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Circulation and Water Properties in the Central Bering Sea During OCSEAP Studies, Fall 1989–Fall 1990

R.K. Reed

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ABSTRACT. Data from three CTD surveys conducted during Outer Continental Shelf Environmental Assessment Program (OCSEAP) cruises in the central Bering Sea during fall 1989, spring 1990, and fall 1990 are used to examine circulation and property distributions. Geostrophic flow was quite variable, except in Pribilof and Zemchug Canyons where it was consistently westward. The variability of flow and small transports are difficult to reconcile with any permanent current system. The relatively cold temperatures near the temperature maximum suggest the absence of inflow through Amukta Pass near 172°W. The distributions of nutrients in fall 1989 and spring 1990 are also presented and discussed.

1. INTRODUCTION

The Bering Sea Shelf/Slope Exchange Study was conducted by personnel at the Pacific Marine Environmental Laboratory through sponsorship of NOAA's Outer Continental Shelf Environmental Assessment Program (OCSEAP) and the Department of the Interior's Minerals Management Service. The objective of the study was to enhance understanding of water exchange and of property and momentum fluxes between the basin and shelf of the eastern Bering Sea. A major consideration was the effect of submarine canyons on exchange processes.

The analysis here is concerned only with CTD (conductivity/temperature/depth) and nutrient data collected during three OCSEAP cruises (September 1989, April–May 1990, and September–October 1990). Satellite-tracked drifting buoys were also deployed on the cruises. Some of the buoy data were analyzed by Reed and Stabeno (1990); remaining data are now being analyzed. Nine current moorings were also deployed, and the data collected will be the subject of a subsequent study.

2. DATA AND METHODS

Essentially the same station grid was occupied on each of the three cruises in the study; the locations of the stations are shown in Fig. 1. CTD casts were taken during the cruises with a Seabird SBE-9 system to 1500 m or, in lesser depths, to within about 10 m of the bottom. Data were recorded (on disk in a minicomputer) only during the downcast at lowering rates of 30–50 m min^{-1}. Temperature and salinity corrections were derived from data taken on most casts. Various routines were used to eliminate spurious data and to derive 1-m averages of temperature and salinity, which were used to compute density and geopotential anomaly.

Nutrient samples were usually taken on alternate CTD casts at depths of 3, 10, 25, 50, 75, 100, 150, 200, and 300 m, and near bottom. Samples were drawn from Niskin bottles on the rosette sampler into 125-mL polyethylene bottles and were frozen for later analyses ashore. The analyses were performed on a Technicon Autoanalyzer II following methods of Whitledge et al. (1981). They yielded measurements of nitrate (NO_3), nitrite (NO_2), ammonia (NH_3), phosphate (PO_4), and silica (SiO_4).

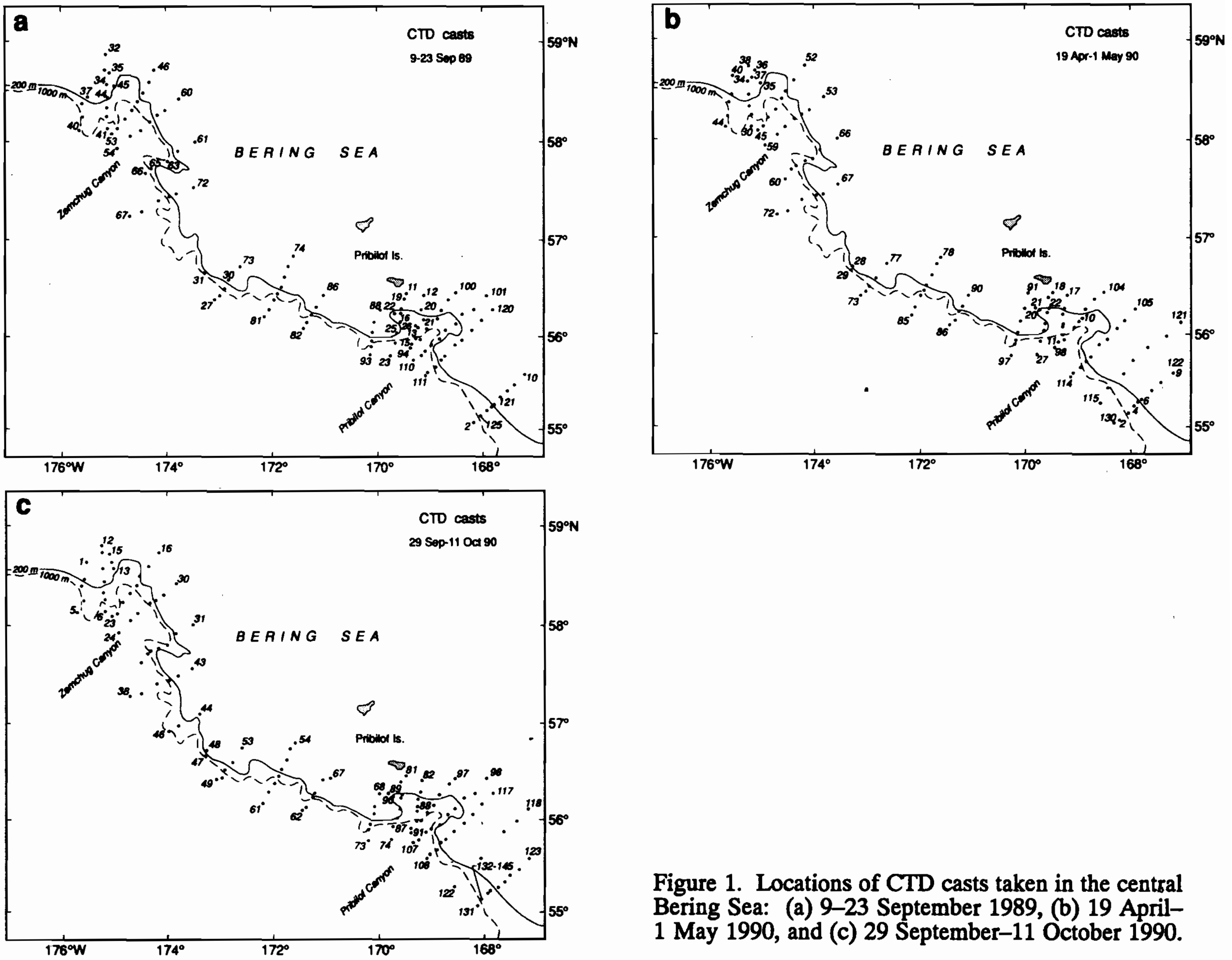

Figure 1. Locations of CTD casts taken in the central Bering Sea: (a) 9–23 September 1989, (b) 19 April–1 May 1990, and (c) 29 September–11 October 1990.

3. GEOSTROPHIC FLOW

Although CTD casts were taken to a maximum depth of 1500 m, more data are available to infer circulation if a shallower reference level is used. Earlier work (Kinder et al., 1975; Reed et al., 1988; Reed and Stabeno, 1989) in this region suggests that 1000 m is a realistic reference level for upper-ocean geostrophic flow. The geopotential topography of the sea surface, referred to 1000 decibars (db; 1 db ≈ 0.98 m), for the three cruises is shown in Fig. 2.

During fall 1989 (Fig. 2a), geostrophic flow in the southern part of the region and in Pribilof Canyon was to the northwest or west. Between ~171° and 175°W, however, flow was mainly to the southeast. Farther north (in Zemchug Canyon) flow was again to the northwest. In spring 1990 (Fig. 2b), a well-developed onshore flow was present in the southern part of the area. (At the start of this cruise, 19 April, the flow had been to the northwest, however.) Westward flow occurred in Pribilof Canyon, and northwestward flow occurred near Zemchug Canyon. In between the canyons, flow was southeastward or alternated between onshore and offshore. In fall 1990 (Fig. 2c), westward flow occurred in the canyons, although it was relatively weak. Between the canyons, regions of weak onshore or offshore flow were present. In summary, over this 1-year period there was considerable variability in flow along most of the slope.

At the start and end of both the fall 1989 and the spring 1990 cruises, satellite-tracked drifters were launched between stations 5 and 6 (Figs. 1a and 1b). The initial movements of the drifters were in good agreement with geostrophic flow estimates in all cases. Furthermore, flow along the slope was similar regardless of the reference level used. A 26-h time series of CTD casts was taken during 10–11 October 1990 (stations 132–145; Fig. 1c); the standard deviation of geopotential anomaly (0/1000 db) was only 0.007 dyn m, which suggests that internal tides had little effect on the geopotential topography. Thus the flows shown in Fig. 2 certainly appear to be realistic, and aspects of flow variability are discussed further in section 6.

4. PHYSICAL PROPERTY DISTRIBUTIONS

4.1. Horizontal Distributions of Surface Salinity

Sea-surface salinity in this area has large spatial and temporal variability, especially over the shelf (Reed et al., 1988; Reed and Stabeno, 1989). The distributions shown in Fig. 3 reflect the effects of freshwater discharge, ice formation, and mixing. They also are similar to the distributions of surface flow over the shelf, referred to a shallow level such as 100 db (not shown).

The patterns shown in Fig. 3 do not vary greatly during the three periods. Salinity <32.0‰ was found during each cruise near the Pribilof Islands. This is an extension of the low-salinity water from outer Bristol Bay (Schumacher and Kinder, 1983). Shelf water elsewhere was typically 32.2–32.6‰. There was considerable variability in the surface salinity of the offshore waters, but values of 32.4–32.8‰ were common. The patterns suggest weak northwest flow over most of the shelf. Offshore, the distributions should not be used to infer surface flow because the deeper baroclinic structure is quite important.

4.2. Vertical Sections of Temperature and Salinity

Figure 4 presents vertical sections of temperature and salinity for fall 1989 (stations 74–81) and spring 1990 (stations 78–85); these data are from the same location over the slope and shelf near 172°W. These sections are also used to present nutrient data in section 5. Figure 4a shows surface temperatures of 7°–9°C. A subsurface temperature minimum (<3.5°C) was present near

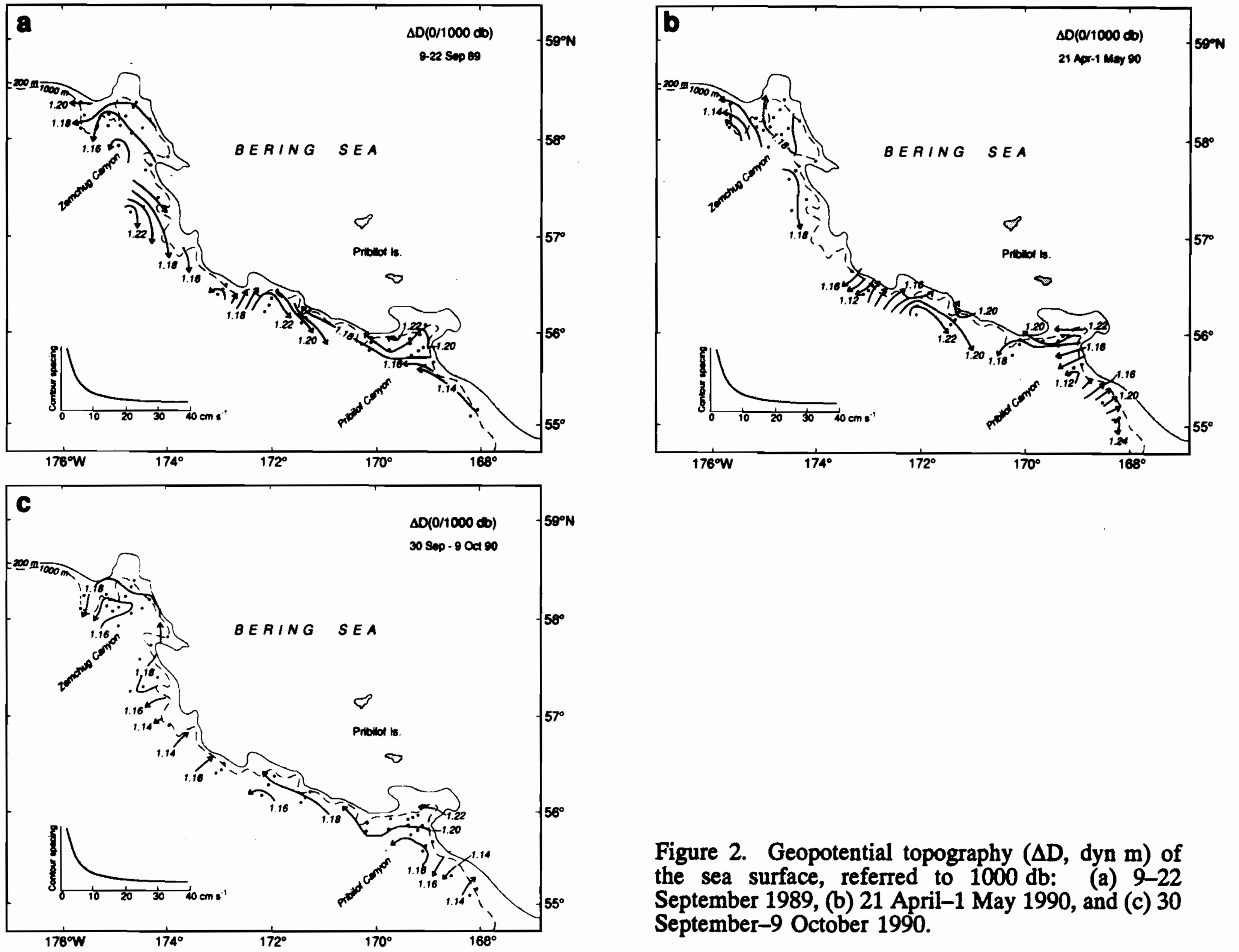

Figure 2. Geopotential topography (ΔD, dyn m) of the sea surface, referred to 1000 db: (a) 9–22 September 1989, (b) 21 April–1 May 1990, and (c) 30 September–9 October 1990.

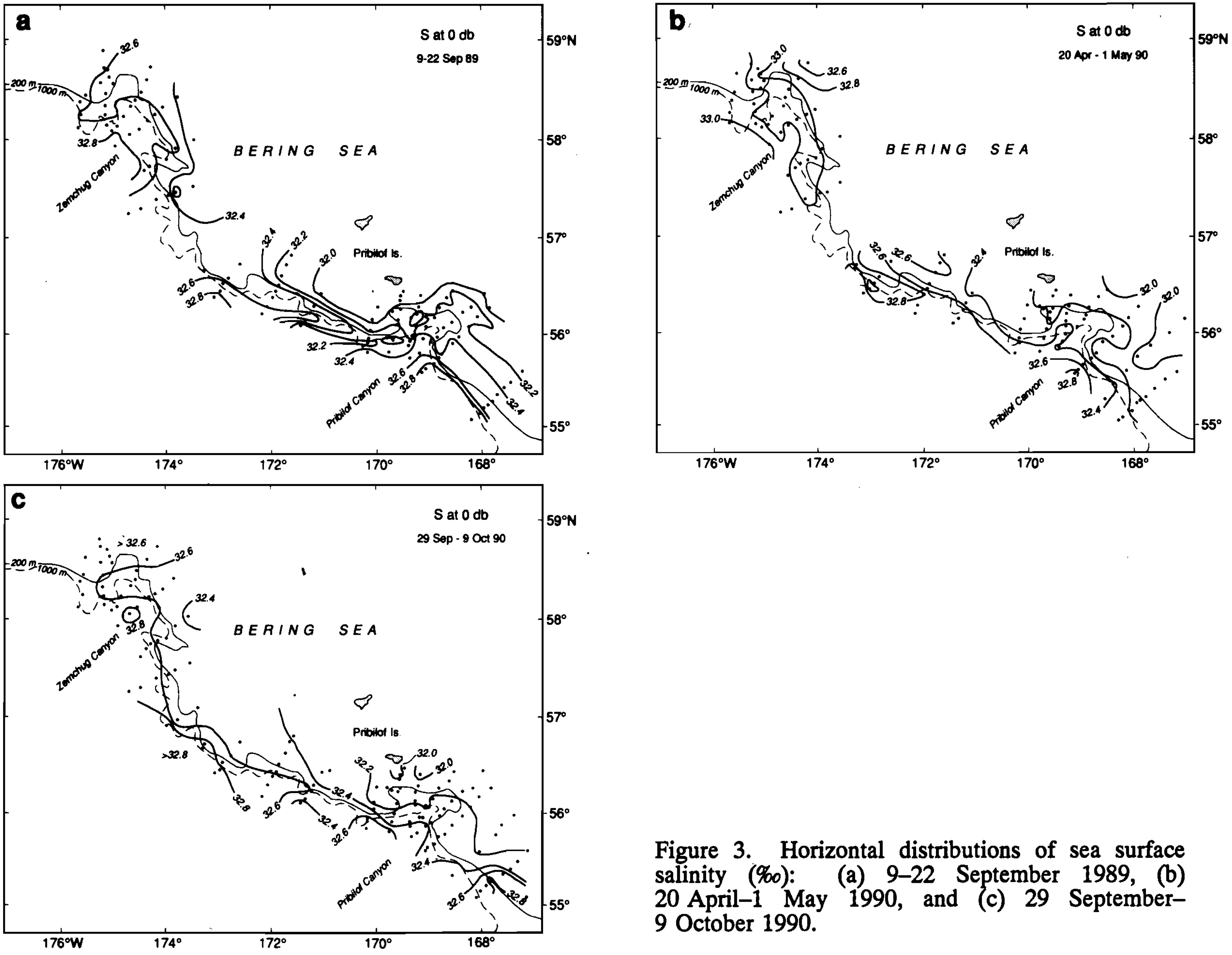

Figure 3. Horizontal distributions of sea surface salinity (‰): (a) 9–22 September 1989, (b) 20 April–1 May 1990, and (c) 29 September–9 October 1990.

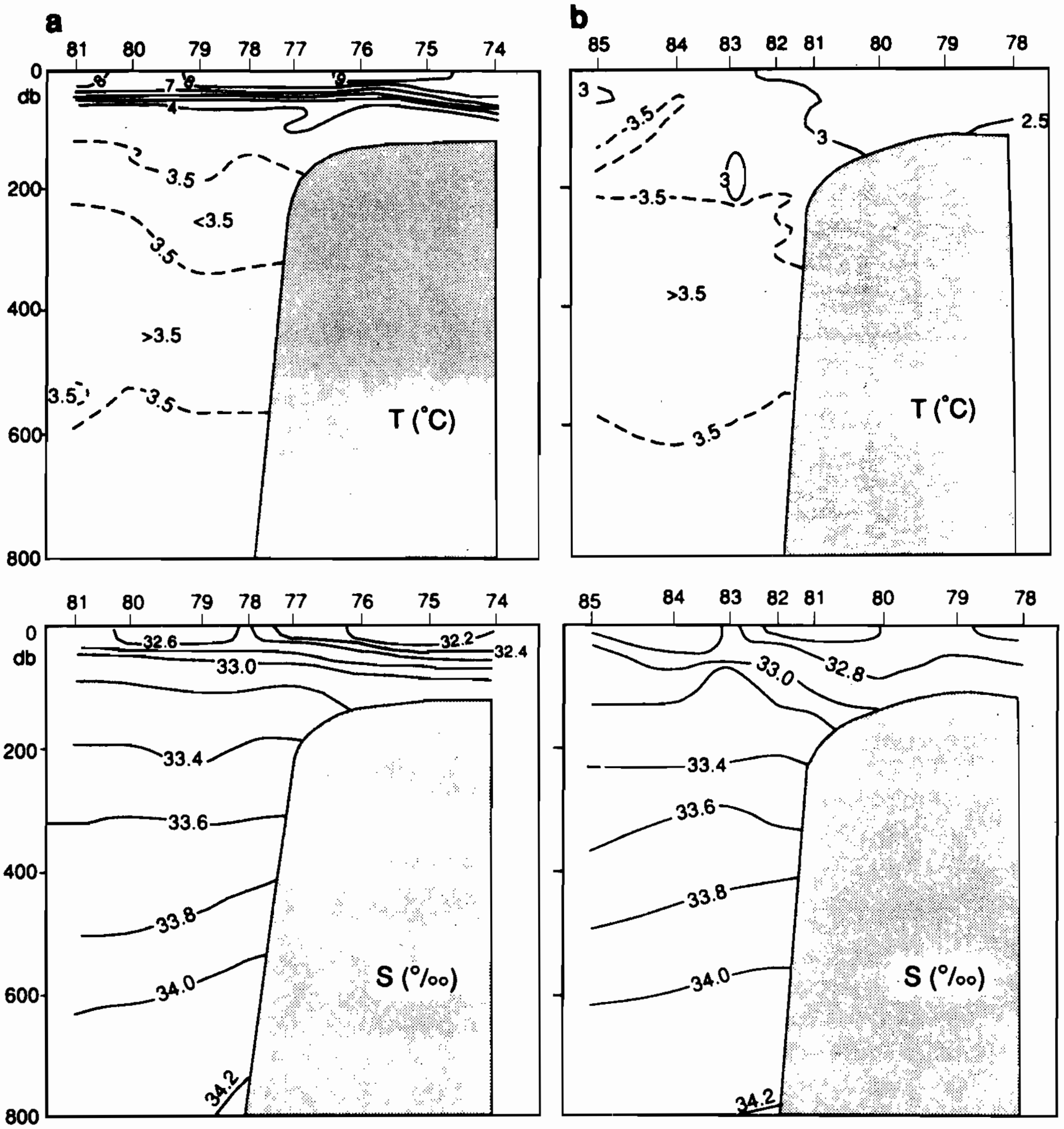

Figure 4. Vertical sections of temperature (°C) and salinity (‰): (a) 19 September 1989 (stations 74–81) and (b) 27 April 1990 (stations 78–85).

200 db; a subsurface maximum (>3.5°C) was present near 400 db. In spring 1990 (Fig. 4b), surface temperature was near 3°C; the subsurface minimum was at the surface at some stations but below the surface at others. The maximum (>3.5°C) was again present near 400 db. The slope of the isohalines below ~200 db indicates southeast flow in agreement with Fig. 2. Surface salinity over the shelf was appreciably lower in fall 1989 (Fig. 4a) than in spring 1990 (Fig. 4b).

4.3. Temperature Near the Subsurface Maximum

The Bering Sea is characterized by a temperature-minimum layer, from the surface to near 200 db, and by a temperature-maximum layer below the minimum, typically centered at 300–400 db. The temperature minimum is deepest and has the most extreme (coldest) temperatures off the coast of Siberia and Kamchatka (Sayles et al., 1979); although it is formed by winter convection, it persists year-round, and its distribution is altered by subsurface advection and diffusion. On the other hand, the temperature-maximum layer is mainly affected by horizontal advection of water from the North Pacific through the Aleutian Island passes (Sayles et al., 1979). Kinder et al. (1975) concluded that the maximum occurred near the sigma-t density surface of 26.8, but Reed and Stabeno (1989) found the maximum occurred just south of the Pribilof Islands in spring 1988 at a mean sigma-t density of 26.62. Thus the depth and density of the maximum can vary considerably, presumably as a result of variations in the source waters.

Temperature near the maximum during the three OCSEAP cruises is shown in Fig. 5. The mean sigma-t densities at the maximum were 26.80 ± 0.09, 26.76 ± 0.06, and 26.78 ± 0.07 during fall 1989, spring 1990, and fall 1990, respectively. The mean temperatures on these surfaces were 3.65° ± 0.06°, 3.70° ± 0.06°, and 3.66° ± 0.04°C during fall 1989, spring 1990, and fall 1990, respectively. The mean differences are not statistically significant. In fall 1989 (Fig. 5a), the coldest temperatures were in the northern part of Pribilof Canyon, and the warmest were in Zemchug Canyon. The warmest temperatures in spring 1990 (Fig. 5b) were in two zones of temperature >3.7°C, one near 170°W in Pribilof Canyon and one in Zemchug Canyon. The coldest were near 173°W. In fall 1990 (Fig. 5c), the coldest temperatures were north of Zemchug Canyon, and the warmest were in the southern part of the study area. In general though, there was not a trend of decreasing temperature toward the north during the three cruises. The relatively cold temperatures present during all these cruises suggest there was an absence of warm (Alaskan Stream) inflow through the central Aleutian Island passes. This is discussed further in section 6.

5. NUTRIENT DISTRIBUTIONS

5.1. Vertical Sections of Nutrients

Vertical sections of PO_4, NO_3, and SiO_4 are shown during 19 September 1989 (Fig. 6a) and 27 April 1990 (Fig. 6b). These are the same sections used for temperature and salinity in Fig. 4. The nutrients near the surface have considerably lower concentrations in fall 1989 than in spring 1990. The 1989 spring bloom of diatoms (late April and May; Whitledge et al., 1986) appears to be responsible for the nutrient depletion recorded in September 1989. The effects of the 1990 spring bloom would not yet be apparent in April 1990.

All dissolved constituents in this region are strongly affected by circulation (Coachman, 1986). The concentrations of PO_4 and NO_3 at 200–300 db near the continental slope were higher during fall 1989 (Fig. 6a) than during spring 1990; for SiO_4, however, this pattern was reversed. This disagreement suggests that there may be small systematic errors in one or more nutrients, perhaps as a result of freezing the samples.

5.2. Nutrients at 100 db

Concentrations of the three nutrients are shown for fall 1989 (Fig. 7) and spring 1990 (Fig. 8). The systematic differences discussed in section 5.1 also appear in these figures. The patterns do not seem to reflect possible differences in origin of waters nor do they generally parallel the geostrophic flow. This is puzzling and again points to the possibility of small systematic or random errors in the data.

6. DISCUSSION

An interesting feature in the data examined here is the considerable spatial and temporal variability in the offshore (depths >1000 m) flow, except in Pribilof and Zemchug Canyons where

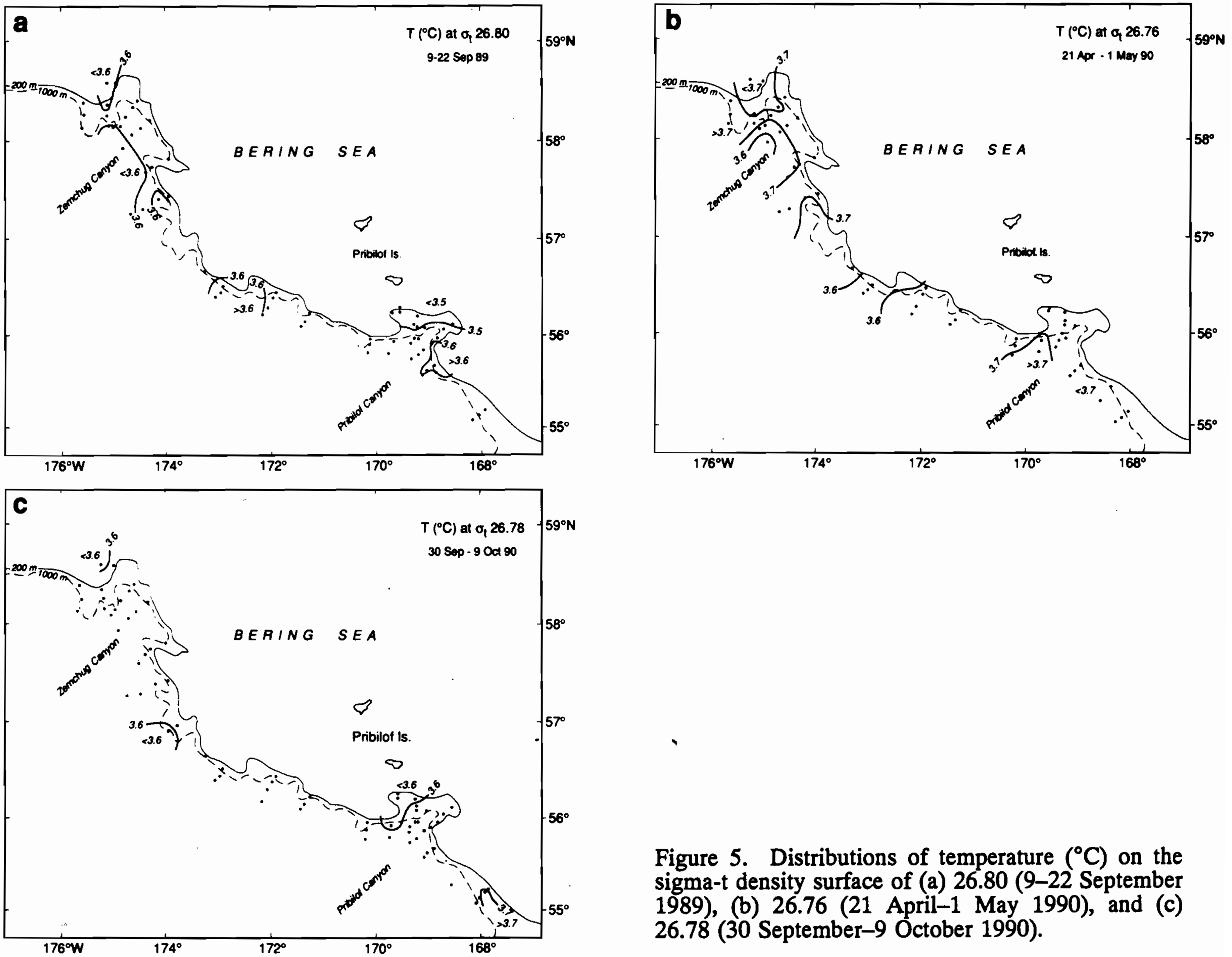

Figure 5. Distributions of temperature (°C) on the sigma-t density surface of (a) 26.80 (9–22 September 1989), (b) 26.76 (21 April–1 May 1990), and (c) 26.78 (30 September–9 October 1990).

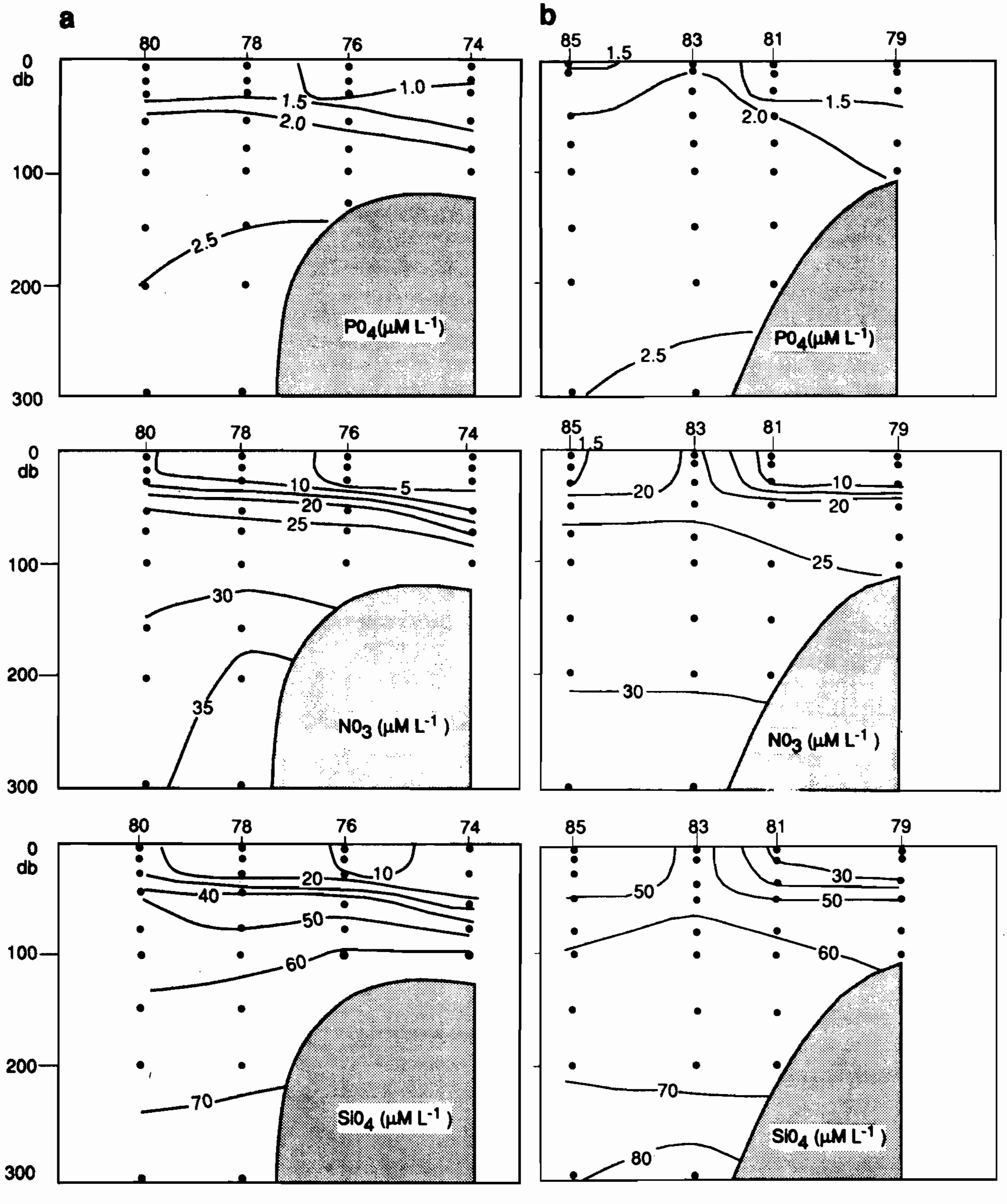

Figure 6. Vertical sections of phosphate (PO_4, μM L^{-1}), nitrate (NO_3, μM L^{-1}), and silica (SiO_4, μM L^{-1}), (a) 19 September 1989 (stations 74–80) and (b) 27 April 1990 (stations 79–85).

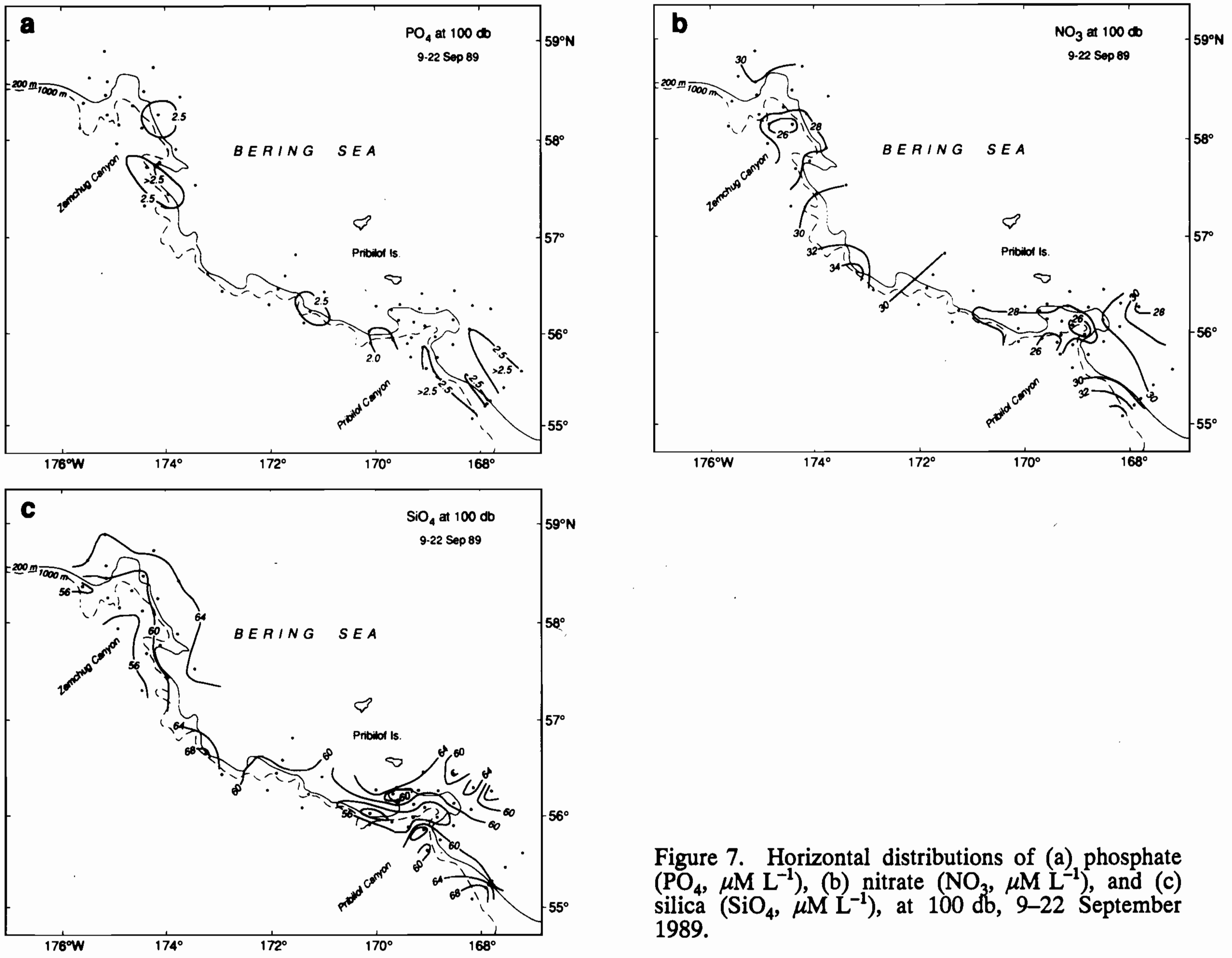

Figure 7. Horizontal distributions of (a) phosphate (PO$_4$, μM L^{-1}), (b) nitrate (NO$_3$, μM L^{-1}), and (c) silica (SiO$_4$, μM L^{-1}), at 100 db, 9–22 September 1989.

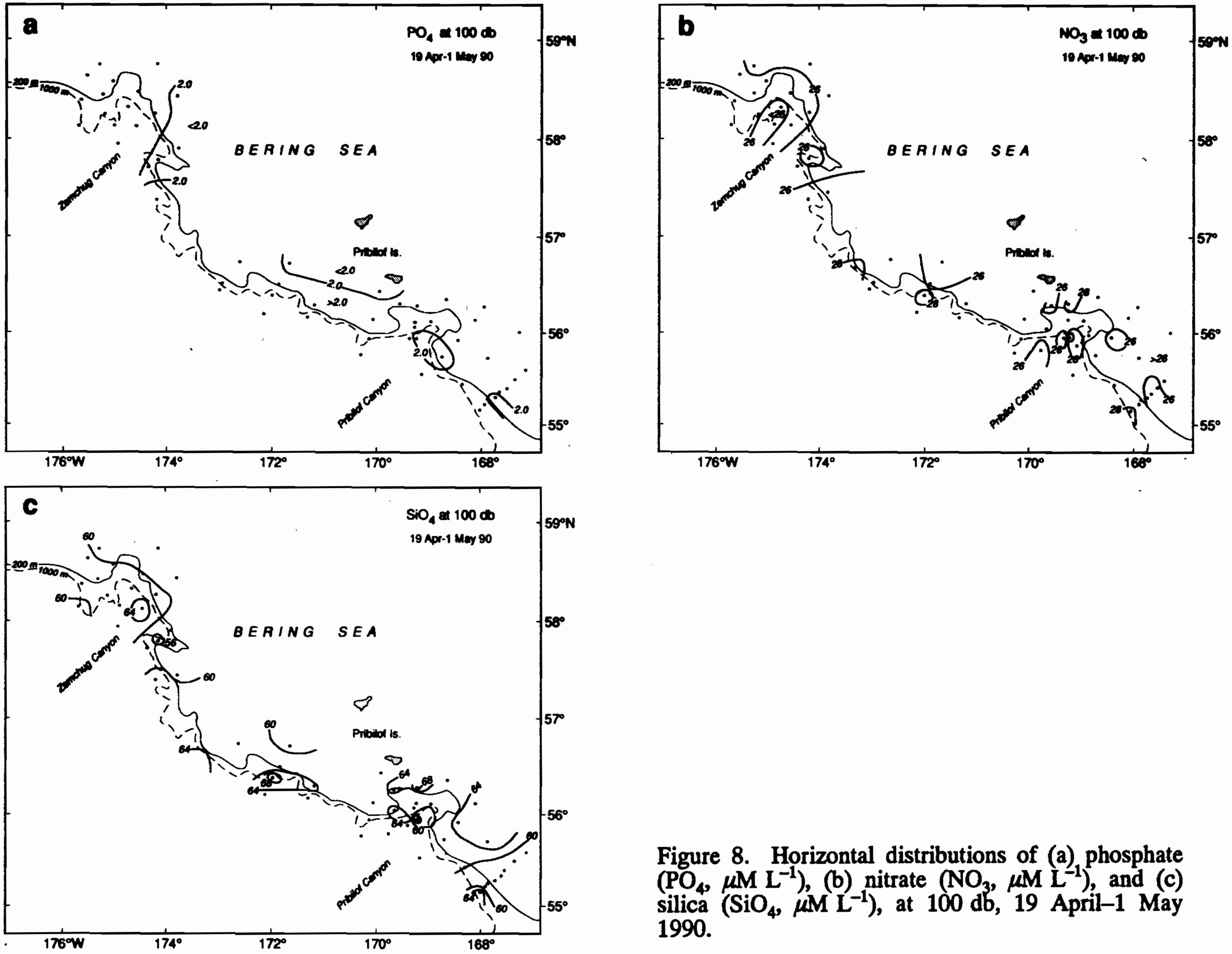

Figure 8. Horizontal distributions of (a) phosphate (PO$_4$, μM L^{-1}), (b) nitrate (NO$_3$, μM L^{-1}), and (c) silica (SiO$_4$, μM L^{-1}), at 100 db, 19 April–1 May 1990.

it was consistently westward. Over the shelf, the flow was weak but was generally in the same direction (westward or northwestward).

Except in the canyons, the offshore flow is so variable or weak that it is hard to justify identifying it as the "Bering Slope Current" (Kinder et al., 1975). Volume transport of the various branches of flow were generally $<2 \times 10^6$ m^3 s^{-1}. The flow along the slope here is presumably an eastward extension of the northward inflow through the deep pass near 180° (Sayles et al., 1979), which normally has a transport of $2\text{–}3 \times 10^6$ m^3 s^{-1} (Reed, 1990). Kinder et al. (1975) concluded that much of the variability of flow along the slope was caused by planetary waves. Reed and Stabeno (1990) found a clear example of Lagrangian chaos in a set of drifter data. Further examination of the drifter data from this study should reveal much more about the characteristics of this variable flow.

Another aspect of flow is suggested by the data in Fig. 5. During all three cruises, temperatures at sigma-t ~26.8 were quite cold (generally <3.7°C). Conversely, during fall 1986 (Reed et al., 1988) and spring 1988 (Reed and Stabeno, 1989) temperatures were >4.0°C in places. During fall 1986, at least, there was clear evidence for an inflow of warm Alaskan Stream water through Amukta Pass (near 172°W) that produced the warm subsurface water. Relatively cold temperatures during the three cruises reported here, during August 1972 (Kinder et al., 1975), and during June 1987 (Reed et al., 1988), however, suggest the absence of inflow, or at least a weak inflow, through Amukta Pass. Thus there is appreciable variability in this inflow as well as variability in flow all along the slope.

7. ACKNOWLEDGMENTS

I especially thank Carol DeWitt for her many efforts and for serving as Chief Scientist on two of these cruises. The efforts of the officers and crew of the NOAA ship *Miller Freeman* are also appreciated. S. Bograd, K. Krogslund, D. Lambourn, L. Lawrence, W. Parker, and P. Proctor assisted with data collection, preparation, and analysis. I also thank J.D. Schumacher for advice and support. This work was supported by the Outer Continental Shelf Environmental Assessment Program of NOAA and the Minerals Management Service of the Department of the Interior. This is a contribution (0134) to the Fisheries Oceanography Coordinated Investigations of NOAA and contribution No. 1291 from the Pacific Marine Environmental Laboratory.

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