Journal of Marine Research, 55, 565–575, 1997

Long-term measurements of flow near the Aleutian Islands

by R. K. Reed[1] and P. J. Stabeno[1]

ABSTRACT

In summer 1995, the Alaskan Stream at 173.5W was very intense; the peak geostrophic speed was ~125 cm s^{-1}, and the computed volume transport above 1000 db, referred to 1000 db, was 9 × 10^6 m^3 s^{-1}. Flow north of the central Aleutians was shallow, convoluted and weak (2–3 × 10^6 m^3 s^{-1}). A sequence of CTD casts across Amukta Pass, spaced irregularly in time during 1993–1996, showed a mean northward (southward) geostrophic transport of 1.0 (0.4) × 10^6 m^3 s^{-1}, for a net flow into the Bering Sea of 0.6 × 10^6 m^3 s^{-1}. The source of this flow was the Alaskan Stream except in 1995, when it was Bering Sea water. Results from two 13-month current moorings west and east of the pass were quite different. To the west, flow was weak and variable and appeared to have a barotropic component. To the east, flow was stronger and unidirectional eastward.

1. Introduction

Upper-ocean circulation near the central Aleutian Islands is characterized by the swift, westward flowing Alaskan Stream on the southern side and by a relatively weak, eastward flow on the northern side (Favorite, 1974; Sayles *et al.*, 1979). There is exchange between these two flows, however, through the two deep passes across the ridge near 180 and 172W (Reed and Stabeno, 1994). One of our objectives was to obtain frequent samples of the density field across the pass near 172W (Amukta Pass; Fig. 1), primarily because it is a pathway for relatively warm (>4°C) Alaskan Stream water into the Bering Sea (Reed, 1995). This inflow affects water properties and also the velocity field in the Bering Sea, but some aspects of this interaction are not understood (Stabeno and Reed, 1994). Thus another goal was to obtain direct current measurements in the Bering Sea to the west and east of Amukta Pass in order to examine the background flow and the downstream effects of inflow through the pass. We present results from these measurements here; in order to orient the reader and provide large-scale information on circulation, however, we first show results from a synoptic survey in summer 1995.

CTD (conductivity, temperature, depth) casts were taken with Seabird SBE-9 or SBE-911 Plus systems and with salinity calibration samples on all casts. The current measurements were from taut-wire, subsurface moorings, using Aanderaa RCM-4 or 7

1. National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, Washington, 98115-0070, U.S.A.

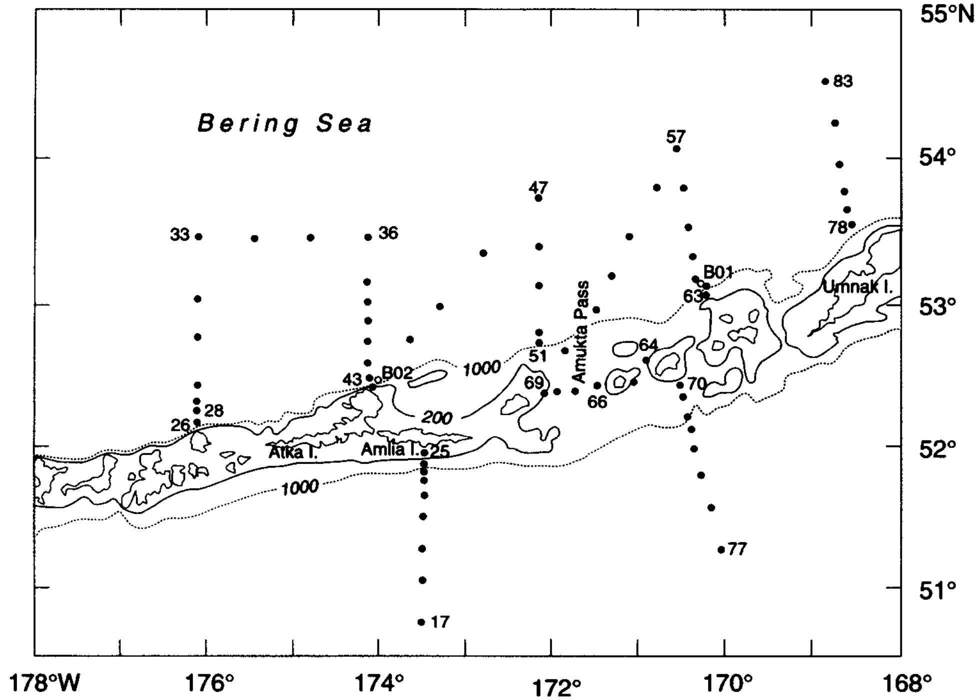


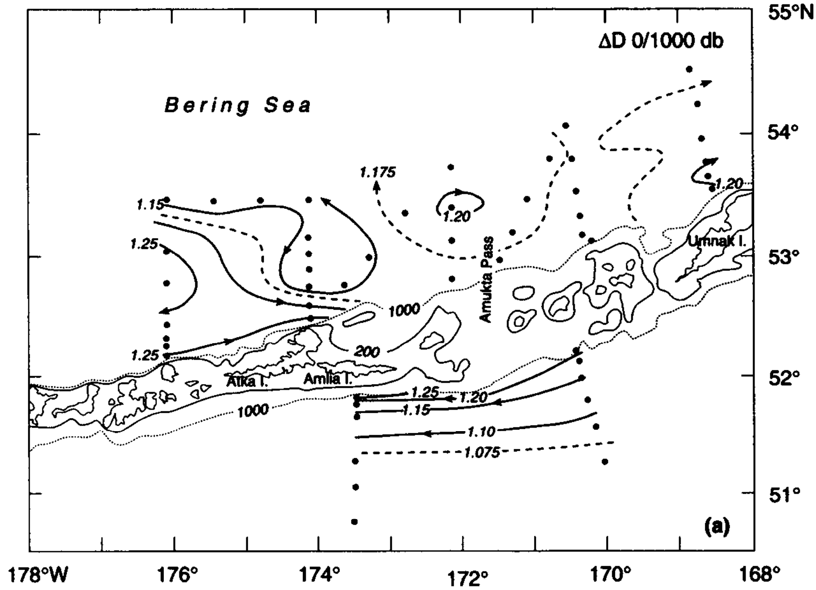
Figure 1. Location of CTD casts taken during 24 August–2 September 1995. The position of current moorings BO1 and BO2 are also shown. The 200- and 1000-m isobaths are from National Ocean Survey chart 513.

meters. The data records (with a sampling interval of 1 hr) were passed through a 35-hr filter to remove tidal signals and obtain daily net vectors and mean temperature.

2. Circulation, summer 1995

Figure 1 shows the location of 66 CTD casts taken from the NOAA ship *Surveyor* during summer 1995. The locations of two current moorings recovered (B01 and B02), which were deployed in summer 1994, are also shown.

The geopotential topography of the sea surface, referred to 1000 db (decibars) and 300 db, is shown in Figure 2. Figure 2a indicates an intense Alaskan Stream, especially south of Amlia Island at 173.5W. North of the islands at 176.1W, there was appreciable relief across the eastward flow, which was bifurcated by an eddy-like feature. To the east of 173W, the flow was convoluted, and the relief was small. Also the direction of surface flow, referred to 300 db (Fig. 2b), was similar to that referred to 1000 db. The most striking feature, however, is the lack of surface relief, referred to 300 db, across the Alaskan Stream, except on the inshore part of the section at ~171W. Thus there was little vertical shear in the upper 300 db of the stream, unlike in September 1993 (Reed and Stabeno, 1994). Figure 2b also suggests that flow through Amukta Pass resulted from a part of the a



b

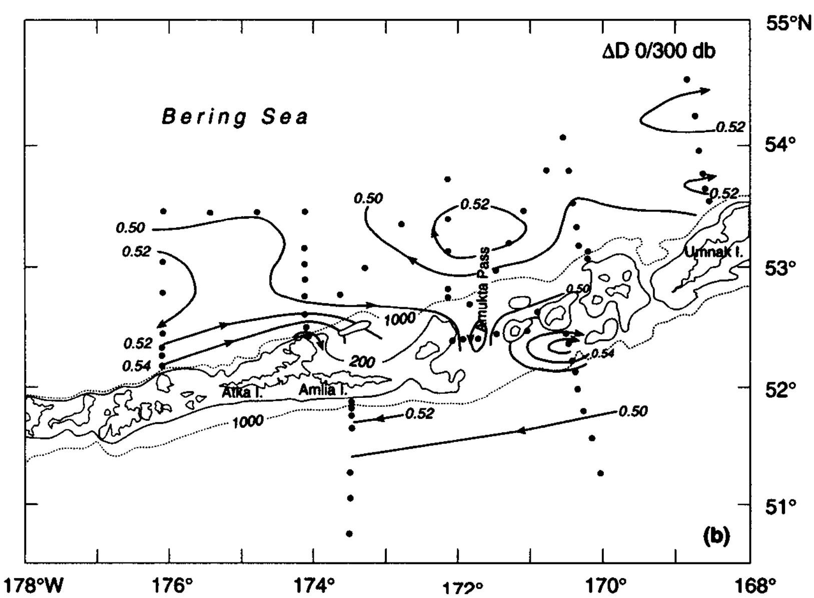


Figure 2. Geopotential topography (dyn m) of (a) the sea surface, referred to 1000 db; and (b) the sea surface, referred to 300 db, 24 August–2 September 1995.

eastward flow in the Bering Sea moving southward through the western side of the pass and then turning northward through the eastern side. This is discussed in more detail in the next section.

In the Alaskan Stream at 173.5W, the upper 1000-db transport (9×10^6 m^3 s^{-1}), referred to 1000 db, was almost two standard deviations greater than the mean in the region 170–180W (Favorite, 1974). Also, it was $\sim 2 \times 10^6$ m^3 s^{-1} greater than the westward transport near 170W. Although Favorite (1974) concluded that stream transport variations referred to 1000 db are meaningful, he inferred that westward baroclinic velocities extend to ~4000 db. Transports referred to such deep levels are often about three times those referred to 1000 db (Warren and Owens, 1988; Roden, 1995). (We used the 1000-db level for comparison with Favorite's database noted above.) North of the islands, the upper 1000-db transports were generally $2\text{–}3 \times 10^6$ m^3 s^{-1}. At some locations, however, larger values and better mass conservation were obtained with reference levels above, rather than at, 1000 db (Fomin, 1964, for example).

The most striking aspect of these data is the high geostrophic speeds in the Alaskan Stream at 173.5W between stations 22 and 23 (see Fig. 1). At 100 db, the computed speed, referred to 1500 db, was 112 cm s^{-1}; the speed at the sea surface was 70 cm s^{-1}. There was an appreciable geopotential slope at 1500 db, however, and an estimate of the true speed at 100 db is ~125 cm s^{-1}. This appears to be the largest geostrophic speed reported for the Alaskan Stream south of the central Aleutians; Reed (1984) showed a similar adjusted speed of ~110 cm s^{-1}. The existence of a subsurface speed maximum in the stream is common, and Reed and Stabeno (1989) attributed this to the typical eastward winds deflecting near-surface waters offshore and thus reducing the near-surface, but not the deeper, density gradients. The surface temperatures and salinities at stations 22 and 23 (see Fig. 1) were 9.9°C, 31.8‰ and 6.5°C, 33.0‰, respectively; comparable values at 100 m were 4.8°C, 33.1‰ and 5.3°C, 33.2‰. These extreme gradients at the sea surface would reduce the geopotential slope there, in agreement with the above hypothesis.

3. Amukta Pass CTD sections

In September 1993, a CTD section was taken across Amukta Pass (Reed and Stabeno, 1994). These results showed: (1) a northward inflow of relatively warm, Alaskan Stream water on the eastern side of the pass; (2) a retroflection of part of the inflow, and thus a southward outflow, on the western side of the pass; (3) a net northward transport of 0.8×10^6 m^3 s^{-1}; (4) a marked decrease of near-surface temperature and increase of near-surface salinity, by ~3°C and 1‰, respectively, as a result of tidal mixing near the pass; and (5) a signature of the warm, subsurface stream waters downstream of the pass in the Bering Sea. Subsequently, this CTD section has been reoccupied eight more times, using essentially the same station spacing. Each section took about 4 hr to occupy and is thus nearly synoptic. The main results from this time series are given in Table 1. Most of these sections were taken without any supporting CTD data north and south of the Aleutians; hence detailed interpretation of all the data is not possible.

Computed geostrophic volume transports, referred to 300 db (near bottom), varied

Table 1. Summary of results from Amukta Pass CTD sections, 1993–1996. The standard error is based on two standard deviations and thus has a significance level of 95%.

		Northward flow		Southward flow		
Date	Max. temp. (at σ_t 26.70; °C)	Max. speed (cm s^{-1})	Transport (10^6 m^3 s^{-1})	Max. speed (cm s^{-1})	Transport (10^6 m^3 s^{-1})	Net transport (10^6 m^3 s^{-1})
10 Sep 93	4.30	33	1.3	31	0.5	0.8
15–16 July 94	4.16	53	0.9	20	0.4	0.5
23 Aug 94	4.26	29	1.1	8	0.1	1.0
25 Aug 94	4.24	32	0.8	14	0.3	0.5
30 Aug 94	4.26	69	1.0	13	0.4	0.6
12–13 Sep 94	4.39	44	0.8	7	0.0	0.8
5 Mar 95	3.84	73	1.3	18	0.5	0.8
30 Aug 95	3.85	25	0.8	17	0.9	−0.1
18–19 Apr 96	4.14	34	0.7	15	0.2	0.5
Mean ± std. error	4.16 ± 0.13	44 ± 12	1.0 ± 0.2	16 ± 5	0.4 ± 0.2	0.6 ± 0.2

considerably (Table 1). The northward transport (generally on the eastern side of the pass) varied from 0.7 to 1.3 × 10^6 m^3 s^{-1}, with a mean of 1.0 × 10^6 m^3 s^{-1}. The southward flow (generally on the western side) was between 0.1 and 0.9 × 10^6 m^3 s^{-1}, with a mean of 0.4 × 10^6 m^3 s^{-1}. The net transport varied from 0.1 southward to 1.0 × 10^6 m^3 s^{-1} northward, with a mean of 0.6 × 10^6 m^3 s^{-1} northward. The maximum geostrophic speeds were between 25 and 73 cm s^{-1} in the northward branch and between 7 and 31 cm s^{-1} in the southward branch; depths of the maximum speeds varied considerably. (There was no apparent relation between computed transports or speeds and the phase of predicted tidal currents.) Reed (1995) showed that subsurface maximum temperatures in the Bering Sea during Alaskan Stream inflow were generally >4°C and had a σ_t density of ~26.7. As seen in Table 1, seven of the nine data sets had subsurface temperatures at σ_t 26.7 that were >4.1°C. During the two cruises in 1995, however, considerably lower temperatures occurred, which would suggest that stream water was not present then.

Figure 3 shows vertical sections of temperature, with the depth of the σ_t-26.70 surface, from all of the cruises listed in Table 1. The sections from 10 September 1993, 23 August 1994, and 12–13 September 1994 show steeply sloping isotherms on the eastern side of the pass, and bottom water generally >4°C. The σ_t-26.7 surface generally parallels the isotherms. These data thus clearly indicate a strong inflow of Alaskan Stream water on the eastern side of the pass with weaker outflow of stream water on the western side. The sections of 15–16 July and 30 August 1994 show similar flow but colder bottom water than those just discussed. The observations of 25 August 1994 and of 18–19 April 1996, however, show northward flow of stream waters on the western side of the pass and weak southward flow to the east. Note also that large changes in thermal slopes occurred during the last week of August 1994.

During 30 August 1995 (Fig. 3), near-bottom pass waters were generally much colder

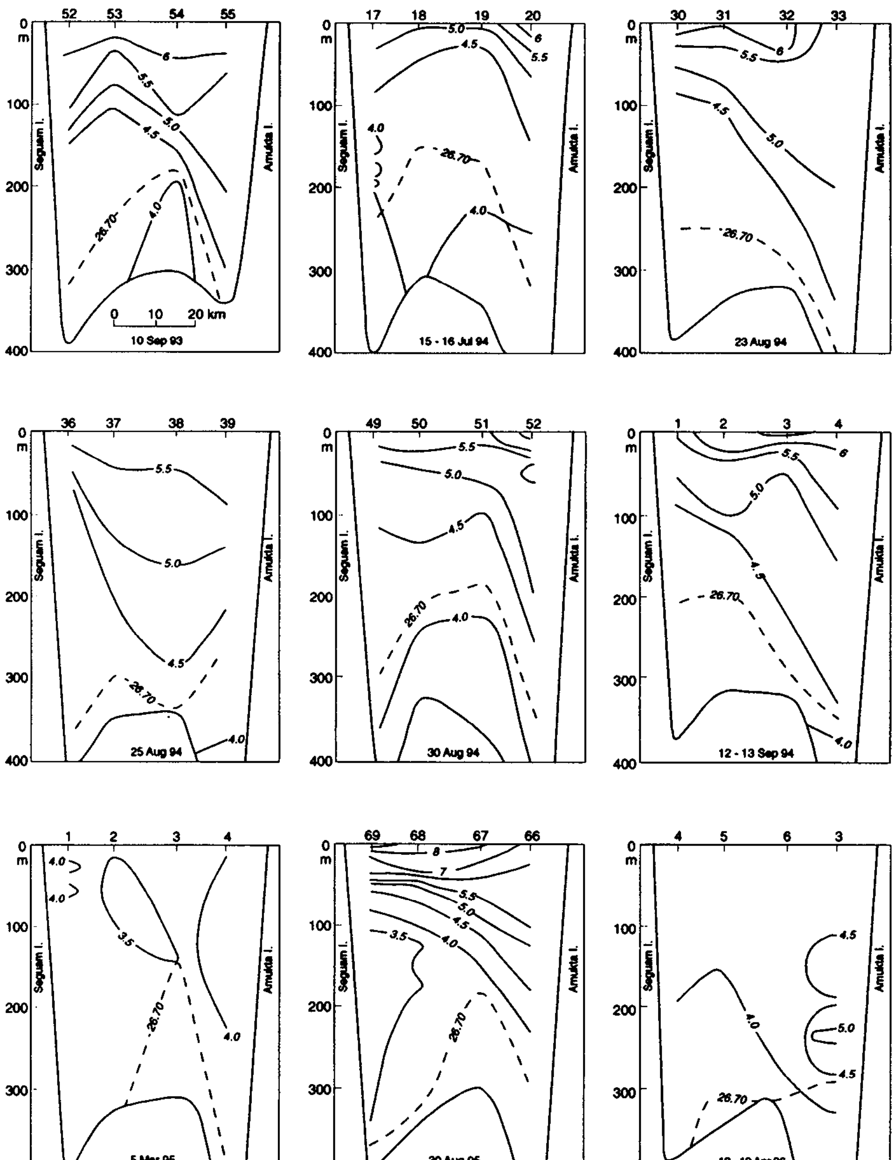


Figure 3. Vertical sections of temperature (°C) across Amukta Pass during 10 September 1993, 15–16 July 1994, 23 August 1994, 25 August 1994, 30 August 1994, 12–13 September 1994, 5 March 1995, 30 August 1995, and 18–19 April 1996. The depth of the σ_t-26.70 surface is also shown.

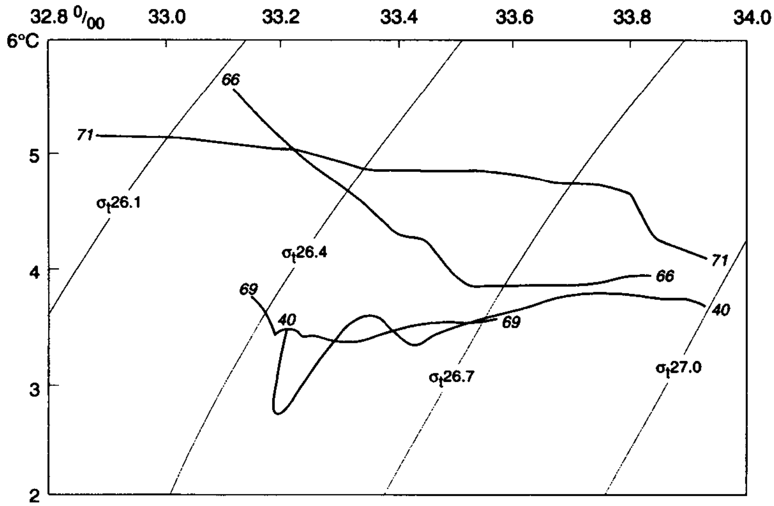


Figure 4. Temperature-salinity plots between 100 and 400 m for stations 40, 66, 69, and 71, 27–31 August 1995. See Figure 1 for station locations.

than in 1993 or 1994, but surface waters were the warmest (>9°C) observed. Also, the 0/300-db geopotential topography (Fig. 2b) shows southward flow of Bering Sea water near 172W, with northward flow of this water on the eastern side of the pass. Figure 4 shows temperature-salinity plots for stations 69 and 66 (in the pass) and stations 40 and 71 (the plausible source waters; see Figs. 1 and 2b). The characteristics at station 69 are much like those at station 40, except that station 69 has a more linear plot with lower bottom salinity. Below ~225 m, the temperature-salinity plot at station 66 is more like those at stations 69 and 40 than that at station 71 (Alaskan Stream water). Although some Alaskan Stream water may have been present in upper waters on the eastern side of the pass, conditions during 30 August 1995 mainly resulted from the presence of Bering Sea water and the resulting geostrophic flow (Fig. 2b). Water properties during 5 March 1995 (Fig. 3) were much like those at station 69 and the lower part of station 66, and we infer that little Alaskan Stream water was present even though baroclinic flow was strong (Table 1). In general, waters below ~150 m in the pass and adjacent Bering Sea exhibit little seasonal change (Reed, 1995). It is possible, of course, that the Alaskan Stream itself might have been abnormally cold during that time, as occasionally but irregularly occurs (see Favorite *et al.,* 1976). At any rate, the April 1996 data (Table 1) showed a return of typical Alaskan Stream water.

Thus, flow through Amukta Pass was generally northward on the eastern side and southward on the western side, although two exceptions were noted above. This pattern was present whether the source for the flow was Alaskan Stream water from the south or Bering Sea water from the north. The pass is ~45 km in width and is thus wider than the entering or exiting branches of flow (see Figs. 2b and 3). Our estimates of the internal radius of deformation are 10–20 km, in agreement with the existence of bidirectional flow.

The initial flow, whether Alaskan Stream water or Bering Sea water, thus partially retroflects and moves in the opposite direction. Although there is considerable variability, even on short time scales (Table 1), these data, and especially those in Reed (1995), suggest that the presence or absence of Alaskan Stream water in the pass may occur over time scales of months to years and not as high-frequency events. When part of the Alaskan Stream does flow through the pass, the impulse of this inflow may enhance alongslope flow to the north and east (Stabeno and Reed, 1994).

4. Current time series

Two subsurface current moorings (BO1 and BO2; see Fig. 1) were deployed on the north side of the Aleutian ridge in July 1994; they were retrieved in August 1995. The two mooring sites were chosen to measure flow to the east (downstream) of Amukta Pass, where northward inflow should be detectable, and to the west of the pass where inflow effects should be absent.

Flow at BO1, the easternmost mooring (Fig. 5), was much as expected (Stabeno and Reed, 1994); that is, it was moderately intense and nearly unidirectional throughout the water column, it was directed toward ~70°, and it was quite stable ($KE'/\overline{KE}$ ratios generally <1; Table 2). There also was a clear winter intensification of flow down to ~600 m. Net vectors decreased from 23 to 4 cm s^{-1} (Table 2). Excluding the short uppermost record (at 170 m), the linear correlation of flow at 270 m with that at 570 m and 750 m was 0.56 and 0.06, respectively. Thus, flow in the upper 600 m or so was coherent, but this flow was not coherent with that near the bottom. The subsurface temperature record is of interest as a possible index of warm Alaskan Stream inflow through the pass, with the values at 270 m being most appropriate (Reed, 1995). Generally, temperature at 270 m was >4°C until late January 1995 (Fig. 5); after then, there were only a few, very brief appearances of >4°C water. This is in good agreement with results in Table 1 and the previous discussion of flow through Amukta Pass.

At BO2 (Fig. 6), flow was generally weaker than at BO1 and was much more variable in direction above ~300 m. Furthermore, there were intense, pulse-like events of variable direction, with intermittent weak flow, at the upper two meters. In fact, net flows at 140 and 240 m were both 4 cm s^{-1} but were eastward and *westward,* respectively; the eddy/mean kinetic energy ratios were ~30 times greater than at the upper 2 meters at BO1 (Table 2). It should be noted, however, that at 240 m flow was often eastward, as at 140 m, except for the strong westward flow in August–November 1994. The linear correlation of flow at 140 m with that at 240, 540, and 790 m was 0.61, 0.11, and 0.16, respectively. Thus flow below ~300 m seemed to be largely decoupled from that above.

The most striking feature in Figure 6 is the relatively stable *westward* flow at 540 and 790 m. A plausible scenario for the observed flow structure might be a westward barotropic flow of ~2 cm s^{-1}, with temporally varying baroclinic flows superimposed, mainly above 300 m. The forcing mechanism for such a barotropic flow is unknown. At any rate, the observed flow at BO2 was not similar to the observed geostrophic flow in Figure 2 or to

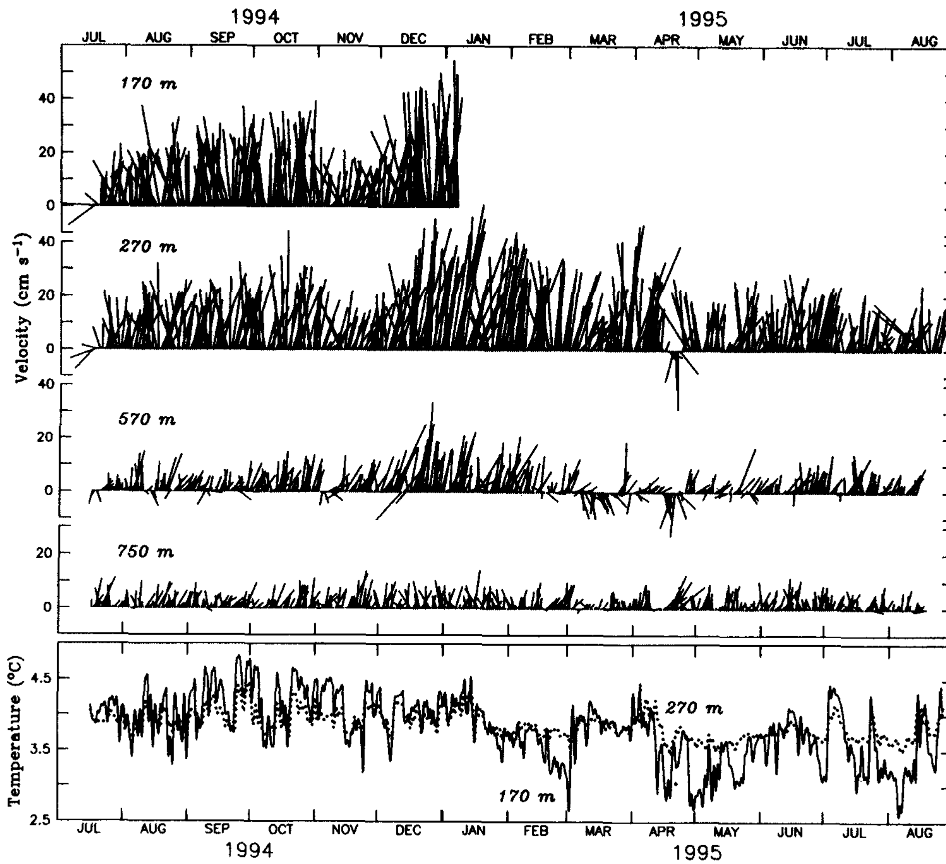


Figure 5. Daily net current vectors and temperature at 170 and 270 m (after use of a 35-hr filter) at mooring B01. On the vector plots, up is directed toward 60°.

Table 2. Information on current measurements, July 1994–August 1995. $\overline{KE}$ is the kinetic energy of the mean flow per unit mass [$\overline{KE} = \frac{1}{2}(\overline{u}^2 + \overline{v}^2)$], and KE' is the eddy kinetic energy per unit mass [$KE' = \frac{1}{2}(\sigma_u^2 + \sigma_v^2)$], where σ_u^2 and σ_v^2 are the variances of the velocity components u (eastward) and v (northward).

Station	Location (water depth)	Meter depth (m)	Dates (day/mo/yr)	Net flow ± s.e. (cm s^{-1})	Dir. (°T)	$\overline{KE}$ (cm^2 s^{-1})	KE' (cm^2 s^{-3})	$KE'/\overline{KE}$
BO1	53°08.4′N	170	16/07/94–07/01/95	23.4 ± 2.5	59	274	64	0.2
	170°17.6′W	270	16/07/94–26/08/95	19.9 ± 2.0	66	198	68	0.3
	(803 m)	570	16/07/94–15/08/95	5.7 ± 1.1	83	16	24	1.5
		750	16/07/94–21/08/95	4.5 ± 0.4	71	10	7	0.7
BO2	52°26.3′W	140	17/07/94–24/08/95	4.3 ± 1.5	91	9	72	8.0
	174°05.7′W	240	17/07/94–18/08/95	3.9 ± 2.2	277	8	48	6.0
	(1033)	540	17/07/94–24/08/95	3.1 ± 0.5	250	5	11	2.2
		790	17/07/94–03/08/95	2.1 ± 0.3	265	2	4	2.0

s.e. (standard error) = 2[(variance)(integral time scale)/record length]$^{1/2}$.

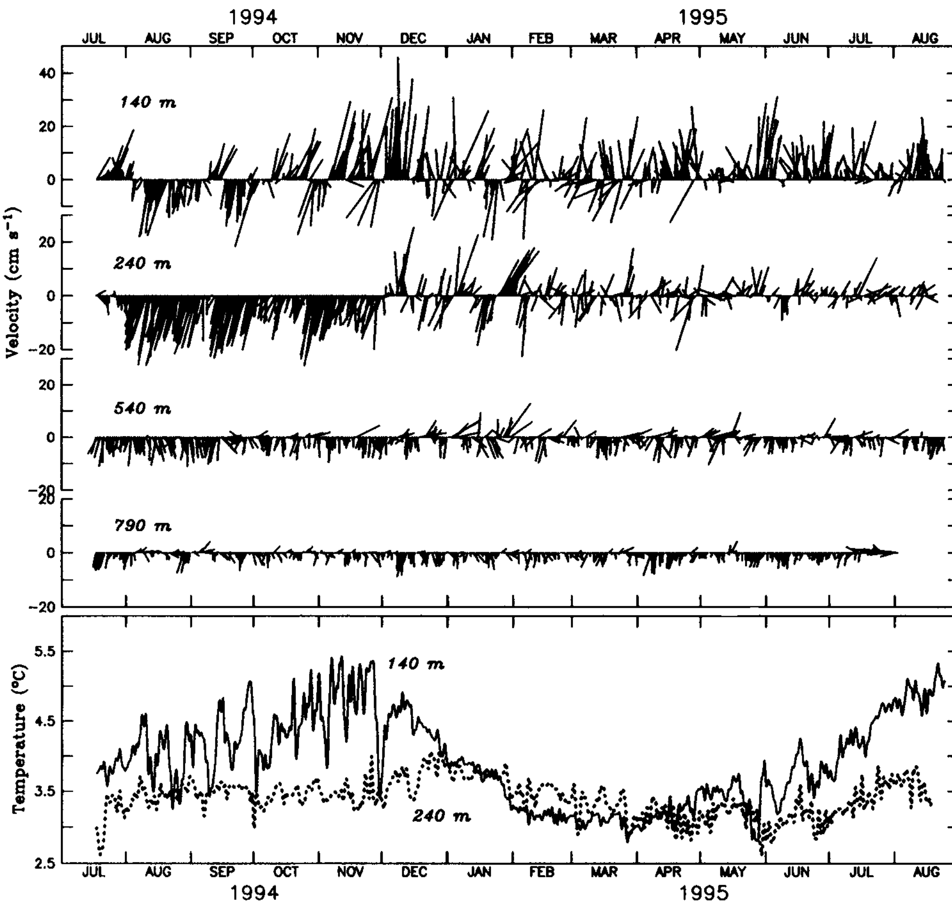


Figure 6. Daily net current vectors and temperature at 140 and 240 m (after use of a 35-hr filter) at mooring B02. On the vector plots, up is directed toward 90°.

that discussed by Reed and Stabeno (1994). The temperature at 240 m is low, as expected, with no apparent influence from Alaskan Stream water.

Although the measured flow at BO2 does not easily fit with our concepts, that at BO1 does. The relatively stable flow at BO1 is typical of the Alaskan Stream (Reed and Stabeno, 1989), which appeared to be the source of waters at BO1 for about the first half of the record (Fig. 5). The strongest flow was confined to the upper 300 m as expected for flow through a pass of 300–500 m depth. To the east and north of site BO1 (Fig. 1), the Bering Slope Current (BSC; Kinder et al., 1975; Stabeno and Reed, 1994) flows northwestward near the continental slope but then turns westward, and offshore, near 58N. The BSC is typically weak, convoluted, and sometimes rife with eddies (Stabeno and Reed, 1994). Since water at BO1 is at least the partial source for the BSC, the relatively shallow nature of the BSC is plausible, but its high eddy energy appears to be a downstream modification of the source flow.

5. Summary

During summer 1995, the Alaskan Stream was quite strong, with a volume transport of ~9 × 10^6 m^3 s^{-1} (referred to 1000 db) and a peak geostrophic speed of ~125 cm s^{-1}. North of the islands, transports were typically 2–3 × 10^6 m^3 s^{-1}, but some variation of reference level was required to obtain reasonable continuity. Nine CTD sections in Amukta Pass showed bidirectional flow (both northward and southward) with a mean net transport of 0.6 × 10^6 m^3 s^{-1} northward. Flow was of Alaskan Stream origin except in 1995, when Bering Sea water was the source. A current mooring in the Bering Sea near 170W measured a fairly stable flow that decreased downward in agreement with geostrophy. Another mooring near 174W, however, indicated weak, variable motion with the suggestion of a westward barotropic flow of ~2 cm s^{-1}.

Acknowledgments. We thank the officers and crews of the NOAA ships *McArthur, Miller Freeman,* and *Surveyor.* We also thank W. Parker, C. DeWitt, C. Hadden, L. Long, D. Kachel, S. Salo, and L. Lawrence. Penetrating comments by a reviewer were quite helpful. This is contribution FOCI-B 280 to the Fisheries Oceanography Coordinated Investigations and is part of the Coastal Ocean Program of NOAA. Contribution number 1744 from NOAA, PMEL.

REFERENCES

Favorite, F. 1974. Flow into the Bering Sea through Aleutian Island passes, *in* Oceanography of the Bering Sea with Emphasis on Renewable Resources, D. W. Hood and E. J. Kelley, eds., Inst. of Mar. Sci., Univ. of Alaska, Fairbanks, 3–37.

Favorite, F., A. J. Dodimead and K. Nasu. 1976. Oceanography of the subarctic Pacific region, 1960–1971. Int. N. Pac. Fish. Comm. Bull., *33,* 187 pp.

Fomin, L. M. 1964. The Dynamic Method in Oceanography, Elsevier, 212 pp.

Kinder, J. H., L. K. Coachman and J. A. Galt. 1975. The Bering Slope Current system. J. Phys. Oceanogr., *5,* 231–244.

Reed, R. K. 1984. Flow of the Alaskan Stream and its variations. Deep-Sea Res., *31,* 369–386.

—— 1995. On the variable subsurface environment of fish stocks in the Bering Sea. Fish. Oceanogr., *4,* 317–323.

Reed, R. K. and P. J. Stabeno. 1989. Recent observations of variability in the path and vertical structure of the Alaskan Stream. J. Phys. Oceanogr., *19,* 1634–1642.

—— 1994. Flow along and across the Aleutian Ridge. J. Mar. Res., *52,* 639–648.

Roden, G. I. 1995. Aleutian basin of the Bering Sea: Thermohaline, oxygen, nutrient, and current structure in July 1993. J. Geophys. Res., *100,* 13,539–13,554.

Sayles, M. A., K. Aagaard and L. K. Coachman. 1979. Oceanographic Atlas of the Bering Sea Basin, Univ. of Washington Press, 158 pp.

Stabeno, P. J. and R. K. Reed. 1994. Circulation in the Bering Sea observed by satellite-tracked drifters: 1986–1993. J. Phys. Oceanogr., *24,* 848–854.

Warren, B. A. and W. B. Owens. 1988. Deep currents in the central subarctic Pacific Ocean. J. Phys. Oceanogr., *18,* 529–551.

Received: *16 July, 1996;* revised: *31 October, 1996.*