Additional Current Measurements in the Alaskan Stream near Kodiak Island[1]

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ABSTRACT

Long-term records from four current meters in the Alaskan Stream off Kodiak Island are presented. The net flows decreased with depth and appeared to be in approximate geostrophic equilibrium. Large fluctuations were not common, and the flow was dominated by low-frequency energy. This behavior, which is also supported by temperature and salinity data, suggests a vertically coherent flow with occasional lateral meanders.

The eddy kinetic-energy levels in this region of the Alaskan Stream were quite low, especially in comparison with those in the Kuroshio and Gulf Stream. The flux of momentum across the inshore edge of the Stream appeared to be onshore and to represent a transfer of energy from the mean flow to smaller scales; an eddy viscosity of not more than 10^6 cm^2 s^{-1} was indicated. The impact on shelf waters of the small, onshore eddy heat flux is unclear.

1. Introduction

Recently, Reed *et al.* (1981) presented results from the first long-term current measurement in the high-speed region of the Alaskan Stream. Only six-month records at 980 m, plus temperature data at 480 m, were obtained, however. The measurements reported here, near the same site occupied previously off Kodiak Island, extend the available data approximately six-fold and allow additional analyses and conclusions.

In September 1981 two current moorings (stations 1 and 2) were deployed by the NOAA ship *Discoverer* offshore from Kodiak Island as shown in Fig. 1, and they were retrieved in July 1982. Details of the moorings are given in Table 1. Aanderaa RCM-4 rotor/vane current meters were used on taut-wire moorings, constructed from Kevlar line, with floats just above the upper meters. All of the meters had temperature and conductivity sensors, and only the instrument at 1020 m lacked a pressure sensor. The data records were checked for errors, and the time series, with a sampling interval of 1 h, were passed through a 35-hour filter. Daily net vectors were then derived and are used in the following presentations and analyses. The temperature and conductivity data were similarly checked for errors and filtered, and average daily values were computed; most of the records exhibited some drift, and corrections were derived from nearby CTD (conductivity/temperature/depth) casts before and after the series.

2. Net flow and geostrophy

Table 1 shows the net (vector-average) flow derived from the entire series for each meter. At the deep mooring, station 2, the direction of net flow is virtually the same at all levels, and the speeds decrease with depth as expected (Favorite *et al.*, 1976). The value at 1020 m (8 cm s^{-1}, 224°) is similar to that (6 cm s^{-1}, 235°) at 980 m from the same site during February–August 1980. We had planned to have the upper meters on these two moorings at the same level in order to examine horizontal shear; unfortunately, this did not occur, but the data suggest there was relatively little shear in the upper water column between the two sites. The net direction at station 1 was slightly more southerly than at station 2.

Our earlier, limited comparison of measured and computed geostrophic flow indicated reasonable agreement (Reed *et al.*, 1981). Again, we have only two CTD sections, and neither was simultaneous with the current measurements. The second CTD section was taken on 24 July 1982 after retrieval of the moorings; unfortunately, two of the instruments had stopped recording before retrieval, and the measured currents at 305 and 1020 m (see Fig. 2) were undergoing an extreme oscillation at the end of the record and cannot be meaningfully compared with the geostrophic flow, which was quite similar to the results in Table 2.

The first CTD section (see Fig. 1) was taken on 7 September 1981, and the geostrophic flows, rotated in the direction of measured currents, are compared with the measurements during the first five days of the record (mid-point time is 15 September 1981), when the speeds and directions at all meters were

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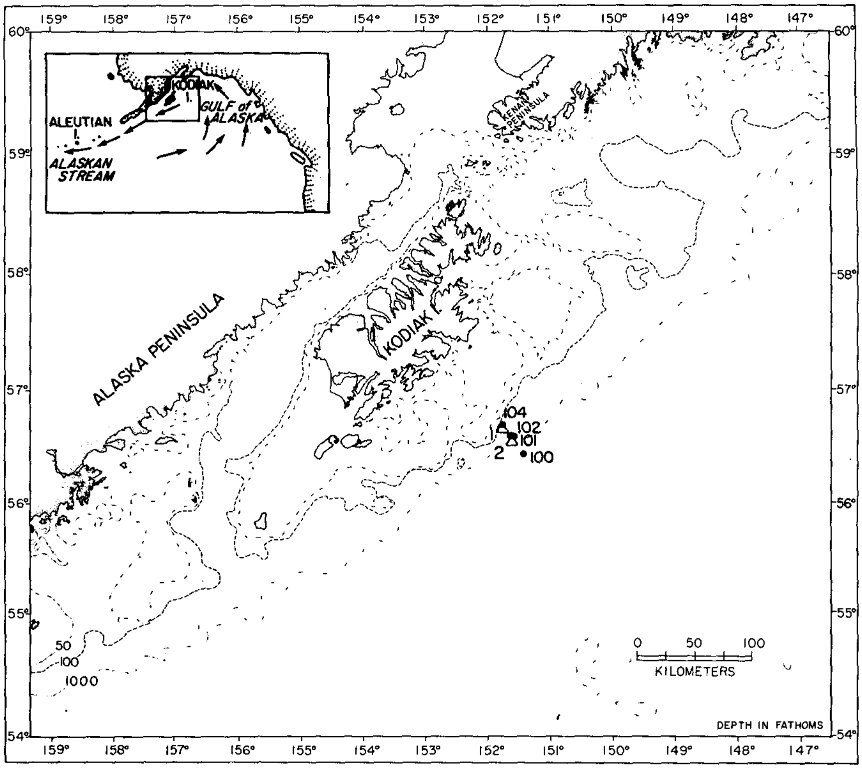

FIG. 1. Location of observations in the Alaskan Stream near Kodiak Island, September 1981–July 1982. The closed circles indicate CTD casts, the triangles denote current moorings, and the isobaths are in fathoms (1 fathom = 1.829 m).

fairly stable. This period is slightly shorter than that recommended by Taft (1978) but seems to be the best compromise in this changing flow field. As indicated in Table 2, the computed baroclinic *shear* at station 2 is close to the measured shear, and the absolute agreement would be excellent if one assumed that the reference level of 1500 db actually had a speed of 3 cm s^{-1}. This is plausible and is in agreement with the conclusion of Reed *et al.* (1980) that some baroclinic structure exists from 1500 to about 3000 db. [In fact, Warren and Owens (1984) reported measured westward speeds of 3 and 2 cm s^{-1} at 2 and 3 km in the Alaskan Stream at 175°W.] The comparison for mooring 1 was derived by adjusting the initial calculation, based on a reference level of 700 db, for the isopycnal slope at 700 db by the Jacobsen-Jensen method (see Reed *et al.*, 1980) to approximate a 1500-db reference level. This adjustment more than doubled the initial result, and the comparison (Table 2) again suggests some flow (5 cm s^{-1}) at the reference level of 1500 db. A single comparison such as this cannot be definitive but does suggest that the Alaskan Stream in this region has a baroclinic structure that is approximately geostrophic.

TABLE 1. Information on current moorings near Kodiak Island.

Station	Location	Water depth (m)	Meter depth (m)	Dates	Net flow (cm s^{-1}, °T)
1	56°39'N 151°46'W	700	230	13 Sep 81– 11 July 82	28, 207
2	56°31'N 151°40'W	1730	305	13 Sep 81– 22 July 82	24, 219
			520	13 Sep 81– 19 Feb 82	19, 230
			1020	13 Sep 81– 22 July 82	8, 224

TABLE 2. Comparison of geostrophic flow (referred to 1500 db; 7 September 1981) and measured net velocities (13–17 September 1981) at the stations off Kodiak Island.

Stations	Depths (m)	Computed geostrophic velocity (cm s^{-1})	Measured velocity (cm s^{-1})	Difference (measured − geostrophic) (cm s^{-1})
102–104 (1)	230	24	29	5
100–101 (2)	305	18	20	2
	520	14	17	3
	1020	8	12	4

3. General features of the flow and properties

Figure 2 presents daily net vector plots of flow after application of a 35-hour filter. The three meters at the deep mooring (station 2) reveal flow that is visually coherent vertically. Periods of relatively strong and weak flow occur simultaneously at all three levels, and the "lower-frequency events" are obviously well correlated. (In fact, vertical correlation coefficients in the alongstream direction were >0.8 but were only 0.3–0.4 in the across-stream direction.) The major difference in flow is simply that velocity consistently decreases with depth. The record suggests the following scenario of major features: 1) fairly weak flow with a period of oscillatory motion during October–early November, 2) intense and directionally stable flow from early November until, perhaps, March 1982, 3) a period of rather variable flow during March–May, and 4) flow of increasing intensity through June with a short oscillatory event near the end of the series.

The rapid increase in velocity at all the meters during early November is an interesting feature. The observations prior to this change indicate relatively small velocities; this is in agreement with the conclusions of Reed (1984) that in summer 1981 the inflow into the Gulf of Alaska had become disrupted, and transport and velocities off Kodiak Island were only about half their normal values. The rapid spinup in November then presumably reflects a return to a more normal circulation pattern (Favorite *et al.*, 1976) in the eastern part of the Alaskan Stream.

The record at 230 m at the inshore mooring (station 1) does not reveal all of the features apparent in the series at the deep mooring. For example, there were only a few very brief periods of northerly flow inshore, and the large rotary event that occurred in October offshore seems to be essentially absent inshore. On the other hand, there are several rapid reductions of the flow which seem to have shorter duration than comparable features offshore.

The temperature and salinity plots (daily averaged values after application of a 35-hour filter) in Fig. 3 also have vertically coherent features and periods of variable and relatively constant values coincident with those in flow (Fig. 2). The series at station 1, however, has some features that are not similar to those at station 2 (e.g., relatively warm water inshore during December–February versus relatively cold water offshore). The changes in temperature and salinity at the offshore station are related to changes in flow in a very similar way to the evolution of features at this site in 1980 (Reed *et al.*, 1981). During the period of weak, oscillatory flow near the start of the record, the water was relatively warm and dilute, in early November temperature decreased (and salinity increased), and conditions changed rapidly again near

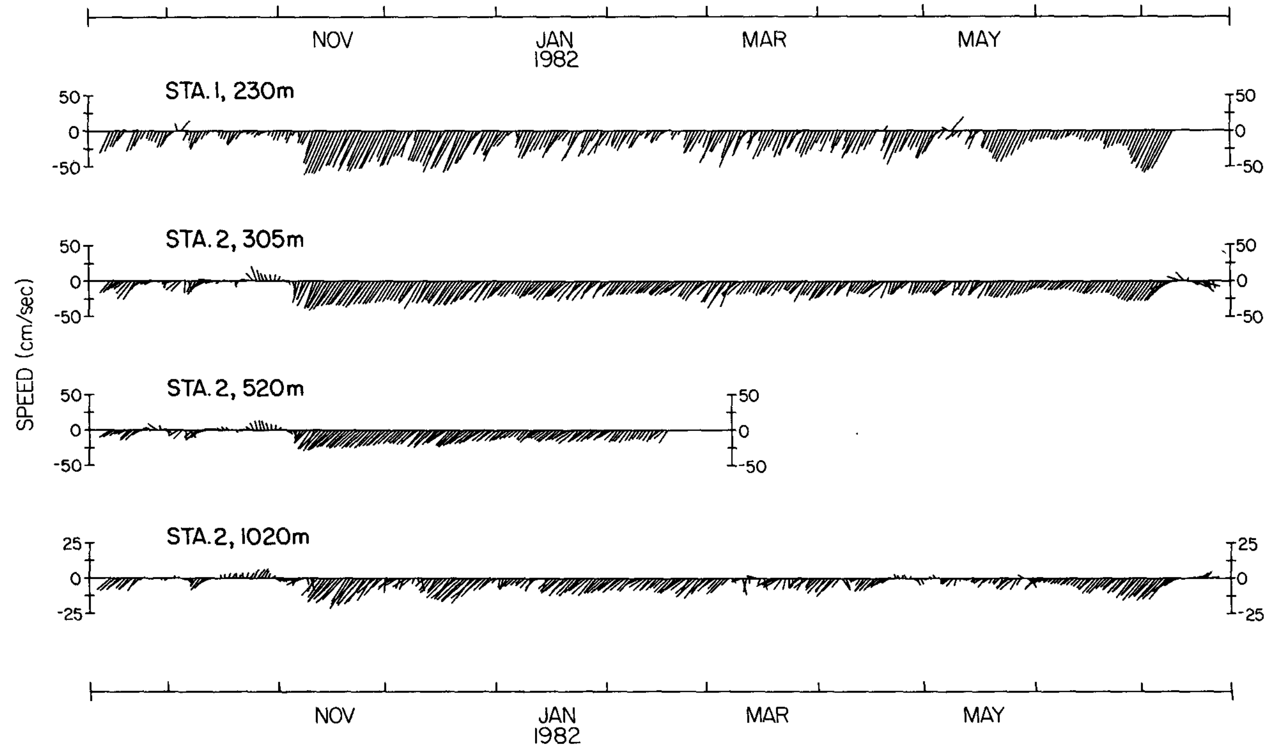

FIG. 2. Daily net current vectors (after use of a 35-hour filter) at stations 1 and 2, 15 September 1981–21 July 1982. North is up on these plots.

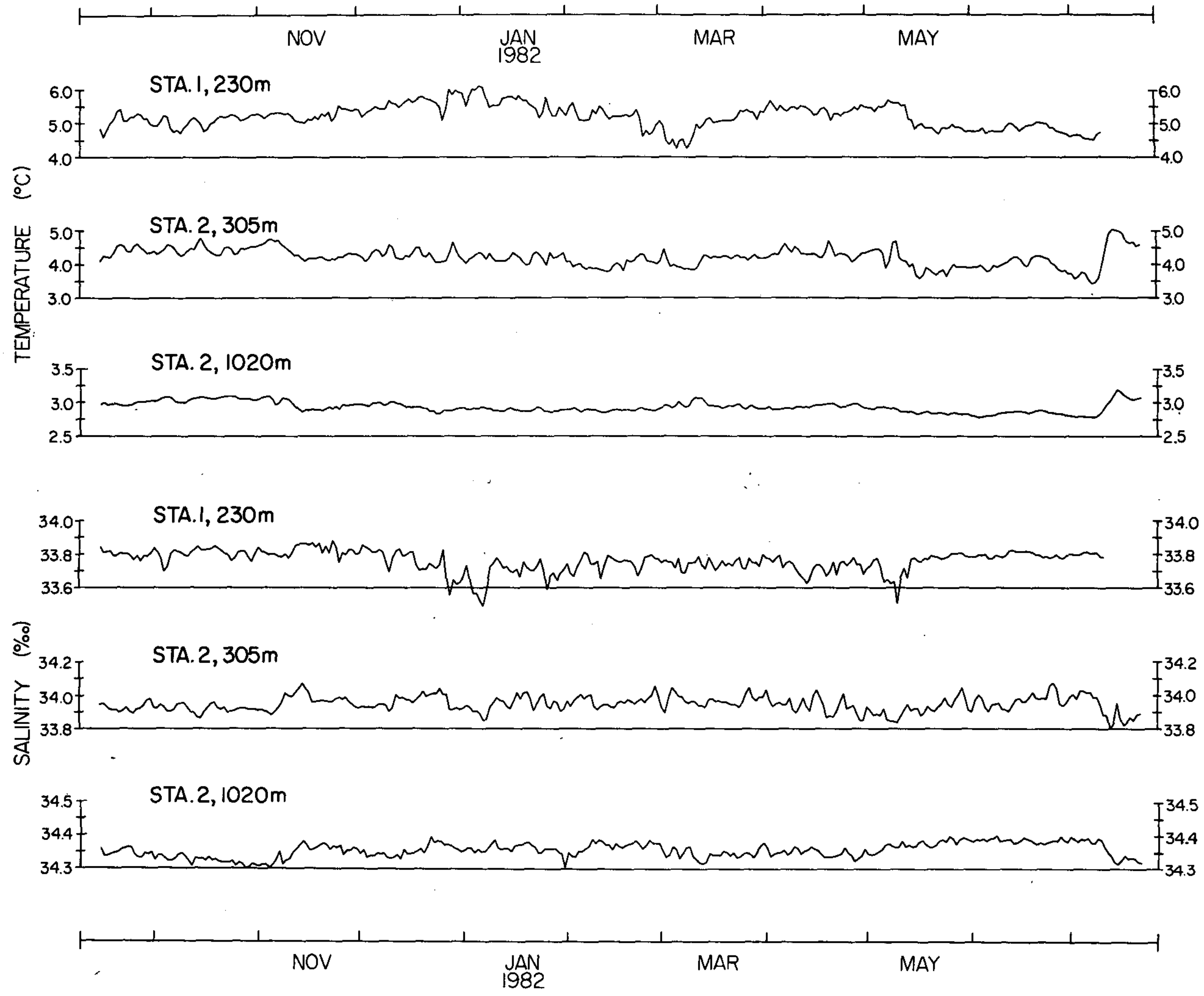

FIG. 3. Daily averaged temperature and salinity (corrected by comparison with CTD casts; 35-hour filter applied) at stations 1 and 2, 15 September 1981–21 July 1982. Data at station 2, 520 m are not shown because of lack of CTD data for comparison with the end of this series. Maximum corrections were: station 1, 230 m (0.10°C, 0.04‰); station 2, 305 m (0.18°C, 0.16‰); and station 2, 1020 m (0.05°C, 0.19‰).

the end of the record. This sequence of events suggests that the first oscillatory period resulted from a region of anticyclonic curvature in the streamlines with a resulting offshore movement of the inshore (warmer, less saline) water; as the streamlines straightened and velocity increased in early November, the offshore (cooler, more saline) water moved back onshore. The data imply that the Stream moved laterally, in a vertically coherent manner, but that changes are not highly coherent between the two stations.

4. Energy levels

Kinetic energy of the mean flow ($\overline{KE}$) and fluctuating or eddy kinetic energy (KE'), and their ratios, were derived from the current data and are listed in Table 3. Because Fig. 2 indicated considerable variation in net flow and steadiness of flow over time scales of months or so, the energy variables have been derived both over periods of a month and for the entire record. It should be stressed that the observations here are in the high speed region of the Alaskan Stream, where peak surface speeds frequently exceed 100 cm s^{-1} (Favorite *et al.*, 1976; Royer, 1981; Reed, 1984). Hence the mean energy of this environment is more akin to western boundary currents than the interior of gyres, and comparisons should be made accordingly.

For the entire series, the greatest fluctuating or eddy kinetic energy was at station 1 (Table 3); eddy energy at the offshore station decreased with depth. The kinetic energy of the mean flow at station 2, however, decreased downward relatively more rapidly, and thus the $KE'/\overline{KE}$ ratios increased with depth. The monthly ratios are typically quite small, but the period 15 October–13 November has values > 1 as a result of the small net flow and the rotational motion. The ratio for the ten-month record at 1020 m in

TABLE 3. Energy statistics of 35-hour filtered, daily averaged velocity measurements in the Alaskan Stream, 15 September 1981–21 July 1982. $\overline{KE}$ is the kinetic energy of the mean flow per unit mass $[\overline{KE} = \frac{1}{2}(\bar{u}^2 + \bar{v}^2)]$, and KE' is the fluctuating kinetic energy per unit mass $[KE' = \frac{1}{2}(\sigma_u^2 + \sigma_v^2)]$. The velocity components u and v are approximately across-stream and alongstream as determined by the direction of minimum velocity variance; the components are for axes of 295° and 205° respectively for the upper meters at both stations, and the axes are 315° and 225° for the two deeper levels at station 2. The variances of the u and v components are σ_u^2 and σ_v^2. Energy units are $cm^2 s^{-2}$.

	Sta. 1 (230 m)			Sta. 2 (305 m)			Sta. 2 (520 m)			Sta. 2 (1020 m)		
Period	$\overline{KE}$	KE'	$KE'/\overline{KE}$	$\overline{KE}$	KE'	$KE'/\overline{KE}$	$\overline{KE}$	KE'	$KE'/\overline{KE}$	$\overline{KE}$	KE'	$KE'/\overline{KE}$
15 Sep–14 Oct	111	79	0.7	125	39	0.3	69	41	0.6	14	13	0.9
15 Oct–13 Nov	107	70	0.7	39	160	4.1	19	107	5.6	0	22	—
14 Nov–13 Dec	1373	66	0.1	765	14	0.0	519	10	0.0	114	29	0.3
14 Dec–12 Jan	834	136	0.2	540	20	0.0	315	19	0.1	84	21	0.3
13 Jan–11 Feb	401	45	0.1	391	10	0.0	218	8	0.0	80	7	0.1
12 Feb–13 Mar	271	110	0.4	416	23	0.1				61	14	0.2
14 Mar–12 Apr	409	43	0.1	280	18	0.1				30	15	0.5
13 Apr–12 May	294	135	0.5	221	19	0.1				7	11	1.6
13 May–11 Jun	258	92	0.4	229	17	0.1				16	7	0.4
12 Jun–11 Jul				346	39	0.1				95	9	0.1
Entire series	393	156	0.4	281	83	0.3	182	79	0.4	35	27	0.8

Table 3 is smaller than that for the six-month record in 1980 (Reed *et al.*, 1981), which was characterized by a rotary event of relatively long duration. (Table 2 of Reed *et al.*, 1981, is somewhat misleading because the final entry is simply an average of the monthly values since comparisons were made mainly with results from records of one–two months duration of Taft, 1978; the $KE'/\overline{KE}$ ratio for the entire record is 2.7 rather than the average listed.) The ratios in Table 3 for the entire series are all <1.

Table 4 compares energy statistics for the Alaskan Stream with those in the Kuroshio and Gulf Stream. Since the Alaskan Stream flows along the Alaska Peninsula and Aleutian Island arc (Favorite *et al.*, 1976), its path is constrained by a topographic margin, and the comparison is made with regions of the Kuroshio and Gulf Stream before they leave the coasts at 140°E and Cape Hatteras, respectively, and probably undergo an increase in eddy energy (Richardson, 1983). The results (Table 4) show that the

TABLE 4. Comparison of energy of the Alaskan Stream with that in the Kuroshio west of 140°E and in the Gulf Stream south of Cape Hatteras. Total record length equals number of records times record length, and the energy values for more than one record are averages.

Source	Location	Record length (mo)	Number of records	Depth (km)	KE' ($cm^2 s^{-2}$)	$KE'/\overline{KE}$
Alaskan Stream						
Reed *et al.* (1981)	57°N, 152°W	6	1	1.0	50	2.7
Present paper	57°N, 152°W	5–10	3	0.2–0.5	106	0.4
		10	1	1.0	27	0.8
Warren and Owens (1984)	51°N, 175°W	14	2	2.0–3.0	2	0.4
Kuroshio						
Taft (1978)	31–33°N, 132–137°E	1–2	4	1.8–2.8	8	8.0
	33°N, 137°E	1–2	2	3.7–4.3	11	1.4
Taira and Teramoto (1981)	35°N, 139°E	10	1	0.2	160	0.1
	33°N, 139°E	9	1	1.7	56	19.4
Gulf Stream						
Lee and Waddell (1983)	30°N, 80°W	7	2	0.4	210	0.1
	30°N, 79–80°W	7	5	0.4–0.6	170	0.4
	30°N, 77–80°W	7	7	0.8–1.0	144	5.8
Brooks and Bane (1983)	33–34°N, 76–77°W	4	16	0.2–0.4	352	2.3

Kuroshio and Gulf Stream typically have two–four times as much eddy energy (*KE'*) at similar levels as the Alaskan Stream. Except for the six-month record in the Alaskan Stream noted above, all of the other data sets have $KE'/\overline{KE}$ ratios < 1; this generally contrasts with results for the Kuroshio and Gulf Stream where five of the eight values are >1. The exception to large ratios in the Kuroshio and Gulf Stream results from larger net flows (60–80 cm s^{-1} for the two ratios of 0.1 and >30 cm s^{-1} for the value of 0.4) than were observed in the Alaskan Stream. Thus, the eddy energy in the Alaskan Stream is generally less than in these other boundary currents in comparable bounded flow regions; the $KE'/\overline{KE}$ ratios are also typically smaller in the Alaskan Stream than in the Kuroshio or Gulf Stream where the net flows are similar. Hence the Alaskan Stream seems to be a more stable flow than typical western-boundary currents.

5. Time scales

Figure 4 presents spectra of the flow variability in an energy-preserving form. All of the distributions are characterized by a rapid decrease in energy toward higher frequencies. Only the spectrum at station 1 has any peaks at intermediate frequencies that are statistically significant. The slight peak centered at 37 days is, perhaps, real but its energy excess over the general trend is only ~2% of the total; the peaks at 9 and 11 days, however, clearly rise above the low-energy background and contribute ~8% of the variance. These latter features appear to be similar to an 11-day peak noted by Niebauer *et al.* (1981) in a water depth of ~300 m at a site ~ 200 km upstream of our moorings. They concluded that these fluctuations were not wind forced but were probably wavelike features being steered along the coast by bottom topography. The absence of such features at station 2 suggests that they do not propagate offshore into the main part of the Alaskan Stream.

Figure 4 indicates that 40–55% of the total eddy energy is in the lowest-frequency band centered at 148 days (104 days at station 2, 520 m); results from the deepest meter are the least red, and the next deepest level has the highest percentage of low-frequency variance, perhaps because of its greater bandwidth. In the Kuroshio and Gulf Stream and their downstream extensions, one typically finds much or

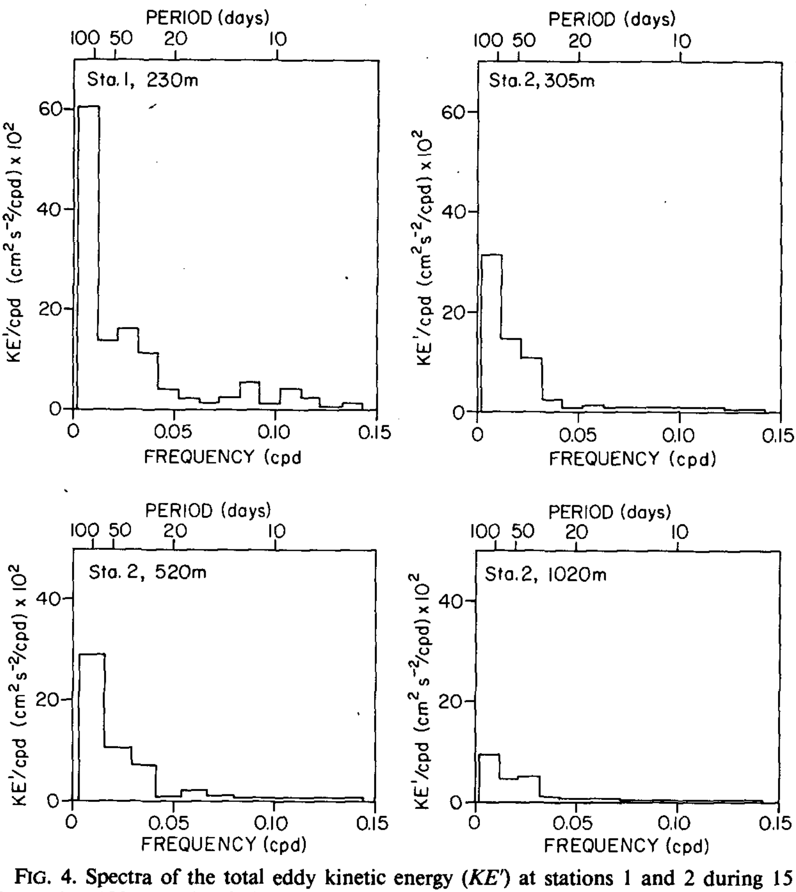

FIG. 4. Spectra of the total eddy kinetic energy (*KE'*) at stations 1 and 2 during 15 September 1981–8 July 1982, except 15 September–18 February for station 2 (520 m). Only 1, 9, 10 and 5% of the total *KE'* is in the *u*-component at station 1 (230 m), station 2 (305 m), station 2 (520 m), and station 2 (1020 m), respectively.

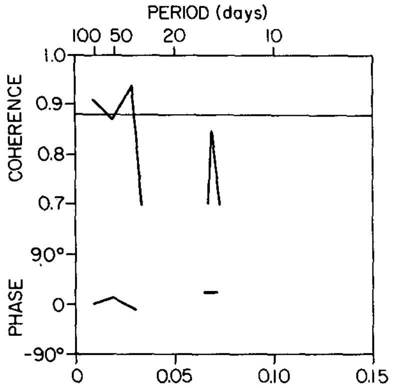

FIG. 5. Coherence and phase estimates of the v-component (alongstream) velocities between 305 and 1020 m at station 2, 15 September 1981–8 July 1982. The 95% significance level for coherence is the horizontal line.

even most of KE' at intermediate frequencies (Taira and Teramoto, 1981; Lee and Waddell, 1983; Schmitz *et al.*, 1982; and Hendry, 1982). The vertical coherence functions between alongstream velocities at 305 and 1020 m at station 2 are shown in Fig. 5. The three lowest-frequency bands are the most coherent, and the fluctuations are all in phase. The fourth value shown (at 15-day period), which does not coincide with an energy peak at 305 or 1020 m, may be among the 5–10% expected to reach this value through chance. Whereas the western-boundary currents are typified by appreciable variance in the intermediate or "mesoscale band" of perhaps 20–70 days, our data suggest that the Alaskan Stream is dominated by vertically coherent, low-frequency energy.

Although the Alaskan Stream is a flow bounded by the Aleutian arc, the map of Cheney *et al.* (1983) suggests some increase of sea-height variability in downstream regions. The data of Warren and Owens (1984) in Table 4, however, indicate a quite stable deep flow downstream, and the increase in sea-height fluctuations could largely occur by exchange of upper waters of differing density through the passes there (Reed, 1984). The relatively low levels of mesoscale energy in the Stream, plus the stability of the flow discussed above, imply that this system may not be greatly affected by wave-like motions. A kinematic argument supports this view. Potential-vorticity conservation in prograde flows (such as the Kuroshio and Gulf Stream) over a topographic feature tends to create a series of crests and troughs (a periodic planetary wave) that extend far downstream, but retrograde flows (such as the Alaskan Stream) typically have only a single disturbance or meander in the streamlines (Holton, 1979) that is relatively less energetic.

6. Eddy fluxes

The available data permit estimates of the eddy fluxes of momentum, heat, and salt which are contained in Table 5. The values were derived for the common period when data were obtained at the inshore station and from two levels at the offshore station. The standard errors in these estimates were computed from the record variances and integral time scales (Bendat and Piersol, 1971; Luyten, 1982). It is apparent that the magnitudes of the covariances, especially $\overline{u'v'}$, are quite small, and several of the mean values are smaller than the standard errors. Consequently, we have not shown cospectra because estimates in individual bands are subject to very large relative errors, and the comparative plots were quite inconsistent. The mean covariances are used here, however, to make some inferences about the processes of importance to the Alaskan Stream.

The onshore eddy flux $\overline{u'v'}$ is of relevance to questions of the effects of the Stream on surrounding waters and the means by which energy is transferred. The values at the two upper meters are about the same size as their errors, but they can be used to place limits on the eddy viscosity. The $\overline{u'v'}$ value at station 2 (305 m) is difficult to interpret because we are unsure of the detailed, time-averaged horizontal gradients of velocity in this region; station 1, however, lies in a region where the long-term velocity is decreasing inshore, and an average shear ($\partial v/\partial x$) of -5×10^{-6} s^{-1} was taken from the results of 17 transport sections near Kodiak Island (see Reed *et al.*, 1980). Combining the $\overline{u'v'}$ of $+3.7$ cm^2 s^{-2} with this average velocity shear (-5×10^{-6} s^{-1}) gives a negative turbulent kinetic energy flux or a transfer of energy from the mean flow to the eddies or smaller scales. The value of $\overline{u'v'}$ likely has the correct sign, but its magnitude may be appreciably in error; a *maximum*

TABLE 5. Estimates of mean velocity components, mean temperature and salinity, and the mean eddy fluxes of momentum, heat, and salt. The estimates are for the common period 15 September 1981–10 July 1982, the u and v components are as defined in Table 3, and the overbars and primes indicate mean and eddy quantities respectively. The computed standard errors in the eddy flux estimates (see text) are also given.

Station (depth)	$\bar{u}$ (cm s^{-1})	$\bar{v}$ (cm s^{-1})	$\bar{T}$ (°C)	$\bar{S}$ (‰)	$\overline{u'v'}$ (cm^2 s^{-2})	$\overline{u'T'}$ (cm °C s^{-1})	$\overline{v'T'}$ (cm °C s^{-1})	$\overline{u'S'}$ (cm ‰ s^{-1})	$\overline{v'S'}$ (cm ‰ s^{-1})
1 (230 m)	1.1	28.0	5.20	33.76	3.7 ± 3.8	0.18 ± 0.09	0.13 ± 0.89	−0.04 ± 0.02	0.20 ± 0.18
2 (305 m)	6.1	23.8	4.20	33.95	7.7 ± 6.9	−0.16 ± 0.15	−0.78 ± 0.53	0.00 ± 0.02	0.19 ± 0.06
2 (1020 m)	−0.2	9.0	2.93	34.36	0.3 ± 1.5	−0.01 ± 0.02	−0.26 ± 0.13	0.00 ± 0.00	0.07 ± 0.04

eddy viscosity of $\sim 2 \times 10^6$ cm^2 s^{-1}, however, is indicated. These results are opposite to those of Webster (1965), which provided evidence that the fluctuations on the inshore side of the Gulf Stream from Florida to Cape Hatteras help drive the mean flow. Furthermore, the $\overline{u'v'}$ term here is one–two orders of magnitude less than for the Gulf Stream along the eastern seaboard (Webster, 1965; Brooks and Bane, 1983; Lee and Waddell, 1983), and our eddy viscosity contrasts with their values of 10^7–10^8 cm^2 s^{-1}.

According to the signs of $\overline{v'T'}$ and $\overline{v'S'}$ at station 2 in Table 5, heat is being transferred upstream and salt downstream, which is hard to reconcile with the Alaskan Stream being the source of heat and low-salinity water in the region (Favorite *et al.*, 1976). The situation is probably an artifact resulting from the local y-axis not being aligned with the large-scale orientation of the Stream. The onshore eddy heat and salt fluxes ($\overline{u'T'}$ and $\overline{u'S'}$) at station 1, however, do have the expected signs, and they are of special interest because of possible effects on coastal waters. (The sign of $\overline{u'T'}$ at station 2 is opposite to that at station 1, which indicates a change in average slope of the isotherms between the stations.) We had earlier concluded (Schumacher and Reed, 1980) that the thermohaline properties of shelf waters might be appreciably affected by the propagation of eddies from the Stream inshore. The sign of the $\overline{u'T'}$ flux at station 1 does indicate heat transport onshore, but its magnitude is relatively small. We cannot conclude that onshore eddy heat flux is unimportant here, however, because there were no data in the upper 200 m where transfer onto the continental shelf would occur.

7. Conclusions

About 40 months of current records have now been obtained in the Alaskan Stream near Kodiak Island. Insofar as this region is typical of the Stream as a whole, and numerous hydrographic data suggests that it is (Favorite *et al.*, 1976), one may generalize the results from these observations to infer certain characteristics of the Alaskan Stream. The flow is vertically coherent but is baroclinic and appears to be in geostrophic equilibrium. The Stream does undergo some velocity fluctuations, but the marked ones are relatively rare and are of fairly long period, especially in deeper water. The events are believed to result from coherent, lateral meanders of the flow, which significantly alter water properties. The fluctuating energy level of the Alaskan Stream is relatively low, being appreciably less than in the Gulf Stream or Kuroshio. The marked stability of the Alaskan Stream and the dominance of low-frequency energy suggest that periodic planetary waves are not typically present or contribute little variability to the system. Along the inshore edge of the Stream, momentum appears to be transferred onshore to smaller scales, and onshore heat flux also occurs. Eddy viscosity appears to be only about 10^6 cm^2 s^{-1}, which is much less than typical estimates for western-boundary currents.

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