PERGAMON

Deep-Sea Research I 46 (1999) 925–949

DEEP-SEA RESEARCH
PART I

Hydrography and circulation of the West Antarctic Peninsula Continental Shelf

David A. Smith, Eileen E. Hofmann*, John M. Klinck, Cathy M. Lascara

Center for Coastal Physical Oceanography, Crittenton Hall, Old Dominion University, Norfolk, VA 23529, USA

Received 12 February 1998; received in revised form 17 May 1998; accepted 17 May 1998

Abstract

The water mass structure and circulation of the continental shelf waters west of the Antarctic Peninsula are described from hydrographic observations made in March–May 1993. The observations cover an area that extends 900 km alongshore and 200 km offshore and represent the most extensive hydrographic data set currently available for this region. Waters above 100–150 m are composed of Antarctic Surface Water and its end member Winter Water. Below the permanent pycnocline is a modified version of Circumpolar Deep Water, which is a cooled and freshened version of Upper Circumpolar Deep Water. The distinctive signature of cold and salty water from the Bransfield Strait is found at some inshore locations, but there is little indication of significant exchange between Bransfield Strait and the west Antarctic Peninsula shelf. Dynamic topography at 200 m relative to 400 m indicates that the baroclinic circulation on the shelf is composed of a large, weak, cyclonic gyre, with sub-gyres at the northeastern and southwestern ends of the shelf. The total transport of the shelf gyre is 0.15 Sv, with geostrophic currents of order 0.01 m s^{-1}. A simple model that balances across-shelf diffusion of heat and salt from offshore Upper Circumpolar Deep Water with vertical diffusion of heat and salt across the permanent pycnocline into Winter Water is used to explain the formation of the modified Circumpolar Deep Water that is found on the shelf. Model results show that the observed thermohaline distributions across the shelf can be maintained with a coefficient of vertical diffusion of 10^{-4} m^2 s^{-1} and horizontal diffusion coefficients for heat and salt of 200 and 1200 m^2 s^{-1}, respectively. When the effects of double diffusion are included in the model, the required horizontal diffusion coefficients for heat and salt are 200 and 400 m^2 s^{-1}, respectively.

* Corresponding author. Fax.: 001 757 683 5550; e-mail: hofmann@ccpo.odu.edu.

0967-0637/99/$ – see front matter
PII: S0967-0637(98)00103-4

1. Introduction

The water mass structure and circulation of the waters that overlie the continental shelf to the west of the Antarctic Peninsula (Fig. 1a) have been studied in a limited manner since the early part of this century. The first description of the region was based upon measurements from several hydrographic stations that were occupied in and around Bransfield Strait as part of the *Discovery* Investigations (Clowes, 1934). Little was added to this description until the implementation of the International Southern Ocean Studies (ISOS) program (Neal and Nowlin, 1979) and the First International BIOMASS Experiment (FIBEX) (El-Sayed, 1994) in the 1970s and 1980s, respectively. The ISOS program provided limited hydrographic measurements of the shelf waters north of the South Shetland Islands and inside Bransfield Strait (Gordon and Nowlin, 1978; Sievers and Nowlin, 1984). The FIBEX program provided more extensive coverage of the Bransfield Strait, but the hydrographic measurements were usually limited to the upper 200 m of the water column (e.g. Stein, 1983; Stein and Rakusa-Suszczewski, 1983). Neither program included the shelf waters to the west and southward along the Antarctic Peninsula.

The Second International BIOMASS Experiment (SIBEX) (El-Sayed, 1994), some US field programs (e.g. Research on Antarctic Coastal Ecosystem Rates (RACER); Huntley et al., 1991), and German oceanographic research studies provided limited observations of Antarctic Peninsula shelf waters outside of Bransfield Strait. Cruises done as part of SIBEX and German studies extended hydrographic coverage north and south of Anvers Island (Stein, 1992); the RACER program provided coverage to the west of Bransfield Strait and in the Gerlache Strait (Niiler et al., 1991). These hydrographic measurements suggested that the continental shelf circulation west of the Antarctic Peninsula may be composed of more than one gyre (Stein, 1992) and that the near-surface circulation is continuous with that of the Bransfield Strait (Niiler et al., 1990; Stein and Heywood, 1994). Two recent analyses of historical hydrographic measurements (Capella et al., 1992; Hofmann et al., 1996) provide additional insight into the water mass structure in the Bransfield Strait and west Antarctic Peninsula region.

From March to May 1993, an extensive hydrographic survey was made of the shelf waters west of the Antarctic Peninsula (Fig. 1b) as part of the Palmer Long Term Ecological Research program (Smith et al., 1995). The study region (Fig. 1a) included the western portion of Bransfield Strait and extended 900 km southward along the western side of the Antarctic Peninsula. The 200 km offshore extent of the study region included nearshore coastal waters as well as offshore oceanic waters.

Throughout this region hydrographic measurements were made along across-shelf transects with a 100 km alongshelf separation (Fig. 1b). These data provide the most extensive hydrographic survey of the continental shelf waters west of the Antarctic Peninsula to date. Thus, the primary objectives of this paper are to use these hydrographic data to provide a description of the water mass structure and circulation of the shelf waters west of the Antarctic Peninsula, quantify the mixing and exchange between oceanic and continental shelf waters, and suggest transport pathways by which oceanic waters are introduced onto the continental shelf.

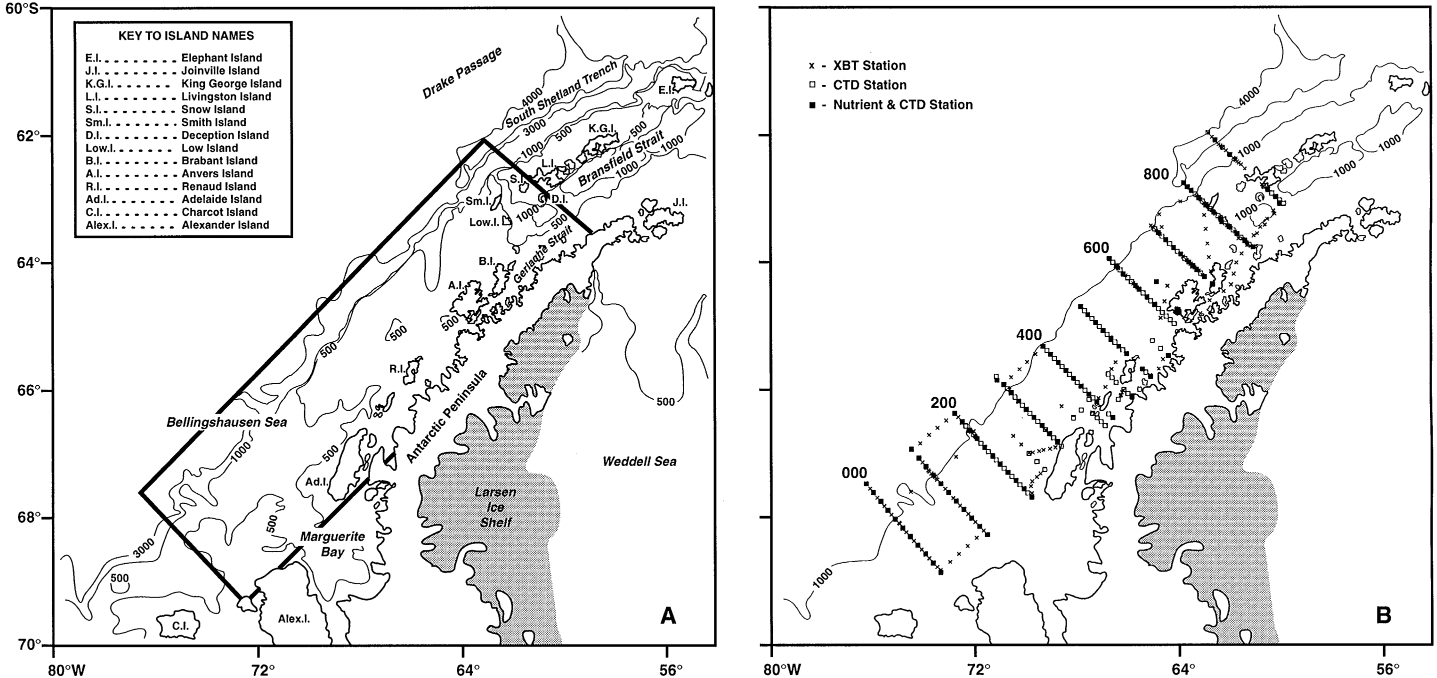

Fig. 1. (A) Map of the west Antarctic Peninsula region. Solid line indicates study region. Bottom bathymetry contours are given in meters. (B) Distribution of hydrographic and XBT stations sampled during March to May 1993. Along shelf transects are numbered consecutively from 000 at the southern end of the study region to 900 at the northern end. Bottom bathymetry contours are given in meters.

The next section describes the hydrographic data and methods used in this study. This is followed by a description of the water masses and circulation in the west Antarctic Peninsula region derived from these data. The final section provides a quantitative assessment of the mixing between oceanic and continental shelf waters and exchange pathways.

2. Data sources and methods

Individual stations were aligned in across-shelf transects running parallel to a southernmost transect (the 000 line) and perpendicular to a baseline running along the coast. Across-shelf transects are named according to their distance (in kilometers) from the 000 line, with the northernmost transect being the 900 line. The stations shown in Fig. 1b were occupied from north to south, starting with the outer shelf stations on the 900 line.

Along each of the ten across-shelf transects, conductivity-temperature-depth (CTD) measurements were made at 10 km intervals with one of two SeaBird 911^+ Niskin/Rosette sensor systems; the first was the system aboard the *RVIB* Nathaniel B. Palmer, the second was on a Bio-Optical Profiling System (BOPS) (Smith et al., 1984). In waters shallower than 500 m, vertical profiles of temperature and conductivity were obtained with the BOPS to within a few meters of the bottom. In deeper waters, the other CTD system was used, and vertical profiles were done to within 10–30 m of the bottom. In all, 232 hydrographic stations were occupied.

Water samples were taken at discrete depths from the Niskin or Go Flo bottles and analyzed on board with a Guildline Salinometer to provide calibrations for the salinity sensors. Throughout the cruise, cross-sensor comparisons were performed in order to ensure that the two CTD systems were providing consistent measurements. Additionally, the temperature and conductivity sensors from both CTD systems underwent pre- and post-cruise calibrations by SeaBird Electronics. These calibrations as well as the ones done during the cruise showed no significant drift in either sensor with either time or depth. Thus, it was unnecessary to apply corrections to the temperature and conductivity data. These data were then processed using the procedures and algorithms given in UNESCO (1983). Complete descriptions of the sensor calibrations and data processing are given in Smith et al. (1993a) and Smith et al. (1993b).

Whenever possible the spatial resolution of the temperature field was increased by using Expendable Bathythermograph (XBT) probes. The XBT measurements were usually made between the hydrographic stations, which along some of the across-shelf transects gave a resolution of 5 km (Fig. 1b). Additional XBT measurements provided coverage between the across-shelf transects (Fig. 1b).

All XBT data were collected using T-6 (nominal maximum depth of 460 m) or T-7 (nominal maximum depth of 760 m) probes, which were deployed with either a deck-mounted or hand-held launcher, depending on ice conditions. The probe types were either Sippican or Sparton, and comparisons between the temperature profiles showed no appreciable difference between the two. A complete description of the XBT data collection and post processing is given in Smith et al. (1993c).

At 95 of the hydrographic stations, water samples obtained from the Niskin and Go Flo bottles were analyzed for nutrient (nitrate, nitrite, phosphate, silicate) concentrations using a Technicon AutoAnalyzer. The nutrient measurements were primarily confined to the upper 200 m; however, a limited number were taken at greater depths, i.e., usually at the bottom and one to two other depths. Measurements of dissolved oxygen concentration were made at standard depths for stations beyond the shelf break and at the surface and bottom at stations on the shelf. At some of the shelf stations oxygen samples were taken at intermediate depths.

3. Results

3.1. Water mass structure

The potential temperature–salinity (θ–S) diagram constructed from the hydrographic measurements (Fig. 2) shows clusters of values at specific θ–S ranges. Temperatures of -1.8 to $1.0°C$ and salinities of 33.0–33.7 found at σ_0 values less than 27.4 represent Antarctic Surface Water (AASW), where the scatter indicates the temporal and spatial changes that occurred in AASW during the 10-week cruise. The temperature minimum at about $-1.5°C$ at salinities of 33.8–34.0 (σ_0 of 27.2–27.4) is associated with Winter Water (WW), which is considered to be the end member for AASW (Mosby, 1934; Sievers and Nowlin, 1984). This water mass is formed by winter cooling and it is the portion of AASW that retains the θ–S structure from the previous winter. The signature of WW in the θ–S diagram was eroded by the mixing and seasonal heating within the upper water column during March through May 1993. Oxygen values between 5 and 7 $ml\,l^{-1}$ are associated with AASW (Fig. 3a), which is continually renewed by contact with the surface. The highest oxygen values are associated with seasonal surface waters, which may be super-saturated due to biological processes (Sievers, 1982).

The cluster of points on the θ–S diagram (Fig. 2) at temperatures of $1.5°C$ and salinities between 34.6 and 34.73 represents Circumpolar Deep Water (CDW), which is found at depths of 1000 m or more in central Drake Passage and is the most voluminous water mass in the Antarctic Circumpolar Current (ACC) (Sievers and Nowlin, 1984). Within the ACC, CDW sub-divides into two varieties, Upper CDW (UCDW) and Lower CDW (LCDW), which reflect different properties acquired from different source regions. UCDW can be traced across the ACC by the location of relative oxygen minima and nutrient maxima (Callahan, 1972; Sievers and Nowlin, 1984). South of the Polar Front, UCDW is further characterized by a subsurface maximum in temperature due to the presence of the overlying temperature minimum, which is associated with AASW (WW). The relationship between dissolved oxygen, nitrate and σ_0 (Fig. 3a and b) shows the distinct oxygen minimum (4.1 $ml\,l^{-1}$) and nitrate maximum (34–35 $\mu mol\,l^{-1}$) corresponding to density values near 27.72. These densities correspond to UCDW and agree with those given in Sievers and Nowlin (1984).

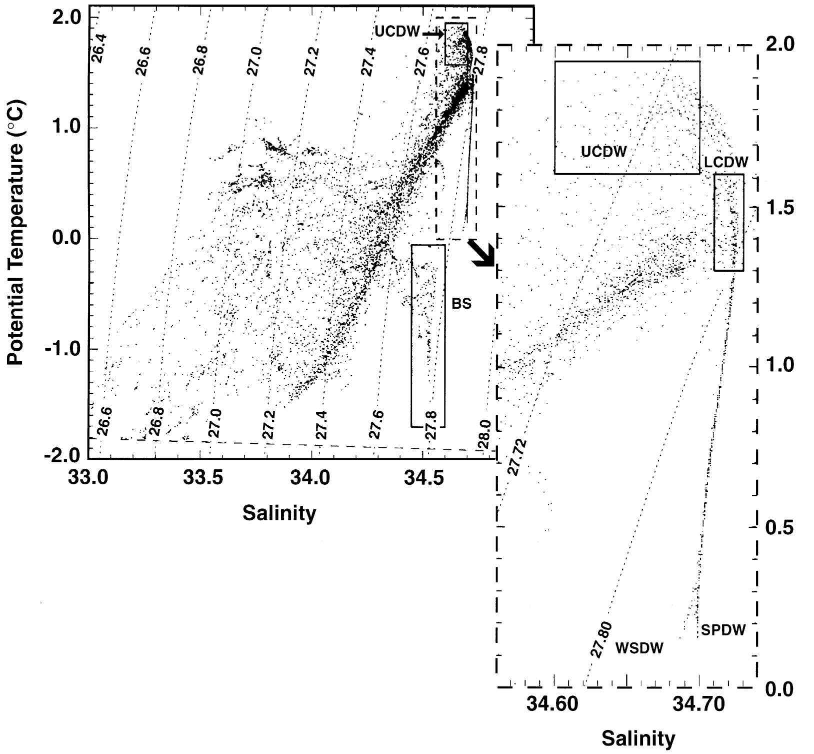

Fig. 2. Potential temperature-salinity diagram constructed from measurements made from March to May 1993 at the locations shown in Fig. 1B. The dashed curved lines represent contours of σ_0. The enlarged dashed region shows the temperature and salinity ranges associated with Upper Circumpolar Deep Water (UCDW) and Lower Circumpolar Deep Water (LCDW), South Pacific Deep Water (SPDW), and Weddell Sea Deep Water (WSDW). The region outlined in the solid box corresponds to the temperature and salinity associated with Bransfield Strait (BS) water.

LCDW is characterized by a salinity maximum, which is derived from North Atlantic Deep Water (NADW) (Gordon, 1967; Reid et al., 1977; Whitworth and Nowlin, 1987), and by a local nitrate minimum (Sievers and Nowlin, 1984; Whitworth and Nowlin, 1987). The salinity maximum observed in the west Antarctic Peninsula region (34.729) is similar to that observed in Drake Passage (Sievers and Nowlin, 1984). This is the lowest CDW salinity maximum in the Southern Ocean and results because Drake Passage is furthest removed from the NADW source of this water (Whitworth and Nowlin, 1987). The local minimum in nitrate that occurs between 32 and 33 $\mu mol\,l^{-1}$ at a σ_0 of 27.8 (Fig. 3b) corresponds to LCDW. This is within the range of values reported for LCDW in Drake Passage (Sievers and Nowlin, 1984; Whitworth and Nowlin, 1987).

On the continental shelf, landward of the southern boundary of the ACC, there exists a cooler (1.0–1.4°C) and slightly fresher (34.6–34.7) version of UCDW. This water represents UCDW that has been modified as it moved onto the shelf.

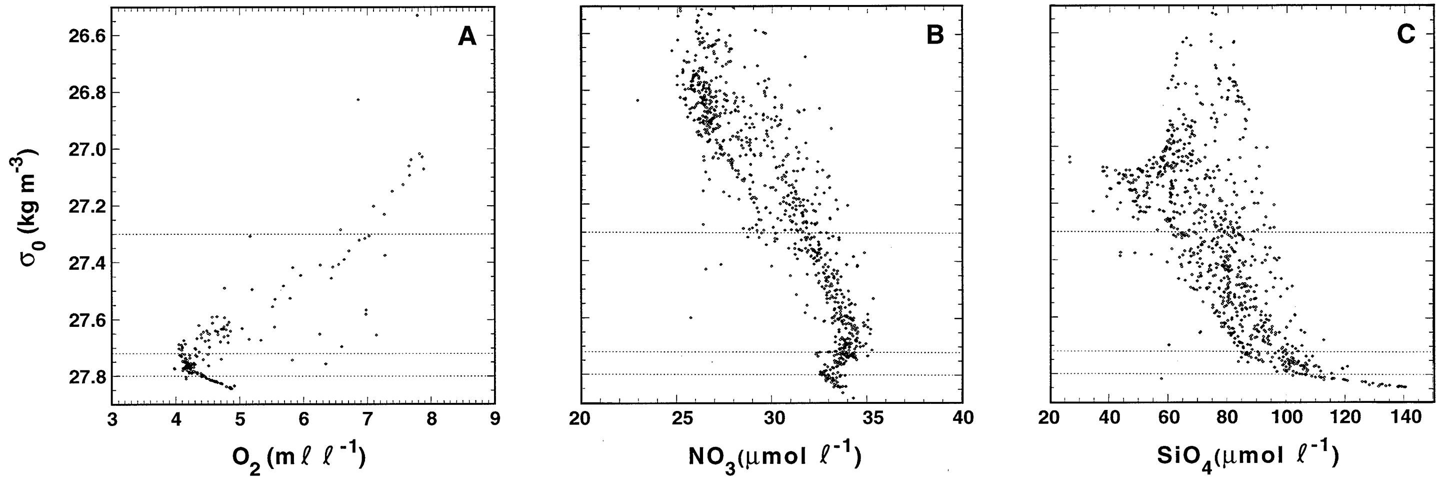

Fig. 3. Relationships between σ_0 and (A) oxygen, (B) nitrate, and (C) silicate obtained from measurements made in March to May 1993 at the locations shown in Fig. 1B. Nutrient and oxygen measurements were provided by Dr. D. Karl, University of Hawaii.

Two deep water masses with distinct characteristics are located below LCDW and are represented by the two branches in θ–S space below 0.3°C and at salinities greater than 34.65. The branch that terminates at the lower salinity represents Weddell Sea Deep Water (WSDW) (Sievers and Nowlin, 1984). This water flows westward along the Scotia Sea to fill the South Shetland Trench (Fig. 1b), which is believed to be the western extent of WSDW in Drake Passage (Nowlin and Clifford, 1982). The branch that terminates at the higher salinity is South Pacific Deep Water (SPDW), which has its origins in the deep southeast Pacific Basin and flows eastward through Drake Passage (Sievers and Nowlin, 1984). The SPDW is characterized by relatively high silicate concentrations as evidenced by values in excess of 130 μmol l^{-1} seen in the silicate-density relationship (Fig. 3c).

A final water mass in the θ–S diagram (Fig. 2), which is colder and fresher than most sampled in the study region, is Bransfield Strait (BS) Water. This water mass is observed inside Bransfield Strait and lacks the distinct temperature maximum associated with CDW found over the rest of the west Antarctic Peninsula shelf. Minimum oxygen values sampled at depth in the Bransfield Strait were found to be in excess of 5.5 ml l^{-1} (Fig. 3a) and are approximately 1.5 ml l^{-1} higher than those sampled at similar densities along the western Antarctic Peninsula.

3.2. Vertical distributions

The vertical distribution of temperature and salinity at specific across-shelf locations provides a description of the water masses over the continental shelf west of the Antarctic Peninsula (Figs. 4 and 5). The AASW, which is found in the upper 100–150 m of each transect, varies in character from north to south. Along the northern and middle portions of the study region (Fig. 4), AASW is above 0°C and is less than 0°C at the southernmost transect (Fig. 5a). The 300 line was occupied late in the cruise and had experienced significant cooling. This cooling occurred without an accompanying increase in salinity from brine rejection (Fig. 5b), as would be expected for recent cooling not yet sufficient for ice formation.

The location of WW can be tracked across shelf by following the 0°C isotherm in Figs. 4 and 5a. The lack of WW at the middle portion of the 800 line (Fig. 4a) and in the inner portion of the 600 line (Fig. 4b) suggests that this layer was eroded by mixing with the warmer waters above and possibly those below. These intense mixing regions coincide with areas of shallow topography. The outcropping of the 0°C isotherm on the inner portion of the 800 line, which occurs near one of the deep basins of the Bransfield Strait, marks the thermal front separating the surface waters of the Bransfield Strait from those of the west Antarctic Peninsula continental shelf. Along the 300 line, which was occupied towards the end of the cruise, the entire upper water column is composed of temperatures below 0°C. The 0°C isotherm deepens slightly onshore and is found near 150 m.

All transects show temperatures in excess of 1.6°C below 200 m at the outer edge of the continental shelf, which is associated with UCDW. The penetration of this water mass onto the continental shelf is limited to the shelf break region on the 800 and 600 lines (Fig. 4) but extends 20–30 km onto the shelf along the 300 line (Fig. 5a). This

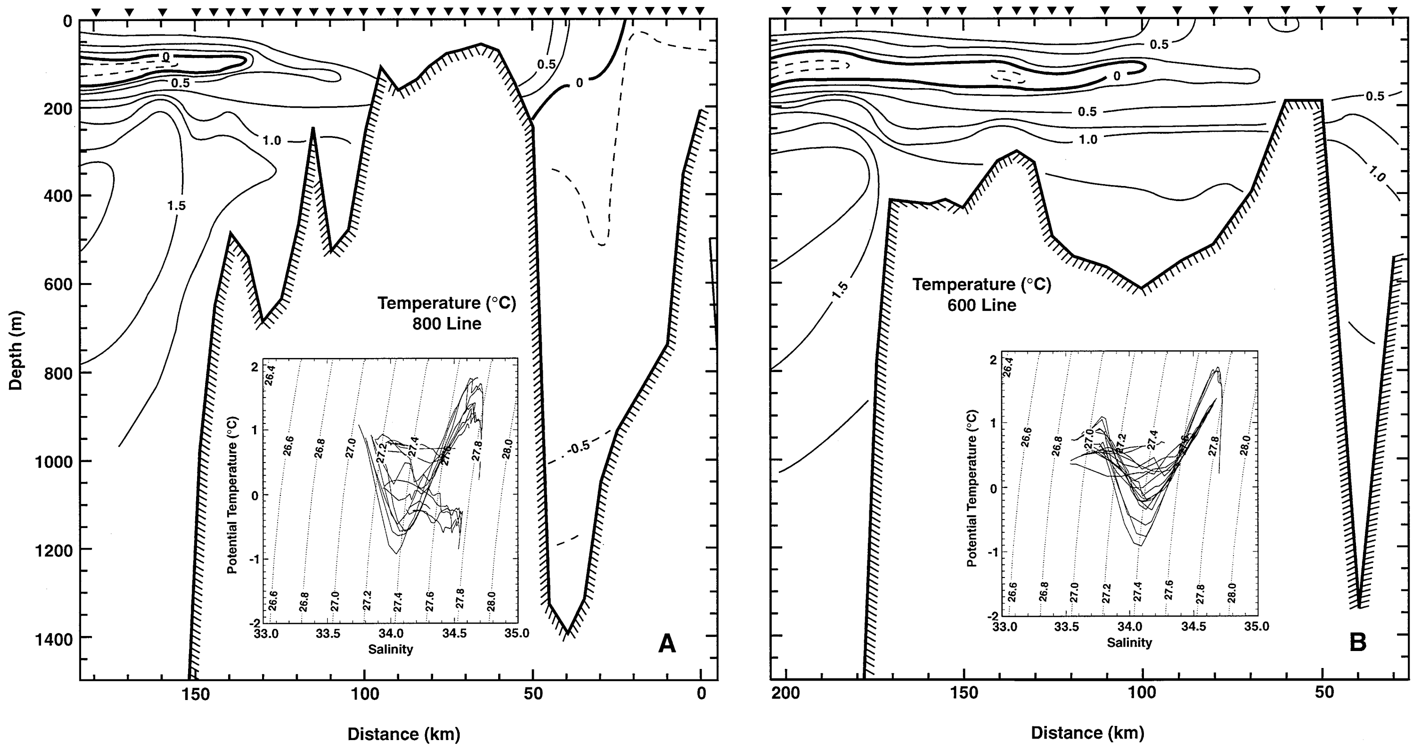

Fig. 4. (A) Temperature distribution in the upper 1500 m along the 800 line across-shelf transect, which is at the northern end of the study region (cf. Fig. 1B). Solid lines represent positive temperatures; dashed lines represent negative temperatures. The heavy line represents the 0°C isotherm. Contour interval is 0.25°C. The triangles indicate the location of the CTD and XBT stations along the transect. The inset shows the potential temperature-salinity distribution constructed from the measurements made at the CTD stations along the transect. Hatching indicates the bottom. (B) Same as Fig. 4A, except for the 600 line across-shelf transect, which is towards the middle portion of the study region (Fig. 1B).

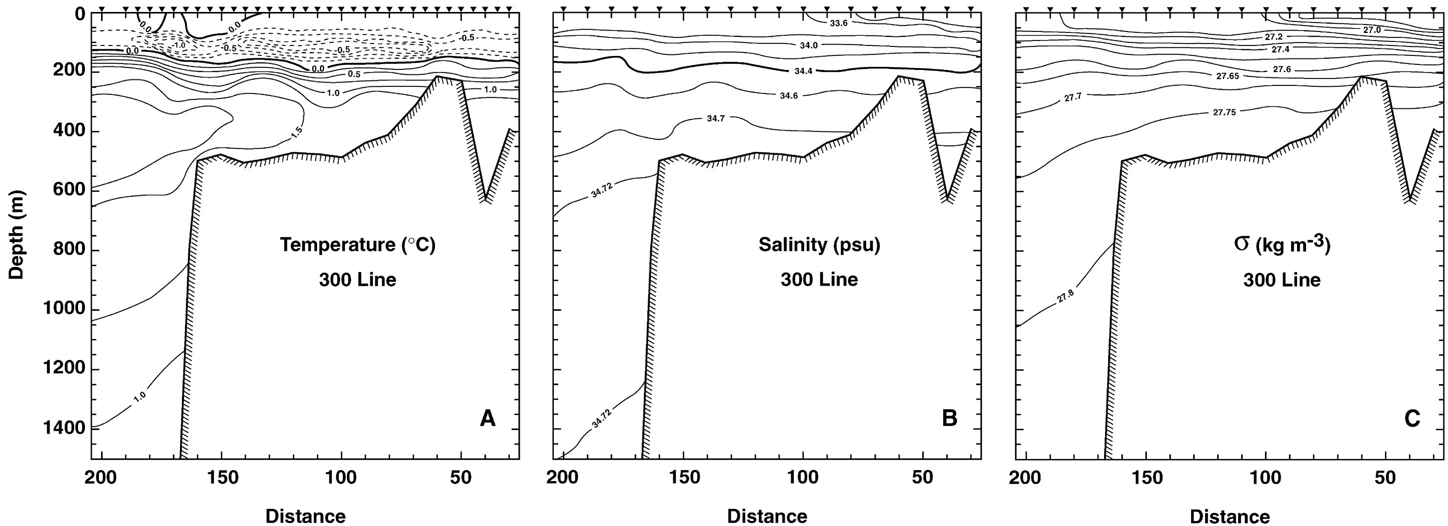

Fig. 5. (A) Same as Fig. 4A, except for the 300 line across-shelf transect, which is towards the southern portion of the study region (Fig. 1B) and without the θ–S inset. (B) Salinity distribution in the upper 1500 m along the 300 line across-shelf transect. The heavy line represents the 34.40 isohaline. Contour interval is 0.20 from 33.40 through 34.60. The 33.70 and 33.72 contours are also included. (C) Density distribution in the upper 1500 m along the 300 line across-shelf transect. Contour intervals are 0.10 and 0.05 for the density ranges of 26.80 through 27.70 and 27.65 through 27.80, respectively.

intrusion is indicated by the closed temperature contours in excess of 1.6°C indicating the presence of a distinct temperature maximum extending across the shelf (Fig. 5a). The intrusion of UCDW is not as obvious in the salinity and density distributions at the outer shelf (Fig. 5b and c).

The axis of UCDW can be tracked by the location of the temperature maximum along each transect (Figs. 4 and 5a) and is sloped upward toward the shelf edge between depths of 600 and 400 m. Similarly, the axis of LCDW off the shelf edge is located by the salinity maximum (Fig. 5b) and the 27.80 σ_0 surface (Fig. 5c) at depths of 800 m to more than 1000 m. The upward slope of UCDW and LCDW layers is consistent with the geostrophically balanced ACC located seaward of the shelf edge.

On the 600 and 300 transects, a cooler version of CDW occupied the shelf below 200 m (Figs. 4b and 5a). This water mass is also found on the outer portion of the 800 transect (Fig. 4a), but its across-shelf extent is limited by topography. The θ–S diagrams for the 800 and 600 transects (Fig. 4a and b) show a well-defined thermal separation between UCDW and the shelf waters. Moreover, the tight relationship in the θ–S diagrams indicates that waters on the shelf retain their integrity well inshore of the shelf break.

The inner 800 line exhibits properties associated with BS water, which appears as cooler and less saline water on the θ–S diagram from this transect (Fig. 4a). The separation between Bransfield Strait and west Peninsula shelf waters is further illustrated by a temperature section along the axis of Gerlache Strait (Fig. 6). Water warmer than 0°C is found at the southern end of the Gerlache Strait section near Anvers and Brabant Islands. The only other region of water warmer than 0°C is found at the mid-point of the section where it passes Brabant Island and Gerlache Strait and is in direct contact with the waters over the continental shelf. With this exception, water in Gerlache Strait is less than 0°C, which is characteristic of BS water.

3.3. Horizontal distributions

Along the western Antarctic Peninsula, the southern boundary of the ACC is distinguished by the 1.6°C isotherm, which corresponds to the southern extent of the ACC determined from oxygen, temperature, and salinity properties as presented in Orsi et al. (1995). Temperatures greater than 1.6°C, which correspond to UCDW, are found along the outer continental shelf in the southern and northern portions of the study region (Fig. 7). The onshelf location of this water is more pronounced at the southern end and is lacking in the mid-portion of the study region. The 1.4°C isotherm is continuous over the entire region and provides a boundary for the transition between UCDW and the cooler form of UCDW that floods the shelf below 200 m. Water warmer than 1.0°C is found along the innermost portion of the study region. The only water below 200 m that is less than 0°C is found in Bransfield Strait. The boundary between the waters west of the Antarctic Peninsula continental shelf and those in Bransfield Strait represent the strongest temperature gradient observed below 200 m.

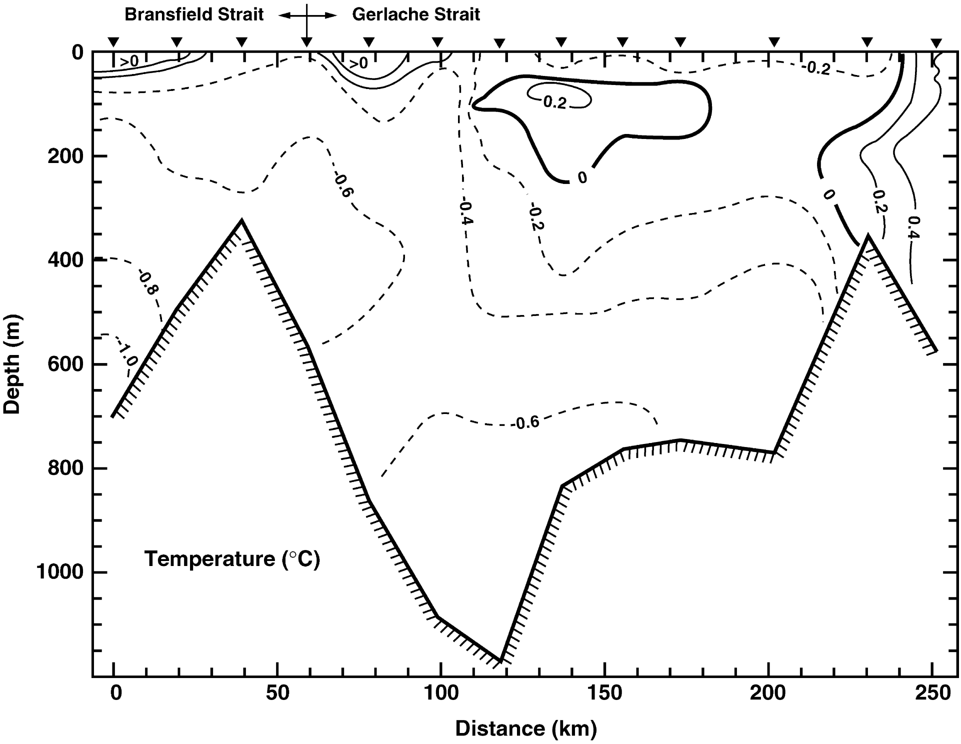

Fig. 6. Temperature distribution along the axis of the Gerlache Strait constructed from XBT measurements. Solid lines represent positive temperatures; dashed lines represent negative temperatures. The heavy line represents the 0°C isotherm. Contour interval is 0.2°C. The triangles indicate the location of the XBT stations along the transect and the hatching indicates the bottom. The transition from the Gerlache Strait to Bransfield Strait is indicated by the arrow at the top of the figure.

While the core method mentioned above is useful to locate UCDW and to examine its potential contribution to the shelf waters, it is potentially misleading, because the core properties of the water masses (e.g. the maximum temperature) change depth and density surfaces. However, the distribution of potential temperature and salinity on the 27.74 σ_0 surface (Fig. 8), which corresponds to UCDW (Fig. 2), show UCDW at the outer shelf and the cooler and fresher form of the water overlying the shelf, which is consistent with the isotherm distributions shown in Fig. 7. Along the 300 line (Fig. 8), a 20–30 km intrusion of UCDW onto the shelf is seen and is consistent with the patterns in the vertical sections from this location (cf. Fig. 5). The inner portions of the 400, 500 and 600 lines are occupied by water with density less than 27.74, indicating that the inshore waters of the northern region do not exchange, or have limited exchange with those of the southern shelf region.

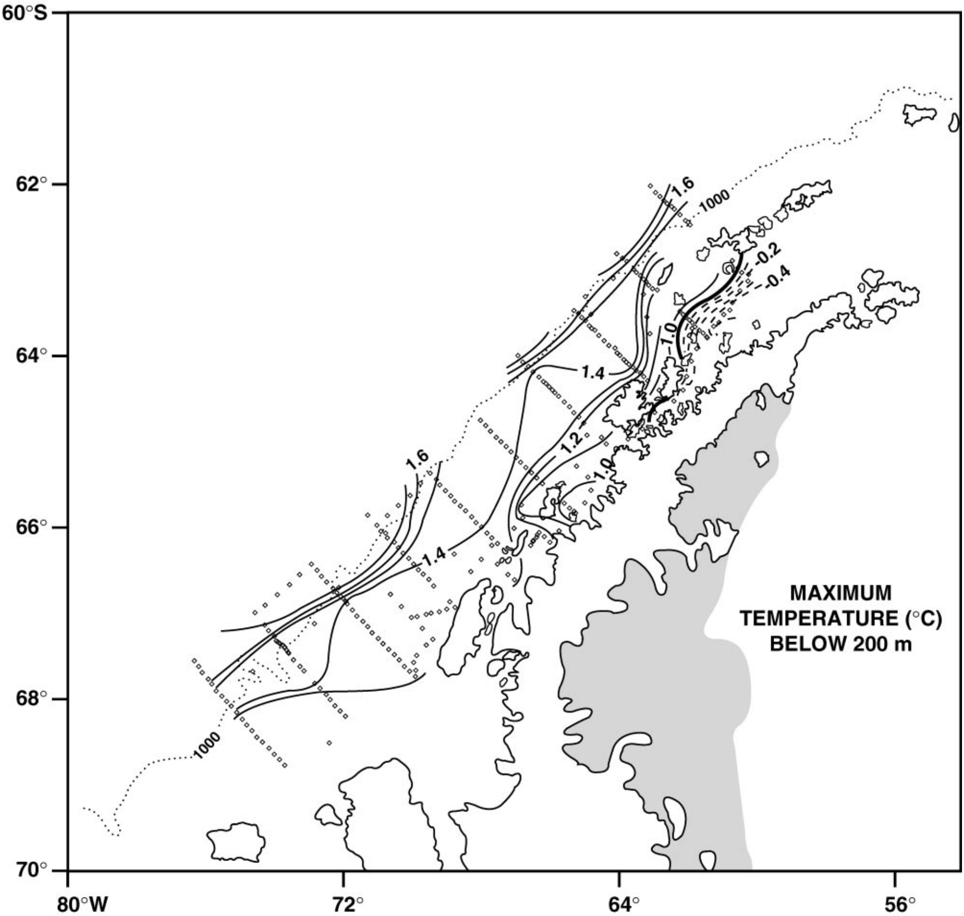

Fig. 7. Distribution of the maximum temperature below 200 m. Solid lines represent positive temperatures; dashed lines represent negative temperatures. The heavy line represents the 0°C isotherm. Contour interval is 0.1°C. Open squares indicate the station locations used to construct the temperature distribution. The dotted line indicates the 1000 m isobath.

3.4. Dynamic height field

The dynamic topography (Fig. 9) for 200 m relative to 400 m for the region west of the Antarctic Peninsula was calculated from the hydrographic observations. This depth span is below the region that is influenced by seasonal variability and shallow enough to provide coverage of most of the continental shelf. The dynamic topography shows baroclinic flow, assuming no flow at 400 m, exists as a large cyclonic gyre covering the shelf. This gyre is attached to the ACC, which flows to the northeast along the outer edge of the continental shelf. Flow is to the south along the inner portion of the shelf and appears to be continuous along the inner shelf and to be

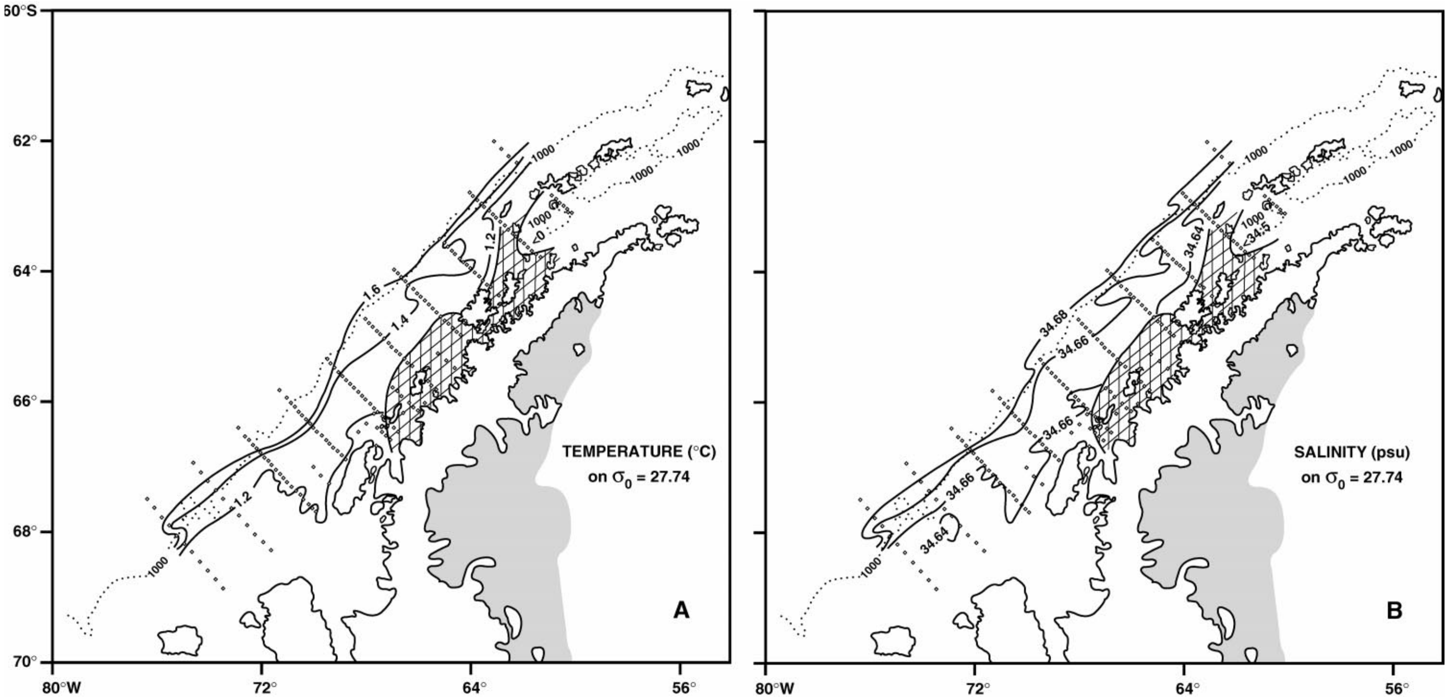

Fig. 8. (A) Temperature on the 27.74 kg m^{-3} σ_0 surface. Contour interval is 0.2°C. Open squares indicate the station locations used in the analysis. The hatched area indicates the region where the entire water column was lighter than 27.74 kg m^{-3}. The dotted line indicates the 1000 m isobath. (B) Same as Fig. 8A except for salinity. Contour interval is 0.02.

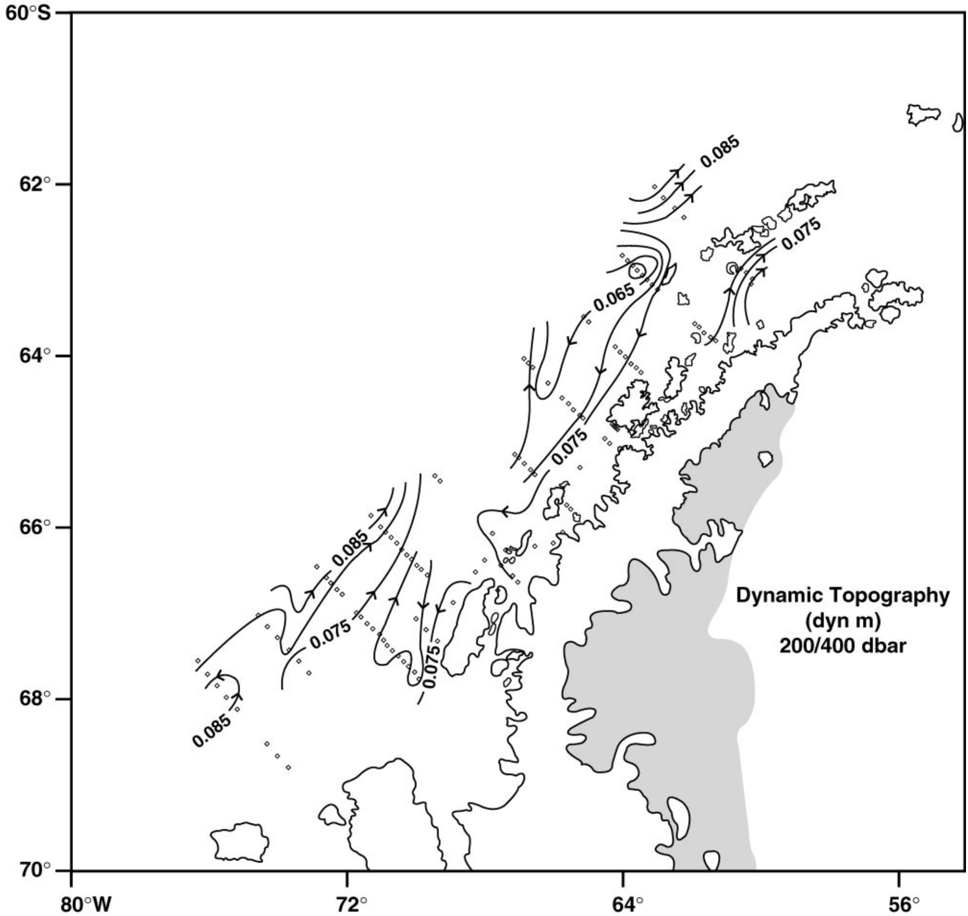

Fig. 9. Distribution of the dynamic topography west of the Antarctic Peninsula calculated for the 200 db surface relative to the 400 db surface from the March to May 1993 temperature and salinity measurements. Contour interval is 0.005 dyn m. Open squares indicate the station locations used to construct the dynamic topography. The arrows indicate the direction of flow.

weakly connected in the mid-portion of the study region. The shelf gyre has two cyclonic sub-gyres separated by the shallow topography along the mid-portion of the study region (the 400 line). The northern sub-gyre is more intense and smaller scale than the southern sub-gyre. The northward flow in the Bransfield Strait is associated with the Bransfield Current (Niiler et al., 1990).

The gradient in the dynamic topography for the northern end of the shelf gyre corresponds to a transport of about 0.15×10^6 m^3 s^{-1} between 200 and 400 m. The transport associated with the southern edge of the gyre is somewhat less, being on the order of 0.1×10^6 m^3 s^{-1}. The transport associated with the ACC and the Bransfield Current is similar to that of the gyres.

The geostrophic velocities between 200 and 400 m for most of the west Antarctic Peninsula continental shelf, calculated from the dynamic height field, are on the order of 0.01–0.02 m s^{-1}. The geostrophic velocities associated with the Bransfield Current and the southern extent of the Antarctic Circumpolar Current ACC are 0.03–0.04 m s^{-1}.

4. Discussion and summary

4.1. General water mass characteristics

4.1.1. AASW

AASW displays a broad range of characteristics because it is affected by a large variety of mechanisms, including atmospheric exchange, ice formation and melting, and exchange across the permanent pycnocline. During the winter, the ocean surface layer is uniformly mixed to 100 m depth or more with the water very near the freezing point. As the season progresses toward summer, ice melts, freshening thin (20–30 m) layers at the surface, which warm by solar heating. Storms mix this surface water with waters deeper in the mixed layer, creating a number of layers with different characteristics. In the fall, surface warming decreases, and the storm intensities increase, leading to a breakdown of the seasonal pycnoclines and a return to the thick, cold, uniform mixed layer during the winter (Hofmann and Klinck, 1998a, in press).

During late summer and fall of 1993, seasonal pycnoclines started as warm and fresh layers, which were progressively eroded by surface winds and cooling. These changes create considerable variability in AASW, which is seen in the scatter in the θ–S plot (Fig. 2) and the alongshore variability observed in the change of surface properties from north to south (Figs. 4 and 5). The southern portion of the study region was occupied later in the cruise, and the alongshelf gradient in surface temperature reflects the cooling that occurs in the austral fall.

4.1.2. CDW

CDW is represented in these observations by two varieties, UCDW and LCDW, which are oceanic water masses and are associated with the ACC. At the edge of the continental shelf west of the Antarctic Peninsula, the core of the LCDW is found between 800 and 1000 m (cf. Fig. 4), and UCDW can appear at depths of 200–400 m, which is above the shelf break. Thus, the relative shallowness of UCDW, coupled with the deep continental shelf, produces a water mass structure at depth on 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 AASW (discussed in next section) to form a modified version of UCDW. This modified water mass is found throughout the west Antarctic Peninsula continental shelf region below 200 m (cf. Fig. 8), extends well inshore of the shelf break, and is found in the nearshore regions inside of the 200 m isobath (Smith et al., 1995). Hence, this provides a consistent deep source of heat and salt and low oxygen water for the west Antarctic Peninsula continental shelf.

At the southern and middle portions of the study region, water warmer than 1.0°C is found in contact with the bottom across the shelf (Fig. 4a and b). This indicates that the shelf along the Antarctic Peninsula is not a site of the cold, dense shelf water that is found on other shelf systems such as the Weddell and Ross Seas (Jacobs et al., 1970, 1985; Hofmann and Klinck, 1998b). A possible explanation for the absence of the cold, dense shelf water along the Antarctic Peninsula may be the relatively warm atmospheric conditions in the region. This region is not generally affected by the katabatic winds (due to cold air draining from the continental plateau), which are important in other places around Antarctica (Parish and Bromwich, 1987; Schwerdtfegger and Amaturo, 1979). Furthermore, the warmer atmospheric temperatures may lead to the region being an area of net annual ice melt, as opposed to a region of ice formation as proposed by Gloerson et al. (1992). This net ice melt would tend to freshen the surface waters, making them lighter and less likely to sink. In addition to the warmer atmospheric conditions, the presence of warm oceanic water across the shelf provides a potential source of heat from below. Thus, the presence of UCDW on the shelf may inhibit (or reduce) winter ice formation and therefore reduce the accompanying brine rejection, again resulting in lighter surface waters, or shallower winter convection.

4.2.2. *Exchanges with Bransfield Strait*

One potential pathway of water mass interaction along the western Antarctic Peninsula, which must be investigated, is the interaction of waters in the Bransfield Strait with adjacent waters through the Gerlache Strait. The θ–S diagram (Fig. 2), the vertical temperature distribution along the 800 line (Fig. 4a), and the temperature section along the Gerlache Strait (Fig. 6) indicate minimal mixing of Bransfield Strait waters with those to the west of the Peninsula. The shallow (200 m) sill at the western end of Bransfield Strait effectively restricts exchanges with the shelf along the west Antarctic Peninsula. The downward tilt of the isotherms along the inner portion of the 600 line (Fig. 4b) suggests some flow from the Bransfield Strait to the west Antarctic Peninsula shelf. The waters on the inner portion of the 600 transect, which aligns with the mouth of the Gerlache Strait, are 0.2°C cooler and 0.05 fresher than adjacent shelf waters. A mixture of 80% west Antarctic Peninsula water and 20% water from the Bransfield Strait could produce this observed θ–S signature. Again, the strong thermal front that exists between west Antarctic Peninsula and water in the Bransfield Strait (Fig. 6) and the light water along the inner portion of the study region are indications that this exchange is limited and possibly episodic in nature.

Openings between islands along the Gerlache and Bransfield Straits provide the only deep connection to the shelf west of the Antarctic Peninsula. Capella et al. (1992) indicate that deep exchange may occur in these regions; however, the data analyzed for this study indicate that the exchange is not sufficient to alter the deep water mass structure of the west Antarctic Peninsula shelf. Temperatures less than 0°C are characteristic of the deeper waters in Bransfield Strait and likely form by deep convection of winter surface waters (Gordon and Nowlin, 1978; Killworth, 1983) or by isopycnal exchange with waters on the northwest Weddell shelf (Whitworth et al., 1994). These low temperatures are not at depth along the inshore portions of the other across-shelf transects to the south (cf. Figs. 4 and 5a). Thus, throughout the majority of the study region, there is no inner shelf front comparable to those observed on temperate and mid-latitude continental shelves.

The water mass structure within the upper waters of Bransfield Strait has been described as complex and as arising from mixing from different water types (Stein, 1989). Sievers (1982) suggested that waters in the upper 200 m of Bransfield Strait could be classified as being of Antarctic Peninsula continental shelf origin, a mixture of central Bransfield Strait water, and a mixture of Bellingshausen Sea water. Stein (1989) and Stein and Heywood (1994) suggest that westerly and northwesterly gales are a primary mechanism for transporting warmer Drake Passage waters into Bransfield Strait. At the same time, the outflow of cold Weddell Sea water in the upper 500 m is increased in the eastern Strait. Therefore, episodic wind-induced transport may be important in regulating heat and salt balances in the Bransfield Strait.

Drifters deployed in Gerlache Strait as part of the RACER field programs showed that the surface flow is to the northeast and persists as a coherent feature into the southwestern portion of the Bransfield Strait (Niiler et al., 1990). Once inside, this flow continues northeast along the axis of the Strait (Niiler et al., 1991). Surface velocities associated with this flow can be in excess of 0.50 $m\,s^{-1}$ and provide a mechanism for transporting surface water from the west Antarctic Peninsula continental shelf into Bransfield Strait. However, the distribution and limited amount of CDW (defined as water in excess of 1.0°C) in Gerlache Strait (cf. Fig. 8) suggests little exchange with the shelf to the west. The input of CDW is controlled by bathymetry, with the only real source being at the western end of the Strait and through a gap north of Brabant Island. It may be that the surface pressure gradient in Gerlache Strait is sufficient to drive outward flow at depth, thereby preventing the inflow of shelf waters from the west Antarctic Peninsula. Hence, the signature of this water mass is weak, and the little water that does enter Gerlache Strait may be rapidly mixed.

4.3. Heat and salt budgets

An important aspect of the hydrography of the west Antarctic Peninsula continental shelf is understanding the source of the deep shelf waters and the processes by which they are created. Earlier work (Potter and Paren, 1985) suggested that the across-shelf transport of CDW is driven by ice melting processes in the inner shelf region. Outflow of the buoyant surface water produced by ice melt is replaced by onshore transport of CDW at depth. This circulation is self sustaining, with the upwelled CDW providing the heat source that maintains the ice melting and hence the circulation. The across-shelf velocities associated with this circulation were estimated to be 0.006 $m\,s^{-1}$ (Potter and Paren, 1985). A similar circulation has been suggested to exist in the Ross Sea (MacAyeal, 1985). Estimates of net glacial melt from the Ross Sea extrapolated to the entire Antarctic Shelf (Jacobs et al., 1985) provide a net flux of 2000 $km^3\,yr^{-1}$, which is equivalent to 0.125 $m\,yr^{-1}$ for the west Antarctic Peninsula shelf. The west Antarctic Peninsula region, however, has fewer ice shelves, so the net freshwater flux may be lower than the value for the Ross Sea. The net freshwater flux from George VI sound, near Marguerite Bay, is estimated to be 2.1 m yr^{-1} (Potter and Paren, 1985), which is larger by about an order of magnitude than the values obtained in the Ross Sea. However, this ice shelf is limited in geographic extent relative to the west Antarctic Peninsula continental shelf. Also, the rate at which this fresh water can escape the near shore region is unknown as is whether this water is transported across the shelf to the shelf break or, more likely, is trapped against the coast. Therefore, other dynamics may be responsible for the across-shelf movement of UCDW.

The simplest hypothesis for the system is that UCDW moves along isopycnal surfaces onto the shelf then cools (primarily) and freshens (slightly). The general temperature and salinity characteristics on the shelf west of the Antarctic Peninsula are relatively stable over a year and from year to year, and the WW portion of AASW is sufficiently deep to retain its basic θ–S characteristics over an annual cycle (Hofmann and Klinck, 1998a). This stability means that there are sharp boundaries that persist throughout the year between waters with different temperatures and salinities, which give rise to diffusive fluxes. Because of these relatively time invariant gradients, it is possible to estimate heat and salt fluxes to obtain an estimate of the volume exchange between the ocean and shelf waters.

A diffusive model was developed to test the potential pathways of water mass exchange, which are illustrated schematically in Fig. 10. The model assumes that vertical diffusion of heat and salt between shelf waters and AASW are balanced by an onshore, horizontal diffusion from CDW (Pathways A and D in Fig. 10). Horizontal diffusion in this model represents a number of processes including mesoscale variability, intrusive layering, small-scale turbulent exchanges as well as long term background advective processes.

The equation for this balance is

$$\frac{\partial}{\partial x}\left(K_{\mathrm{h}}\frac{\partial T}{\partial x}\right)+\frac{1}{\rho_o c_p}\frac{\partial (F_{\mathrm{h}})}{\partial z}=0, \tag{1}$$

where x is the directed offshore, z the upward, T is the temperature, K_{h} is horizontal diffusivity (assumed to be the same for heat and salt), F_{h} is the vertical flux of heat, ρ_o (= 1028 kg m^{-3}) is water density and c_p (= 3987 J kg^{-1} °C^{-1}) is the specific heat of seawater. A bulk budget is obtained by integrating Eq. (1) over a typical width for the continental shelf from the shelf break to the coastal zone, taken to be the 200 m isobath, and from the bottom ($z = -h_{\mathrm{b}}$) to the bottom of the winter water layer ($z = -h_{\mathrm{s}}$). Assuming that the flux of heat through the bottom and the coastal wall are zero, the budget for heat becomes

$$H K_{\mathrm{h}}\left.\frac{\partial T}{\partial x}\right|_{\mathrm{sb}}+L\frac{F_{\mathrm{h}}}{\rho_o c_{\mathrm{p}}}=0, \tag{2}$$

where $H = 100$ m is the thickness of the water below WW, $L = 150$ km is the width of the shelf and the subscript *sb* indicates values at the shelf break. A budget for salinity

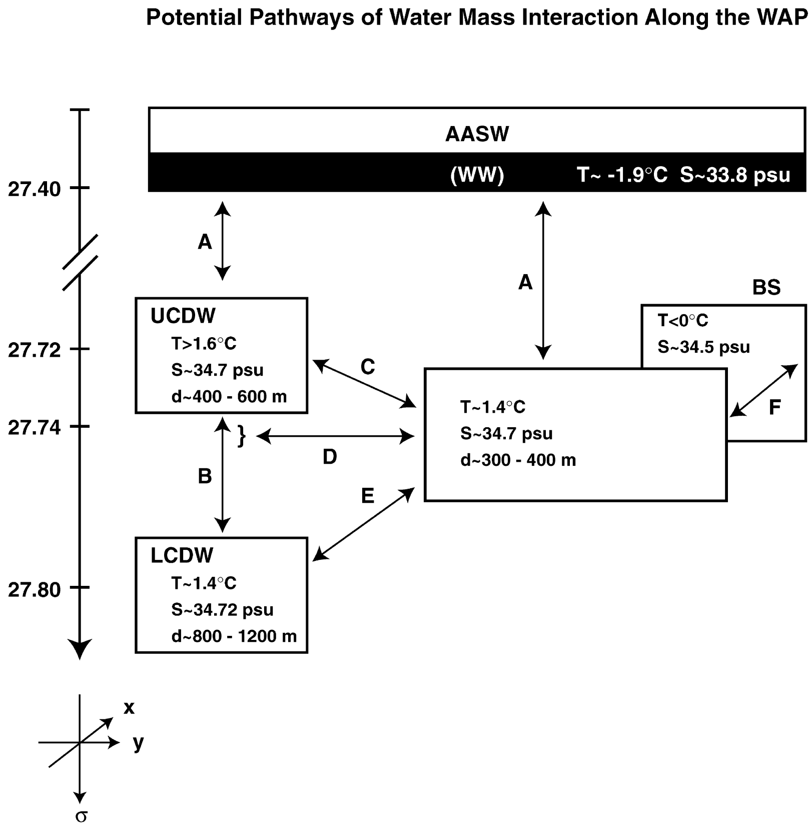

Fig. 10. Schematic representation of the water masses along the western Antarctic Peninsula. The horizontal axes represent the along- and across-shelf dimensions (x and y, respectively). The vertical axis represents density. Generalized temperatures (T), salinities (S) and depths (d) are reported for each water mass. Water mass naming convention is the same as in Fig. 2. Potential pathways of water mass interaction are labeled A through F and are discussed in the text.

can be obtained by a similar process yielding

$$H K_\mathrm{h} \frac{\partial S}{\partial x}\bigg|_\mathrm{sb} + L \frac{F_\mathrm{s}}{\rho_o} = 0, \tag{3}$$

where F_s is the vertical flux of salt.

The unknown quantities in these budgets are the diffusivities. Estimates of temperature and salinity along with their gradients at the shelf break can be used to calculate the unknown quantities. The comparison of the calculated budgets of heat and salt provide a consistency check for the assumed dynamics.

The vertical heat flux from the deep shelf waters and AASW was estimated from historical hydrographic measurements to be 12 W m^{-2} (Hofmann et al., 1996). The observed vertical temperature difference across the permanent pycnocline is 3.0°C over a distance of about 150 m and is consistent throughout the year. An equivalent turbulent heat flux can be obtained with these gradients and a vertical diffusion coefficient approximately equal to $10^{-4}\,m^2\,s^{-1}$, which is consistent with values estimated for the Weddell Sea (Martinson, 1990) and under a west Antarctic ice sheet (Potter and Paren, 1985).

Using $12\,W\,m^{-2}$ as the average heat loss across the shelf, and a horizontal temperature difference at the shelf break of 0.5°C in 25 km, Eq. (2) yields a horizontal diffusivity (K_h) of approximately $200\,m^2\,s^{-1}$. This represents the horizontal diffusivity required to maintain an onshore flux of heat necessary to balance the heat exported to the surface layer.

Similar calculations are made to estimate the onshore salt flux required to balance the vertical salt flux from deep shelf waters and the WW portion of AASW. Using the same value for vertical diffusivity of salt as used in the heat budget ($K_v \sim 10^{-4}\,m^2\,s^{-1}$) and a vertical salt difference of 0.7 over 150 m results in a vertical salt flux of 0.5 mg salt $m^{-2}\,s^{-1}$. Using a horizontal salinity change of 0.02 over 25 km, gives the required horizontal diffusivity of approximately $1200\,m^2\,s^{-1}$.

The above calculation results in horizontal diffusivities that are within reasonable oceanographic ranges and demonstrates that, to a first order approximation, the proposed balance is dynamically consistent. The factor of 6 difference between the diffusivities estimated by the temperature and salinity calculations suggests that some important dynamics are neglected. One possible neglected process is the alongshore exchange of heat and salt. While little evidence for significant alongshore gradients exists in the vertical sections (Figs. 4 and 5), there is an indication of colder, fresher water that exists mid-shelf along the upper and lower portions of the region on the property distributions along the 27.74 density surface (cf. Fig. 8). The possibility that the colder, fresher water along the northern portion of the domain originates in the Weddell Sea and is then transported around the tip of the Antarctic Peninsula as part of the westward flow known to exist near the Antarctic margin (Jacobs, 1991) cannot be dismissed; however, the observations from March – May 1993 do not indicate that this process has a major influence on the shelf. The colder, fresher water disappears along the inner portion of the study region (Fig. 8), indicating that the inshore waters from the northern portion of the region do not exchange with those of the southern portion of the region. The cold, fresh water along the mid-shelf in the southern domain most likely originates in nearby Marguerite Bay.

In the above calculation, identical values were used for the heat and salt vertical diffusivities, thereby ignoring any contribution from double diffusive processes. Vertical profiles of temperature, salinity and density from the west Antarctic Peninsula continental shelf suggest that double diffusive instabilities exist. Thus, the potential contribution of double diffusion can be estimated by recalculating the horizontal diffusion coefficient values needed to balance the terms in Eqs. (2) and (3) using a ratio of 3.3 for the vertical diffusion of heat versus that of salt as has been observed in the Weddell Sea (Martinson, 1990). This ratio results in horizontal diffusivities for heat and salt of 200 and $400\,m^2\,s^{-1}$, respectively, which provides a more consistent balance. Thus, the potential importance of double diffusion to the heat and salt balances in this region warrants further examination but is beyond the scope of this study.

In the above calculation, the horizontal flux of heat and salt is purely isopycnal, which would require water from just below core UCDW to resupply the shelf (Pathway D in Fig. 10). If a process like double diffusion is included in the calculation, where differential vertical transfers of heat and salt are allowed (more heat than salt), then an exchange that favors pathway C on Fig. 10 is preferred. Pathway C would involve UCDW moving onto the shelf and cooling and slightly freshening to form the observed shelf θ–S signature. The direct evidence of UCDW on the shelf (Fig. 5a) suggests that it is the likely source shelf waters.

The possibility that core LCDW contributes to the shelf waters through pathway E must also be investigated. Pathway E would require core LCDW to be lifted 200–400 m to the shelf, where it would then have cool and mainly freshen to produce the θ–S structure observed along the shelf. For these reasons, it is doubtful that core LCDW is the main source for the shelf along the western Antarctic Peninsula. The contribution of LCDW to the shelf is indirectly possible, and indirectly included in the calculation above through its interaction with core UCDW along pathway B. The evidence of limited exchange between Bransfield Strait and the west Antarctic Peninsula discounts pathway F as a major contributor to the shelf water characteristics.

4.4. Transport pathways

The dynamic topography (200 relative to 400 m) for the continental shelf west of the Antarctic Peninsula (Fig. 9) indicates a large cyclonic gyre on the shelf with two cyclonic sub-gyres. This pattern is consistent with that obtained from dynamic topography fields constructed for this region from observations obtained during SIBEX (Stein, 1992) and the circulation pattern constructed from historical hydrographic observations (Hofmann et al., 1992, 1996). However, the higher resolution observations used in this study allow the spatial extent and strength of the gyres to be better defined.

The southern end of the northern sub-gyre is associated with variation in the shelf break topography (Fig. 1a); the northern end of the southern sub-gyre is aligned with a deep across-shelf depression. These bathymetric features and corresponding circulation may provide conduits for moving UCDW onto and across the continental shelf. The bottom topography rises above 300 m in the region between the two sub-gyres; hence, exchanges between the two ends of the large shelf gyre are limited or prohibited, and recirculation and retention of properties in each end is likely to result. The separation between the two sub-gyres contributes to differences in the distribution of the maximum temperature below 200 m between the northern and southern portions of the study region (cf. Fig. 7).

However, the sub-gyres may be connected at the surface, in which case exchanges between the regions are possible, and a net barotropic flow superimposed on the baroclinic circulation (Fig. 9) could change the transport pathways over the shelf.

Also, mesoscale eddies may exist on this shelf, which can distort the dynamic topography. Given the large alongshore distance between hydrographic lines, it is not possible to tell how much of the structure supporting the idea of multiple sub-gyres is due to aliasing of smaller scale circulation features.

The ACC flows along the outer shelf and provides a mechanism to transport properties from south to north at the outer edge of the study area. The proximity of the ACC, and associated water masses, to the shelf along the west Antarctic Peninsula is unique to the Antarctic system. Orsi et al. (1995) examined the circumpolar extent of the ACC and showed that in other regions the southern boundary of the ACC is located well off the shelf. However, the exact location of the ACC relative to the shelf break varies in time and space, and the forcing of the outer shelf circulation by the ACC is episodic (Hofmann and Klinck, 1998a).

Exchanges from north to south may occur along the inner shelf as a result of the weak southward flow. Geostrophic velocities are estimated to be 0.02–0.03 $m\,s^{-1}$, which leads to a displacement of about 2–3 $km\,d^{-1}$. Hence, the time to transport properties and material along the inner shelf is long, which suggests that exchanges of the waters below the pycnocline on the west Antarctic Peninsula continental shelf are limited.

The water mass structure and dynamic topography on the west Antarctic Peninsula continental shelf support the suggestion that there is limited exchange along the shelf either north or south. To the north, the shelf narrows considerably, limiting the possibility of exchange. It has been shown earlier that exchanges between the west Antarctic Peninsula continental shelf and Bransfield Strait are limited below 200 m due to bathymetry, although some exchange occurs through Gerlache Strait. To the south, the study region is open to the Bellingshausen Sea; hence, it is possible that the shelf waters exchange with those of the Bellingshausen Sea.

Climatological winds over the west Antarctic Peninsula continental shelf are from the northeast (Trenberth et al., 1989), which are downwelling favorable. The tendency for these winds would be to pile water along the coast, driving a current to the south. This current may be enhanced in the southern portion of the domain by meltwater from the permanent glaciers located in Marguerite Bay. This southward wind and buoyancy driven current along the coast is consistent with the baroclinic circulation shown in Fig. 9.

Acknowledgements

This research was supported by the US National Science Foundation, Office of Polar Programs, grant No. DPP-90-11927. Computer facilities and support were provided by the Commonwealth Center for Coastal Physical Oceanography at Old Dominion University. Thanks are extended to Dr. D. Karl at the University of Hawaii for providing the nutrient and oxygen data used in this analysis and to T. Houlihan for processing the samples. Thanks are also extended to R. Locarnini, B. Lipphardt, E. Sharp, A. Sutherland and B. Weber for their invaluable assistance in collecting the CTD measurements and for ensuring the high quality of these data.

References

Callahan, J.E., 1972. The structure and circulation of deep water in the Antarctic. Deep-Sea Research 19, 563–575.

Capella, J.E., Ross, R.M., Quetin, L.B., Hofmann, E.E., 1992. A note on the thermal structure of the upper ocean in the Bransfield Strait-South Shetland Islands region. Deep-Sea Research 39, 1221–1229.

Clowes, A.I.J., 1934. Hydrography of the Bransfield Strait. Discovery Reports 9, 1–64.

El-Sayed, S.Z., 1994. History, organization and accomplishments of the BIOMASS Programme, In: El-Sayed, S.Z. (Ed.), Southern Ocean Ecology: the BIOMASS Perspective. Cambridge University Press, Cambridge, pp. 1–8.

Gloersen, P., Campbell, W.J., Cavalieri, D.J., Comiso, J.C., Parkinson, C.L., Zwally, H.J., 1992. Arctic and Antarctic Sea Ice, 1978–1987: Satellite Passive-microwave Observations and Analysis. National Aeronautics and Space Administration, 290 pp.

Gordon, A.L., 1967. Structure of Antarctic waters between 20°W and 170°W. Antarctic Map Folio Series, folio 6, Bushnell, V.C. (Ed.), 14 plates, American Geographical Society, New York, 10 pp.

Gordon, A.L., Nowlin, Jr. W.D., 1978. The basin waters of the Bransfield Strait. Journal of Physical Oceanography 8, 258–264.

Hofmann, E.E., Klinck, J.M., Lascara, C.M., Smith, D.A., 1996. Water mass distribution and circulation west of the Antarctic Peninsula and including Bransfield Strait. In: Ross, R.M., Hofmann, E.E., Quetin, L.B. (Eds.), Foundations for Ecological Research West of the Antarctic Peninsula, American Geophysical Union, Washington DC, Antarctic Research Series, Vol. 70, pp. 61–80.

Hofmann, E.E., Lascara, C.M., Klinck, J.M., 1992. Palmer LTER: Upper ocean circulation in the LTER region from historical data, Antarctic Journal of the United States 27, 239–241.

Hofmann, E.E., Klinck, J.M., 1998a. Thermohaline variability of the waters overlying the West Antarctic Peninsula Continental Shelf, In: Jacobs, S., Weiss, R. (Eds.), Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin, Antarctic Research Series, American Geological Union, Washington DC, Vol. 75, pp. 67–81.

Hofmann, E.E., Klinck, J.M., 1998b. Hydrography and circulation of Antarctic Continental Shelf: 150°E eastward to the Greenwich Meridian. In: Brink, K.H., Robinson, A.R. (Eds.), The Sea, The Global Coastal Ocean, Regional Studies and Synthesis, vol. 11, John Wiley & Sons, New York, pp. 997–1042.

Huntley, M.E., Karl, D.M., Niiler, P.P., Holm-Hansen, O., 1991. Research on Antarctic Coastal Ecosystem Rates (RACER): an interdisciplinary field experiment. Deep-Sea Research 38, 911–941.

Jacobs, S.S., 1991. On the nature and significance of the Antarctic Slope Front. Marine Chemistry 35, 9–24.

Jacobs, S.S., Amos, A.F., Bruchhausen, P.M., 1970. Ross Sea oceanography and Antarctic Bottom Water formation. Deep-Sea Research 17, 935–962.

Jacobs, S.S., Fairbanks, R.G., Horibe, T., 1985. Origin and evolution of water masses near the Antarctic continental margin: evidence from $H_2{}^{18}O/H_2{}^{16}O$ ratios in seawater. In: Jacobs, S.S., (Ed.), Oceanology of the Antarctic Continental Shelf, Antarctic Research Series, vol. 43, American Geophysical Union, Washington, DC, pp. 59–85.

Killworth, P.D., 1983. Deep convection in the world ocean. Reviews of Geophysics and Space Physics 21, 1–26.

MacAyeal, D.R., 1985. Evolution of tidally triggered meltwater plumes below ice shelves. In: Jacobs, S.S. (Ed.), Oceanology of the Antarctic Continental Shelf, Antarctic Research Series, vol. 43, American Geophysical Union, Washington DC, pp. 133–143.

Martinson, D.G., 1990. Evolution of the Southern Ocean winter mixed layer and sea ice: open ocean deepwater formation and ventilation. Journal of Geophysical Research 95, 11,641–11,654.

Mosby, H., 1934. The waters of the Atlantic Antarctic Ocean. Scientific Results of the Norwegian Antarctic Expedition 1927–1928 11, 1–131.

Neal, V.T., Nowlin, Jr. W.D., 1979. International Southern Ocean studies of circumpolar dynamics. Polar Record 19, 461–471.

Niiler, P.P., Amos, A., Hu, J.-H., 1991. Water masses and 200 m relative geostrophic circulation in the western Bransfield Strait region. Deep-Sea Research 38, 943–959.

Niiler, P., Illeman, J., Hu, J.-H., 1990. RACER: Lagrangian drifter observations of surface circulation in the Gerlache and Bransfield Straits. Antarctic Journal of the United States 25, 134–137.

Nowlin, Jr. W.D., Clifford, M., 1982. The kinematic and thermohaline zonation of the Antarctic Circumpolar Current at Drake Passage. Journal of Marine Research 40, 481–507.

Orsi, A.H., Whitworth III, T., Nowlin, Jr. W.D., 1995. On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep-Sea Research I 42, 641–673.

Parish, T.R., Bromwich, D.H., 1987. The surface windfield over the Antarctic ice sheets, Nature 328, 51–54.

Potter, J.R., Paren, J.G., 1985. Interaction between ice shelf and ocean in George VI Sound, Antarctica. In: Jacobs, S.S. (Ed.), Oceanology of the Antarctic Continental Shelf, Antarctic Research Series, vol. 43, American Geophysical Union, Washington DC, pp. 35–58.

Reid, J.L., Nowlin, Jr., W.D., Patzert, W.C., 1977. On the characteristics and circulation of the southwestern Atlantic Ocean. Journal of Physical Oceanography 7, 62–91.

Schwerdtfegger, W., Amaturo, L.R., 1979. Wind and weather around the Antarctic Peninsula, Technical Report 79.00.S1, Department of Meteorology, University of Wisconsin, Madison, 65 pp.

Sievers, H.A., 1982. Description of the physical oceanographic conditions, in support of the study on the distribution and behavior of krill. Instituto Antartico Chileno Scientific Series, No. 28, pp. 73–122.

Sievers, H.A., Nowlin, Jr., W.D., 1984. The stratification and water masses at Drake Passage. Journal of Geophysical Research 89, 10,489–10,514.

Smith, D.A., Lascara, C.M., Klinck, J.M., Hofmann, E.E., Smith, R.C., 1995. Palmer LTER: Hydrography in the inner shelf region, Antarctic Journal of the United States 30, 258–260.

Smith, D.A., Locarnini, R.A., Lipphardt, Jr., B.L., Hofmann, E.E., 1993b. XBT data collected aboard the RV Nathaniel B. Palmer March-May 1993. CCPO Technical Report No. 93-06, Center for Coastal Physical Oceanography, Old Dominion University, 158 pp.

Smith, D.A., Locarnini, R.A., Lipphardt, Jr., B.L., Hofmann, E.E., 1993c. Hydrographic data collected aboard the RV Nathaniel B. Palmer March–May 1993. CCPO Technical Report No. 93-04, Center for Coastal Physical Oceanography, Old Dominion University, 215 pp.

Smith, D.A., Smith, R.C., Menzies, D., 1993a. Oceanographic data collected aboard the RV Nathaniel B. Palmer March–May 1993. CCPO Technical Report No. 93-05, Center for Coastal Physical Oceanography, Old Dominion University, 265 pp.

Smith, R.C., Baker, K.S., Fraser, W.M., Hofmann, E.E., Karl, D.M., Klinck, J.M., Quetin, L.B., Preźelin, B.B., Ross, R.M., Trivelpiece, W.Z., Vernet, M., 1995. The Palmer LTER: a long-term ecological research program at Palmer station, Antarctica, Oceanography 8, 77–86.

Smith, R.C., Booth, C.R., Star, J.L., 1984. Oceanographic bio-optical profiling system. Applied Optics 23, 2791–2797.

Stein, M., 1983. The distribution of water masses in the South Shetland Islands area during FIBEX. Memoirs of the National Institute for Polar Research, Special Issue No. 27, 16–23.

Stein, M., 1989. Seasonal variation of water masses in Bransfield Strait and adjacent waters. Archiv Fischereiwissenschaft 39, 15–38.

Stein, M., 1992. Variability of local upwelling off the Antarctic Peninsula, 1986–1990. Archiv Fischereiwissenschaft 41, 131–158.

Stein, M., Heywood, R.B., 1994. Antarctic environment-physical oceanography: The Antarctic Peninsula and Southwest Atlantic region of the Southern Ocean, In: El-Sayed, S.Z. (Ed.), Southern Ocean Ecology. Cambridge University Press, Cambridge, pp. 11–24.

Stein, M., Rakusa-Suszczewski, S., 1983. Meso-scale structure of water masses and bottom topography as the basis for krill distribution in the SE Bransfield Strait February–March 1981. Meeresforschung 30, 73–81.

Trenberth, K.E., Olson, J.G., Large, W.G., 1989. A global ocean wind stress climatology based on ECMWF analysis, NCAR Technical Note, NCAR/TN-338 + STR, 93 pp.

UNESCO, 1983. Algorithms for computation of fundamental properties of seawater. In: Fofonoff, N.P., Millard, Jr., R.C., (Eds.), Technical Papers in Marine Science, vol. 44, 53 pp.

Whitworth, T., III, Nowlin, Jr., W.D., 1987. Water masses and currents of the Southern Ocean at the Greenwich Meridian. Journal of Geophysical Research 92, 6462–6476.

Whitworth, T., III, Nowlin, Jr., W.D., Orsi, A.H., Locarnini, R.A., Smith, S.G., 1994. Weddell Sea shelf water in the Bransfield Strait and Weddell-Scotia Confluence. Deep-Sea Research I 41, 629–641.