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THERMOHALINE VARIABILITY OF THE WATERS OVERLYING THE WEST ANTARCTIC PENINSULA CONTINENTAL SHELF

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Regularly-spaced observations from four cruises between January 1993 and February 1994 provide the first description of variability in temperature and salinity on the west Antarctic Peninsula continental shelf. The largest variations occurred in Antarctic Surface Water temperatures due to seasonal heating and cooling; accompanying salinity changes were smaller. The Winter Water portion of the surface water was eroded during the austral summer and fall and re-established the following winter. Erosion of Winter Water was most pronounced over topographic highs. The deep shelf waters are composed of a modified version of Circumpolar Deep Water, which has been cooled relative to its Upper Circumpolar Deep Water source. No evidence was found to support the formation of dense shelf water in this region. The outer portion of the west Antarctic Peninsula continental shelf is influenced by meandering of the Antarctic Circumpolar Current, which provides a mechanism for episodic inputs of deep water and the exchange of shelf waters at periodic intervals. This across-shelf exchange occurs at specific sites that are associated with changes in bottom topography and with time scales of a few weeks to months.

1. INTRODUCTION

The continental shelf region west of the Antarctic Peninsula supports a large biomass of Antarctic krill (*Euphausia superba*) [*Ross et al.*, 1996*a*] and large populations of predators such as penguins [e.g., *Fraser and Trivelpiece*, 1996] and seals [*Costa and Crocker*, 1996] that depend on krill as a food source. Within the past few years it has become apparent that the biological productivity of the Antarctic food web in this region is strongly linked to the physical aspects of the ecosystem [*Ross et al.*, 1996*b*]. However, understanding and defining the physical-biological linkages has been difficult because of the lack of information on seasonal and annual variability in the structure of the physical environment.

In 1990, a Long-Term Ecological Research (LTER) program [*Smith et al.*, 1995] was established at Palmer Station (64°46′S, 64°04′W) on Anvers Island (Figure 1). The non-land based part of the Palmer LTER study region (Figure 1) extends 900 km southward from the western portion of Bransfield Strait along the western side of the Antarctic Peninsula. The study region extends 200 km across the continental shelf and includes the region inshore of the islands as well as the shelf break region.

One of the goals of the Palmer LTER was to provide a description of seasonal variability in the physical environment that could be used as a framework for interpreting changes in the marine ecosystem. Thus, four cruises took place in the study region between January 1993 and February 1994 (Table 1). One of the objectives of these cruises was to describe the water mass structure and variability of the continental shelf waters west of the Antarctic Peninsula. Hydrographic measurements were made along several across-shelf transects with a 100 km along-shelf separation. These data provide the most extensive space and time coverage currently available of this or any portion of the Antarctic continental shelf. The primary objective of this paper is to use the thermohaline observations to provide a description of the variability in the water mass structure of this region.

The next section describes the hydrographic data and methods used in this study. That is followed by a description of the observed variability in water mass structure. The discussion and summary section provides an assessment of the variability and potential exchanges between oceanic and continental shelf waters.

2. DATA AND METHODS

Station transects were aligned parallel to a southernmost across-shelf transect (the 000 Line) and perpendicular to a baseline which defines the inshore extent of the grid (Figure 1). Each across-shelf transect was named in terms of its distance in kilometers from the 000 Line,

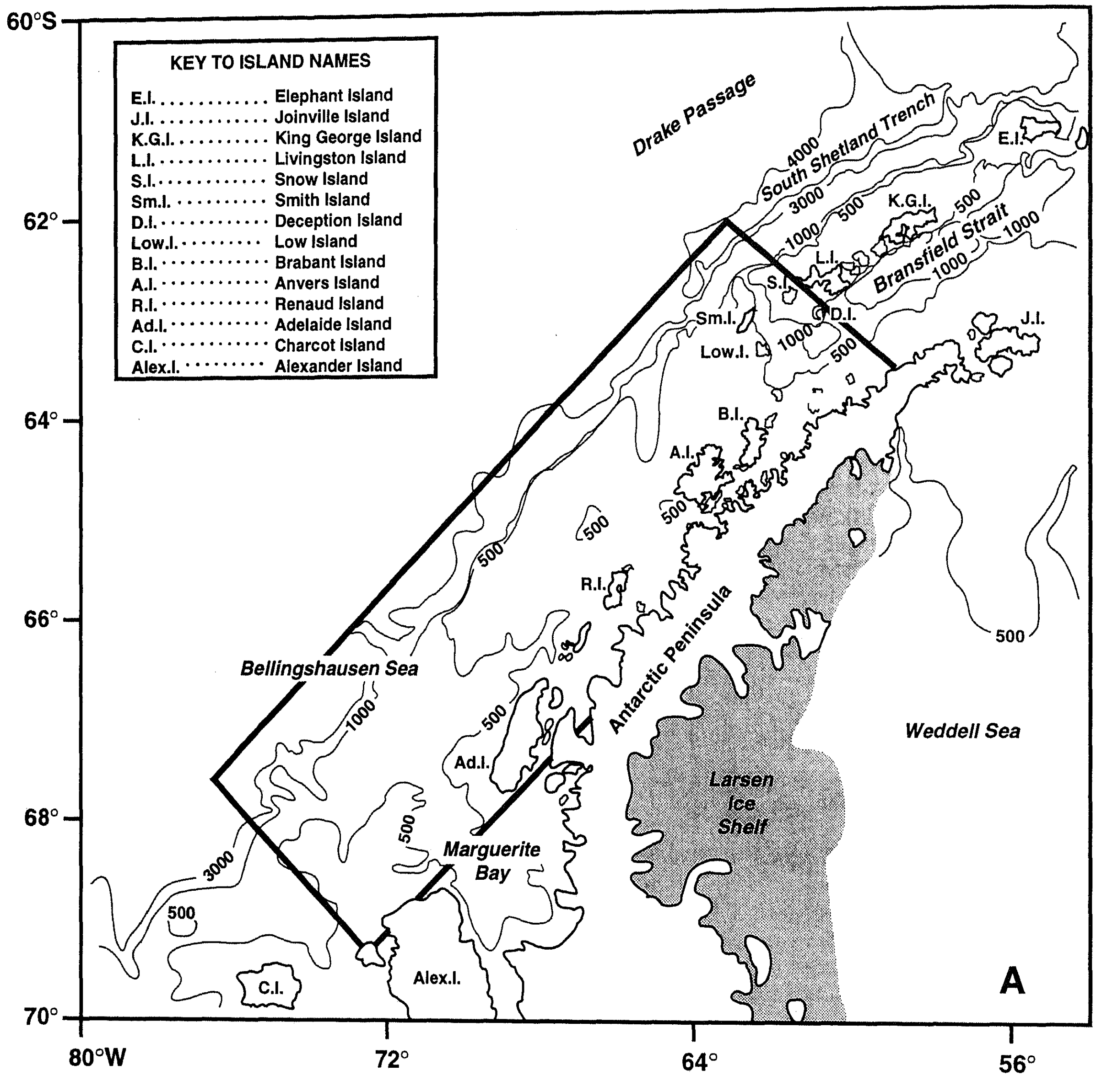

Fig. 1. Base map of the Bransfield Strait and west Antarctic Peninsula region. The region included in the Palmer LTER offshore study region is indicated by the solid lines. The southern and northern boundaries correspond to the 000 and 900 Lines, respectively. Bottom topography contours are in meters. Bathymetry is from ETOPO5, distributed by the National Geophysical Data Center. Shaded regions indicate the permanent ice shelves.

with the 900 Line being the northernmost across-shelf transect. Between January 1993 and February 1994, four cruises occurred in the offshore study region (Table 1), each differing in the amount of the study region that was covered. The fall (March-May) 1993 cruise included the entire area between the 000 and 900 Lines. The 1993 summer (January-February) and winter (August-September) cruises encompassed the region between the 600 and 200 Lines and the summer (January-February) 1994 cruise covered the region between the 600 and 300 Lines. This analysis is focused on portions of the hydrographic data sets that are common to all four cruises, i.e., the

Table 1. Season, dates, number of stations occupied and research vessel used for the four 1993-1994 cruises west of the Antarctic Peninsula.

Season	Dates	CTD Stations	Research Vessel
Summer 1993	8 January - 7 February	69	*Polar Duke*
Fall 1993	25 March - 15 May	225	*N.B. Palmer*
Winter 1993	23 August - 30 September	42	*Polar Duke*
Summer 1994	11 January - 7 February	72	*Polar Duke*

region between the 600 and 200 Lines (Figure 2) for all but the summer 1994 cruise (Figure 2*d*), which is missing one transect.

Along each transect, conductivity-temperature-depth (CTD) measurements were made at 20-km intervals, except on the fall cruise, where a 10-km interval was used. On all cruises, a SeaBird CTD mounted on a Bio-Optical Profiling System (BOPS) [*Smith et al.*, 1984] was used to make vertical profiles to within a few meters of the bottom or to 500 m in deeper waters. During the fall cruise, the SeaBird 911$^+$ Niskin/Rosette CTD system on the *RVIB Nathaniel B. Palmer* extended all measurements to within a few meters of the bottom.

Water samples were taken at discrete depths and analyzed for salinity with a Guildline Salinometer either onboard ship or after return to Palmer Station. During the fall cruise, cross-sensor comparisons between the BOPS and ship CTD systems ensured that the two systems provided consistent measurements. Pre- and post-cruise calibrations by SeaBird Electronics and comparison with the discrete salinity samples showed no significant drift in the temperature and conductivity sensors with time or depth. Thus, no corrections were made to the temperature and conductivity data. The hydrographic data from all cruises were processed using the procedures and algorithms given in *UNESCO* [1983]. Complete descriptions of the sensor calibrations and data processing are given in *Lascara et al.* [1993], *Smith et al.* [1993*a,b*], and *Klinck and Smith* [1994].

3. REGIONAL CHARACTERISTICS

3.1. *Continental Shelf Characteristics*

The northern boundary of the continental shelf west of the Antarctic Peninsula is formed by Bransfield Strait (Figure 1). The main connection between the west Antarctic Peninsula shelf and Bransfield Strait is through the narrow Gerlache Strait, with a maximum depth of about 700 m. To the south, the continental shelf is open toward the Bellingshausen Sea. The continental shelf is 500 m deep at the outer edge (Figure 1) with rugged bathymetry characterized by shallow plateaus, deep trenches, and considerable along-shore variability. In the mid-portion of the study area, a shallow (less than 500 m) plateau separates the shelf into northern and southern parts. To the north, the continental shelf is intersected by a deep (500 to 700 m) trench that extends seaward from Brabant and Anvers Islands. Similarly, in the southern portion of the study region, a deep trench transects the continental shelf and connects Marguerite Bay to the outer shelf.

3.2. *Sea Ice Distribution*

Sea ice formation and decay is potentially important to the thermohaline properties of this continental shelf. During summer 1993, the entire study region was essentially ice-free (Figure 2*a*), with patches of thin, melting first-year ice observed only at the inner station on the southernmost transect [*Lascara*, 1996]. From satellite-derived measurements, *Stammerjohn and Smith* [1996] characterized the sea ice cover in the study region in summer 1993 as below average for the period 1979 to 1994. However, this summer followed a winter with above-average sea ice cover [*Stammerjohn and Smith*, 1996].

In fall 1993, the region between the 600 and 200 Lines was ice free (Figure 2*b*). In August-September 1993, sea ice was encountered throughout the study region (Figure 2*c*), but the northern portion of the study region contained relatively new ice. In January-February 1994, sea ice was encountered at the southern inshore portion of the study region (Figure 2*d*).

4. THERMOHALINE DISTRIBUTIONS

4.1. *Temperature-Salinity Characteristics*

The potential temperature (θ) and salinity measurements obtained between 100 m and 500 m from the region common to all four cruises (Figure 2) were used to construct θ-S diagrams (Figure 3). Because of the considerable

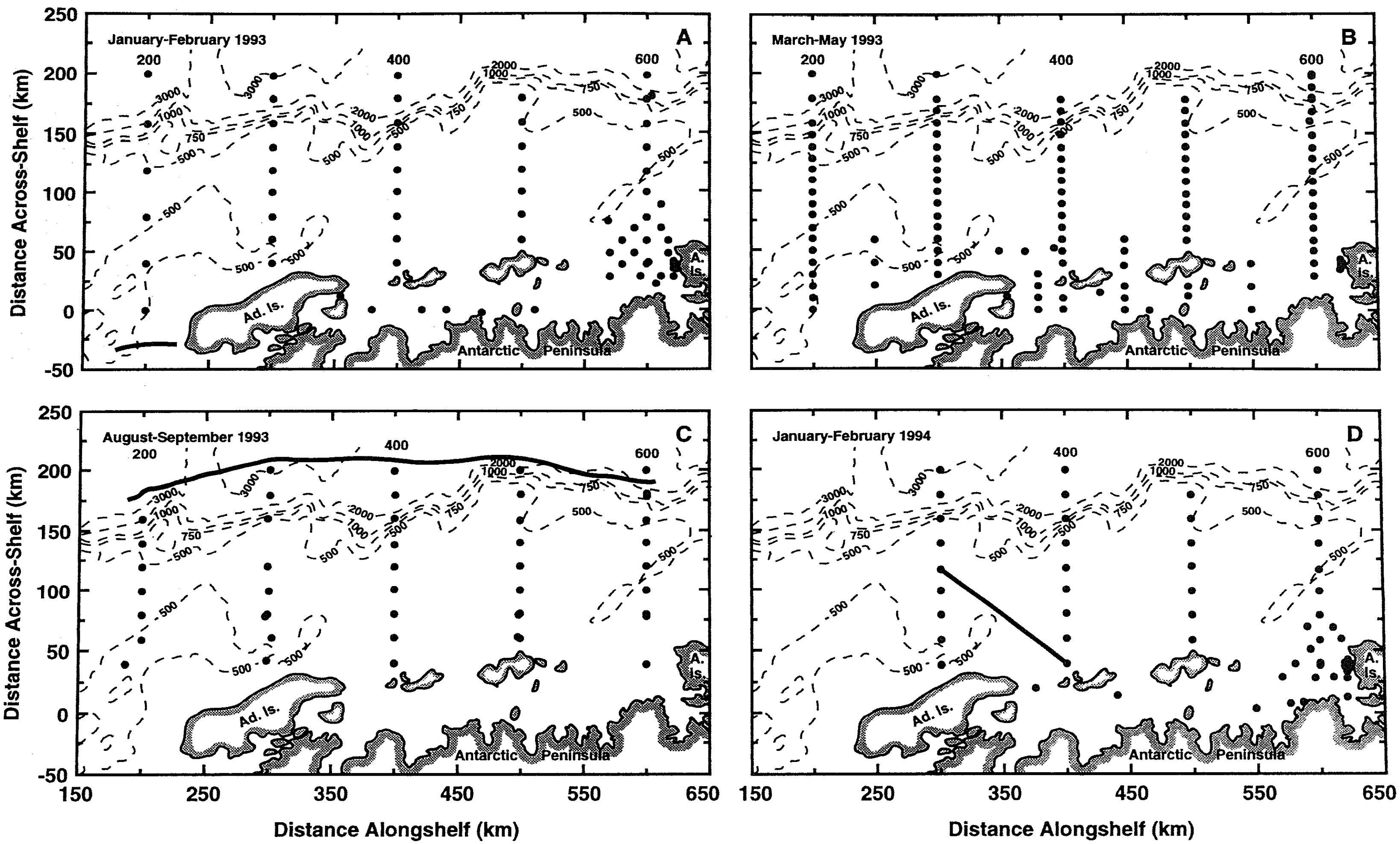

Fig. 2. Distribution of the CTD stations occupied in A) January-February 1993, B) March-May 1993, C) August-September 1993, and D) January-February 1994. The heavy lines indicate the seaward positions of the ice edge. The dashed lines are bottom bathymetry in meters.

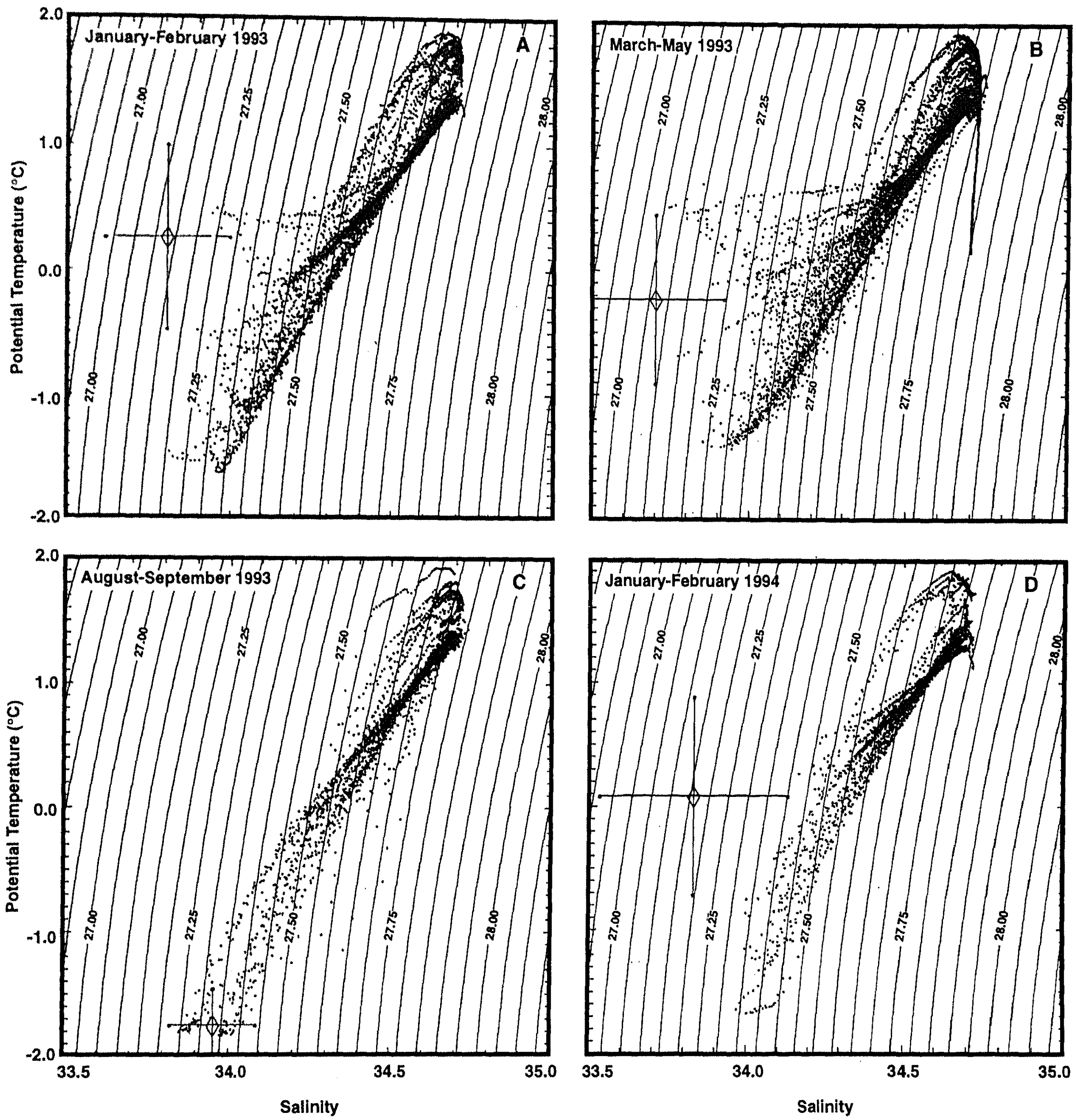

Fig. 3. Potential temperature-salinity diagrams constructed using observations above 500 m from the region common to the four cruises for A) January-February 1993, B) March-May 1993, C) August-September 1993, and D) January-February 1994. The solid lines indicate the one standard deviation values for the average temperature and salinity values (diamonds) measured above 100 m. The contours represent lines of constant σ_0.

variability of the surface waters, values above 100 m are displayed by mean and standard deviation. The largest variability in the surface water characteristics occurred in the summer (Figures 3*a,d*) and fall (Figure 3*b*). Variability in the winter was small (Figure 3*c*).

Antarctic Surface Water (AASW) is defined at its base by a temperature minimum (-1.5 to -1.8°C) at salinities of 33.9 to 34.0 (Figure 3) at σ_0 values of 27.3 to 27.4 [*Mosby*, 1934; *Gordon et al.*, 1977]. Above this base temperature and salinity, the characteristics of the AASW change over the time of the observations. During the winter, the entire upper water column was composed of near freezing (-1.8°C) water (Figure 3*c*). However, during the summer and fall, solar insolation warmed the water near the surface and isolated a core of AASW, defined by a temperature minimum of less than 0.0°C, which has been referred to as Winter Water (WW) [*Mosby*, 1934; *Sievers and Nowlin*, 1984]. The WW temperature minimum is seen in the summer (Figures 3*a,d*) and fall (Figure 3*c*), indicating that it is a persistent feature in this region.

A prominent water mass observed on all cruises is Upper Circumpolar Deep Water (UCDW), characterized by salinities between 34.6 and 34.73 and temperatures of 1.5°C to 2.0°C (Figure 3) [*Gordon*, 1967; *Reid et al.*, 1977; *Sievers and Nowlin*, 1984; *Whitworth and Nowlin*, 1987]. UCDW is found between 200 and 800 m [*Sievers and Nowlin*, 1984] and the thermohaline properties of this water mass were constant over the period of the observations. The shelf is flooded with a modified form of UCDW that is cooler (1.0-1.4°C) and less saline (34.6) relative to UCDW, which in this study is referred to as West Antarctic Peninsula modified Circumpolar Deep Water.

4.2. *Vertical Distributions*

The vertical distributions of temperature and salinity in the northern (600 Line) and southern (300 Line) portions of the study region from each cruise (Figures 4 through 7) show the across-shelf distributions of the water properties seen in the θ-S diagrams. Descriptions of these vertical sections are given below.

4.2.1. ***600 Line.*** In the summer, the WW portion of AASW is indicated by temperatures less than 0.0°C (Figure 4*a*) and salinity of 34.0 (Figure 5*a*) at about 100 m. By fall (Figure 4*b*), the WW minimum is warmer than in summer and is found only in the middle and outer shelf. In winter, the upper water column is less than -1.5°C to 80 m to 120 m (Figure 4*c*). At the outer edge of the winter section (Figure 4*c*), this layer deepens to almost 200 m. By January-February 1994, a temperature minimum layer is again present between 80 and 100 m, but only in the middle and outer shelf. The WW first mixes away in summer over the topographic feature at 40 km (Figure 4*a*) before progressively mixing farther offshore (Figure 4*b*) during the fall. In the following summer (Figure 4*d*), the erosion of WW has progressed farther than in the previous summer (Figure 4*a*).

On all cruises, warm (>1.5°C) and saline (34.7) UCDW was observed at the outermost stations below 200-250 m (Figure 4). However, the vertical structure of the thermohaline properties at the outer end of the transect varies between the cruises. In summer and fall of 1993 (Figures 4*a,b*) the 1.8°C isotherm, which coincides with the core of UCDW and hence reflects the southern region of the ACC [*Orsi et al.*, 1995], was encountered at the outer edge of the transect. In the winter 1993, the presence of UCDW is reduced relative to the other times and the downward sloping temperature and salinity isopleths (Figures 4*c* and 5*c*) suggest that the southern ACC boundary is located off the shelf edge. By summer 1994 (Figures 4*d* and 5*d*), UCDW is again present but only at the outermost station on the transect, suggesting that the ACC is seaward of the shelf edge relative to its position the previous summer.

Over the continental shelf, the modified form of UCDW occurred below 200 m and extended across the shelf to the innermost station, as indicated by temperatures greater than 1.0°C and salinities greater than 34.6 (Figures 4 and 5). The 1.5°C isotherm, which is a good indicator of the boundary between UCDW and the cooler shelf water, shows that there was an intrusion of oceanic water in fall (Figure 3*b*) which is clearly absent a few months before and after (Figures 3*a* and 3*c*). Water warmer than 1.5°C was at or offshore of the shelf break in all other cruises. Given that the thermohaline structure of the modified UCDW differed from cruise-to-cruise, the deeper waters on the shelf change on a time scale no longer than the interval between the observations.

4.2.2. ***300 Line.*** In the southern study region in summer 1993, WW extended across the shelf and was centered around 100 m (Figures 6*a* and 7*a*). By fall, the WW layer had warmed (Figure 6*b*), with the largest mixing occurring over the topographic high around 50 km. By winter (Figure 6*c*), the upper water column was near freezing (-1.8°C) to depths exceeding 100 m. The following summer (Figures 6*d* and 7*d*), the thermohaline properties of the upper 100 m were similar to those observed the previous year (Figures 6*a* and 7*a*). However, in January-February 1994, the water at the surface was not as warm or as saline as observed in 1993 (Figures 6*d* and 7*d* versus 6*a* and 7*a*) and the WW layer was colder in 1994. This change in temperature-salinity properties of the surface waters was not unique to the 300 Line. The θ-S diagram (Figure 3) shows that the average properties of the upper 100 m computed from all measurements were cooler and fresher in January-February 1994 than in January-February 1993. Such a pattern is consistent with the colder 1993 winter and the later break-up of ice over the west Antarctic Peninsula shelf in 1994.

UCDW was found at the outer portion of the 300 Line below 200 m on all cruises (Figures 6 and 7). On three of the cruises, temperatures approaching 2.0°C were encountered at the offshore end of the section (Figures 6*b,c,d*), indicating that the core of UCDW and the southern boundary of the ACC [*Orsi et al.*, 1995] were situated along the outer shelf. Below 200 m, the middle to inner shelf was composed of the modified form of UCDW (T<1.5°C) while the outer shelf was UCDW (>1.5°C). In August 1993 (Figure 6*c*), the offshore temperatures were

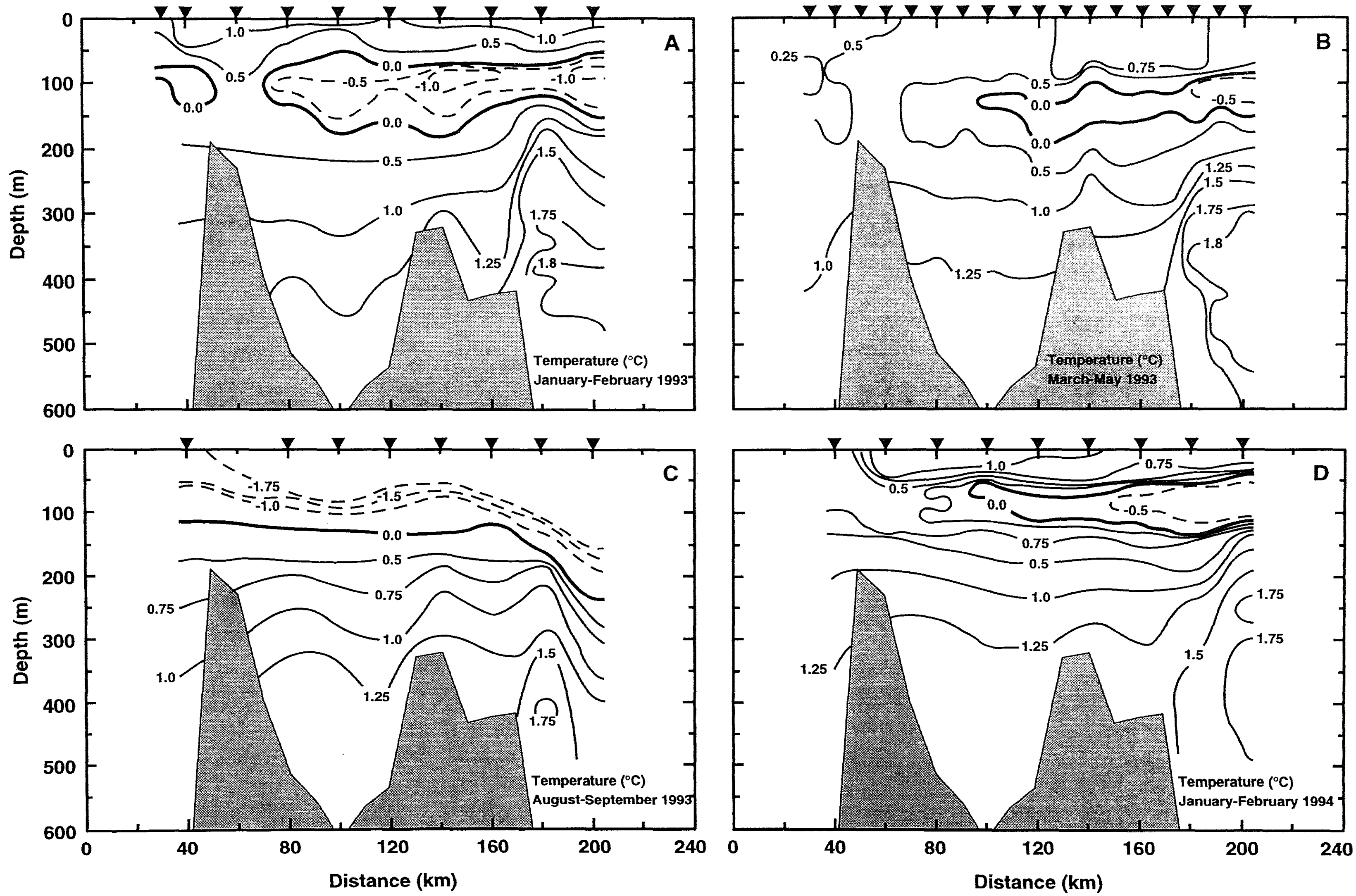

Fig. 4. Vertical sections of temperature along the 600 Line constructed from CTD measurements for A) January-February 1993, B) March-May 1993, C) August-September 1993, and D) January-February 1994. Station location is indicated by the triangles. Dashed lines indicate negative temperatures; solid lines are positive temperatures.

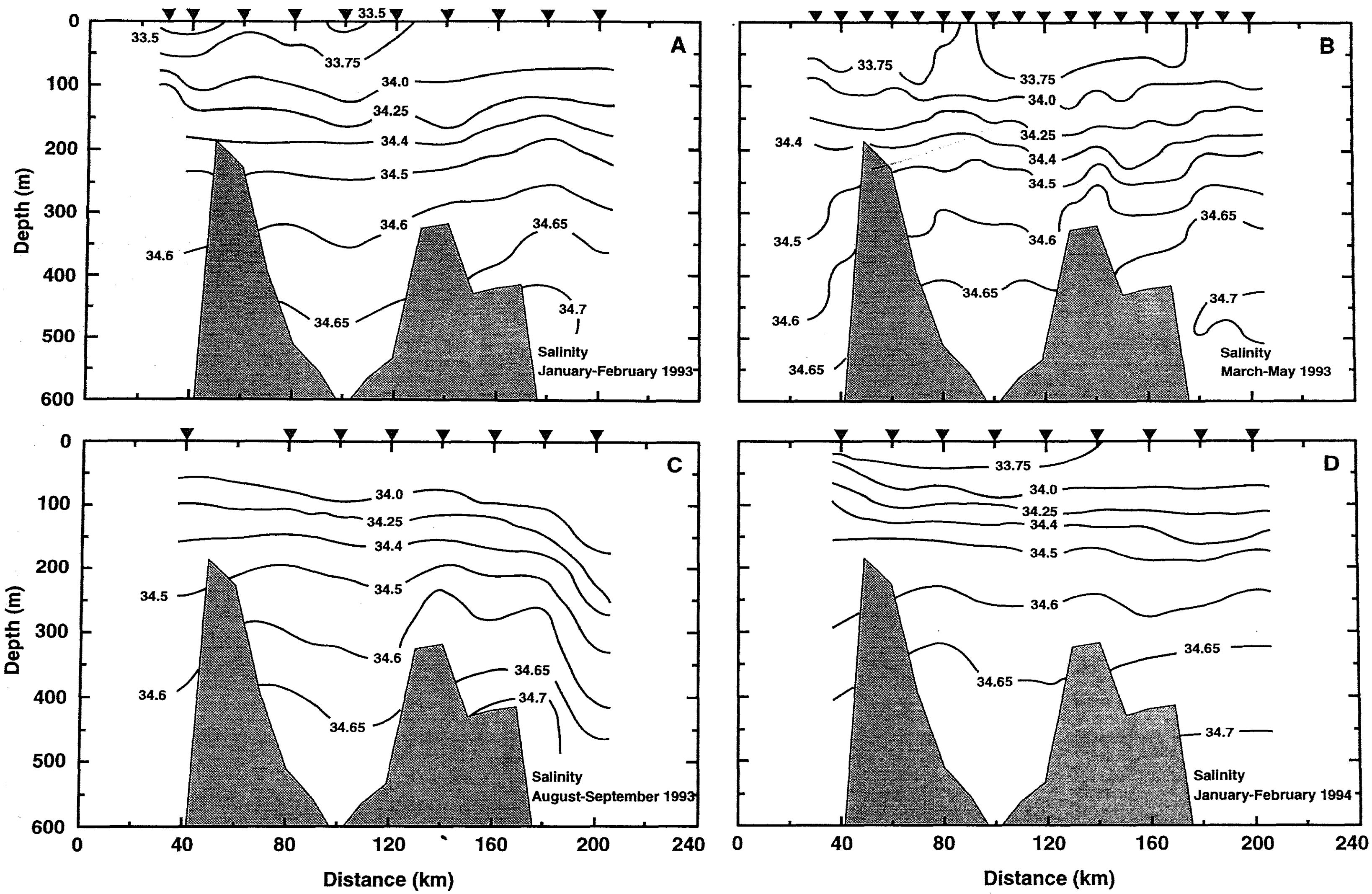

Fig. 5. Vertical sections of salinity along the 600 Line from A) January-February 1993, B) March-May 1993, C) August-September 1993, and D) January-February 1994. Station location is indicated by the triangles.

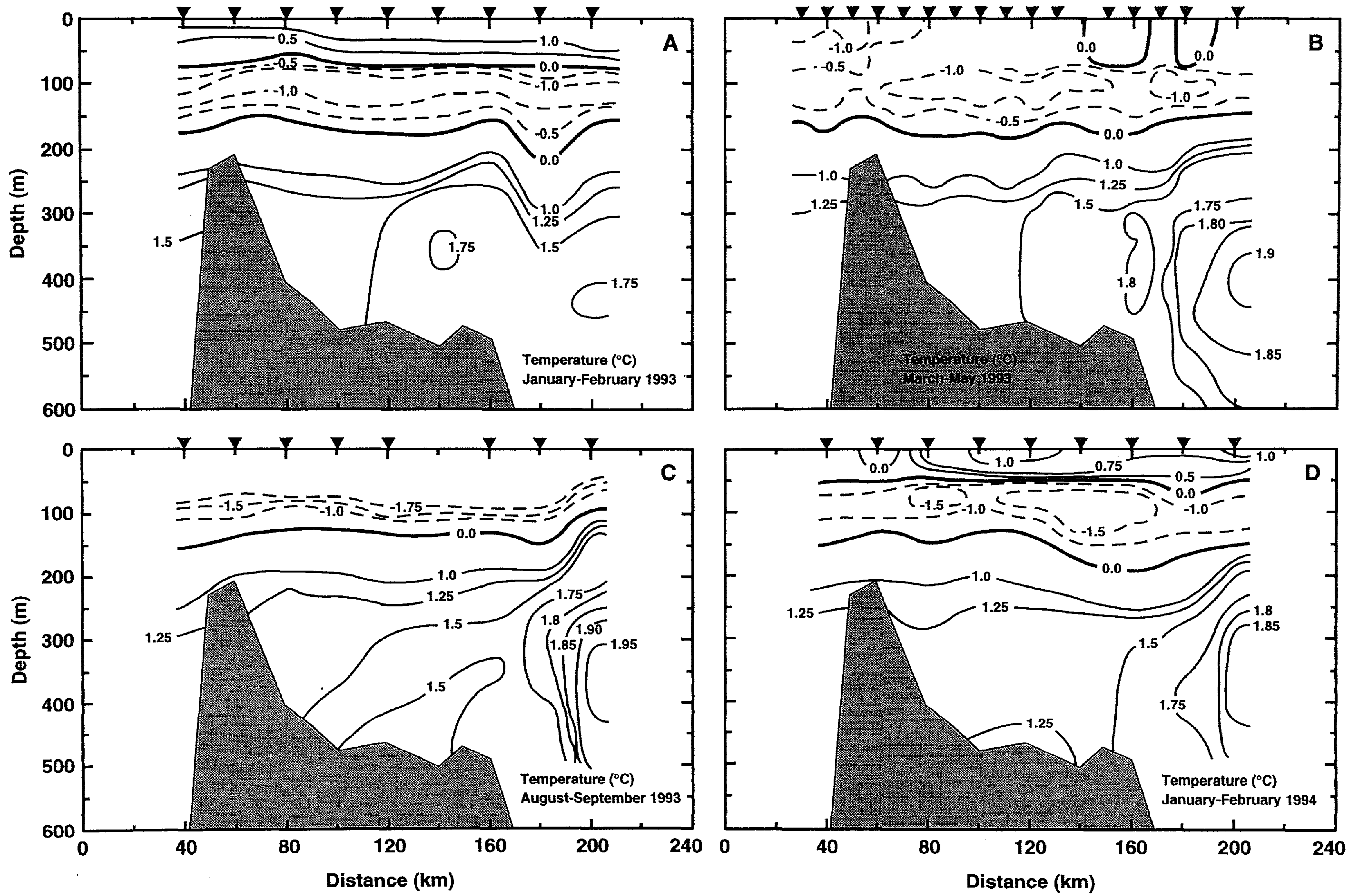

Fig. 6. Vertical sections of temperature along the 300 Line from A) January-February 1993, B) March-May 1993, C) August-September 1993, and D) January-February 1994. Station location is indicated by the triangles. Dashed lines indicate negative temperatures; solid lines are positive temperatures.

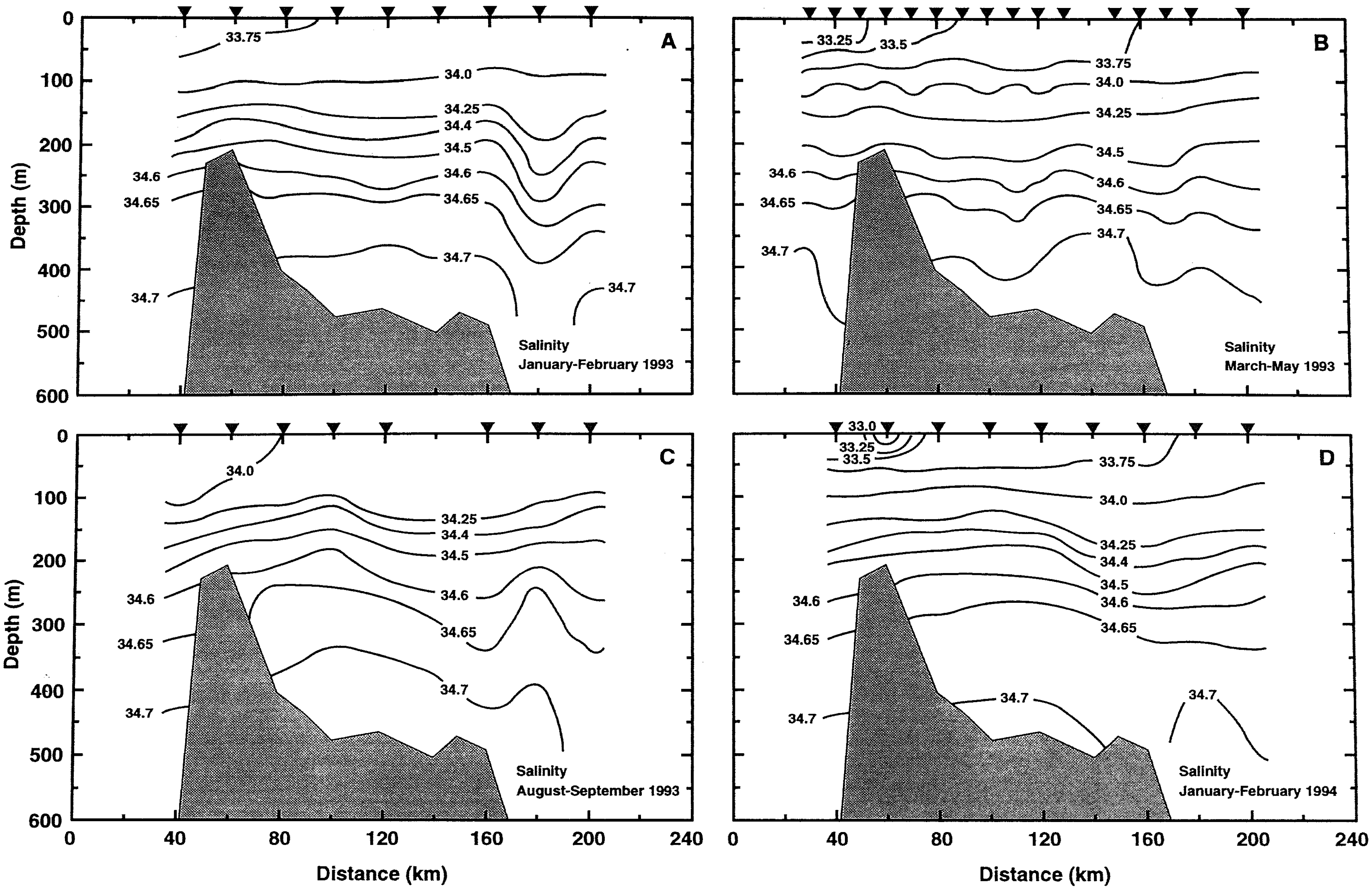

Fig. 7. Vertical sections of salinity along the 300 Line from A) January-February 1993, B) March-May 1993, C) August-September 1993, and D) January-February 1994. Station location is indicated by the triangles.

the warmest (approaching 2.0°C), indicating that the ACC was pressed against the continental slope. The vertical structure of the UCDW varied over the time of the cruises with the largest change occuring between January-February 1993 (Figure 6*a*) and January-February 1994 (Figure 6*d*). This indicates that the deeper shelf waters were modified at a time scale of a few months.

4.3. *Temperature Maximum Distribution*

The distribution of the temperature maximum below 250 m from the 1993 summer cruise (Figure 8*a*) shows that water warmer than 1.5°C extended onshore in a band between the 200 and 400 Lines. In the northern portion of the study region, water warmer than 1.5°C was found only at the outer end of the 600 Line. The 1.6°C isotherm marks the southern boundary of the ACC, which is located at the outer ends of the 200, 400 and 600 Lines. The 1.5°C isotherm, which approximates the seaward boundary of the modified UCDW, indicates that this water mass covered most of the continental shelf northeast of the 400 Line, the inner portion of 400 Line, and the middle and inner shelf at the southern end of the study region. The water temperatures on the inner shelf were cooler to the north compared to the south by about 0.2°C. The coolest temperatures were found in the vicinity of Anvers Island and coincide with the shallow seamount on the inner part of the 600 Line (Figure 4). This reflects the effect of localized mixing of the cooler WW with surface waters on the larger scale temperature maximum distribution.

By the fall, only about six weeks later, the distribution of the temperature maximum below 250 m had shifted such that the isotherms were oriented primarily alongshore (Figure 8*b*). The southern boundary of the ACC (1.6°C) was located at the outer end of the 200, 300, 400 and 600 Lines. Temperatures greater than 1.5°C were found along the outer continental shelf region over most of the region. The modified version of UCDW covered the entire shelf region inshore of the 1.5°C isotherm below 250 m. Temperatures greater than 1.0°C were also found along the innermost portion of the study region.

The temperature maximum distribution in the winter of 1993 (Figure 8*c*) showed UCDW extending onshore at the 200 Line with an orientation that is similar to the previous summer, although reduced in extent. Water warmer than 1.5°C extended to the mid-shelf region. A smaller band of UCDW was observed extending onshelf at the 600 Line. The 1.6°C isotherm shows that the southern boundary of the ACC is located along the outer shelf. The orientation of the 1.4°C isotherm is similar to that observed in the fall, oriented from offshore to inshore from the 200 to 600 Lines. Water over the inner shelf was warmer than during the fall cruise.

In summer 1994, UCDW extended onshore from the 600 Line to mid-shelf. Along the 300 and 400 Lines, the southern boundary of the ACC was present and UCDW was present at the the outer portions of the transects. The 1.4°C isotherm indicated that modified UCDW was present over most of the shelf and water with temperatures of 1.3°C was found on the inner shelf.

5. DISCUSSION AND SUMMARY

5.1. *Thermohaline Variability*

These temperature and salinity observations from the west Antarctic Peninsula continental shelf are the first to document variability in AASW and WW through successive measurements made in the same year. These show that the thermohaline properties of water above the permanent pycnocline (at about 150 m) undergo a seasonal pattern of changes driven by exchange with the atmosphere, changes in solar heating, and the formation and melting of sea ice. The surface mixed layer in winter is composed of near freezing water to about 100 m (Figures 4*c* and 6*c*) which is capped in the summer by a warm layer 30 to 50 m thick (Figures 4*a,d* and 6*a,d*). The core of WW undergoes gradual erosion over the summer and fall by gaining heat from warmer water both above and below this layer. The offshore to inshore gradients, especially in salinity, argue against AASW formation offshore and then advection onto the shelf, although similar erosion of AASW does occur offshore. It is more likely that AASW is locally produced on the shelf by vertical fluxes.

Two minor variations in the above pattern of water property changes are evident in the observations. First, there is an indication that the WW layer mixes more rapidly in water shallower than 300 m. There is a localized disappearance of WW at the inner portion (at about 40 km) of the 600 Line and a similar, but less intense, warming of WW at the inner part of the 300 Line, at about 50 km. Second, the temperature of WW is warmest at the coast and becomes cooler offshore. This pattern may be due to increased mixing in the nearshore region, stronger winds (and deeper mixing) along the coast due to topographic steering or a decreased cooling in winter near shore due to more complete ice cover during the winter.

The water mass structure below 150 m is composed of UCDW and a modified (cooled) form of UCDW (Figure 3). The relatively shallow depth of UCDW at the shelf edge (Figures 4 and 6), coupled with the deep continental shelf, produces a deep water mass structure over the shelf that is essentially oceanic in origin. This differs from mid-latitude continental shelves where the bottom shelf waters are typically a mixture of locally derived waters. Once on the shelf, UCDW mixes with WW to form a

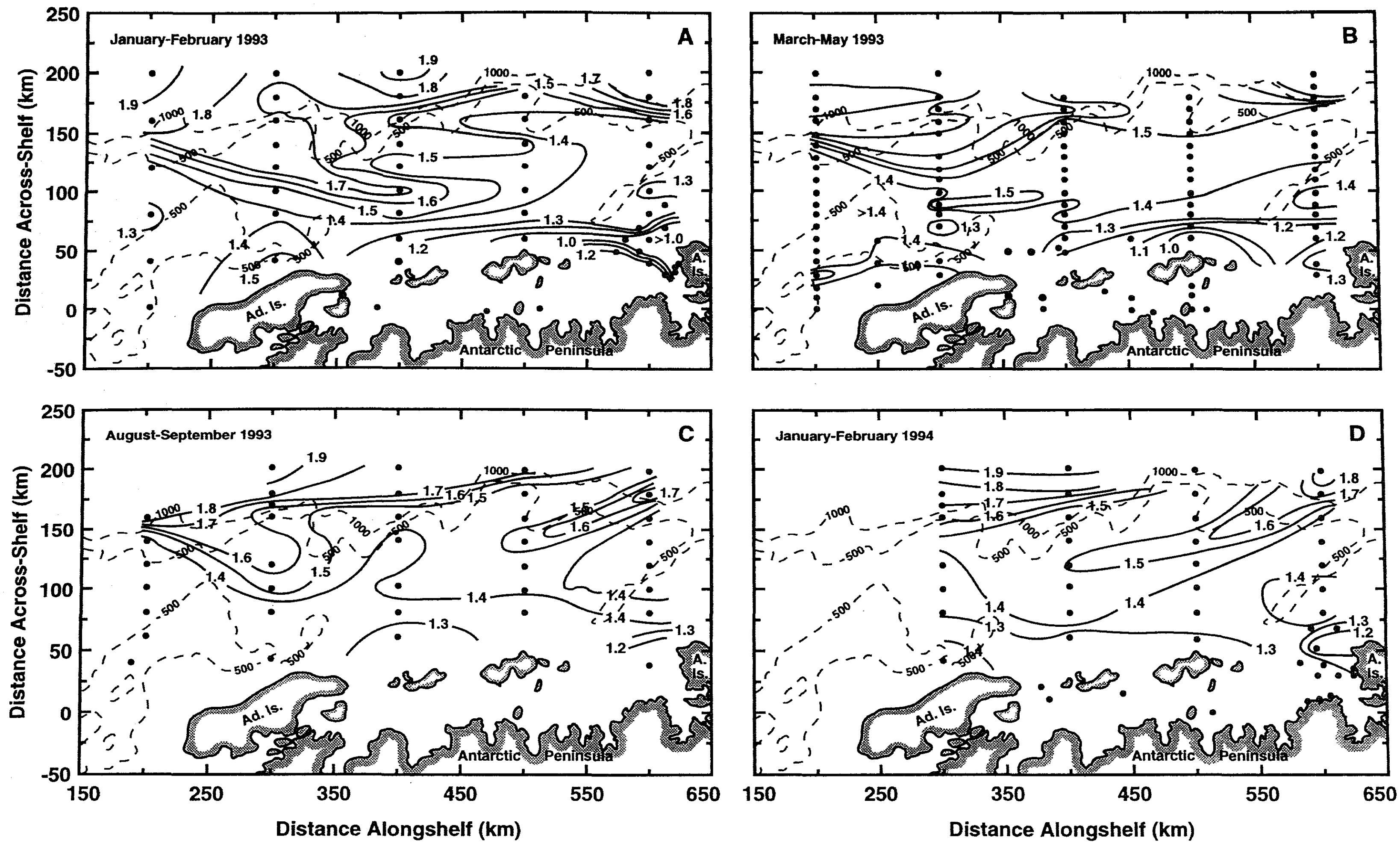

Fig. 8. Distribution of the temperature maximum below 250 m constructed from temperature measurements made in A) January-February 1993, B) March-May 1993, C) August-September 1993, and D) January-February 1994. Station distribution is indicated by the dots. Dashed lines are bottom bathymetry in meters.

modified version of CDW which is found over the shelf below 200 m (cf. Figures 4 through 8), extends well inshore of the shelf break, and is found in the nearshore regions inside the 200-m isobath [*Smith et al.*, 1998].

The presence of oceanic water at depth and WW near the surface creates a permanent pycnocline that is evident in the θ-S (Figure 3) observations. There are no observations in these data that indicate that the surface waters, which reach freezing temperatures in winter, become salty enough to breach this pycnocline and create dense shelf water. The exact reason for this failure to create dense shelf water is not known, but it is likely related to the relatively mild conditions over this shelf (no katabatic winds from the continent) and the near balance between sea ice formation and melting (surface salinity remains below 34.0).

Water near the coast is colder and fresher than that in the middle of the shelf (Figures 4 through 7). It would be tempting to attribute this to runoff from landfast ice, but these differences extend below 300 m and thus could not be created by ice melt near the surface. The more likely explanation is that colder and fresher water from Bransfield Strait enters this region through Gerlache Strait, where the Coriolis deflection causes it to flow southwestward along the coast. Mixing of water from Bransfield Strait with that near the coast can produce the observed temperature and salinity properties [*Smith et al.*, 1998].

5.2. *UCDW Intrusions*

The intrusion of UCDW onto the west Antarctic Peninsula continental shelf was consistently observed near the 200, 300 and 600 Lines (Figure 8). These are regions where the outer shelf bathymetry is variable and where across-shelf trenches intersect the shelf break (Figure 2). The region offshore of the 200 and 300 Lines shows the largest onshore intrusion of UCDW. *Domack et al.* [1992] also noted onshore movement of UCDW at this location and suggested that it was related to local bathymetry. Assuming topographic effects as the underlying cause, two potential mechanisms, exchange through submarine canyons driven by alongshore flow and ACC meanders created by variations in the location of the shelf break, may account for the movement of UCDW onto the west Antarctic Peninsula shelf.

Submarine canyons are known to be important in the exchange and flushing of mid-latitude continental shelves [*Freeland and Denman*, 1982; *Noble and Butman*, 1989; *Klinck*, 1996]. Although the deep depressions on the Antarctic continental shelf are not strictly submarine canyons, they could function in a similar manner and provide conduits for moving UCDW onto the west Antarctic Peninsula continental shelf.

However, the presence of a deep trench is not sufficient to provide onshore movement of UCDW. The second part of the onshore movement of UCDW is the the proximity of the southern boundary of the ACC to the shelf edge. In the Southern Hemisphere, looking in the direction of the flow, the higher pressure will be to the left of the current. Along the west Antarctic Peninsula shelf the ACC flows from west to east, which will produce a pressure gradient that slopes upward offshore. Recent modeling studies [*Klinck*, 1996] show that this type of pressure gradient will force upcanyon flow. Therefore, the combination of across-shelf canyons and onshore movement of the ACC are needed to push water onto the west Antarctic Peninsula continental shelf. This mechanism could explain the episodic nature of the appearance of UCDW at the outer shelf edge and the corresponding variability in the distribution of the modified UCDW over the continental shelf. Also, the ACC location, as determined by the 1.6°C isotherm, at one section was not correlated with its location along the entire extent of the outer study region. This suggests that variability in the location of the ACC along the outer shelf does not occur as a large-scale shift in position, but rather as local meanders.

Movement of the ACC relative to the shelf break and subsequent movement of UCDW onto the west Antarctic Peninsula continental shelf is similar to that observed on other continental shelves bordered by intense boundary currents. For example, meandering of the Gulf Stream and the East Australian Current is known to force water exchanges across the the southeastern U.S. continental shelf [see review in *Atkinson et al.*, 1985] and east Australian shelf [*Andrews and Gentien*, 1982], respectively. Moreover, *Atkinson* [1977] suggested that the frequency of exchanges on the southeastern U.S. shelf is related to the seasonal and interannual variability in the location of the Gulf Stream relative to the shelf break.

The ACC in Drake Passage is known to shift its location during the year [*Hofmann and Whitworth*, 1985] and perhaps over longer time scales [*Klinck and Smith*, 1993]. Thus, changes in the location and strength of the ACC may have pronounced effects on the residence times and flushing of the subpycnocline waters on the west Antarctic Peninsula continental shelf. The subpycnocline waters mix with WW resulting in a large flux of heat and salt through this region [*Klinck*, 1998; *Smith et al.*, 1998], which may be modified by changes in the ACC. Thus, the thermohaline properties of the west Antarctic Peninsula continental shelf may be determined by remote forcing from a large-scale oceanic current. Along the full circumpolar extent of the ACC, its southern-most boundary is closest to the shelf break along the west Antarctic Peninsula shelf [*Orsi et al.*, 1995; *Kim*, 1995; *Whitworth et al.*, this volume]. This portion of the Antarctic continental shelf may therefore be more affected by variations in the ACC than by local oceanic or atmospheric processes.

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