NOAA Technical Report ERL 433-PMEL 38

Geostrophic Flow in the Central Bering Sea, Fall 1986 and Summer 1987

R.K. Reed
J.D. Schumacher
A.T. Roach

January 1988

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

NOAA Technical Report ERL 433-PMEL 38

Geostrophic Flow in the Central Bering Sea, Fall 1986 and Summer 1987

R.K. Reed
J.D. Schumacher
A.T. Roach

Pacific Marine Environmental Laboratory
Seattle, Washington

January 1988

U.S. Department of Commerce
C. William Verity, Secretary

National Oceanic and Atmospheric Administration

Environmental Research Laboratories
Boulder, Colorado
Vernon E. Derr, Director

NOTICE

Mention of a commercial company or product does not constitute an endorsement by NOAA Environmental Research Laboratories. Use for publicity or advertising purposes of information from this publication concerning proprietary products or the tests of such products is not authorized.

For sale by the National Technical Information Service, 5285 Port Royal Road
Springfield, VA 22161

CONTENTS

Page

ABSTRACT 1

1. INTRODUCTION 1

2. DATA METHODS 1

3. RESULTS, FALL 1986 2

   3.1 Geostrophic Flow 2

   3.2 Property Distributions 4

   3.3 Volume Transport 7

4. RESULTS, SUMMER 1987 8

   4.1 Geostrophic Flow, Properties, and Transport 9

   4.2 Flow Through Amchitka Pass 10

5. COMPARISON WITH OTHER CIRCULATION PATTERNS 11

6. ACKNOWLEDGMENTS 12

7. REFERENCES 12

Geostrophic Flow in the Central Bering Sea, Fall 1986 and Summer 1987*

R.K. Reed, J.D. Schumacher, and A.T. Roach

ABSTRACT. Data from a synoptic CTD survey over a large region in the central Bering Sea in fall 1986 are used to derive the major features of circulation. Geopotential topographies reveal the following flows: (1) a well-developed eastward flow that subsequently turned toward the northwest; (2) a cyclonic gyre north of Amukta Pass; and (3) a weak flow, with some local intensifications, paralleling the continental slope. Volume transports, relative to 1000 db, in these branches (in the order above) were approximately (1) 4×10^6 m^3 s^{-1}; (2) 2×10^6 m^3 s^{-1}; and (3) 1×10^6 generally, but 3–4 $\times 10^6$ m^3 s^{-1} in two locations. Also, a northward inflow through Amukta Pass was inferred from subsurface temperature. Data from a cruise in summer 1987 reveal a relatively strong northward flow through Amchitka Pass but the absence of inflow in Amukta Pass. Previous climatological and synoptic data sets have shown numerous eddylike features that appear to be transient. Comparison of results from various circulation patterns suggests that the eastward flow that turns toward the northwest frequently occurs.

1. INTRODUCTION

Recently, physical scientists at the Pacific Marine Environmental Laboratory and fisheries scientists at the Northwest and Alaska Fisheries Center have joined in an effort, Fisheries Oceanography Coordinated Investigations (FOCI), to gain understanding of the influence of various environments on recruitment of fish stocks. To date, most FOCI activity has been in Shelikof Strait in connection with pollock (*Theragra chalcogramma*). The FOCI observations reported here were obtained from cruises in the central Bering Sea. Our objectives were to determine the flow field and property distributions over large regions, as synoptically as possible, preparatory to more detailed, interdisciplinary studies at a later date.

Many different schemes for circulation in the deep Bering Sea have been presented (see Hughes et al., 1974, for details). Most show numerous complex features that often differ considerably from one map to the next. The region appears to be rife with eddies and gyres that are quite transient. Thus using data over different periods may produce artifacts in areas where changing mesoscale features were present. Synoptic data will also not yield a reliable long-term mean circulation in areas of rapid change, but a number of such data sets might allow discrimination between the permanent and transient aspects of the flow.

This report examines data from the cruises in fall 1986 and summer 1987. The upper-ocean circulation is derived by the geostrophic relation, some property distributions are presented to elucidate features of the flow, and volume transport estimates are presented and discussed. The flow fields found are also discussed and compared with those presented by others.

2. DATA AND METHODS

CTD (conductivity/temperature/depth) casts were made from the NOAA ship *Miller Freeman* during the periods 24 October–5 November 1986 and 6–15 June 1987. A Seabird CTD

* Contribution No. 921 from NOAA/Pacific Marine Environmental Laboratory.

was used, and the data obtained (24 samples s^{-1}) were stored on disk in a MicroVAX computer. Data were recorded only during the downcast at lowering rates of 30–45 m min^{-1}. A bottle sample was taken (at varying depths) on almost all casts to provide calibration. Various routines eliminated spurious scans and derived 1-m averages of temperature and salinity from which density and geopotential anomaly were computed.

3. RESULTS, FALL 1986

Locations of CTD casts taken during 24 October–5 November 1986 are shown in Fig. 1.

3.1 Geostrophic Flow

CTD casts on this cruise were taken to 1500 m, or near the bottom in shoaler regions. No direct current measurements were made, and the most appropriate reference level for flow computations cannot be precisely determined. Kinder et al. (1975), however, compared drogue measurements with geostrophic calculations and found suitable reference levels between 800 and 1800 m. Speeds at 1000 m were generally less than 2 cm s^{-1}. From our data, a map (not shown)

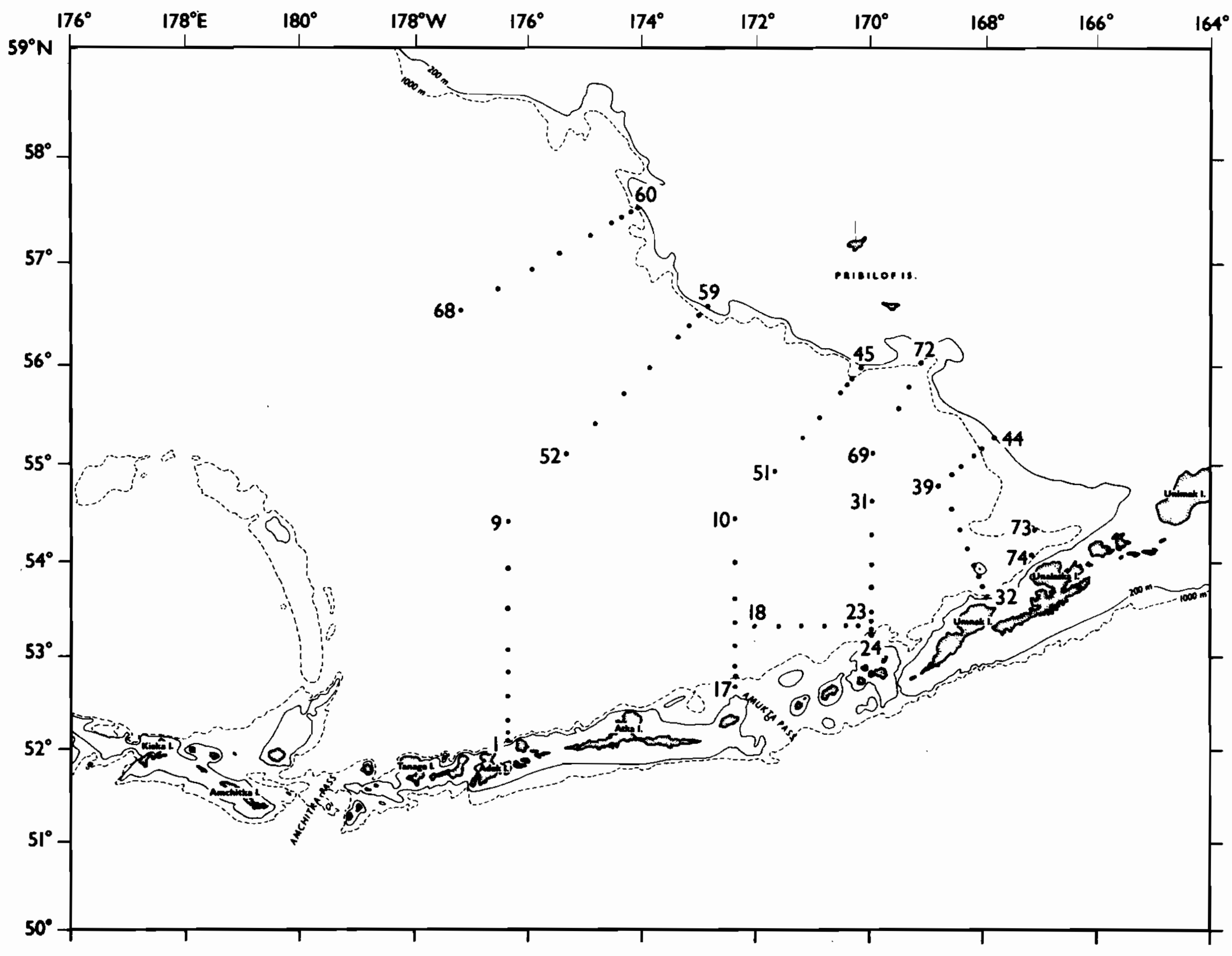

Figure 1. Locations of CTD casts taken in the central Bering Sea, 24 October–5 November 1986.

of the 1000-decibar (db) topography, referred to 1500 db, had only 20% of the relief of the 0/1000-db map. This percentage did differ over the region, however; it was smallest near the continental margin of the basin. In fact, the flow direction at 1000 db was different from that derived for the sea surface in a few areas. We prefer to use 1000 db as a reference surface, rather than 1500 db, because there are sizable areas near the margin of the basin that have depths >1000 m but <1500 m. Thus 1000 db used as a reference level shows the continuity of features better; in depths >1500 m, virtually no difference in near-surface flow patterns results from use of 1000 db as opposed to 1500 db.

The geopotential topography of the sea surface, referred to 1000 db, is shown in Fig. 2. There was a relatively intense eastward flow north of Adak Island, much of which subsequently turned toward the northwest. There appeared to be little continuity of flow along the north side of the Aleutian Islands. A very intense flow occurred north of Umnak Island, and another was found in the canyon south of the Pribilof Islands; flow along the slope elsewhere was weak, however. Finally, a large cyclonic gyre was centered near 54.5°N, 171°W. This flow field is compared in Sec. 5 with the circulation patterns found by others.

Figure 3 shows the geopotential topography at 300 db, referred to 1000 db. The relief on this surface is about 55% of that shown in Fig. 2. The major features of flow on the two surfaces shown are very similar, however. The flow north of Umnak Island had weakened, when

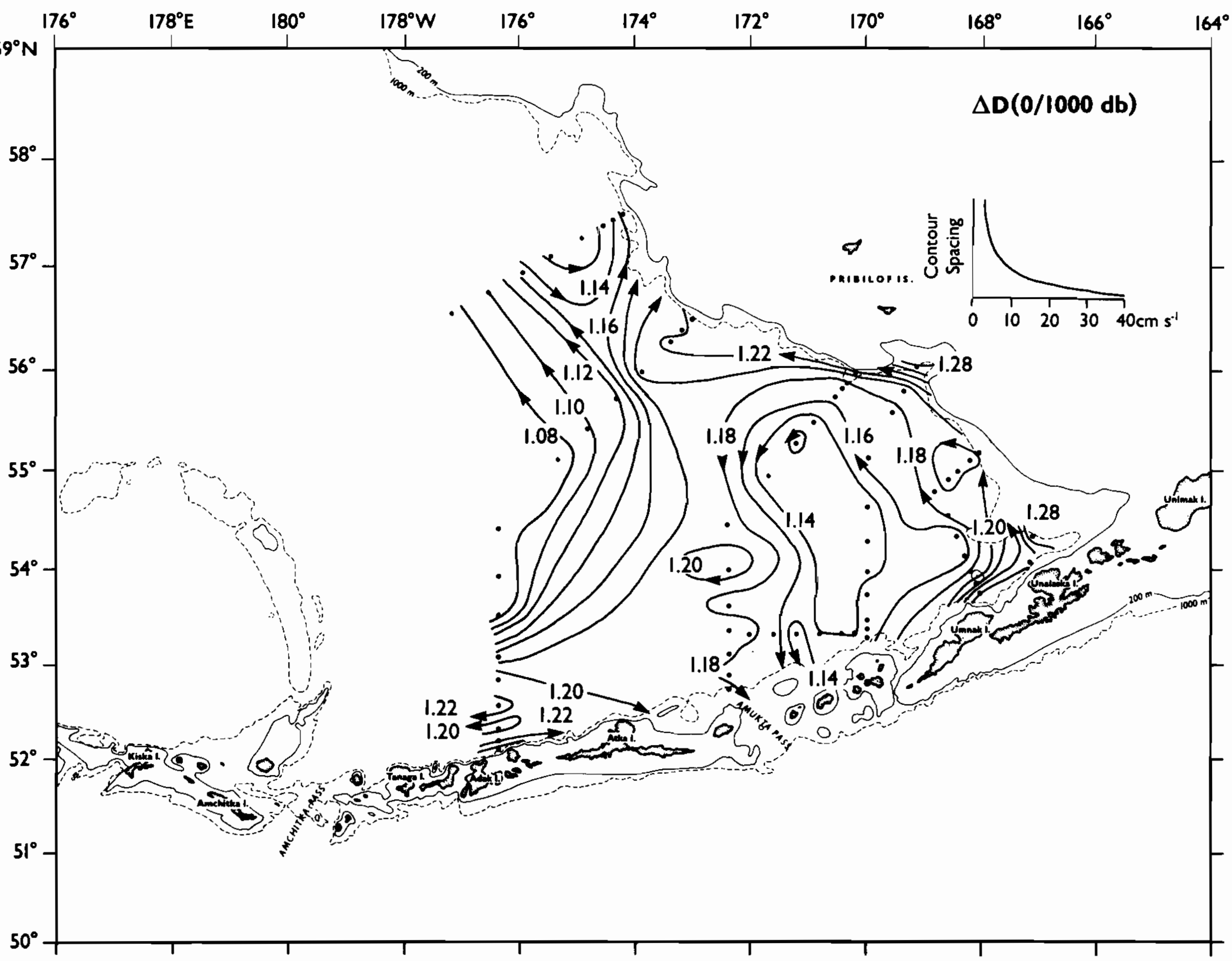

Figure 2. Geopotential topography (ΔD, dyn m) of the sea surface (0 db), referred to 1000 db.

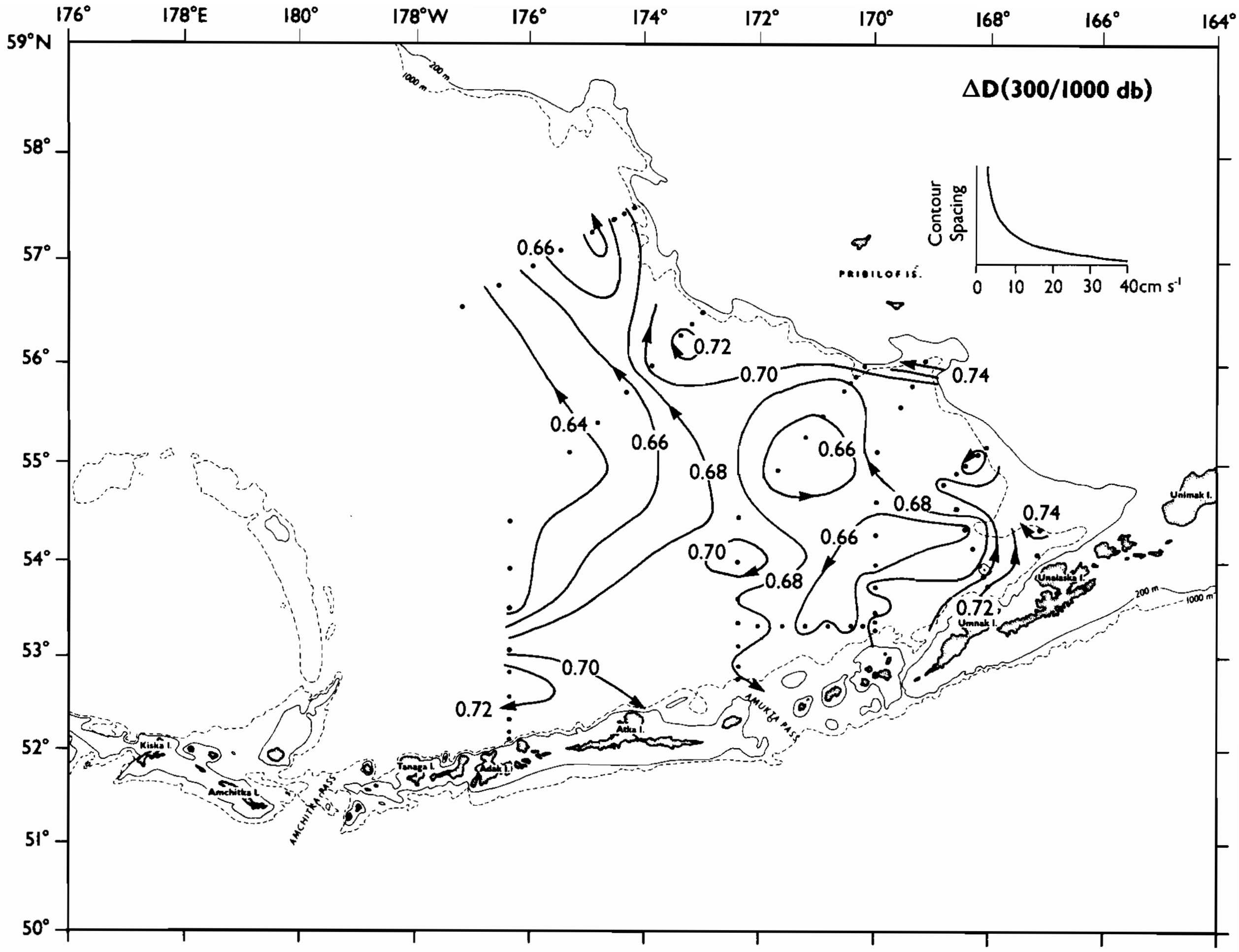

Figure 3. Geopotential topography (ΔD, dyn m) at 300 db, referred to 1000 db.

compared with that at the surface, relatively more than elsewhere, and the large cyclonic gyre had changed shape and perhaps partially split.

3.2 Property Distributions

Before examining volume transport, we present certain property distributions to elucidate some aspects of the flow. The surface salinity distribution (Fig. 4) shows highest salinities in the western part of this region, and a secondary tongue of >33.0‰ to the northeast of Amukta Pass. Using the criterion that relatively low salinity represents intrusions of Alaskan Stream water into the Bering Sea (Dodimead et al., 1963), one would infer the absence of northward flow in Amukta Pass. The zones of low-salinity water near the eastern Aleutians occurred where the surface geostrophic flow (Fig. 2) had appreciably intensified; coupled with the weakness of flow at 300 db, this suggests that the surface intensification largely resulted from this low-salinity, near-surface water.

The subsurface temperature maximum typical of the Bering Sea generally lies near the sigma-t density surface of 26.80 in the depth range 200–400 m. The distribution of temperature

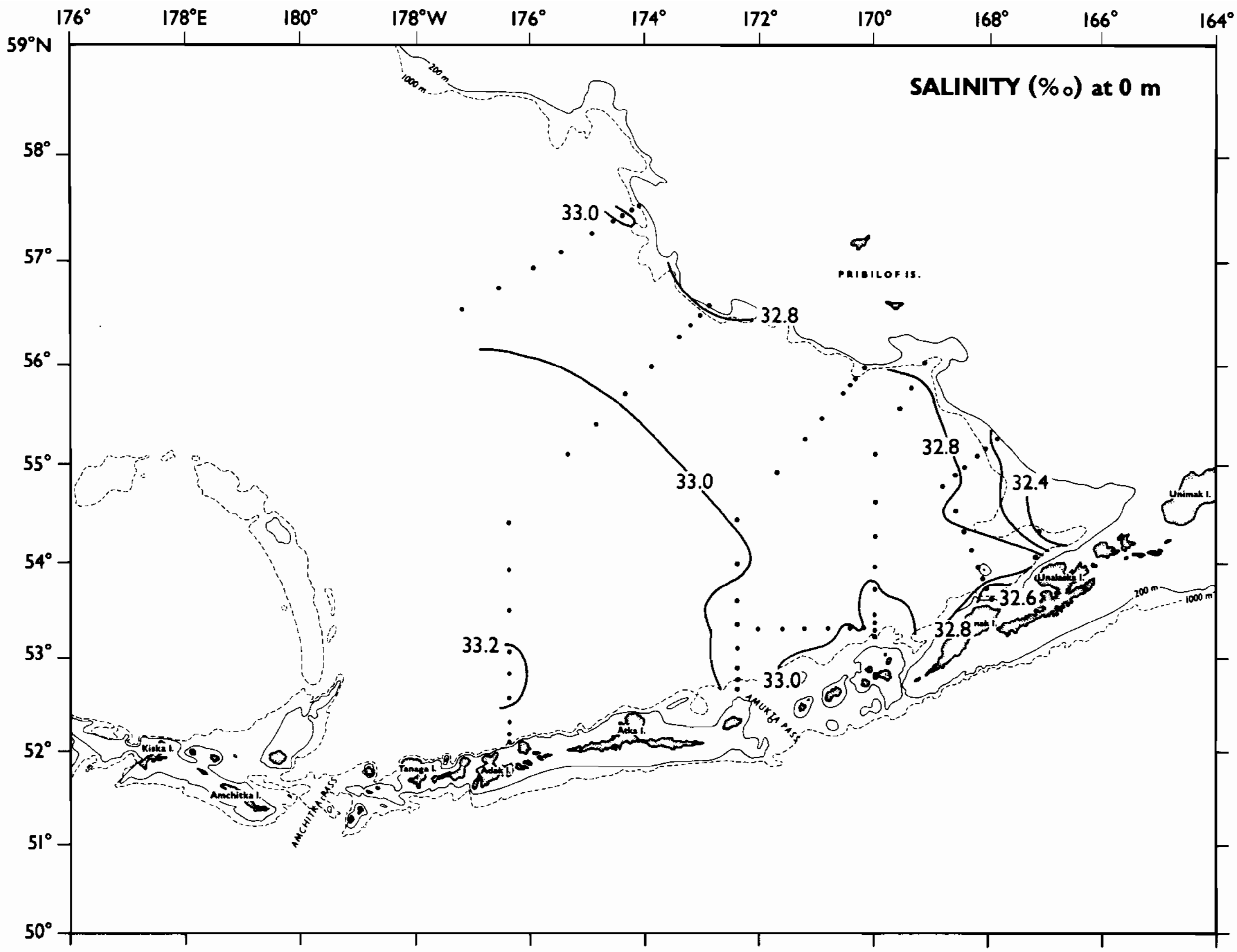

Figure 4. Sea surface salinity (‰).

on this surface (Fig. 5) is unlike the patterns of flow (Figs. 2 and 3) in some respects but like them in others. Relatively warm water does extend northwestward along the continental slope in agreement with the direction of flow. A striking feature seen in Fig. 5 is the tongue of warm water (>4°C) extending northeast from Amukta Pass. This strongly suggests an inflow of Alaskan Stream water (Reed, 1984), which was not indicated by surface salinity patterns (Fig. 4). This ambiguity is discussed further in Sec. 4.1. Curiously, there was also >4°C water at one other location (station 15).

Figure 6 shows temperature-salinity (T–S) curves for the two most extreme water masses found (station 7, which has a well-developed temperature minimum layer, and station 25, without such a feature), plus the curve for station 15, which has isolated warm water at sigma-t = 26.80. The T–S curve for station 25 clearly shows why warm subsurface water, but high-salinity surface water, was present; the curve is virtually linear from 0 to 400 m, which suggests vertical mixing of this water as it flowed through the pass (sill depth 430 m; Favorite, 1974), and a resultant cooling and increase in salinity of the surface water. Reed (1984) noted that surface salinity patterns may be altered by tidal mixing in a pass and must be used with caution. The T–S properties for station 15 are clearly intermediate between the "recent" Alaskan Stream water and "typical" Bering Sea water, and presumably formed by mixing around the large cyclonic gyre.

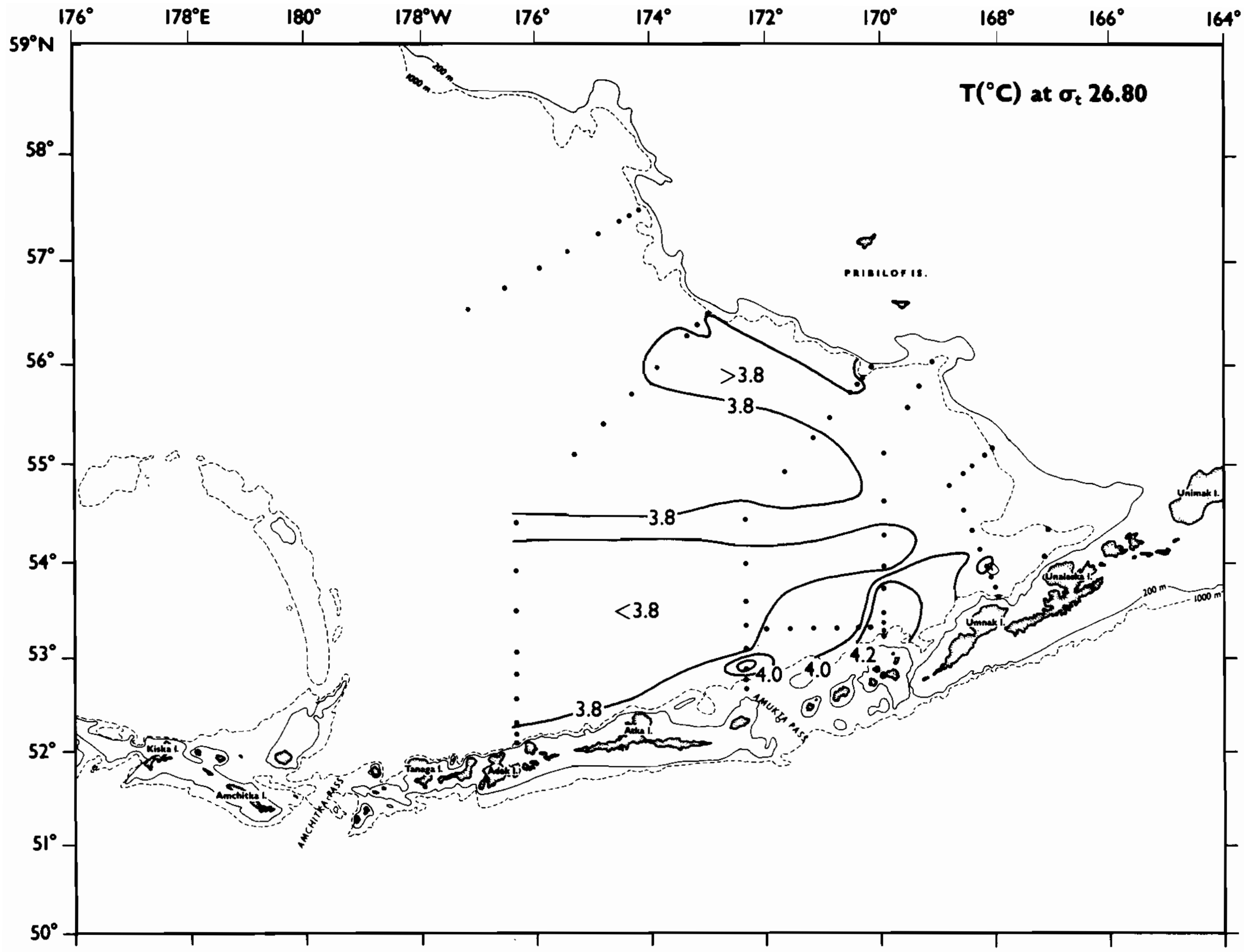

Figure 5. Temperature (°C) at the sigma-t (σ_t) density surface of 26.80.

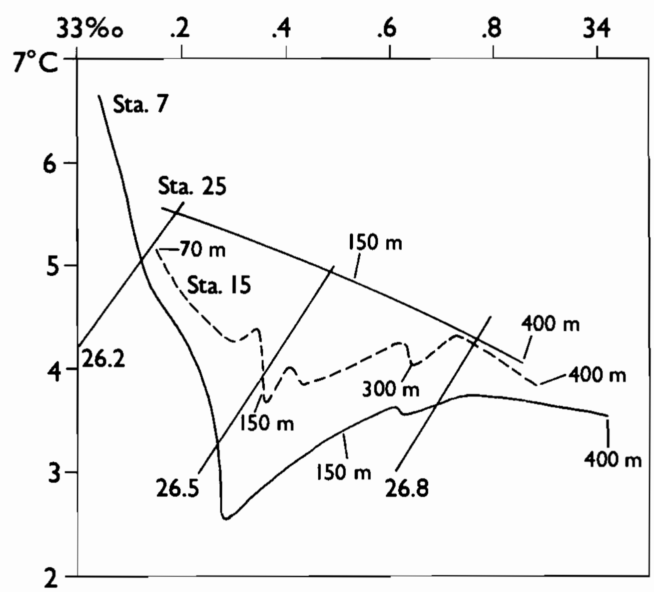

Figure 6. Temperature-salinity curves for stations 7, 15, and 25. Unlabeled numerals are sigma-t density surfaces.

Other information, however, implies that mixing near the gyre may not be especially vigorous. Of the 74 CTD casts, 12 had one or more secondary temperature inversions >0.20°C; 9 of the 12 stations were on the periphery of the large cyclonic gyre. Several of the features were in regions where the vertical T–S gradients would preclude double-diffusive processes. They thus seem likely to be intrusions of various subtypes of water that were not quickly eroded by mixing.

3.3 Volume Transport

Following the rationale discussed in Sec. 3.1, we present volume transport relative to 1000 db in Fig. 7. This represents on average about 75% of the transport relative to 1500 db; regional variations are as noted for geopotential relief. North of Adak Island, 4×10^6 m^3 s^{-1} flows eastward and then turns toward the northwest. (The small transports associated with the counterflows on the southern part of this section are not shown.) The northernmost section has transport essentially equivalent to the eastward flow. The next section to the south appears to have additional flow of about 1×10^6 m^3 s^{-1} along the slope from the southeast, but the flow moved toward the shelf before reaching the northernmost section (see Fig. 2). The counterflows

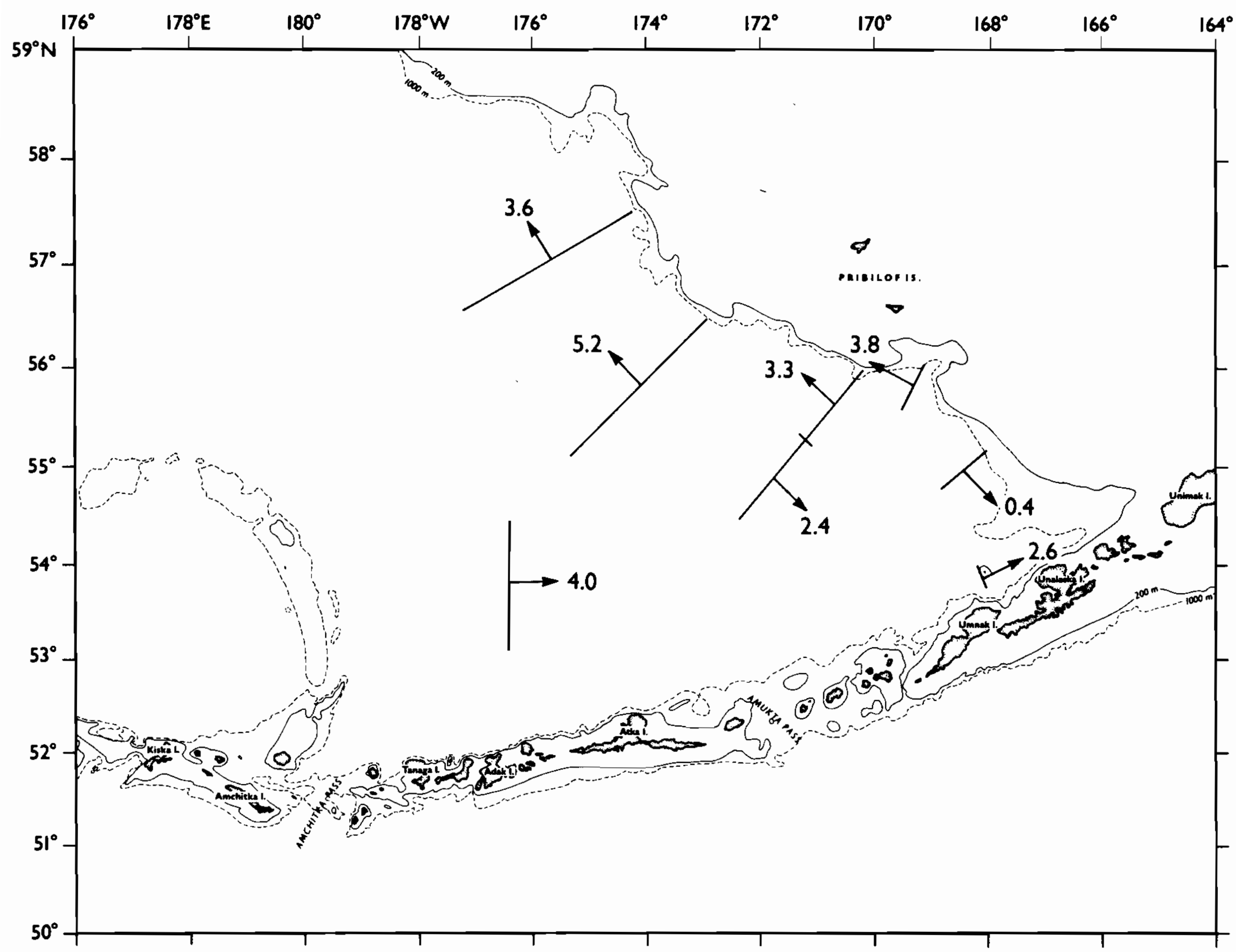

Figure 7. Computed volume transport (10^6 m^3 s^{-1}) relative to 1000 db.

around the northern part of the cyclonic gyre (southeast of the Pribilof Islands) also support the existence of about 1×10^6 m^3 s^{-1} flowing near the slope from the southeast. Thus far the transports neatly balance.

Results for the remaining three sections in Fig. 7 do not balance, however. Two flows of $3-4 \times 10^6$ m^3 s^{-1} are present, and the section between them has essentially zero flow. Did the flow north of Umnak Island perhaps intrude onto the shelf and then reappear south of the Pribilof Islands? Why does only about 1×10^6 m^3 s^{-1} of this latter flow continue northwest in water deeper than 1000 m? Are the rather intense flows in these canyonlike features locally formed, confined, and then dissipated? Observations presented here are not adequate to provide definitive answers.

4. RESULTS, SUMMER 1987

Locations of CTD casts taken during the 6–15 June 1987 cruise are shown in Fig. 8. Because this cruise lacked the data density of the one in fall 1986, the observations are not analyzed in the detail attempted in Sec. 3.

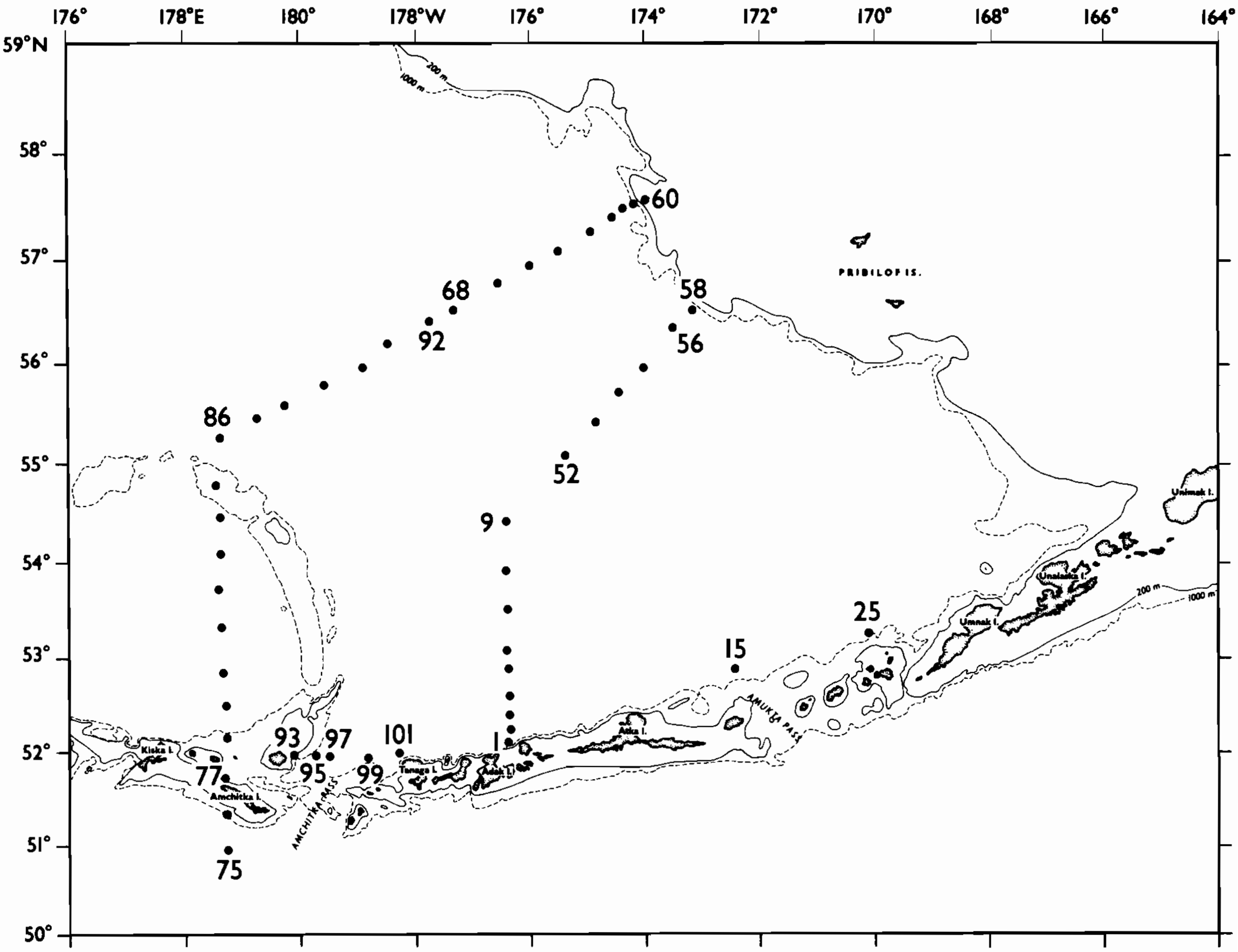

Figure 8. Locations of CTD casts taken in the central Bering Sea, 6–15 June 1987.

4.1 Geostrophic Flow, Properties, and Transport

The geopotential topography of the sea surface, referred to 1000 db, is shown in Fig. 9. Because of the sparse data, a contour interval of 5 dyn cm, rather than 2 dyn cm, was used. A major feature is a fairly intense northward inflow through Amchitka Pass, which continues eastward just north of the Aleutian Islands. Unlike in fall 1986, flow elsewhere on the section north of Adak Island is weak, and no strong eastward flow is shown on the western section north of Amchitka Island. It is tempting to speculate, as a result of the similarity of geopotential values, that some of the eastward flow north of Adak Island eventually turned cyclonically to feed the northwest flow to the north. At any rate, northwest flow near the continental slope is present, as it was in fall 1986. Finally, a well-developed anticyclonic eddy is present near 56.5°N, 177°W.

Temperature on the sigma-t density surface of 26.80 was again mapped and is shown in Fig. 10. A zone of water warmer than 3.8°C is present north of Amchitka Pass. In fact, the value at station 99 is 3.98°C as compared with 4.05°C at station 76, which indicates the source of warm water to the north was the Alaskan Stream south of the Aleutians. There is a hint of continuity of a secondary zone of warm water near 53°N, and a weak eastward flow. To the north, the pattern and values are similar to those in fall 1986. The temperature northeast of Amukta Pass

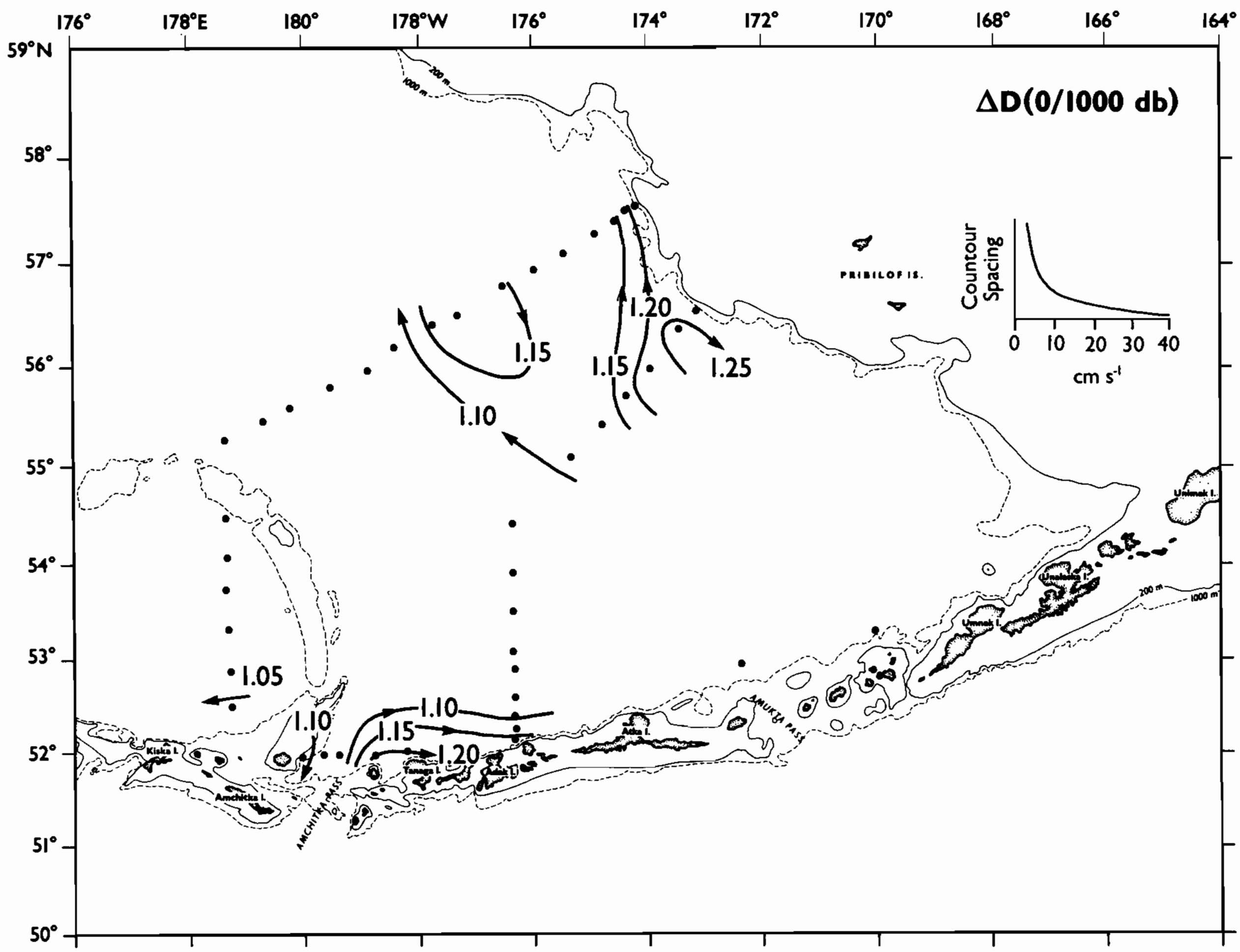

Figure 9. Geopotential topography (ΔD, dyn m) of the sea surface (0 db), referred to 1000 db.

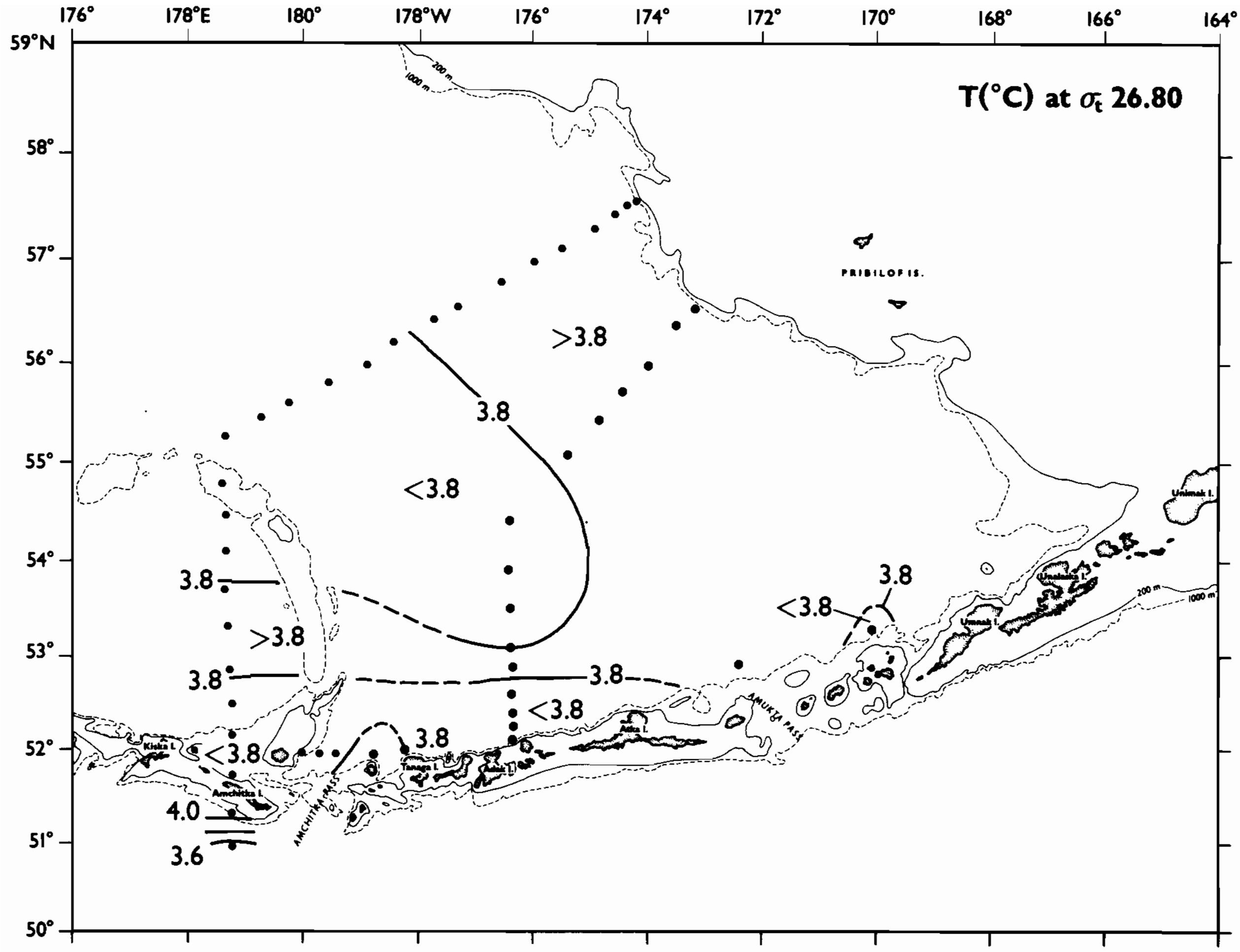

Figure 10. Temperature (°C) at the sigma-t (σ_t) density surface of 26.80.

(station 25) is 3.79°C compared with 4.31°C there in fall 1986, when there was an intrusion of Alaskan Stream water. The variability of flow through the passes appears to be a characteristic feature.

Volume transport in June 1987 was computed for those sections that had been occupied in fall 1986. The values, referred to 1000 db, were 2.8, 3.4, and 3.9 × 10^6 m^3 s^{-1} for stations 1-9, 52–58, and 61–66, respectively (not shown). They average 0.9 × 10^6 m^3 s^{-1} less than results for these three sections in fall 1986 (compare with Fig. 7), but the details of flow structure during the two periods differ considerably.

4.2 Flow Through Amchitka Pass

During the June 1987 cruise, stations 93–101 were taken just north of Amchitka Pass, and estimates of flow through the pass are possible. Figure 11 shows vertical sections of sigma-t density and geostrophic flow. On the west side of the pass (stations 93–95), there is southward outflow; elsewhere the flow is generally northward. The net volume transport was 3.5 × 10^6 m^3 s^{-1} northward. Similar sections reported by Favorite (1974), from winter 1968 and

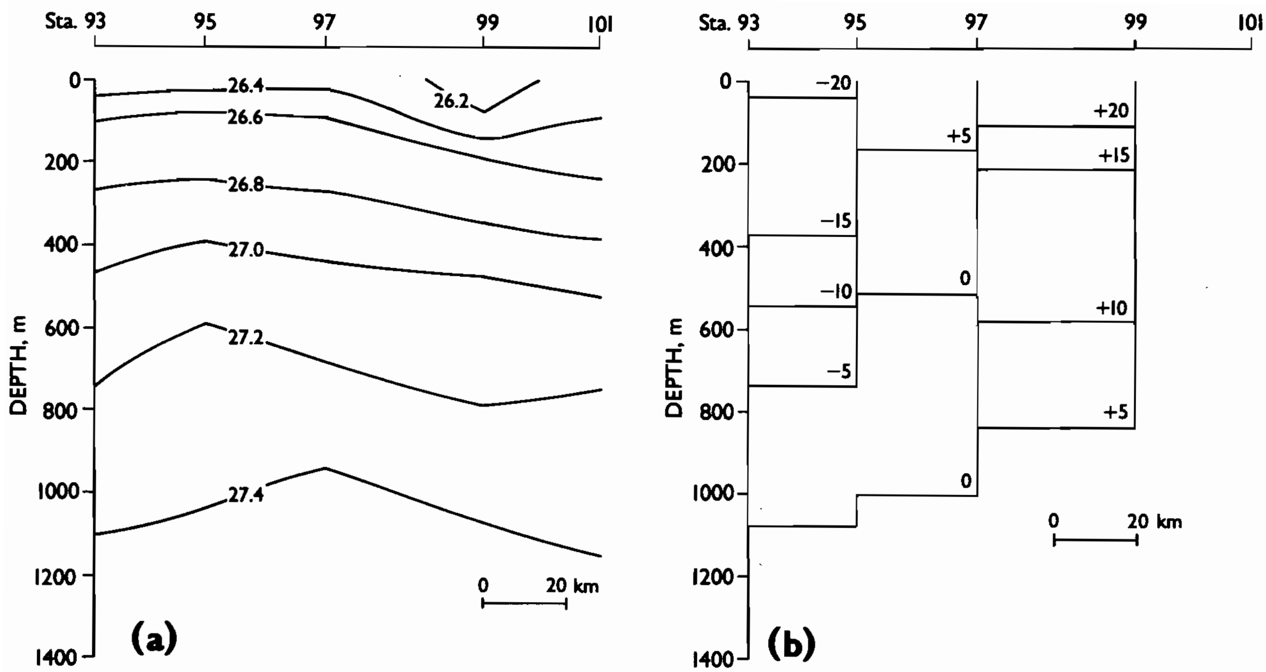

Figure 11. Vertical sections of (a) sigma-t density and (b) geostrophic flow (cm s^{-1}; plus is northward, and minus is southward), referred to 1500 db, except 1100 db for stations 93–95.

summer 1970, revealed net northward flows of 5×10^6 and 4×10^6 m^3 s^{-1}, respectively. Conversely, Reed (1984) inferred net southward flows of 4×10^6 and 2×10^6 m^3 s^{-1} in winter 1980 and summer 1981. The results imply that flow through Amchitka Pass varies considerably. A feature that might be important to the occurrence of northward flow is the "spurlike" shoal indicated by the 100-m isobath just southeast of the pass (see base maps in previous figures). If the Alaskan Stream were in an inshore position and were affected by this feature, conservation of potential vorticity should induce anticyclonic curvature and possible northward flow through the pass. If the stream were farther offshore, such an effect would seem unlikely.

5. COMPARISON WITH OTHER CIRCULATION PATTERNS

The circulation system found in fall 1986 differs considerably from the proposed schemes reviewed by Hughes et al. (1974). In particular, the two large-scale cyclonic features evident in Fig. 2, especially the eastern one, were generally absent. Ohtani et al. (1972), using data from six years, did show a feature similar to the eastward flow, which moved into the slope region toward the northwest, but the cyclonic gyre north of Amukta Pass was not present. The summer geopotential topographies in Sayles et al. (1979) were prepared by averaging over space and time. They showed an eastward flow with cyclonic tendency west of 174°W; to the east a large anticyclonic, rather than cyclonic, gyre was indicated.

Two synoptic data sets are available, which cover sizable portions of the region examined here. The RV *Thomas G. Thompson* surveyed a region along the continental slope from the Pribilof Islands northward, with limited data to the south, in August 1972 (Kinder et al., 1975). In May–June 1971 the RV *George B. Kelez* made casts east of 173°W and south of 56°N

(Favorite and Ingraham, 1973). The circulation presented by Kinder et al. (1975) was somewhat different from that found here. Along the continental slope, a complex, banded structure was found with some flow to the southeast. Favorite and Ingraham (1973) showed flow to the northwest along the slope, but a large anticyclonic gyre, which seemed to be related to an offshore intrusion of low-salinity water, occurred south of the Pribilof Islands. Their data set closely matches ours, however, in showing both of the large-scale cyclonic features (near the same locations) discussed. Finally, Royer and Emery (1984) presented results from a satellite-tracked drifter that showed a tendency for cyclonic circulation in the central and eastern region.

In summary, it is apparent that flow to the northwest along the slope is quite variable, at least on smaller scales. Eddies of either sense of rotation may be present; Kinder et al. (1980) suggested flow instabilities and wind forcing as the most plausible generating mechanisms. The data here and the results of Favorite and Ingraham (1973) also suggest that intrusions of low-salinity water from the shelf may be important in initiating smaller-scale features. Although climatological data do not generally show a cyclonic gyre north of Amukta Pass, one other synoptic data set does. It is uncertain if this feature frequently occurs, but it might be related to eastward flow on the north side of the Aleutians or northward flow in the central passes. Finally, we suggest that the eastward flow north of Adak Island frequently turns cyclonically toward the northwest (apparent in two climatological data sets, suggested by others, and seen in two synoptic ones), although details of its structure may vary. This feature seems likely to represent an eastward extension of inflow through Amchitka Pass or through Near Strait (~53°N, 170°E; Favorite, 1974).

6. ACKNOWLEDGMENTS

We thank W. Taguchi and the officers and crew of the NOAA ship *Miller Freeman*. The CTD casts were taken by K. Curre, C. DeWitt, D. Doughtery, D. Kachel, P. Proctor, A. Roach, and T. Vance; C. DeWitt did the final data processing. This report is a contribution to the Fisheries Oceanography Coordinated Investigations of NOAA.

7. REFERENCES

Dodimead, A.J., F. Favorite, and T. Hirano, 1963. Salmon of the North Pacific Ocean: Part II, Review of oceanography of the subarctic Pacific region. International North Pacific Fisheries Commission Bulletin No. 13, Vancouver, B.C., Canada, 195 pp.

Favorite, F., 1974. Flow into the Bering Sea through Aleutian Island passes. In *Oceanography of the Bering Sea*. D.W. Hood and E.J. Kelley (Eds.), Occasional Publication No. 2, University of Alaska, Fairbanks, 3–37.

Favorite, F., and W.J. Ingraham, Jr., 1973. Oceanography. In *Annual Report 1971*. International North Pacific Fisheries Commission, Vancouver, B.C., Canada, 89–97.

Hughes, F.W., L.K. Coachman, and K. Aagaard, 1974. Circulation, transport and water exchange in the western Bering Sea. In *Oceanography of the Bering Sea*. D.W. Hood and E.J. Kelley (Eds.), Occasional Publication No. 2, University of Alaska, Fairbanks, 59–98.

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

Kinder, T.H., J.D. Schumacher, and D.V. Hansen, 1980. Observation of a baroclinic eddy: An example of mesoscale variability in the Bering Sea. *J. Phys. Oceanogr. 10*:1228–1245.

Ohtani, K., Y. Akibi, and Y. Takenouti, 1972. Formation of western subarctic water in the Bering Sea. In *Biological Oceanography of the Northern North Pacific Ocean*. Y. Takenouti et al. (Eds.), Idemitsu-Shoten, Tokyo, 31–44.

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

Royer, T.C., and W.J. Emery, 1984. Circulation in the Bering Sea, 1982-83, based on satellite tracked drifter observations. *J. Phys. Oceanogr. 14*:1914–1920.

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

★ U.S. GPO: 1988 573-002/80513