DEEP-SEA RESEARCH
PART II

Deep-Sea Research II 51 (2004) 1925–1946

www.elsevier.com/locate/dsr2

Water-mass properties and circulation on the west Antarctic Peninsula Continental Shelf in Austral Fall and Winter 2001

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Accepted 13 July 2004

Abstract

Hydrographic measurements made during the US Southern Ocean Global Ocean Ecosystem Dynamics cruises, which took place from April to June and July to September 2001, provide a description of changes in water-mass distributions and circulation patterns in the Marguerite Bay region of the west Antarctic Peninsula continental shelf that result from seasonal variability and offshore forcing by the southern boundary of the Antarctic Circumpolar Current (ACC). The primary seasonal change in water-mass properties is the reduction in Antarctic Surface Water and replacement by a thick Winter Water layer. The primary effect of the ACC is to pump warm ($>1.5\,^{\circ}$C), salty (34.65–34.7), and nutrient-rich Circumpolar Deep Water (CDW) onto the continental shelf below 200 m at specific sites that correspond to bathymetric features, such as Marguerite Trough. The CDW intruded onto the continental shelf, moved across shelf, and entered Marguerite Bay. This flow pattern was observed during both cruises, suggesting that onshelf intrusions of CDW are a regular occurrence on this shelf. The number of CDW intrusions observed suggests that 4–6 events can occur in a year. Regions where CDW intrusions occur are characterized by surface waters that are above freezing in winter. Diffusive heat fluxes based on estimated diffusivities are insufficient for the observed rate of temperature decay of CDW intrusions. Localized, bathymetrically controlled vertical mixing is suggested as the primary heat transfer mechanism. The hydrographic and Acoustic Doppler Current Profiler measurements show a southwesterly flowing coastal current along Adelaide Island that enters the north side of Marguerite Bay and exits around Alexander Island. This current, which may result from seasonal, coastal buoyancy forcing, was present in fall and winter, but was better developed in fall. This current may be part of a larger cyclonic gyre that overlies the northern part of the area surveyed during the two cruises.

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0967-0645/$ - see front matter
doi:10.1016/j.dsr2.2004.08.001

1. Introduction

The hydrographic structure of the water overlying the central western Antarctic Peninsula (WAP) continental shelf (Fig. 1) results primarily from forcing at the air-sea boundary and at the outer continental margin. Sea-ice cover in this region melts completely during the austral summer (Stammerjohn and Smith, 1996), leaving the shelf waters exposed to atmospheric forcing. Air-sea exchange contributes to the large seasonal variations in the thermohaline properties in Antarctic Surface Water (AASW) in the upper 100–120 m overlying the continental shelf (Hofmann et al., 1996; Smith et al., 1999). This water mass is replaced in the austral fall and winter by near-freezing Winter Water (WW). Beneath the AASW and WW is warmer ($\theta > 1\,^{\circ}$C) and saltier ($S > 34.64$) water that covers the shelf below the permanent pycnocline at 150–200 m (Smith et al., 1999). This deep water mass derives from Circumpolar Deep Water (CDW), which is present at the outer edge of the WAP continental shelf at depths of 200–600 m (Hofmann and Klinck, 1998a; Smith et al., 1999).

The WAP outer continental shelf break and slope has no Antarctic Slope Front (Whitworth et al., 1998; Smith et al., 1999) associated with sharp horizontal gradients in temperature, salinity, and density (Jacobs, 1991), which is typical of the shelf break in other parts of the Antarctic. Thus, there is no dynamic barrier to block flow of CDW from the deep ocean onto the continental shelf (Talbot, 1988). Consequently, the outer WAP shelf region is directly affected by the northeastward flowing Antarctic Circumpolar Current (ACC), with its southern boundary located on the upper continental slope along the 750–1000 m isobath (Hofmann and Klinck, 1998a).

The presence of the southern boundary of the ACC along the outer WAP continental shelf produces subsurface, onshelf intrusions of CDW (Hofmann and Klinck, 1998a; Dinniman and Klinck, 2004), which in turn affects the thermohaline properties of the subpycnocline waters (Klinck, 1998; Smith et al., 1999), nutrient and phytoplankton distributions (Prézelin et al., 2000, 2004), and sea-ice concentration (Smith and

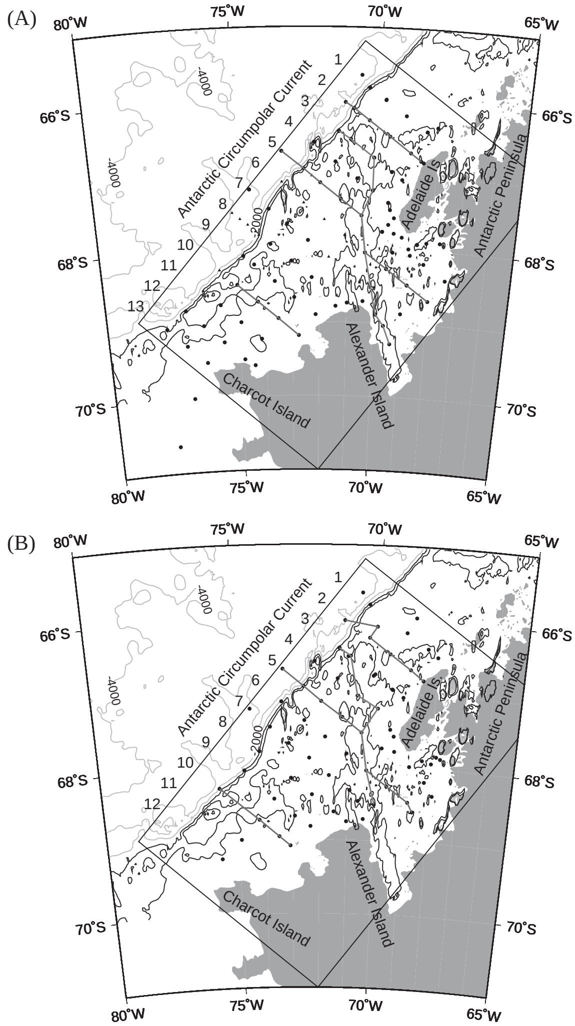

Fig. 1. Map of study area showing the location of the hydrographic (circles) stations occupied during the (A) April–May 2001 and (B) July–August 2001 cruises. The across-shelf transects are numbered from north to south and the lines indicate the sampling locations used to construct the across-shelf vertical hydrographic distributions described in the text. Geographic locations are identified and bottom bathymetry contours are 500, 1000, 2000, 3000 and 4000 m. Marguerite Bay is the indentation in the Antarctic Peninsula coastline between Adelaide and Alexander Islands. The large box is the domain used in Figs. 7–10.

Klinck, 2002) of the shelf waters. The subsurface CDW intrusions tend to occur at preferred sites along the WAP shelf that are associated with bathymetric variations (Hofmann and Klinck, 1998a; Dinniman and Klinck, 2004). In addition, shelf-scale cyclonic gyres, with length scales of 200–400 km alongshelf and 100–150 km across-shelf, have been observed on the WAP continental shelf (Stein, 1992; Smith et al., 1999).

This study uses extensive hydrographic and direct velocity measurements obtained from two cruises in the austral fall (April–May) and winter (July–August) of 2001, which were part of the US Southern Ocean Global Ocean Ecosystems Dynamics (SO GLOBEC) field program (Hofmann et al., 2002), to extend the description of the water-mass properties and circulation of WAP continental shelf. These measurements covered the southwestern portion of the WAP shelf in the region of Marguerite Bay and extended north and south of Adelaide and Alexander Islands, respectively (Fig. 1). The large spatial scale and repeated measurements allow descriptions of changes in water mass distributions, estimation of the frequency and duration of CDW intrusions, and a description of variability of the shelf-wide circulation. These data also represent the first high-resolution and coincident hydrographic and current measurements for this region.

The following section provides a description of the hydrographic and Acoustic Doppler Current Profiler (ADCP) velocity measurements used in this study. This is followed by analyses and descriptions of these data and a discussion and summary of the effect of CDW intrusions on the heat budget of this region and the circulation of the WAP continental shelf.

2. Data sources and methods

2.1. Hydrographic data distribution

The hydrographic data used in this analysis were collected during two cruises aboard the United States icebreaker RVIB *Nathaniel B. Palmer*. The stations occupied during the austral fall cruise (Fig. 1A) provide coverage of the continental shelf to the north and south of Marguerite Bay. Those occupied during the austral winter cruise (Fig. 1B) covered essentially the same area, but with fewer stations in the southern part of the study region and within Marguerite Bay. For both cruises, the individual stations, with spacing ranging from 10 to 40 km, were aligned in across-shelf transects with 40-km spacing that ran perpendicular to a baseline situated along the coast (Fig. 1).

The April–May survey grid consisted of thirteen across-shelf transects and 81 stations (Fig. 1A, Table 1). Thirteen of the originally planned stations in the central portion of the survey region were not occupied because of weather conditions. The outer-most stations on some southern transects were not occupied because of time constraints; instead, eXpendable Conductivity-Temperature-Depth (XCTD) probes were used (Table 1). The stations were occupied from north to south, starting with the outer-most station on survey transect 1.

On the July–August cruise, only 69 of the planned survey stations were occupied either because of time constraints or sea ice conditions (Fig. 1B, Table 1). The stations that were occupied coincided with the April–May station locations, and the winter survey also was run from north to south. No XCTDs were used on this cruise.

2.2. Hydrographic data collection

The hydrographic measurements were collected using a SeaBird 911+ Niskin/Rosette conductivity-temperature-depth (CTD) sensor system, which included dual sensors for temperature and conductivity. Other sensors mounted on the CTD-Rosette system measured dissolved oxygen concentration, transmission, fluorescence, and photosynthetically active radiation. The 24-place Rosette was equipped with 10-L Niskin bottles, and water samples were taken at the surface and bottom, above, within and below the oxygen-minimum layer that characterizes CDW, throughout the subpycnocline waters, and at a series of standard depths between 100 m and the surface. All hydrographic casts were done to within 5–20 m of the bottom, depending on weather and sea-state conditions. The CTD measurements were processed using the procedures and algorithms given in UNESCO (1983).

On each CTD cast, water samples were taken at several depths for salinity determinations to

Table 1
Summary of the hydrographic stations occupied during the 2001 austral fall and winter Southern Ocean GLOBEC cruises

Cruise	Dates	Sampling time	CTD stations	XCTD stations
April–May	24 April–5 June	29 April–2 June	81	16
July–August	24 July–31 August	27 July–25 August	69	0

Table 2
Summary of the differences in the salinity (S) values obtained from the primary (0) and secondary (1) CTD conductivity sensors and differences between the CTD sensor values and those measured from bottle salinity (Sb) samples for the April–May and July–August 2001 Southern Ocean GLOBEC cruises

Cruise	S0-S1 (psu)	S0-Sb (psu)	S1-Sb (psu)	T0-T1 (°C)
April–May	-0.009 ± 0.0047 (413)	-0.0002 ± 0.0053 (388)	-0.0007 ± 0.0053 (390)	0.0013 ± 0.0047 (399)
July–August	-0.00354 ± 0.106 (334)	0.0034 ± 0.0058 (296)	0.00272 ± 0.0053 (294)	0.00082 ± 0.0106 (339)

The difference in the primary (0) and secondary (1) CTD temperature (T) sensors is also given. The number of samples on which the differences are based is shown in parentheses.

provide calibration of the conductivity sensors on the CTD. The conductivities of the discrete salinity samples were measured during the cruise, usually within 72 h of collection, using a Guildline AutoSal 8400B Number 2 laboratory salinometer and converted to salinity. The primary and secondary CTD conductivity sensors were compared for internal consistency, and the salinity values computed using the sensors were then compared with the bottle salinities (Table 2). Details of the salinity calibrations for the fall and winter cruises are given in US SO GLOBEC Report Number 2 (2001) and US SO GLOBEC Report Number 3 (2001), respectively.

2.3. Acoustic Doppler current profiler data

The RDI 150 kHz Acoustic Doppler Current Profiler (ADCP) system mounted in the hull of the RVIB *Nathaniel B. Palmer* was configured to acquire velocity measurements with an 8-m pulse length, in fifty 8-m depth bins using five-minute ensemble averages. This configuration provided velocity measurements from the first bin, at 31 m, to 300 m and sometimes 350 m. Depth bins 4–12 were used as the reference layer. Data collection started once the ship was past the 200-mile limit of the Argentine Exclusive Economic Zone (Table 1) and continued until this boundary was again reached at the end of the cruise.

For most of the cruise, the ADCP was run in bottom tracking mode as the water was less than 500 m deep (Fig. 1). Bottom tracking was disabled when the ship was in water deeper than 500 m for more than a few hours. While the ship moved through sea ice, the ADCP was unable to receive sufficient samples to generate proper statistics. During these times, accurate current measurements were made only while the ship was stationary or moving slowly. Such conditions occurred only during the winter cruise. Storms during the fall cruise interfered with accurate ADCP measurements.

Preliminary processing of the ADCP data was done during the cruise using an automated version of the Common Oceanographic Data Access System (CODAS) developed by Firing and Hummon from the University of Hawaii. Following the cruises, final processing and quality control of the ADCP data was performed by Hummon. The data were calibrated and edited using CODAS. Heading corrections were made using data collected by the Ashtech ADU-2 GPS system onboard the RVIB *Nathaniel B. Palmer*.

3. Results

3.1. Water mass structure

The potential temperature-salinity (θ-S) diagram constructed from the April–May CTD and XCTD observations (Fig. 2A) shows AASW with temperatures of −1.5–1.0 °C and salinities of 33.0–33.7 at σ_θ values less than 27.4. The large scatter in AASW properties reflects the temporal changes in near-surface water due to seasonal heating and cooling during the summer and fall.

The temperature minimum at −1.6 to −1.7 °C at a salinity of 34.1 was associated with the remnant WW produced during the previous winter, which had undergone mixing with AASW and subpycnocline waters (Fig. 2A). By the austral winter, WW with temperatures less than −1.8 °C at a salinity of 34.1 was formed by local cooling. The AASW layer was greatly reduced and this water was on or near the freezing line (Fig. 2B), indicating that the upper waters were in the winter state throughout the July–August cruise. However, the large variability in salinity seen in the AASW indicates that the salt increase due to sea-ice freezing was not yet complete and that not all of the upper water-column water had been converted to WW.

Water with temperatures of 1.0–2.0 °C and salinities of 34.6–34.74 represents CDW, which is composed of two varieties: Upper and Lower CDW. The Upper CDW (UCDW) is characterized by a temperature maximum at a potential density of 27.72. Lower CDW (LCDW) is characterized by a salinity maximum of 34.74 at a potential density of 27.8. These water masses were present off the shelf in the fall and winter (Figs. 2A, B) and showed little variability between the two seasons.

A water mass that is intermediate between AASW and CDW, characterized by temperatures of 1.0–1.5 °C and salinities of 34.3–34.6, was observed during these cruises (Figs. 2A, B). This water is a mixture of UCDW and AASW (Klinck, 1998; Smith et al., 1999; Smith and Klinck, 2002), which forms a cooler and less saline water mass, which has been referred to as modified CDW water (Hofmann and Klinck, 1998b).

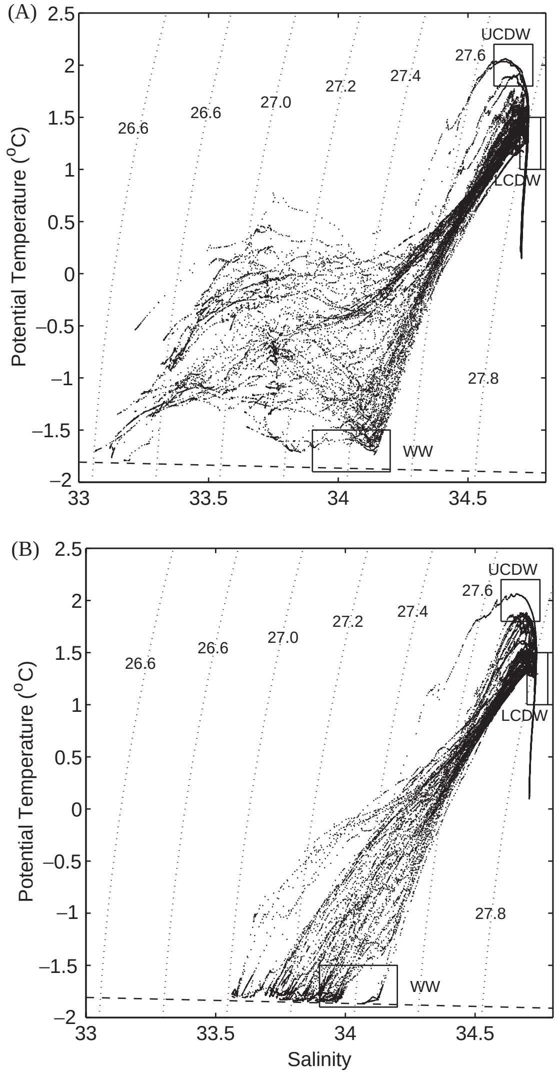

Fig. 2. Potential temperature-salinity diagram constructed from (A) April–May 2001 and (B) July–August 2001 hydrographic observations. The temperature and salinity ranges that characterize UCDW, LCDW and WW water masses are shown by the boxes. The potential density at the surface for the indicated temperature and salinity is indicated by the dotted lines. The freezing point of seawater is indicated by the dashed line.

An additional water type, seen in the fall, is characterized by temperatures of −1.7–−1.8 °C and salinities of 33.1–33.2 (Fig. 2A). This water was observed at the surface in the CTD casts from inshore waters near the ice shelves on Adelaide

Island in the northern part of the study region (Fig. 1).

3.2. Hydrographic observations

3.2.1. Vertical structure

The vertical distributions of potential temperature, salinity, and potential density along across-shelf transects from different parts of the study region provide a description of the water-mass structure and changes in this structure between the two survey periods. These sections illustrate specific features of the WAP continental shelf thermohaline distributions and the extent of the onshelf flow of oceanic waters.

The vertical temperature distribution along line 2 in the northern part of the study region (Fig. 1) during April–May 2001 (Fig. 3A) showed a maximum of 1.8 °C centered at 300 m at the outer edge of the continental shelf. This water has a salinity of 34.7–34.72 (Fig. 3C) indicating that it was UCDW. The 1.8 °C isotherm at the outer shelf edge indicates the presence of the Southern ACC Front (Orsi et al., 1995). Below 300 m at the outer shelf, temperature decreased and salinity increased to a maximum of 34.74 at 1200 m (not shown), which is characteristic of LCDW. Above 300 m, temperature decreased to a minimum of 1.5 °C (Fig. 3A) and salinity decreased to 34.1 (Fig. 3C) at about 100 m, which is the core of the WW layer. Above the WW layer was AASW.

Water warmer than 1.0 °C flooded the shelf below 200 m across the entire section (Fig. 3A). The salinity below 200 m was greater than 34.65 (Fig. 3C) which indicates the offshore origin of this water. The potential density surfaces below 200 m (Fig. 3E) sloped upward from the shelf edge onto the shelf, indicating onshelf movement and cooling of oceanic CDW. The temperature and salinity distributions above 200 m (Figs. 3A, C) show that the remnant WW layer extended across the shelf. There was a warmer, less saline and lower density layer in the upper 100 m at the two inner-most stations on line 2 (Figs. 3A, C, E), representing a low salinity coastal current.

In July–August, the vertical property distributions along line 2 still showed the presence of the ACC at the outer shelf edge, flooding of warm and salty water below 200 m, and upward sloping density surfaces below 200 m (Figs. 3B, D, F). The primary differences were in the waters above 200 m, which were colder than −1.8 °C over most of the section. Salinity and density of the water above 100 m increased relative to the April–May observations, likely as the result of cooling and brine rejection during sea-ice formation. The surface waters not at freezing were found at the two inner-most stations on the transect.

The property distributions along the across-shelf transect constructed from the outer stations on line 5 and the inner stations on line 6 (cf. Fig. 1) are similar to those seen along the section to the north. The southern boundary of the ACC was present at the shelf edge in fall (Fig. 4A) and winter (Fig. 4B), warm salty water flooded the shelf below 200 m (Figs. 4C, D), and the potential density surfaces slope upwards at the outer shelf edge (Figs. 4E, F). The waters above 100 m showed the transition from AASW in the fall to WW in the winter. The WW layer in fall was more eroded along this section than along the line 2 section. At the stations inside Marguerite Bay, the WW layer was completely gone and water near 0 °C extended from about 175 m to the surface.

In the southern part of the study region, along line 10 (Fig. 1), the across-shelf temperature and salinity distributions in the fall (Figs. 5A, C) showed modified CDW and shelf water below 200 m and AASW above. The WW layer was eroded, although there is a suggestion of this layer in the temperature distribution at the outer part of the section (Fig. 5A). The density surfaces sloped downwards towards the inner portion of the section, which suggests flow to the south–southwest on the inner shelf. In winter, 1.5 °C water was observed at the outer shelf below 300 m, and the surface waters were near freezing at the outer two station locations (Fig. 5B). Salinity in the upper 100 m decreased onshore, and the offshore salinity below 200 m was characteristic of UCDW (Fig. 5D). The potential density surfaces above 200 m reflect the colder and more saline water present in winter relative to the fall (Fig. 5F versus Fig. 5B). Below 200 m the density structure in the two seasons was similar (Figs. 5E, F).

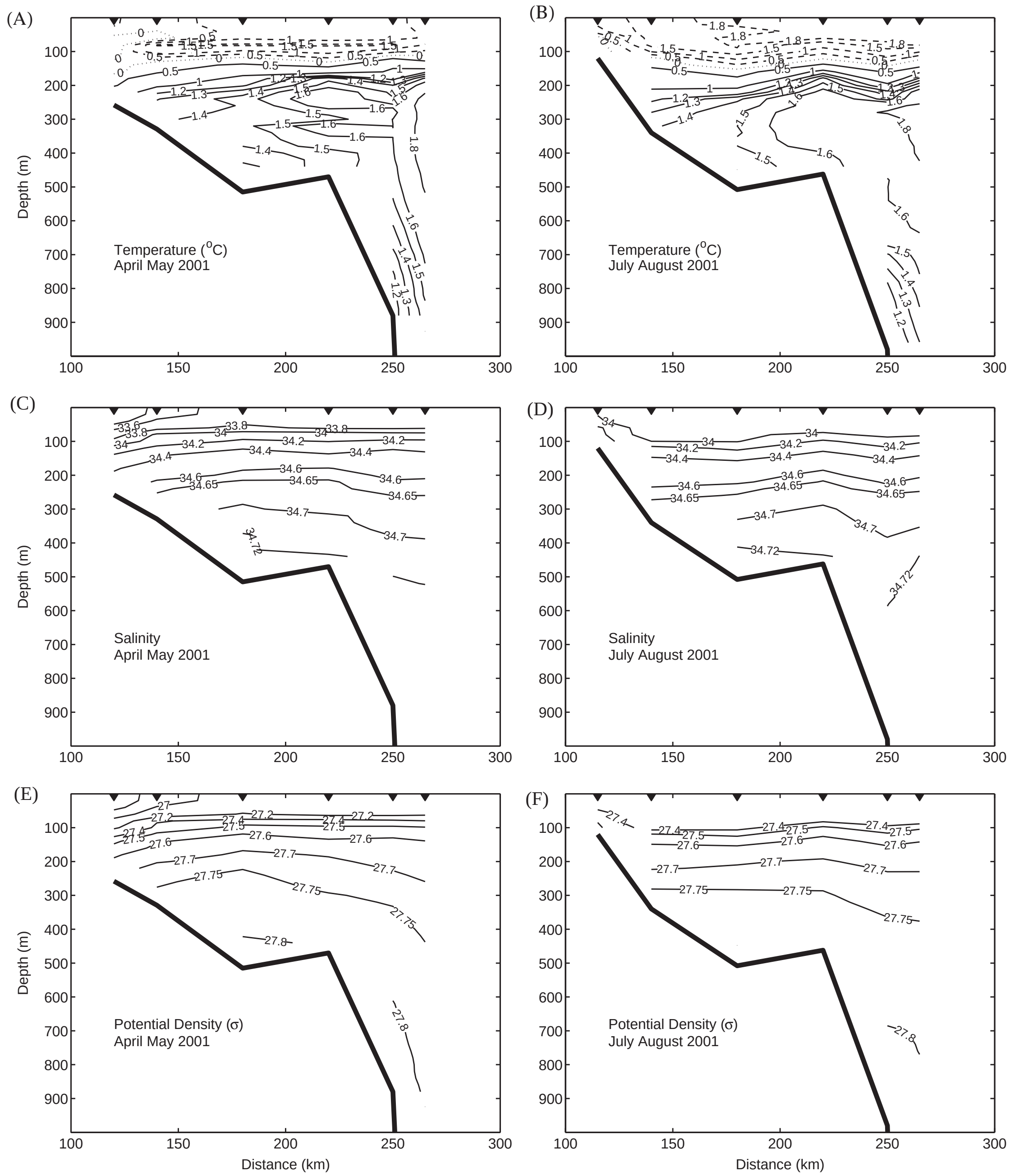

Fig. 3. Vertical across-shelf sections of potential temperature, salinity, and potential density constructed from measurements made during April–May 2001 (A, C, E) and July–August 2001 (B, D, F) along line 2 in the northern portion of the study region. The station locations used to construct the sections are shown on Fig. 1 and the station spacing along the transect is indicated by the triangles.

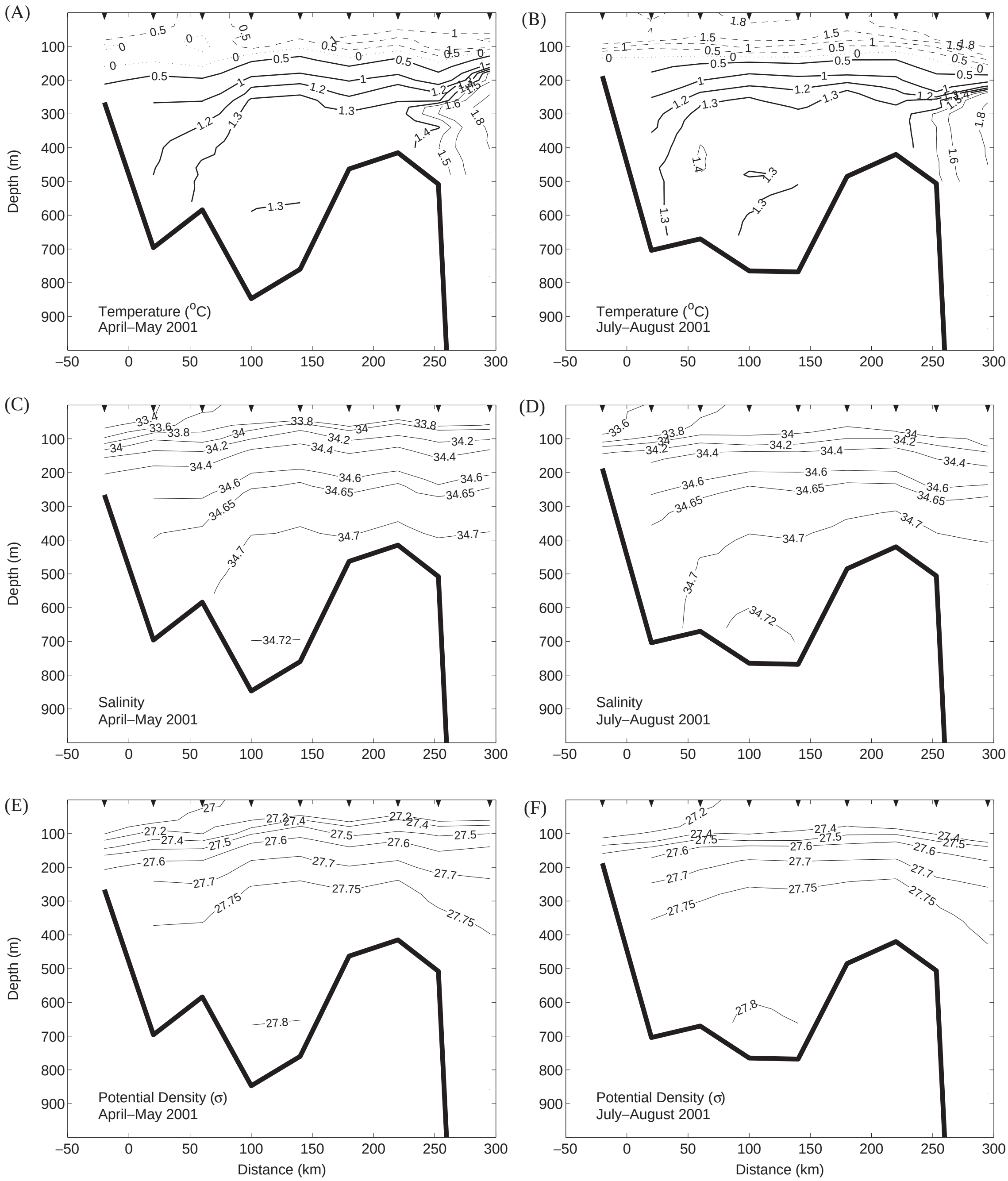

Fig. 4. Vertical sections of potential temperature, salinity, and potential density constructed from measurements made during April–May 2001 (A, C, E) and July–August 2001 (B, D, F) along the outer portion of line 5 and the inner portion of line 6. The station locations used to construct the sections are shown on Fig. 1 and the station spacing along the transect is indicated by the triangles.

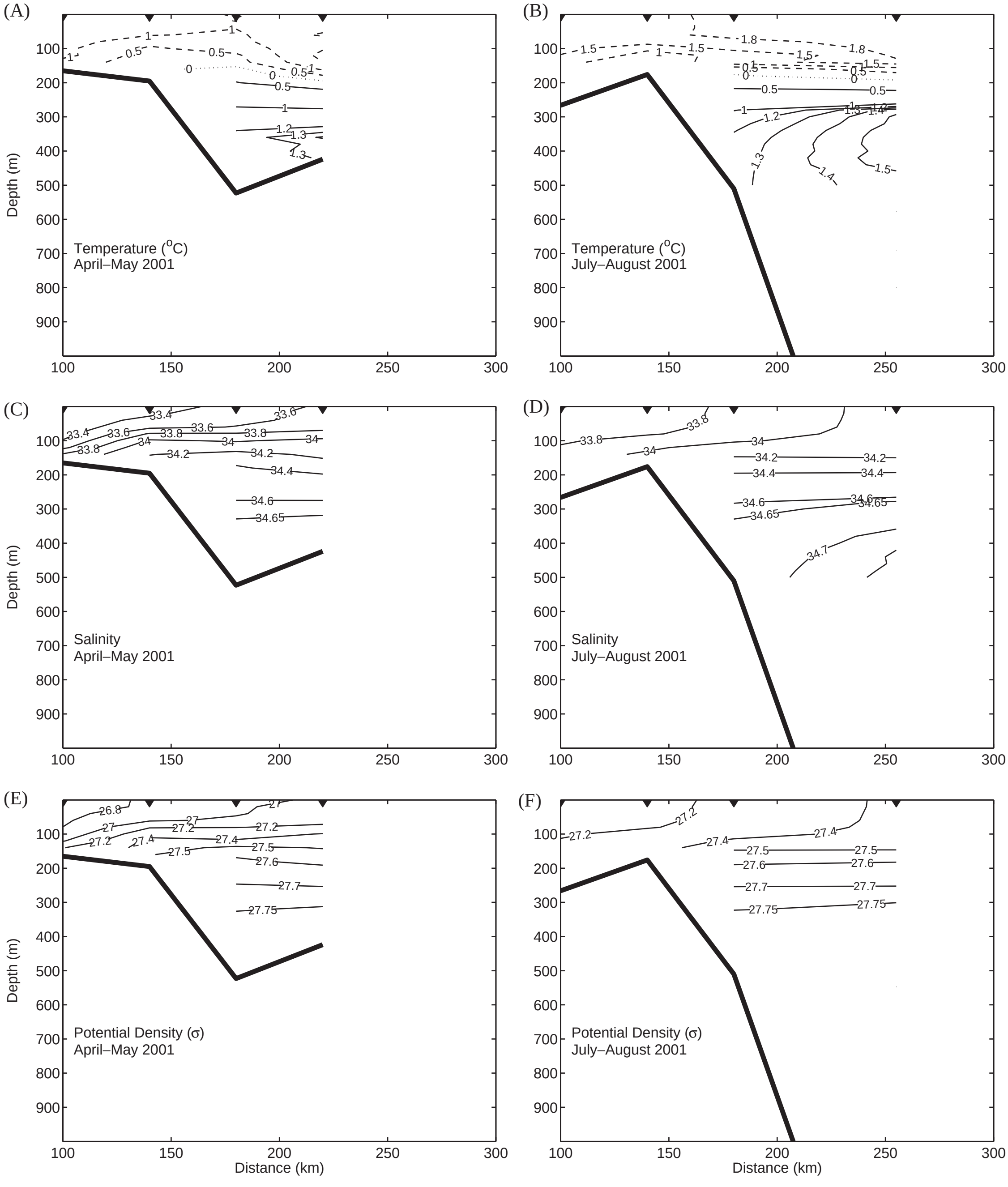

Fig. 5. Vertical across-shelf sections of potential temperature, salinity, and potential density constructed from measurements made during April–May 2001 (A, C, E) and July–August 2001 (B, D, F) along line 10. The station locations used to construct the sections are shown on Fig. 1 and the station spacing along the transect is indicated by the triangles.

The hydrographic section along the axis of Marguerite Trough (Fig. 1) shows oceanic water along this deep connection from the outer WAP shelf and into inner Marguerite Bay (Fig. 6). In April–May, an isolated region of 1.5 °C water was observed between 250 and 400 m (Fig. 6A) with cooler water on either side. Salinity along Marguerite Trough below 200 m was 34.7–34.72 (Fig. 6C) with potential densities of 27.75–27.8 (Fig. 6E). The WW layer was eroded and surface temperature and salinity decreased inside Marguerite Bay (Figs. 6A, C). In the winter, the thermohaline properties below 200 m were similar to those observed in the fall (Figs. 6B, D, F), but the temperature below 200 m was only 1.4 °C. The surface waters were near freezing except for a small region around a shallow bank, at about 75 km along the transect, where surface waters were above freezing.

3.2.2. Surface temperature and salinity

The temperature distribution at 10 m from April to May (Fig. 7A) shows the progressive cooling of the surface waters that occurred over the course of the cruise. Surface waters in the northern part of the study region, which were sampled first, ranged from −0.4 to −1.0 °C, while surface water in the southern part of the survey grid had cooled to −1.2 to −1.4 °C by the end of the cruise. The salinity distribution at 10 m (Fig. 7C) showed highest salinities (33.8–33.6) at the shelf edge in the northern part of the study region, which extended onto the shelf and into Marguerite Bay along the axis of Marguerite Trough. Low salinities of 33.4–33.2 were found on the inner shelf around the northern side of Adelaide Island, along Alexander Island, and near Charcot Island (Fig. 7C).

Near-surface water temperature in winter is near freezing throughout the study region, which gives little horizontal contrast. However, the difference between the temperature at 10 m and the freezing temperature at the ambient salinity (Fig. 7B) does show large-scale patterns. Departures from freezing of 0.06–0.08 °C were found throughout the northern part of the study region, especially along the axis of Marguerite Trough. A second area above freezing by 0.06 °C was found along the northern tip of Adelaide Island. Departures from freezing of 0.02–0.04 °C occurred along the outer shelf. The largest departures from freezing of 0.1 °C occurred at the entrance to Marguerite Bay along the southern flank of Marguerite Trough and along the southern side of Adelaide Island (Fig. 7B). The salinity distribution in winter at 10 m showed the highest salinities (34.0–33.9) along the outer shelf edge and along the axis of Marguerite Trough (Fig. 7D). Lowest salinities were on the inner shelf and inside Marguerite Bay.

3.2.3. Temperature maximum below 200 m

The distribution of the temperature maximum below 200 m (Fig. 8) provides a way to track movement of CDW and modified CDW on the WAP shelf. This approach assumes that the isotherm patterns can be used to approximate the current flow. Also, the southern boundary of the ACC is denoted by the 1.6 °C isotherm and the Southern ACC Front is denoted by the 1.8 °C isotherm below 200 m (Orsi et al., 1995), which allows these features to be located.

In April–May, the 1.8 and 1.6 °C isotherms were present along the outer edge of the continental shelf over the entire study region (Fig. 8A), indicating that the ACC was situated along the shelf edge. Temperatures greater than 1.6 °C extended onto the WAP shelf in the northern end of the survey grid and between survey transects 6 and 7. The onshelf movement of the 1.6 °C isotherm in the northern study region was associated with a meander in the southern ACC boundary, which was aligned with the northeastern side of Marguerite Trough. The temperature section along Marguerite Trough (cf. Fig. 6A) clearly shows the intrusion as water below 200 m warmer than 1.5 °C.

The 1.4 °C isotherm forms the boundary between the CDW and modified CDW that is found on the WAP continental shelf (Smith et al., 1999). This isotherm extended to the inner shelf in the northern study region, towards the shelf break in the central region, and along the outer shelf in the southern region (Fig. 8A). This pattern suggests that there were two regions of onshelf flow separated by offshelf flow.

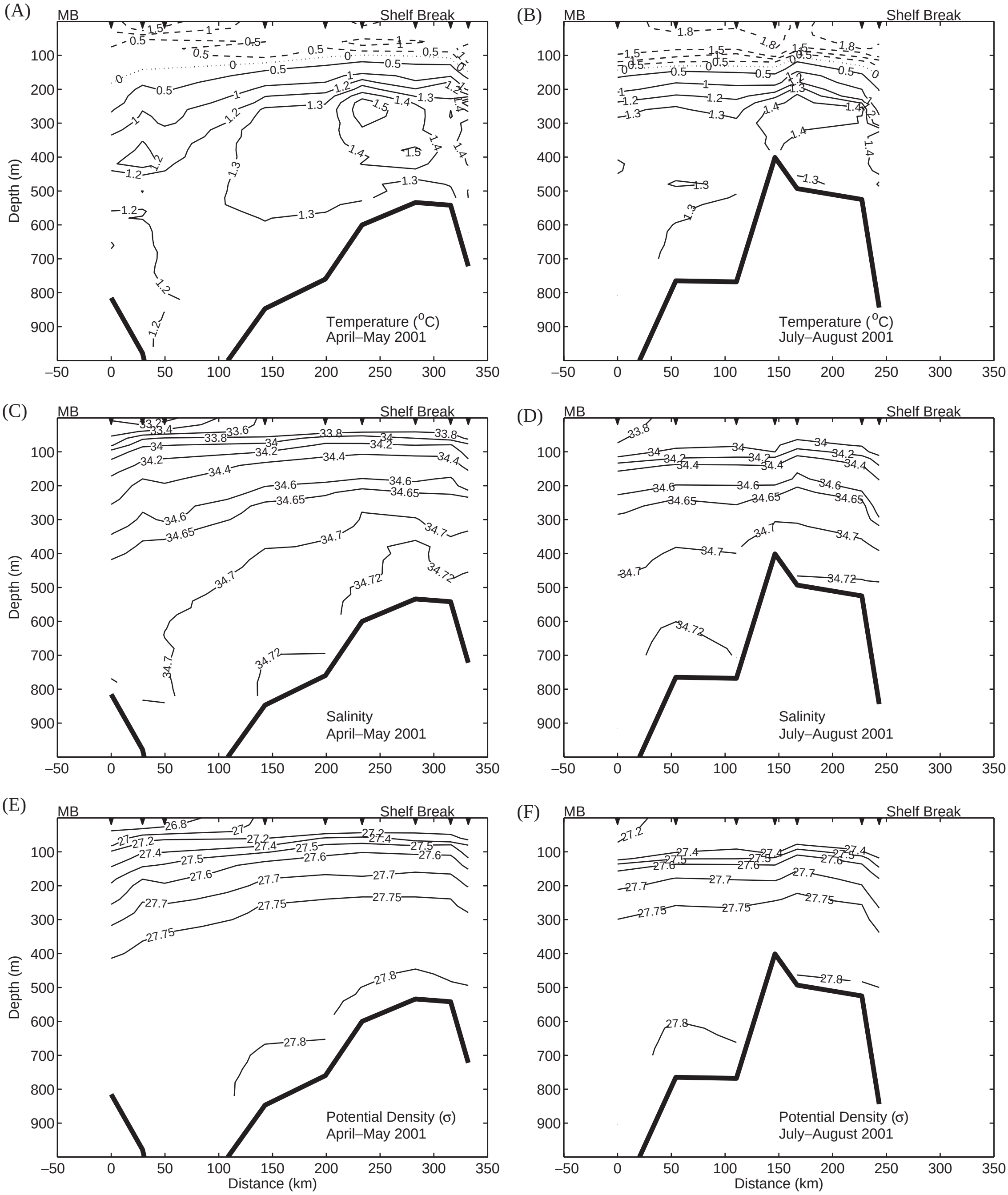

Fig. 6. Vertical sections of potential temperature, salinity, and potential density constructed from measurements made during April–May 2001 (A, C, E) and July–August 2001 (B, D, F) along a transect that runs along the axis of Marguerite Trough. The station locations used to construct the sections are shown on Fig. 1 and the station spacing along the transect is indicated by the triangles. Marguerite Bay is indicated by MB.

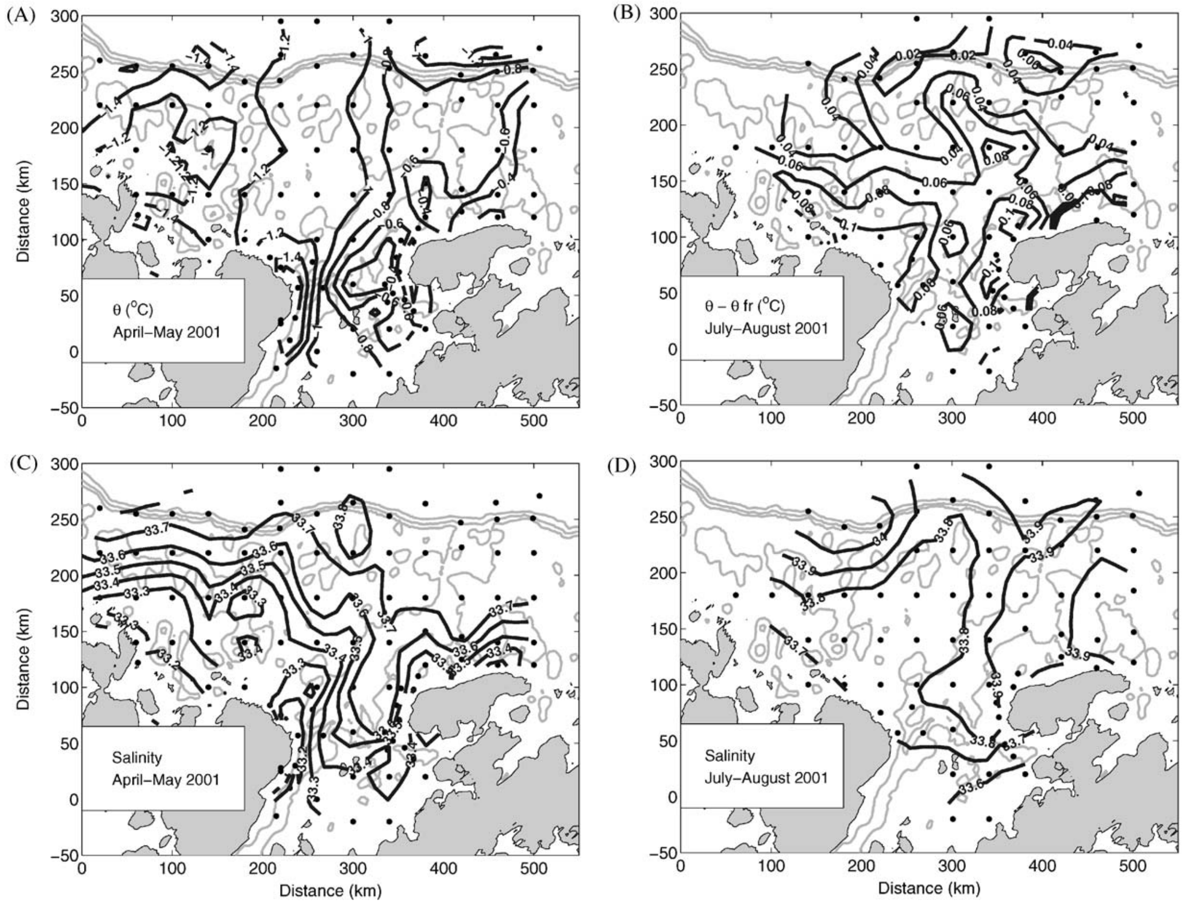

Fig. 7. Distribution of potential temperature (θ) and salinity at 10 m constructed from the April–May 2001 observations (A, C), the difference between the observed water temperature and freezing temperature (θ fr) at the ambient salinity (B), and salinity (D) constructed from the July–August 2001 observations. Station locations used to construct the distributions are shown and bathymetry contours are 500, 1000, and 1500 m. Light shading shows land and geographical names are given on Fig. 1.

The 1.2 °C isotherm is the edge of the colder inner shelf waters along the western sides of Adelaide and Alexander Islands. The only exception was in the mid-portion of the study region, where this isotherm extended into Marguerite Bay aligned with Marguerite Trough. The isotherm pattern suggests flow from the outer WAP in the northern study region, extending along Marguerite Trough, and into inner Marguerite Bay. In the southern study region, this isotherm extends across the shelf, reaching to within 40 km of the shelf edge. Water below 200 m in the inner reaches of Marguerite Bay in April–May was warmer than 0 °C.

During July–August 2001, the pattern of the temperature maximum below 200 m (Fig. 8B) is similar to that seen in the fall. The 1.6 and 1.8 °C isotherms were again along the shelf break indicating the presence of the ACC. The two regions of onshelf isotherm deflection were still evident near transects 2 and 3 and transects 6 and 7, respectively, with the intervening region of offshelf isotherm deflection. An isolated region of water warmer than 1.4 °C occurred in Marguerite Trough at the entrance to Marguerite Bay. The 1.3 and 1.4 °C isotherms extended about 50 km further off the shelf in the southern study region than observed in April–May (Fig. 8B versus Fig. 8A).

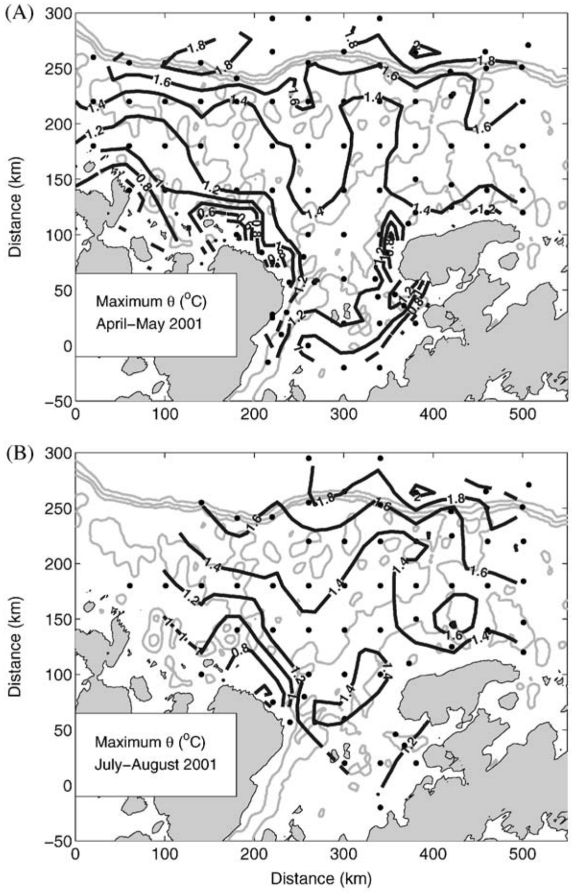

Fig. 8. Horizontal distribution of the maximum in potential temperature (θ) below 200 m constructed from the (A) April–May 2001 and (B) July–August 2001 observations. Station locations used to construct the distributions are shown and bathymetry contours are 500, 1000, and 1500 m. Light shading shows land and geographical names are given on Fig. 1.

3.2.4. Temperature and salinity anomaly

The range of temperature and salinity below 200 m was small, so differences across the study region and between the two cruises are best seen as anomalies. Thus, an average temperature and salinity vertical profile was calculated for each cruise using the observed values. This average profile was then subtracted from each observed profile and the resulting anomaly field at specific depths was plotted. The temperature and salinity anomaly fields at 300 m (Fig. 9) provided the best contrast.

In April–May 2001 the temperature and salinity anomalies at 300 m were positive over the northern and central portions of the survey region (Figs. 9A, C), showing clearly the onshelf movement of warm, salty UCDW. Positive anomalies coincided with locations of ACC meanders onto the shelf and Marguerite Trough. Negative temperature and salinity anomalies occur along the southern tip of Adelaide Island, along Alexander Island and across the continental shelf in the southern part of the survey region.

Temperature and salinity anomalies at 300 m in July–August (Figs. 9B, D) are similar to those seen in the fall, with positive anomalies in the north and central parts of the study region and negative anomalies in the southern region. Two distinct positive anomalies occur along the axis of Marguerite Trough with a possible third region at the outer shelf edge. These potentially represent three separate UCDW intrusions that moved onto the WAP via Marguerite Trough. The inner-most feature, along the inner parts of transects 5 and 6, had the lowest temperature and salinity anomalies, suggesting that the intruded UCDW had cooled and freshened as it moved onshore.

3.2.5. Dynamic height

Stratification of the WAP continental shelf waters is weak (Smith et al., 1999; Smith and Klinck, 2002), so the baroclinic velocity based on dynamic topography does not represent all of the flow. One measure of the stratification is the buoyancy frequency squared ($N^2 = -g\,\frac{\partial \rho}{\partial z}$) which was estimated for individual stations and average conditions for each cruise. The near-surface N^2 can reach $10^{-4}\,s^{-2}$ but maximum values in the pycnocline are around $5 \times 10^{-5}\,s^{-2}$ with deeper values a factor of 10 or more smaller. Dynamic mode calculations result in first internal radii of deformation of around 5 ± 1 km for any station on either cruise.

The dynamic topography at the surface relative to 400 m, constructed from the vertically integrated density anomaly, represents the baroclinic circulation (Fig. 10). The dynamic topography for April–May (Fig. 10A) showed a cyclonic gyre over the northern part of the study region between

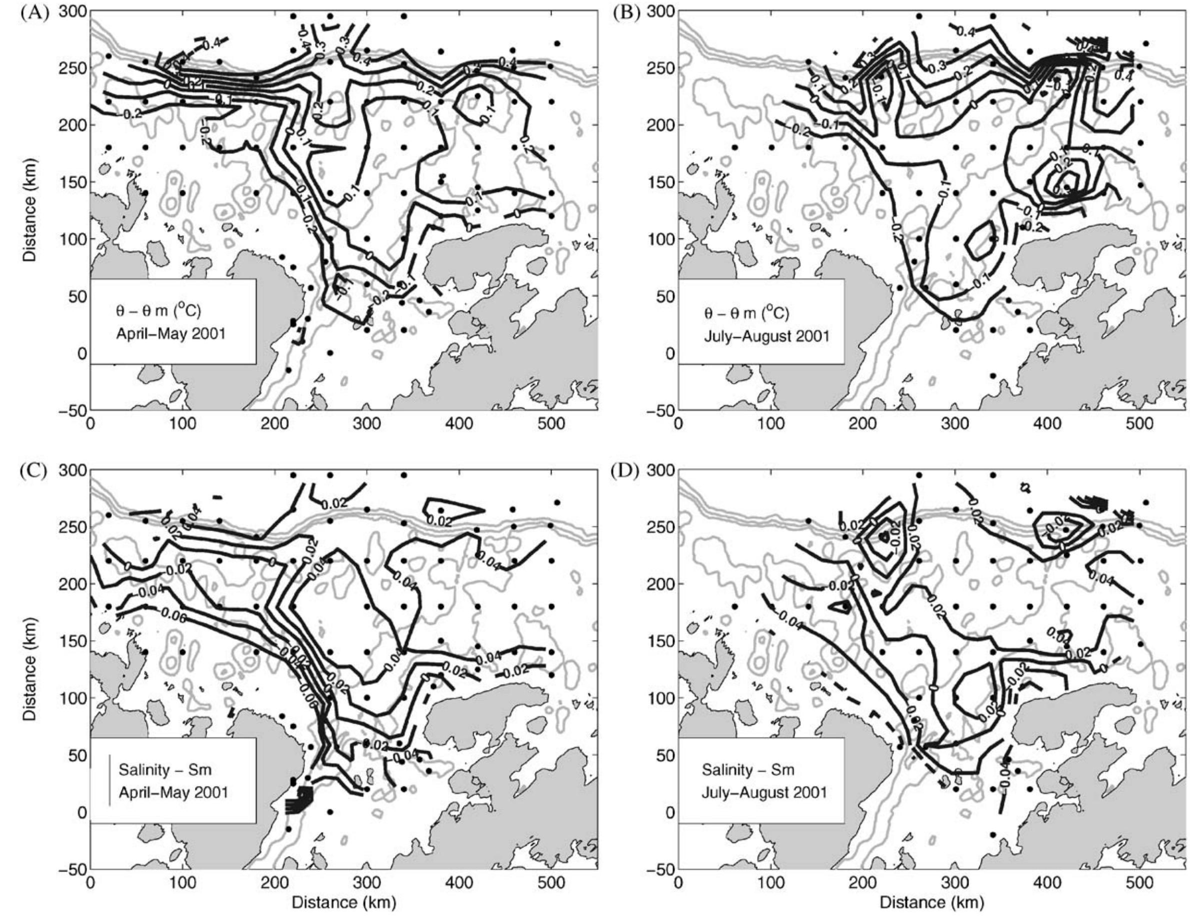

Fig. 9. Horizontal distribution of the potential temperature (θ) and salinity anomaly fields at 300 m constructed from the April–May 2001 (A, C) and July–August 2001 (B, D) observations. The spatial average of potential temperature (θ m) and salinity (Sm) at 300 m was subtracted to construct the anomaly distribution. Station locations used to construct the distributions are shown and bathymetry contours are 500, 1000, and 1500 m. Light shading shows land and geographical names are given on Fig. 1.

transects 1 and 7. This flow extended along Marguerite Trough and into Marguerite Bay.

The southwesterly flow along the offshore side of Adelaide Island turned around the southern tip of the Island and flowed into Marguerite Bay. On the other side of the Bay near Alexander Island, the flow was outward, suggesting that there is a general cyclonic circulation within Marguerite Bay. The outward flow from Marguerite Bay joined with the southerly flow which dominated the continental shelf in the southern third of the study region. This southerly flow is consistent with the slope of the isopycnals observed along the inner part of transect 10 (cf. Figs. 5E, F).

In July–August the cyclonic gyre in the northern part of the study region (Fig. 10B) was still present, although weaker than in April–May. The offshelf flow in the southern third of the study region was still apparent. A suggestion remains of southwesterly flow along the offshore side of Adelaide Island that turns into Marguerite Bay and of southward flow over the continental shelf in the southern part of the study region. However, the reduced number of stations occupied during the July–August cruise (cf. Table 1) does not allow full resolution of these features.

The dynamic height difference over 100 km across the onshelf limb of the circulation is

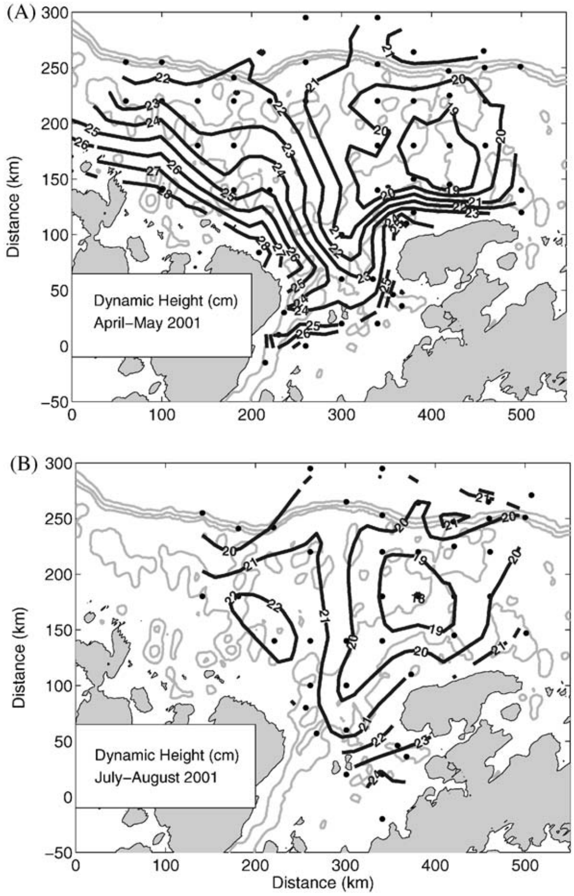

Fig. 10. Dynamic topography at the surface relative to 400 m constructed from the (A) April–May and (B) July–August 2001 observations. Station locations used to construct the distributions are shown and bathymetry contours are 500, 1000, and 1500 m. Light shading shows land and geographical names are given on Fig. 1.

0.03 m (0.21–0.18 dynamic meters) in both realizations of the gyre. This difference corresponds to a velocity of $0.03\,\mathrm{m\,s^{-1}}$ or $2.6\,\mathrm{km\,d^{-1}}$ at 67 °S. This weak circulation would move water parcels from the outer to inner WAP continental shelf, a distance of about 130 km, in about 50 days.

The surface flow based on drifters (drogued at 15 m) is consistent with this described flow along Adelaide Island, through Marguerite Bay and southwestward along Alexander Island (Beardsley et al., 2004). Surface flow is estimated to be $0.1\,\mathrm{m\,s^{-1}}$ with peak speeds twice this during stronger winds. ADCP measurements of sub-pycnocline flow (discussed in the next section) show that deep flow is consistent in speed and direction with these surface drifters. Thus the dynamic topography is a reliable indicator of the flow direction but a poor indicator of speed.

3.2.6. *ADCP-derived velocity measurements*

The ADCP-derived currents are available along the cruise track for both cruises, although the data recovery is reduced during July–August due to sea ice. Tidal flow is not removed from these observations because it is only of order $1–5\,\mathrm{cm\,s^{-1}}$ in this area (Amos, 1993; Klinck, 1995); and is not a primary component of the total flow. More problematic are the strong inertial oscillations due to strong and frequent wind events (Howard et al., 2003; Beardsley et al., 2004), which are difficult to remove due to their episodic nature. To reduce the influence of these oscillations, the 5-minute average ADCP measurements were depth averaged from 183 m to the deepest good measurement (to a maximum depth of 423 m) and gridded into boxes that were 16.7 km on a side. Averaging onto a spatial grid has the effect of time averaging the 5-minute data thus reducing the influence of the inertial oscillations. Nevertheless, there are occasional vectors that do not follow the pattern of the rest of the flow due to these oscillations.

The ADCP-derived vertically averaged currents below 183 m along the April–May cruise track (Fig. 11A) showed sub-pycnocline current patterns that are generally consistent with those suggested by the hydrography and dynamic topography (Figs. 7–10), although the ADCP currents show variability. The general pattern of the flow is onto the shelf off Adelaide Island, a cyclonic circulation through Marguerite Bay and offshore flow in the center of the sampling region. There is indication of two gyres within Marguerite Bay: one south of Adelaide Island and the other over Marguerite Trough east of Alexander Island. These flows are consistent with the flow suggested by the temperature maximum (Fig. 8A) and dynamic topography (Fig. 10A) distributions.

There is a region of onshore flow at the shelf break off Alexander Island, which is not indicated in the dynamic topography. The temperature

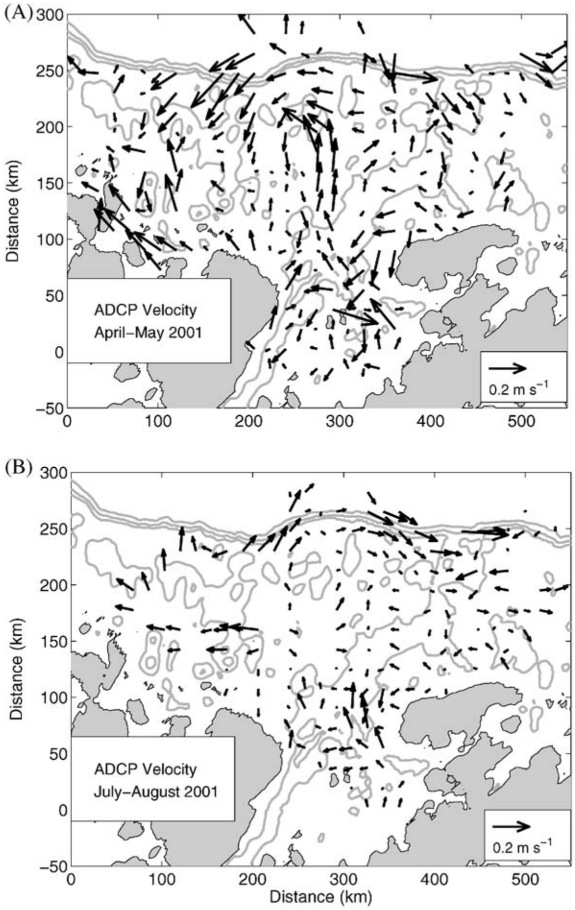

Fig. 11. Acoustic Doppler Current Profiler-derived velocity distributions for the (A) April–May 2001 and (B) July–August 2001 cruises. The ADCP records were averaged in depth from 183 to 423 m (bins 20–50) and over a spatial grid with 16.7 km spacing. Bathymetry contours are 500, 1000, and 1500 m. Light shading shows land and geographical names are given on Fig. 1.

maximum distribution has a weak plume of warm (1.6 °C) water associated with these currents (Fig. 8A) so this may be the beginning of an intrusion of UCDW onto the shelf in this area.

The more prominent flow vectors during the April–May cruise are 0.05–0.20 m s^{-1}, which is faster than indicated by the dynamic topography but consistent with velocity estimates from the surface drifters (Beardsley et al., 2004). There are only a few vectors at the shelf break indicating strong northeastward flow associated with the ACC, which may indicate that the ACC was offshore during the time that these measurements were made.

The ADCP-derived currents from the July–August survey (Fig. 11B) had reduced coverage because of interference from sea ice. Flow speeds are 0.1–0.15 m s^{-1} which are higher than indicated by the dynamic topography (Fig. 10B). A more consistent ACC occurred along the shelf break with an offshore meander near the center of the study area and an onshore meander off Adelaide Island along Marguerite Trough. Offshore flow at 0.05 m s^{-1} away from the mouth of Marguerite Bay is indicated. There is no clear indication of flow along Adelaide Island or of cyclonic flow within Marguerite Bay.

The weaker flow is consistent with the weaker dynamic topography (Fig. 10B). The plume of warm (1.6 °C) water at the shelf break off Adelaide Island is consistent with the measured flow.

4. Discussion and summary

4.1. Contribution of LCDW

The water mass structure in the Southern Ocean GLOBEC study region is relatively simple, consisting of AASW, WW, UCDW, and a modified (cooled) form of UCDW. However, one issue that is not clear is the contribution of LCDW to the water mass properties on the WAP continental shelf. LCDW water is present at the outer shelf edge and in deep depressions, such as Marguerite Trough, that intersect the WAP continental shelf. These depressions can provide pathways for this water to move onto the shelf. It is important to determine how much LCDW is present on the WAP continental shelf because of its effect on heat and salt budgets (discussed below). Also, LCDW is characterized by a silicate maxima (Smith et al., 1999; Serebrennikova and Fanning, 2004) and is thus a potential source of nutrients to the shelf.

Water with temperatures of 1.3–1.4 °C, which is characteristic of LCDW (cf. Fig. 2), fill the deeper parts of Marguerite Trough (Figs. 6A, B). However, this temperature range is also characteristic of the modified form of UCDW that floods the WAP shelf below 200 m (cf. Fig. 2). The LCDW salinity maximum (34.74) provides a better way to locate this water. The excess salt of the LCDW should remain discernible because the deep salinity gradients everywhere are weak (Figs. 6C, D) and the vertical diffusivity is small, about $10^{-5}\,m^2\,s^{-1}$ (Howard et al., 2004).

LCDW is clearly seen in the potential temperature-salinity diagrams for sections that extended beyond the shelf break. However, only stations in Marguerite Trough showed the presence of LCDW on the WAP continental shelf (Fig. 12). In April–May, the salinity maximum associated with LCDW was present, but weak (Fig. 12A). The potential temperature-salinity diagram from the July–August cruise shows clearly the presence of LCDW in Marguerite Trough (Fig. 12B). The stations at which LCDW was present are those in the deeper part of the Trough, which is near the entrance to Marguerite Bay.

The presence of LCDW in Marguerite Trough might be expected because this bathymetric feature provides a deep connection between the outer and inner shelf. However, the depth of Marguerite Trough at the shelf edge is about 750 m, which is shallower than the core of LCDW which is near 900–1000 m. Thus, how LCDW gets into Marguerite Trough is not immediately apparent. One possibility is that there is another connection without a shallow sill at the shelf edge between the outer shelf and Marguerite Trough that is not resolved in the current bathymetry for this area. This could account for the presence of LCDW along the inner part of the hydrographic section that runs along the Trough and not along the outer portion. A second possibility is that meandering of the ACC at the shelf edge pumps LCDW over the sill and into Marguerite Trough. This would require that the LCDW be lifted about 200–300 m. The dynamics of how this might occur must await the development of high resolution numerical models or other theoretical studies for this shelf region.

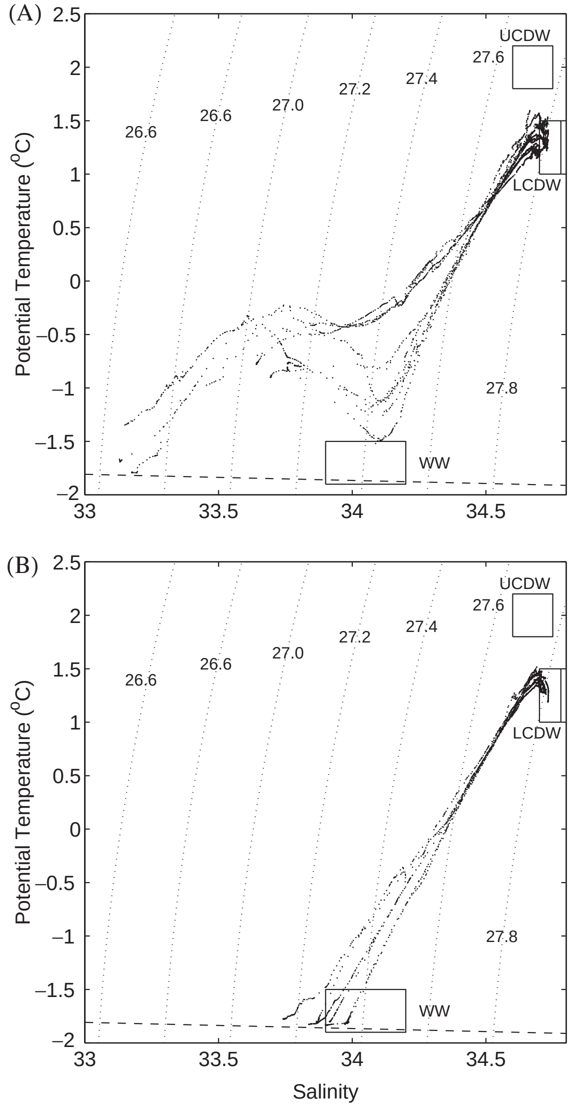

Fig. 12. Potential temperature-salinity diagrams from the stations occupied along the axis of Marguerite Trough in (A) April–May 2001 and (B) July–August 2001. The temperature and salinity ranges that characterize UCDW, LCDW and WW water masses are shown by the boxes. The potential density at the surface for the indicated temperature and salinity is shown dotted lines. The freezing point of seawater is indicated by the dashed line.

4.2. UCDW intrusions

The onshelf movement of CDW along the WAP continental shelf was described earlier (e.g., Potter and Paren, 1995; Talbot, 1988; Domack et al., 1992) but the extent to which these events occur along the WAP continental shelf was not appreciated until repeated measurements were made in this region, such as those described in Prézelin et al. (2004) and those from Southern Ocean GLOBEC. Dinniman and Klinck (2004) discuss the dynamics underlying the movement of CDW onto the WAP within the context of a numerical circulation model developed for this region. Their analysis indicates that movement of CDW onto the WAP occurs when the ACC flows along the outer shelf edge and is deflected offshore by the variable topography. As the topography turns in front of the ACC, some of the water continues in a straight line onto the shelf. Thus, the introduction of CDW requires the presence of the ACC and variable topography.

Intrusions of CDW onto the WAP continental shelf are certainly related to the presence of the ACC, the location of which is determined by the 1.8 °C isotherm (Orsi et al., 1995). Thus, monitoring the location of this isotherm provides a means for inferring areas where CDW intrusions can occur. Also, movement of this isotherm away from the WAP shelf edge, perhaps due to changes in the location of the core of the ACC (Hofmann and Whitworth, 1985) or changes in the ACC transport (e.g., Whitworth, 1983), would prevent the onshelf movement of CDW, which in turn will alter heat, salt and nutrient distributions, as well as biological production on this shelf.

4.3. UCDW intrusion frequency

The temperature and salinity anomaly (Fig. 9) provide an approach to determine the number of UCDW intrusions for the period covered by the 2001 cruises. In April–May positive temperature and salinity anomalies of 0.15 °C and 0.05, respectively, were observed along the inner part of transect 4 (Figs. 9A, C), indicating the presence of warmer and saltier UCDW. The temperature maximum below 200 m showed onshelf deflection of isotherms (Fig. 8A). A second area of positive temperature and salinity anomalies occurred at the outer end of the transects 2 and 3, suggesting that one UCDW intrusion was already on the continental shelf during the April–May survey and that a second was beginning at the outer shelf in the northern part of the study region.

The temperature and salinity anomalies for the July–August cruise (Figs. 9B, D) showed positive anomalies over Marguerite Trough at the entrance to Marguerite Bay, along the inner parts of the across-shelf transects 3 and 4, and along the outer portion of transect 3 in the northern part of the survey region. This pattern suggests that the UCDW intrusion on the continental shelf in April–May moved further onto the shelf and that the intrusion that was beginning at the outer shelf in April–May moved farther onto the shelf. The displacement of the UCDW intrusion on the shelf between April–May and July–August was about 100–125 km. The time between the two surveys is about 45 days, which gives an average speed of about 0.026 m s^{-1}, which is consistent with the dynamic topography but slow compared to the surface drifter and ADCP velocity measurements. A third intrusion may have started at the outer shelf in July–August.

The hydrographic distributions indicate that two and possibly three UCDW intrusions occurred on the WAP continental shelf during the 5–6 months encompassed by the two survey cruises. If this is representative of the frequency of these events, then 4–6 UCDW intrusions could occur on this part of the WAP shelf in a year. Intrusions of UCDW are known to occur on other parts of the WAP continental shelf (e.g., Smith et al., 1999; Prézelin et al., 2000). Thus, if the frequency of occurrence observed in the Southern Ocean GLOBEC study region is assumed to be representative of that in other areas, then these events control the thermohaline characteristics of this shelf. Moreover, more than one UCDW intrusion can be present at a given time, each being in a different stage of decay (e.g., releasing heat and nutrients).

The South Atlantic Bight on the southeast US continental shelf, is similarly influenced by episodic inputs of oceanic waters (Atkinson, 1977; Atkinson et al., 1985). The Gulf Stream flows along the shelf break and meanders in response to wind forcing and bottom variations. Gulf Stream-derived water moves onto the shelf via bottom intrusions during the summer when shelf waters are stratified and winds are upwelling favorable (Atkinson, 1985; Atkinson et al., 1987). Onshelf movement of oceanic water at other times occurs via Gulf Stream frontal eddies (e.g., Lee et al., 1991). The frequency of bottom intrusions for the South Atlantic Bight shelf was estimated to be 4–6 per year (Atkinson et al., 1987), which is similar to the CDW intrusion frequency for the Southern Ocean GLOBEC study region. The area included in these estimates is similar for both systems.

4.4. UCDW intrusion heat flux and mixing estimates

The intrusion of UCDW across the shelf break displaces shelf water and constitutes a heat flux to the WAP shelf. The temperature of the oceanic water decreases to that of the shelf in a few months (Figs. 3–6) either by vertical mixing into the surface layers and to the atmosphere or by lateral mixing with shelf water.

A volume integral of the advective-diffusive equation (Gill, 1982, Section 4.4) is used to estimate the eddy diffusivities required for this transfer. The region used for this calculation is the northeastern half of the cyclonic gyre (Fig. 10) where the movement of oceanic water onto the WAP continental shelf is most pronounced. A region 100 km on a side and 400 m deep (from the permanent pycnocline to the bottom at about 600 m) was chosen; similar results were obtained with different size regions.

Average temperature and salinity profiles were constructed from the hydrographic observations, with a 2-m resolution, for the oceanic, mid-shelf and inner-shelf (Marguerite Bay) areas. The assumption in this calculation is that mid-shelf water in the volume is replaced with oceanic water by advection. The volume looses heat by either vertical or horizontal diffusion. The specific heat, c_p, was calculated at each depth from temperature and salinity. Due to the small variation in water properties, there was little change in c_p which had a value of approximately $3999\,\mathrm{J\,kg^{-1}\,{}^{\circ}C^{-1}}$. Therefore, ρ and c_p can be factored from the vertical integrals with little error in the result.

The volume and time averaged heat budget is

$$\rho c_p \left[\frac{u}{L}\,\overline{T_{\mathrm{o}} - T_{\mathrm{m}}} - \frac{k}{H}\frac{\partial T}{\partial z}\bigg|_{\mathrm{top}} - \frac{K}{L}\frac{\partial T}{\partial x}\bigg|_{\mathrm{s}} \right] = 0,$$

where u is the advective speed, T_{o} is the oceanic temperature profile, T_{m} is the mid-shelf temperature profile, $L = 100\,\mathrm{km}$ is the horizontal size of the volume, $H = 400\,\mathrm{m}$ is the thickness of the volume, k and K are the vertical and horizontal diffusivities, respectively. The overbar indicates a vertical average of the temperature difference. This budget is used to estimate the horizontal and vertical eddy diffusivities based on the assumption of complete water modification either by vertical or horizontal flux every 60 d.

The vertical average temperature change between the ocean and mid-shelf is 0.3 °C. The average vertical temperature gradient in the pycnocline is $0.03\,{}^{\circ}\mathrm{C\,m^{-1}}$. Balancing advection and vertical diffusion requires a vertical diffusivity $k = 7.7 \times 10^{-4}\,\mathrm{m^2\,s^{-1}}$, which is similar to the values found by Smith and Klinck (2002). However, recent estimates of vertical heat diffusivity are 70 times smaller ($k = 1 \times 10^{-5}\,\mathrm{m^2\,s^{-1}}$, Howard et al., 2004). If the smaller diffusivity is correct, then it should take 70 times longer to dissipate the temperature anomaly of UCDW, which means that an intrusion should last a decade or more ($70 \times 60\,\mathrm{d} = 11\,\mathrm{yr}$).

An alternative is for heat to diffuse laterally to the rest of the shelf, especially the cooler parts of the inner shelf. The lateral temperature gradient between the mid- and inner-shelf is 0.18 °C over a distance of L. Balancing advection and lateral diffusion requires that $K = 1600\,\mathrm{m^2\,s^{-1}}$. There are no direct estimates of lateral diffusivity in this region, but a value this large would remove all horizontal gradients; which is not observed.

The above calculation shows that background levels of turbulent diffusion of heat are not sufficient to cool the intrusions of UCDW in the time that is observed, which suggests that other processes must be active to accomplish this mixing. One possibility is that localized mixing over shallow and variable topography accomplishes the heat transfer. This mixing is most easily seen in the winter when surface temperature should be at the freezing point for the given salinity, but it is not always so (Fig. 7). Certain areas near southern Adelaide Island (Fig. 7B) and along the coast of Alexander Island have water temperature 0.1 °C above freezing. Such exposure of the deep warm water is accomplished by breeching the cold WW layer which is seen at some stations (Fig. 4A, at a distance of 50 km). Such areas will have thinner sea ice in winter and because they are tied to bathymetry, will occur with some certainty from year-to-year.

4.5. Regional circulation

The ADCP flow measurements show a southwesterly flow along the west side of Adelaide Island (Figs. 10, 11). This current is associated with salinity less than 33.6 (Figs. 3C, 7C) in the fall and slightly higher salinity (33.9) in winter. This current is likely a continuation of the southwesterly flow on the inner shelf that exists north of the study region (Smith et al., 1999). The low salinity suggests that this current results from buoyancy forcing due to sea ice melt near the coast. The southwest coast of Adelaide Island is characterized by a coastal polynya in winter, which may contribute to the higher salinity. The effect of the polynya on the coastal flow is unknown.

Flow over most of the shelf tends to be south-southwestward (Figs. 10, 11). However, in the central study region the flow turns offshore to form a closed cyclonic gyre, which is consistent with observations on other parts of the WAP continental shelf (Stein, 1992; Smith et al., 1999). The southerly flow along the western side of Adelaide Island may represent the inner limb of this larger shelf-wide flow or a separate buoyancy-driven southerly flowing coastal current or both. The cyclonic gyre is potentially important in retaining planktonic organisms on the shelf and for providing a connection between the inner and outer shelf environments (Lawson et al., 2004; Chapman et al., 2004).

ADCP-derived velocity measurements on the outer shelf indicate the northeasterly flowing ACC, which is influenced by meanders and instabilities. Offshore flows and flow reversals, such as those seen in the northern part of the study region, are consistent with an offshelf meander that then turns southward over the continental shelf. These meanders are likely persistent features of the flow that are associated with bathymetric variations. Time changes in the ACC transport are likely to contribute to these flow variations.

Acknowledgements

This research was supported by the U.S. National Science Foundation, Office of Polar Programs by grant No. OPP 99-09956 to EEH and JMK and grant No. OPP 99-10092 to RCB. Support for S. Howard was provided by grant No. OPP 99-10102 to Earth and Space Research. We thank the hydrographic team members on the two cruises, Sue Beardsley, Rosario Sanay, Aparna Sreenivasan, Sinan Husrevoglu, Jason Hyatt, and Hae-Cheol Kim, for their efforts in ensuring that the hydrographic data sets were of the highest quality. We also thank the Captains and crew of the RVIB *Nathaniel B. Palmer* and the Raytheon Support personnel on the April–May and July–August 2001 cruises for their help and assistance in acquiring the hydrographic data used in this analysis. Computer facilities and support used for the hydrographic data analyses were provided by the Commonwealth Center for Coastal Physical Oceanography at Old Dominion University. This is US GLOBEC contribution number 448.

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