WATER MASS DISTRIBUTION AND CIRCULATION WEST OF THE ANTARCTIC PENINSULA AND INCLUDING BRANSFIELD STRAIT

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Historical hydrographic data from Bransfield Strait and the region west of the Antarctic Peninsula were analyzed to provide descriptions of water mass distributions and circulation patterns. Circumpolar Deep Water (CDW), which is characterized by temperatures above 1.0°C, salinities of 34.6 to 34.73, and oxygen values below 4.5 ml l^{-1}, is the most prominent water mass in this region, is found between 200 and 700 m, and is present in all seasons throughout the region examined. Below 200 m this water mass floods the continental shelf west of the Antarctic Peninsula. CDW is also found in Bransfield Strait, but the distribution is limited to the northern side of the Strait near the South Shetland Islands. Mixing of CDW results in reduction of the oxygen content of the overlying waters by 25 to 45%, which suggests an average annual entrainment rate for the west Antarctic Peninsula of 0.7 to 1.43×10^{-6} m s^{-1}. The freshwater input needed to balance the salinity input from CDW is on the order of 0.63 m y^{-1}, which can be supplied by local precipitation and advection of ice into the region from the Bellingshausen Sea, which then melts. The annual heat flux associated with CDW is 12 W m^{-2}, which is sufficient to melt this amount of ice. A second prominent water mass, Bransfield Strait Water (< 0°C, 34.45 to 34.6), is found throughout the central and southern portions of the Strait. The circulation pattern, constructed from historical data sources, for the region west of the Antarctic Peninsula shows that the large-scale geostrophic flow may be composed of one or more clockwise gyres. This mesoscale variability is likely the result of the rugged bottom topography and has implications for the transport and retention of physical and biological properties. Surface drifters indicate that the circulation in Bransfield Strait is clockwise and may be continuous with the circulation west of the Antarctic Peninsula above 500 m. The circulation pattern inferred from historical temperature distributions suggests that the westward flowing Polar Slope Current, which has been observed north of the South Shetland Islands, does not extend beyond Smith Island.

1. INTRODUCTION

The region west of the Antarctic Peninsula encompasses an area of 22,000 km^2 that reaches from the tip of the Peninsula to Alexander Island and extends from the coastal waters adjacent to the Peninsula to the oceanic waters offshore of the shelf break (Figure 1a). This larger region is composed of two subregions: Bransfield Strait, which covers the northeast one-third, and an extensive shelf-slope area that covers the remaining two-thirds of the region. Each subregion can be distinguished on the basis of geometry, hydrographic properties, and circulation.

Descriptions of the water mass distributions and circulation patterns for the region west of the Antarctic Peninsula have been based on limited surveys that have primarily covered the Bransfield Strait and nearby areas (Figure 1b). The first of these was done as part of the R/V *Discovery* cruises [*Clowes*, 1934]. Little additional hydrographic survey work

was done in this region until the 1970s when some stations were occupied along the axis of the Bransfield Strait [*Gordon and Nowlin*, 1978] and along the northern flank of the South Shetland Islands [*Nowlin and Clifford*, 1982; *Sievers and Nowlin*, 1984] as part of the International Southern Ocean Studies (ISOS) program. More hydrographic measurements were made in the Bransfield Strait region in the 1980s as part of the First International BIOMASS Experiment (FIBEX) and other Antarctic krill research activities [e.g., *Stein*, 1983; *Stein and Rakusa-Suszczewski*, 1983; 1984]. These studies yielded primarily measurements of temperature distributions in the upper 500 m, but are still useful for characterizing the water column structure in this region. During the Second International BIOMASS Experiment (SIBEX), multidisciplinary cruises were conducted in an expanded study area that included portions of the west Peninsula shelf to the south and west of Bransfield Strait [*Stein and Heywood*, 1994]. Additional hydrographic measurements
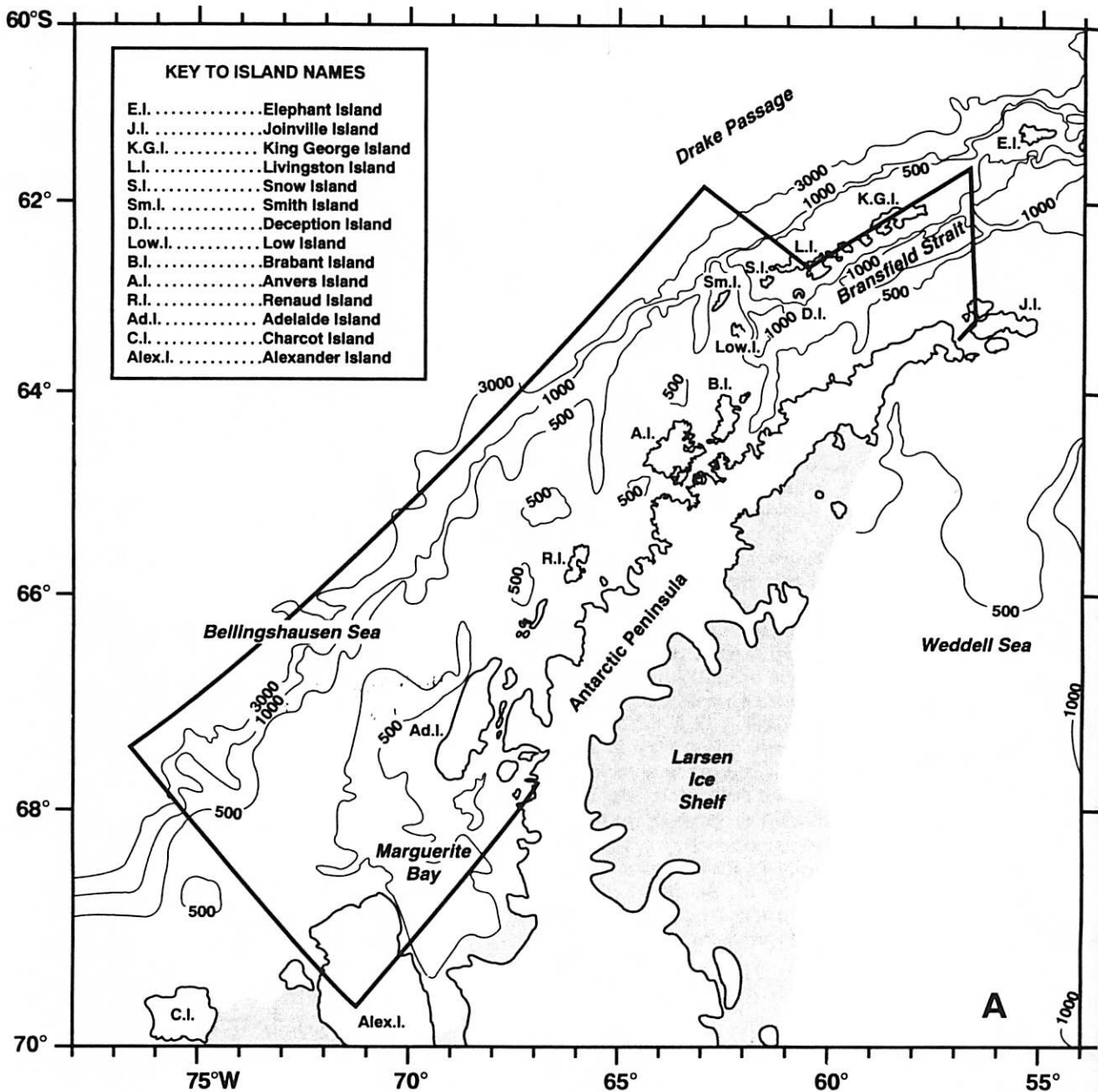
Fig. 1a. Base map of the Bransfield Strait and west Antarctic Peninsula region. The region used for analysis of historical hydrographic data sets is indicated. Bottom topography contours are in meters. Shaded regions indicate the permanent ice shelves.

are available from cruises undertaken as part of United States and German oceanographic studies [e.g., *Huntley et al.*, 1991; *Niiler et al.*, 1991; *Stein*, 1992] that occurred in the Antarctic Peninsula region during the last decade. Limited current meter measurements have been made on the shelf-slope region north of the South Shetland Islands [*Pillsbury et al.*, 1981] and inside Bransfield Strait [*Wittstock and*

Zenk, 1983]. No current meter measurements are available for the west Peninsula shelf area.

With the establishment of the Long-Term Ecological Research (LTER) program at Palmer Station on Anvers Island, interest has developed in understanding the hydrographic and current structure of the waters west of the Antarctic Peninsula. Hence, the objective of this paper is to
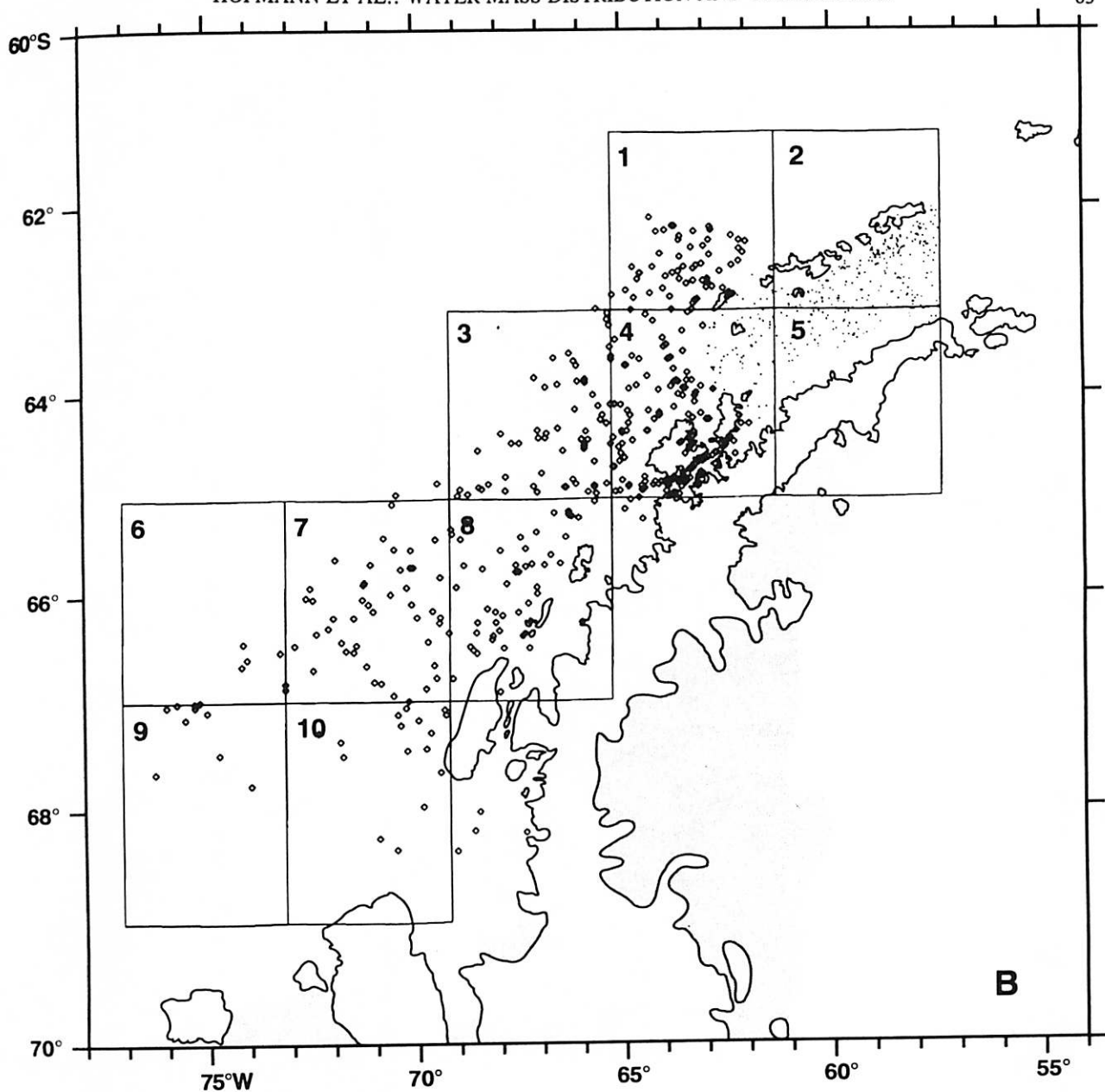
Fig. 1*b*. Distribution of the historical hydrographic stations used in the analysis. Dots indicate stations in Bransfield Strait and diamonds indicate stations west of the Antarctic Peninsula. Also shown are the 2° latitude by 4° longitude subregions used for the regional analysis. The uneven size of the subregions results from the Mercator projection.

synthesize existing hydrographic and current observations for this region in order to provide a context for analysis and interpretation of hydrographic data obtained as part of the LTER. This synthesis is based on a review of descriptions from the literature and an analysis of historical hydrographic data sets obtained from the U.S. National Oceanographic Data Center (NODC) and from the Alfred Wegener Institute in Bremerhaven, Germany. This latter data set includes the Southern Ocean hydrographic data set that was compiled by *Gordon and Molinelli* [1982].

The next two sections provide a description of the region and the data sets. This is followed by an analysis of the water mass characteristics and circulation west of the Antarctic Peninsula that is derived from the historical data sets.

The observed distributions and patterns are then compared with those derived from theoretical circulation modeling studies that have been done for the region west of the Antarctic Peninsula. The final section presents a discussion and summary.

2. PHYSICAL SETTING

2.1. *Geography*

The northern and southern boundaries of Bransfield Strait (Figure 1a) are formed by the South Shetland Islands and the Antarctic Peninsula, respectively. The Strait proper is composed of three deep basins which are separated by sills less than 1500 m deep. The western end of Bransfield Strait is bounded by a shallow sill that is about 500 m deep; the eastern end is open towards the Weddell Sea. The shelf-slope region to the north and south of the South Shetland Islands is 200 to 500 m deep and deepens rapidly towards the center of Bransfield Strait and towards Drake Passage. The shelf to the north of the Islands is interrupted by two narrow cuts, one between Smith and Snow Islands and one between King George and Elephant Islands, which have depths of 500 to 600 m. These provide the only deep connections between the Strait and Drake Passage. The only deep connection between Bransfield Strait and the region to the west is through the narrow Gerlache Strait. Hence, exchange of Bransfield Strait waters with surrounding oceanic waters to the north and west is limited to the upper 500 m. Exchanges with the Weddell Sea to the east can occur throughout most of the water column.

The continental shelf in the region west of the Antarctic Peninsula is 200 to 500 m deep. This shelf is intersected by cuts, 500 to 700 m deep, that extend seaward from Brabant, Anvers, and Adelaide Islands. The latter deep channel connects Marguerite Bay to the outer shelf. Shallow plateaus, deep holes, and an outer shelf that deepens rapidly towards Drake Passage characterize the remainder of the shelf. An additional characteristic of this shelf, which is typical of Antarctic shelves, is that it deepens onshore. This structure and the overall rugged topography of the shelf result from the geologic processes (e.g., ice scour) that formed the region. The deeper shelf inshore and the presence of several islands can potentially restrict exchanges between nearshore and offshore regions.

2.2. *Wind Patterns*

Wind stress is one of the major forces affecting circulation in the Southern Ocean. Direct observations of this important meteorological forcing are limited due to the small number of observation sites south of 45°S [*Bromwich and Stearns*, 1993]. Wind stress climatologies are available for the global ocean, which are based on ship observations [e.g., *Hellerman and Rosenstein*, 1983] or global atmospheric

forecast models, such as European Center for Medium Range Weather Forecasting (ECMWF) [*Trenberth et al.*, 1989]. Each approach for obtaining wind stress climatologies involves assumptions, and for the Southern Ocean some of these can be questionable. Recent analyses [*Chelton et al.*, 1990] indicate that the *Trenberth et al.* [1989] climatology may be more representative of the wind stress for the Southern Ocean.

The *Trenberth et al.* [1989] wind climatology illustrates the general structure and seasonal variation of the wind stress west of the Antarctic Peninsula (Figure 2). The annual average wind stress (not shown) shows a clear pattern of northwesterly stress on the western side of Drake Passage north of 60°S. South of 60°S, the winds diminish in strength considerably and turn more northerly and then northeasterly. On the eastern side of Drake Passage, the winds are mainly westerly. Partitioning the wind stress variance into annual and semi-annual components [*Trenberth et al.*, 1990, Figure 6] shows that in the vicinity of the Antarctic Peninsula, the zonal component of wind stress has a significant (more than 60% of the total variance) annual variation, while the meridional component has a significant semi-annual variation. The semi-annual change in wind speed over the Southern Ocean has been attributed to the latitudinal difference in timing of seasonal heating of the atmosphere south of 35°S [*van Loon*, 1967; *van Loon and Rogers*, 1984a, 1984b], which creates two maxima in the atmospheric meridional surface pressure gradient field. Direct measurement of atmospheric pressure and surface winds during the First GARP Global Experiment (FGGE) from a large number of free drifting surface buoys in the Southern Ocean [*Large and van Loon*, 1989] verified the existence of a semi-annual variation in atmospheric conditions over the ocean south of 60°S.

West of the Antarctic Peninsula, the wind is primarily from the north-northeast (Figure 2), which produces a down-welling circulation over the continental shelf and a southward flow along the coast. This, when combined with the northward flow of the Antarctic Circumpolar Current (ACC) at the outer shelf region, would result in a clockwise circulation over the shelf, in the absence of any other forcing mechanism. The monthly-averaged wind stress fields show a semi-annual variation in wind stress for the region of interest, with the weakest stress occurring during austral summer (Figure 2a) and strong stress occurring during austral winter (Figure 2b). In general, the wind strength changes by a factor of two or more with little variation in wind direction.

The wind stress estimates provided by *Trenberth et al.* [1990] are produced from an atmospheric model with a grid spacing of 2.5 degrees, which is too coarse to properly represent all of the land topography in the Antarctic Peninsula region. The tall mountain chain along the Antarctic Peninsula, along with topographic steering by nearshore channels and numerous islands, create local changes in the wind field on scales of 10s of kilometers. However, the
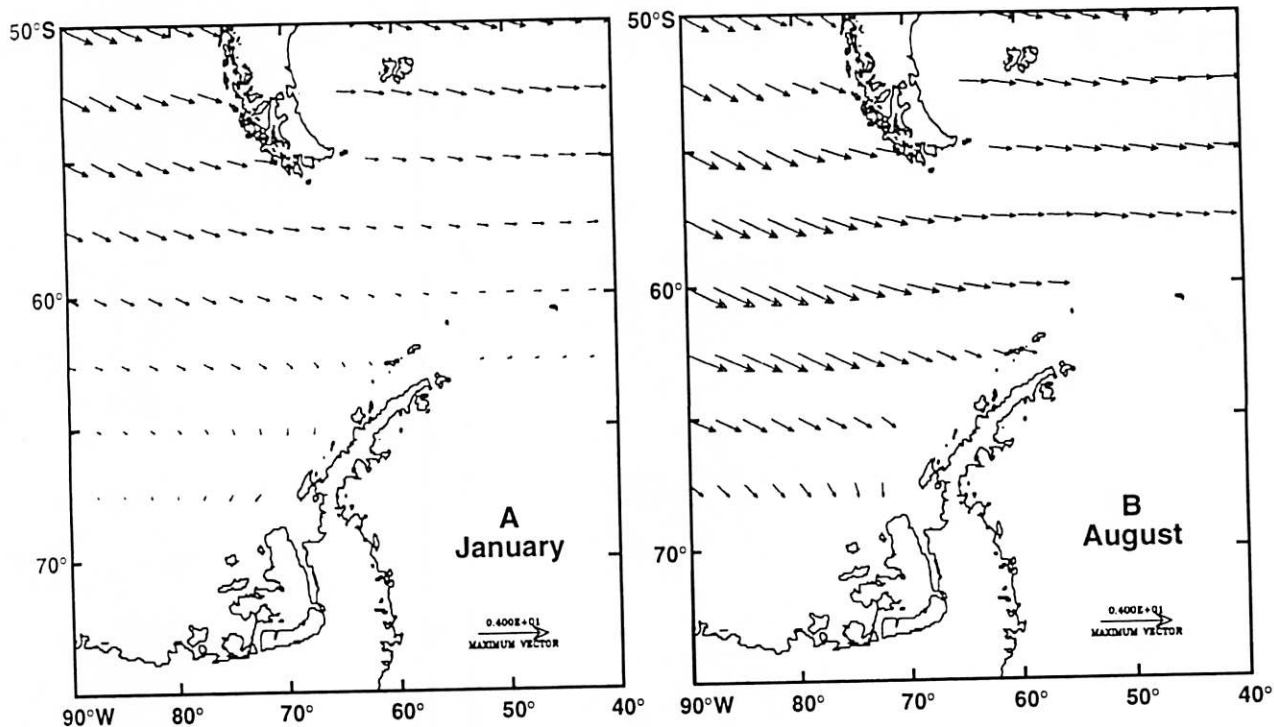
Fig. 2. Wind stress (dynes cm⁻²) estimated from ECMWF analysis for a) January and b) August.

general patterns observed in the large-scale fields are consistent with those seen in wind records from land-based automatic weather stations [*Bromwich and Stearns*, 1993].

2.3. *Sea Ice*

The spatial and temporal distribution of sea ice west of the Antarctic Peninsula is described by *Stammerjohn and Smith* [this volume]. The annual advance and retreat of sea ice affects the ice-ocean-atmosphere dynamics of this region by modifying the flux of heat, salt, and momentum between the ocean and atmosphere. Brine rejection associated with ice formation coupled with oceanic cooling can produce local areas of surface water of higher density. Intense convective overturning is possible in these areas, which leads to mixing and contributes to the development of deep mixed layers. In some cases, the combination of brine rejection and cooling is sufficient to lead to the formation of deep water masses, such as Antarctic Bottom Water, as is observed in the Weddell Sea. The region west of the Antarctic Peninsula, however, is not noted as a region of deep water formation. In the austral spring, as the sea ice melts, a layer of lower density water is produced which stabilizes the upper water column and thereby restricts mixing and allows local heating to occur [*Deacon*, 1937]. This change in surface buoyancy when coupled with warming from increased solar irradiance results in the formation of a shallow seasonal pycnocline.

3. HYDROGRAPHIC DATA

Hydrographic data were obtained from the NODC and the German Hydrographic Office for the region shown in Figure 1a. The two data sets were compared and those from the German Hydrographic Office that were duplicates of NODC stations were eliminated from the analysis. The resultant data set consisted of 598 hydrographic and XBT stations from the NODC archive and an additional 293 from the German Hydrographic Office archive. About half of the NODC stations provided temperature and salinity measurements; the remainder were Expendable Bathythermograph (XBT) profiles (Table 1). All of the stations from the German archive provided temperature and salinity measurements. Oxygen measurements were available for 226 of these hydrographic stations (Table 1). The NODC and German Hydrographic Office data sets have undergone extensive quality control procedures which are detailed in *NODC* [1991] and *Olbers et al.* [1992]. Additional quality control procedures for this analysis consisted of checking property value ranges and visual inspection of property-property plots and vertical profiles.

The combined data set was partitioned by season and region. Seasonal coverage is uneven, with most of the observations concentrated in the austral summer (Table 1). However, station coverage for Bransfield Strait and non-Bransfield Strait regions is similar (Table 1, Figure 1b). Hence, analyses of property distributions are not biased

TABLE 1. Summary of the number of available hydrographic stations by season and subregions. Seasons are designated as: Spring (September, October, November); Summer (December, January, February); Fall (March, April, May); and Winter (June, July, August). The regions and subregions are shown in Figures 1 and 4, respectively.

Season/Region	NODC Data		German Data	
	CTD/Bottle	XBT	CTD/Bottle	Oxygen
Spring	33	8	9	6
Summer	173	237	176	198
Fall	92	52	88	22
Winter	3	0	20	0
Bransfield Strait	173	134	172	111
West Peninsula	128	163	121	115
Subregion 1	23	20	29	32
Subregion 2	104	70	92	58
Subregion 3	11	37	15	13
Subregion 4	77	99	81	63
Subregion 5	35	30	39	25
Subregion 6	2	3	1	2
Subregion 7	16	15	15	17
Subregion 8	18	15	16	8
Subregion 9	3	4	3	1
Subregion 10	12	3	2	7
Total	301	297	293	226

towards a particular area. Sorting the hydrographic data into 2° latitude by 4° longitude subregions (Table 1, Figure 1b) provided sufficient coverage for examining regional differences in water mass properties.

4. WATER MASS PROPERTIES AND DISTRIBUTION

4.1. *Water Mass Properties*

The *in situ* temperature-salinity (T-S) diagram constructed from the combined hydrographic data sets (Figure 3) shows that salinity ranges from about 33.0 to 34.73; temperature ranges from -1.8°C to slightly greater than 2°C. The wide range of temperature and salinity values seen in the upper

100 m in the austral summer and fall illustrates the variability in water properties that is produced by seasonal processes, such as melting of sea ice, wind mixing, and the development and decay of upper water column stratification. During the austral winter and spring, the scatter in T-S space in the upper 100 m is reduced and salinities remain above 33.8. During these seasons, most of the region of interest is ice covered [*Stammerjohn and Smith*, this volume], which limits ocean-atmosphere exchange.

The most prominent feature in T-S space is Circumpolar Deep Water (CDW), characterized by a salinity maximum (salinities up to 34.73) and a temperature maximum (T>1°C). The presence of CDW in the Antarctic Peninsula region was noted in early hydrographic studies [*Deacon*, 1937; *Gordon*, 1967], and it is the most voluminous water mass transported by the Antarctic Circumpolar Current [*Sie-*
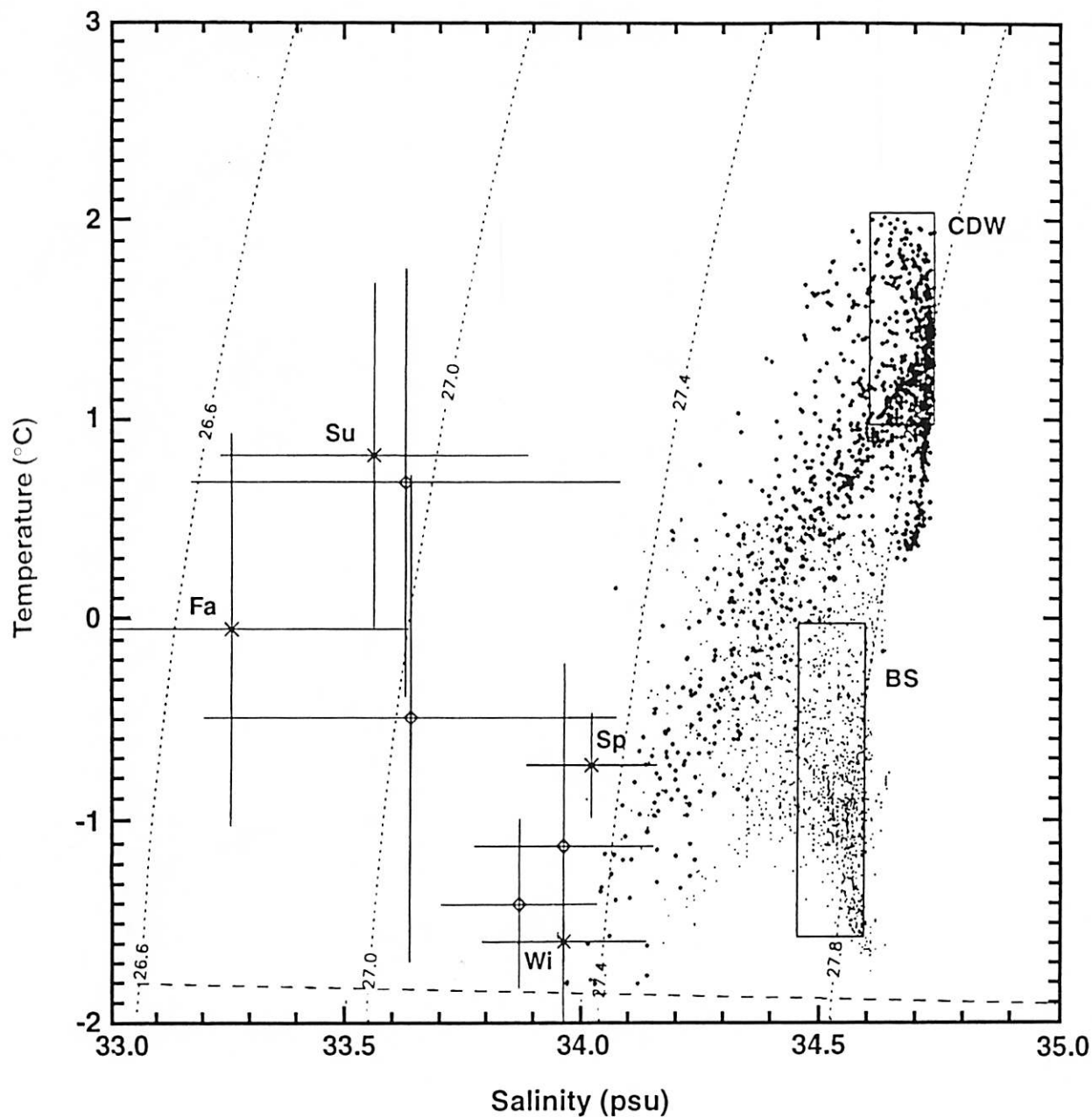
Fig. 3. *In situ* temperature-salinity diagram constructed from the combined NODC and German Hydrographic data sets. Diamonds indicate observations below 100 m from west of the Antarctic Peninsula; dots indicate observations below 100 m from Bransfield Strait. The solid lines indicate the one standard deviation values for temperature and salinity measured above 100 m in the austral spring (Sp), summer (Su), fall (Fa) and winter (Wi) in Bransfield Strait (×) and west of the Antarctic Peninsula (○). The minimum standard deviation value for salinity in the austral fall is 32.88. The boxed regions provide a general reference for Circumpolar Deep Water (CDW) and Bransfield Strait (BS) Water; they are not intended as precise definitions of the temperature and salinity ranges that characterize these water masses. The contours represent lines of constant σ_t. The heavy dashed line represents the freezing point of surface sea water as a function of salinity.

vers and Nowlin, 1984]. A second region of tight clustering occurs at temperatures of less than 0°C and salinities of 34.45 to 34.6. This water is found in Bransfield Strait, is derived from water of Weddell Sea origin, and has been referred to as Bransfield Strait (BS) water [*Whitworth et al.*, 1994]. CDW and Bransfield Strait water are present in all seasons.

An additional characteristic of the water mass structure in the Antarctic Peninsula region is a temperature minimum (-1.0 to -1.8°C) at salinities of 34.00 (Figure 3), which defines Antarctic Surface Water (AASW). This water has been attributed to winter cooling [*Mosby*, 1934; *Gordon et al.*, 1977; *Toole*, 1981] and during the austral winter the entire upper water column is composed of AASW. During the austral summer, increased solar insolation warms the surface waters and isolates a core of AASW that appears as a distinct temperature minimum around 100 m at the outer edge of the continental shelf. The depth of the core of the temperature minimum shallows onshore [*Toole*, 1981]. This feature has been referred to as Winter Water [*Mosby*, 1934; *Sievers and Nowlin*, 1984] and it is the only part of AASW that remains the same regardless of season. Therefore, this water mass is used as a reference for oxygen, heat, and salt budgets described in section 7. In the region of interest, Winter Water is characterized by temperature and salinity values of -1.5°C and 34, respectively.

The regional water mass distribution is obtained by examining T-S characteristics in 2° by 4° subregions (Figure 4). CDW is clearly evident north of the South Shetland Islands (subregion 1) and throughout the west Peninsula shelf. However, the signature of this water mass, while present, is not well defined in the inshore waters along the western side of the Antarctic Peninsula (subregions 8 and 10). CDW is found along the southern flank of the South Shetland Islands (subregion 2) and in the western end of Bransfield Strait (subregion 4), although the signal of CDW is weak in this area. CDW is not present in the southeastern region of the Strait (subregion 5). Bransfield Strait Water of Weddell Sea origin is present in subregions 2 and 5.

Temperature-oxygen diagrams for Bransfield Strait (Figure 5*a*) and the west Peninsula (Figure 5*b*) show differences in the two regions. The oxygen minimum associated with CDW is more pronounced for the region west of the Peninsula, reflecting the presence of this water mass throughout the area. The oxygen minimum is less defined in Bransfield Strait, which is consistent with the limited penetration of CDW into this region.

4.2. Water Mass Distributions

Capella et al. [1992b] present an analysis of the horizontal temperature distribution at 300 m in Bransfield Strait that is based upon XBT and limited CTD measurements. This distribution (Figure 6) suggests pathways by which CDW enters the Strait. Water with temperatures characteristic of

CDW (>1°C) enter Bransfield Strait through the gap between Smith and Snow Islands. A similar intrusion of CDW was seen in hydrographic measurements made during FIBEX [*Sievers*, 1982; *Stein*, 1983; *Stein and Rakusa-Suszczewski*, 1983] and in the western Bransfield Strait as part of the Research on Antarctic Coastal Ecosystem Rates (RACER) field programs [*Niiler et al.*, 1991]. The 300-m temperature distribution (Figure 6) shows CDW extending along the southern flank of the South Shetland Islands and as far east as Elephant Island. A strong temperature boundary separates CDW from the colder waters of Bransfield Strait in the Strait proper [*Capella et al.*, 1992b; *Stein and Heywood*, 1994]. Limited penetration of CDW from Drake Passage into Bransfield Strait and spreading along the southern flank of the South Shetland Islands are consistent with the patterns obtained from the regional T-S analysis (Figure 4). The cold (<0°C) water seen at 300 m to the north of the South Shetland Islands is associated with the Polar Slope Current [*Nowlin and Zenk*, 1988]. Temperature measurements west of the Peninsula were limited, but water of 1°C, which is indicative of CDW, occurs on the shelf west of Bransfield Strait.

The distribution of the temperature maximum constructed from the NODC and German hydrographic data (Figure 7) shows that Bransfield Strait waters are generally less than 0°C. The exceptions to this are along the southern flank of the South Shetland Islands and along the western end of the Strait where temperatures are warmer due to intrusion of CDW into Bransfield Strait. Temperatures over the continental shelf west of the Antarctic Peninsula have maximum temperatures that are between 1.5 and 1.0°C, which indicates the extensive coverage of CDW. The presence of the 1.5°C isotherm along the shelf break shows that CDW is always present and therefore provides a continuous source of warmer water to this shelf. Although the resolution in the historical data is not sufficient to show the penetration of CDW into Bransfield Strait between Smith and Snow Islands, the general pattern that emerges is that this water mass floods the continental shelf west of the Antarctic Peninsula and is a prominent feature in the northern and western portions of Bransfield Strait.

5. CIRCULATION

5.1. Bransfield Strait

The first description of the upper water column circulation in Bransfield Strait comes from dynamic topography maps that were constructed from hydrographic measurements made during the *R/V Discovery* cruise [*Clowes*, 1934]. The surface dynamic topography indicates that part of the eastward flow associated with the Antarctic Circumpolar Current turns into Bransfield Strait between Snow, Smith, and Low Islands. This produces a clockwise meander north of Smith Island, which has been subsequently observed in surface
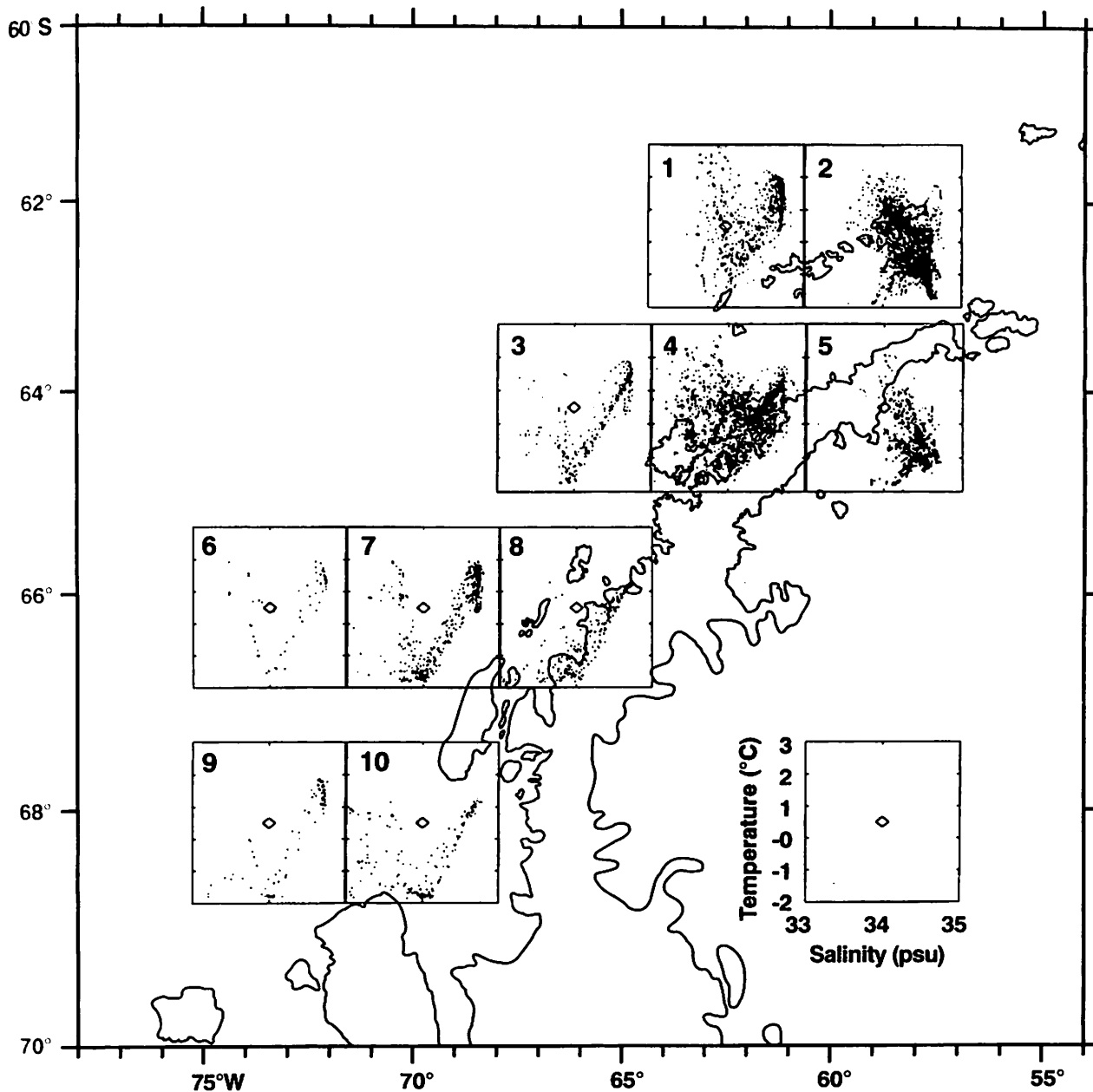
Fig. 4. *In situ* temperature-salinity diagrams constructed from the combined NODC and German Hydrographic data sets that were subsetted by 2° by 4° subregions. The open diamond indicates the center of the T-S space and is provided as a reference point. The individual T-S plots are centered at the latitude and longitude corresponding to the center of the subregion.

geostrophic velocities computed from hydrographic observations made during FIBEX [*Stein and Rakusa-Suszczewski,* 1983], SIBEX [*Stein,* 1986; *Heywood and Priddle,* 1987; *Stein and Heywood,* 1994], and RACER [*Amos et al.,* 1990; *Niiler et al.,* 1991]. The mean maximum surface geostrophic velocity associated with the meander was estimated to be 0.08 m s⁻¹ [*Niiler et al.,* 1991]. Inside the Strait, dynamic topography fields [*Clowes,* 1934; *Stein and Rakusa-Susz-*

zewski, 1983; *Stein,* 1988] show that this flow continues eastward along the southern side of the South Shetland Islands. At the eastern end of Bransfield Strait, a branch of the flow leaves the Strait between King George and Elephant Islands; the remainder continues eastward.

Additional evidence for surface flow into Bransfield Strait through the gap between Smith and Snow Islands comes from two FGGE (First GARP Global Experiment) drifters
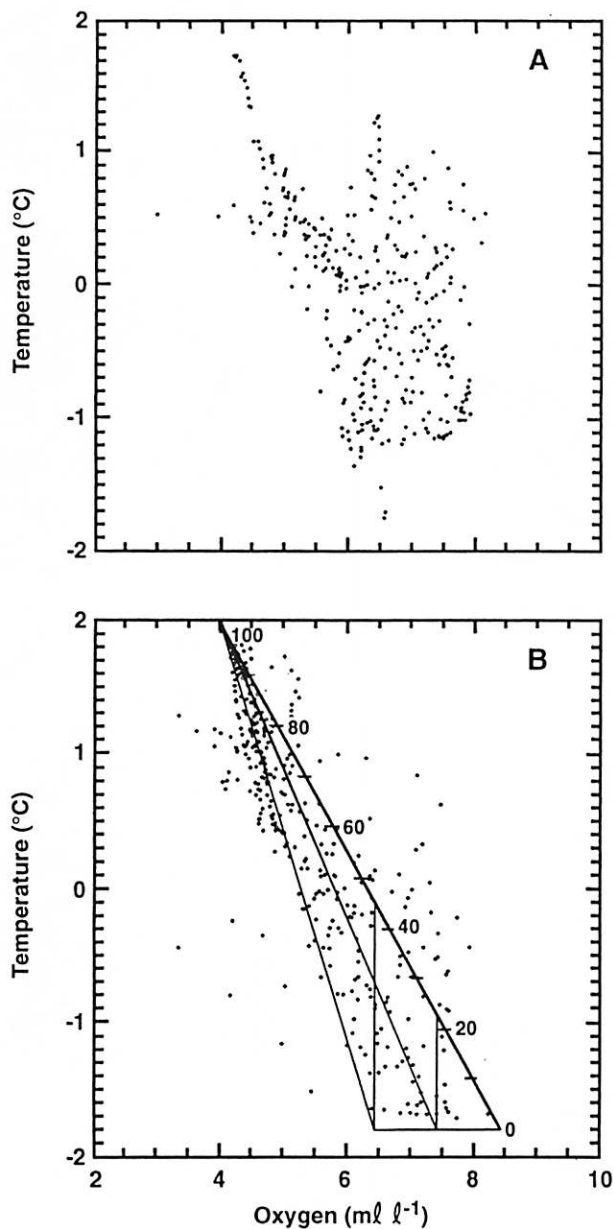
Fig. 5. *In situ* temperature-oxygen diagrams constructed from the German Hydrographic data set for a) Bransfield Strait and b) west of the Antarctic Peninsula. The heavy line connects undersaturated CDW (2°C) with fully-saturated surface water (8.54 ml l^{-1}) at the freezing point (-1.86°C). The thinner lines connect CDW with the range of oxygen values observed for Winter Water (6.5 to 7.5 ml l^{-1}). The vertical lines represent the required proportions of CDW and fully-saturated water that are needed to produce the observed Winter Water oxygen values.

that drifted through the region in 1979 (Figure 8). Buoy No. 54611 approached the South Shetland Islands from the west. At about 62°W it turned, drifted southward and then westward along the northern side of the South Shetland Islands.

The buoy again turned southward and drifted into Bransfield Strait between Smith and Snow Islands. Once inside the Strait, the buoy drifted east to about 56°W, where it reversed and drifted to the west. The total time for the buoy to make a clockwise circuit around Bransfield Strait was 33 days (beginning on June 28), which gives an average surface velocity of 0.32 m s^{-1}.

Drifters that were deployed in Gerlache Strait as part of the RACER field programs show that surface flow in this region is to the northeast and persists as a coherent feature into the southwestern portion of the Bransfield Strait [*Niiler et al.*, 1990]. Once inside the Strait this flow turns to the northeast [*Niiler et al.*, 1991]. Surface geostrophic velocities associated with this flow can be in excess of 0.50 m s^{-1} and provide a mechanism for transporting water from the west Peninsula shelf into Bransfield Strait.

An additional feature of the flow in the Bransfield Strait region is the westward flowing Polar Slope Current [*Nowlin and Zenk*, 1988], which is found in Drake Passage to the north of the South Shetland Islands. This current is narrow (10 km), characterized by cold temperatures (less than 0°C) and is found at depths of about 400 to 600 m. Average velocities associated with the Polar Slope Current, as determined from current meter observations, are about 0.10 m s^{-1} [*Nowlin and Zenk*, 1988].

5.2. Circulation West of the Peninsula

The availability of measurements that can be used to describe the circulation west of the Antarctic Peninsula is considerably less than for the Bransfield Strait. Hydrographic observations made in this region as part of the BIOMASS program show southward flow offshore of Anvers Island [*Stein*, 1981; 1982; 1986; 1988] and between Anvers and Renaud Islands [*Kock and Stein*, 1978]. More recently, *Stein* [1992] presented dynamic topography contours, relative to 200 decibars, that were constructed from a large-scale hydrographic survey made in this region as part of SIBEX. These show an upper water column circulation that is composed of two clockwise gyres: one near Anvers and Brabant Islands and one near Adelaide Island. Additional evidence for a clockwise gyre near Anvers Island is provided by the second FGGE buoy (Figure 8). This buoy approached the South Shetland Islands from the west, but did not enter Bransfield Strait. Rather, it turned south between 66°W and 65°W and then west at about 62°W. This trajectory suggests a clockwise surface circulation in the region west of Bransfield Strait that extends westward as far as Anvers Island. Once past Anvers Island, this buoy continued southward along the coast.

The description of the circulation in the region west of the Antarctic Peninsula was further refined by surface drifters that were deployed north of Anvers Island as part of the RACER field studies [*Niiler et al.*, 1990]. The drifter trajectories in this region did not show directed coherent flow,
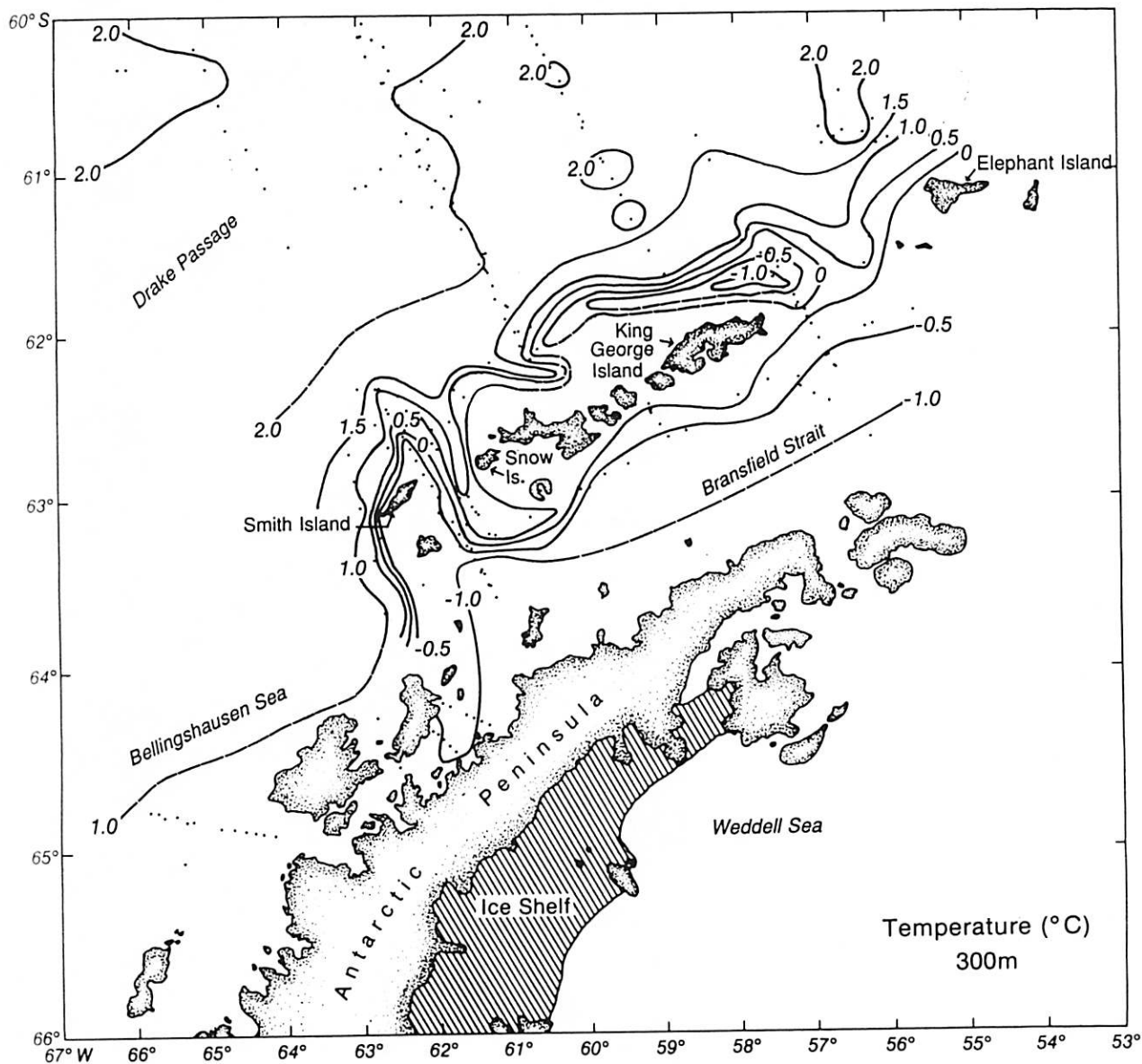
Fig. 6. Horizontal temperature distribution maps at 300 m constructed from CTD and XBT observations made in Bransfield Strait. Figure adapted from *Capella et al.* [1992b].

but rather a slow meandering surface circulation. A similar pattern is seen in the FGGE drifter trajectory as it drifted past Anvers Island (Figure 8).

5.3. *Schematic Circulation*

The major circulation features described for Bransfield Strait and the west Antarctic Peninsula region were used to construct a schematic of the flow for this region (Figure 9). This circulation shows flow into Bransfield Strait from west of the Antarctic Peninsula, the Weddell Sea, and through the gaps between the South Shetland Islands. The latter path-

way provides a source of CDW to the northern portion of Bransfield Strait. Thus, Bransfield Strait receives a variety of water types which contribute to the complex upper water column water mass structure that has been described for this region [*Stein*, 1983, 1986, 1989]. Flow out of the Strait may also occur along the same pathways as well as at the eastern end. North of the South Shetland Islands, the Polar Slope Current carries water of Weddell Sea origin to the west.

Over the continental shelf west of the Peninsula, the general circulation is clockwise. The outer portion of this circulation is provided by the northeasterly flowing ACC; the inner portion is provided by the southward coastal flow. As
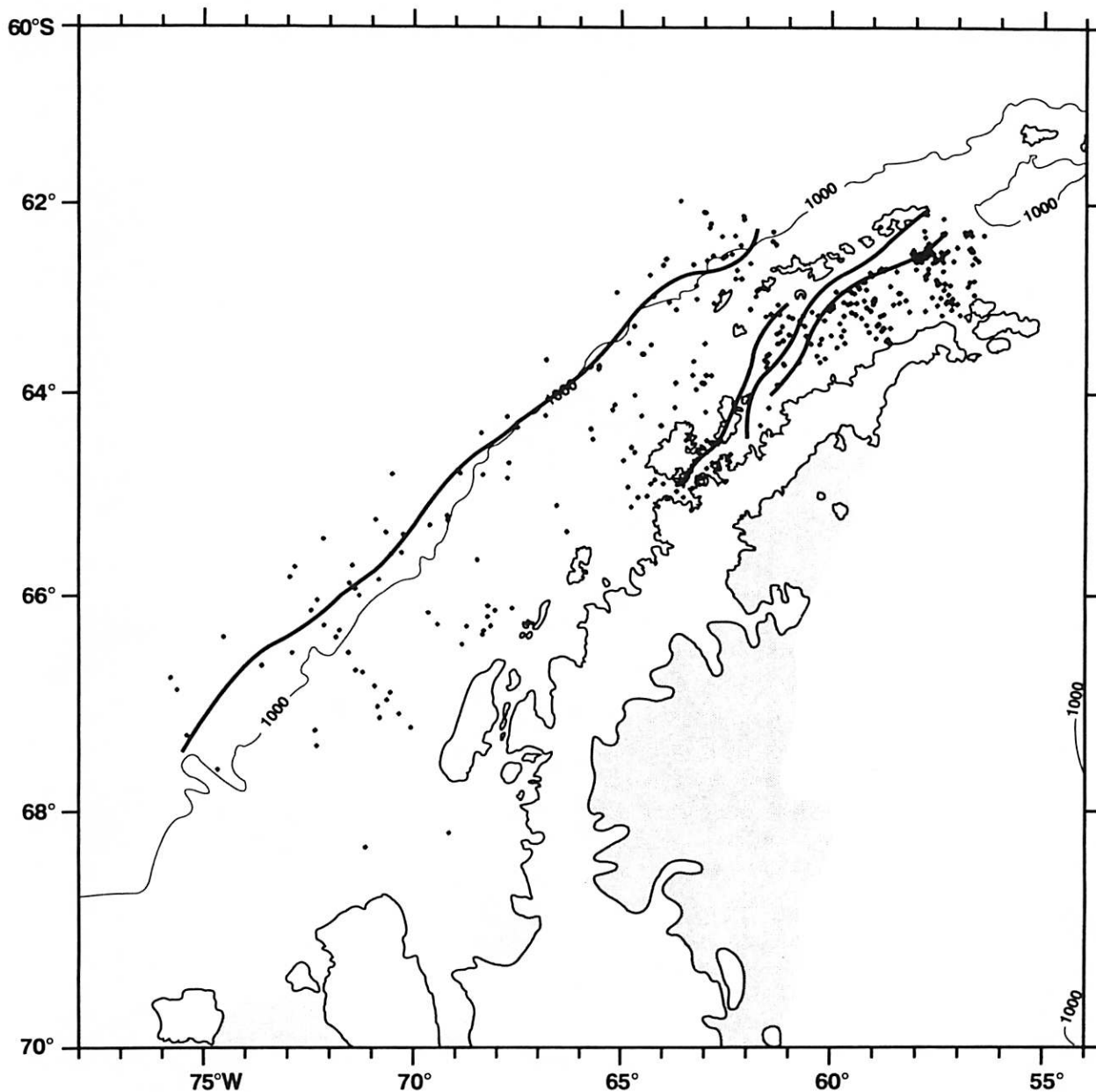
Fig. 7. Distribution of the temperature maximum below 200 m. The hydrographic stations used for the analysis are shown.

suggested by *Stein* [1992], there may be one or more meso-scale gyres within this clockwise flow.

6. THEORETICAL CIRCULATION STUDIES

6.1. *Large-Scale Circulation Models*

Several global ocean modeling studies have been undertaken, most of which are based on grids with resolutions that

are more than 2° of latitude and longitude. As a result, the simulated circulation fields poorly resolve the coastal area off the Antarctic Peninsula. However, two recent circulation modeling studies that consider spatial scales of the order of a few 10s of kilometers include the Antarctic Peninsula region: a global model [*Semtner and Chervin*, 1988, 1992] and a Southern Ocean model, the Fine Resolution Antarctic Model (FRAM) [*The FRAM Group*, 1991; *Webb et al.*, 19-91]. Both models use ocean depths that are extracted from a five-minute bathymetry and smoothed over a spatial scale
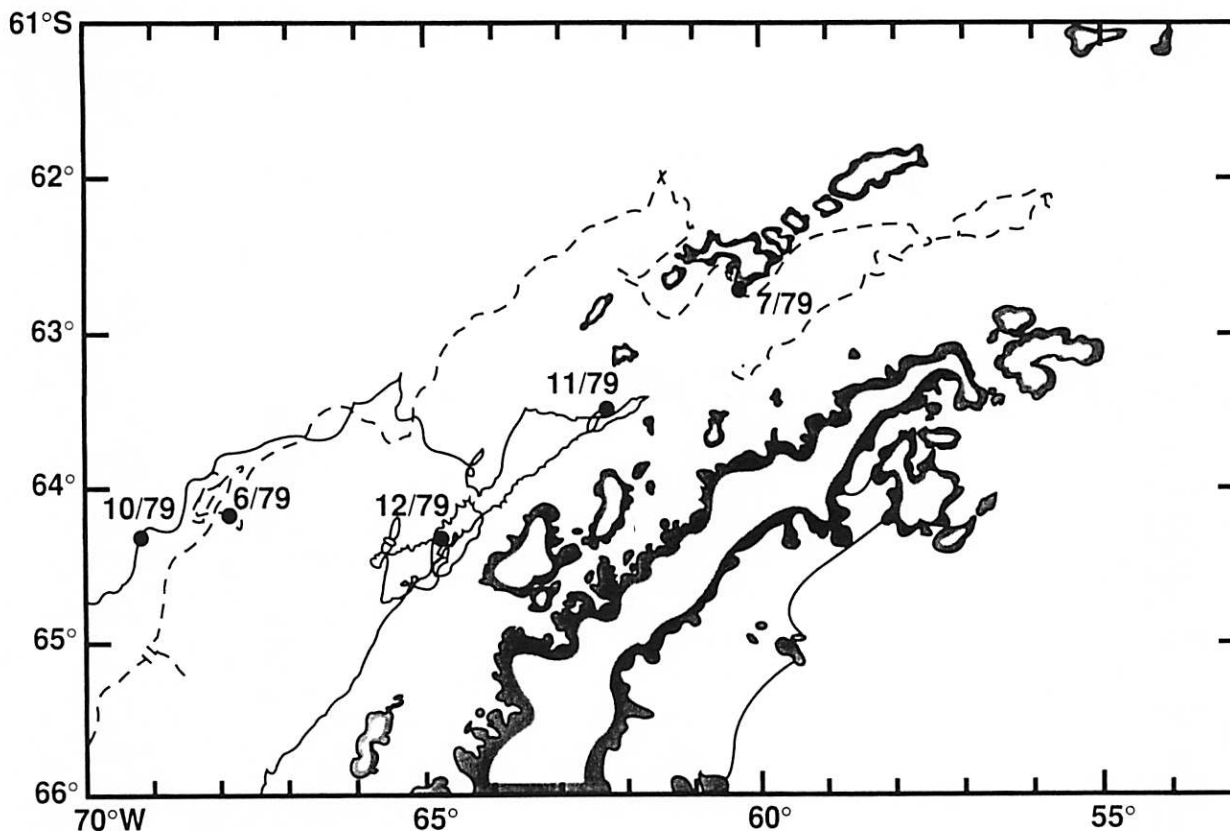
Fig. 8. Trajectories of two FGGE surface drifters that moved through the region in 1979 are shown by the solid (Buoy No. 54612) and dashed line (Buoy No. 54611). The start of each month is indicated on the buoy trajectories.

of about 1° of latitude and longitude. The effect of this smoothing is to greatly reduce the continental shelf area west of the Antarctic Peninsula such that it is represented only by general features. Also, atmospheric forcing in the coastal areas is very important, but little effort was expended to incorporate realistic forcing in these regions in the global circulation and FRAM calculations. The focus of these modeling studies was on producing realistic simulations of large-scale ocean circulation; therefore, the lack of emphasis on producing realistic flows over continental shelf regions is not surprising. However, for both models, the shelf circulation has been shown to have some realism [*Webb et al.*, 19-91; *Semtner and Chervin*, 1992] and to be of some use in describing the circulation over the continental slope.

The simulated vertical temperature structure along a zonal section at 65.9°S (Figure 10a) and flow at 290 m (level 8 of the model) (Figure 10b) from the FRAM calculation provide examples of the information that is obtained for coastal regions from large-scale calculations. Both fields are from the six-year average solution of the FRAM calculation. To the west of the Antarctic Peninsula, CDW occurs between 200 and 1200 m, with the core (2°C) of this water mass being

well defined at 90°W. At depths of about 500 m, this warm water extends towards the coast and the deeper isotherms move upwards towards the land mass. Both features are consistent with observations. However, the bathymetry used for the FRAM calculation included a much reduced continental shelf around the Antarctic; thus, penetration of CDW onto the continental shelf west of the Antarctic Peninsula is not observed in the model solutions.

The circulation at 290 m (Figure 10b) has a simple structure, with strong northeastward flow due to the ACC over the deep areas and weak alongshore flow nearer to the coast. The flow near the coast shows some meandering, but there is no indication of gyres on the shelf or a southwestward current near the coast. This lack of agreement with observations for this region is likely due in large part to the crude representation used for the shelf bathymetry and, possibly, improper specification of wind and buoyancy forcing.

6.2. Regional Circulation Models

The time-dependent, three-dimensional, primitive equations model developed by *Semtner* [1974] was used to simu-
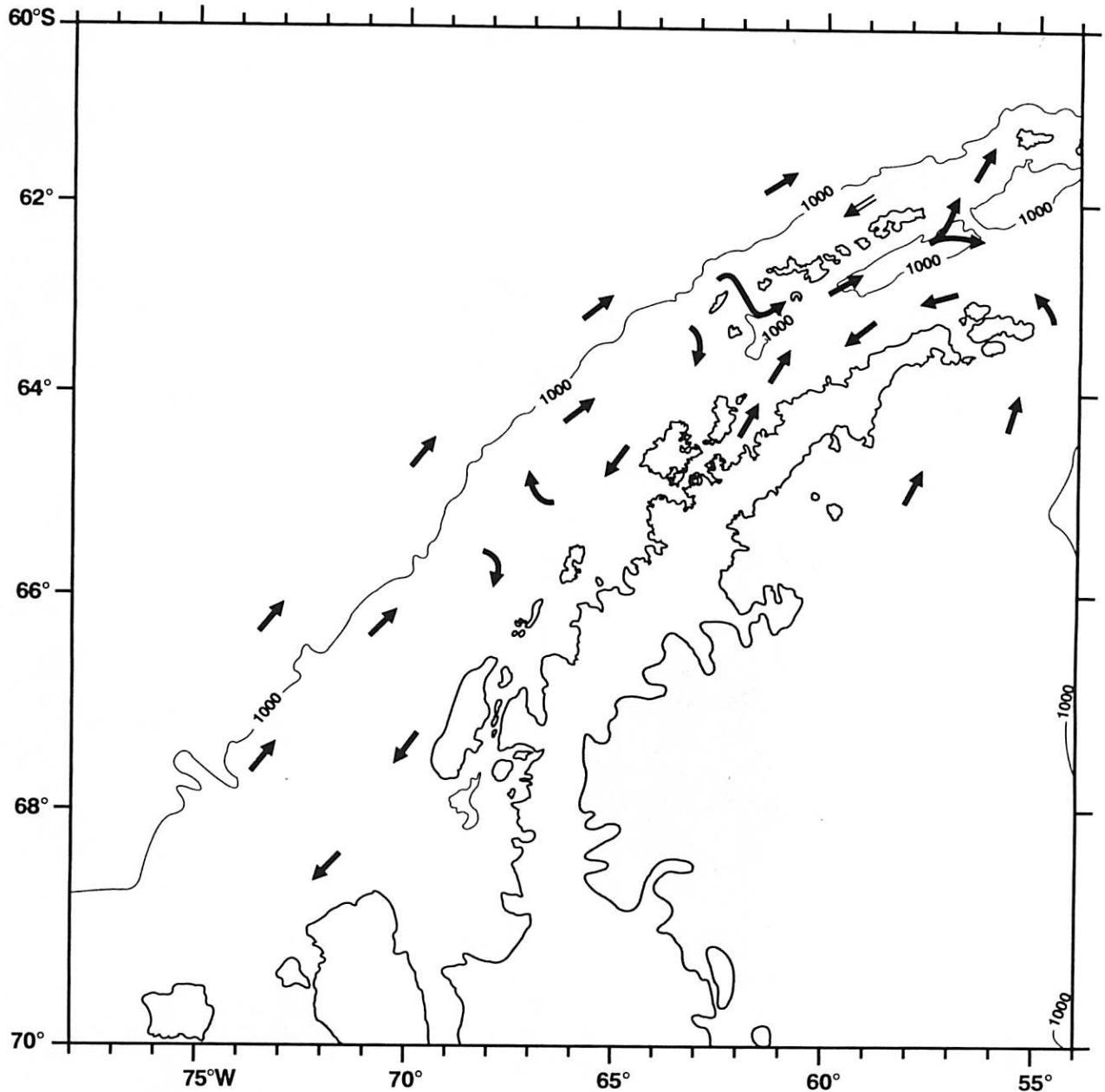
Fig. 9. Schematic of the circulation in Bransfield Strait and west of the Antarctic Peninsula constructed from historical data sources. The open arrow to the north of the South Shetland Islands represents the westward flowing Polar Slope Current. Figure adapted from *Hofmann et al.* [1992b].

late the circulation in the region around the Bransfield Strait and South Shetland Islands. The modifications made to this circulation model to adapt it for this region are described in *Capella* [1989] and some of the simulated circulation patterns are shown in *Capella et al.* [1992a]. A representative simulated surface (0 to 50 m) circulation from January is shown in Figure 11. West of about 60°W, the effect of the Antarctic Peninsula is to force the flow, which is oriented along isobaths, in a general northeasterly direction where it

joins the flow of the Antarctic Circumpolar Current. East of 58°W, the flow north of the South Shetland Islands is to the west. Near Elephant Island, a complex circulation pattern develops, which is likely in response to the complex topography in this region. Flow in the southeastern portion of the Bransfield Strait is to the west, which is the result of flow from the Weddell Sea into the Strait. Surface flow in the northern portion of the Strait is primarily to the north. The surface flow at the western end of Bransfield Strait is con-
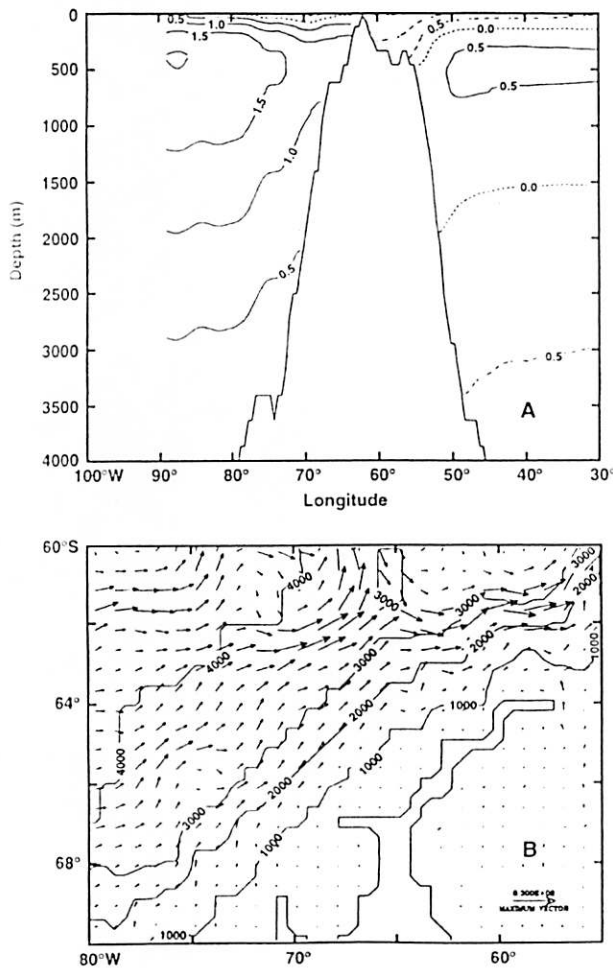
Fig. 10. a) Simulated vertical temperature section from the six-year average of the FRAM solution along 65.9°S. Contour interval is 0.5°C. Solid lines indicate positive temperatures; dashed lines indicate negative temperatures. The bottom topography is representative of that used in the FRAM calculation. b) Simulated horizontal flow from the six-year average of the FRAM solution at a depth of 290 m (model level 8). The heavy solid line is the coastline as represented in the model. The light solid lines are depth contours at 1000 m intervals.

tinuous with that further west. The simulated circulation pattern shown in Figure 11 is primarily the result of the Ekman response to wind forcing. Consequently, the simulated circulation fields from other months [Capella, 1989] show variations in the upper 150 m that are produced by the seasonal changes in the overlying wind field. These consist primarily of changes in the intensity of the flow; the general surface circulation pattern remains the same.

The model by Capella [1989] did not include sea ice and to date, no attempts have been made to implement a coupled sea ice-ocean circulation model for the west Antarctic Peninsula region. However, a coupled sea ice-mixed layer-pycno-

cline model was developed to investigate ice and upper ocean circulation dynamics in the Weddell Sea [Lemke et al., 1990]. This model couples a two-layer dynamic-thermodynamic sea ice model [Hibler, 1979], which includes a prognostic snow layer with a one-dimensional prognostic mixed layer model [Lemke, 1987]. The simulations from this model show clearly the importance of spatial and temporal variability in the vertical oceanic heat flux. Furthermore, the snow layer greatly affects ice thickness [Owens and Lemke, 1990] and the seasonal cycle of ice extent is very sensitive to the ice dynamics [Stössel et al., 1990].

7. DISCUSSION

7.1. CDW West of the Antarctic Peninsula

7.1.1. Distribution. CDW is the most prominent feature of the waters west of the Antarctic Peninsula. This water mass is found in the central portion of Drake Passage at depths of 1000 m or more [Sievers and Nowlin, 1984]. Towards the Antarctic shelf region, CDW rises in response to the equatorward Ekman transport of surface waters. Hence, at the outer shelf, CDW is found at 400 to 700 m. The deep continental shelf west of the Antarctic Peninsula, about 500 m at the shelf break, results in a water mass structure at depth on the shelf that is similar to the deeper offshore waters. Thus, CDW is found over the shelf between 150 to 200 m and the bottom. This is different from mid-latitude shelf systems where shelf breaks are shallower and shelf bottom waters are not typically oceanic in character. Also, the greater depth of the Antarctic shelf west of the Peninsula reduces the effect of wind mixing to a smaller portion of the water column than is found on mid-latitude shelves. The upper 150-200 m undergoes modifications that result from seasonal changes in wind forcing and heat and salt fluxes. However, the deeper waters are not affected by these processes, which allows the oceanic character of the bottom waters to remain intact.

The mechanism by which this water moves onto the shelf is not known. Domack et al. [1992] observed intrusion of CDW onto the continental shelf off Adelaide Island to be associated with a coastward bend in the 3000-m contour and to intrude onto the shelf from the northeast. Potter and Paren [1985] suggest that across-shelf transport of CDW is driven by ice melting processes in the inner shelf region. Essentially the outflow of the more buoyant surface water produced by ice melt is replaced by onshore transport of CDW at depth. The upwelled CDW provides the heat source (see below) 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].

Within the Bransfield Strait there is clear separation between CDW and Bransfield waters. CDW is confined pri-

marily to the southern flank of the South Shetland Islands. The signature of this water mass attenuates to the east [*Stein*, 1986] and its presence is weak or missing in the central and southern Strait [*Gordon and Nowlin*, 1978; *Makarov et al.*, 1988]. Several studies [e.g., *Sievers*, 1982; *Capella et al.*, 1992b] have noted the strong interleaving that occurs at the front that separates oceanic and Bransfield waters and have suggested that this is an important mechanism by which these waters are mixed.

7.1.2. CDW and Winter Water Oxygen Values.

Sievers [1982] showed that upwelling north of the South Shetland Islands resulted in the injection of CDW into the upper water column. Entrainment of this low oxygen water has been suggested as an explanation for the undersaturated oxygen concentrations that are associated with Antarctic surface waters [*Gordon et al.*, 1984; *Smith and Tréguer*, 1994]. The oxygen values associated with Winter Water, which does not undergo seasonal modification, in the region west of the Peninsula range between 6.5 and 7.5 ml l^{-1} (Figure 5b), which are 76 to 88% of the saturation oxygen value of 8.54 ml l^{-1} at -1.8°C, respectively. This reduction in oxygen requires a mixture of 22 to 45% of CDW and 78 to 55% of Winter Water, respectively (Figure 5b).

Assuming a 100 m thick layer, the oxygen values suggest an annual entrainment of 22 to 45 m of CDW, which corresponds to entrainment rates of 0.7 to 1.43 × 10 m s^{-1}, respectively. These estimates are similar to those obtained for the Weddell Sea [*Gordon et al.*, 1984] and Prydz Bay [*Smith and Tréguer*, 1994]. However, the entrainment rates estimated for the Peninsula region should be used with caution since these are derived from primarily austral summer observations (Table 1). Thus, this estimate assumes that the austral summer undersaturation values are typical of the entire mixed layer in winter. The estimates made by *Gordon et al.* [1984] were based on winter observations only in which the entire upper 100 m consisted of Winter Water. Moreover, this calculation assumes no contribution from non-conservative processes, such as oxidation of organic material and heterotrophic respiration. No data exist for the region west of the Peninsula from which estimates for these processes can be made. However, studies from other regions [*Skopintsev*, 1976; *Knauer et al.*, 1979] suggest that these rates should be low. Also, the T-O_2 relationship shown in Figure 5b is distinct, which lends support to the contention that this is the result of conservative processes.

7.1.3. CDW Salt and Heat Fluxes.

The salt introduced by entrainment of CDW over a year requires an input of freshwater to reduce CDW salinity (34.73) to that of Winter Water (34.00). Assuming a 100 m thick layer and a range of vertical diffusion rates of 10^{-5} to 10^{-4} m^2 s^{-1}, a simple salt budget shows that 0.063 to 0.63 m y^{-1} of freshwater are needed to produce the observed Winter Water salinity. *Gordon* [1981] estimated the annual maximum freshwater input due to excess of precipitation over evaporation and continental runoff between 60°S and 70°S to be 0.40 m y^{-1}. Esti-
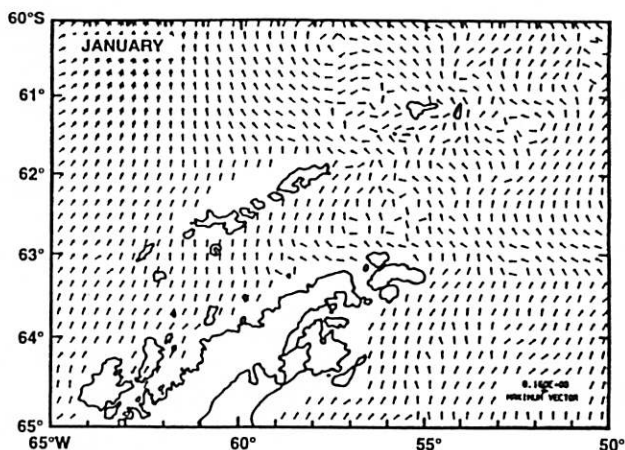

Fig. 11. Simulated surface (0-50 m) circulation obtained for January. Figure from *Capella et al.* [1992a].

mates for west of the Antarctic Peninsula give annual precipitation rates of 0.45 to 0.80 m [*Domack and Williams*, 1990]. Sleet and snow are the principal components of the annual precipitation total, but rain and drizzle are common along the western Antarctic Peninsula [*Griffith and Anderson*, 1989]. Annual precipitation rates at Palmer Station on Anvers Island range from 0.40 to 1.00 m y^{-1} [e.g., *Antarctic Journal of U.S.*, 1991, 1992, 1993]. These precipitation estimates can provide from two-thirds to all of the freshwater needed to balance the salt input. Assuming that the lower rates are more representative, then additional freshwater must be supplied from other sources.

Freshwater input from glacial melt is small along the west Antarctic Peninsula [*Dixon and Domack*, 1991; *Domack and Ishman*, 1993]. However, freshwater could be obtained if there is a net advection of sea ice into the region which then melts. Melting of sea ice would be encouraged by the upward flux of warm CDW. The average temperature associated with Winter Water is slightly above freezing (-1.5°C), which can be taken as direct evidence for continued influx of warm water.

The average rate of heat input, estimated for a vertical diffusion rate of 10^{-4} m^2 s^{-1} and a 3°C temperature difference between CDW (1.5°C) and Winter Water (-1.5°C), is 12 W m^{-2}. This value is similar to that estimated by *Gordon et al.* [1984] for the Weddell Sea. Since the temperature difference between CDW and Winter Water persists throughout the year (Figure 3), this estimated heat flux is likely representative of an annual flux. The rate at which ice can be melted by this heat flux is 3.71 × 10^{-8} m s^{-1}, which converts to an annual rate of 1.2 m y^{-1}. *Potter and Paren* [1985] estimated an ice melt rate of 1.1 to 3.6 m y^{-1} due to upwelling of CDW west of the Antarctic Peninsula. The salinity budget suggests that a melting rate of 2.06 × 10^{-8} m s^{-1} (0.63 m y^{-1}) is needed to provide sufficient freshwater to maintain the salinity associated with Winter Water. Melting of this

amount of ice requires about 7 W m^{-2}, which is less than the heat provided by CDW. Thus, the heat flux from below is sufficient to melt the required amount of ice, even without the addition of surface heating.

The rate at which sea ice must be brought into the region to satisfy the needs of the salt budget can be estimated by balancing the volume flux of sea ice per unit width of the shelf with the ice melting rate over some distance. For a distance of 1000 km and 1 meter thick ice, the advective velocity required to satisfy this balance is 0.04 m s^{-1}. Direct current measurements for the region west of the Antarctic Peninsula are not available. However, this velocity is within values reported for continental shelf systems. Reducing the ice thickness by 50% gives an advective speed of .075 m s^{-1}, which is still within the range of values reported for horizontal flows on continental shelves. A clockwise circulation west of the Peninsula (Figure 9) would favor advection of ice from the Bellingshausen Sea along the mid and outer part of the west Antarctic Peninsula continental shelf.

These calculations suggest that the addition of freshwater from ice melt is an important part of the heat and salt budgets of the west Antarctic Peninsula shelf region. Moreover, the upward heat flux and resultant ice melt may moderate the amount of ice cover as well as the climate of the region. The shelf region west of the Peninsula is not noted for formation of deep water as is found on the Weddell Sea shelves. It may be that the presence of warm water so near the surface inhibits formation of dense water by preventing ice from forming. Thus, the west Antarctic Peninsula shelf may be a region of ice melt as opposed to a region of ice formation as suggested by *Gloerson et al.* [1992] and *Stammerjohn and Smith* [this volume].

7.2. Bransfield Strait Waters

The cold deep waters that fill the Bransfield Strait may form locally [*Gordon and Nowlin*, 1978] since the distinct basins in the Bransfield Strait would restrict exchanges at depth. However, *Whitworth et al.* [1994] argue that the deep waters in Bransfield Strait are a mixture of CDW of the ACC, the colder and slightly fresher CDW in the Weddell Sea, and the shelf waters from the northwest Weddell Sea. A mixture of this water flows westward north of the Antarctic Peninsula, where it sinks along isopycnals to renew the deep waters of the Bransfield Strait. As indicated by *Whitworth et al.* [1994], this mixing scheme can occur throughout the year and does not depend on winter convection, which has not been observed in Bransfield Strait. This water is then trapped in the deep basins and consequently has little effect on the deep thermohaline circulation. Above 1000 m, the colder water in the southern portion of the Strait may be partially or wholly derived from inflows from the Weddell Sea.

Fine scale hydrographic surveys suggest a complex water mass structure within the upper waters of Bransfield Strait

that arises from the mixing of 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 waters from west of the Antarctic Peninsula 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, this wind-induced heat transport may be an important aspect of the heat budget of this region.

Simulated Lagrangian particle studies [*Capella et al.*, 1992a] for the Bransfield Strait region support the suggestion that the Bransfield Strait receives inputs from the west Antarctic Peninsula region and the Weddell Sea. The simulated particle trajectories indicate that the effect of water from the west Peninsula region is confined to the western portion of the Strait, whereas water from the Weddell Sea affects the southern and eastern portions.

7.3. Circulation

The schematic circulation suggests that flow west of the Antarctic Peninsula and in Bransfield Strait is characterized by mesoscale structure. Coherent along- and across-shelf flows are not well developed. Rather, localized gyres occur over the shelf west of the Peninsula and flow north of the South Shetland Islands is associated with a large meander. The gyres over the shelf have length scales that appear to be dictated by the rugged bottom topography.

The small internal Rossby radius of deformation associated with Antarctic regions (10 to 15 km) implies narrow currents. Hence, coherent flows may exist, but sampling to date has been on scales too coarse to resolve these features. Also, the small coherence scale for the circulation suggests that small eddies should also be present. Some indication of eddies is seen in the simulated circulation patterns given in *Capella* [1989] and *Heywood and Priddle* [1987] describe the occurrence of an eddy at the eastern end of King George Island. This latter study suggested that eddies may be important in the retention of phytoplankton biomass. Also, *Stein* [1988] describes what appears to be a permanent eddy near Elephant Island.

The effect of buoyancy forcing resulting from ice formation and retreat has not been considered for the region west of the Antarctic Peninsula. However, the dynamics that underlie some of the circulation features on the shelf south of Alaska may provide insight about coastal currents west of the Antarctic Peninsula. The continental shelf off the south coast of Alaska is wide (more than 100 km) and uniformly 200 to 300 m deep. The circulation on the shelf is driven primarily by surface wind stress and freshwater (runoff and glacier melt) inputs from the coast [*Royer*, 1981; *Johnson et*

al., 1988]. The Alaska Coastal Current, which is a narrow (10 to 20 km) westward flowing current on the inner shelf, is thought to be forced primarily by surface buoyancy due to freshwater inflow [*Royer*, 1981]. Variations in the strength and intensity of this current have been correlated with freshwater additions [*Royer*, 1981].

Conditions over the Peninsula shelf are similar to those in Alaska, with a downwelling wind stress (which is stronger during austral spring and fall, but more alongshore during the austral summer) and the potential for freshwater addition near the coast due to sea ice and glacier melt. The Antarctic does not have the rainfall that occurs over Alaska so the runoff is reduced, which may result in a less intense coastal current. However, the conditions west of the Antarctic Peninsula are such that a coastal current could exist, at least during the austral summer months, when there is freshwater addition from the coast and southward winds. Some evidence for a southwestward flowing coastal current is found in the dynamic topography contours given in *Stein* [1992]. However, the sampling grid on which these maps are based is too coarse to accurately resolve a narrow coastal current.

7.4. *Polar Slope Current*

It has been suggested that the Polar Slope Current to the north of the South Shetland Islands is continuous around Antarctica [*Nowlin and Zenk*, 1988]. However, the simulated circulation shown in *Capella* [1989] suggest that this current does not extend west beyond the gap between Smith and Snow Islands. Recent XBT and CTD measurements made along transects that crossed the shelf break region north of Livingston Island and west of Smith Island [*Hofmann et al.*, 1993] support the suggestion that the Polar Slope Current is not continuous. However, these measurements and the modeling study of *Capella et al.* [1992a] are not sufficient to determine the fate of this current. This must await additional measurements and circulation modeling studies. The fate of the Polar Slope Current has implications for Antarctic krill research as well since it has been suggested as a mechanism for transporting krill embryos released north of the South Shetland Islands to the west where they then may be transported into Bransfield Strait [*Quetin and Ross*, 1984].

Determining the fate of the Polar Slope Current once it reaches the gap between Smith and Snow Islands could potentially alter the way in which coastal currents are viewed. Well-defined ocean currents are not known to simply disappear. However, this is what the Polar Slope Current seems to do once it encounters the gap between Smith and Snow Islands. There is not a parallel with other systems that can be used as a model to determine the conditions that are needed for this current to remain intact or dissipate. This is a feature of the circulation in the Peninsula region that is worthy of future sampling and modeling efforts.

7.5. *Future Directions*

CDW is ubiquitous throughout the region west of the Peninsula and in the northern portion of Bransfield Strait. In addition to affecting heat and salt budgets of this region, CDW potentially has an effect on biological productivity and distributions. For example, it has been shown that the presence of this water mass is important to the reproductive cycle of Antarctic krill [*Hofmann et al.*, 1992a]. Moreover, the region west of the Antarctic Peninsula supports large populations of Antarctic krill and top predators, such as penguins, seals, and whales. Upwelling of CDW, which is high in nutrients [*Sievers and Nowlin*, 1984], could provide predictable regions of enhanced production. Also, upwelling of this warm water may provide predictable regions of open water in winter. Therefore, a careful and thorough mapping of the distribution of CDW is essential for understanding the potential effects of climate change on environmental conditions and biological production in the Peninsula region.

The present description of circulation west of the Antarctic Peninsula and in Bransfield Strait relies to a large extent on limited hydrographic measurements from which dynamic calculations have been made. However, one limitation of the geostrophic velocity fields obtained from this approach is that the water column west of the Peninsula is not strongly stratified so there is not a large geostrophic shear over the shelf. Therefore, an as yet unquantified barotropic circulation may be an important component of the total circulation in this region. *In situ* current measurements (e.g., current meters, drifters) are needed to define the total circulation of this area.

Surprisingly few of the historical hydrographic data were from cruises dedicated specifically to mapping hydrographic distributions and circulation patterns in the Peninsula region. Most of the historical data used in this review were obtained from multidisciplinary programs designed for biological sampling. Thus, the spatial resolution and station locations were not optimal for resolving hydrographic and circulation features. Furthermore, the low density of hydrographic observations necessitated the use of relatively large latitude and longitude sub-areas, which in some cases combined different hydrographic regimes. Observations are particularly limited along the inner portion of the shelf and during the austral winter. Future sampling and modeling efforts for this region must be designed to include higher resolution measurements, all seasons, and the entire water column.

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