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A Time Series of Temperature, Salinity, and Geopotential Across the Southeastern Bering Sea Shelf, 1995–1999

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Contents

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Abstract. CTD (conductivity/temperature/depth) casts were taken during sixteen occupations of a standard section across the southeastern Bering Sea shelf during 1995–1999. Vertical sections of temperature and salinity, plus computed geopotential anomaly values, are presented here. Water temperatures varied from ∼ –1 to 10°C, and salinities varied from ∼31.3 to 33.1. Nontidal flow was organized but was generally <5 cm s^{-1}. Six sections were obtained during 1997, a year with considerable sea ice. The melting sea ice produced low salinity (<31.4) that altered geopotential gradients inshore and reversed the typical southeastward geostrophic flow. Thus these waters are subject to large seasonal changes and occasional marked interannual ones.

1. INTRODUCTION

The southeastern Bering Sea shelf is a vast region with a distance of nearly 300 km between the 50- and 200-m isobath (Fig. 1). Coachman (1986) noted that this shelf is the widest outside the Arctic. The nontidal currents inshore of the 150-m isobath seldom exceed 5 cm s^{-1} (Schumacher and Kinder, 1983; Coachman, 1986; Reed and Stabeno, 1996). The region is also unusual, besides having the wide shelf and weak flow, as a result of large seasonal changes in water and air temperatures and wind forcing. Sea surface temperatures typically range from about –1 to 10°C over the years; bottom temperatures vary from ∼ –1 to 7°C (Reed, 1995). Salinity increases downward from about 31.2–32.5 at the surface to 31.4–33.0 at the bottom (Reed, 1995).

The main factor determining water temperatures over the shelf is the amount of sea ice in the previous winter–spring (Coachman, 1986; Neibauer, 1988; Neibauer and Day, 1989). Swan and Ingraham (1984) presented bottom-water temperature anomalies during 1950–1982. In this data set, 1976 was the coldest year. Neibauer and Day (1989) attributed most of the sea-ice variability to atmospheric, not oceanic, forcing. The winter position of the atmospheric Aleutian Low was found to explain up to 40% of the variations. This mode of variability was found to be linked to El Niño–Southern Oscillation events, however. During summer (July–August), with typical light winds, changes in heat content of the water over the shelf are dominated by insolation; at other times, latent and sensible heat flux are important (Reed, 1978).

In early 1995, as part of the Fisheries Oceanography Coordinated Investigations of NOAA's Coastal Ocean Program, moorings were established to measure currents and physical-biological variables (Stabeno *et al.*, 1998) at two sites (M2 and M3; Fig. 1). Along this line,

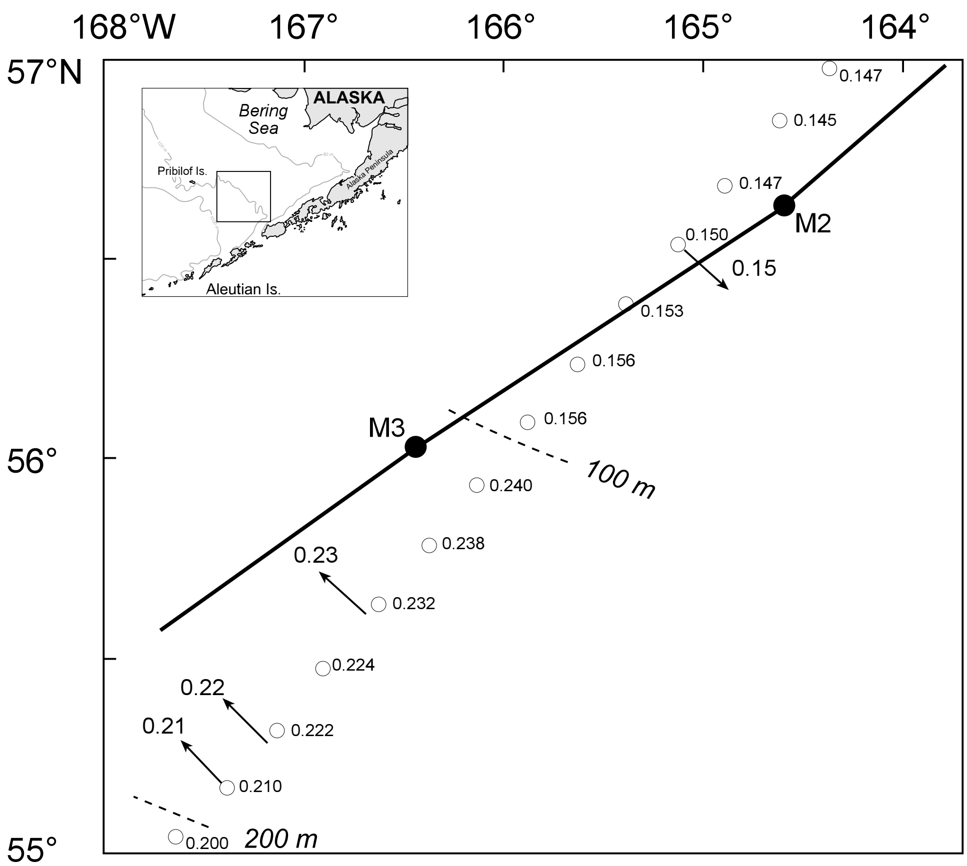

Figure 1. The location of CTD sections used here, 1995–1999, and the sites of current moorings (M2 and M3). The open circles indicate the location of stations, with mean computed geopotential anomalies at the sea surface, referred to 60 or 100 db, on the PROBES line, spring 1979–1981.

with extensions to the northeast and southwest, CTD (conductivity, temperature, depth) casts have been made on sixteen cruises (1995–1999). These data provide a time series of temperature, salinity, and geopotential over this period and are used here to examine ocean conditions and their variability. A similar analysis of geopotential (Reed, 1998) was performed on data from the nearby PROBES (Processes and Resources of the Bering Sea; Coachman, 1986) line, which is also shown in Fig. 1.

2. DATA AND METHODS

CTD casts were made at lowering speeds of 15–30 m min^{-1}. The data are thought to be accurate to at least 0.01°C and 0.01 in salinity. Each occupation of this CTD line took five days or less; thus the data are essentially synoptic. Data from each cast were examined to ensure against spurious values, such as density inversions. The use of dual temperature and salinity sensors reduced significant data gaps and helped verify data quality.

A computed quantity, geopotential anomaly (in dynamic meters, dyn m, which has units of 10^5 erg g^{-1}) is shown at each station on the location map of each figure. These values are for the sea surface, referred to 60 db (decibars; 1 db $\cong$ 0.98 m) inshore of 100 m, and referred to 100 db offshore of 100 m. Directions of flow computed from the anomaly values, assuming a balance between pressure gradient and Coriolis accelerations, are shown by arrows on the maps. The location of the stations on the temperature and salinity sections were produced by downward extrapolation of longitude.

3. RESULTS

Data from 16 cruises during 1995–1999 are presented in Figs. 2–17 below.

3.1 1995 Data

Figure 2 shows the location map, with station numbers and computed geopotential anomalies, for 12–14 March 1995. It was the only section occupied in 1995. Only about half of the planned stations were taken because of operational constraints. The arrows indicate even numbers of geopotential anomaly, as discussed above, based on the tendency for motion to start from high to low values and turn to the right. There are oppositely directed values of 0.13 dyn m, suggesting an eddy-like feature, and a value of 0.14 dyn m toward the southeast.

On the temperature and salinity sections (Fig. 2), the inverted "T" for station 8 at 75 db indicates that there were no temperature or salinity data below that level; at station 15, the "T" indicates no data above 20 db. The temperature section shows that the lowest temperatures (<0°C) were at station 15; the highest temperatures were >4°C at station 6. Salinity varied from <31.8 to >32.8. Our occupation of the section in mid-March, however, was not during the most extreme winter conditions. These were in late March–early April, when much of the shelf was ice-covered (Stabeno *et al.*, 1998). It now appears clear that 1995 was an extensive ice year, but that the cold conditions were short-lived (Stabeno *et al.*, 1998).

3.2 1996 Data

Three sections were occupied in 1996. Again, however, none were taken over the complete planned section. Figure 3 shows conditions during 13–15 February 1996. Offshore, near-bottom waters were warmer than 5°C; the coldest waters inshore were less than –0.5°C. In offshore waters, a strong halocline coincided with the sharp thermocline there. Inshore salinities were slightly less than in March 1995 (Fig. 2), possibly as a result of some melting ice prior to the observations. A southeastward flow is indicated in Fig. 3 near 56.5°N, 165°W. This is much like the southeastward flow from the mean of spring PROBES data (Fig. 1). Reed (1998) concluded that this feature likely results from the northwestward offshore flow approaching shoal water near the Pribilof Islands and retroflecting back toward the southeast

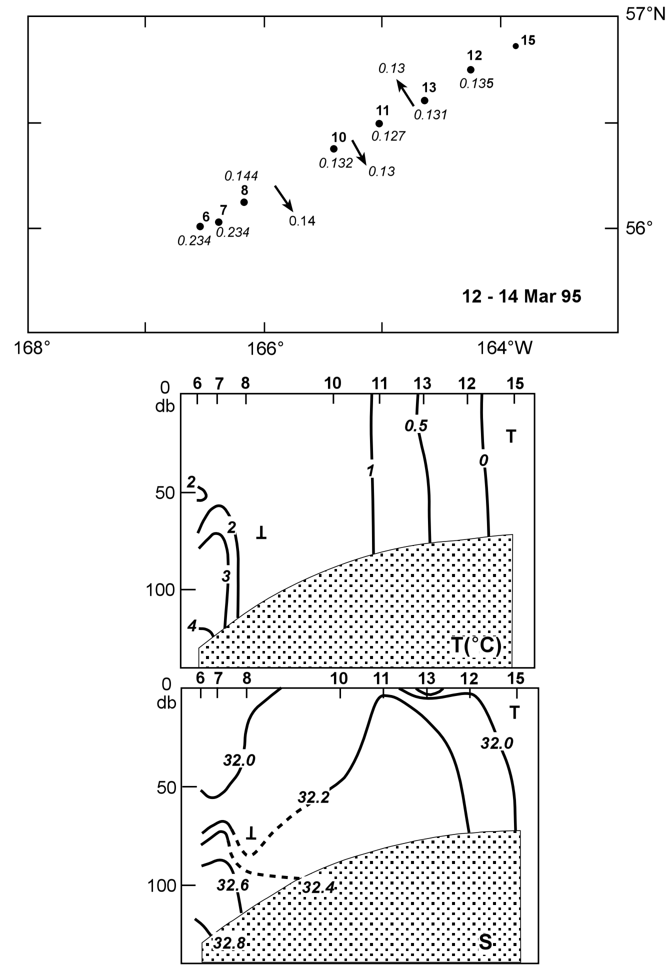

Figure 2. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 12–14 March 1995.

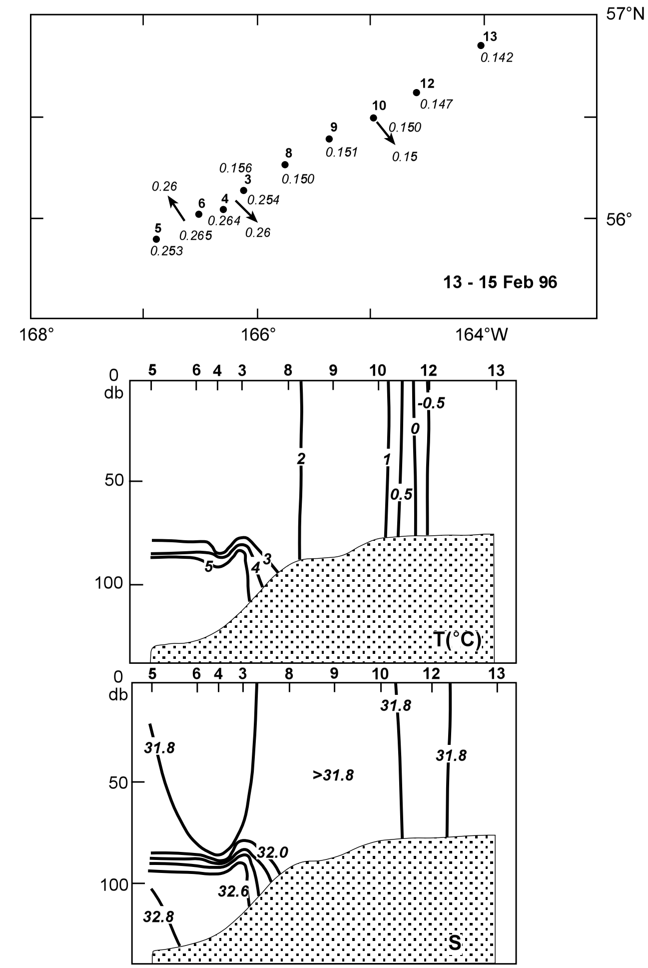

Figure 3. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 13–15 February 1996.

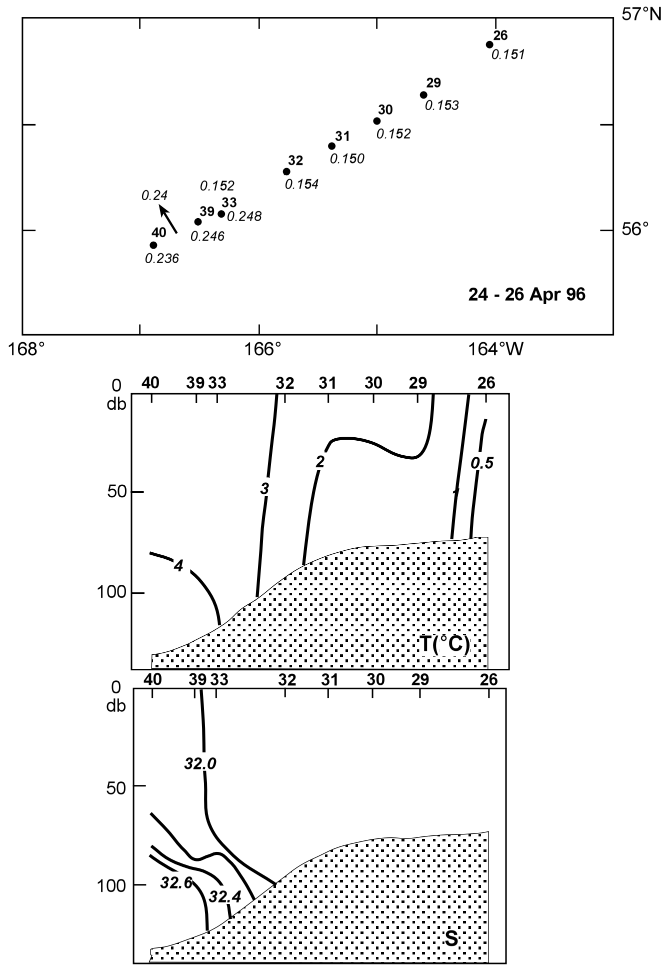

Figure 4. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 24–26 April 1996.

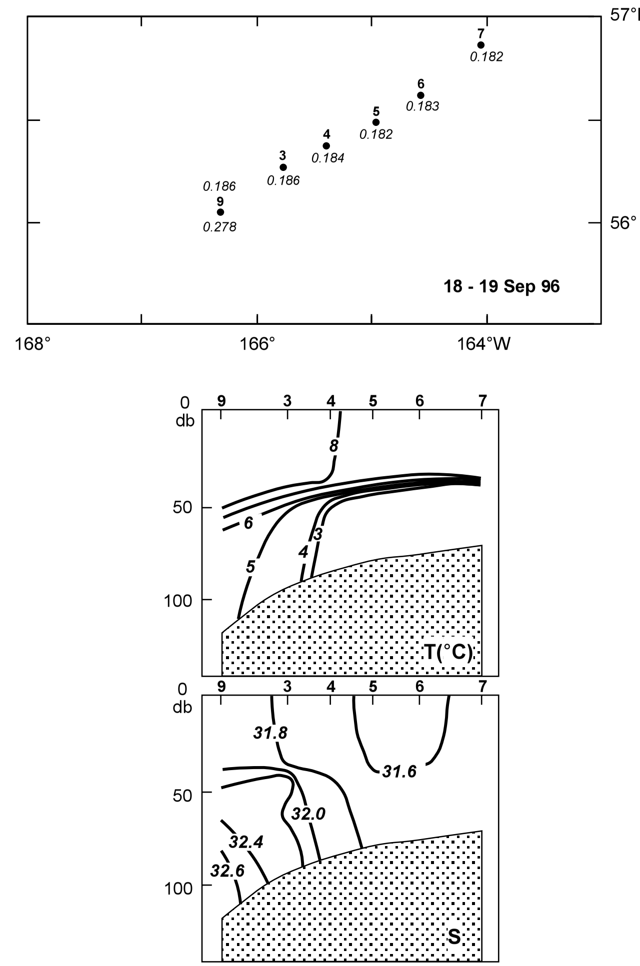

Figure 5. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 18–19 September 1996.

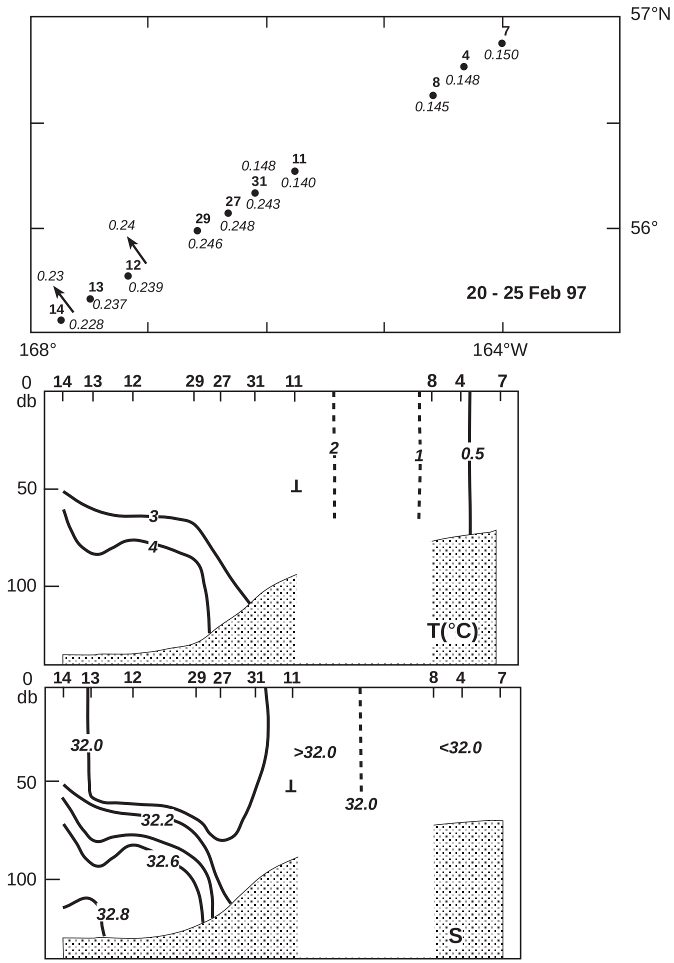

Figure 6. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 20–25 February 1997.

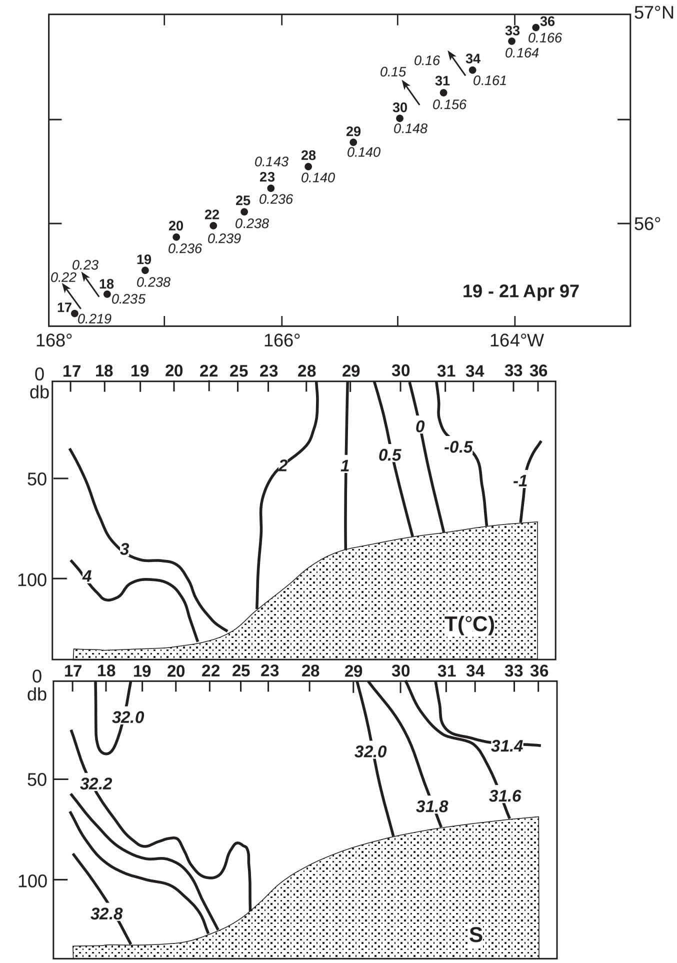

Figure 7. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 19–21 April 1997.

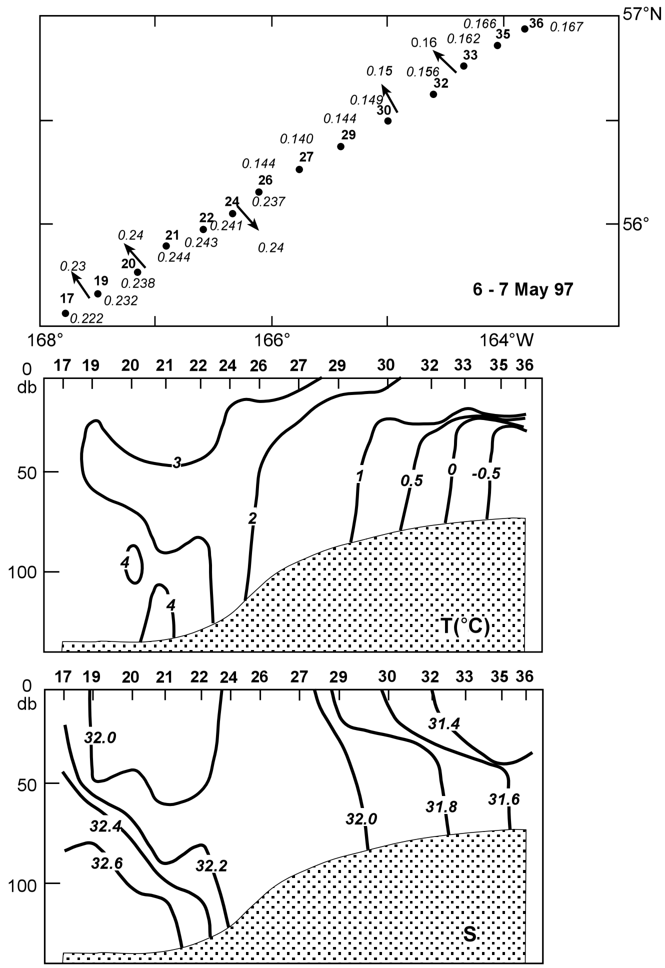

Figure 8. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 6–7 May 1997.

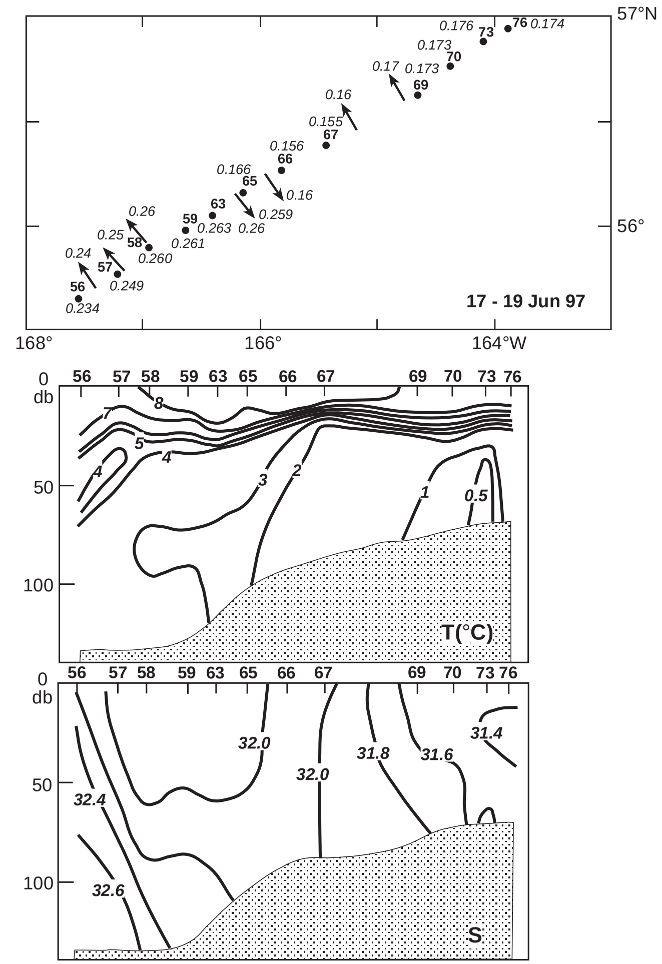

Figure 9. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 17–19 June 1997.

in shoaler, inshore waters. In Fig. 3, there also seems to be a clockwise-rotating eddy as indicated by the 0.26 dyn m vectors. This occurs ∼20% of the time in this area (Reed, 1998).

During 24–26 April 1996 (Fig. 4), inshore waters were warmer than in mid-February and had similar salinity (Fig. 3). Offshore, near-surface waters in late April were warmer and more saline than in mid-February (Fig. 3). Near-bottom waters offshore, however, were cooler and fresher in April than in February. In Fig. 4, there is no indication of significant flow except for the typical northwestward flow offshore.

Only six stations were occupied in mid-September 1996 (Fig. 5). Near-surface waters were from 7 to >8°C, and near-bottom waters were from <3 to >5°C. There was a zone of relatively fresh water (<31.6) above 50 db at stations 5 and 6. There was no significant flow at the time of this section.

3.3 1997 Data

During late February 1997 (Fig. 6), inshore waters were warmer than in mid-March 1995 (Fig. 2) or in mid-February 1996 (Fig. 3); inshore salinities were similar during these periods. Offshore waters in winter were similar during 1995, 1996, and 1997 in salinity, but 1996 and 1997 (Fig. 3 and Fig. 6) were warmer than in 1995 (Fig. 2). Figure 6 also indicates northwestward flow offshore but quite weak flow inshore.

The April 1997 section (Fig. 7) was the first in which all of the planned stations were occupied. The four subsequent 1997 sections also had good data coverage. Figure 7 indicates inner shelf waters that were < −1°C and had salinity <31.4. These are quite extreme winter–spring conditions (Reed, 1995) and resulted from ice over the shelf during late March–early April (Stabeno *et al.*, 1999). Relatively intense northwestward flow occurred offshore (between stations 17 and 18; Fig. 7). The most striking feature is the northwestward flow inshore of station 30. It results from the very low (<31.4) near-surface salinity caused by melting ice (Stabeno *et al.*, 1999). Consequently, the normal inshore southeastward flow (Reed, 1998; Fig. 1) was reversed.

In early May (Fig. 8), inshore waters were still quite cool and fresh, and a reversed, northwestward flow also occurred inshore. By mid-June (Fig. 9), near-surface waters everywhere were >7°C. Inshore salinity was still relatively low, and northwestward flow was present between stations 67 and 69. More typical southeastward flow did occur between stations 65 and 66. Well-developed northwestward flow was offshore of 167°W (Fig. 9). By early July (Fig. 10), surface waters were mainly >9°C, but inshore salinities were <31.6. Weak northwestward flow was present inshore. Relatively strong flow (11 cm s^{-1}) occurred between stations 16 and 17. In September (Fig. 11), near-surface waters inshore had cooled somewhat but were still relatively fresh. A more typical southeastward flow (Reed, 1998) was present between stations 18 and 20.

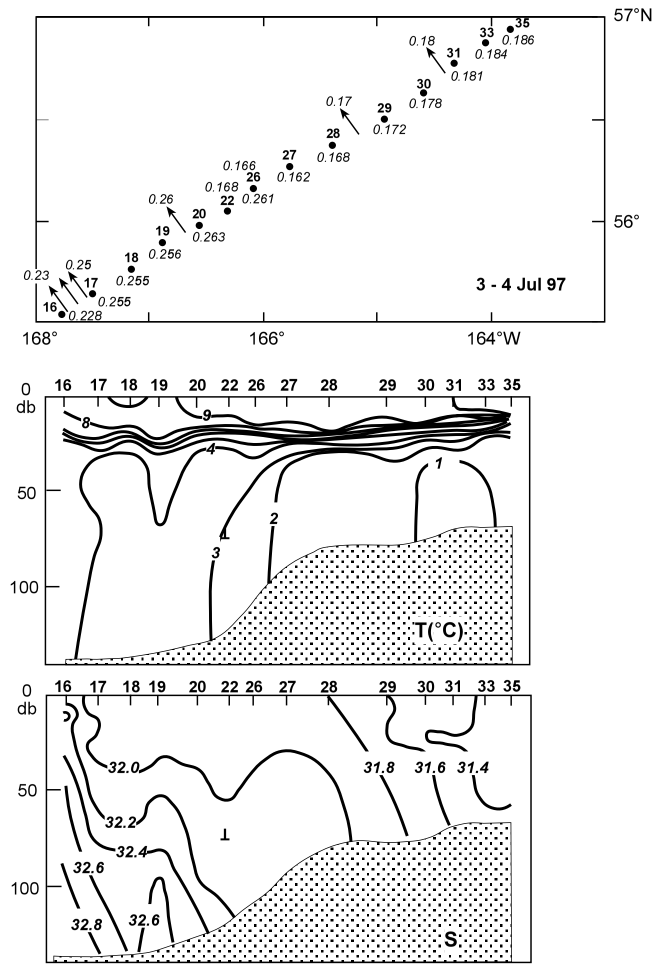

Figure 10. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 3–4 July 1997.

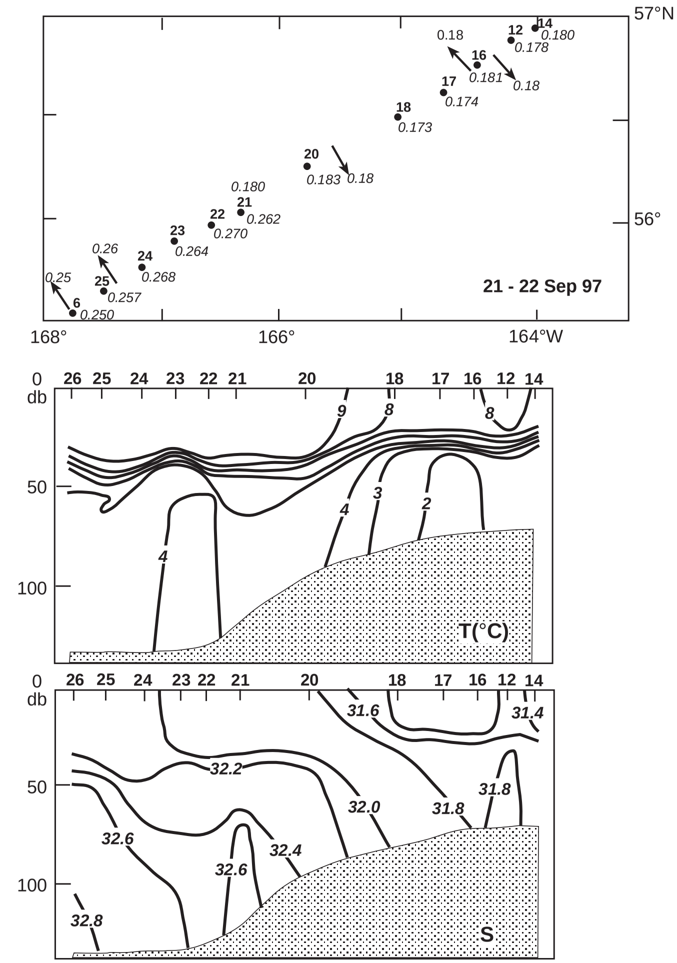

Figure 11. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 21–22 September 1997.

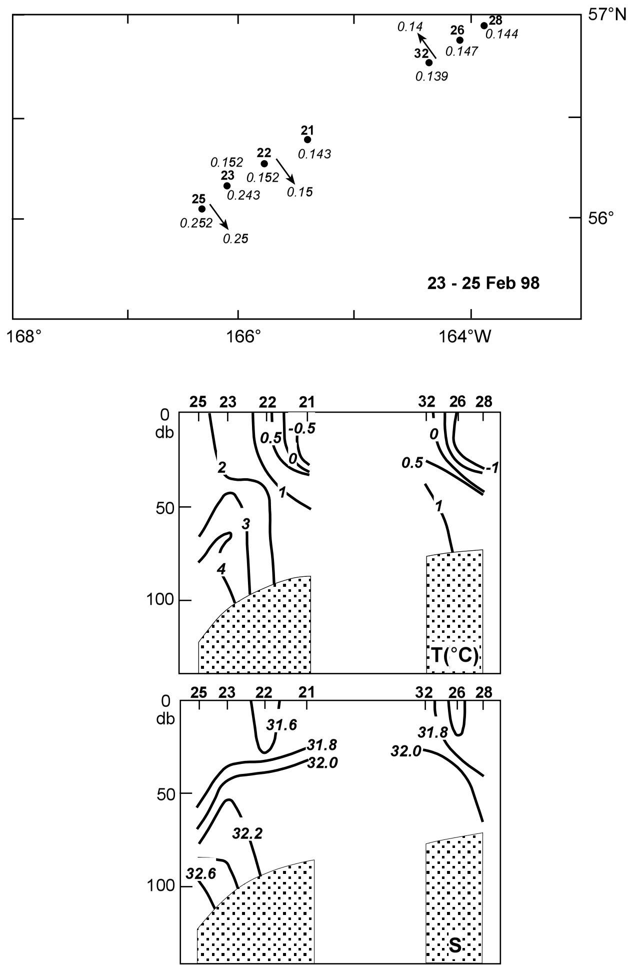

Figure 12. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 23–25 February 1998.

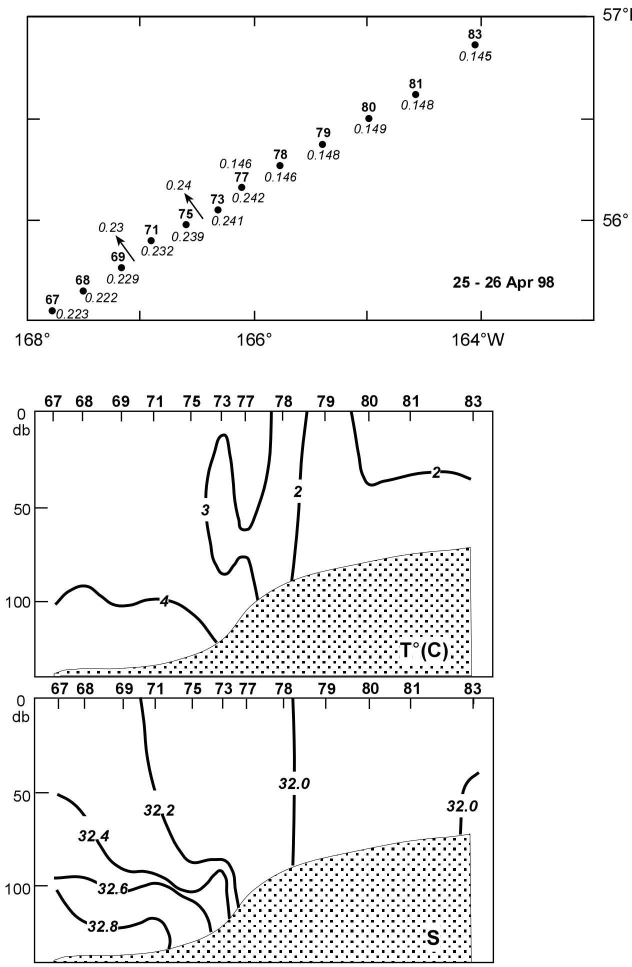

Figure 13. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 25–26 April 1998.

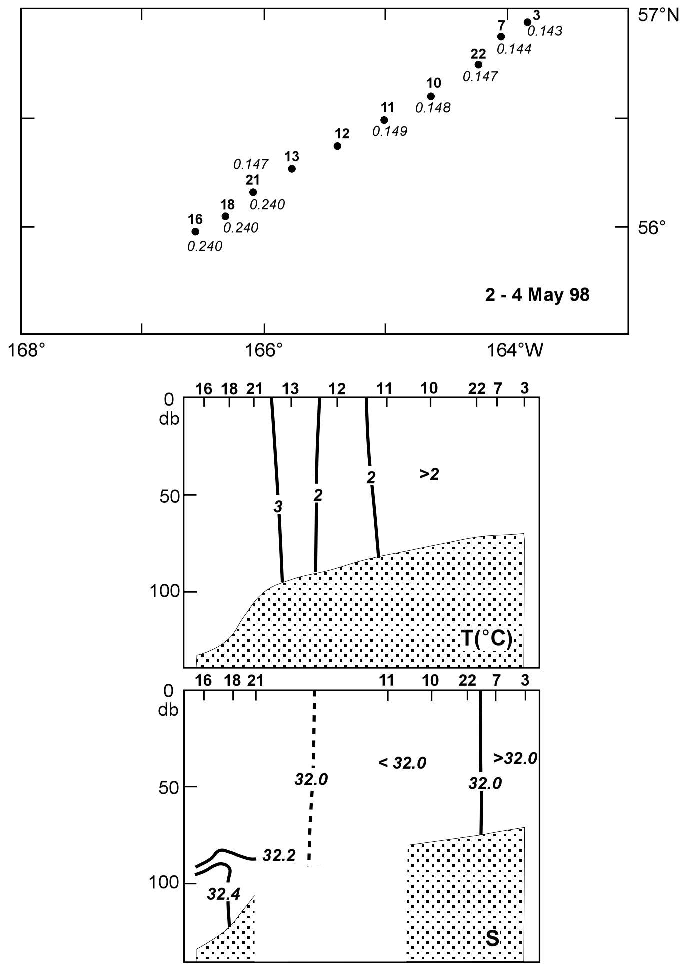

Figure 14. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 2–4 May 1998.

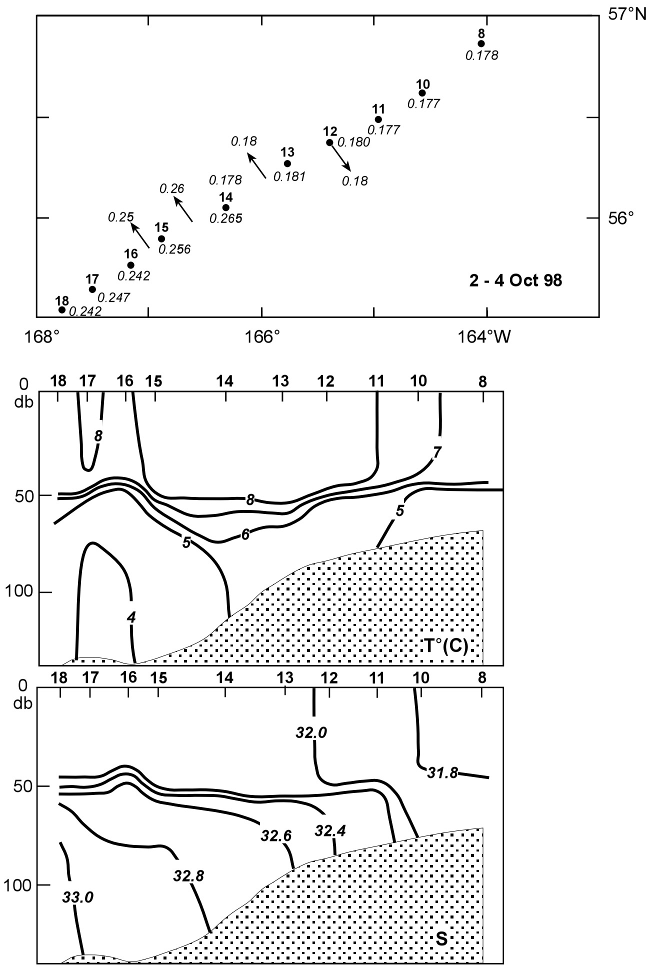

Figure 15. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 2–4 October 1998.

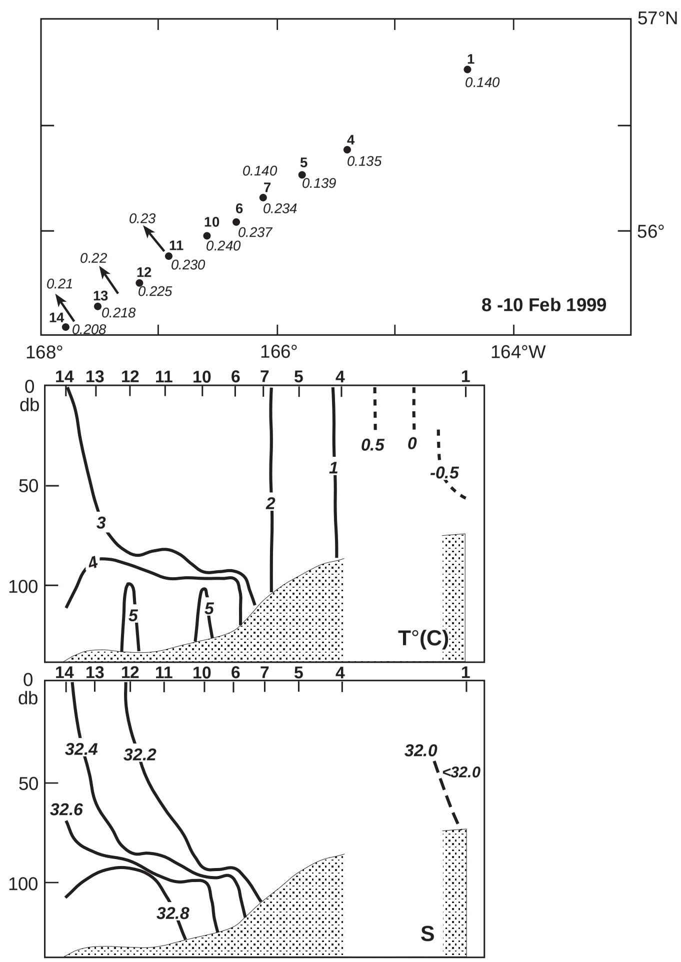

Figure 16. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 8–10 February 1999.

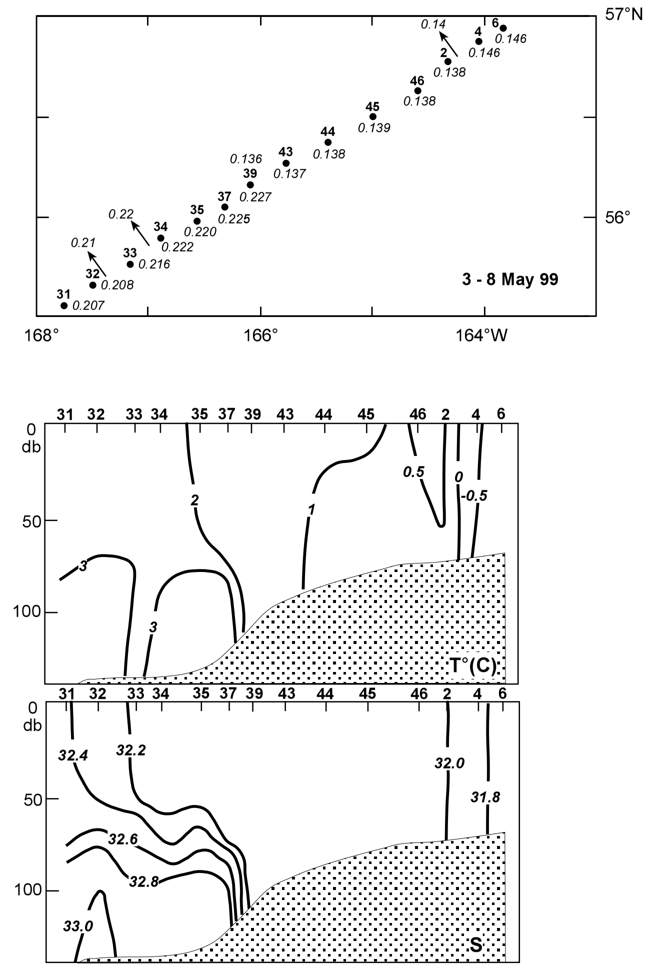

Figure 17. Vertical sections of temperature (°C) and salinity with station locations and sea-surface geopotential anomalies (dyn m), referred to 60 or 100 db, 3–8 May 1999.

3.4 1998 Data

During late February 1998 (Fig. 12), near-surface waters were generally cool (<0.5°C) from inshore to the central shelf at ~90 m depth; they were not especially fresh, however. This section only had seven stations, but there was both northwestward and southeastward flow. In late April 1998 (Fig. 13), waters were fairly warm and saline in comparison with April 1996 (Fig. 4) and April 1997 (Fig. 7). Flow was weak, except offshore of 100 m. The section during 2–4 May 1998 (Fig. 14) was incomplete, but the data show water properties much like Fig. 13; geostrophic flow was insignificant everywhere. In early October 1998 (Fig. 15), upper waters were more saline than in fall 1996 (Fig. 5) or fall 1997 (Fig. 11), but 1998 upper waters were relatively cool. Figure 15 shows weak southeastward flow inshore and northwestward flow offshore.

3.5 1999 Data

The inshore part of the February 1999 section (Fig. 16) was incomplete; offshore waters were relatively warm and saline compared with 1996 (Fig. 3), 1997 (Fig. 6), or 1998 (Fig. 12). There was no significant flow in February 1999 (Fig. 16), except offshore of ~140 m, where it was toward the northwest. In early May 1999 (Fig. 17), the section was complete. Offshore deep waters were cooler and more saline than in February 1999 (Fig. 16).

4. DISCUSSION

The first five sections presented here were incomplete because of operational constraints; most of the remaining sections were largely complete, however. In general, the data show the effects of seasonal warming from winter into early fall. Seasonal effects on salinity seem limited here as well as in Reed (1995).

Interannual effects can be pronounced. Although both 1995 and 1997 were substantial "ice years" (Stabeno *et al.*, 1999), we only have one section in 1995, and it was before the onset of ice. Observations in 1997 (Figs. 6–11), however, show the effects of ice through much of the year. The most noticeable effect is persistent low salinity over the inner shelf. As seen in Figs. 7–11, the low-salinity water was present into early fall. The effect of the low-salinity water reversed the normal (southeastward) inshore flow. This southeastward flow seems to be a retroflected branch of the offshore northwestward flow that "feels bottom" near the Pribilof Islands and turns southeastward (Reed and Stabeno, 1996; Reed, 1998). Although 1995 and 1997 were substantial ice years, they were not as severe as 1976 (Stabeno *et al.*, 1999).

5. CONCLUSIONS

The data presented here provide additional information on water property distributions during the period 1995–1999. The observations were along a single line across the southeastern Bering Sea shelf from water depths of ~70 to ~140 m. Although the data were not distributed evenly in time, some data are available over all months except August and November–January.

Water temperatures varied from ~ –1 to 10°C; salinity ranged from ~31.3 to 33.1. Geostrophic speeds were mainly <5 cm s^{-1}, but a value of 11 cm s^{-1} was obtained from early July 1997. Substantial changes occurred during 1997 as a result of sea ice. Salinity was as low as 31.3. The normal inshore southeastward geostrophic flow reversed as a result of the persistent dilute water. Although net, nontidal circulation over the shelf is weak, it is not constant.

6. ACKNOWLEDGMENTS

I thank Phyllis Stabeno for support, suggestions, and insight. I thank Sheri Rees for preparing data products that accelerated preparation of this report. David Kachel also provided considerable assistance. Carol DeWitt, David Kachel, William Floering, Sheri Rees, and Sigrid Salo collected data at sea. Shipboard observations were conducted aboard the NOAA Ship *Miller Freeman* and the R/V *Wecoma*. Program support was provided by NOAA's Coastal Ocean Program, Southeast Bering Sea Carrying Capacity. This is contribution FOCI-B373 to the Fisheries Oceanography Coordinated Investigations.

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