Physical Oceanography in the Scotia Sea during the CCAMLR Synoptic Survey, Austral Summer 2000.

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ABSTRACT

In January and February 2000 four ships conducted a large hydrographic survey in the Scotia Sea as part of the CCAMLR Synoptic krill survey. There were 169 CTD stations to at least 1000 m depth making this the largest synoptic data set since 1981. A hydrographic section at Drake Passage is used to define water masses and ocean fronts. In 2000 the sub-Antarctic Front (SAF) and Polar Front (PF) were unusually close together, and the entire Synoptic Survey is south of the PF. The survey area is bisected by sub-Antarctic Circumpolar Current Front (SACCF) and the Southern Boundary of the Antarctic Circumpolar Current (SBACC). In Drake Passage these fronts were widely spaced. We present a further two hydrographic sections east of Drake Passage showing that the relative location of these fronts changes east of Drake Passage. Horizontal maps across the survey area show that close to Drake Passage properties are aligned in a south-west to north east direction. By a longitude of approximately 35°W, properties become orientated in a north-south direction. A map of geopotential anomaly shows the flow field across the survey area and allows identification of oceanic fronts. In months previous to the survey the giant icebergs A22B and B10A crossed the Scotia Sea and closely followed the geopotential field from this data set. For transport of biological matter from the Antarctic Peninsula to South Georgia, the SACCF is not going to be only important front. It will most likely be an interaction between the SBACC and the SACCF.

1: Introduction

The Scotia Sea in the south west Atlantic (20°- 65°W) has always had special place in the history of oceanography. Bounded by the Weddell Sea to the south, the South Atlantic Ocean on the north and east, and the Pacific Ocean on the west of Drake Passage (Figure 1) it has long been recognised as a region important in the global oceans circulation (Gordon *et al.*, 1977; Rintoul *et al.*, 2001; Whitworth III, 1977). With the rise of the southern whale fishery at South Georgia in the early 20th century, the South Atlantic became the focus of the first fully integrated regional oceanographic programme – the *Discovery Investigations* (Kemp *et al.*, 1929). The aim of the *Investigations* were widespread but we can paraphrase them as trying to understand the ecosystem and the physical processes that control it. Key results from the *Investigations* was the defining of the regional oceanography through the seminal works of Deacon (1933, 1937), and the distribution of plankton by Mackintosh, (1936). These strands were eventually put together with the distribution of whales to provide what is the perhaps the generally accepted view of operation of the ecosystem (Hardy, 1967). Research intensity declined as the whale fishery collapsed, and there was essentially a lull until the later part of the 20th century when the combination of technological advances (e.g. introduction of digital instruments) brought major scientific advances. Our understanding of both the regional circulation and its global importance, by regional studies and by collation of large historical datasets has increased (Foster & Middleton, 1984; Locarnini *et al.*, 1993; Nowlin Jr. & Clifford, 1982; Orsi *et al.*, 1995). Similar advances have occurred in our understanding of the ecosystem (Atkinson & Sinclair, 2000; Everson & Murphy, 1987; Trathan *et al.*, 1995; Ward *et al.*, 1997).

To summarise the regional physical oceanography, the Scotia Sea is dominated by the eastwards drift of the Antarctic Circumpolar Current (ACC) that undergoes extensive topographic steering (Moore *et al.*, 1997; Orsi *et al.*, 1995). The strength of the flow of the ACC through Drake Passage is of course not constant and can be in the range <100 to >140 Sv (x $10^6 m^3 s^{-1}$) (Cunningham *et al.*, in press; Hofmann, 1985), it is also variable on several time scales (Meredith *et al.*, 1996; Whitworth III & Peterson, 1985). There are stronger current jets within the ACC at each of continuous circum-Antarctic oceanographic fronts: these are the Sub-Antarctic Front (SAF), the Polar Front (PF), the Southern Antarctic Circumpolar Current Front (SACCF) and the Southern Boundary of the Antarctic Circumpolar Current (SBACC) (Orsi *et al.*, 1995). The location of these fronts is reasonably well defined in constricted locations such as Drake Passage (Baker Jr *et al.*, 1977; Challenor *et al.*, 1996), and between the Maurice Ewing Bank and South Georgia (Trathan *et al.*, 1997; Trathan *et al.*, 2000), but in the open ocean and in the absence of topographic restrictions, there locations are more variable (Foster & Middleton, 1984; Gordon *et al.*, 1977; Moore *et al.*, 1999; Orsi *et al.*, 1995). Despite being dominated by the ACC, there is a strong northwards component to the circulation caused by previously noted topographic steering and the outflow of waters from the Weddell Sea (Naveira Garabato *et al.*, 2002b; Schodlok *et al.*, 2002). These currents interact with the topography to create a region of high mixing (Heywood *et al.*, 2002), and intense water mass modification (Locarnini *et al.*, 1993).

Various studies have shown that the oceanographic fronts in the ACC may be also be significant for the transport of biological matter throughout the Scotia Sea (Hofmann *et al.*, 1998; Murphy *et al.*, 1998; Thorpe *et al.*, 2002; Tynan, 1998). Unfortunately with the exception of the SAF and PF which have extensive surface signatures and can be observed by satellite (Moore *et al.*, 1997, 1999), frontal locations have only been determined on large scales by interpretation of historical non-synoptic data sets (Orsi *et al.*, 1995).

This study provides a synoptic picture of the locations of the ACC fronts south of the PF using data collected as part of the 2000 CCAMLR Synoptic Survey (Figure 1). In the next section we will describe the methodology of the collection and collation of the physical oceanographic data set. In section 3 we will describe the characteristics of the ACC fronts during the Synoptic Survey, and their locations across the entire Scotia Sea. Finally in section 4 we compare our results with the literature.

2: Methods

The physical oceanographic programme during the Synoptic Survey was in support of the acoustic goals of the CCAMLR survey (Hewitt *et al.*, 2002; Watkins *et al.*, in press). This meant that during the acoustic survey CTD measurements were limited to 1000 m depth, or the maximum water depth when it was less than 1000m. This depth limit was of course disappointing in that it placed a restriction on the data we could obtain. But this must be balanced against the tremendous opportunity of obtaining a synoptic data set across virtually the entire Scotia Sea. The survey stations are shown in FIGURE 1. So that the region could be survey most rapidly, three of the ships operated along the interlocking survey lines described (Watkins *et al.*, in press), with ships running every third transect. In contrast the Atlantida worked only on the east of the Scotia Sea and around the South Sandwich Islands. At the end of the Synoptic Survey and on return back to the Falkland Islands across Drake Passage the RRS *James Clark Ross* completed the World Ocean Circulation Experiment (WOCE) line SR1 and made a further 29 full ocean depth CTD stations. The numbers of stations from each platform is shown in Table 1.

To ensure comparability of data across the survey, the four ships involved in the experiment used identical or similar CTD equipment manufactured by Sea-Bird Electronics, Inc., USA, and followed the same physical protocol for taking measurements. The RRS *James Clark Ross*, the *Yuzhmorgeologiya* and the *Kayu Maru* used a Sea-Bird 911*plus* with a compatible 12 bottle water sampling rosette to take measurements. On these ships the CTD unit was operated with a sample rate of 24 Hz, and data was then reduced during processing to 1 Hz averages. The *Atlantida* used a Sea-Bird SEACAT *SBE 19* with a compatible rosette recording at 2 Hz, which was then again reduced to 1Hz. The protocol for taking the CTD measurements was as follows: once the ship was on station the CTD unit was lowered to a depth of between 5-10 m and then held at this depth for approximately 2 minutes to allow the sensors to settle. After this time period the CTD was brought back to as close to the surface as was safe – the actual depth depending on the sea conditions - and then lowered continuously and smoothly to the maximum depth of the CTD cast. On all ships, water samples were taken from the rosettes at every station. These samples were then analysed for salinity and dissolved nutrients (the nutrient data are reported elsewhere).

The method of analysing the salinity samples were different for each ship. On the *James Clark Ross* 855 salinity samples were taken, of which 120 were duplicates. These samples were analysed against standard seawater on a Guildline Autosal model 8400B, that had been serviced and calibrated in June 1999. In general salinity samples were analysed two stations at a time using two vials of Ocean Scientific standard seawater (batch P132, 1997), one vial at the beginning of the samples and one at the end. After this CTD data from the *James Clark Ross* had an accuracy of 0.002 salinity units. Although the salinity data were analysed in a different way, data from the *Yuzhmorgeologiya* were reduced and calibrated in an identical way to those of the *James Clark Ross* and are completely comparable. Data from the *Kayu Maru* and *Atlantida* were processed using a different method but the CTD data were still adjusted to the water samples. During the compilation of the Synoptic Survey CTD data, compatibility was ensured through intercomparison between close stations. The interlocking nature of the transects showed that that this compatibility was consistent throughout the survey area. FIGURE 2 shows the potential temperature – salinity (θ/S) data for the entire survey area.

Throughout the survey the RRS *James Clark Ross* collected water velocity down to a depth of typically ~ 300 m in 2 minute ensembles using a Research Development Instruments (RDI) vessel mounted acoustic Doppler current meter (VM-ADCP) operating at 153.6 kHz. The transducer for this sensor is within a sea chest and bathed in oil to protect it from ice damage and all data were adjusted to take this into account. Water velocity data from the ADCP relative to the ship was processed by first correcting the heading using an Ashtec ADU unit (Griffiths, 1994), and by then extracting residual current data by differencing the ADCP water velocity data with ship velocity data derived from real time differential GPS (DGPS) using Stanley (Falkland Islands) as a base station. Throughout the whole survey area we expect the accuracy of the DGPS to be sufficient to provide good ship velocity data (King *et al.*, 1996). Finally the 2 minute averages were corrected for a scaling factor and misalignment angle against DGPS data. When the *James Clark Ross* was on-station the 2 minute data was again averaged against time over the duration of the station –i.e. when the ship was stationary. This gave on-station water velocity data of typically 1.5 hours duration.

3: Results and discussion

3.1 The Extended SR1 hydrographic section

FIGURE 2 demonstrates the inter-compatibility of the data set, and as expected, virtually all of the data are south of the Polar Front (PF). To understand the water masses present in the survey area we will follow the analysis of Orsi *et al.* (1995), and begin by looking at the θ/S data in Drake Passage. Here the transect of 29 CTD stations were to full ocean depth with nominal spacing ~35km, and calibrated to WOCE standards. The *James Clark Ross* completed this section at the end of the Synoptic Survey, and to increase its utility we will include an additional two CTD stations, also from the *James Clark Ross* that were collected on the Synoptic transect AP12 (see Watkins *et al.* (in press) for details regarding section identification). This extended SR1 section is shown outlined in red in FIGURE 1. Because of the regional oceanography described above, this transect could be expected to show all of the water masses we would expect to encounter in the Scotia Sea. In addition differences between water mass properties are more apparent because ocean fronts are pushed together as the ACC is squeezed through the channel. FIGURE 3 shows the potential temperature salinity data for these 31 stations.

The common regional water masses are also shown on FIGURE 3, and are taken from the literature (Cunningham *et al.*, in press; Deacon, 1937; Orsi *et al.*, 1995; Sievers & Nowlin Jr., 1984; Thorpe, 2001). To put the water masses into spatial context, FIGURE 4 shows the hydrographic section for this extended SR1 section. We will consider the water masses in three regions, and describe the defining features of these water masses from the surface to the sea floor.

3.1.1 North of the Polar Front (PF)

The Polar Front on this section can easily be seen by a large gap in θ/S space in FIGURE 3, and it appears at a latitude of 56° 51.8'S on FIGURE 4. Here we consider waters between the Burdwood Bank on the north of Drake Passage and the PF. As should be expected, the plots in FIGURES 3 and 4 show that this region contains the one water mass that is not present in the rest Synoptic Survey – this is Sub-Antarctic Zone water (SAZ) described in Gordon *et al.* (1977). SAZ water is restricted to north of the Polar Front unless part of an eddy, and surface waters are above 7°C with salinities of greater than 34.1. The northern limit of this water mass is at the Sub-Tropical Front (STF). At the northern extremity we found the typical strong counter-current on the north Burdwood Bank and reported in Cunningham *et al.* (in press). Here the slope of isopycnals is reversed and there are strong surface geostrophic currents were up to 20 cms^{-1} to the west. South of this isopycnals rise towards the PF and there is a strong easterly geostrophic current that increased in velocity to the PF. Within this region there is no near surface temperature minimum (θ_{min}) and potential temperature falls and whilst salinity increases until it reaches a deep maximum at a pressure of approximately 3400 dbar (FIGURE 3). Beneath this, both potential temperature and salinity decrease. In 2000 the SAF and the PF are within one station spacing and FIGURE 3 shows no intermediate water masses between these fronts. Cunningham *et al.* (in press) showed with the benefit of repeats of the SR1 section over several years, that this is not common.

3.1.2 Between the PF and the Southern Boundary of the Antarctic Circumpolar Current (SBACC)

The area between these two fronts bounds the waters of the Antarctic Circumpolar Current (ACC). A full description of the properties that define the

SBACC are given by Orsi *et al.* (1995). Here we use the common definition as it being bounded by the southern extent of UCDW, and in Drake passage the southern extent of this zone is a latitude of 60°45.9'S, and this can be seen as a strong shoaling of the isopycnals at this point. In the ACC, surface temperatures generally decrease with increasing latitude, whereas salinity is approximately constant between 33.75-34.8. These surface waters extend to a near-surface potential temperature minimum at approximately 150 dbar pressure whilst salinity increases to ~34.0. This water mass is Antarctic Surface Water (AASW). Water in the θ_{min} is Winter Water (WW) that receives its properties during the austral winter when strong winds mix the surface waters to create a thick mixed layer with cold temperatures, and increased salinity. When spring and summer return, the AASW is formed as the surface waters heat up and create a cap on the WW. The value of the θ_{min} can be linked to latitude with the temperature decreasing with increasing latitude (Brandon *et al.*, 2000).

Beneath the WW, both θ and S increase and the water mass changes from WW to Circumpolar Deep Water (CDW). This is the most voluminous water mass in the global ocean and it can be divided into Upper Circumpolar Deep Water (UCDW) and Lower Circumpolar Deep Water (LCDW). The core of the UCDW is defined by the subsurface θ_{max}, and like in the surface waters, throughout the ACC waters, the temperature of this core is from 2.5°C < θ_{max} < 1.5°C and it is colder at higher latitudes. In addition to the decrease in temperature of the core of the UCDW, in FIGURE 4 we can see that the core of the UCDW is not at a constant depth in the ACC. At the northern extremity close to the PF, the UCDW is centred at approximately 800 dbar pressure. With increasing latitude the UCDW shoals towards the surface and at it does not penetrate further south than 60°45.9'S. Orsi *et al.* (1995)

suggest that this is a good approximation for the location of the SBACC. We should therefore expect all the CTD data in the ACC waters in the survey to sample at least down to the UCDW.

Beneath the θ_{max} the temperature decreases all the way to the bottom of the CTD profile. However salinity continues to increase until it reaches a deep maximum (S_{max}) that marks out the core of LCDW. Here the salinity range is relatively narrow at $34.71 < S < 34.73$ and temperatures are in the range $1.2°C < \theta < 1.6°C$ although of course at this temperature as potential density of the water (σ_θ) is controlled by the salinity, the potential density of the core of the LCDW does not vary significantly, and the potential density plot shows that in the same way that the UCDW shoals, so does this water mass. At the PF the depth of the core is at 2700 dbar, and by the SBACC at 60°45.9'S, it has risen to within 1000 dbar of the surface. This shoaling is particularly clear in FIGURE 4 in the upward slope from left to right of the region bounded by the 34.7 isohaline and the slope in all of the isotherms and isopycnals.

Beneath CDW, both θ and S decrease and the CTD data passes through Weddell Deep Water (WDW) - a modified form of LCDW, and finally Weddell Sea Deep Water (WSDW). This WSDW is part of a counter current that can be seen flowing to the east through Drake Passage (Cunningham *et al.*, in press; von Gyldenfeldt *et al.*, 2002). It has temperatures of $\theta < 0°C$ and salinities $S < 34.68$, and because the CDW shoals with increasing latitude there is a wedge shape region of WDW in Drake Passage with a greater volume at the south of the section. At the deepest CTD stations on the south of the ACC the water mass properties are tending towards those held by Weddell Sea Bottom Water (WSBW) which is the densest water mass in the region.

Within the ACC waters there is an eddy at a latitude of 59°31'S, and Cunningham *et al.* (in press) have shown that this eddy is persistent from year to year. Orsi *et al.* (1995) showed that within the ACC is another circumpolar front that they called the Southern Antarctic Circumpolar Current Front (SACCF). One indicator for this front that $\theta > 1.8$°C (Orsi *et al.*, 1995), and on the extended SR1 section this located at ~ 59°S. Within the ACC FIGURE 4(D) shows that the strongest geostrophic current is at the location of the SAF and PF. The second maximum of >20 cms^{-1} at the surface is linked to SBACC, and the final frontal jet of > 10 cms^{-1} is linked to the SACCF

3.1.3 South of the Antarctic Circumpolar Current (ACC)

South of the SBACC the waters are influenced by the islands of the Antarctic Peninsula. Surface waters are much more dense, and salinity jumps from ~33.9 to 34.2 whilst temperatures increase to ~1.3°C. These changes give rise to a counter current under the edge of the jet associated with the SBACC (FIGURE 4d). At the end of the WOCE section on the flanks of Drake Passage from the surface to the sea floor the temperature decreases steadily to 0.3°C and salinity increases uniformly throughout water column to almost 34.5.

South of the WOCE section we only have two CTD stations and so our conclusions become more general, but as we should expect a weaker geostrophic shear, the fewer stations should not critically affect our conclusions. From the Antarctic Peninsula to the most southern station at 63°14'S surface temperatures decrease from 1.2°C to 0.33°C at the centre of the Bransfield Strait, before rising again to 0.55°C at the northern edge of the Weddell Sea. The surface salinity distribution varies in the opposite sense. With the surface value rising to a maximum in the centre of Bransfield Strait of 34.41 before falling back to 34.17 at the southern end.

This salinity increase and temperature decrease is indicative of the Weddell-Scotia Confluence (WSC) - the meeting point between waters of the Weddell Sea and the Scotia Sea (Deacon & Foster, 1977; Patterson & Sievers, 1980; Whitworth III *et al.*, 1994). At this point, the salinity increases only 0.06 in 460 m of water - from 34.41 to 34.47, and temperature falls 0.32°C to –0.25°C. These small changes – in particularly the low salinity change results in the typically observed decreased vertical stability at the WSC and is coupled to a strong jet of > 50cms^{-1} in a direction of approximately 080° in actual velocity as measured from the ADCP on *James Clark Ross.* This jet, and the relatively uniform properties are most likely a result of the strong tidal mixing that takes place in this region (Muench *et al.*, 2002).

South of this, vertical stability increases, and for the final CTD station in this section in 490 m of water on the northern edge of the Weddell Sea. Waters are more typical of the edge of the Weddell Sea. In FIGURE 3 the difference in the θ/S relation is clear. Surface salinity has been reduced to 34.17 as fresh water from sea ice melt has diluted the surface waters whilst the surface temperature has increased to 0.5°C. The combination of the reduced salinity and increased temperature reduces the surface density, and leaves the water in the WSC as a clear dense surface band between the Weddell and Scotia Seas at this point.

At the edge of the Weddell Sea we see the re-emergence of the near surface $\theta_{\min}$ that indicates Winter Water (WW). Here temperatures fall from the surface value to < –1.3°C at 140 dbar, this is coupled to a salinity increase ~34.43. This cold, saline $\theta_{\min}$ is very distinctive in FIGURE 3. The salinity increase is actually caused by salt rejection from winter ice formation. Beneath the WW both θ and S increase to the sea floor at 490 m and θ of –0.73°C, S of 34.60, and σ_θ 27.82 kgm^{-3}. If extended in θ/S space the end member for this station is clearly going to be the same as that at the deepest stations in Drake Passage. We can therefore assume that south of the bank and in deeper water will be Weddell Sea Water. This WSW flows northwards across the Bransfield Strait whilst descending depth contours on its route (Naveira Garabato *et al.*, 2002b). By the time it has flowed around the northern edge of the South Shetland Islands it has reached a depth of approximately 3500 dbar.

3.1.4 Summary of the Extended SR1 Section

In this hydrographic section we have seen that in 2000 the PF and SAF were unusually close together. However this should not be important in the rest of the Synoptic Survey area as both of these fronts should be expected to turn northwards east of Drake Passage, and so will leave the survey area (Moore *et al.*, 1997; Orsi *et al.*, 1995). Within the stations across the Scotia Sea we should see AASW at the surface with UCDW and LCDW beneath this. Both isohalines and isotherms would be expected to shoal from north to south and at the southern end of the survey region, we could expect to a modified form of Weddell Sea Water. Although comparing FIGURES 2 and 3, we will not see any water with such extreme characteristics as that found at the south of the extended SR1 section.

3.2 Downstream of Drake Passage

Having described the extended SR1 section we will now describe a further two hydrographic sections downstream of Drake Passage.

3.2.1 Transect SS07/08

For our first downstream section, we will combine the 7 CTD stations make up SS07 and taken by RRS *James Clark Ross*, with a further two more southern stations that come from the southern part of SS08 and taken by *Yuzhmorgeologiya* (Watkins *et al.*, in press), this section is outlined in red in FIGURE 1. By combing the two sections the 9 CTD stations cover a latitudinal range of 59°31'S to 62°41'S, crosses both the Shag Rocks bank and the South Orkneys plateau. As one of the Synoptic transects the data here only extend to just over 1000 m depth and full depth on the shallower regions. The section is shown in FIGURE 5.

Clearly, as expected, this entire section is south of the PF, and downstream of the constriction of Drake Passage, the fronts are separating and water masses are mixing together. Although more difficult to see than in the Sr1 section because of the two shallow water regions on the section, FIGURE 5 shows that isopycnals slope upwards from the north to the south. Using the Orsi *et al.* (1995) criteria, the location of the SBACC is at the poleward extension of the UCDW. With the station spacing on the Synoptic Survey the exact location is hard to identify, however here it is most likely very close to 58°38'S. From the northern end of the section to the SBACC we see the expected AASW, with a core at pressures of approximately 150 dbar. Beneath this is the UCDW, although here we never reach the properties of LCDW. Also within this band is the SACCF. Using physical property indicators (Orsi *et al.*, 1995) this is located just north of 57°19'S, but east of Drake Passage, the front is harder to locate without extremes of physical properties. Here, this front is approximately 140 km north of the SBACC. With the location of these fronts defined, we can examine the

ACC waters. From the north of the section and over the Shag Rocks Bank there is a doming of all properties indicating a cyclonic circulation around the bank. South of the bank and up to the SACCF, isohalines and isopycnals slope upwards. This sloping gives the geostrophic shear associated with the SACCF. Between this front and the SBACC there is little geostrophic shear. South of the ACC we can see that the classical signal of the WSC has already disappeared. There is still a slightly increased salinity just north of 60°S and cooler surface water, but it is no longer associated with the decreased vertical stability seen in the extended SR1 section. The absence of the classical signal of the WSC by this longitude has been previously noted (Foster & Middleton, 1984; Muench *et al.*, 1990b) and a subsequent historical analysis has shown that downstream of the initial meeting of the Weddell and Scotia seas, the WSC water is modified through mixing processes (Whitworth III *et al.*, 1994). South of the Orkneys we see that properties change much more gradually as we moved into Weddell Sea waters. In fact further south than this section, horizontal property gradients are so low that staircases in potential temperature and salinity can develop (Muench *et al.*, 1990a).

3.2.2 Transect SS02

For the final hydrographic section we shall describe SS02, a section with 8 CTD stations to 1000 m and done by the *Yuzhmorgeologiya* (FIGURE 6, and surrounded by a green box in FIGURE 1). Throughout this section the ship kept having to divert due to the presence of icebergs (Watkins *et al.*, in press). As it is just east of South Georgia we should expect that both the SACCF and the SBACC have moved further north, and them to have become spaced further apart. Clearly FIGURE

6a shows that again we are sampling no waters north of the ACC, and since there is no evidence of interleaving and mixing between the ACC waters and SAZ waters, the PF is well north of 51°49'S at this longitude. We start again by defining the southern limit of the ACC (SBACC), and this is approximately 57°S, and is associated with a slow geostrophic jet. The location of the SACCF is harder to determine, and clearly our identification parameters used in Drake Passage must be modified as we move further eastwards. The CTD stations do not go deep enough for the alternative definitions given in Orsi *et al.* (1995), and their definition of S > 34.73 at a depth of greater than 800 m indicates that the SACCF could be north of this section.

We shall see below that indeed the SACCF is north of 51°49'S, and the ACC waters on this section are between these two fronts. Like in FIGURE 5, the ACC waters have low shear, with isohalines and resulting isopycnals less than 1000 dbar in depth being almost horizontal. South of the SBACC there is no indication of the WSC, and water has the characteristics of the northern extension of the Weddell Gyre (Orsi *et al.*, 1993). There is a low salinity lens of water at approximately 59°S that most likely has been formed through the melting of ice. At the most southerly station the near surface θ_{min} of WW is very cold at –1.61°C and S of 34.26. Again vertical temperature and salinity gradients are smooth here like on the southern extremity of SS07/08 suggesting a low energy environment. Finally we can see that the core of LCDW is within 700 m of the surface.

3.2.2 Summary

By looking at two further hydrographic sections across the Synoptic Survey area we have seen how both the water mass properties, and the relative location of the ocean fronts varies. The signal that has been interpreted as the WSC disappears before the SS07/08 composite, and we can see that this feature is limited to the vicinity of the Antarctic Peninsula. East of Drake Passage, the PF and SAF leave the study area, and the distance between the SACCF and the SBACC changes. On the SR1 section the two fronts were almost 140 km apart, as we move downstream, by the SS07/08 composite there is a remarkably similar distance of 145 km between them. By SS02 this has increased to at least 700 km. We saw in both transects that between these fronts the isohalines are generally horizontal although it is worth noting again that this survey was not eddy resolving. As we head further to the east there is an increasing part of the survey area filled with water from the edge of the Weddell Gyre. We also saw that from west to east properties are modified and there is mixing.

3.3 Horizontal surfaces

Having considered selected vertical sections in the Scotia Sea we now combine all of the data from all ships and generate horizontal surfaces at selected depth horizons. This will help us to understand what is happing across the entire Synoptic Survey area both to the west of the Antarctic Peninsula, and around the South Sandwich Islands. We have chosen three pressure levels: 50 dbar, 500 dbar and finally 1000 dbar. The reasons for the choice of each level will be made clear as each level is described.

3.3.1 50 dbar pressure level

FIGURE 7 shows the potential temperature, salinity and potential density at 50 dbar. We have chosen this depth level because as we have seen in the hydrographic sections, it is above the near surface θ_{min} and so it shows the seasonal layer. As we should expect, FIGURE 7a shows that isotherms with temperature > 2°C are generally orientated from the south west to the north east. Higher temperatures are in the north west whilst it is coldest in the south east of the Scotia Sea. This orientation of isotherms is also seen in synoptic satellite derived sea surface temperature data (Moore *et al.*, 1997). Water with temperature below 0°C at this level is restricted to the Bransfield strait and east of the Antarctic Peninsula. The orientation of isotherms is with temperatures –1°C > θ > 2°C is different from the warmer northern waters, being more latitudinaly orientated east of the Antarctic Peninsula, and at a latitude of ~30°W they become longitudinally orientated. This orientation means that the South Sandwich islands are surrounded by cold waters < 1°C

The location of the PF and SAF are easily seen in Drake Passage as the constriction in temperature contours in the range 3-6°C. The location of the other fronts is however not clear as they are defined through properties that are at greater depth. There is a tongue of colder water extending from the tip of the Antarctic Peninsula towards the South Orkney Islands, although from the salinity data at this level (Figure 7b) this is not a continuous water mass. At South Georgia there was the expected temperature gradient along the island, with colder waters at the south east end and warmer at the north west (Brandon *et al.*, 1999; Whitehouse *et al.*, 1996).

The salinity data at 50 dbar is shown in FIGURE 7b. The pattern is broadly similar with most isohalines being orientated from south west to north east at lower latitudes than a line drawn between the Antarctic Peninsula and South Georgia. North of this line there is low salinity surface water (S < 34.0) that makes up a large portion of the AASW. This water is again restricted to south of the PF, but it is bounded further to the south by more saline water. South of this line the pattern is different.

There is a tongue of $S > 34.4$ extending from the northern tip of the Antarctic Peninsula in a north easterly direction. This high salinity tongue is the long-established signal of the WSC that we noted in the extended SR1 section in FIGURE 4. and was not present in the SS07/08 composite (FIGURE 5). We can see in FIGURE 7b that it clearly does not extend as far as the Orkney Islands. The influence of the tongue does however extend south of the AASW and a band of higher salinity extends to almost 35°W and almost the Southern tip of South Georgia. South east of this tongue there is no clear signal in the orientation of the isohalines. This suggests that the observed distribution is being affected by eddies generated at the edge of the Weddell Sea. By 25°W the isohalines are clearly orientated in longitudinally.

Finally in FIGURE 7c the potential density plot shows, perhaps not surprisingly, that some isopycnals are generally orientated in the same direction as the previously described properties in a south-west t north –east direction. The $\sigma_\theta = 27.0$ kgm^{-3} isopycnal outcrops in this direction but east of the Antarctic Peninsula, the more dense isopycnals are latitudinaly orientated. We can also see that east of the Peninsula, the spacing between isopycnals is increased, and so the gradient between them reduces. At the Peninsula itself the influence of the higher salinity and cold temperatures of the WSC is clear, and here we find the densest water at this depth level with $\sigma_\theta > 27.6$ kgm^{-3}. This dense tongue of water does not extend past the longitude 50°W, although a higher density signal is seen in the 27.4 kgm^{-3} extending to the South Orkney Islands. Variations in potential temperature and salinity seen in 7a and 7b that showed the influence of the WSC as far as 35°W are therefore density compensating.

3.3.2 500 dbar pressure level

FIGURE 8 shows the potential temperature, salinity and potential density data from the 500 dbar pressure level. We have chosen this depth strata as an intermediate level of our CTD data, and here the range of temperature across the survey area has reduced to approximately 4.8°C. We are now observing conditions beneath both the WW and near surface θ_{min}, and consequently below immediate influence of the atmosphere. Again we see the strongest gradient at the PF and SAF, and south of this boundary the entire Synoptic Survey region is within a 3.4°C range. All isotherms > 2°C are clearly orientated in the direction from the Peninsula towards South Georgia and water <1°C is not seen on the west of the Peninsula. At this depth, isotherms in the range 1.0°C > θ > 1.5°C gradually decrease in latitude from 63°S at 65°W to ~58°S by 35°W. East of South Georgia, isotherms mirror the arc of the South Sandwich islands and turn northwards. The only location with θ < 0°C at this depth is within the region we have identified as the WSC and just east of Elephant Island. Five CTD stations just to the south of this region show that this water is not connected to the Weddell Sea water here.

The strongest gradient in the salinity field in FIGURE 8b is, as expected, seen at the SAF and PF. South of this the field is in the relatively narrow range of 34.60 < S < 34.68 across the Synoptic Survey area. FIGURE 8c shows the density field. We can see that with the upward slope of the isohalines seen in the hydrographic sections, we are observing the expected "slice" of isopycnals across the Scotia Sea, but clearly the distribution reveals more than a slope of isopycnals upwards towards the Antarctic continent. The strongest gradient is at the SAF and PF, but in contrast to both the temperature and salinity data, with the exception of the densest isopycnal at this level

(27.8 kgm^{-3}), east of 50°W successive isopycnals are orientated in a north-south direction with decreasing longitude. East of South Georgia the 27.7 kgm^{-3} is also orientated in a north–south direction. There is no density signal in the vicinity of the WSC, and we see that the reduced stratification noted above is caused through higher density at the surface with its origin in higher salinities (FIGURES 7b&7c), and not an increase in density at the seafloor. The 27.8 kgm^{-3} isopycnal is the densest at this level and it is generally restricted to the Weddell Sea region. Close to the Peninsula this water follows the South Scotia ridge system, before breaking northwards at the South Orkney Islands, and it can be considered the northern boundary of Weddell Sea Water.

3.3.3 1000 dbar pressure level

The final depth strata we consider is the deepest common level across the Synoptic Survey area, 1000 dbar (FIGURE 9). At this pressure, the temperature gradient across the survey region has again decreased and it is only approximately 3°C with the strongest gradients at the SAF and PF. Again we see that coldest waters are limited to the east of the Antarctic Peninsula. Although isotherms > 1°C still follow the same general direction previously noted west of South Georgia, they decrease in latitude at a greatly reduced rate and not go as far northwards, or as rapidly as isotherms at shallower depth strata. Isotherms > 2°C turn northwards at lower latitudes. As above, isotherms colder than this turn northwards east of South Georgia. The 0.5°C isotherm can be taken as a proxy for the northward extension of the Weddell Gyre and we can see that it surrounds the South Sandwich islands.

Within this temperature range, from FIGURE 2 we could expect to see a large salinity gradient across the survey area. However FIGURE 4b shows that this gradient will be beneath the 1000 m depth of the CTD casts of the Synoptic Survey when south of the PF. The salinity only varies by approximately 0.5 across the entire Synoptic Survey region at this depth, and there is no evidence of the WSC. In addition there is no general orientation of isohalines across the region south of 56°S. North of this latitude isohalines are orientated in a north south direction.

In FIGURE 9c the direction of the potential density isopycnals at this depth reflects the θ distribution. Density does not vary significantly and there is only a range of 0.1 kgm^{-3} south of the PF and SAF. The variation shows that the isopycnals are still sloping towards the surface in the direction of the Antarctic continent although the shear from this gradient is greatly reduced when compared with surface levels. All isopycnals become orientated in a north-south direction, the denser ones turning north with increasing distance from Drake Passage.

3.3.4 Summary

The horizontal sections from the Synoptic Survey have shown that a synoptic picture of the Scotia Sea is, of course, more complicated than the historical schematic ocean circulation patterns. The traditional view was a scheme whereby deep waters in low latitudes flow southwards towards Antarctica whilst rising towards the surface (Deacon, 1937; Wüst, 1935). South of the PF they are modified, and then return northwards. We saw in selected hydrographic sections that this is broadly true. However the horizontal maps reveal another component to the circulation pattern. From all three pressure levels we can see that as well as this sloping from south to north, there is a rotation in the fields centred on the North Scotia Ridge. In the 50 dbar fields this rotation was not apparent. Clearly at this depth level the latitudinal effect of seasonal forcing is overriding this signal, and the most obvious feature is the high salinity tongue of the WSC. By 500 dbar and away from meteorological influence, the rotation is apparent in the temperature distribution (FIGURE 8b). But it is far more obvious in the potential density distribution where the combined effects of θ and S come into play. South of the waters that have come through Drake Passage, Weddell Sea waters (bounded by the 27.8 kgm^{-3} isopycnal) do not penetrate significantly across the South Scotia Ridge system at this depth level, with greater transports to the north occurring below the depth of this survey (Naveira Garabato *et al.*, 2002a).

At our deepest depth level (FIGURE 9), the isotherms do not decrease latitude with eastwards direction very rapidly. They do however clearly rotate around South Georgia. Such a distribution is not seen in the salinity field. As θ increases, it becomes relatively more important in determining the potential density distribution and FIGURE 9c showed that despite this increasing influence, the slope in the density field is not large with the virtually the entire field being orientated in a south-east to north west direction. The only exception to this is north of the South Sandwich Islands where the isopycnals again turn south.

3.4 Geopotential Field

Having described the water mass distribution across the Synoptic Survey area, we can use our data set to derive a synoptic flow field. Essentially if we vertically map our horizontal fields we would be able to deduce an anti-clockwise rotation from 1000 dbar to the 50 dbar level. Of course this vertical shear represents the flow field and we can map this by deriving the geopotential anomaly ($\Delta\Phi$) from the θ and S data. We will follow Orsi *et al.* (1995) and derive a field at the 50 dbar pressure level relative to the 1000 dbar level. These authors suggested that at 50 dbar the effect of seasonable variability will be reduced. We can show that is the case by comparing the θ distribution in FIGURE 7a with SST maps (e.g. Moore *et al.*, (1997)). A better depth horizon to use would be deeper, but to ease comparison with previous works we use this depth level. Derivation of geopotential anomaly gives the height of a particular pressure surface above a reference level. By using 1000 dbar as a reference level we are implicitly stating that it is parallel to the geoid, and that $\Delta\Phi = 0$ Jkg^{-1} at this level. FIGURE 9c shows the density surface at our reference level is not flat, and the small slope noted above will influence our results. However as most of the baroclinicity in the ACC is above this depth it will not invalidate this analysis. Where CTD stations do not go as deep as the reference level, their deepest level is set to that of the closest adjacent station. A map of this resulting geopotential field is shown in FIGURE 10.

Water will flow along the contours of $\Delta\Phi$ shown in FIGURE 10, and both Orsi *et al.* (1995) and Thorpe (2001) using different data sets identified values of geopotential that can approximate the location of the PF, the SACCF, and SBACC. Both authors found that the location of the PF can be approximated by the $\Delta\Phi = 9.0$ Jkg^{-1}, the SACCF can be given by the $\Delta\Phi = 4.5$ Jkg^{-1}, that a value of $\Delta\Phi = 3.5$ Jkg^{-1} is a good locator for the SBACC, and finally that $\Delta\Phi = 3.0$ Jkg^{-1} is a good locator for the northern edge of the Weddell Gyre (Orsi *et al.*, 1995), that we will call here the Weddell Front (WF). It is worth noting that although this data is most likely as ‘synoptic’ as it is possible to get over such a large geographical area, it still represents a snapshot of what we believe is a dynamic region.

The location of the PF matches well with the value of geopotential, and as expected this geopotential value is only seen on the SR1 section. Of more interest are the other fronts of the ACC. The location of the SACCF from both the geopotential and hydrographic sections give good agreement, and this front crosses from > 63°S at 70°W, to 52°S at 35°W before re-entering the Synoptic Survey region north of the South Sandwich Islands. Given the potential importance of this front for transporting biological matter across the Scotia Sea (see for example Hofmann *et al.*, 1998), it is perhaps surprising at how far the SACCF is from the key krill breeding ground of Elephant Island (Siegel *et al.*, 1998). This front is however much closer to shore near to the other major krill ‘source’ of the South Shetland Islands (Hewitt *et al.*, in press).

The SBACC ($\Delta\Phi$ = 3.5 Jkg^{-1}) crosses the Scotia Sea in a similar manner to the SACCF. Its major features are that it does come close to all of the major recognised krill breading grounds along the Antarctic Peninsula. The spacing between the SACCF and the SBACC is variable, and although the two were approximately 140 km apart on the SR1, and SS07/08 sections (FIGURES 4&5), they are within one station spacing of each other on the section SS10 (see Watkins *et al.*, in press for labelling details). The final highlighted geopotential ($\Delta\Phi$ = 3.0 Jkg^{-1}) is close to the northern extremity of the Weddell Sea Gyre. This again agrees with the analysis presented earlier in that the CTD stations with the most extreme ‘Weddell Sea’ characteristics are at the southern extremities of both the extended SR1 and SS10 sections. In Figure 10 we can see that these stations are actually further south of the WF that any others during the CCAMLR Synoptic Survey. We suggest that this front is not free to move in the same way as the SACCF and SBACC because of the proximity of the South Scotia Ridge.

If we compare the location of these fronts with other data collected during the Synoptic Survey, the results are very encouraging and can explain some of the observed features well. Holm-Hansen *et al.* (in press) have presented the surface chlorophyll (chl-a) data during the survey from both ship based observations, and satellite data for the period of the Synoptic Survey. In their FIGURE 2(B) they present a SeaWiFS monthly average picture for January 2000, and amongst the highest values south of the PF is a band along what Figure 10 shows to be in the vicinity of the WF. The northern limit of their high chl-a values also appears to be associated with one of the identified fronts: the SACC. This front has been implicated previously in biological activity (Tynan, 1998), and in particular the region of higher chl-a in the region along the SR1 section appears to be bounded by the SACCF. Other data sets also confirm this analysis. For example, Ward *et al.* (in press) have shown that certain species of zooplankton are only found within certain water mass areas, and the krill distribution pattern found by Siegel *et al.* (in press) can be clearly linked again to the different regimes between the identified ocean fronts.

4: Summary

The CCAMLR Synoptic Survey gave a tremendous opportunity to sample the Scotia Sea. The collation and analysis of the data from four ships has given us a very detailed view of what was actually happening over a one month period. Having analysed the hydrographic data and derived the geopotential field, it is sensible to ask how representative is it and how does it compare to previous works? We have already noted that our findings are in general agreement with the published literature (Orsi *et al.*, 1995), although in the specific details such as frontal locations, this study does show different features (Naganobu *et al.* in press). This perhaps should not be surprising given the synoptic nature of this work, but it is encouraging to see that this work defines a location for the SACCF around South Georgia that is in agreement with other synoptic studies (Brandon *et al.*, 2000; Brandon *et al.*, 1999; Trathan *et al.*, 1997).

To see how representative this study is we were fortunate that during the two months previous to the Survey, two very large natural passive drifters crossed the Scotia Sea: these were the giant icebergs B10A and A22B which had calved from ice shelves on the edge of the Antarctic continent. FIGURE 11 shows the path these icebergs (Long & Ballantyne, 2002) superimposed on the derived geopotential anomaly field. The ship *RRS James Clark Ross* passed A22B at South Georgia during the survey, and at this point it was still over 60 x 15 km and was grounded on the shelf. We could expect the icebergs to not follow the exact path of the geopotential field as they would be strongly influenced by the wind, but even with this in mind the agreement is very encouraging. Both icebergs cross contours (this will be partially due to the Ekman drift in the prevailing winds pushing them to the north), but they do follow the general pattern. Of particular note is the path of A22B when it is close to South Georgia. The iceberg looks as if it is set to drift to the north of the island before getting caught in the gyre in the geopotential anomaly field, and sent to the south of the island. B10A crosses fewer contours, but it spent a long time in Drake Passage oscillating in a re-circulation pattern.

The path of these two icebergs is also particularly interesting for the Synoptic Survey, as one long established hypothesis developed to explain size differences between krill at either end of South Georgia, suggested that the krill would have originated in different oceans. Hardy & Gunther (1935) proposed that krill at the north end of the island would have originated in the Bellingshausen Sea whereas krill at the southern end would have come from the Weddell Sea. Figure 11 shows that at South Georgia, the iceberg from west of the Peninsula (B10A) passed towards the north of the island before breaking up, whereas the iceberg from the Weddell Sea (A22B) passed to the south. Although this appears to confirm the hypothesis, tracing back the path of the icebergs shows that it is not so simple. In the central Scotia Sea at ~ 57°S, 45°W the giant icebergs actually passed within 20 km of each others tracks, and could have easily crossed.

We have already noted that the ACC fronts are not fixed in space away from the major topographical features such as Drake Passage, and once downstream and in the Scotia Sea, the SACCF and SBACC fronts are free to move and interact with each other. It is this interaction that may prove more important for transport of biological matter through the Scotia Sea rather than any one single front.

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FIGURE Captions

FIGURE 1: The station positions in the Scotia Sea taken in January and February 2000 as part of the CCAMLR Synoptic Survey. Crosses represent the locations of CTD stations made by the *James Clark Ross*. Triangles are the locations of CTD stations made by the *Yuzhmorgeologiya*. Stars represent the locations of CTD stations made by the *Kayu Maru* and hexagrams the locations of stations made by the *Atlantida*. Note that the stations of the first three ships alternate across the Scotia Sea whereas the Atlantida stations are restricted to the region east of 30°W. The three coloured boxes pick out CTD sections that are described in the text.

FIGURE 2: A potential temperature / salinity (θ/S) plot of all of the data collected at the stations in FIGURE 1. Red is data measured by the *James Clark Ross*, light blue by the *Kayu Maru*, black by the *Atlantida* and green by the *Yuzhmorgeologiya*. Density contours are σ_0 units in steps of 0.1 kgm^{-3}.

FIGURE 3: A potential temperature salinity (θ/S) plot for the extended SR1 section (see text). The locations of common regional water mass definitions have been marked on this theta / salinity space. NB the *y-axis* on this plot has been restricted in the range –2 º to 5 ºC.

FIGURE 4: The hydrographic section for the extended Drake Passage section. The first three properties consist of three panels, one from 0 –1000 m and the second 0 – 4500 m. The location of the PF, SACCF and SBACC are marked on this

plot.(A) Potential temperature (ºC), (B) Salinity, (C) Potential density σ_o (kg m^{-3}), (D) Geostrophic velocity referenced to the sea floor (cms^{-1}).

FIGURE 5:The transects SS07/08 collected by the RRS *James Clark Ross* and the *Yuzhmorgeologiya*. This section crosses the entire Scotia Sea and the fronts that were so close together in Drake Passage have already begun to separate. A) potential temperature; B) Salinity, (C) Potential density σ_o (kg m^{-3})

FIGURE 6:The transect SS02 collected by the *Yuzhmorgeologiya*. This section again crosses the Scotia Sea and just to the east of South Georgia. A) potential temperature. B) Salinity, (C) Potential density σ_o (kg m^{-3}).

FIGURE 7: Physical properties at a depth of 50 dbar during the Synoptic Survey. A) potential temperature, θ, °C. B) Salinity. *S*. C) Potential Density, σ_θ , kgm^{-3}.

FIGURE 8: Physical properties at a depth of 500 dbar during the Synoptic Survey. A) potential temperature, θ, °C. B) Salinity. *S*. C) Potential Density, σ_θ , kgm^{-3}.

FIGURE 9: Physical properties at a depth of 1000 dbar during the Synoptic Survey. A) potential temperature, θ, °C. B) Salinity. *S*. C) Potential Density, σ_θ , kgm^{-3}.

FIGURE 10: Geopotential anomaly ($\Delta\Phi$) j kg^{-1} during the Synoptic Survey at the 50 dbar pressure level relative to 1000 dbar. Contours for 3.0, 3.5 and 4.5 j kg^{-1} are coloured blue.

Figure 11: The drift track of the giant icebergs B10A and A22B across the Synoptic Survey study area superimposed on the geopotential anomaly at 50 dbar from this study. Locations of the icebergs are from QuikSCAT satellite and solid circles are every 10 days.

Table

Table 1: Numbers of CTD stations taken by each ship as part of the CCAMLR Synoptic Survey

Ship	**Number of CTD stations**
Yuzhmorgeologiya	35
Kayu Maru	36
Atlantida	26
James Clark Ross	72
Total	169

References

ATKINSON, A. & SINCLAIR, J.D. (2000) Zonal and seasonal vertical migration of copepod assemblages in the Scotia Sea. Polar Biology, 23, 46-58.

BAKER JR, J.D., NOWLIN JR, W.D., PILLSBURY, R.D. & BRYDEN, H.L. (1977) Antarctic circumpolar current: space and time fluctuations in the Drake Passage. Nature, 268(25 August 1977), 696-699.

BRANDON, M.A., MURPHY, E.J., TRATHAN, P.N. & BONE, D.G. (2000) Physical oceanographic conditions to the northwest of the sub- Antarctic Island of South Georgia. Journal of Geophysical Research-Oceans, 105(C10), 23983-23996.

BRANDON, M.A., MURPHY, E.J., WHITEHOUSE, M.J., TRATHAN, P.N., MURRAY, A.W.A., BONE, D.G. & PRIDDLE, J. (1999) The shelf break front to the east of the sub-Antarctic island of South Georgia. Continental Shelf Research, 19(6), 799-819.

CHALLENOR, P.G., READ, J.F., POLLARD, R.T. & TOKMAKIAN, R.T. (1996) Measuring surface currents in Drake Passage from altimetry and hydrography. Journal of Physical Oceanography, 26(12), 2748-2759.

CUNNINGHAM, S.A., ALDERSON, S.G., KING, B.A. & BRANDON, M.A. (in press) Transport and variability of the Antarctic Circumpolar Current in Drake Passage. Journal of Geophysical Research.

DEACON, G.E.R. (1933) A general account of the hydrology of the Southern Ocean. Discovery Reports, 7, 171-238.

DEACON, G.E.R. (1937) The hydrology of the Southern Ocean. Discovery Reports, 15, 3-122.

DEACON, G.E.R. & FOSTER, T.D. (1977) The boundary region between the Weddell Sea and Drake Passage currents. Deep-Sea Research, 24, 505-510.

EVERSON, I. & MURPHY, E. (1987) Mesoscale variability in the distribution of krill *Euphausia superba*. Marine Ecology Progress Series, 40, 53-60.

FOSTER, T.D. & MIDDLETON, J.H. (1984) The oceanographic structure of the eastern Scotia Sea - I. Physical oceanography. Deep-Sea Research, 31(5), 529-550.

GORDON, A.L., GEORGI, D.T. & TAYLOR, H.W. (1977) Antarctic polar front zone in the western Scotia Sea - summer 1975. Journal of Physical Oceanography, 7, 309-328.

GRIFFITHS, G. (1994) Using 3DF GPS Heading for improving underway ADCP data. Journal of Atmospheric and Oceanic Technology, 11(4), 1135-1143.

HARDY, A. (1967) Great Waters. Collins, London.

HARDY, A.C. & GUNTHER, E.R. (1935) The plankton of the South Georgia whaling grounds and adjacent waters, 1926-1927. Discovery Reports, 11, 1-456.

HEWITT, R.P., KIM, S., NAGANOBU, M., GUTIERREZ, M., KANG, D., TAKAO, Y., QUINONES, J., LEE, Y.-H., SHIN, H.-C., KAWAGUCHI, S., EMERY, J.H., DEMER, D.A. & LOEB, V.J. (in press) Variation in the biomass density and dispersion of Antarctic krill in the vicinity of the South Shetland Islands throughout the 1999/2000 austral summer. Deep Sea Research Part II.

HEWITT, R.P., WATKINS, J.L., NAGANOBU, M., TSHERNYSHKOV, P., BRIERLEY, A.S., DEMER, D.A., KASATKINA, S., TAKAO, Y., GOSS, C., MALYSHKO, A., BRANDON, M.A., KAWAGUCHI, S., SIEGEL, V., TRATHAN, P.N., EMERY, J.H., EVERSON, I. & MILLER, D.G.M. (2002) Setting a precautionary catch limit for Antarctic Krill. Oceanography, 15(3), 26-33.

HEYWOOD, K.J., NAVEIRA GARABATO, A.C. & STEVENS, D.P. (2002) High mixing rates in the abyssal Southern Ocean. Nature, 415, 1011-1014.

HOFMANN, E.E. (1985) The large-scale horizontal structure of the Antarctic Circumpolar Current from the FGGE drifters. Journal of Geophysical Research, 90(C4), 7087-7097.

HOFMANN, E.E., KLINCK, J.M., LOCARNINI, R.A., FACH, B. & MURPHY, E.J. (1998) Krill transport in the Scotia Sea and environs. Antarctic Science, 10(4), 406-415.

HOLM-HANSEN, O., KAHRU, M., HEWES, C.D., KAWAGUCHI, S., KAMEDA, T., SUSHIN, V.A., KRASOVSKI, I., PRIDDLE, J., KORB, R., HEWITT, R.P. & MITCHELL, B.G. (in press) Distribution of chlorophyll-a in surface waters of the Scotia Sea as determined by both shipboard measurements and from satellite data. Deep Sea Research Part II, this volume.

KEMP, S., HARDY, A.C. & MACKINTOSH, N.A. (1929) Discovery Investigations: Objects, equipment and methods. Discovery Reports, 1, 141-232.

KING, B.A., ALDERSON, S.G. & CROMWELL, D. (1996) Enhancement of shipboard ADCP data with DGPS position and GPS heading measurements. Deep-Sea Research Part I-Oceanographic Research Papers, 43(6), 937-947.

LOCARNINI, R.A., WHITWORTH III, T. & NOWLIN, W.D. (1993) The importance of the Scotia Sea on the outflow of Weddell Sea Deep Water. Journal of Marine Research, 51(135-153), 135-153.

LONG, D.C. & BALLANTYNE, J. (2002) Is the number of antarctic icebergs really increasing? In: *EOS*, *83*, pp. 469-474.

MACKINTOSH, N.A. (1936) Distribution of the macroplankton in the Atlantic sector of the Antarctic. Discovery Reports, 9, 65-160.

MEREDITH, M.P., VASSIE, J.M., HEYWOOD, K.J. & SPENCER, R. (1996) On the temporal variability of the transport through Drake Passage. Journal of Geophysical Research, 101(C10), 22485-22494.

MOORE, J.K., ABBOT, M.R. & RICHMAN, J.G. (1997) Variability in the location of the Antarctic Polar Front (90° -20°W) from satellite sea surface temperature data. Journal of Geophysical Research, 102(C13), 27825-27833.

MOORE, J.K., ABBOT, M.R. & RICHMAN, J.G. (1999) Location and dynamics of the Antarctic Polar Front from satellite sea surface temperature data. Journal of Geophysical Research, 104(C2), 3059-3073.

MUENCH, R.D., FERNANDO, H.J.S. & STEGEN, G.R. (1990a) Temperature and salinity staircases in the Northwestern Weddell Sea. Journal of Physical Oceanography, 20(2), 295-306.

MUENCH, R.D., GUNN, J.T. & HUSBY, D.M. (1990b) The Weddell-Scotia confluence in midwinter. Journal of Geophysical Research, 98(C10), 18177-18190.

MUENCH, R.D., PADMAN, L., S.L., H. & FAHRBACH, E. (2002) Upper ocean diapycnal mixing in the northwestern Weddell Sea. Deep Sea Research Part II, 49(21), 4843-4861.

MURPHY, E.J., WATKINS, J.L., REID, K., TRATHAN, P.N., EVERSON, I., CROXALL, J.P., PRIDDLE, J., BRANDON, M.A., BRIERLEY, A.S. & HOFMANN, E. (1998) Interannual variability of the South Georgia marine ecosystem: Biological and physical sources of variation in the abundance of krill. Fisheries Oceanography, 7(3-4), 381-390.

NAGANOBU, M., BRANDON, M.A., ITO, K., SEGAWA, K. & SIEGEL, V. (in press) Comparison between the CCAMLR 2000 and KY 1988 Surveys on environmental variability of krill in the Scotia Sea, Antarctica. Deep-Sea Research II.

NAVEIRA GARABATO, A.C., HEYWOOD, K.J. & STEVENS, D.P. (2002a) Modification and pathways of Southern Ocean Deep Waters in the Scotia Sea. Deep Sea Research Part I, 49(4), 681-705.

NAVEIRA GARABATO, A.C., MCDONAGH, E.L., STEVENS, D.P., HEYWOOD, K.J. & SANDERS, R.J. (2002b) On the export of Antarctic Bottom Water from the Weddell Sea. Deep-Sea Research Part II: Topical Studies in Oceanography, 49(21), 4715-4742.

NOWLIN JR., W.D. & CLIFFORD, M. (1982) The kinematic and thermohaline zonation of the Antarctic Circumpolar Current at Drake Passage. Journal of Marine Research, 40 (supplement), 481-507.

ORSI, A.H., NOWLIN JR, W.D. & WHITWORTH III, T. (1993) On the circulation and stratification of the Weddell Gyre. Deep-Sea Research, 40(1), 169-203.

ORSI, A.H., WHITWORTH III, T. & NOWLIN JR, W.D. (1995) On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep-Sea Research part I, 42(5), 641-673.

PATTERSON, S.L. & SIEVERS, H.A. (1980) The Weddell - Scotia Confluence. Journal of Physical Oceanography, 10(10), 1584-1610.

RINTOUL, S.R., HUGHES, C.W. & OLBERS, D. (2001) The Antarctic Circumpolar Current System. In: Ocean Circulation and Climate (Ed. by G. Siedler, J. Church & J. Gould), pp. 271-302. Academic Press, London.

SCHODLOK, M.P., HELLMER, H.H. & BECKMANN, A. (2002) On the transport, variability and origin of dense water masses crossing the South Scotia Ridge. Deep-Sea Research Part II: Topical Studies in Oceanography, 49(21), 4807-4825.

SIEGEL, V., KAWAGUCHI, S., WARD, P., SUSHIN, V., LOEB, V. & WATKINS, J.L. (in press) Krill demography in the Atlantic Sector of the Antarctic during the CCAMLR Survey 2000. Deep Sea Research Part II, this volume.

SIEGEL, V., LOEB, V. & GROGER, J. (1998) krill (Euphausia superba) density, proportional and absolute recruitment and biomass in the Elephant Island region (Antarctic Peninsula) during the period 1977 to 1997. Polar Biology, 19, 393-398.

SIEVERS, H.A. & NOWLIN JR., W.D. (1984) The stratification and water masses at Drake Passage. Journal of Geophysical Research, 89(C6), 10489-10514.

THORPE, S.E. (2001) Variability of the Southern Antarctic Circumpolar Current in the Scotia Sea and its implications for transport to South Georgia. In: *School of Environmental Sciences*, pp. 212. University of East Anglia, Norwich.

THORPE, S.E., HEYWOOD, K.J., BRANDON, M.A. & STEVENS, D.P. (2002) Variability of the southern Antarctic Circumpolar Current front north of South Georgia. Journal of Marine Systems, 37, 87-105.

TRATHAN, P.N., BRANDON, M.A. & MURPHY, E.J. (1997) Characterization of the Antarctic Polar Frontal Zone to the north of South Georgia in summer 1994. Journal of Geophysical Research-Oceans, 102(C5), 10483-10497.

TRATHAN, P.N., BRANDON, M.A., MURPHY, E.J. & THORPE, S.E. (2000) Transport and structure within the Antarctic Circumpolar Current to the north of South Georgia. Geophysical Research Letters, 27(12), 1727-1730.

TRATHAN, P.N., EVERSON, I., MILLER, D.G.M., WATKINS, J.L. & MURPHY, E.J. (1995) Krill biomass in the Atlantic. Nature, 373, 201-202.

TYNAN, C.T. (1998) Ecological importance of the southern boundary of the Antarctic circumpolar current. Nature, 392, 708-710.

VON GYLDENFELDT, A.B., FAHRBACH, E., GARCÍA, M.A. & SCHRÖDER, M. (2002) Flow variability at the tip of the Antarctic Peninsula. Deep Sea Research Part II, 49(21), 4743-4766.

WARD, P., ATKINSON, A., SCHNACK-SCHIEL, S.B. & MURRAY, A.W.A. (1997) Regional variation in the life cycle of Rhicalanus gigas (Copepoda: Calanoida) in the Atlantic sector of the Southern Ocean - re-examination of existing data (1928-1993). Marine Ecology Progress Series, 157, 261-275.

WARD, P., GRANT, S., BRANDON, M.A., SIEGEL, V., SUSHIN, V. & LOEB, V. (in press) Mesozooplankton Community Structure in the Scotia Sea during the CCAMLR Survey: January-February 2000. Deep-Sea Research II.

WATKINS, J.L., HEWITT, R.P., NAGANOBU, M. & SUSHIN, V. (in press) The CCAMLR-2000 survey: a multinational, multi-ship biological oceanography survey of the Atlantic sector of the Southern Ocean. Deep-Sea Research Part II, this issue.

WHITEHOUSE, M.J., PRIDDLE, J. & SYMON, C. (1996) Seasonal and annual change in seawater temperature, salinity, nutrient and chlorophyll *a* distributions around South Georgia, South Atlantic. Deep-Sea Research, 43(4), 425-443.

WHITWORTH III, T. (1977) Monitoring the transport of the Antarctic Circumpolar Current at Drake Passage. Journal of Physical Oceanography, 13(11), 2045-2057.

WHITWORTH III, T., NOWLIN JR, W.D., ORSI, A.H., LOCARNINI, R.A. & SMITH, S.G. (1994) Weddell Sea Shelf Water in the Bransfield Strait and Weddell Scotia Confluence. Deep-Sea Research, 41(4), 629-641.

WHITWORTH III, T. & PETERSON, R.G. (1985) The volume transport of the Antarctic Circumpolar Current at Drake Passage. Journal of Physical Oceanography, 15, 810-816.

WÜST, G. (1935) Schichtung und Zirkulation des Atlantischen Ozeans. Das Bodenwasser und die Stratosphare. Wissenschaftliche Ergebnisse der Deutschen Atlantik Expedition 'Meteor' 1925-1927., Berlin.