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# A note on cross-shelf exchange in the northern Gulf of Alaska

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## Abstract

The continental shelf of the Gulf of Alaska (GOA) is a complex system characterized by large freshwater runoff and strong winds. The GOA supports one of the world's richest ecosystems, including numerous species of fishes, marine mammals and sea birds. The mechanisms that provide nutrients to support this ecosystem are not well understood. The rivers and streams that provide freshwater to the shelf are low in nitrate, and the regional winds favor downwelling. High concentrations of nitrate are available in the deep basin of the GOA, but these must be introduced to the shelf in order to support the high productivity. We present evidence for cross-shelf exchange due to three different mechanisms. Episodes of downwelling relaxation result in a flux of saline, nutrient-rich water onto the shelf at depth. Eddies, formed in the northeastern GOA, propagate along the shelf-break influencing cross-shelf exchange by carrying shelf-origin water from the formation region into the basin and by interacting with the shelf-break circulation. Bathymetric steering in the many canyons that incise the GOA shelf results in flow into the canyons where strong tidal mixing results in cross-isobath movement of water properties.

## 1. Introduction

Circulation in the Gulf of Alaska (GOA) is dominated by two current systems, the cyclonic subarctic gyre in the basin and the Alaska Coastal Current (ACC) on the continental shelf (Fig. 1). The eastern boundary current of the subarctic gyre is the northward flowing Alaska Current that flows along the shelf-break. The Alaska Current is a typical broad, highly variable eastern boundary current. At the head of the GOA, the current turns southwestward following the shelf-break and forms the Alaskan Stream, the western boundary current of the eastern subarctic gyre. The Alaskan Stream can have current speeds as high as 100 cm s$^{-1}$ (Cokelet et al., 1996; Reed and Stabeno, 1999; Stabeno and Reed, 1991).

The ACC is a baroclinic coastal current driven by winds and freshwater runoff. Due to seasonal cycles in the forcing, the ACC has a strong

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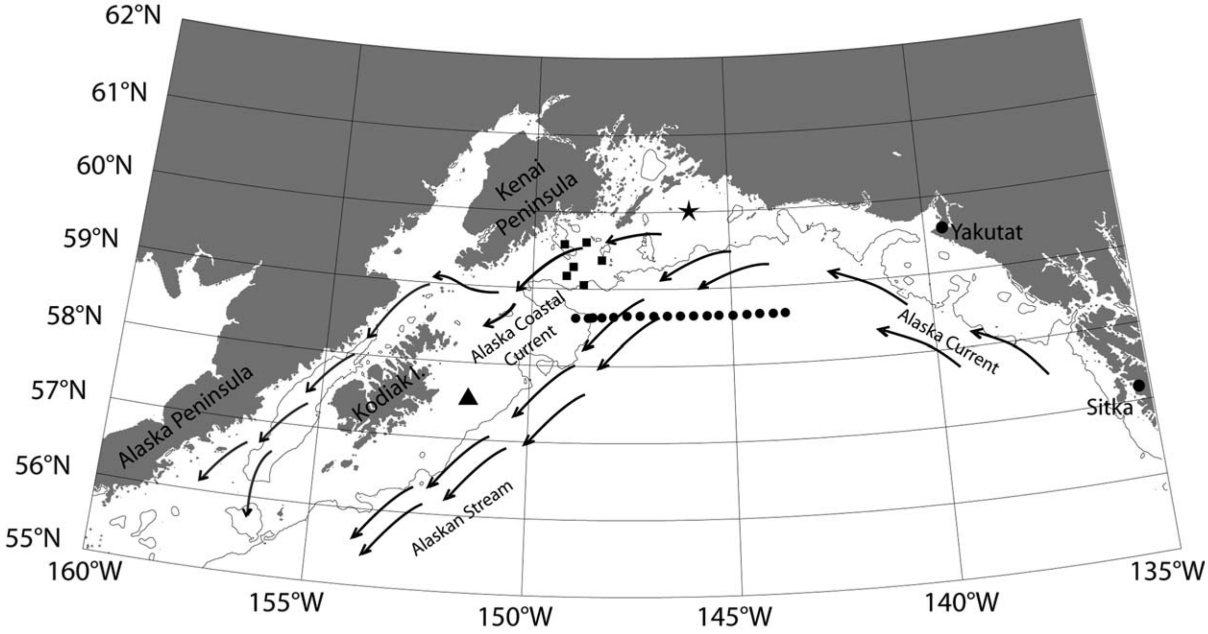

Fig. 1. Schematic of Gulf of Alaska circulation. Symbols denote data locations: star—upwelling index data shown in Figs. 2 and 3; squares—mooring data shown in Fig. 3; circles—eddy CTD transect shown in Figs. 4 and 5; triangle—Chiniak Canyon mooring data shown in Fig. 10.

seasonal signal with a maximum baroclinic flow in autumn and maximum total transport in winter (Schumacher et al., 1989).

The basin of the GOA has been described as a high-nutrient, low-chlorophyll (HNLC) environment. Winter mixing combined with horizontal advection provide ample nutrients to the surface in the center of the basin (Wheeler, 1993). However, due to iron limitation (Boyd et al., 1995; Martin et al., 1989), chlorophyll concentrations remain low throughout the year (Wong et al., 1995). In the coastal waters, on the other hand, the freshwater input supplies iron but little nitrate. In fact, using a biochemical marker for iron stress, La Roche et al. (1996) found that phytoplankton were iron stressed in the basin interior but not in the coastal waters or the transitional waters between the basin and the shelf. On the GOA shelf, summer (post-bloom) production is nitrate-limited.

The GOA supports a rich ecosystem, including numerous species of fishes, marine mammals and seabirds. The mechanisms that provide nutrients to support this ecosystem are not well understood. Given the iron limitation in the basin and the nitrate limitation on the shelf, cross-shelf exchange must be of importance. This note will explore three cross-shelf exchange mechanisms that are responsible for supplying a significant amount of the necessary nutrients. These mechanisms include episodic upwelling (in a primarily downwelling environment), eddies, and tidal mixing combined with bathymetric steering.

## 2. Relaxation of downwelling

As noted above, the GOA is predominantly a downwelling system. The National Oceanic and Atmospheric Administration's Pacific Fisheries Environmental Laboratory (NOAA/PFEL) uses US Navy Fleet Numerical Meteorological and Oceanographic Center (FNMOC) pressure fields to calculate an upwelling index for coastal stations along the eastern Pacific coast (Pacific Fisheries

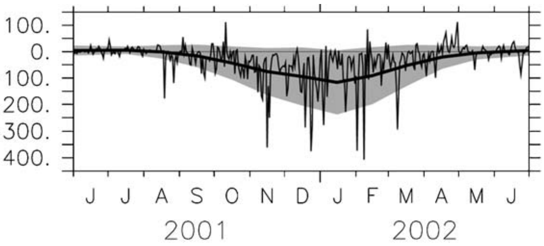

Fig. 2. Monthly climatology (bold black line) and daily average during 2002 (thin black line) of the upwelling index ($m^3 s^{-1}$ per 100 m of coastline) at 60°N, 146°W. Calculated from average daily upwelling index from 1967 to 2003 downloaded from NOAA's Pacific Fisheries Environmental Laboratory (NOAA/PFEL) (www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/). Gray shading denotes one standard deviation from the monthly climatology.

Environmental Laboratory, 2003). The upwelling index for 60°N, 146°W in the northern GOA exhibits maximum monthly climatological downwelling averaging 116 $m^3 s^{-1}$ per 100 m of coastline in January. Maximum daily averaged downwelling values can exceed 400 $m^3 s^{-1}$ per 100 m of coastline (Fig. 2). During winter, the downwelling winds both spin up the ACC and result in the on-shelf flux of high-nutrient basin water in the surface Ekman layer. These nutrients are consumed supporting the high production on the shelf during the spring bloom. During summer, the downwelling winds relax and the climatological upwelling index is near zero. Periods of upwelling occur throughout the year but are most common during the summer (Fig. 2). These short periods of upwelling may make nutrients available to the euphotic zone along the coast but we have not quantified the magnitude of that source. We examine the impact of relaxation of downwelling. This impact can occur throughout the year but is most easily observed during winter. At the surface, nutrients are non-conservative due to biological utilization. However, at depth, nutrients are relatively conservative and have a strong linear relationship with salinity (Mordy et al., 2005). Thus, we use salinity as a surrogate for nutrients at depth.

The average response of the ocean to atmospheric forcing is clear. In autumn, the upper water column freshens due to increased runoff and the confinement of the low salinity water along the coast, due to the prevailing downwelling-favorable winds. At depth there is a similar signal in salinity with a freshening during the fall and winter due to mixing, and increasing salinity at depth during the summer (Stabeno et al., 2004). Since the shelf is wide (~200 km) with many banks and troughs, the oceanic response to the winds on shorter time scales (days–weeks) is more complex.

Six moorings were deployed on the shelf south of the Kenai Peninsula (Fig. 3). During the 6-month period shown in Fig. 3, two intrusions of higher-salinity water onto the shelf occurred during periods of weak winds (relaxation of downwelling). Mooring 5 was deployed on the edge of Amatuli Trough. In December 2001 and again in the latter half of January 2002, salinity began to increase at the mooring site after the downwelling winds had been relaxed for approximately a week (Fig. 3). Both intrusions can be traced onto the shelf, several days later at moorings 3, 10 and 2. Farther to the east, moorings 9 and 8 also were impacted by the increased salinity. The pathway of the higher-salinity water onto the shelf is not clear, since there is a ridge between 5 and the shelf moorings. As the winds increased (downwelling favorable), the deep shelf water responded with decreasing salinity, with the most on-shelf moorings responding first. These two events occurred during winter when the downwelling winds are strongest (resulting in the strongest signal). Unfortunately, presently we only have data from these moorings for one winter so we are unable to determine whether the observed response is typical. However, examination of the upwelling index during winters of other years suggests that the frequency, duration, and magnitude of the relaxation events observed during the winter of 2001/02 were not atypical.

During summer when the winds are weaker, relaxation events resulting in an influx of deep saline water are not as clear. However, the weaker summer winds do result in a general increase of salinity at depth on the shelf especially along the coast (Stabeno et al., 2004) and upwelling events during the spring–autumn period would likely result in a similar influx of saline water to that seen in the data shown in Fig. 3. The on-shelf flux of

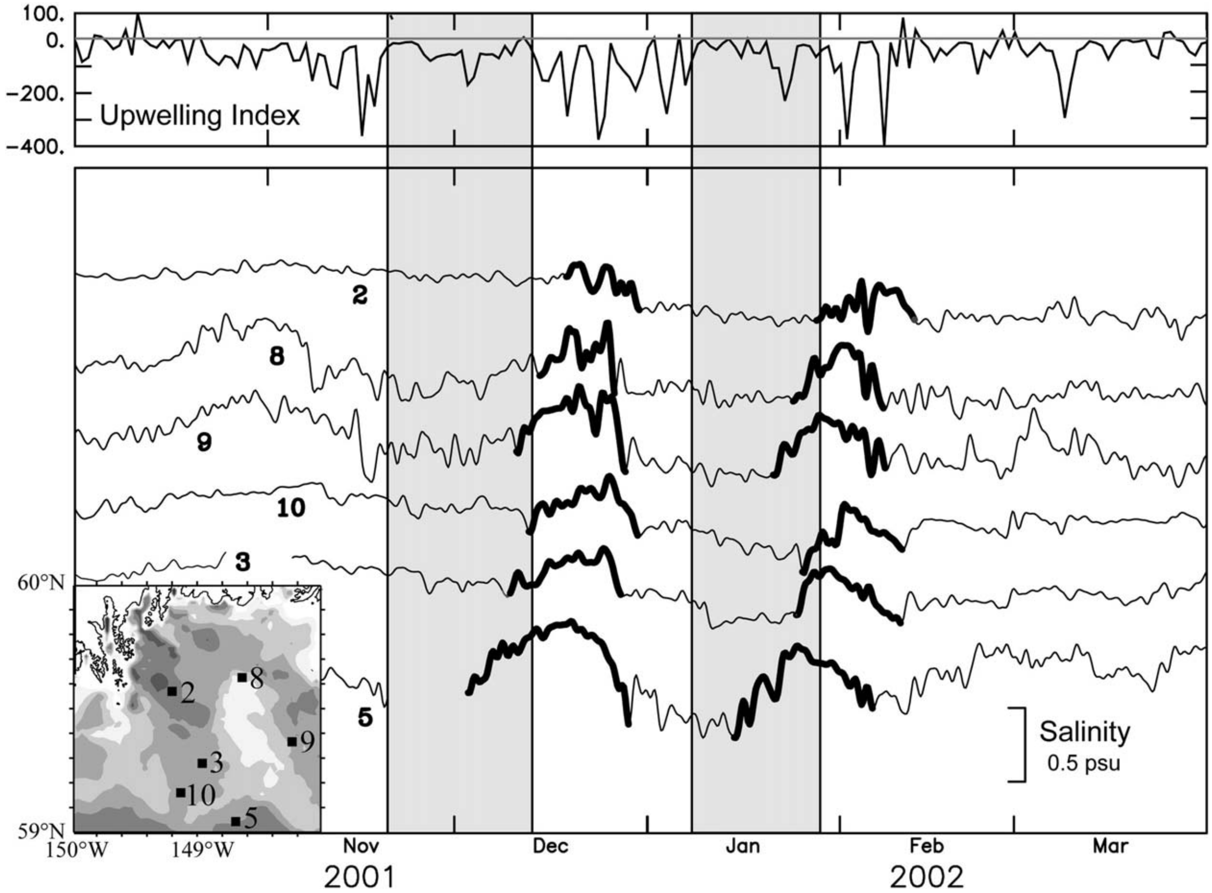

Fig. 3. PFEL Upwelling index ($m^3 s^{-1}$ per 100 m of coastline) at 60°N, 146°W (top), and salinity (psu) from six moorings during October 2001–March 2002. Gray shading denotes periods of weak downwelling winds. Map showing mooring locations is inset. Gray shading on inset denotes bathymetry in 50-m increments from light gray (shallowest) to dark gray (deepest).

saline (and nutrient-rich) water near the bottom can be introduced into the euphotic zone through mixing process on the many banks and troughs that characterize the GOA shelf.

## 3. Eddies

Deep, basin eddies have been implicated as an important mechanism for cross-shelf exchange in the northern Gulf of Alaska (Musgrave et al., 1992; Niebauer et al., 1981; Stabeno et al., 2004) and along the southeast Alaska/British Columbia Coast (Crawford and Whitney, 1999; Thomson and Gower, 1998). Satellite altimetry and model simulations suggest that GOA eddies are preferentially formed in three locations along the eastern boundary of the GOA (Matthews et al., 1992; Okkonen et al., 2001). Haida eddies are formed near the Queen Charlotte Islands (~130–135°W) and have been described by numerous researchers (Crawford, 2002; Crawford et al., 2002; Mackas and Galbraith, 2002; Whitney and Robert, 2002). Sitka eddies, formed near Sitka, Alaska (~137–139°W) were first described by Tabata (1982) and it has been suggested that these eddies may have important implications for migrating salmon (Hamilton and Mysak, 1986; Healey et al., 2000). In this note, we focus on Yakutat eddies, formed quasi-annually during the winter months near Yakutat, Alaska (~141–144°W; Okkonen et al., 2001, 2003). (Following the conventions of earlier GOA eddy studies, we call these eddies "Yakutat eddies" after their formation region.) Satellite altimetry data suggest that, after formation, Yakutat eddies propagate along the shelf-break, reaching the region east of Kodiak Island by spring. The eddies often remain in this region for months. In situ observations of Yakutat eddies have been collected east of Kodiak Island in April 1988 (Musgrave et al., 1992), spring 1999 (Okkonen et al., 2003), and May and September 2003 (Ladd et al., 2005).

Eddies can influence cross-shelf transport in two ways: (1) by entraining and trapping shelf water in their interior during formation and then propagating off-shelf, and/or (2) by interacting with the shelf/slope circulation resulting in cross-shelf transport. Haida eddies, generally propagate away from the shelf into the basin, and have been shown to transport coastal water and shelf-origin zooplankton species up to 1000 km into the interior of the basin (Mackas and Galbraith, 2002; Whitney and Robert, 2002). Sitka eddies also tend to propagate directly into the basin (Crawford, 2002; Matthews et al., 1992), suggesting the first mechanism may be important to Sitka eddies as well. Yakutat eddies, on the other hand, tend to stay close to the shelf-break, suggesting that both mechanisms may be important (Ladd et al., 2005; Okkonen et al., 2001).

In May 2003, the R/V *Kilo Moana* conducted 19 CTD casts (using a Seabird SBE-911 Plus system with dual sensors) across an eddy centered at approximately 58.6°N, 146.3°W (Fig. 4). Combined Topex/Poseidon/ERS altimetry data (AVISO, 2003) show a sea-surface height anomaly of almost 30 cm associated with this eddy. This eddy first appeared in the altimetry data in late January 2003 at ~59°N, 144°W (formation region).

The eddy core waters were characterized by a strong subsurface temperature maximum of ~7.25 °C at a density of $\sigma_t = 25.56\,\mathrm{kg\,m^{-3}}$ and a depth of ~115 m. The core waters were quite distinct from the surrounding basin water: warmer by ~1.25 °C and saltier by ~0.2 psu (Fig. 5). A comparison with World Ocean Atlas climatological data (Levitus and Boyer, 1994; Levitus et al., 1994) shows that waters with $T/S/\sigma_t$ properties similar to the eddy core waters are not the norm off-shelf in the northern GOA during May. In addition, this water-property structure is not within the climatological mean during the winter in the eddy formation region. Unfortunately, we are aware of no observations from the shelf in the formation region during winter 2003. However,

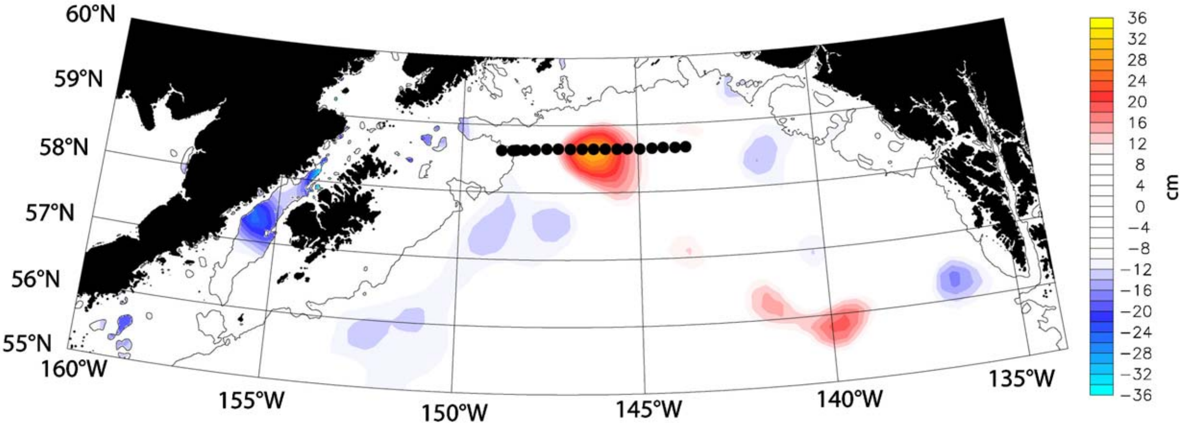

Fig. 4. Sea-surface height anomaly (cm) from merged TOPEX/POSEIDON/ERS altimetry data on 17 May 2003 from the AVISO Altimetry center (www.jason.oceanobs.com/html/donnees/produits/msla_uk.html). Because tidal errors are higher on the shelf, altimetry data from regions shallower than 200 m are not shown. Black contour is the 200 m isobath. Locations of CTD casts from May 2003 are overlain (black dots).

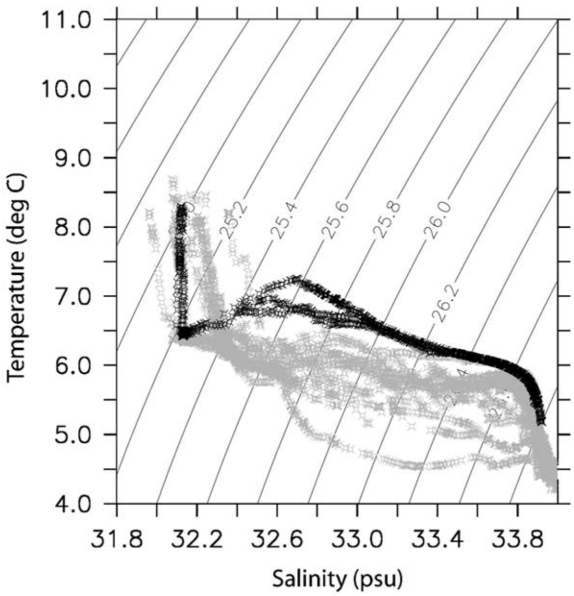

Fig. 5. Temperature/salinity data from the transect shown in Fig. 4. Data from the three casts taken at the center of the eddy are bolded.

data from previous years show that water with these properties occurs on the shelf during the winter. This implies that the core waters of the Yakutat eddy observed near Kodiak Island in May 2003 were derived from shelf-water, trapped in the eddy during formation, and propagated off-shelf to the region near Kodiak Island where they were observed. Because the coastal waters are iron enriched, the Yakutat eddies may be a source of iron to the basin, influencing production. The input of coastal iron is consistent with the high chlorophyll observed in the center of the eddy in late April from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; Fig. 6).

Cross-shelf exchange also may result from interaction of the eddy circulation with the shelf circulation when the eddy impinges on the shelf. Okkonen et al. (2003) showed that the Yakutat eddy observed during the spring of 1999 interacted with the shelf-break frontal jet resulting in localized upwelling zones at the edges of the eddy and enhanced shelf-slope exchange. Shipboard Acoustic Doppler Current Profiler (ADCP) data were collected on the NOAA ship *Miller Freeman* on a cruise that serendipitously crossed the edge of the 2003 Yakutat eddy (Fig. 7). These data show a strong southwestward Alaskan Stream over the continental slope southwest of the eddy. However, the anticyclonic eddy was strong enough to reverse the flow to northeastward where the eddy encroached on the continental slope. The overlain sea-surface height anomaly field shows that the measured velocity aligns with the height isolines (Fig. 7). Geostrophic calculations based upon the sea-surface anomaly slope give an eddy-induced maximum velocity of about 40 cm s$^{-1}$, consistent with ADCP measurements. The ADCP vectors in Fig. 7 are shaded by near-surface salinity values as measured by the ship's thermosalinograph. They show freshening seaward into the edge of the eddy from 32.2 to 31.6 psu, consistent with an anticyclonic eddy containing impounded shelf water. A satellite-tracked drifter (red trajectory, Fig. 7) made five clockwise circuits around the eddy center in the 1-month period bracketing the cruise. The cruise was not designed to study shelf-slope exchange, but the cruise track paralleled the shelf break west of the eddy. The ADCP vectors show onshore flow there. This can be interpreted as the combination of the southwestward Alaskan Stream and the northeastward eddy velocity fields. Whether this onshore flow carries onto the continental shelf is unknown, but it does show that the eddy perturbed the flow shoreward. At the eddy's northeastern edge, the ADCP velocity vectors show some indication of offshore flow of fresher water. Drifters deployed on the shelf often move off-shelf around eddies as shown in Fig. 28 of Stabeno et al. (2004). This offshore flux of coastal waters (in addition to vertical processes within the eddy) could help account for the ring of high chlorophyll often observed around the edges of these eddies (Fig. 6).

## 4. Tidal mixing and topography

Tides are very important to the dynamics of the GOA shelf. Moored current-meter data show that tides account for 20–80% of the energy on the northern GOA shelf depending on location. Using a barotropic tidal model, Foreman et al. (2000)

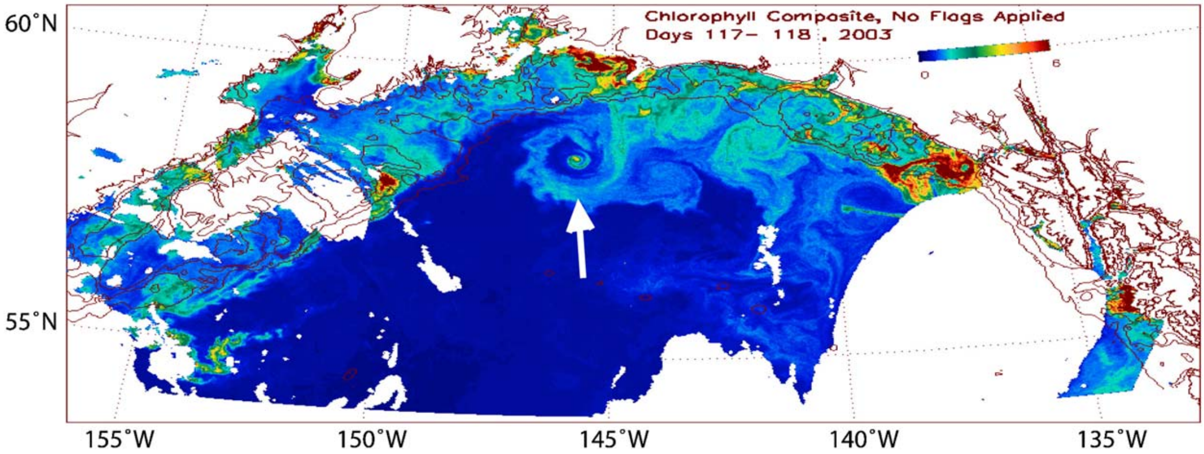

Fig. 6. Surface chlorophyll-*a* (mg m$^{-3}$) composited over 27–28 April 2003 from the SeaWiFS satellite. The Yakutat eddy of interest is noted with a white arrow.

calculate high values of tidal dissipation due to bottom friction (from both the K1 diurnal and the M2 semidiurnal tides) on the banks and canyons east of Kodiak Island. The combination of strong, fluctuating tidal currents and steep, convoluted bathymetry results in enhanced vertical mixing.

The shelves of the GOA are incised with numerous canyons including large canyons such as Shelikof Sea Valley (west of Kodiak Island), and Amatuli Trough (parallel to the Kenai Peninsula), as well as several smaller troughs (Fig. 8). The interaction of the gyre's cyclonic circulation with bathymetry is evident in satellite-tracked drifter trajectories and from current-meter records showing up-canyon mean flow on the east side and down-canyon flow on the west side of the canyons (Fig. 8).

The area to the south and east of Kodiak Island is characterized by complex topography. Three troughs (Stevens, Chiniak and Barnabas) divide the shelf into a series of shallow banks (e.g., Portlock and Albatross Banks). The mean flow results in high salinity, nutrient-rich water advecting into the troughs.

A composite of chlorophyll maps from SeaWiFS (Fig. 9) shows that the region southeast of Kodiak has higher-standing stocks of phytoplankton at the surface during the summer (after the spring bloom) than the shelf area to the northeast where there are fewer troughs. We hypothesize that the intrusion of nutrient-rich water in the troughs and the vertical mixing of the nutrients into the euphotic zone by tides is responsible for supporting production throughout the summer months.

To improve our understanding of the impact of canyons and mixing on the on-shelf fluxes, we examine mooring data from Chiniak Trough. Chiniak Trough is ~150 m deep and lies between two broad banks that are <100 m deep. Time series of temperature and currents (Fig. 10) measured at a mooring on the west side of the trough (see Fig. 8 for location of mooring) shows the strong tidal signal. Interestingly, the time series from the deeper instruments are dominated by a diurnal signal while the upper instrument exhibits a semi-diurnal signal. Flow northwards, up the canyon, brings in colder water, while southward flow is associated with increased temperatures. In addition, on the inflowing tide, the range of temperatures at different depths suggests that the water column is fairly stratified, while on the outflowing tide all of the temperature measurements except for the shallowest (17 m) converge to a narrow temperature range. This suggests that stratified water is flowing past the mooring into the canyon. It mixes within the canyon, and when the tide turns southward, mixed water is advected past the mooring. While we show only 5 days of

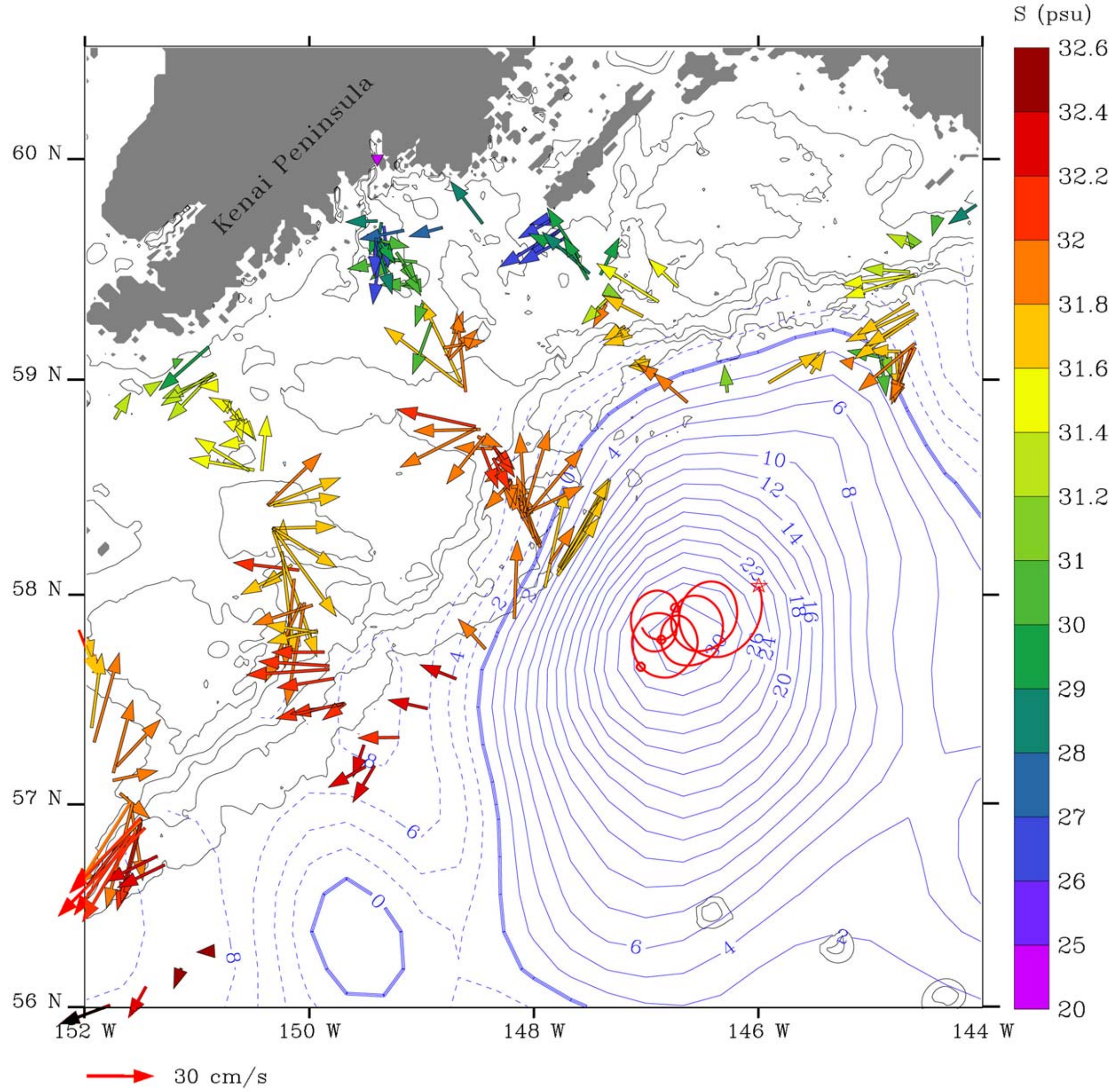

Fig. 7. ADCP velocity vectors (cm $s^{-1}$, color-coded by salinity at 5 m along the ship track in red), sea-surface height anomaly (cm, blue isolines), satellite-tracked drifter trajectory (thick red curve) and bathymetry (black contours at 100, 200 and 1000 m). The velocity vectors are 20-km averages at 38 m, 19 July–4 August 2003, from NOAA ship Miller Freeman cruise MF-03-10. A GPS-based attitude determination unit provided heading accurate to 0.02°. The 150-kHz RDI ADCP data were processed with the University of Hawaii's CODAS system (Firing et al., 1995). The sea-surface height anomalies are from merged TOPEX/POSEIDON/ERS altimetry data on 6 August 2003. The drifter was deployed in May 2003. Its trajectory begins at the star symbol on 15 July and is marked by a dot every 10 days until 15 August. The bathymetry is from Smith and Sandwell (1997) version 8.2.

mooring data for clarity, 2 years of data collected during the summers show similar patterns. Note that the heat content of the water column is not conserved over a tidal cycle, suggesting heat input from the surface and lateral mixing in addition to the vertical mixing. A careful investigation of heat

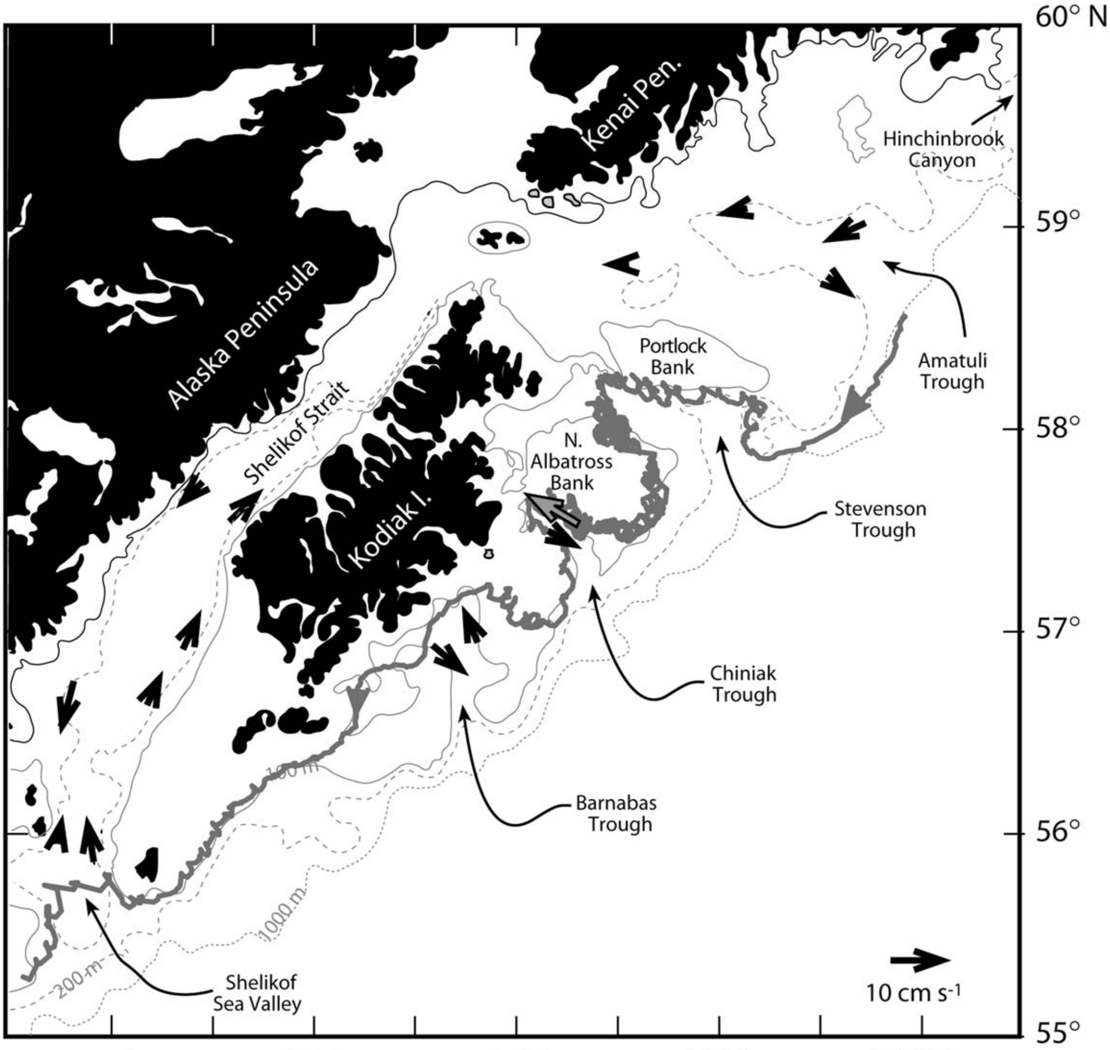

Fig. 8. Trajectory of satellite tracked drifter drogued at 40 m (gray line), mean currents at ~15 m above the bottom from a variety of moorings deployed over numerous years (bold arrows). Time series data from the mooring represented by the outlined arrow are shown in Fig. 10. Black contours represent bathymetry illustrating the troughs and canyons near Kodiak Island. The drifter moved from northeast to southwest. After Stabeno et al. (2004).

content and fluxes would shed insight into the dynamics, but is beyond the scope of this paper.

## 5. Discussion

We have presented observational evidence for three cross-shelf exchange mechanisms, episodic upwelling, eddies, and tidal mixing as influenced by bathymetry. The winds driving the GOA circulation are strongly downwelling favorable over most of the year. During the summer, when the winds are at their weakest, the upwelling index is near-zero but slightly positive. However, the mean seasonal cycle does not tell the whole story.

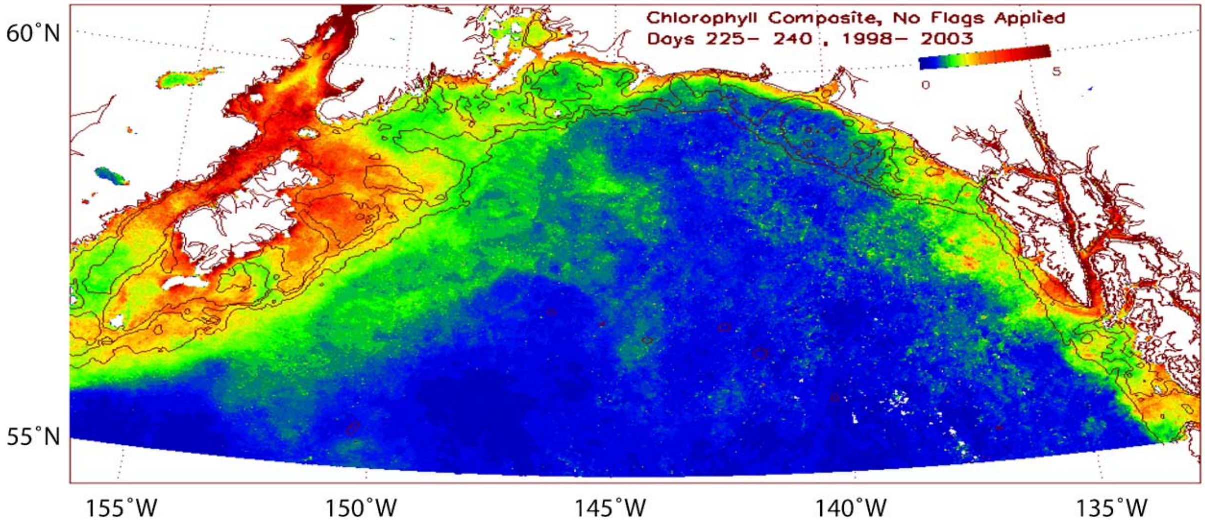

Fig. 9. Surface chlorophyll-*a* (mg m$^{-3}$) composited over July–August 1998–2003 from the SeaWiFS satellite. The 100 and 1000 m isobaths are shown. After Stabeno et al. (2004).

The winds are highly episodic and periods of downwelling relaxation (or even episodic upwelling) occur frequently throughout the year. Salinity data from moorings south of the Kenai Peninsula suggest an inflow of high-salinity water at depth during periods of downwelling relaxation. As nitrate and salinity have a strong, almost linear relationship at depth in the GOA (Mordy et al., 2005), this inflow of high-salinity water suggests a flux of nitrate to the shelf, which can be introduced into the euphotic zone through mixing, particularly tidal mixing, associated with topographic features.

Eddies can influence cross-shelf exchange in two ways. When eddies form, they may trap coastal water in their interior and then propagate offshore providing a source of iron and/or coastal biology to the basin. After formation, when eddies impinge on the shelf, they interfere with the slope circulation resulting in cross-shelf flow. The Yakutat eddies formed in the northern GOA appear to influence cross-shelf exchange in both ways. These eddies obviously enhance production as locally high chlorophyll-*a* concentrations are often observed in SeaWiFS data in a ring around the edge of the eddies and/or as a disk of high chlorophyll in the center of the eddy.

Canyons at the shelf-break have been shown to be important to cross-shelf exchange along the west coast of the United States and Canada (i.e. Allen, 2000; Chen and Allen, 1996; Freeland and Denman, 1982; Hickey, 1997), a region with upwelling favorable winds during the summer. Klinck (1996) showed that the important forces in canyon-induced upwelling are Coriolis acceleration and pressure gradients and their interaction with bathymetric gradients. However, he showed that right-bounded flows (alongshore flows with the coastline on the right in the Northern Hemisphere) result in shallow downwelling in the canyon and weak exchange across the shelf-break. While the GOA shelf includes many canyons that cut into the shelf, the coastal flow is right-bounded, suggesting that the canyon-induced upwelling without mixing cannot be an important mechanism of cross-shelf flow.

Thus, we invoke tidal mixing in combination with bathymetric gradients in order to explain the observed high chlorophyll concentrations at the edges of the banks southeast of Kodiak Island. Flow generally follows bathymetry contours resulting in flow into the canyons. Strong tidal mixing exists over much of the GOA shelf, but in

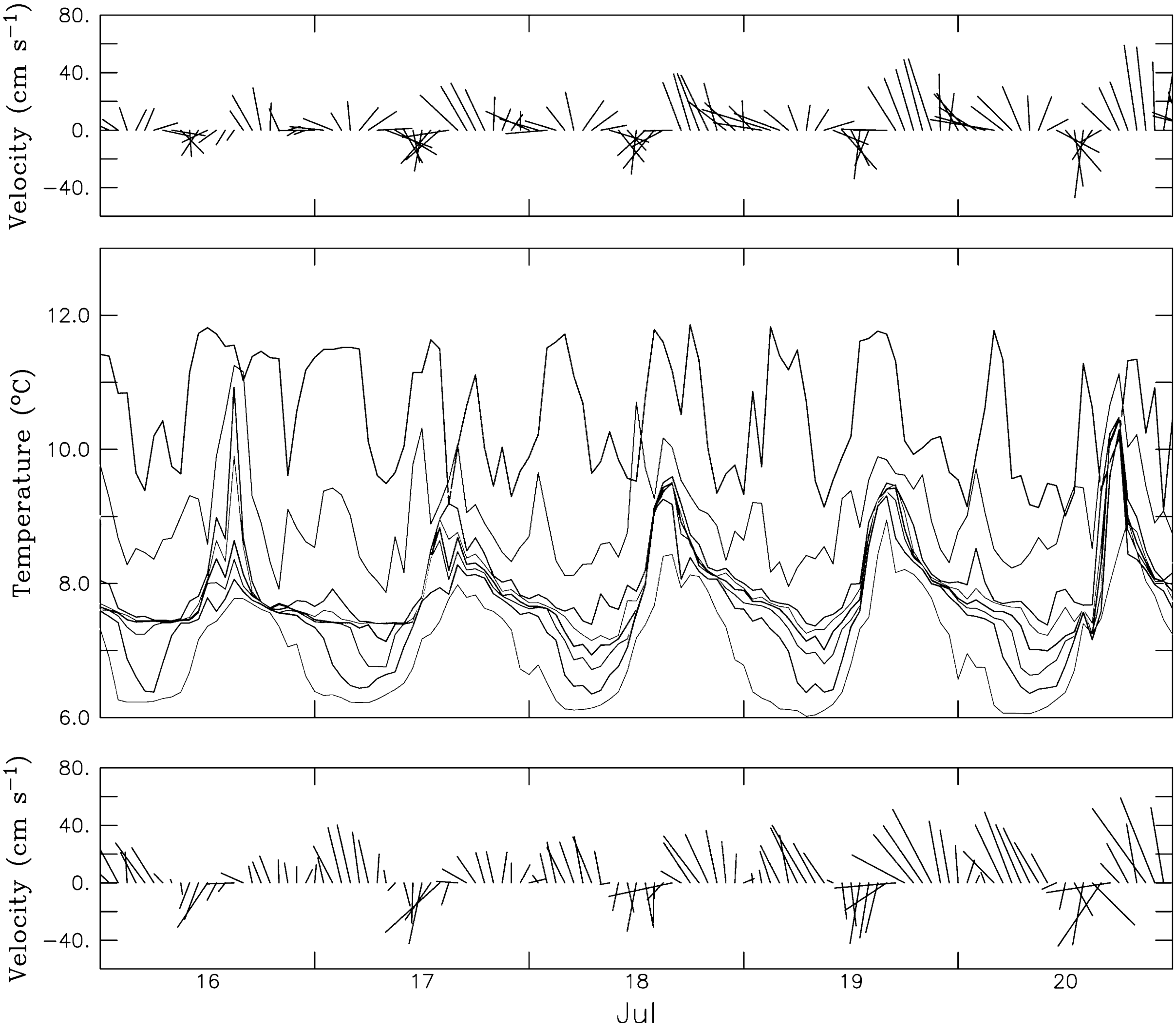

Fig. 10. Data from a mooring deployed in July 2001 in Chiniak Canyon southeast of Kodiak Island, (A) Currents at 16 m (cm s$^{-1}$); (B) temperatures (°C) at different depths (*shallowest* = 16 *m*, *deepest* = 127 *m*); and (C) currents at 110 m (cm s$^{-1}$).

combination with strong bathymetric gradients, the mixing can result in higher cross-isobath movement of water properties. The combination of up-canyon flow and tidal mixing results in deep nutrients being mixed up into the euphotic zone particularly around the edges of the banks. Note that this mechanism invokes tidal mixing and is different from the geostrophic canyon-induced upwelling discussed above (e.g., Allen, 2000; Klinck, 1996).

All of the cross-shelf exchange mechanisms discussed above are due to perturbations to the mean state of the system. They occur preferentially at different timescales and in different locations. The relaxation of downwelling appears to influence deep salinities on the shelf at timescales on the order of weeks and has been observed on the shelf south of the Kenai Peninsula (although it is likely to be important in other regions as well). Yakutat eddies form on the shelf in the northeastern GOA and propagate along the shelf-break toward Kodiak Island on timescales of months. Presumably, they influence cross-shelf exchange all along their propagation path. They have been observed to remain coherent for more than a year and to propagate all the way to the Aleutian Islands (Okkonen, 1996; Okkonen et al., 2001). Tidal mixing occurs on diurnal or semi-diurnal timescales and is likely to be most important in canyons and troughs where the steep convoluted bathymetry diverts the flow onto the shelf and aids in cross-isobath transport of water properties.

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