Journal of Marine Systems, 3 (1992) 169–182
Elsevier Science Publishers B.V., Amsterdam

The Weddell–Scotia marginal ice zone: Physical oceanographic conditions, geographical and seasonal variability

R.D. Muench [a], B.A. Huber [b], J.T. Gunn [a], D.M. Husby [c] and D.G. Mountain [d]

[a] *Science Applications International Corp., Bellevue, WA 98005, USA*
[b] *Lamont-Doherty Geol. Observatory, Palisades, NY 10964, USA*
[c] *Southwest Fisheries Center, NOAA, Monterey, CA 93943 USA*
[d] *National Mar. Fish. Serv., NOAA, Woods Hole, MA 02543, USA*

(Received August 20, 1990; revised version accepted April 8, 1991).

ABSTRACT

Muench, R.D., Huber, B.A., Gunn, J.T., Husby, D.M. and Mountain, D.C., 1992. The Weddell–Scotia marginal ice zone: Physical oceanographic conditions, geographical and seasonal variability. J. Mar. Syst., 3: 169–182.

Physical oceanographic conditions were measured in the Weddell and Scotia Sea marginal ice zones (MIZ's) during 1983, 1986 and 1988. The field work encompassed spring, autumn and mid-winter periods and included retreating, advancing and steady-state ice edges. Observed upper ocean structures, which typify MIZ's and reflect input of low salinity water from melting ice, included low salinity upper layers, lenses and fronts. An upper mixed layer was always present and was generally more fully developed in autumn and winter than at other times of year. Conditions in the deeper waters reflected regional oceanographic processes and significant differences were present between the Weddell and Scotia seas. Weddell Sea Water is a major source of water for the southern Scotia Sea, however, the upper Scotia Sea was dominated by warmer, less saline waters from Drake Passage. The colder, denser Weddell water appeared to have mixed isopycnally with deeper water in the Scotia Sea, present there at depths exceeding 500 m.

The Scotia Sea was dominated by strong gradients and energetic mesoscale features, with currents exceeding 50 cm/s. The northwestern Weddell Sea had, in contrast, current speeds well below about 5 cm/s and small to negligible lateral water property gradients. Our observations suggest that the Weddell western boundary current was weaker than has been estimated in the past. In addition, we found scant evidence of deep winter convection in the Scotia Sea, a process which has been hypothesized in the past to contribute to deep water formation. No evidence was found during winter 1988 in the Scotia Sea of the modified water known as Weddell–Scotia Confluence water.

Background

Introduction

The Weddell and Scotia seas (Figs. 1 and 2) are oceanographically continuous, linked by a broad, deep northward flow from the northwestern Weddell Sea into the southern Scotia Sea. The sea ice cover forms, also, a seasonally varying continuum between the two regions and in winter extends from the Weddell through the southern Scotia Sea. Despite these continuous features, however, the Weddell and Scotia seas differ greatly in both their water mass structures and their energetics. This paper summarizes and integrates selected physical oceanographic results from the AMERIEZ Program (Smith and Garrison, 1990) and uses these results to illustrate contrasts between the Weddell and Scotia seas. The material herein is intended, also, as background for the interdisciplinary AMERIEZ papers presented elsewhere in this volume. Our

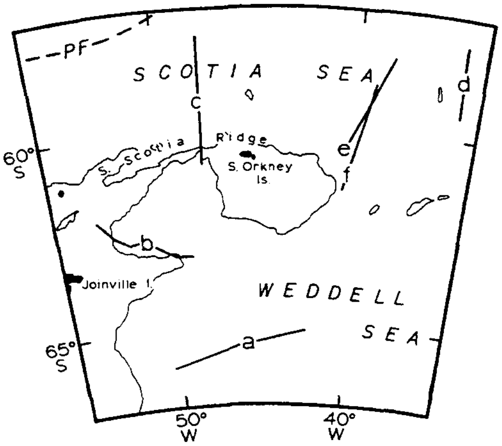

Fig. 1. Geographical location of the study region and of features referred to in the text. Lines *a–f* indicate locations of transects shown in Figs. 4–9 (see also Fig. 2). Dashed line *PF* indicates typical location for the Polar Front. Thin line indicates the 2 km bottom contour.

discussion will be limited to conditions shallower than 1500 m, the maximum sampling depths for the AMERIEZ program.

The oceanographic context

The western Weddell Sea can be characterized as a region of deep, sluggish northward flow which is the westernmost limb of the wind-driven, basinwide cyclonic Weddell Gyre (e.g. Gordon et al., 1978; Deacon, 1979; Gordon et al., 1981). The gyre-associated flow is predominantly barotropic, consistent with the weak lateral and vertical gradients in water properties; geopotential surface heights above the 1000 db level computed from historical data show only very weak baroclinic upper layer currents (Gordon et al., 1978). Total northward transport in the western Weddell is uncertain. Carmack and Foster (1975) derived a

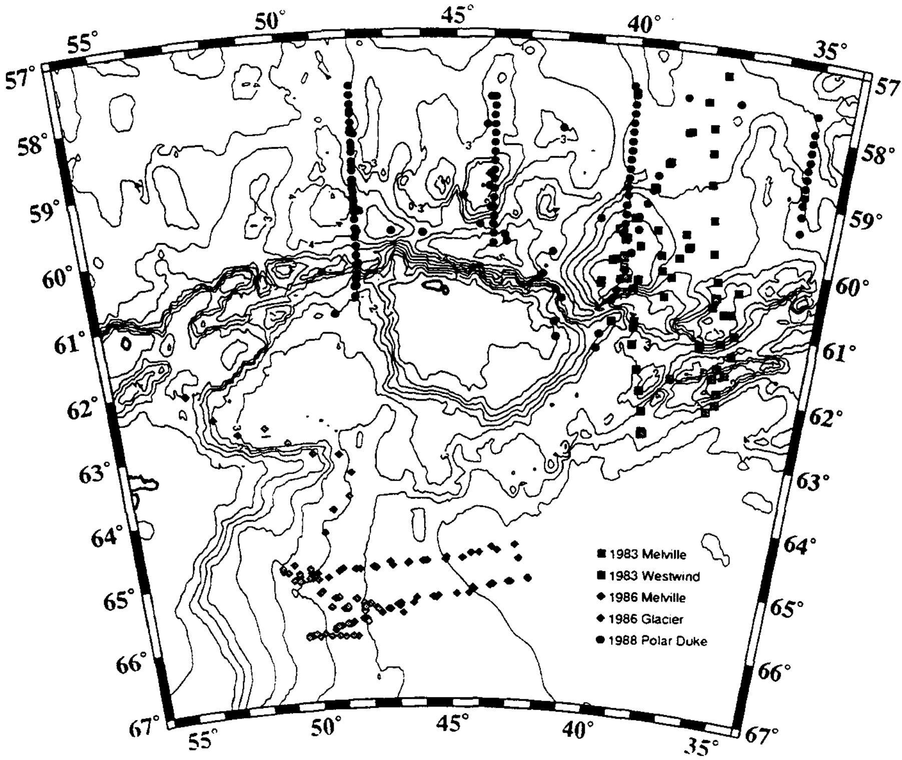

Fig. 2. Positions of CTD casts taken during the 1983, 1986 and 1988 AMERIEZ field programs. Bottom contours are labled in km.

total gyre transport of 97×10^6 m^3/s, however, their value was based upon a relatively small number of short-term current observations. Gordon et al. (1981) postulated a northward transport in the western Weddell of 76×10^6 m^3/s using closure of a wind-driven gyre. They also predicted vertically integrated current speeds of 8 cm/s and a western boundary current width of 225 km at 65°S. Observed mean northward ice drift speeds in the range of 5–10 cm/s (Ackley, 1979) are consistent with the above estimates of current speed.

The upper 1500 m of the Weddell Sea can be divided into three water masses (Carmack, 1977). Uppermost is the Weddell Surface Water, which varies seasonally in temperature and salinity due to warming and ice melting, cooling and freezing. This layer is underlain by a very sharp salinity-controlled pycnocline. Beneath this lies the Weddell Winter Water, which represents a remnant of the preceding winter's cold, convective layer. The Weddell Warm Water underlies the Winter Water. This layer contains the main thermocline between about 100–200 m and has a temperature maximum at 300–500 m. Beneath the sharp pycnocline, which spans a density range of order 0.5 sigma-*t* units, the vertical density gradient is extremely small. Likewise, lateral gradients in temperature, salinity and density are small. Mesoscale structures, which are common in temperate oceans and even over large areas of the Arctic Ocean, have not been observed in the northwestern central Weddell Sea (Muench, 1990).

In sharp contrast, the southern Scotia Sea is dominated by strong vertical and lateral gradients, many associated with mesoscale eddies and frontal structures (see e.g. Foster and Middleton, 1984). This very complex hydrographic field reflects the presence of water masses which originate in the Bellingshausen Sea, in the Weddell Sea, from Bransfield Strait and from the Antarctic Circumpolar Current. Scotia Sea Water is comprised primarily of a mixture of Bellingshausen Sea and Antarctic Circumpolar Current Water, and is readily identifiable in the southern Scotia Sea by subsurface temperature maxima at 400–500 m which can exceed 2–3°C. Weddell Sea Water enters the southern Scotia Sea from the northwestern Weddell Sea over the South Scotia Ridge, through the gaps west and east of the South Orkney Islands. The transitional region in which Weddell and Scotia Sea waters converge and mix is called the Weddell–Scotia Confluence (WSC). Descriptions of the southern Scotia Sea, based primarily upon summer data and with general emphases on the WSC, have been provided by numerous authors but in the greatest detail by Deacon and Moorey (1975), Deacon and Foster (1977), Gordon et al. (1977) and Patterson and Sievers (1980).

The Weddell Sea water column is dominated by vertical processes, whereas the Scotia Sea is dominated by lateral processes. In the Weddell Sea, currents and lateral property gradients are small and the distributions of temperature, salinity and energy are strongly influenced by such vertical processes as double diffusion, cabelling, free convection due to brine rejection from freezing ice, and turbulence due to winds, ice drift and internal wave breaking (see, e.g., Foster and Carmack, 1976; Muench et al., 1990a). Currents and lateral property gradients in the Scotia Sea are large and the distributions of temperature, salinity and energy are controlled primarily by lateral advection and isopycnal mixing (Muench et al., 1990b).

The Weddell–Scotia Sea region is subject to a seasonally varying pack ice cover (Zwally et al., 1983; Comiso and Zwally, 1989) (Fig. 3). In summer, this ice is restricted to the westernmost Weddell sea. In winter, it extends throughout the Weddell Sea and northward for several hundred km into the southern Scotia Sea.

Field program

The AMERIEZ data were collected during field programs in the southern Scotia Sea during November 1983 and June–August 1988 and from the Weddell Sea during March 1986 (Figs. 1 and 2). Each of these programs was focussed on the MIZ. Each used different platforms and instrumentation and will therefore be summarized separately below.

Sampling during the 1983 program was carried out from the R/V *Melville*, which operated in the

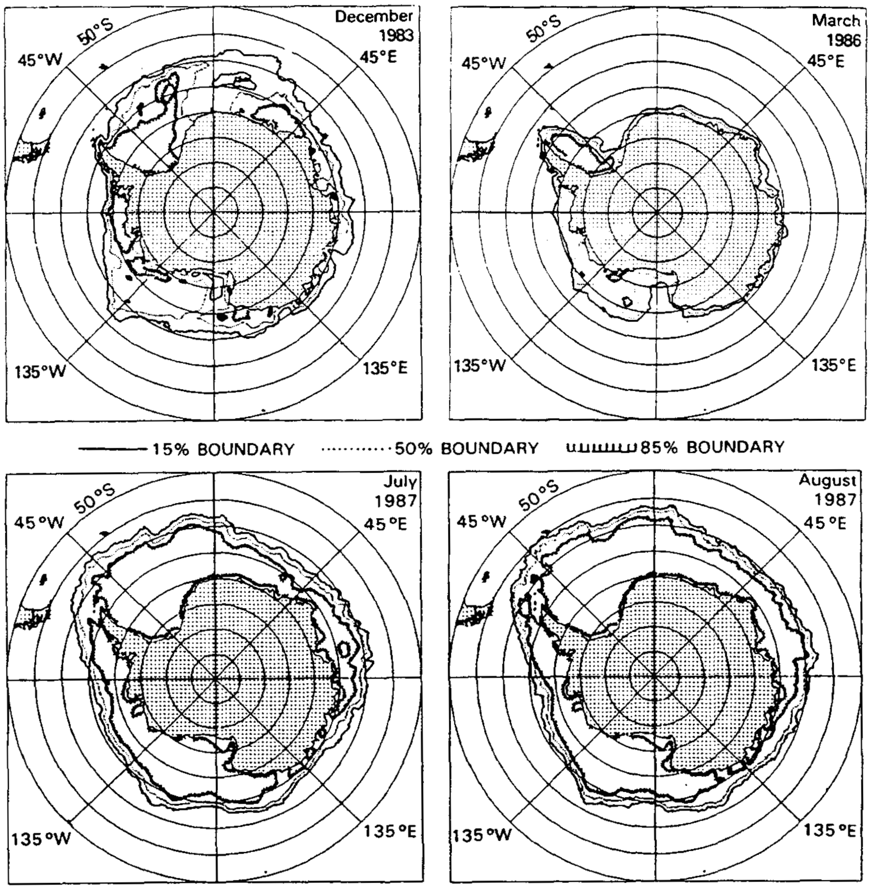

Fig. 3. Extent of sea ice at approximate mid-points of the 1983 and 1986 field programs, and ice extent for July–August 1987 showing ice extent which is typical for winter, from Comiso and Zwally (1989). Ice extent during the winter 1988 field program is not shown, but was similar to that shown here for July–August 1987.

open water and from the USCGC (United States Coast Guard Cutter) *Westwind* operating in the pack ice. Temperature and salinity observations were made from both vessels using vertically profiling conductivity/ temperature/ depth (CTD) systems. A Neil Brown Mark III CTD system was used on the *Melville* and an Ocean Data Equipment model 302 internally recording CTD on the *Westwind*. Standard CTD calibration practices were followed, using water samples collected during the cruise and calibration data obtained in the laboratory. Details are provided in Nelson et al. (1987).

Sampling during the 1986 program was carried out using Neil Brown Mark III CTD systems operated from two vessels; R/V *Melville* and USCGC *Glacier*. Both systems were calibrated prior to and following the cruise and standard calibration practices were followed during the cruise. *Melville* sampled seaward of the ice edge, and *Glacier* carried out sampling in the ice. Details of the cruise, instruments used, calibration and initial data analyses are provided in Husby and Muench (1988).

The June–August 1988 program was carried out during two sequential legs from the ice-strengthened vessel R/V *Polar Duke*. Temperature and salinity measurements were obtained using a SeaBird model SBE 9/11 CTD system which was calibrated prior to and following the field program. Details for this winter field program are provided in Muench et al. (1990b).

Sea-ice distributions are provided for the 1983 and 1986 cruise periods in Comiso and Zwally (1989). Ice cover data for the 1988 cruises was provided in the form of unpublished images showing geographical ice cover and concentration data by J. Comiso (NASA/GSFC, 1990 pers. commun.). Ice extent during the 1983 and 1986 programs, and representative for the 1988 program, is shown in Fig. 3.

Results

Description of the temperature, salinity and density fields

Regional differences in temperature, salinity and density distributions are illustrated here through a sequence of transects, each approximately normal to and bracketing the MIZ, beginning in the northwestern Weddell Sea and progressing northward and eastward into the Scotia Sea (Figs. 4–7).

In the northwestern Weddell Sea, the distributions of T, S and density were characterized by lateral near-uniformity. A transect along about 65.5°S across the MIZ showed generally small lateral gradients and no mesoscale features (Fig. 4). The only significant MIZ-associated structure was a low-salinity layer which underlay the ice edge, was confined to the upper mixed layer, and was probably a remnant of ice melt from the directly preceding summer (not shown in figure, but documented in Nelson et al., 1989). The Winter Water ($T < 0°C$) and Warm Water ($T > 0.4°C$) layers were present. There was a general increase in upper-layer temperature toward the east, away from the ice.

A southeast–northwest transect farther north extended onto the continental slope-and crossed the major outflow of water via the Weddell's western boundary current (Fig. 5). The Weddell Warm Water core was clearly evident ($T > 0.4°C$), and deepened somewhat toward the continental margin. A cold, saline core ($S > 34.71$ ppt at about 800 m, decreasing to less than 34.70 ppt at 1500 m, where temperatures had decreased to less than $-0.2°C$) was present in the western half of the transect over the continental slope. This feature may have been cold, dense shelf water, flowing northward along the continental slope, as discussed for example by Foldvik et al. (1985). The weakly sloping isopycnals indicated that this water was denser than that farther offshore, but did not suggest that significant baroclinic flow was present. In the absence of direct current observations, quantitative statements concerning the currents here are not possible.

The next transect to the north falls fully in the southern Scotia Sea (Fig. 6) and demonstrates clearly the dramatic increase in water column

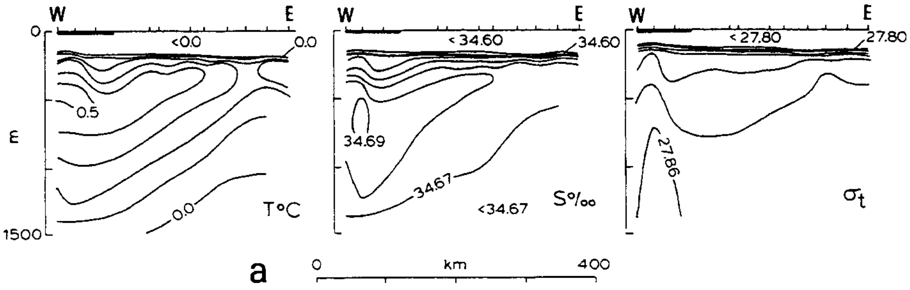

Fig. 4. Distributions of T, S and density (as σ_t) along southernmost (about 65.5°S) zonal March 1986 Weddell Sea CTD transect *a* (from Husby and Muench, 1988). Upper layer contours have been omitted for clarity. Bold dark line at the sea surface on this and the following three figures indicates presence of an ice cover. Tick marks at surface on this and subsequent transects indicate station locations. Location is shown on Figs. 1 and 2.

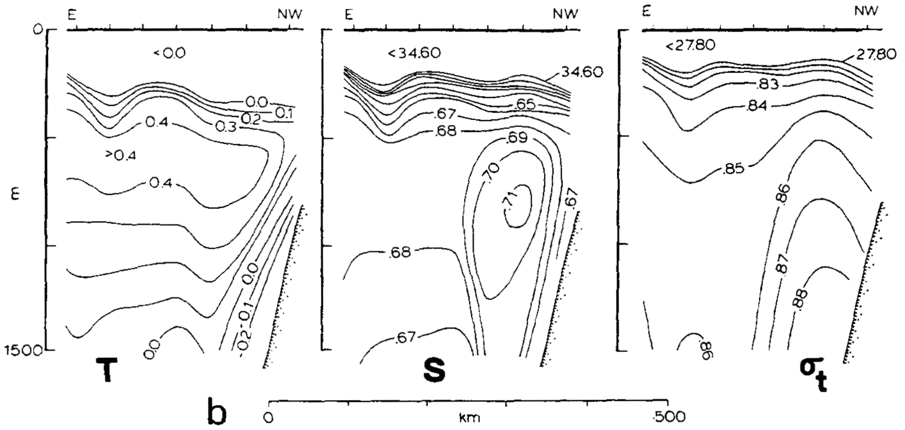

Fig. 5. Distributions of *T*, *S* and density (as σ_t) along March 1986 CTD transect *b* extending southeast–northwest, roughly coincident with the northwestern Weddell Sea continental slope, from about 63.5°S–48.5°W to 62°S–54°W (from Husby and Muench, 1988). Upper layer contours have been omitted for clarity. Location is shown on Figs. 1 and 2.

structure which occurs when the northward-flowing waters from the Weddell Sea converge with the eastward flow from Bransfield Strait and Drake Passage. The warm (> 2°C) waters at 400–500 m in the northern part of the transect are derived from the Polar Front (Muench et al., 1990b). Small scale vertical structures suggest that interleaving was occurring across frontal regions. Temperatures increased throughout the water column toward the north, though there were alternating warm and cold features so that the increase was not monotonic.

The final transect was situated about 750 km farther east in the southern Scotia Sea, or downstream relative to the mean currents (Fig. 7). As farther west, warm deep water reflected the influence of the Polar Front and temperatures generally increased toward the north throughout the water column. While the structure was still complex relative to the northwestern Weddell Sea, it was less complex than farther west in the Scotia Sea. This reflects the decrease in gradients, through lateral mixing processes, during eastward flow from the origin of many of these features farther west where the currents first converge. Persistence of mesoscale features throughout the southern Scotia Sea study area was consistent with Foster and Middleton's (1984) earlier results.

Finally, a limited seasonal intercomparison is possible in the southern Scotia Sea where there was partial spatial coincidence between meridional transects occupied approximately along 40°W during spring 1983 and winter 1988 (Figs. 8 and 9). This comparison suggests that virtually all of the seasonal variability is confined to the uppermost part of the water column. A thermal frontal structure, much more pronounced below the upper mixed layer than within it, was present about 3/4 of the distance from the southern end of the transect both in 1983 and 1988. Temporal variability on a scale of weeks was as large as the interannual variation observed between 1983 and 1988.

Densities (σ_t) in the Weddell Sea were greater than 27.80 below the Weddell Surface Water layer. In the Scotia sea, waters of this density were found from 350 m (Fig. 7) to deeper than 1500 m (Fig. 6). Upper layer water from the northwestern Weddell Sea will mix with deeper water in the Scotia Sea. Water from the Weddell Warm Water layer, having a density of 27.84–27.85, will occur below the 1500 m maximum sampling depth over much of the southern Scotia

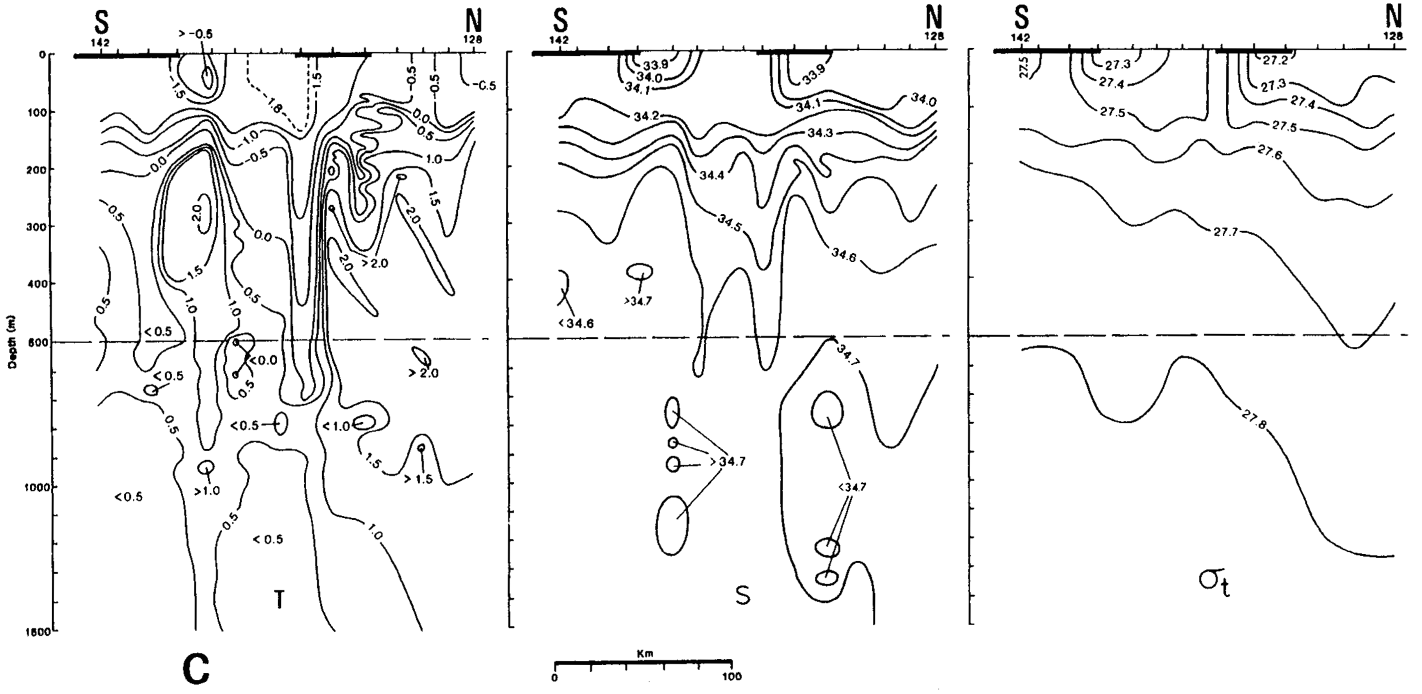

Fig. 6. Distributions of T, S and density (as σ_t) along westernmost (about 48°W) meridional August 1988 southern Scotia Sea transect c (from Muench et al., 1990b). Note that the depth scale is split at 500 m and that the scales and contour intervals are different than for Figs. 4 and 5. Location is shown on Figs. 1 and 2.

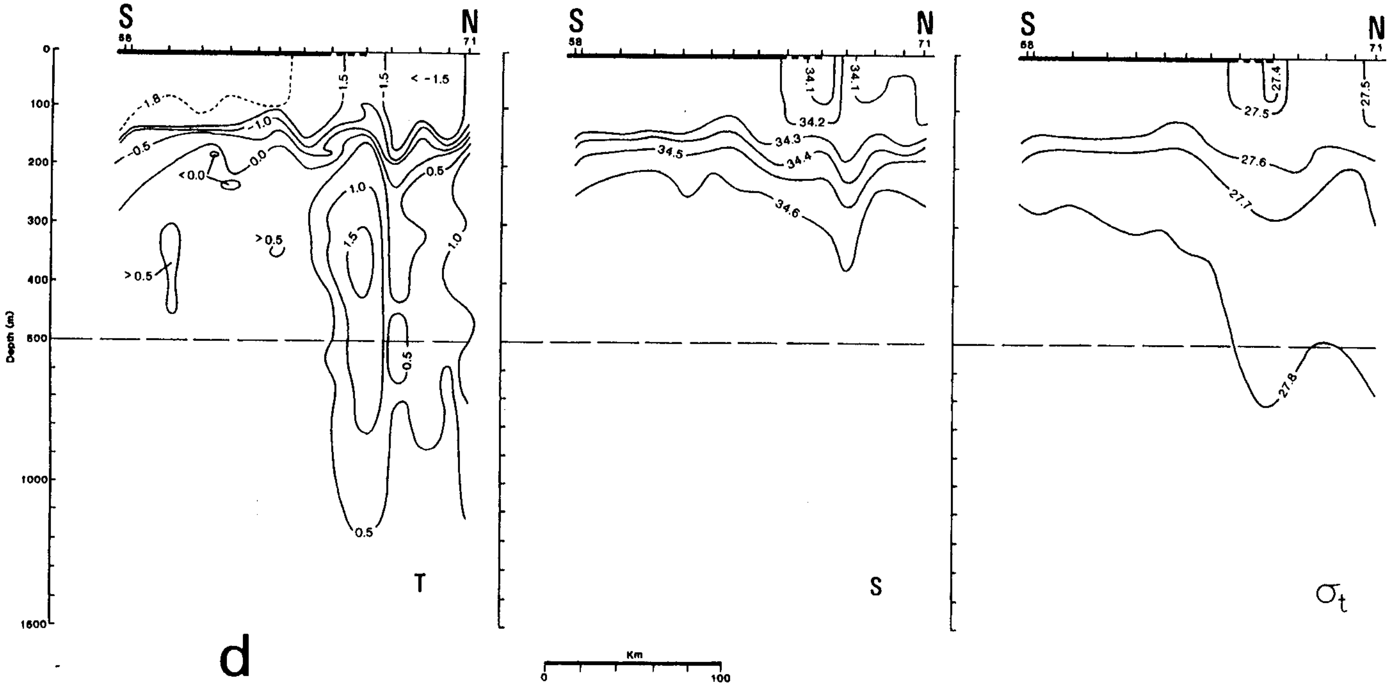

Fig. 7. Distributions of T, S and density (as σ_t) along easternmost (about 35°W) meridional July 1988 southern Scotia Sea transect *d* (from Muench et al., 1990b). Horizontal and vertical scales, and contour intervals, are as for Fig. 6. Location is shown on Figs. 1 and 2.

Sea region. This tendency for upper layer Weddell Sea waters to mix along isopycnal surfaces during northward movement and mix with deeper Scotia Sea waters was recognized by Deacon and Foster (1977).

The regional circulation

No direct observations of currents were made in the northwestern Weddell Sea, a region which has been characterized as having very weak mean currents. The data obtained during autumn 1986 were used by Husby and Muench (1988) to construct a dynamic topography of the sea surface relative to the 1500 db pressure surface. The resulting dynamic relief, and inferred baroclinic circulation, implied that a virtually insignificant surface baroclinic current (> 1 cm/s) was present, consistent with previously published results. This current was northward, following the general trend of the late summer ice edge up to a location east of Joinville Island. At this point, the surface flow appeared to turn westward, again following the ice edge. This baroclinic flow pattern is contrary to the northeastward flow which we might expect to find in this region, and might reflect a summer accumulation of meltwater in the upper ocean layers beneath the ice edge. The surface dynamic topography relative to 500 db showed a similar pattern with about half as much relief. The baroclinic field was weak (< 1 cm/s) relative to the estimated 8 cm/s northward barotropic current speed (Gordon et al., 1981) and the upper layer baroclinic currents probably do not significantly impact the total regional flow in the northwestern Weddell Sea.

Direct evidence of northward surface flow was provided during the months following the 1986 field program by the drift of an ice floe which had been instrumented with an Argos drift buoy. The drift of this floe was qualitatively consistent with previous ice drifts shown by Ackley (1979). It remained essentially motionless from March–April 1986 and accelerated northward in late

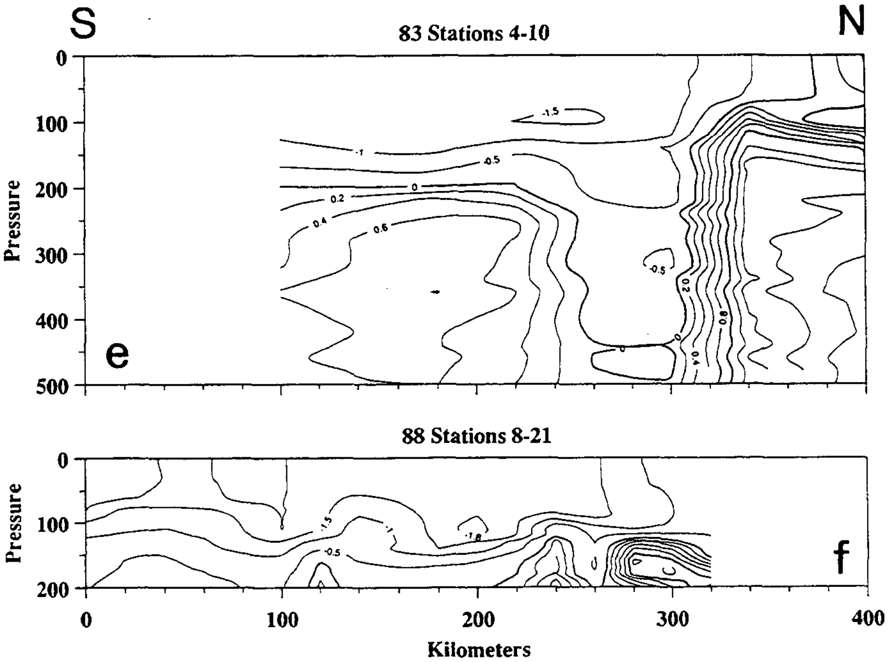

Fig. 8. November 1983 distribution of T along transect e at about 40°W in the southern Scotia Sea (upper) and June 1988 distributions along transect f (lower) which partially overlaps the 1983 transect. Locations are shown on Figures 1 and 2.

April with speeds of 5–10 cm/s, finally veering from northward to eastward in the southern Scotia Sea as it was entrained into the eastward regional current there and providing clear evidence of flow continuity from the Weddell into the Scotia Sea. Though we have no direct observations of surface winds, it is probable that the initial northward acceleration in April was due to south winds. It should be noted here that ice floe drift data are useful qualitative drift indicators, but caution must be exercised when extrapolating their drift to the underlying water because the ice is subject to surface wind and internal ice stresses as well as responding to surface currents.

Surface currents were measured in the southern Scotia Sea during winter 1988 by deploying near surface, drogued, Argos-tracked drift buoys at the upstream (western) end of the study area (Muench et al., 1990b). These drifters documented maximum surface current speeds exceeding 50 cm/s in a cyclonic mesoscale eddy, and general eastward currents in the northern part of the study region were of order 10 cm/s, in contrast to the much slower currents to the southwest in the Weddell Sea.

In addition to the drogued drifters, a single-ice-floe drift measurement was obtained from the Scotia Sea during winter 1988 by deploying an Argos buoy on an ice floe west of the South Orkney Islands (Muench et al., 1990b). There was little motion in the region west of the South Orkneys. By August, the floe had moved northward sufficiently, possibly in response to south winds, that it was entrained into the eastward regional flow.

Muench et al. (1990b) constructed a dynamic topography of the sea surface relative to the 1500 db pressure level for the 'Scotia Sea using the winter 1988 data (the spring 1983 data were too limited in coverage to allow construction of a reasonably complete topography). The resultant topography documented strong eastward baroclinic flow in the northern half of the study area, the eddy in which the drifter was entrained, and

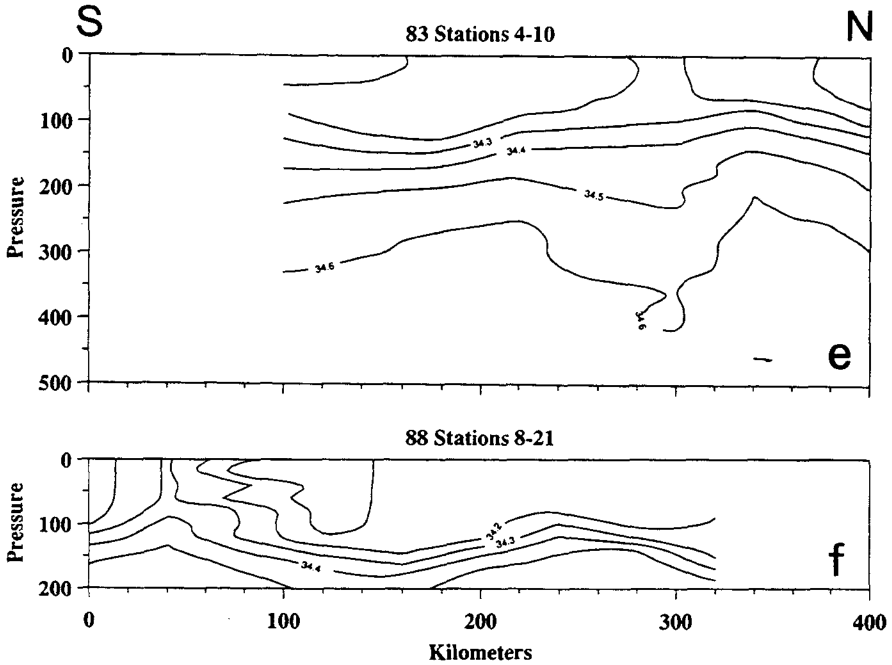

Fig. 9. November 1983 distribution of *S* along transect *e* at about 40°W in the southern Scotia Sea (upper) and June 1988 distributions along transect *f* (lower) which partially overlaps the 1983 transect. Locations are shown on Figs. 1 and 2.

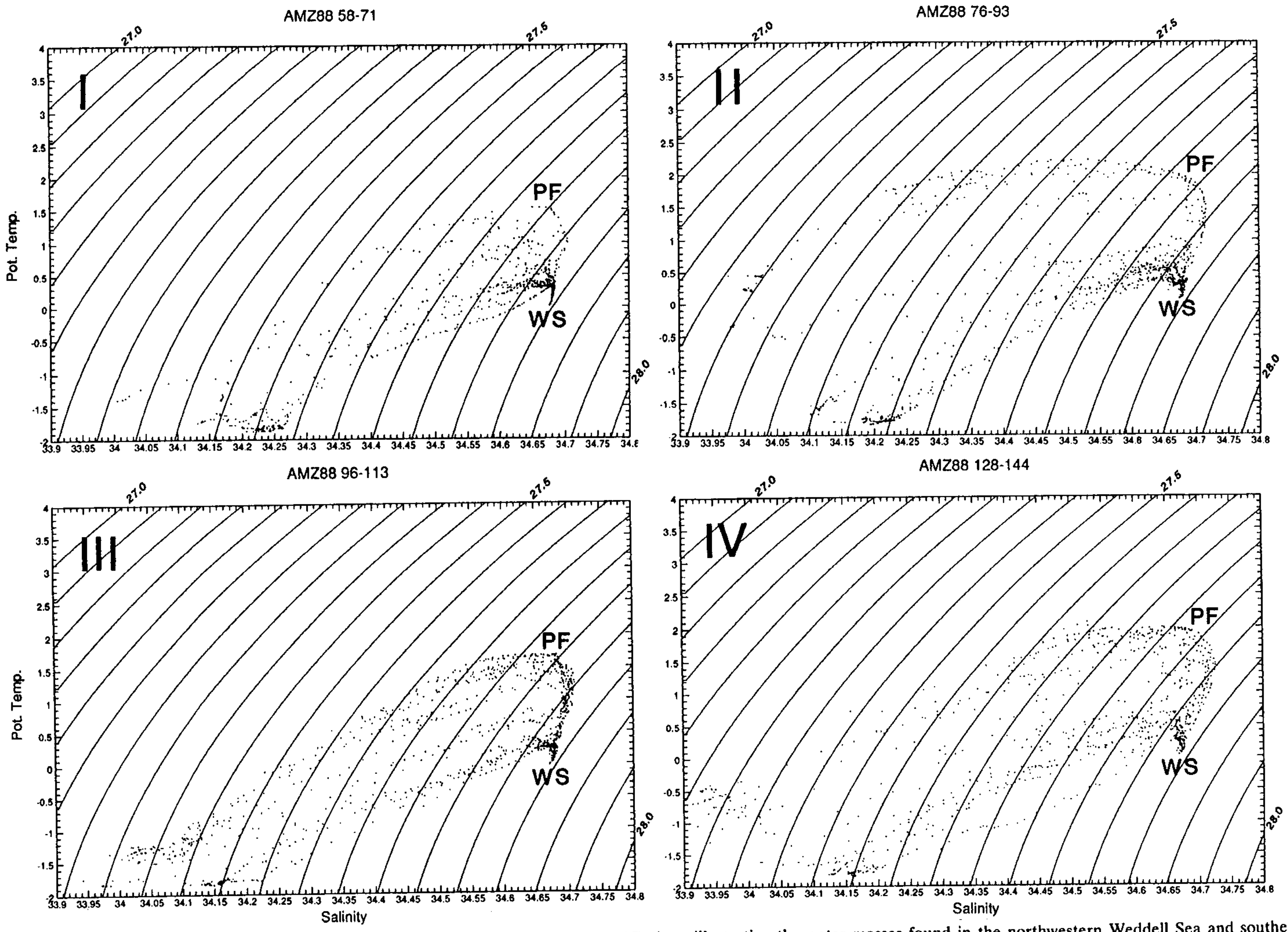

Fig. 10. Potential temperature-salinity diagrams, derived from July–August 1988 CTD data, illustrating the water masses found in the northwestern Weddell Sea and southern Scotia Sea region. One set of end-point characteristics is provided by Polar Front Water (labled *PF*); the other is provided by Weddell Sea water (labled *WS*). Diagram *I* shows characteristics along the 35°W transect, *II* along 40°W, III along 44°W and *IV* along 48°. Locations are shown on Figs. 1 and 2.

another mesoscale feature farther east which might have been either an eddy or a meander.

Sea ice conditions in the MIZ

The seasonal sea ice cover is continuous between the Weddell and Scotia seas. The summer ice in the western Weddell is "multi-year" ice (actually, second-year ice as compared to the true multi-year ice which is found in the Arctic Ocean), whereas that found in the Scotia Sea in winter and spring is a mixture of multi-year ice which has been advected northward from the Weddell Sea and young/first-year ice which has been formed locally.

The primary region of ice formation in the Weddell–Scotia Sea system during winter appears to be in areas of divergence in the southern Weddell Sea. Less important and not documented, but perhaps significant, are localized areas of divergence within the pack which manifest themselves as lead fields. The ice drifts northward, during winter, in the western Weddell Sea under the influence of south winds and northward currents. It flows into the Scotia Sea through the gaps overlying the South Orkney Ridge, soon drifting eastward as it enters the strong eastward currents in the southern Scotia Sea. Continually under the influence of south winds and strong east-northeastward currents, the ice soon is advected into warmer water where it melts rapidly, creating upper layer meltwater lenses and localized frontal structures.

The summer Weddell Sea MIZ behaves basically differently, in terms of ice balance, from the winter Scotia Sea MIZ. The Scotia Sea MIZ is the receiving area for a large amount of ice which is continually advected into the region and melts, with the strong regional currents removing meltwater away toward the east-northeast. The Weddell Sea MIZ shows the effects of in situ melting of ice which had been there from the previous winter. However, ice is not generally advected into the Weddell Sea MIZ. Regional ice drift patterns (cf. Ackley, 1979) show that summer drifts tend to be sluggish, compared with winter drift rates, and northward so that there is no mechanism for providing a continual source of ice into the MIZ. The meltwater lenses found associated with the Weddell Sea MIZ during autumn 1986 were remnants of features from ice melting throughout the preceding summer. Those found along the spring and winter Scotia Sea MIZ were, in contrast, being actively generated and advected away from the region during the observation period.

There is little evidence, with respect to horizontal circulation processes, that the pack ice cover serves as other than a seasonally varying passive tracer whose drift responds to winds and currents. The ice exerts considerably greater control, however, over vertical processes by influencing vertical stratification. Because the Weddell Sea, as compared to the Scotia Sea, is dominated by vertical processes, the ice cover must interact to a greater extent with the Weddell than with the Scotia Sea water column. In the Weddell, the effect is to reduce vertical stability through brine formation, whereas in the Scotia the effect is to increase upper layer stability through melting.

Water masses

Waters enter our study region from the eastern Weddell Sea, from Bransfield Strait and from Drake Passage. The former waters may undergo some modification through vertical processes during their passage through the western Weddell Sea (e.g. Foster and Carmack, 1976; Muench et al., 1990a), however, they appear to fit within a well defined envelope by the time they exit the Weddell Sea via northward flow along the Antarctic Peninsula and for our purposes here may be regarded simply as Weddell Sea Water. This cold, dense water provides an endpoint, in terms of water mass mixing, on a potential temperature–salinity diagram (Fig. 10).

On entering the southern Scotia Sea, Weddell Sea water converges immediately with Scotia Sea water which is warmer, less saline and less dense. The Scotia Sea water includes a variety of water types ranging from relatively warm (~ 2°C at the subsurface core) Polar Front Water to colder water which may have originated from Bransfield Strait (Fig. 10). Subsurface Weddell Sea water mixes along isopycnal surfaces, which can be seen both as interleaving both on the vertical sections and on the potential temperature–salinity plots. It is noted, however, that temperature–silicate characteristics typical of the Weddell regime are observed in the southern Scotia Sea as well and are indicated by high silicate values ($\sim 80\ \mu$mol/l in the upper mixed layer; L. Gordon, Oregon State Univ., 1990 pers. commun.) and a low maximum T.

Previous workers in the region have noted a zonally oriented band, centered roughly on the South Scotia Ridge, of complex mesoscale activity and lowered vertical stability. This anomalous water structure was not deriveable through mixing of the source waters described above, and was hypothesized as being due to deep winter convection (Deacon and Moorey, 1975) or to oceanic lateral boundary layer mixing acting on waters in Bransfield Strait and the continental margin regions to the west (Patterson and Sievers, 1980). While the corresponding surface salinities were in some cases as high as previously reported WSC values, salinities observed at the temperature maximum were lower than those indicative of WSC water (Gordon et al., 1977). Apparently, near-surface lateral mixing processes produce WSC surface characteristics, but development of the deeper characteristics of the WSC require more extensive vertical mixing. This may mean either that the feature is seasonal, present only in-summer, or that the 1983 and 1988 sampling patterns were too far east to sample it. The winter 1988 data were adequate, however, to discount significant vertical convection in the southern Scotia Sea (Muench et al., 1990b). Upper layer stability was increased by continuing melting of ice in the MIZ, rather than being lowered as would occur if significant freezing and brine rejection were occurring.

Summary

The following specific points result from our analyses:

- The regional circulation extends continuously from the northwestern Weddell into the southern Scotia Sea. However, the Weddell Sea upper layer water mixes isopycnally with deeper layers in the Scotia Sea.
- The Scotia Sea is characterized by a very high level of mesoscale activity, reflecting its highly energetic current regime and the convergence there of water masses from the Weddell Sea and from Drake Passage. The northwestern Weddell Sea is characterized, in contrast, by a virtually complete lack of mesoscale activity and by very weak mean currents.
- The ice balance in the MIZ differs between the northwestern Weddell and southern Scotia Sea regions. In the former region, ice melt accumulates through the summer to form upper layer lenses and fronts along the MIZ which are essentially remnant features. In the latter region these lenses and fronts are actively formed as ice is advected into the MIZ and melts.
- Wintertime upper layer stratification in the southern Scotia Sea is strengthened by continual advection of sea ice from the south which then melts in the MIZ. In at least partial consequence of this, the southern Scotia Sea is not a site of deep winter convection.

Acknowledgements

The authors thank two anonymous reviewers for helpful suggestions which have improved this paper. The research reported herein has been supported by National Science Foundation (NSF) Grants DPP-8420646 and DPP-8715979 to Science Applications International Corp. (R.D. Muench and J.T. Gunn), Office of Naval Research contracts N00014-82-C-0064 and N00014-91-C-0030 with SAIC (R.D. Muench and J.T. Gunn), NSF Grant DPP-8219088 to Lamont-Doherty Geological Observatory (B.A. Huber), NSF Grant DPP-8513098 to the National Marine Fisheries Service of the National Oceanic and Atmospheric Admin. (NOAA) (D.M. Husby), and by the Southwest (D.M. Husby) and Northeast (D.G. Mountain) Fisheries Centers of NOAA. This is LDGO contribution number 4771.

References

Ackley, S.F., 1979. Mass-balance aspects of Weddell Sea pack ice. J. Glaciol., 24: 391–405.

Carmack, E.C., 1977. Water characteristics of the Southern Ocean south of the Polar Front. in: M. Angel (Editor), A Voyage of Discovery. Pergamon, Oxford, pp. 15–41.

Carmack, E.C. and Foster, T.D., 1975. On the flow of water out of the Weddell Sea. Deep-Sea Res., 22: 711–724.

Comiso, J.C. and Zwally, H.J., 1989. Polar microwave brightness temperatures from Nimbus-7 SMMR: time series of daily and monthly maps from 1978 to 1987. NASA SP-1223, NASA, Washington, DC, 82 pp.

Deacon, G.E.R., 1979. The Weddell Gyre. Deep-Sea Res., 26: 981–995.

Deacon, G.E.R. and Moorey, J.A., 1975. The boundary region between currents from the Weddell Sea and Drake Passage. Deep-Sea Res., 22: 265–268.

Deacon, G.E.R. and Foster, T.D., 1977. The boundary region between the Weddell Sea and Drake Passage currents. Deep-Sea Res., 24: 265–268.

Foldvik, A., Gammelsrød, T. and Tørresen, T., 1985. Circulation and water masses on the southern Weddell Sea shelf. In: S.S. Jacobs (Editor), Oceanology of the Antarctic Continental Shelf Antarctic Res. Ser. 43, AGU, Washington, DC, pp. 5–20.

Foster, T.D. and Carmack, E.C., 1976. Temperature and salinity structure in the Weddell Sea. J. Phys. Oceanogr., 6: 36–44.

Foster, T.D. and Middleton, J.H., 1984. The oceanographic structure of the western Scotia Sea. Deep-Sea Res., 31: 529–550.

Gordon, A.L., Georgi, D.T. and Taylor, H.W., 1977. Antarctic Polar Front Zone in the western Scotia Sea—Summer 1975. J. Phys. Oceanogr., 7: 309–328.

Gordon, A.L., Molinelli, E. and Baker, T., 1978. Large-scale relative dynamic topography of the Southern Ocean. J. Geophys. Res., 83: 3023–3032.

Gordon, A.L., Martinson, D.G. and Taylor, H.W., 1981. The wind-driven circulation in the Weddell–Enderby Basin. Deep-Sea Res., 28: 151–163.

Husby, D.M. and Muench, R.D., 1988. Hydrographic observations in the northwestern Weddell Sea marginal ice zone during March 1986. NOAA Tech. Memo. NOAA-TM-NMFS-SWFC-106, NOAA/NMFS, Monterey, CA, 33 pp.

Muench, R.D., 1990. A review of mesoscale processes in the polar oceans. In: W.O. Smith (Editor), Polar Oceanography Academic Press, New York, pp. 223–285.

Muench, R.D., Fernando, H.J.S. and Stegen, G.R., 1990a. Temperature and salinity staircases in the northwestern Weddell Sea. J. Phys. Oceanogr., 20: 295–306.

Muench, R.D., Gunn, J.T. and Husby, D.M., 1990b. The Weddell–Scotia Confluence in mid-winter. J. Geophys. Res., 95: 18, 177–18, 190.

Nelson, D.M., Smith, W.O., Jr., Gordon, L.I. and Huber, B.A., 1987. Spring distributions of density, nutrients and phytoplankton biomass in the ice edge zone of the Weddell–Scotia Sea. J. Geophys. Res., 92: 7181–7190.

Nelson, D.M., Smith, W.O., Jr., Muench, R.D., Gordon, L.I., Sullivan, C.W. and Husby, D.M., 1989. Particulate matter and nutrient distributions in the ice-edge zone of the Weddell Sea: relationship to hydrography during late summer. Deep-Sea Res., 36: 191–209.

Patterson, S.L. and Sievers, H.A., 1980. The Weddell-Scotia Confluence. J. Phys. Oceanogr., 10: 1584–1610.

Smith, W.O., Jr. and Garrison, D.L., 1990. Marine ecosystem research at the Weddell Sea ice edge: the AMERIEZ Program. Oceanography, 3: 22–29.

Zwally, H.J., Comiso, J.C., Parkinson, C.L., Campbell, W.J., Carsey, F.D. and Gloersen, P., 1983. Antarctic sea ice, 1973–1976: satellite passive-microwave observations. NASA SP-459, NASA, Washington, DC, 206 pp.