, are concentrated in a relatively small area when compared to the total area of the northern Gulf of Alaska.

Sections 3.2 and 3.3 present evidence of physical processes that lead to this concentration of phytoplankton in eddies.

3.2. Advection of coastal waters at surface

During the intensive Haida Eddy study of 1998–2002 (Miller et al., 2005), a series of iron measurements in the eastern Gulf of Alaska confirmed that the surface, coastal waters hold sufficient iron in late winter to allow spring plankton blooms, but pelagic waters are iron depleted (Johnson et al., 2005). For example, in Haida-2000 four months after formation, surface concentrations of labile, unfiltered FeIII dropped to levels between 0.1 and 0.3 nM. Iron concentrations in eddy surface waters remained in this low range eight and twelve months after formation, and in addition, the iron concentrations in sub-surface waters declined. However, none of these sub-surface FeIII concentrations within eddy waters declined to the low values observed at similar densities in nearby non-eddy waters and at Ocean Station Papa. More recent observations of Sitka Eddies revealed central surface eddy waters to have high iron concentrations in May 2005, prior to drawdown by local primary production (W. Keith Johnson, personal communication, 2006). Subsurface waters were also enriched in iron.

Haida Eddies also transport nutrient-rich coastal waters, including iron, into pelagic regions by entraining slope waters into their outer rings and then transporting these waters into the central gulf. Crawford et al. (2005) present evidence for this process, by superimposing contours of sea surface height anomaly onto SeaWiFS images of chlorophyll in the Haida Eddy region. Haida Eddies clearly entrain and transport coastal, chlorophyll-rich surface waters one to two hundred kilometers into pelagic waters in spring and early summer. However, many Sitka and Yakutat Eddies stay close to the continental margin for most of their life. Those that enter pelagic waters reach into the middle of the Alaskan Gyre, whereas Haida Eddies propagate along the southeastern rim of the gyre with much less impact on HNLC waters. To investigate the impact on surface waters by Sitka and Yakutat Eddies, we present overlays of SSHA on monthly composite chlorophyll images for March–October of the years 2000 and 2001 (Fig. 6) for the gyre region through which Sitka and Yakutat Eddies transit. We use single letters (e.g. **A** rather than Sitka-2000a) to denote eddies to avoid clutter on these figures.

Over the period March–June of both 2000 and 2001 (Fig. 6a) there are higher surface chlorophyll concentrations in year-1 eddies in the northeast portion of the gulf than in central gulf waters. (Year-1 denotes an eddy in its natal year, at age zero to 12 months.) These blooms completely dominate in May 2000 when they fill the northern periphery of the gulf. Chlorophyll concentrations in eddies typically range from 1 to 10 mg m^{-3}, while non-eddy, open-ocean concentrations rarely exceed 0.3 mg m^{-3}. In April and June 2000 the blooms are more restricted to eddy-influenced regions. By June of each year the eddy regions hold more chlorophyll at surface than do non-eddy deep-sea waters, and there are regions of the gulf, shoreward of eddies, that show significant chlorophyll deficits. Along the Alaskan Stream in May 2000, eddy **a** draws high-chlorophyll waters of the continental margin into its outer rings (2.0–7.0 mg m^{-3}), advecting them completely around the eddy, creating a relative chlorophyll minimum region in mid-eddy.

These eight images of Fig. 6a reveal the two distinct processes that dominate eddy-chlorophyll dynamics in spring. First, eddies often support stronger phytoplankton blooms than found in surrounding waters. Second, eddies are able to entrain chlorophyll-rich coastal waters into their outer rings and advect these waters either partially or completely around their circumference, injecting shelf waters and associated biota into pelagic waters. Although not shown here, images of SeaWiFS data from other years reveal similar events. Both processes are observed in Haida Eddies, as noted above, but Sitka and Yakutat Eddies more completely fill surrounding regions with chlorophyll-rich water, perhaps due to the availability of more coastal waters on the wider shelves of the northern gulf.

A more complicated pattern of chlorophyll enrichment appears from July to October (Fig. 6b). Year-1 Eddy **A** in July 2000 is too far away from shelf waters to carry coastal chlorophyll offshore. Similarly, between August and October of 2000 both eddies **A** and **B** are too far offshore to entrain chlorophyll waters from the

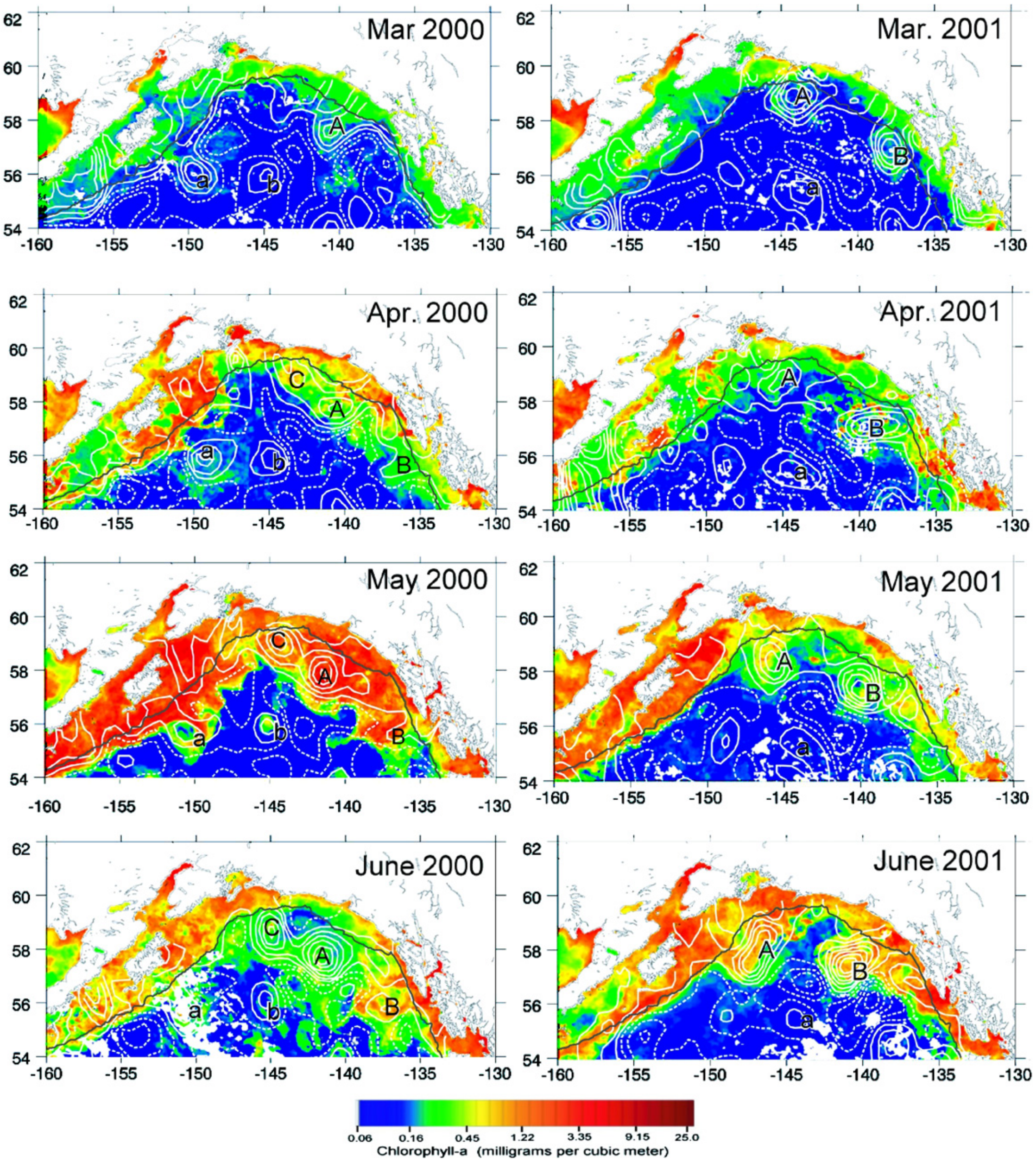

Fig. 6a. Maps of chlorophyll concentration in northern Gulf of Alaska for March to June 2000 and 2001, overlaid by white contours of sea surface height anomaly (SSHA) at 4 cm intervals. Solid contours denote positive anomalies and anticyclonic eddies. Chlorophyll colour-scale is at bottom. The 500 m isobath is plotted in dark grey. Upper case letters denote first-year eddies, lower case denotes older eddies. Left panel A: Sitka-2000a; B: Sitka-2000b; C: Yakutat-2000; a: Sika-1999a; b: Sitka-1998b. Right panel A: Yakutat-2001; B: Sitka-2001; a: Sitka-2000a.

continental margin, but through summer and early autumn they increasingly support enhanced concentrations of chlorophyll (0.8–5.0 mg m^{-3}) compared to nearby mid-gulf waters (~0.4 mg m^{-3}). Eddy **B** of 2001 also supports a late summer/early fall chlorophyll bloom, peaking in September 2001.

Two first-year eddies enter the Alaskan Stream in the summers of 2000 and 2001: Eddy **C** in 2000 and Eddy **A** in 2001. Both eddies are chlorophyll-rich in summer (1.0–2.0 mg m^{-3} in **C**, and 1.0–4.0 mg m^{-3} in **A**) compared to nearby pelagic waters (0.3 mg m^{-3}), and both likely carry continental margin waters into deep-sea regions. Year-2 Eddy **a** in 2000 entrains chlorophyll-rich margin waters.

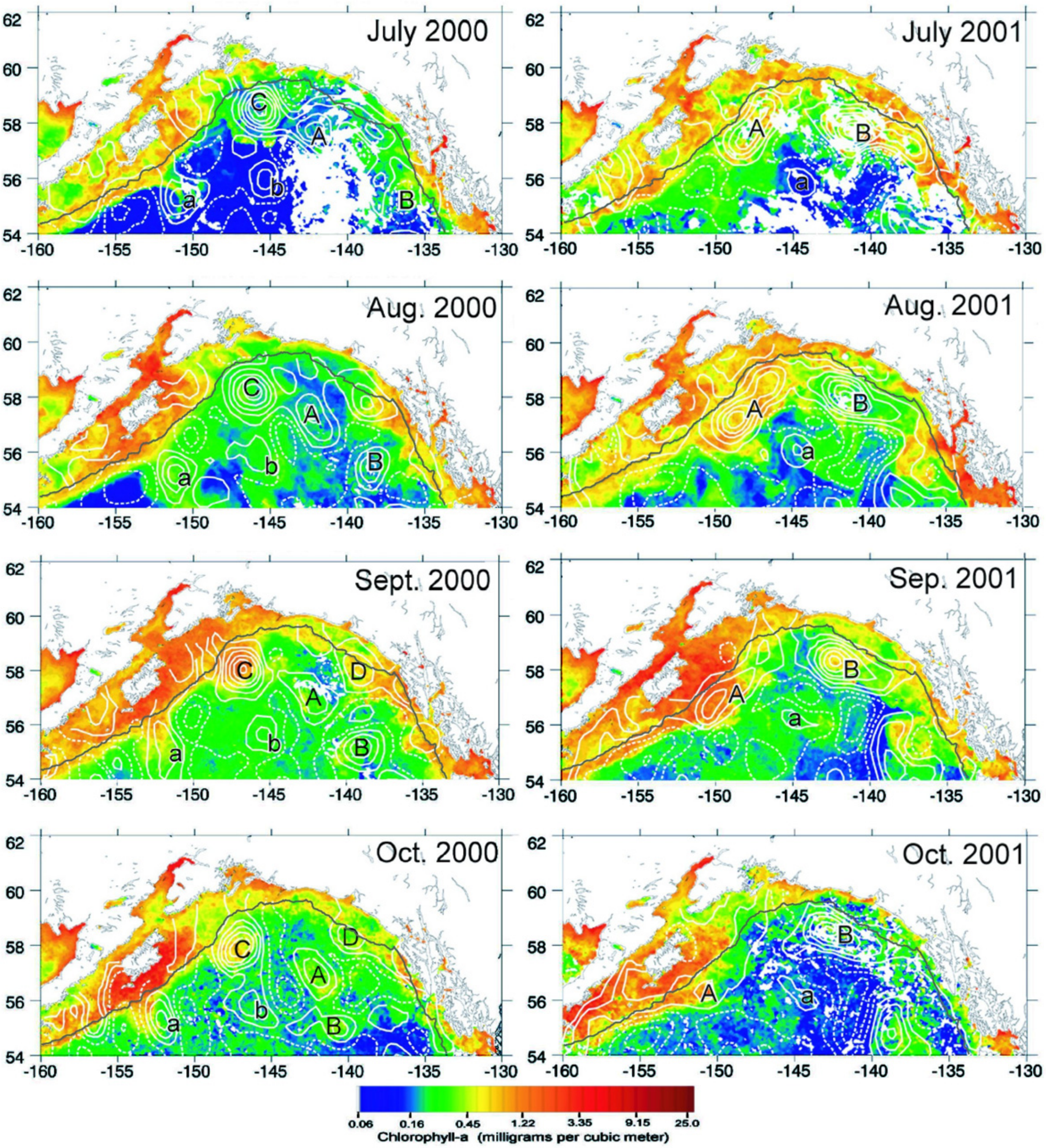

Fig. 6b. Maps of chlorophyll concentration in northern Gulf of Alaska for July to October 2000 and 2001, overlaid by white contours of sea surface height anomaly (SSHA) at 4 cm intervals. Solid contours denote positive anomalies and anticyclonic eddies. Chlorophyll colour-scale is at bottom. The 500 m isobath is plotted in dark gray. Upper case letters denote first-year eddies, lower case denotes older eddies. Left panel A: Sitka-2000a; B: Sitkla-2000b; C: Yakutat-2000; a: Sika-1999a; b: Sitka-1998b. Right panel A: Yakutat-2001; B: Sitka-2001; a: Sitka-2000a.

Fig. 6 reveals advection of coastal waters into pelagic regions on the east, north and northwest sectors of the Alaskan Gyre. In addition, eddies in the Alaskan Stream often advect coastal chlorophyll-rich waters into the southern sector of the gyre where they are carried far to the east in the return flow of this gyre toward North America. Whitney et al. (2005) observe a tongue of high-chlorophyll surface water following this route in SeaWiFS imagery averaged over the summer of 1999. In summary, anticyclonic mesoscale eddies carry coastal waters enriched in iron and chlorophyll far into pelagic waters on west, north and east sides of the gulf, and also push these coastal waters into the southern arc of the Alaska Gyre.

3.3. Deep-sea upward injection of iron to the euphotic layer

Eddies continue to propagate into mid-gulf where their outer rings are too far offshore to entrain coastal iron- and chlorophyll-rich surface waters. Eddy **b** in mid-gulf in May 2000 (Fig. 6a) supports a high chlorophyll concentration in its central waters (1.0–2.0 mg m^{-3}). We surmise that decay of this eddy in winter and spring pushes subsurface isopycnals and waters enriched in iron up to euphotic layers to support this isolated bloom in pelagic waters. However, Eddy **a** in mid-gulf in May 2001 (Fig. 6a) supports no chlorophyll bloom (~0.3 mg m^{-3}), indicating these surface events do not always take place.

Whitney and Robert (2002) describe the impact of eddy upwelling through observations of silicate, temperature, salinity and light transmissivity in Haida-1998 in August 1998 in HNLC waters. They observe low light transmissivity and low silicate levels in outer eddy rings at 50 m below surface. These properties indicate more phytoplankton due iron enrichment. Johnson et al. (2005) find Haida Eddies are already iron-deficient by June of their first year, so some process is needed to re-supply euphotic depths of Haida-1998 with iron in August 1998. Whitney and Robert (2002) propose two upwelling paths of iron. The rising isopycnals of decaying eddies dome in mid-eddy, bringing iron to euphotic depths. Iron also flows upward and outward along sloping isopycnals, entering sub-surface euphotic layers in outer rings of the eddy. Their enriched plankton concentrations in outer rings of sub-surface layers indicate the second process dominates in their samples, taken in summer. However, the impact of winter-long mixing might favour mid-eddy nutrient enrichment as indicated by Sitka-1998 in May 2000 described below.

An isolated phytoplankton bloom took place in the centre of Sitka-1998 in May 2000, well into pelagic regions, as noted in Fig. 6a. Normally, plankton do not bloom at all in these iron-starved, HNLC waters, so such a strong bloom centred exactly in the centre of Sitka-1998 is strong evidence of upwelling of iron. Its position in the centre of the eddy suggests doming of isopycnals lifted iron in deep waters to the surface mixed layer. Whitney and Robert (2002) propose this mechanism, as noted above, but have no observations to confirm it. We have no ship-based observations of this eddy to investigate the hypothesis, but do have observations of another two-year-old eddy where iron enrichment is evident. Haida-2000 was sampled repeatedly in its first sixteen months during an intensive field program of February 2000–September 2001 (Miller et al., 2005). Over the next ten months it propagated to the southwest and decreased in surface elevation to about 5 cm. This low elevation prohibited definitive, continuous tracking by satellite altimetry, but by July 2002 we believe it had moved to 49° 41.40′N, 145° 41.94′W, about 100 km southwest of Ocean Station Papa (OSP 50°N, 145°W). July 2002 marked the beginning of the SERIES iron injection program near OSP (Boyd et al., 2004). Scientists of this program sampled in the centre of Haida-2000 on July 6 and at OSP on July 7, 2002 just prior to the start of the SERIES experiment.

Fig. 7a and b presents profiles of salinity (S) and temperature (T) through this eddy. A sub-surface temperature maximum, a typical eddy feature, is clearly present in this eddy. Below 150 m eddies are usually fresher and warmer than outside waters at the same depth, due to isopycnal depression, with more of the baroclinic potential energy attributed to high temperatures than to reduced salinity. The T–S plot in Fig. 7c reveals the progression of properties from the formation of Haida-2000 in February 2000 to its sampling in July 2002 near OSP, together with the T–S trace from OSP in July 2002. Note how temperature in the halocline, where salinity is greater than 32.8, decreases steadily in time toward background levels at OSP, with greater temperature decline at salinity between 32.7 and 33.4 than in deeper water at salinity near 33.8–33.9. These declining temperatures at lower salinity could be attributed to surface cooling and wind mixing in winter.

Although iron samples were not collected, other properties plotted in Fig. 7d to f reveal an eddy signature. Surface chlorophyll levels are higher than observed at OSP (Fig. 7f). Near-surface silicate levels are lower (Fig. 7d). Depressed silicate and enhanced chlorophyll levels in surface HNLC waters of the Alaska Gyre are evidence of iron input (Whitney et al., 2005). Sub-surface oxygen concentrations are lower (Fig. 7e) in Haida-2000 than at OSP. (Low oxygen levels at depths below the winter mixed layer are another indicator of eddy presence, noted by Aydin et al. (1998), because the continental slope waters where eddies form are oxygen-poor.) These observations are consistent with upwelling in the eddy and iron input to surface waters in the eddy centre.

Unpublished data from observations of a Sitka eddy in May 2005 (Johnson, personal communication, 2006) reveal a core region of high iron levels and very low chlorophyll concentrations, indicating recently upw-

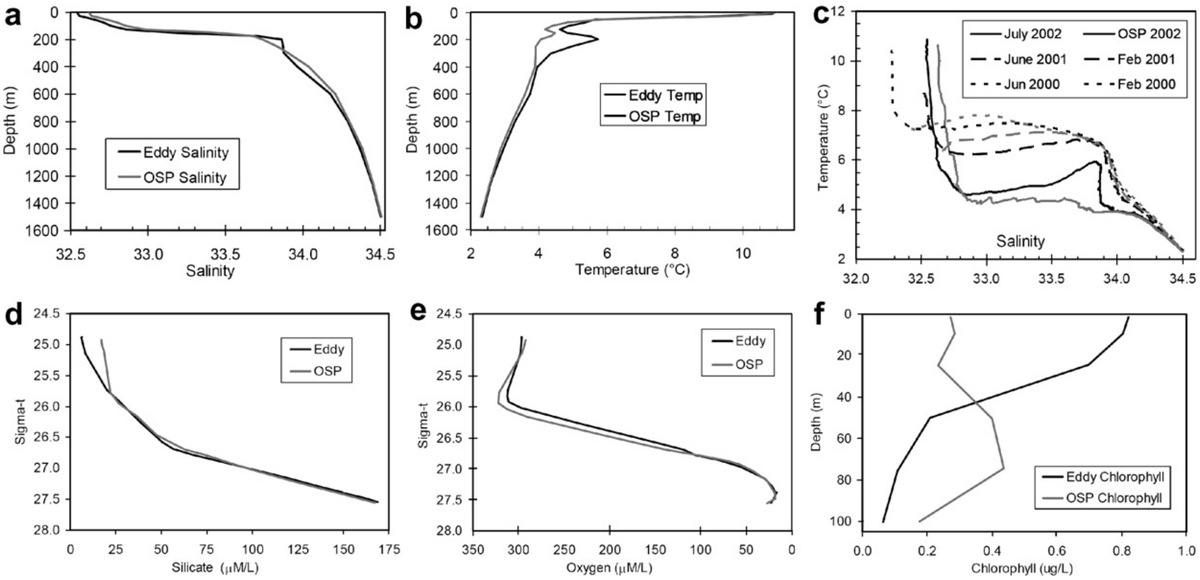

Fig. 7. Profiles through Haida-2000 between February 2000 and July 2002 and through nearby Ocean Station Papa (OSP): (a) salinity-depth, (b) temperature-depth, (c) salinity–temperature, (d) silicate-sigma-t, (e) oxygen-sigma-*t*, (f) chlorophyll-depth.

elled water. Surrounding this core was an outer ring of enhanced chlorophyll and lower iron concentrations. These observations suggest iron rich waters do upwell to the surface in eddy centres to support local primary productivity.

The wind-driven, cyclonic circulation of the Alaska Gyre supports upwelling in mid gyre, with isopycnals doming upward toward mid-gyre. Therefore, sub-surface isopycnals of eddies that completely decay in mid-gyre will seek a density surface much closer to the ocean surface than in waters near the continental margin where eddies form. In some cases these density surfaces will outcrop in mid-gyre waters, injecting iron into the euphotic layer. An example is provided by sampling along WOCE Line P17NE in May–June 1993 that crossed several eddies (D. Musgrave, personal communication 2004). Real-time altimeter products were not available in 1993, so these eddies were sampled by accident. We can recompose the eddy positions of May 1993 with aid of the Internet sea surface height anomaly viewer of the Colorado Center for Astrodynamics Research (Leben et al., 2002). Positions of Yakutat and Sitka Eddies in June 1993 are presented in Fig. 8a as red regions of elevated SSHA. Contours of dissolved silica and sigma-t along P17NE, plotted in Fig. 8b and c, are provided by the Internet site of the WOCE Hydrographic Programme Pacific Atlas. The track of P17NE bisected Sitka-1993a and cut through outer rings of the other two eddies. Therefore, depression of deep silica and sigma-t contours is greatest in Sitka-1993a, and smaller but still significant in Sitka-1993b and Yakutat-1992.

The distribution of temperature with depth in Fig. 8d is typical of other eddies, as noted by Tabata (1982) in the first detailed description of Sitka Eddies. Isopycnals are depressed in the middle of eddies from depths of about 150 m to more than 1000 m, providing the baroclinic structure needed for anticyclonic rotation. Above 150 m depth, contours of temperature and other properties often dome in mid-eddy. This doming can be attributed to upwelling of isopycnals as the eddies lose baroclinic energy, as surmised above. However, similar doming in anticyclonic eddies has been observed by McGillicuddy et al. (1999) near Bermuda, and in Bussol' Eddies by Yasuda et al. (2000). These authors attribute doming in their eddies to the nature of water masses that formed these eddies, rather than eddy decay after formation. We cannot determine the relative contributions of these two processes to this Sitka Eddy of 1993.

The sloping contours of the Alaska Current and Gyre are distorted as they run through Sitka-1993a. The 26.0 and 26.6 sigma-t contours lie at 120 and 270 m, respectively, in the centre of Sitka-1993a. Winter mixed layers of mid-gyre normally enclose the 26.0 sigma-t surface, but do not reach the 26.6 level (Whitney et al., 2007). An Argo profiler that moved into the centre of the Alaska Gyre measured a sigma-t of 26.3 at 10 m depth at the end of March 2002. We can therefore expect that some of the eddy core waters up to a density

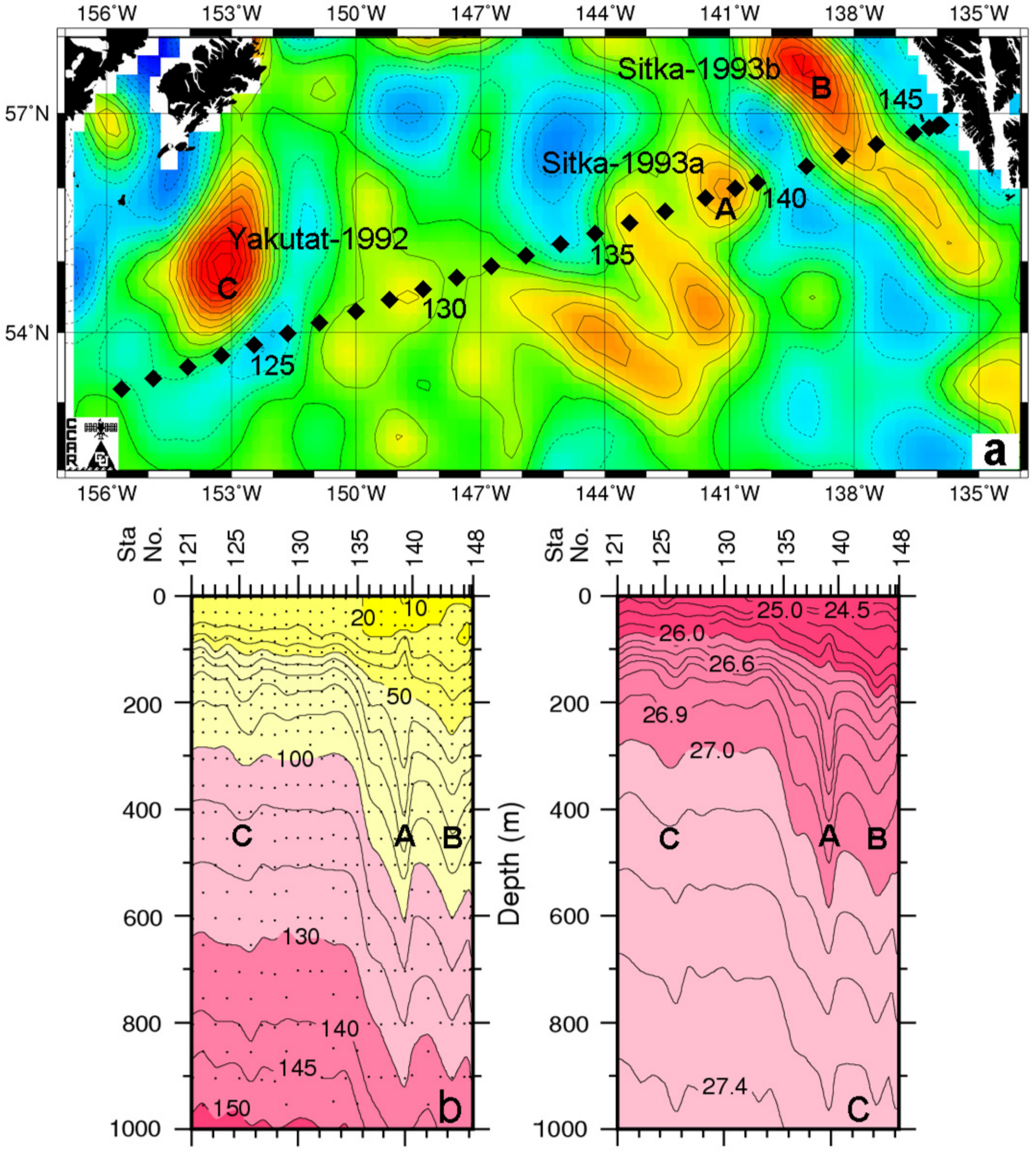

Fig. 8. (a) Location of sampling stations along P17NE. Colour contours denote sea surface height anomaly, at intervals of 2 cm. Solid contours are positive anomalies. (b) Contours of dissolved silica (μM) along P17NE. (c) Contours of sigma-t along P17NE. Locations of eddies are marked by **A**, **B**, and **C**, denoting Sitka-1993a, Sitka-1993b, and Yakutat-1992, respectively.

of about 26.3 will eventually mix into the surface mixed layer in mid-gyre, where their iron will be available for primary producers.

The impact of such upwelling of iron depends on the distribution and number of eddies through the Alaska Gyre. Fig. 4 reveals anticyclonic eddies all through the Gulf of Alaska in September 2005. Two of these eddies, Yakutat-2003 and Yakutat-2004, were close to the middle of the Alaska Gyre. The propagation of eddies far into the gulf is also noted by Onishi et al. (2000) based on their regular sampling of water properties along 145°W north of 50°N.

A qualitative view of the number and impact of eddies in mid-gyre is also provided by water property distributions. Eddy waters on sigma-t surfaces below the winter mixed layer tend to be warmer, saltier and oxygen-poor compared to typical deep gulf waters. Aydin et al. (1998) notice that oxygen levels in gyre waters of sigma-t > 27.0 display considerable scatter, much more than noticed in deep inflows to the gulf from the southwest. They attribute this scatter to eddies from the eastern gulf. We extend their investigation by plotting maps of the geographical distribution of percent oxygen saturation (%O2) in the gulf, using archived profiles of the IOS and NODC archives (Fig. 9). Most measurements are based on titrations of water samples, but a few recent profiles have provided continuous measurements of O2 through a profiling CTD, with spot calibrations based on titrations. We interpolated %O2 concentrations from all samples onto constant sigma-theta surfaces, omitting profiles with significant gaps in the vertical. The 26.5 sigma-theta surface lies just below the outcropping depth of waters in mid-gyre, as noted previously, so no oxygen enrichment from local surface waters is expected on this surface.

Highest oxygen levels in Fig. 9 are in the southwest in North Pacific Intermediate Water (NPIW) formed a some years earlier along the western margin of the North Pacific. Lowest oxygen in Fig. 9 lies along the eastern margin, attributed by Aydin et al. (1998), to its older source in the south, and to biological decay of settling and bottom organic matter of the highly productive upwelling coasts of USA and Canada. These waters form the cores of eddies and are carried into the gulf. Eddies are the only mechanism by which low-oxygen water can cross into mid-gyre. Notice in Fig. 9 the high variability of %O2 in the gyre north of 50°N, which is evidence of low-oxygen waters of eddies moving through higher oxygen levels of background gulf water. These eddies are seldom present south of 50°N in the middle and western gulf, with the result that %O2 seldom drops below 62% there.

We expect this eddy enrichment will lead to accumulation of zooplankton, fish and marine mammals relative to conditions outside eddies. Ream et al. (2005) note that a radio-tagged fur seal interrupted its migration to feed in an anticyclonic eddy in the Alaskan Stream. Marie Robert (personal communication, 2005) notes

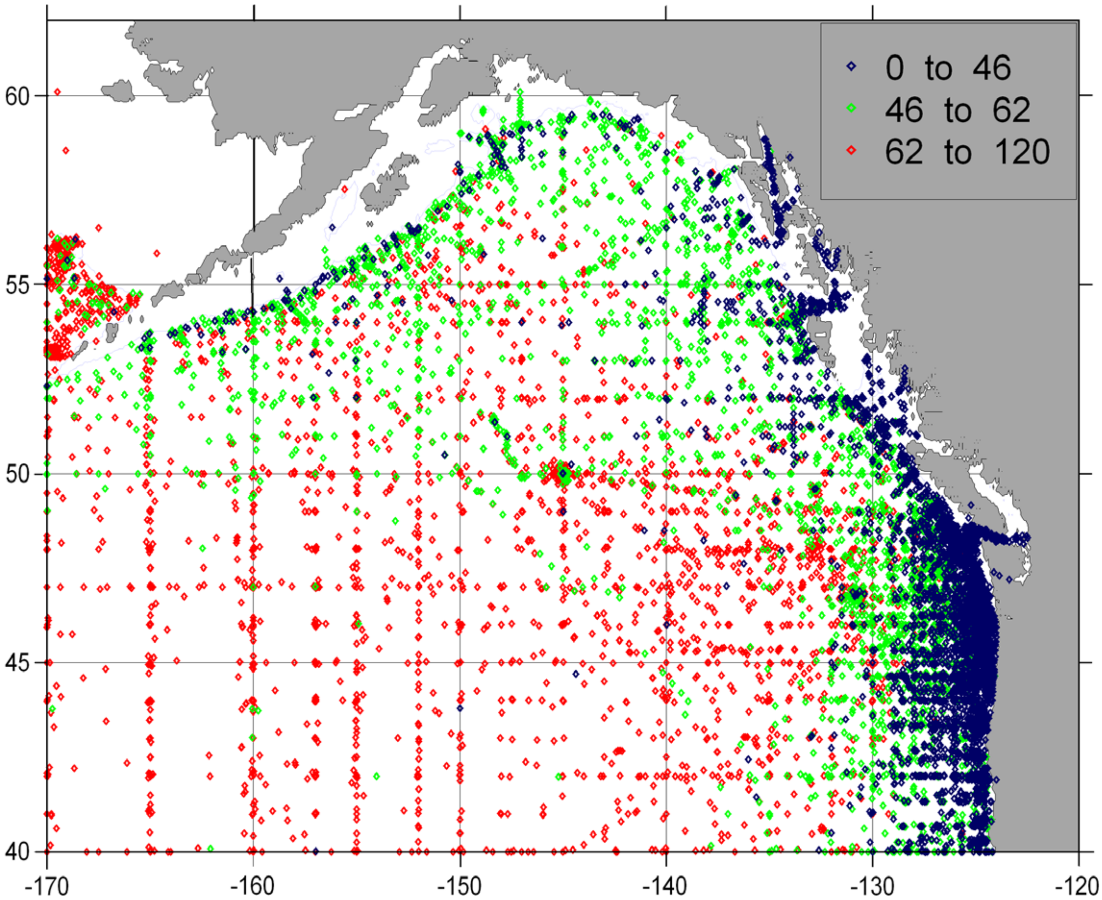

Fig. 9. Percent Oxygen saturation (%O2) in the northeast Pacific on the 26.5 sigma-theta surface. Each dot is based on a single profile of water properties. All data derive from the NODC and IOS archives. Colours denote the range of %O2 according to the scale at top right.

increased sightings of birds and marine mammals in Haida Eddies during her Line P cruises. N. Pinnell (personal communication, 2006) observe whales in Sitka Eddies during a research cruise in April–May 2005. Batten et al. (2006) observe higher zooplankton biomass in near-surface waters in the outer ring of an eddy in the western Gulf of Alaska. Tsurumi et al. (2005) observe higher densities of pteropods in Haida Eddies. We expect future ship-based studies targeting eddies in pelagic regions of the Gulf of Alaska will provide quantitative information on biological enrichment by these eddies.

4. Conclusions

The HNLC waters of the northeast Pacific Ocean receive too little iron for primary productivity to draw down silicate and nitrate in surface waters, even in spring and summer. Our observations of chlorophyll sensed by SeaWiFS north of 54°N in pelagic waters of the gulf found that, on average, more than half of all surface chlorophyll was inside the 4 cm contours of anticyclonic eddies (the ratio approaches 80% in spring months), yet these contours enclosed only 10% of the total surface area of pelagic waters in the gulf.

We outline several processes associated with eddies and the characteristics of the GOA gyre that enhance input of iron to the euphotic layer, reducing the surface area that is actually HNCL and possibly enhancing primary productivity in sub-surface layers not observed by satellite. Eddies carry excess nutrients and iron in their core waters into pelagic regions as they propagate away from the continental margin. Eddies near the continental margin entrain nutrient – (and Fe) – rich and chlorophyll-rich coastal waters into their outer rings, advecting these waters into the basin interior.

These anticyclonic eddies propagate into a cyclonic gyre. As they decay, their depressed isopycnals relax upward, injecting nutrients up toward the surface layer. Subsurface isopycnals of the middle of the Alaska Gyre are much closer to the surface than isopycnals around the margins of the gulf, due to Ekman upwelling in the middle of the Aleutian Low pressure system. Subsurface isopycnals of eddies that decay in mid-gulf will rise to equilibrium depths very close to the surface mixed layer, or even in this layer in winter, providing iron to surface waters.

These mesoscale eddies decay slowly, but steadily, perhaps providing a relatively regular upward supply of macro-nutrients and iron toward euphotic layers. They might behave as isolated oases of enhanced marine productivity in an otherwise iron-poor basin. We note that much of this productivity might be near or just below the base of the surface mixed layer, and therefore poorly sampled by colour-sensing satellites. Therefore, the enhancement of phytoplankton concentrations by eddies may be even greater than noted in our observations.

Acknowledgements

SeaWiFS data files were made available by the NASA GSFC DAAC; SSHA contours by CCAR imagery. Overlays were prepared by Rob Bowen of Diversified Scientific Consulting Ltd. Funding for this work was provided by Fisheries and Oceans Canada to WRC, and by NSF OCE-0000899, OCE-0535386 and NASA NAG5-10620 to ACT. Contribution number 536 from the US GLOBEC program. This paper was presented at the PICES/DFO Symposium on "Time Series of the N.E. Pacific: A symposium to mark the 50th anniversary of Line P" in Victoria, BC, Canada, July 2006.

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