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Transport through Unimak Pass, Alaska

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Abstract

We examined inflow through Unimak Pass (<200 m deep), which is the only major connection between the shelves of the North Pacific Ocean and the eastern Bering Sea. Geostrophic transport was generally northward from the Gulf of Alaska into the Bering Sea. The flow through the pass appeared to be modulated by the seasonal cycle of freshwater discharge. On shorter time scales, transport also was affected by semi-daily variations in tidal mixing. This effect was significant and not anticipated. Near-bottom currents, measured from moorings, were maximum during winter, and significantly correlated ($r = 0.7$) with the alongshore winds. Although the flow through Unimak Pass transported some nutrients from the North Pacific Ocean, the Gulf of Alaska shelf is not the major source of nutrients to the Bering Sea shelf.
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1. Introduction

Numerous investigations have been conducted on the eastern Bering Sea shelf during recent years, and many aspects of circulation are documented. One aspect that has not received adequate attention, however, is the flow of Gulf of Alaska shelf waters northward through Unimak Pass, the only major, direct conduit between the shelves of the North Pacific and eastern Bering Sea (Fig. 1). At its southeastern end, Unimak Pass is shallow ($\sim$70 m) and relatively narrow ($\sim$16 km). Toward the northwest it deepens to a maximum depth of 160 m before shoaling to a sill depth of 100 m, and broadens to $\sim$35 km. Shelf waters of the eastern Bering Sea are linked to those in the nearshore Gulf of Alaska by the southwestward flowing Alaska Coastal Current (ACC; Royer, 1981; Stabeno et al., 1995), which extends for more than 1000 km along the coast of Alaska.

From the head of the Gulf of Alaska, the ACC flows southwestward along the south side of the Alaska Peninsula. While much of the transport in the ACC is diverted off the shelf by bathymetric features or reduced by other mechanisms such as mixing or friction, an unknown portion continues southwestward along the peninsula and eventually through Unimak Pass (Royer, 1981; Reed, 1987). Drifters deployed at the head of the Gulf can enter the Bering Sea through Unimak Pass in as little as $2\frac{1}{2}$ months (Fig. 2). The ACC has a strong baroclinic signal with a large freshwater input occurring in September and October, although the period of maximum total transport occurs in winter when winds are at their strongest (Schumacher et al., 1989). The continuity of these low-salinity waters along the Alaska Peninsula and

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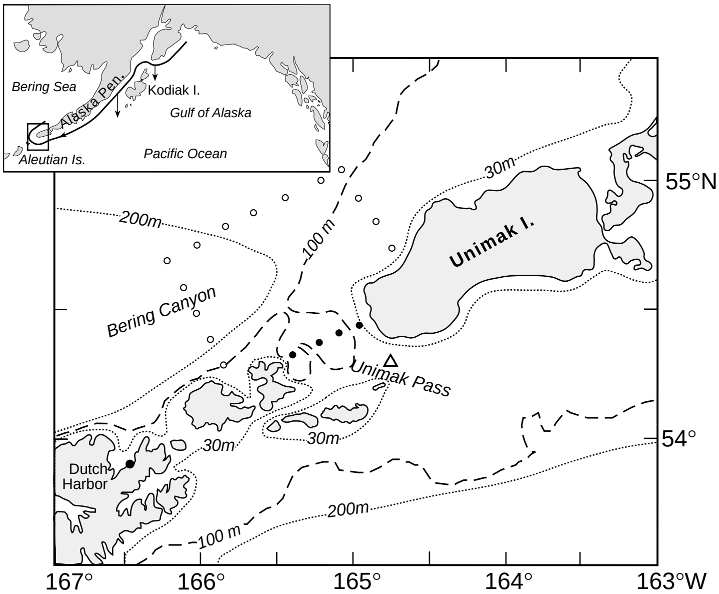

Fig. 1. Location of observations near Unimak Pass. The solid dots indicate the locations of CTD casts across Unimak Pass, and the open circles show locations of CTD stations occupied less often. The triangle is the location of the current moorings.

their northward inflow through Unimak Pass have been presented in earlier research (Schumacher et al., 1982; Reed, 1987). What is not well known, however, is the magnitude and temporal variability in the current, and the water properties, particularly nutrient concentrations, that are transported northward from the Gulf of Alaska onto the eastern Bering Sea shelf.

2. Data and methods

A transect of conductivity, temperature and depth (CTD) casts was occupied 21 times during the period 1995–2000 (Fig. 1). These data are used to derive geostrophic flow through the pass. CTD casts were taken with Seabird SBE-9 or SBE-911 Plus systems. Salinity calibration samples were taken on all casts and analyzed on a laboratory salinometer. During most cruises, water samples for dissolved inorganic nutrients were collected at each station using 5 l Niskin bottles. The samples were frozen and stored at -20°C, and sample analysis was performed at the University of Washington using the WOCE protocol (WOCE, 1994).

In addition to the hydrographic sections, current meters were deployed in a narrow, southeastern part of the channel on three separate occasions, resulting in two, nearly year-long records and one shorter summer record. The narrow width of this part of the pass should permit estimation of bottom transport. These taut-wire subsurface moorings had a current meter $\sim$10 m off the bottom, which measured the current speed and direction, temperature, and conductivity (salinity) at hourly intervals. The current meter data were low-pass filtered using a 35 h, cosine-squared tapered Lanczos filter to remove diurnal and semi-diurnal tidal signals and were then resampled at 6 h intervals.

For comparison with the measured current time series, we used geotriptic winds, computed from 12-hourly atmospheric surface pressure maps. These surface winds (a balance of Coriolis, pressure gradient, centripetal and friction terms) were rotated 15° counterclockwise and reduced in speed by 30% from the geostrophic wind. They were interpolated to 164°W, 54.5°N. Such winds are in good agreement with observed low-pass filtered measured winds along the Alaska Peninsula (Macklin et al., 1993).

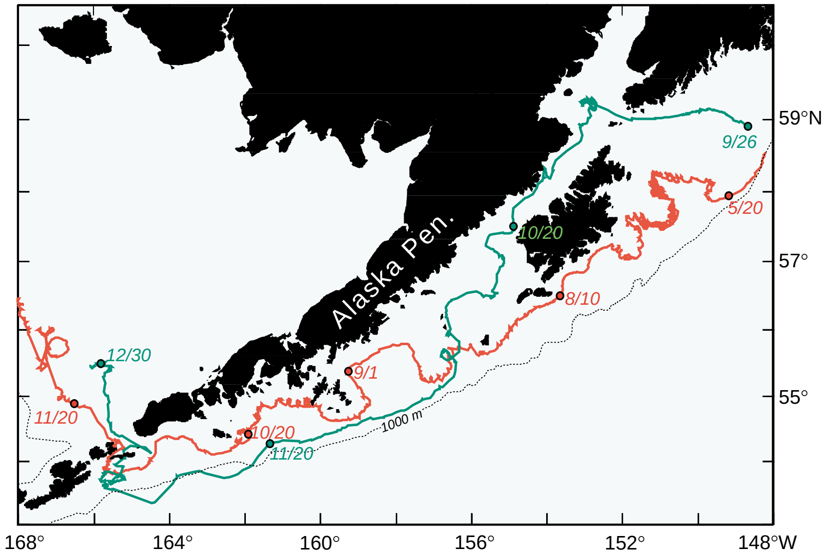

Fig. 2. Trajectories of two satellite-tracked drifters deployed in the northern Gulf of Alaska in 2001.

Satellite-tracked drifters were deployed in the Bering Sea and North Pacific between 1986 and 2001. Positions were obtained $\sim$14 times per day via Service Argos. The drifters were fitted with "holey sock" drogues, or "tristar" drogues during the early 1990s, centered at 40 m, and instrumented with a sensor to indicate drogue loss. Only positions from drifters that have a drogue are presented here.

3. Geostrophic (baroclinic) flow

Table 1 summarizes results from the 21 occupations of the CTD section across Unimak Pass; we list computed geostrophic volume transports and peak speeds, referred to the deepest common level between stations, during each occupation. For the section consisting of four CTD casts across Unimak Pass (Fig. 1), the depths of the stations vary from $\sim$50 m on the eastern side of the pass to 130–160 m to the west. The calculated transport ranged from $\sim$0 to $0.5 \times 10^6\,m^3\,s^{-1}$ northward (Table 1). The mean ($\pm$standard error) of all observations is $0.21 \pm 0.03 \times 10^6\,m^3\,s^{-1}$. This mean value may be biased, however, because most of the transects were in April and May. To address this problem, the data were divided into three "seasons." The first period, winter (21 February–15 March), had five samples with mean geostrophic transport ($\pm$one standard error) of $0.21 \pm 0.03 \times 10^6\,m^3\,s^{-1}$. The second period, spring (21 April–22 May), had 12 samples with mean ($\pm$one standard error) of $0.13 \pm 0.03 \times 10^6\,m^3\,s^{-1}$. The final period, fall (21 August–6 October) had four samples with mean ($\pm$one standard error) of $0.33 \pm 0.08 \times 10^6\,m^3\,s^{-1}$. Although none of these values differ significantly (95% confidence level), the pattern is consistent with the variability in freshwater run-off that provides the baroclinic structure of the ACC. Run-off along the eastern Gulf of Alaska is maximum in late summer and early fall and greatly exceeds any freshwater contribution from the Alaska Peninsula. In general, the geostrophic transport to the east of Unimak Pass in Shelikof Strait (58°N, 155°W) is approximately three times the geostrophic transport in Unimak Pass calculated here (Reed and Bograd, 1995).

During 21–22 May 1996, we examined the effect of the tidal signal on the baroclinic structure in the pass by occupying the CTD transect during ebb tide (flow southeastward from the Bering Sea into the North Pacific; from tidal current predictions at Unimak Pass) and then 7 h later during flood tide

Table 1
Calculated geostrophic transports and maximum speeds across the standard CTD section, referred to near-bottom. The phase of tidal flow during each CTD section is also shown

Date	Northward transport ($10^6\,m^3\,s^{-1}$)	Max. geostrophic speed ($cm\,s^{-1}$)	Phase of tidal flow
23 Feb 95	0.18	16	Flood
15 Mar 95	0.33	34	Ebb
21 Apr 95	0.16	12	Ebb
4 May 95	0.12	22	Flood
21 May 95	0.19	30	Flood
21 Aug 95	0.31	42	Ebb
5 Sep 95	0.51	63	Slack
15 May 96	0.04	12	Slack
21 May 96	0.27	22	Ebb
22 May 96	0.08	20	Flood
25–26 Feb 97	0.14	14	Slack
25 Apr 97	0.22	27	Slack
11 May 97	0.14	23	Flood
26 Sep 97	0.13	23	Flood
21 Feb 98	0.17	15	Flood
29 Apr 98	−0.02	9	Flood
6 Oct 98	0.36	55	Slack
18–19 May 99	−0.03	16	Slack
25 Feb 00	0.24	33	Slack
21 Apr 00	0.16	36	Flood
30 Apr 00	0.19	19	Slack

(flow into the Bering Sea). The transport results were quite different: 0.27 and $0.08 \times 10^6\,m^3\,s^{-1}$ during ebb and flood, respectively (Table 1). Fig. 3 shows sigma-t density sections during the two occupations. During ebb, isolines of sigma-t sloped steeply throughout the water column; during flood, however, density slopes were weak on the western (left) side, and even reversed, below ~ 70 m. Thus during flood, the near-bottom water appeared to be mixed vigorously as it flowed northwestward through the narrow, shoal channel southeast of the CTD section (Fig. 1). Conversely, such a bathymetric effect was lacking during ebb (flow from the deeper water to the northwest). Although the computed surface speeds were little affected by the tides (Table 1), the speeds at mid-depth were. The calculated speeds at 60 m referred to near-bottom were $7\,cm\,s^{-1}$ less during flood than during ebb tide, and $\Delta v/\Delta t = 2.8 \times 10^{-4}$ cm s^{-2}, where v is velocity and t is time. For

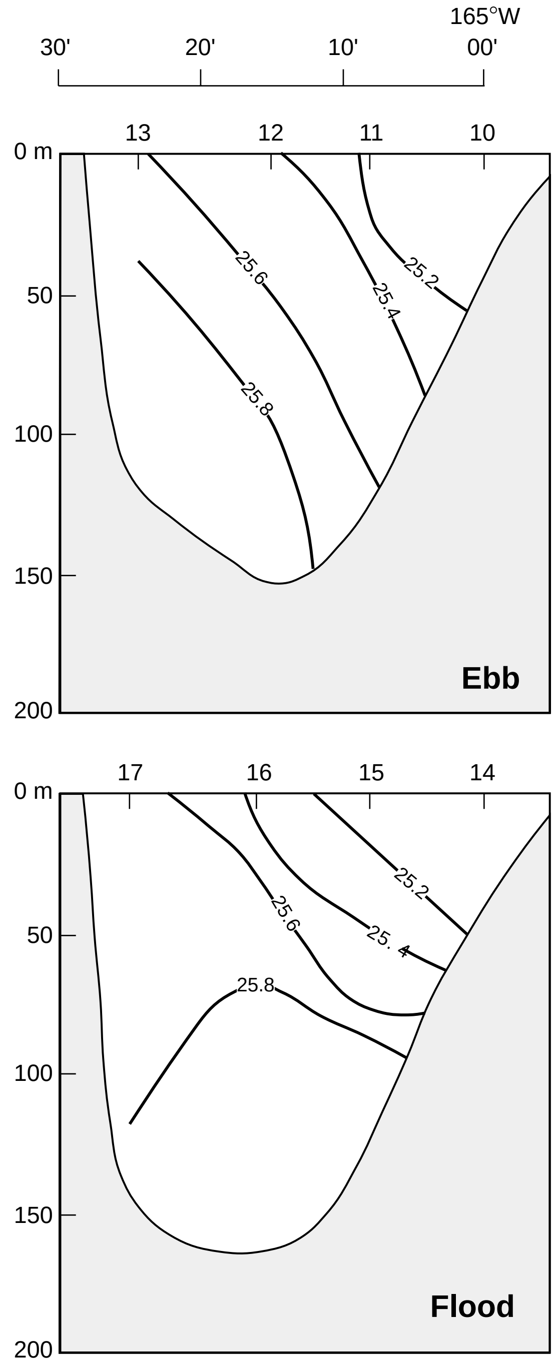

Fig. 3. Vertical sections of sigma-t density across Unimak Pass during ebb (upper) and flood (lower) tidal flow, 21–22 May 1996.

comparison, $fv = 1.0 \times 10^{-3}\,\mathrm{cm\,s^{-2}}$, where f is the Coriolis parameter. Thus, the local change was $\sim 30\%$ of the Coriolis acceleration. Thus, flood tides may produce an ageostrophic flow in the pass. Table 1 shows the predicted tidal phase during each of the CTD sections. The two most extreme transports (5 September 1995 and 18–19 May 1999) occurred during slack conditions. There were nine transects occupied during flood with a mean transport of $\sim 0.13 \times 10^6\,\mathrm{m^3\,s^{-1}}$ and four occupations during ebb with a mean transport of $\sim 0.27 \times 10^6\,\mathrm{m^3\,s^{-1}}$; thus the overall mean may be biased by tidal mixing.

In addition to the hydrographic line across Unimak Pass, three other CTD transects in the Bering Sea were occupied when time permitted (Fig. 1). These were designed to determine the path of the water after entering the eastern Bering Sea at Unimak Pass. Only during 1995 was the complete set of CTD stations done more than once, so we will use these data to examine the salinity and geostrophic flow in the vicinity of Unimak Pass. During April and September 1995, the highest surface salinities on these transects were observed in the Bering Sea basin, with the fresher water occurring around Unimak Island (Fig. 4c and d). Upon entering the Bering Sea, the least saline water occurred near Unimak Island, while the more saline water was found on the outer shelf and in the basin.

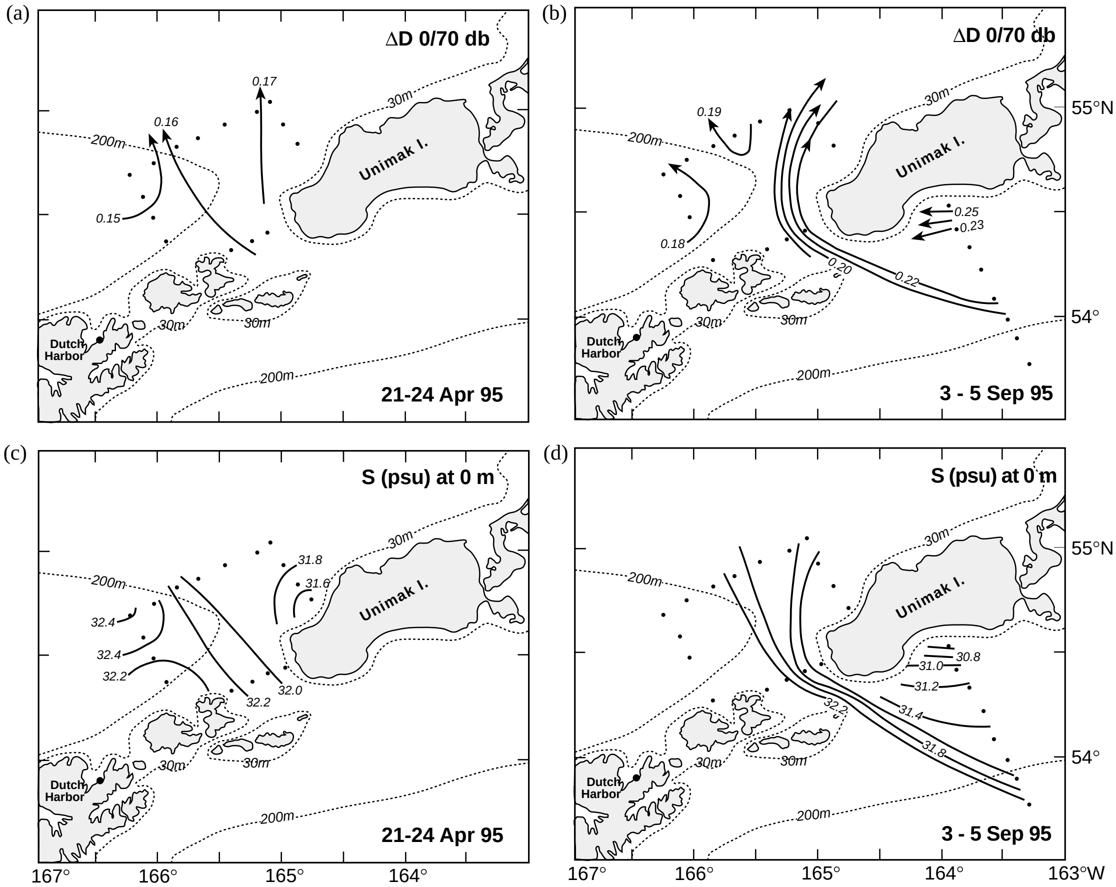

Fig. 4. Geopotential topography of the sea surface in dyn m, referred to 70 db: (a) during 21–24 April 1995 and (b) 3–5 September 1995. Sea surface salinity for (c) 21–24 April 1995 and (d) 3–5 September 1995.

The geopotential topography of the sea surface, referred to 70 decibars (db; 1 db = 0.99 m), is shown for spring and early fall in Fig. 4a and b. In spring, flow through the pass was weak, with a geopotential difference of slightly more than 1 dyn cm. In fall, the difference across the flow was ~ 3 dyn cm. This large seasonal difference in baroclinic flow is much like that observed upstream in the ACC, which results from an autumn increase in freshwater discharge (Royer, 1981; Stabeno et al., 1995). Upon exiting Unimak Pass during April 1995, the water flowed northward following the 100 m isobath, while in September the flow turned more sharply to the northeast and continued along the Unimak Island. Additional evidence for a seasonal difference in flow patterns is suggested by satellite-tracked drifter trajectories.

4. Satellite-tracked drifters trajectories

Since 1986, over 320 satellite-tracked drifters have been deployed in the southeastern Bering Sea and the coastal Gulf of Alaska. Trajectories on the Bering Sea shelf show a northwestward flow along the 100 m isobath ($\sim 4\,\mathrm{cm\,s^{-1}}$) and weaker flow ($\sim 2\,\mathrm{cm\,s^{-1}}$) along the Alaska Peninsula (Reed and Stabeno, 1996). On a closer examination of the drifter data, 43 drifters were deployed in or were advected into the box delineated by the CTD stations north of Unimak Pass (Fig. 1). There has been at least one drifter from each year since 1986. Most of the drifters (26) followed a trajectory northward or northwestward similar to the blue trajectory (D1) in Fig. 5a or the green (D1) one in Fig. 5b. Eight drifters traveled to the northeast along the Alaska Peninsula (the red trajectories 'D2' in Fig. 5a and b). Three drifters were advected southward through the pass and into the North Pacific, or went aground on the Krenitzin Islands (D3 in Fig. 5b). Typically, the drifters advected southward were on the western side of the pass, while those that were advected northward were on the eastern side. However, during winter northward flow is also evident on the western side of the pass (Fig. 2). The remaining drifters either lost their drogue, went aground, or ceased transmitting before exiting the box.

A seasonal pattern is suggested in the temporal distribution of the observed trajectories upon exiting into the Bering Sea. Satellite-tracked drifters advected northward over the outer shelf (water depth between 100 and 180 m) were in the vicinity of Unimak Pass from March through December, while drifters that eventually followed along the Alaska Peninsula were all in the vicinity of the Unimak Pass between late April and mid October. Current meter moorings were deployed along the Peninsula to the east of Unimak Pass (near 164°W) in 1999. Unfortunately, the deployment period of the moorings was limited to just the spring and summer. Current records show, however, an increase of flow along the peninsula in mid-May (Stabeno et al., in preparation). During March and April, a highly variable flow was evident along the Alaskan Peninsula; during May along-shelf flow toward the northeast increased and persisted during the summer. The development of this flow occurs in conjunction with the establishment of the front along the 50-m isobath (Kachel et al., 2002). Thus the CTD, drifters, and current meter data all suggest that the existence of northeastward flow along the Alaska Peninsula is seasonal.

5. Near-bottom current measurements

Current moorings have been deployed on three occasions in the narrow, southeastern end of Unimak Pass (Fig. 1 and Table 2). Data from the first deployment in 1980 were analyzed by Schumacher et al. (1982), but are presented here for comparison with those collected more recently, 1995–1997. All moorings showed a net northward (annual average $\sim 17\,\mathrm{cm\,s^{-1}}$) flow from the North Pacific into the Bering Sea. Using the hourly measurements, which include tides, the flow at 60 m was northward over 60% of the time. This combination of tidal and wind forced currents had maximum hourly velocities $>230\,\mathrm{cm\,s^{-1}}$. Daily averaged velocities were substantial and at times exceeded $140\,\mathrm{cm\,s^{-1}}$. We assumed that the bottom flow was zero in our geostrophic calculations, and

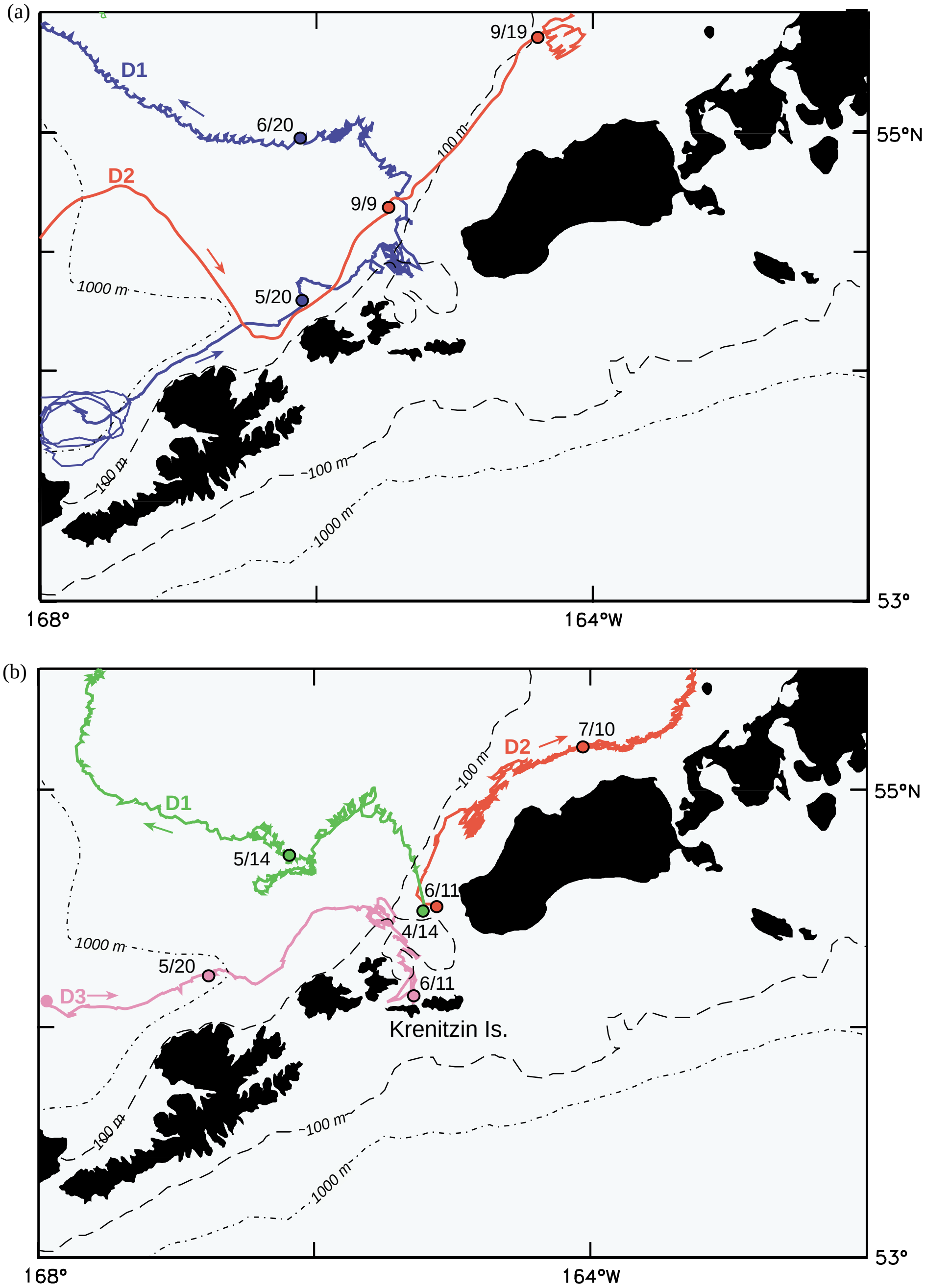

Fig. 5. Trajectories of satellite-tracked drifters drogued at ~40 m and deployed in the Bering Sea. The arrows indicate the direction of flow. The small-scale variability evident on trajectories on the shelf results from tidal motion.

so this bottom flow observed in the mooring data represents a barotropic component to the currents (Pond and Pickard, 1978). The mean flow, when multiplied by the width (16 km) and depth (70 m) of the channel (Fig. 1), gives an annual barotropic transport of $\sim 0.19 \times 10^6\,m^3\,s^{-1}$. If mean barocli-

Table 2
Statistics of flow from the current meters. Each current meter was at a depth of approximately 60 m. Maximum velocities are along 283°. Correlations are between currents at 280° and winds (164°W, 54.5°N) along 270°, which are alongshore winds

Start date	Length (days)	Net flow ($cm\,s^{-1}$, °T)	Maximum daily velocity ($cm\,s^{-1}$)	Principal axis (°T)	Correlation with winds
22 Mar 1980	147	12.4 283°	70	285	0.70
21 Feb 1995	342	17.0 253°	99	268	0.62
25 Sep 1996	365	16.8 254°	142	277	0.74

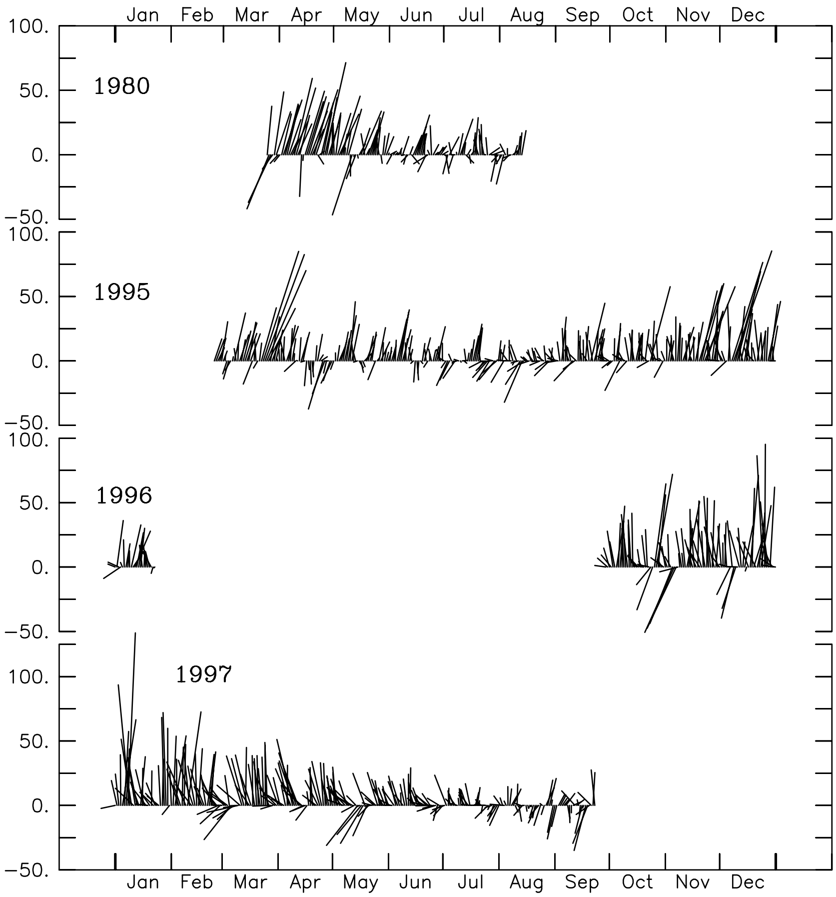

Fig. 6. Daily net current vectors at ~70 m during the three occupations of the mooring site. Vectors have been rotated so that up is 280°T.

nic flow in Unimak Pass is taken as $0.22 \times 10^6\,m^3\,s^{-1}$ (average of the winter, spring and fall estimates), then the barotropic flow constituted approximately a half of the total transport in Unimak Pass. This is the same as the result that Schumacher et al. (1982) derived from the 1980 data set.

The annual signal evident in the current records (Fig. 6) is expected due to the strong seasonal signal in wind forcing. The average monthly velocity was maximum in January ($33\,cm\,s^{-1}$) and minimum in August ($<1\,cm\,s^{-1}$). Superimposed on the annual signal, the non-tidal velocities (and transports) varied significantly through the

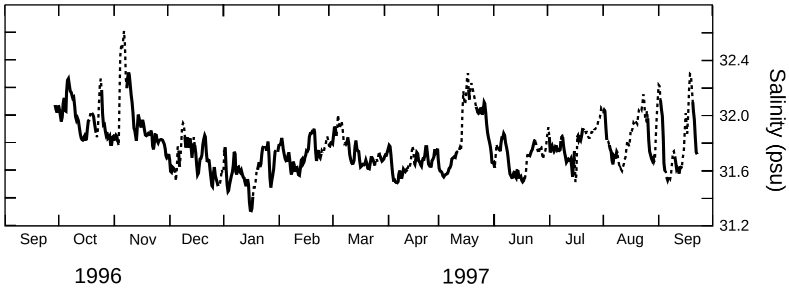

Fig. 7. Time series of low-pass filtered salinity measured at the mooring site in Unimak Pass. The dashed line indicates periods when the flow was from the Bering Sea into the Gulf of Alaska, and the solid line when the flow was in the opposite direction.

year, with flow reversals lasting from a day to a week (Fig. 6). Current velocities were significantly correlated with the along-peninsula winds (Table 2; $r \cong 0.69$). These winds spin up the ACC and confine its flow along the Alaska Peninsula (Schumacher et al., 1982; Stabeno et al., 1995). The resulting flow then enters Unimak Pass (Fig. 2).

From the CTD data, the highest salinities occurred at the western side of Unimak Pass and fresher water at the eastern side. Inflow of Bering Sea water along the western side of the pass was evident in the satellite-tracked drifter trajectories (i.e. D3 trajectory in Fig. 5b). The low-pass filtered time series of salinity measured at the mooring site within the pass revealed variability on various time scales (Fig. 7). The time series is divided into two parts. The solid lines represents periods when the daily averaged flow was northwestward from the Gulf of Alaska into the Bering Sea, and the dashed lines indicate when the flow was southeastward from the Bering Sea into the Gulf of Alaska. During periods when transport was from the Bering Sea into the North Pacific, salinity would increase sharply (dashed line). When the currents reversed, fresher North Pacific shelf water was advected through the pass (solid lines). Maximum salinity was 32.6 psu in November during a period of southeastward flow, and minimum salinity was <31.4 psu in January during a period of northwestward flow. An examination of salinity during just those periods when flow was northwestward (solid lines), shows a decrease of salinity from October through January of ~ 0.6 psu, and is indicative of the increased freshwater run-off observed during late summer/fall in the Gulf of Alaska. This delay is consistent with the amount of time it takes a drifter to be transported from the head of the Gulf of Alaska to Unimak Pass (Fig. 2).

6. Nutrients

The southeastern Bering Sea supports a productive ecosystem and is home to many species of fish, crustaceans, and molluscs, as well as seabirds and marine mammals (Sinclair and Stabeno, 2002). During the annual production cycle, new production dominates during spring in what are often short-lived ice-associated blooms (Niebauer et al., 1990; Stabeno et al., 1999, 2001), while recycled nitrogen (in the form of ammonia) drives production in the summer. Approximately one-half of the nutrients necessary to support the ecosystem over the southeastern shelf must be replenished (as new nitrogen) each year. The source of that nitrogen is contentious, but it has been hypothesized that flow through Unimak Pass may be a source. The data collected at Unimak Pass permit examination of this hypothesis.

In spring (April), the water flowing through Unimak Pass contains dissolved inorganic nitrogen, phosphorus and silicate. Concentrations of nitrate are sufficient to support new production by phytoplankton. Although there is variation in nutrient concentrations in Unimak Pass among years, the easternmost waters generally had the lowest nitrate concentrations (Fig. 8a and b). The nitrate concentrations ranged from ~ 5 to

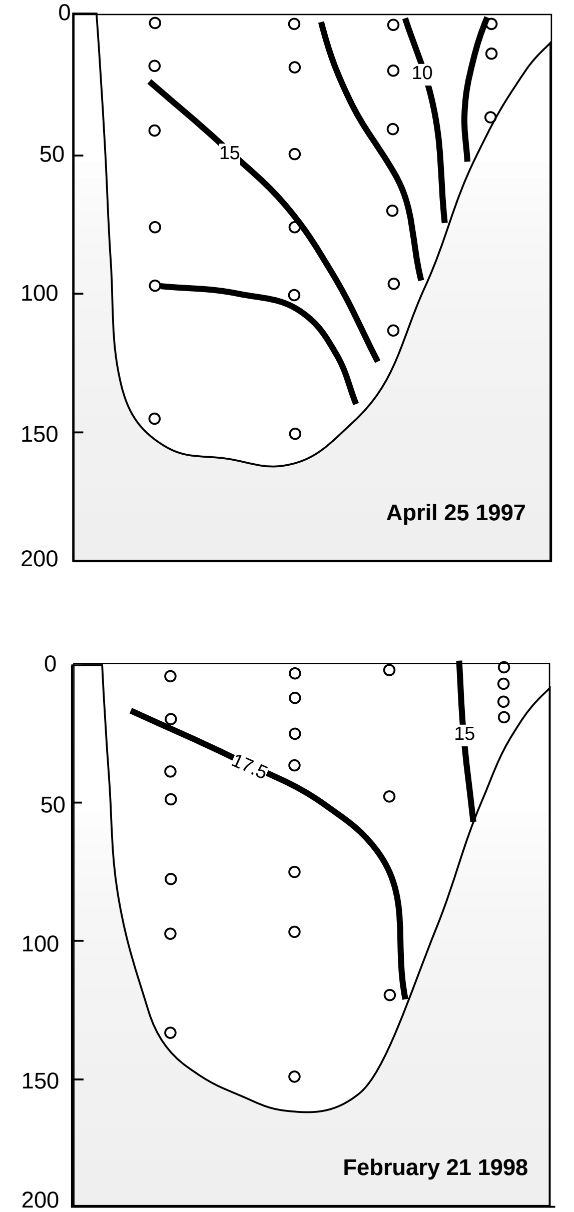

Fig. 8. Contours of concentration of nitrate (mmol kg^{-1}) measured at the four CTD stations across Unimak Pass for 25 April 1997 and 21 February 1998.

$\sim$14 μM at the surface on the eastern side of the pass; concentrations at depth did not exceed 22 μM. In comparison, slope water from Bering Canyon (Stations 15–18, Fig. 9) had higher concentrations of nitrate at comparable depths, and at depths greater than the pass substantially higher concentrations. Nitrate concentrations at the shelf bottom directly across from Unimak Pass (Stations 10–14) were similar to concentrations observed along the western side of the box (Stations 15–18). Intrusion of water rich in nitrate (concentrations >20 μM) is evident in the northeast corner (Station 9) of the Unimak box. The only source of such water is Bering Canyon.

Not surprisingly, patterns in nutrient concentration are similar to those observed in salinity. The highest salinities and nutrients were observed in Bering Canyon below a depth of 200 m. In the upper 200 m, more saline water was associated with higher nitrate concentrations. The freshest water (and lowest nitrate concentrations) occurred along the eastern side of Unimak Pass and continued along Unimak Island. From the drifter trajectories, it is likely that the higher salinities on the western side of Unimak Pass were a mixture of water from Bering Canyon and the Gulf of Alaska shelf.

7. Summary

From the data discussed above, the geostrophic transport varied from ~ 0 to $0.5 \times 10^6\,m^3\,s^{-1}$, with a maximum occurring in the fall. There was also an unexpected semi-diurnal tidal modulation of $\sim 0.2 \times 10^6\,m^3\,s^{-1}$. Total geostrophic flow had an annual mean of $\sim 0.2 \times 10^6\,m^3\,s^{-1}$. The near-bottom currents varied on time scales of tidal to annual. The mean barotropic transport was $\sim 0.2 \times 10^6\,m^3\,s^{-1}$, or approximately the same as the baroclinic transport, which is similar to the ratio observed upstream in Shelikof Strait (Stabeno et al., 1995).

Each day tidal currents advect nutrient-rich water from Bering Canyon into Unimak Pass, which then mixes with water from the Gulf of Alaska. During late spring and summer, the surface waters of the ACC contain reduced amounts of dissolved nitrogen, and the volume of water flowing through Unimak Pass is relatively small. Thus, the source of the high concentrations of nutrients observed in Unimak Pass and to the

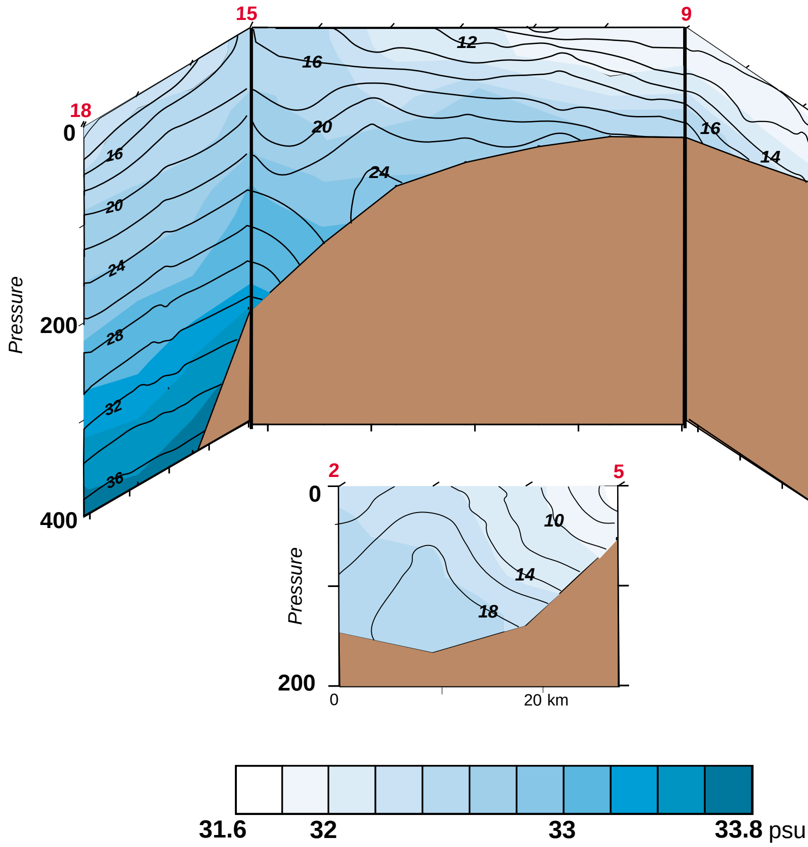

Fig. 9. Salinity (psu) and nitrate (mmol kg^{-1}) along the four sections of the box (Fig. 1) are shown for 4–5 May 1995. Ticks at the bottom of each panel indicate distance (km) and those at the top of the panel indicate locations of CTD casts. Contours of salinity are shaded in blue. Nitrate concentrations are plotted on top of salinity.

north is likely Bering Canyon and not the Gulf of Alaska.

To understand the impact of the enriched water exiting Unimak Pass, some understanding of shelf water structure of the eastern Bering Sea is required. The shelf during late spring and summer is divided into several domains. The water column over the inner shelf (water depth, $z<50$ m) is weakly stratified or well mixed, while that over the middle shelf (50 m $<z<100$ m) is two layered, with a warm surface layer overlaying a cold, nutrient-rich bottom layer. Between these two domains lies the inner front. In general, nutrients are depleted from surface waters of the inner and middle shelf during summer. Along the inner front during summer, nutrients can be replenished from the cold, nutrient-rich lower layer of the middle shelf (Kachel et al., 2002). Unimak Pass, with its mixture of water from the North Pacific and Bering Canyon, may contribute directly to nutrient supply of the southeastern inner front by advection along the Alaska Peninsula. The stronger advection northward from Unimak Pass seaward of the 100 m isobath likely contributes to high productivity of the green belt (Springer et al., 1996). While episodic events of on shelf flux of slope water have been observed (Stabeno and van Meurs, 1999), the supply from Unimak Pass is more persistent and so an important source of nutrients. Thus, while Unimak Pass is not the only source of nutrients to the southeastern Bering Sea shelf, it is an important contributor.

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