The Southern Antarctic Circumpolar Current Front: physical and biological coupling at South Georgia

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Abstract

The coupling of physics and biology was examined along a 160 km long transect running out from the north coast of South Georgia Island and crossing the Southern Antarctic Circumpolar Current Front (SACCF) during late December 2000. Surface and near surface potential TS properties indicated the presence of three water types: a near-shore group of stations characterised by water which became progressively warmer and fresher closer to South Georgia, an offshore grouping in which sea surface temperatures and those at the winter water level were relatively warm (1.8°C and 0.5°C, respectively), and a third in which surface and winter water temperatures were cooler and reflected the presence of the SACCF. The transect bisected the SACCF twice, revealing that it was flowing in opposite directions, north-westward closest to South Georgia and south-eastwards at its furthest point from the island. The innermost limb was a narrow intense feature located just off the shelf break in 2000–3500 m of water and in which rapid surface baroclinic velocities (up to 35 cm s⁻¹) were encountered. Offshore in the outermost limb, shown subsequently to be a mesoscale eddy that had meandered south from the retroflected limb of the SACCF, flow was broader and slower with peak velocities around 20 cm s⁻¹. Chlorophyll a biomass was generally low (<1 mg m⁻³) over much of the transect but increased dramatically in the region of the innermost limb of the SACCF, where a deepening of the surface mixed layer was coincident with a subsurface chlorophyll maximum (7.4 mg m⁻³) and elevated concentrations down to 100 m. The bloom was coincident with depleted nutrient concentrations, particularly silicate, nitrate and phosphate, and although ammonium concentrations were locally depleted the bloom lay within an elevated band (up to 1.5 mmol m⁻³) associated with the frontal jet. Increased zooplankton abundance, higher copepod body carbon mass and egg production rates all showed a strong spatial integrity with the front. The population structure of the copepods *Calanoides acutus* and *Rhincalanus gigas* at stations within the front suggested that rather than simply resulting from entrainment and concentration within the jet, increased copepod abundance was the result of development in situ. Estimates of bloom duration, based on silicate and carbon budget calculations, set the likely duration between 82 and 122 d, a figure supported by the development schedule of the two copepod species. Given this timescale, model outputs from FRAM and OCCAM indicated that particles that occurred on the north...
side of South Georgia in December would have been in the central-southern Scotia Sea 2–3 months earlier, probably in sea ice affected regions.

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1. Introduction

The general circulation of the Southern Ocean is dominated by the eastward flow of the Antarctic Circumpolar Current (ACC). This is a continuous feature linking the three major oceans, and is bounded to the north by the subtropical convergence. The ACC consists of a number of full-depth fronts featuring high velocities, separated by relatively quiescent zones. The fronts are termed (north–south) the Subantarctic Front (SAF), the Polar Front (PF), and the Southern ACC Front (SACCF). The southern limit of the ACC is marked by the Southern Boundary (SACCB) (Orsi et al., 1995). The ACC fronts are at their narrowest meridional constriction at Drake Passage and diverge as the ACC flows downstream into the Scotia Sea. The island of South Georgia lies at the northeastern side of the Scotia Sea (Fig. 1); it is south of the PF but is strongly influenced by the SACCF that loops anti-cyclonically around the island’s shelf from the south before retroreflecting to the east. Before reaching South Georgia the SACCF runs through the southern half of the Scotia Sea and although the island itself lies in the polar open ocean zone (Tréguer and Jacques, 1992), the waters that lie off the north coast may have been seasonally influenced by the presence of ice cover.

Primary productivity within the ACC is highly variable despite the high nutrient low chlorophyll (HNLC) conditions that persist over much of its extent (Tréguer and Jacques, 1992). Maximum phytoplankton growth rates are relatively low, occasioned by a combination of low temperatures, micronutrient limitation, high microplankton grazing pressure and high wind stress which leads to deep mixing over much of the region. However, production within frontal zones is often elevated compared to surrounding oceanic areas (Boyd et al., 1995; van Leeuwe et al., 1997, 1998; Bathmann et al., 1997; Bracher et al., 1999; Barth et al., 2001) and can be spatially extensive. Pollard et al. (1995) carried out a well resolved survey across an ACC front in the southern part of the

![Fig. 1. The study area. (a) South Georgia in relation to frontal positions in the Scotia Sea. From north–south the mean positions of the subAntarctic Front (SAF, Orsi et al., 1995) Polar Front (PF, Moore et al., 1999) Southern Antarctic Circumpolar Current Front (SACCF, Thorpe, 2001) and the Southern Boundary of the ACC (SB, Thorpe, 2001) are shown. Bathymetry >1000 m is shaded grey. (b) South Georgia showing station positions along the transect. Isobaths from 500–3500 m are marked in intervals of 500 m and range from dark grey to white, respectively.](image)
Bellingshausen Sea during spring 1992. They found chlorophyll values up to 5 mg m\(^{-3}\) in a narrow band barely 10 km wide, extending for at least 100 km. This feature remained geographically consistent, persisted for at least 25 d, and was associated with the front (Boyd et al., 1995).

The enhanced production in these regions has been attributed to increased supplies of iron derived from shelf sediments which are available within frontal jets (Boyd et al., 1995; de Baar et al., 1995; Lösch et al., 1997; van Leeu et al., 1997). In contrast, oceanic areas to the north and south of the fronts are thought to be iron limited, and chlorophyll levels are low and contribute little to export production.

As well as being productive, fronts offer a potential means of rapid transport across oceanic regions. Velocities of the order of 0.3 m s\(^{-1}\) have been recorded in frontal jets, and drifter tracks indicate that transit times across the Scotia Sea can be as rapid as 140–160 d for particles entrained within the SACCF (Hofmann et al., 1998).

Studies of krill distribution in the region have highlighted the fact that the area lying between the SACCF and the SACCB is one of high krill abundance (Mackintosh, 1936; Marr, 1962; Hofmann et al., 1998). Studies of the food-web in waters surrounding South Georgia have also emphasised the role of advection in transporting krill into the region (Eversion, 1977; Murphy, 1995; Atkinson et al., 2001). A number of modelling studies have considered the rates and pathways of krill transport in ocean current systems (Murphy, 1995; Murphy et al., 1998; Hofmann et al., 1998). In a study focussed on the frontal flows, Hofmann et al. (1998) noted the potential for enhanced rates of transport in the SACCF to be crucial in the rapid transport of krill to South Georgia. Variation in the transport of krill in the Scotia Sea and their input into the South Georgia region has been highlighted as an important factor in determining the availability of krill to marine predators (Murphy et al., 1998). Variation in the position of the front may result in fluctuations in transport of krill into the region (Thorpe et al., 2002; Trathan et al., 2002).

With this background in mind during cruise JR57 we surveyed a 160 km transect running out from the coast of South Georgia to intersect the SACCF along the north side of the island. Our objectives were to investigate physical structure along the transect and the extent to which production within the region was associated with, and enhanced by, frontal structure.

2. Methods

Two surveys aimed at locating and characterising the SACCF were carried out along a 160 km long transect close to the island of South Georgia during 26–29 December 2000. The transect was run northeastward from nearshore, crossing the shelf on the north coast at approximately right angles and continuing into oceanic waters, and then returning towards the island (Fig. 1). On the outward survey leg underway data on temperature, salinity and photosynthetically active radiation (PAR) were collected with an undulating oceanographic recorder (UOR: Chelsea Instruments Nu Shuttle Mark II) towed at 10kts. Acoustic observations were also made with a Simrad EK500 scientific echo-sounder.

On the inward survey, stations were established every 10 km along the transect (the approximate local Rossby radius; Houry et al., 1987), and at each, a suite of oceanographic and biological measurements were made. Acoustic observations were also made between the CTD stations, comprising 16 discontinuous sections each approximately 10 km in length. Some sections were carried out at night. Sampling took place mainly in the upper part of the water column, where physical and biological gradients were most marked.

2.1. Oceanography

A SeaBird 911plus CTD was deployed to within 10 m of the seabed. Water samples were collected from standard depths with a SeaBird 12-position carousel water sampler carrying 101 Niskin bottles. Samples were analysed for salinity on a Guildline 8400B salinometer calibrated with standard seawater prepared by Ocean Scientific International Ltd. These discrete measurements were used to calibrate the CTD salinity. Downcast CTD
profiles were then averaged on 2 dbar intervals for analysis. Geostrophic velocities were calculated relative to the deepest common layer between adjacent CTD pairs. Surface mixed layer depth (SMLD) was calculated as the depth at which the density differed from the surface density by 0.05 kg m\(^{-3}\).

2.2. Optics

Vertical profiles of photosynthetically active radiation (PAR 400–700 nm) were obtained with an irradiance sensor attached to the UOR. Incident irradiance was continuously measured with a Didcot DRP1 sensor mounted to the ship’s foremast and connected to a data logger. The PAR data was used to calculate photosynthetically available radiation attenuation (K\(_{d\text{PAR}}\)), and from this we determined euphotic depth.

2.3. Chlorophyll biomass and nutrients

Samples for the estimation of chlorophyll \(a\) (chl \(a\)) and nutrients were taken at 20, 40, 60, 80, 100 and 125 m, and a near-surface (~7 m) sample was collected from the ship’s non-toxic, seawater supply. Additional samples for nutrient analyses were taken from 150, 175 and 200 m, and four depths between 200 m and the bottom of the cast.

Discrete water samples for the determination of chl \(a\) were filtered onto Whatman GF/F glass fibre filters. Concentrations of chl \(a\) were determined on a benchtop fluorometer after extraction in 90% acetone for 24 h at 4 °C (Parsons et al., 1984).

In vivo chlorophyll fluorescence was measured every 2 m with a Chelsea Instruments, Aqua Tracka fluorometer mounted on the CTD frame. For each station, the fluorometer was calibrated by regression analysis of extracted chl \(a\) values against in vivo fluorescence at discrete depths \((R^2 \geq 0.85)\). Integrated water column chl \(a\) was obtained by integrating values at 2 m intervals from the surface to 125 m.

SeaWiFS data were obtained from NASA’s Goddard Distributed Active Archive Center (DAAC). Level 2 GAC (Global Area Coverage) data were processed with SeaDAS software.

Microplankton species composition representative of the surface mixed layer (SML) was determined at each station from water samples collected at 20 m and preserved in 1% acid lugols solution. A 50 ml aliquot of each sample was settled for 24 h by the Utermöhl technique, and identification and enumeration was carried out under an inverted microscope. Species counted ranged in size from ~1–200 \(\mu\)m.

Concentrations of Si(OH)\(_4\)–Si (silicate), NO\(_3\)–N (nitrate), PO\(_4\)–P (phosphate), NH\(_4\)–N (ammonium), and NO\(_2\)–N (nitrite) were measured colorimetrically with a Technicon-based autoanalyser within ~1 h of collection (Whitehouse, 1997).

2.4. Meso-zooplankton

At each station a motion compensated bongo net (mouth opening 61 cm dia., net mesh 200 \(\mu\)m) with solid cod-ends was deployed from 200–0 m. Upon recovery the contents of one cod-end were immediately diluted with surface seawater at ambient temperature and then taken into the laboratory for examination and sorting of fresh and live material, and those of the other were preserved in 10% (v:v) formalin in seawater for analysis in the UK. From the former, species stages of two of the biomass dominant species which commonly occur in the ACC and were present at all of the stations sampled were selected for further study. Female Calanoides acutus and Rhincalanus gigas were sorted and incubated in groups of 10 for 24 h to determine egg production rates (EPR) (see Ward and Shreeve, 1995 for further details). At the conclusion of these experiments females were removed, briefly rinsed in ammonium formate and placed in pre-weighed ultra light-weight tin foil capsules. Additionally, approximately 30 individuals belonging to stages CIV and CV of Calanoides acutus from each station were frozen for C mass determination. Samples were frozen at –80°C and subsequently dried at 60°C onboard ship within 1 week of collection. They were then transferred to the UK in a sealed container where they were again dried at 60°C to constant weight. Dry mass was measured on a Mettler MT5 balance to an accuracy of \(\pm 1\ \mu\)g. Whole samples were then
analysed for carbon, hydrogen and nitrogen with a Fisons® EA 1108 elemental analyser with acetanilide as a standard.

In the UK the formalin preserved samples were split into appropriate aliquots with a Folsom plankton splitter and examined under a binocular microscope. Zooplankton were identified to species and stage or higher taxonomic categories and enumerated. A mean number of 1563 individuals (range 714–2880) was counted in each sample. Data were analysed with the statistical package PRIMER5 (Primer-E Ltd., 1994). Standardised data (no. ind. m⁻²) were log transformed (log x + 1) and subjected to cluster analysis (q-type) to group stations based on the Bray-Curtis similarity measure and complete linkage classification of abundance data (Field et al., 1982). The similarity matrix produced by q-type clustering was ordinated using non-metric multidimensional scaling (MDS) to represent the samples as points in low dimensional space. In this way points close together represent samples that are similar in species composition and points further away correspond to different communities. Analysis of similarity (ANOSIM) and similarity percentages (SIMPER) routines were also performed; ANOSIM is roughly analogous to a standard 1-way ANOVA test allowing testing of assemblage differences between groups of samples but does not make any distributional assumptions. SIMPER examines how much each species contributes to the average sample dissimilarity between groups (Clarke and Warwick, 1994).

2.5. Acoustics

Acoustic data were collected with a Simrad EK500 scientific echo sounder, operating hull-mounted 38, 120 and 200 kHz transducers. The outward survey was undertaken during daylight whereas the return survey measurements were made between stations during both day and/or night. The ping rate of the echo sounder was set at 2.5 s and the survey speed was 10 kts. The acoustic data were logged with a SonarData Echolog-EK, and post-processing was carried out with SonarData Echoview software. The echosounder was calibrated at Stromness Harbour, South Georgia, on 24 December by the standard target techniques (Foote et al., 1987).

2.6. Identification of krill

Acoustic backscatter that could be attributed to Antarctic krill (Euphausia superba) was delineated from other sources of backscatter by the relative values of signal return at two different frequencies, specifically by calculating the dB difference, where mean volume backscattering strength (ΔMVBS) = sound velocity (Sv) at 120 kHz – Sv at 38 kHz. A range of ΔMVBS has been attributed to krill. Previous studies have used 2–12 or 2–16 dB. In this study, fishing of acoustic targets had shown that small krill were prevalent in the transect area (mean total length 32.3 mm), and that swarms of these krill had a considerable proportion (16%) of the backscatter with a ΔMVBS in the 12–14 dB range, and lesser amount in the 14–16 dB range (4%). Acoustic scatterers smaller than krill tend to have a ΔMVBS greater than 12 dB (Madureira et al., 1993). Therefore, 2–14 ΔMVBS was chosen so that most of the biomass due to krill would be included, whilst minimizing the inclusion of other targets. Target strength (TS) was calculated from \( S_A \) (mean backscattering area (m²) per horizontal area (nautical miles²)) in dBkg⁻¹ (Foote and Stanton, 2000), and the TS to length and length to weight relationships given in Brierley and Watkins (1996).

3. Results

3.1. Station grouping and identification of the SACCF

A detailed description of the oceanography along this transect and a full depth characterisation of the SACCF and associated physical fluxes is provided by Meredith et al. (2002). Despite the stations being conducted to the full depth of the ocean (around 300 m on the shelf, down to approximately 3500 m in the deep ocean), we focus here on the waters most significant for the pelagic ecosystem, i.e. the upper 200 m.
Stations along the transect fell into three groups based on their surface and near-surface properties (Fig. 2); deep water properties show a similar, but not identical, division (see Meredith et al., 2002). Stations in the first group (69–75), at the north-easternmost end of the transect, were comparatively warm at the surface (up to 1.8°C), and also at the potential temperature minimum (T-min) of the winter water (WW) (0.5°C). Salinities were around 33.94 at the surface, rising to 34.05 at the WW layer. The second group (stations 101–119), lying closest to South Georgia, showed broad similarities to stations 69–75, particularly at the WW level, for which the potential temperature and salinities were similar. Above the WW, salinity was lower than at stations 69–75, and the water became progressively warmer and fresher with increasing proximity to South Georgia. Surface waters at the station closest to Cumberland Bay (station 119) were the freshest and warmest measured along the entire section (S = 33.67; T = 2.37°C), reflecting the impact of freshwater discharge from the island, combined with water mass retention on the shelf, and hence greater cumulative warming through insolation (cf. Brandon et al., 1999). Overall, the characteristics shown by these two groups of stations (69–75 and 101–119) are typical of waters lying between the PF and the SACCF (Orsi et al., 1995), with some modification of the shelf waters as noted above.

The central group of stations (78–97) showed markedly different characteristics from those on either side, reflecting the presence of the SACCF and waters between the SACCF and the SACCB: these waters were much cooler at the WW layer (−0.7 ≤ 0.3°C) and at the very surface (<1.3°C). They were also marginally more saline at the WW layer, and slightly fresher at the surface. Their potential temperature/salinity curves showed much greater variance than for the other 2 groups, indicative of strong mixing (mostly in the form of isopycnal interleaving). It is important to note that this group also differs in its Circumpolar Deep Water (CDW) properties: at the potential temperature maximum, temperatures at stations in the 2 outermost groups were close to 2°C, whereas at stations 78–97 they were generally cooler. The potential temperature/salinity properties indicate that not only did our transect bisect the SACCF twice but also that it was flowing in opposite directions—north-westward closest to South Georgia, and south-eastward at its furthest point from the island. The crossing closest to South Georgia is in approximately the location expected from analyses of historical hydrographic data (e.g. Orsi et al., 1995), i.e. flowing anticyclonically around the shelf slope of South Georgia in water depths of ~2500 m. The crossing farthest from South Georgia is more surprising, since it is south of the general position expected for the eastward flowing retroflected limb of the SACCF (Orsi et al., 1995; Thorpe et al., 2002). From analysis of AVHRR satellite imagery (not shown), we believe the crossing of the SACCF farthest from South Georgia is actually part of a mesoscale eddy that has meandered south from the retroflected limb of the SACCF to reach the location of the transect. The most extreme gradients associated with the SACCF coincide with the boundaries between the groups shown in Fig. 2, namely station pairs 75–78 and 97–101. The horizontal gradients of properties can most clearly be observed in vertical sections: those for potential temperature, salinity and density are shown in Fig. 3.

The vertical field of potential temperature (Fig. 3a) clearly shows the cold WW layer centred
around 100 m depth. The extremes of this layer were concentrated in two lenses, at stations 78 and 88. Surface temperatures were colder above these two lenses, and the WW between was colder than elsewhere on the section. Salinities and densities within these two WW lenses were also marginally lower than at adjacent stations (3b, c). An interruption to the WW layer was seen at station 110, close to the top of the South Georgia shelf break. Here, a strong vertical feature with higher potential temperatures and salinities intruded into the WW layer (Fig. 3b). Closer to South Georgia, stations 113–119 showed some evidence of doming, indicative of a recirculating flow probably steered by local bathymetry. Waters in the central group of stations (78–97) showed pronounced doming of isohalines and isopycnals (Figs. 3b and c), consistent with the opposing direction of flow of the two limbs of the SACCF. The doming of the isopycnals extended to the sea surface (Fig. 3c), and was also present to the full depth of the ocean (not solely the upper 200 m shown), as can be inferred from the different CDW properties of the SACCF stations. The bi-directional structure of the SACCF crossings was most apparent in the vertical field of geostrophic velocity (Fig. 3d). This was calculated relative to the deepest common level between CTD stations pairs but here we show just the upper 200 m to be comparable with the other data presented in Fig. 3. Fig. 3d shows that on the nearshore crossing the SACCF was a narrow, intense feature with surface baroclinic velocities up to around 35 cm s\(^{-1}\) (between stations 94 and 97), whereas further along the transect it was somewhat broader and slower, with peak velocities around 20 cm s\(^{-1}\) (between stations 75 and 78). Generally peak velocities coincided spatially with the boundaries between the water mass groups shown in Fig. 2. The exception was the crossing of the SACCF closest to South Georgia, where peak velocity occurred between stations 94 and 97 although the water mass boundary fell between the adjacent station pair (97–101). This was an effect of the deep water gradients on the velocity field as Meredith et al., 2002 noted that the divisions of the three groups were slightly different in deep compared to the surface and near-surface waters, e.g. for station 101, which had properties typical of waters outside of the SACCF (e.g. Fig. 2), but which nonetheless was subject to high geostrophic velocities (Fig. 4).

3.2. Optics and hydrography

The depth of the euphotic zone (i.e. the depth with 1% of the irradiance level at the surface) varied considerably along the length of the transect (Fig. 4). Generally, euphotic depth was greatest at station 81 and became progressively
shallower to the north and south. The shallowest depth was associated with the shelf region (stations 104, 107, and 110). The SMLD was also extremely variable, ranging from 105 to 31 m along the transect. The shelf region exhibited the shallowest SMLDs with the deepest located at station 101 associated with a region of high chlorophyll biomass. Here, SMLD exceeded the euphotic depth by approximately 40 m (Fig. 4).

3.3. Chlorophyll distribution

Chl $a$ biomass (Fig. 5a) was generally low ($<1 \text{ mg m}^{-3}$) over much of the transect, with two notable exceptions: the shelf area (stations 116–107) and the southernmost area of the SACCF (stations 101, 97, 94). Over the shelf, total integrated chl $a$ biomass ranged from 94–225 \text{ mg m}^{-2} \text{ (Table 1)}, but the highest integrated chl $a$ values (273–554 \text{ mg m}^{-2}) were in the southern region of the SACCF. The highest single concentration (7.4 \text{ mg m}^{-3}) encountered along the transect was part of a pronounced subsurface chlorophyll maximum (SCM) at 25 m at station 101, where biomass remained elevated down to 100 m.

It was not possible to obtain a SeaWIFS satellite image during the period of the survey because of heavy cloud cover. However, a clear image of the area surrounding South Georgia was obtained on the 6 January (see Fig. 9). Although the satellite could not detect the SCM at station 101 or anywhere else, estimates of chl $a$ from SeaDAS analysis reflect those of shipboard measurements.
whereby an area of high biomass (station 97) could be detected in the vicinity of the front followed by an area of low chl \( a \) around stations 88–85, and again by a slight increase of productivity around station 78.

In the southern part of the front, diatoms made up approximately 95% of the chl \( a \) biomass, and at least 50% of the cell counts at stations 101–97 consisted of large diatoms >80 \( \mu \)m in length. The dominant species found were *Thalassiothrix* sp., *Leptocylindrus* sp., *Corethron criophilum* (Castracane, 1886) and *Corethron inerme*, (Thomas and Bonham, 1990) which are found throughout the Scotia Sea. There were few ice-associated diatoms such as *Nitzschia kerguelensis*.

### 3.4. Nutrient distribution

On the island’s shelf (stations 119–107) near-surface (0–100 m) silicate, nitrate and phosphate (Fig. 4b–e) concentrations were relatively high, although somewhat lower than in pre-bloom conditions measured previously in this area (Whitehouse et al., 1993, 1996). There was a subsurface peak in ammonium concentrations (>1 mmol m\(^{-3}\)) at ~50 m. Within the region between the two crossings of the SACCF (stations 91–81) nutrient concentrations were generally higher and this was especially so for silicate (~45 mmol m\(^{-3}\)). At stations identified above as being in the inshore limb of the SACCF (101–94) silicate, nitrate and phosphate depletion occurred (down to 13, 21, 1.4 mmol m\(^{-3}\), respectively) coincident with increased phytoplankton abundance (see above). Within the bloom near-surface ammonium concentrations were also low (<0.2 mmol m\(^{-3}\)), but the bloom lay within a band of elevated ammonium (up to 1.5 mmol m\(^{-3}\)) associated with the frontal jet. At the outermost stations (69–78) nutrient concentrations were similar to those on the island shelf including a subsurface ammonium peak of ~1.2 mmol m\(^{-3}\) at 60 m. Nitrite (not shown) concentrations changed little along the transect with near-surface levels increasing slightly south-to-north.

### 3.5. Total copepod abundance

Total copepod abundance along the transect varied considerably, ranging from 12,553 to 304,312 ind. m\(^{-2}\) (0–200 m). Highest abundances were associated with the SACCF and particularly the jet (stations 101 and 97) and the lowest with stations to the north of the front in oceanic water (stations 78–91) (Fig. 5). Cluster analysis of log transformed abundance data revealed three main groupings of stations along the transect—the first of these formed by the four stations located over the shelf (stations 110–119), the second by stations 88 and 78, and the third encompassing the frontal jet and remaining off-shelf stations (Fig 6a). MDS produced an ordination with low stress (0.11), which indicated that the data were well represented in 2D ordination space (Fig. 6b), and ANOSIM indicated significant differences between all groups (Global \( R > 0.875 \)). The data were further tested with SIMPER to characterise which species were responsible for the similarities within and differences between groups (Table 2). With the exception of the small neritic calanoid *Drepanopus forcipatus*, which was restricted to the shelf stations, variations in the abundance of small calanoids (principally *Metridia* spp., *Ctenocalanus citer* and *Microcalanus pygmaeus*, and cyclopoids (*Oithona* spp.)) variously served to define the

<table>
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ND = Not determined.
groups. Thus group one was characterised by a high abundance of all copepodite stages of *D. forcipatus*, group 2 by a general paucity of copepods of all species, and group 3 by an increased abundance of all smaller calanoids and the cyclopoid *Oithona* spp. For a broader overview of zooplankton distribution in this part of the Southern Ocean the reader is referred to Atkinson et al. (2001).

3.6. Population structure: *Calanoides acutus* and *Rhincalanus gigas*

Total abundance of *Calanoides acutus* varied considerably along the transect ranging from 27 to 4682 ind. m$^{-2}$, with the highest abundance associated with stations 94–101 located in the frontal jet (Fig. 7a). Stage frequency distribution was also variable, with younger stages (CI–CIII) being particularly abundant at those stations in the frontal region (>50% of the population at stations 94–101). The proportion of older stages (CIV–CVI) was higher at the remaining stations particularly those over the inner shelf (stations 113–119), where the new generation was all but absent. Females were absent at a few stations and constituted a low proportion of the population at all others.

Total abundance of *Rhincalanus gigas* was less variable than for *C. acutus*, ranging from...
Older copepodite stages dominated at most stations, and as with *C. acutus* the proportion of younger stages again increased in the frontal region, although this was not associated with the pronounced peak in abundance seen in that species. Over-wintered populations of both species were restricted to the inner shelf stations (Fig. 7b).

Older lipid storing copepodite stages CIV, CV and CVI females of *C. acutus* and CVI females of *R. gigas* were sufficiently abundant to determine carbon mass at most stations (Table 3). Highest carbon masses were again found to be associated with the productive frontal region (Stations 104–94) and were between 4 and 7 fold greater at these stations than elsewhere on the transect. Egg production by both species was negligible over much of the transect but was significant only within the SACCF at stations 104-91, with the maxima of both species located within the jet (Table 3).

### 3.7. Acoustic zooplankton biomass estimation

On the outward underway passage along the transect acoustic zooplankton biomass was highly variable although a dense swarm occurred between stations 97–101 at the end of an extensive layer (Fig. 8a). Mean acoustic biomass was 94.62 g m$^{-2}$ with 83.42 g m$^{-2}$ (88.2%) attributable to krill (dB diff 2–14). There were very few large targets (dB diff $>$ 14) constituting $< 1\%$ of the biomass. Smaller targets (dB diff $< 14$) made up around 10\% of the biomass (Fig. 8b).

On the return leg constructed from sections of transect between stations over day and night, the biomass was considerably lower (48.42 g m$^{-2}$, Fig. 8c), and only 42\% was attributable to krill (dB diff 2–14). Even allowing for the fact that some of the biomass may have been missed due to migration of krill above the transducers at night, the biomass is lower overall, irrespective of the time of day. The layered structure seen on the outward transect between stations 101 and 88 was not evident on the return. The proportion of smaller targets was much higher on the return leg, although the absolute biomass was very similar.

Comparing the 2 biomass estimates emphasises the variability of krill biomass distribution, which may well have been a result of swarming behaviour.

### 3.8. Estimating the SACCF bloom’s magnitude and longevity

Our nutrient, chlorophyll and zooplankton data all indicated that the inner limb of the SACCF was extremely productive. Here nutrient drawdown was significant in comparison to surrounding waters, and chlorophyll biomass, net zooplankton abundance and condition and acoustically estimated zooplankton biomass were all high. As the

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### Table 2

Mesozooplankton abundance (ind. m$^{-3}$) of taxa identified by the Similarity percentages analysis (SIMPER) as contributing $\geq 4\%$ to either similarity within groups or dissimilarity between groups previously identified by Bray-Curtis clustering and MDS analysis (see text for details). Taxa are ordered in respective of overall abundance across all groups.

<table>
<thead>
<tr>
<th>Species</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copepoda</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Oithona</em> spp.</td>
<td>172.0</td>
<td>72.0</td>
<td>299</td>
</tr>
<tr>
<td><em>Drepanopus forcipatus</em></td>
<td>204.0</td>
<td>0.0</td>
<td>1.5</td>
</tr>
<tr>
<td><em>Metridia</em> spp.</td>
<td>43.0</td>
<td>9.9</td>
<td>66.4</td>
</tr>
<tr>
<td>CI–CIII</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Ctenocalanus</em> spp.</td>
<td>15.6</td>
<td>15.4</td>
<td>51.0</td>
</tr>
<tr>
<td><em>Oncaea</em> spp.</td>
<td>1.1</td>
<td>0.3</td>
<td>23.5</td>
</tr>
<tr>
<td><em>Calanoides acutus</em></td>
<td>2.2</td>
<td>0.3</td>
<td>11.2</td>
</tr>
<tr>
<td><em>Microcalanus pygmaeus</em></td>
<td>1.71</td>
<td>1.3</td>
<td>9.7</td>
</tr>
<tr>
<td><em>Metridia</em> spp.</td>
<td>3.4</td>
<td>0.8</td>
<td>7.2</td>
</tr>
<tr>
<td>CIV–CVI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Scoleciithricella minor</em></td>
<td>1.53</td>
<td>3.3</td>
<td>4.3</td>
</tr>
<tr>
<td><em>Rhincalanus gigas</em></td>
<td>2.1</td>
<td>0.6</td>
<td>3.2</td>
</tr>
<tr>
<td><em>Calanus simillimus</em></td>
<td>1.8</td>
<td>0.2</td>
<td>1.6</td>
</tr>
<tr>
<td><em>Euchaeta antarctica</em></td>
<td>$&lt; 0.1$</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td><em>Calanus propinquus</em></td>
<td>$&lt; 0.1$</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Other Taxa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Pteropoda:</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Limacina helicina</em></td>
<td>0.4</td>
<td>1.2</td>
<td>44.8</td>
</tr>
<tr>
<td><em>Chaetognatha</em></td>
<td>3.9</td>
<td>0.3</td>
<td>3.5</td>
</tr>
<tr>
<td><em>Euphausiacea:</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Thysanoessa</em> spp <em>Calyptopes</em></td>
<td>0.0</td>
<td>$&lt; 0.1$</td>
<td>1.1</td>
</tr>
<tr>
<td><em>Thysanoessa</em> spp. <em>Furcilia</em></td>
<td>$&lt; 0.1$</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td><em>Siphonophora:</em></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><em>Diphyes antarctica</em></td>
<td>0.0</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Appendicularia:</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Fritillaria</em> spp.</td>
<td>6.2</td>
<td>0.3</td>
<td>4.9</td>
</tr>
</tbody>
</table>

106–972 ind. m$^{-2}$. Older copepodite stages dominated at most stations, and as with *C. acutus* the proportion of younger stages again increased in the frontal region, although this was not associated with the pronounced peak in abundance seen in that species. Over-wintered populations of both species were restricted to the inner shelf stations (Fig. 7b).
phytoplankton bloom was dominated by diatoms and silicate is essential for diatom growth we have used a silicate depletion budget to assess the blooms magnitude. The SMLD at station 101 was 105 m, and at stations 97 and 94, 75 m. The integrated silicate standing stock in the SML at station 101 was 1.67 mol m$^{-2}$, at station 97, 1.08 mol m$^{-2}$ and at station 94, 1.31 mol m$^{-2}$. A deficit was calculated by comparing these integrated silicate values with those representing mixed surface water from the previous winter: in this case the remnant of this water found at the

![Fig. 7. Stage frequency composition of the copepods *Calanoides acutus* (a) and *Rhincalanus gigas* (b) along the transect.](image)

**Table 3**

Carbon mass (CM, $\mu$g Ind.$^{-1}$) for *Calanoides acutus* stages CIV–CVI females and *Rhincalanus gigas* stage CVI females and egg production rates (EPR eggs fem. d$^{-1}$) by station along the transect

<table>
<thead>
<tr>
<th>Station</th>
<th>CM</th>
<th>EPR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>C. acutus</em></td>
<td><em>R. gigas</em></td>
</tr>
<tr>
<td>119</td>
<td>25</td>
<td>119</td>
</tr>
<tr>
<td>116</td>
<td>24</td>
<td>143</td>
</tr>
<tr>
<td>113</td>
<td>22</td>
<td>83</td>
</tr>
<tr>
<td>110</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>107</td>
<td>39</td>
<td>149</td>
</tr>
<tr>
<td>104</td>
<td>80</td>
<td>183</td>
</tr>
<tr>
<td>101</td>
<td>71</td>
<td>258</td>
</tr>
<tr>
<td>97</td>
<td>75</td>
<td>320</td>
</tr>
<tr>
<td>94</td>
<td>66</td>
<td>239</td>
</tr>
<tr>
<td>91</td>
<td>39</td>
<td>127</td>
</tr>
<tr>
<td>88</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>85</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>81</td>
<td>43</td>
<td>108</td>
</tr>
<tr>
<td>78</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>75</td>
<td>42</td>
<td>106</td>
</tr>
<tr>
<td>72</td>
<td>38</td>
<td>69</td>
</tr>
<tr>
<td>69</td>
<td>23</td>
<td>45</td>
</tr>
</tbody>
</table>

No data (--).
Silicate concentrations in South Georgia surface shelf waters are typically 25–30 mmol m$^{-3}$ in winter prior to a bloom (Whitehouse et al., 1993, 1996). However, although the bloom’s southern limit (station 101) was at the interface between the island’s shelf water and the SACCF jet, the majority of the bloom was located within the SACCF meander (Fig. 4). The SACCF surface mixed layer to the north of the bloom, where chl a levels were $<$1 mg m$^{-3}$, had a mean silicate concentration of $\sim$45 mmol m$^{-3}$ underlying which were concentrations $>$56 mmol m$^{-3}$ at the T-min. At the bloom stations, the mean T-min silicate concentration was 46 mmol m$^{-3}$ ($\sim$43–49 mmol m$^{-3}$). Therefore, we have assumed that the bloom occurred in water that had a pre-bloom silicate concentration of $\sim$45 mmol m$^{-3}$ and have calculated a budget referenced to this value.

Given a pre-bloom silicate concentration of 45 mmol m$^{-3}$, the silicate deficit within the bloom ranged from 2.06 mol m$^{-2}$ at station 94 to 3.05 mol m$^{-2}$ at station 101. To assess the bloom’s magnitude we have calculated a carbon equivalent for this silicate deficit. C:Si ratios of phytoplankton assemblages in the Scotia and Weddell Seas vary according to the species involved (especially the predominance of diatoms) and their size, and is also dependent on the state of the bloom. Ratios from $<2$ to $>7$ have been reported (cf. Nelson et al., 1987; Tréguer et al., 1990; Priddle et al., 1995). For the purposes of our budget we have used the Priddle et al. (1995) locally measured C:Si ratio of 4, which involved phytoplankton species similar to those in the present study. Therefore, our silicate deficits are equivalent to $\sim$99–146 g C m$^{-2}$. So as to err towards a conservative estimate, we have considered the highest production rate measured in the waters to the NE of South Georgia, the equivalent of $\sim$1.2 g C m$^{-2}$ d$^{-1}$ (Owens et al., 1991). As with the present study, this measurement was also made near an incursion of cold, silicate-rich high latitude water (Whitehouse et al., 1993). Therefore, if phytoplankton growth rates had been high and linear, and no grazing had occurred, the bloom would have been growing for $\sim$82–122 d. We emphasise the approximate nature of this estimate due to the high variability around the few data points.
available to us. However, it serves to illustrate the magnitude and probable longevity of the bloom.

4. Discussion

During our survey the SACCF was located twice, once centred close to station pairs 94–97 and again at stations 75–78. The inshore crossing was associated with north-westward flow, as expected for the general anticyclonic loop of the SACCF around South Georgia. The second was part of the eastward flowing retroflected SACCF, which had looped southward as part of the mesoscale field. In between these crossings, there was an active zone of strong mixing and steep property gradients. Inshore of the SACCF, on the South Georgia shelf, there was significant modification of surface water masses through freshwater input.

A marked subsurface chlorophyll maximum was associated with the main frontal jet in a band some 20 km wide. This feature coincided with a rapid deepening of the surface mixed-layer with elevated chl a concentrations extending down to a depth of almost 120 m at station 101. Such deep chlorophyll maxima have been previously reported in the Southern Ocean by Nelson et al. (1987), Bathmann et al. (1994, 1997), and Veth et al. (1997). Bathmann et al. (1997) suggested subduction of surface water and ruled out *in situ* growth. Pollard et al. (1995) report similar findings from a spring cruise to the Bellingshausen Sea, where narrow banded layers of chlorophyll were associated with the southern edge of an ACC front. Boyd et al. (1995) noted the high production rates coincident with the front despite the presence of a deep mixed layer and a shallow euphotic zone. Using oxygen flux observations in conjunction with production data they estimated the critical depth and SMLD to be approximately equal (70–80 m). A common paradigm in oceanography is that phytoplankton blooms can develop only when the surface mixed-layer is shallower than a critical depth at which vertically integrated respiration is balanced by integrated photosynthesis (e.g. Sverdrup, 1953). Using the reformulation of Sverdrup’s critical depth calculation developed for the Southern Ocean (Nelson and Smith, 1991), we can estimate how this parameter may affect phytoplankton growth along the frontal jet. With a SMLD of 10^4 m, Kd_{PAR} of 0.0697, a mean daily surface irradiance of 28.73 mol m^{-2} s^{-1} (our most conservative estimate during the period of the cruise), and net compensation irradiance of 35 μmol m^{-2} s^{-1} (Nelson and Smith, 1991), the critical depth is estimated to be 109 m. Therefore, although the deep mixed layer at station 101 is some 40 m below the base of the euphotic zone, SMLD is shallower than the critical depth providing a light environment favourable for growth. Indeed, at a depth of 125 m, phaeopigments accounted for less than 25% of total chlorophyll biomass (data not shown) indicating that this deep biomass was composed mainly of healthy cells.

4.1. Bloom timing

Our measurements were made at the end of December, which, given the estimates of bloom duration (82–122 d), places the starting point sometime between September and October. This is a conservative estimate made on the basis of phytoplankton drawdown of 1.2 g C m^{-2} d^{-1} (maximum rate measured for the eastern end of South Georgia (Owens et al., 1991). Although rates of up to 2.75 g C m^{-2} d^{-1} have been recorded previously at the western end of the island (Gilpin et al., 2002), these measurements were made in water between the PF and the SACCF as opposed to the bloom in this study that was located between the SACCF and the SACC. A rate of 1.2 g C m^{-2} d^{-1} is a more reasonable (perhaps over generous) rate for water of Scotia Sea origin (cf. Jacques, 1989; Tréguer and Jacques, 1992). Therefore, by using a relatively high rate of carbon drawdown and not taking into consideration grazing pressures we are likely to have underestimated the blooms longevity. Support for our estimated timescale is provided by the zooplankton data, and in particular the higher abundance of copepods within the front compared to elsewhere on the transect and the stage frequency distribution of the biomass dominant species *Calanoides acutus* and *Rhinocalanus gigas*. Rather than the increased plankton abundance in the jet resulting from entrainment and concentration
(sensu Voronina, 1970; accumulation in a zone of convergence), the increased proportion of younger stages of both *C. acutus* and *R. gigas* within the front, and the broadly comparable abundance of females with stations outside, suggest development in situ. A timescale of at least 70–90 d is suggested based on what we know about egg hatching times, likely naupliar development rates and the development schedule of early copepods previously determined for these two species at South Georgia (see Ward and Shreeve, 1998; Shreeve and Ward, 1998; Shreeve et al., 2002). Given the high current velocities within the front it is highly likely that copepod development commenced upstream of the island. Similar enhancement of copepod biomass and EPRs have been found in the PF during spring (Fransz and Gonzalez, 1997) and were also attributed to increased primary production rather than physical concentration (Bathmann et al., 1997).

### 4.2. Source of the bloom

Production was highly localised within the front, with chlorophyll and nutrient properties of the surrounding water clearly indicating that production was not, and had not been, widespread. The estimated timescales of bloom development from nutrient and zooplankton data, along with the fast current speeds measured within the front, suggest the likely point of origin of the bloom to be upstream of South Georgia. Examination of SeaWiFS images for the period preceding the survey indicated that the bloom was not apparent along the transect. Images from 11 December show that chl *a* was elevated in a band along the south side of the island as well as southwards along 36W, but chl *a* levels remained low along the transect (Fig 9a). Variable cloud cover largely obscured the transect during the following month, but 1 week after sampling the transect the bloom could be clearly seen (Fig. 9b). From monthly composite images (December and January, data not shown), elevated chl *a* levels can be seen over the southern shelf and also in oceanic water which lies in the mean path of the SACC to the SSE of the island. We judge the southern shelf not to have been a supply source for the phytoplankton encountered on the transect for the following reasons. First the mean position of the front as determined from historical data by Thorpe et al. (2002) shows it passing anticyclonically around the island, being steered by bathymetry, but not actually intruding over the southern shelf. Second there is a strongly developed neritic zooplankton community over the shelf (Ward and Shreeve, 1999; Atkinson et al., 2001), which was not apparent along the transect except at stations on the northern shelf.

Drifter data are limited for the region, but estimates suggest that in the South Atlantic sector of the Southern Ocean within the Antarctic Zone south of the PF the mean near-surface current speeds are of the order of 28 cm s⁻¹ (Hofmann

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Fig. 9. SeaWiFS images from the 11 December 2000 (a) and 6 January 2001 (b). Note the absence of a bloom along the transect 2 weeks before sampling (a) and the elevated chl *a* biomass apparent within the SACC 1 week after sampling (b).
et al., 1998). Current speeds may be enhanced in the SAACF region, but the figure gives a general indication of the expected speeds in the region. The few data available from satellite-tracked buoys (30 m drogued) in this area also indicate that rapid transfers of surface waters across the Scotia Sea do occur. Ichii and Naganobu (1996) reported on the tracks of two buoys that moved across the Scotia Sea to pass separately to the east and west of South Georgia. Both buoys were released in the Antarctic Peninsula region 3–4 months before reaching South Georgia. Such transport rates, taken in conjunction with our predicted bloom development times potentially places its origin a considerable distance upstream of South Georgia in the Scotia Sea.

4.3. Model outputs

Further information on the expected tracks and time-scales for tracer transport in the Scotia Sea can be obtained by modelling particle drift with output from General Circulation Models. Using the mean velocity field from the Fine Resolution Antarctic Model (FRAM; Webb et al., 1991), which does not resolve seasonal or interannual processes, we have back-calculated the pathways of tracers that would pass through the region where the SACCF was observed in this study. These trajectories indicate a pathway that passes north and west of the South Orkney Islands, moving eastward between about 59°S and 60°S, before moving northwards at about 38°W, and then moving east to wrap around the east of the island (Fig. 10a). The time scales for such transport in FRAM are extremely slow compared to iceberg and drifter tracks, a point noted in previous model analyses of tracers in this region Hofmann et al. (1998). In FRAM, it appears that the transport around the east of the island is particularly poorly quantified, with tracers taking several months to move around the island,
whereas drifters and icebergs consistently show movement across the same region taking only a few weeks. The general track of the model tracers is quite similar to that seen by iceberg A20A (National Ice Center; www.natice.noaa) and the northward transport tracks of the satellite drifters so it does appear to give a reasonable representation of the general pathway of transport but not the time scale.

In an effort to get a better view of the time scales of particle transport we have used output from a recent run of the Ocean Circulation and Climate Advanced Modelling Project (OCCAM; Webb et al., 1998). The OCCAM model was forced with high frequency winds to introduce realistic temporal and spatial variability into the simulation (see Fox et al., 2000 for further details). OCCAM is considered to give a better representation of the general rates of flow in the region; however, the pathways of transport in OCCAM are biased to the east as a result of problems in resolving the ocean circulation in the central Scotia Sea (Thorpe et al., 2002). We undertook tracer tracking using the 5-day mean velocity field output from OCCAM for 2 of the years for which data are available (1993 and 1994) for the surface level (10 m) and a deeper level (50 m). We looked at the 3 months prior to January and identified all those cells for which transport would take particles through the region off the central north coast of South Georgia. The resulting runs show a high degree of variation between years and between layers, and, as expected, the track of particles is biased to the eastern side of the Scotia Sea, although the trajectories do pass to the north of the South Orkney Islands in the South Scotia Sea (Thorpe, 2001). Transport in the deeper layer is, as expected, much slower, so the region from which particles could have come in a 2–3 month period is much more restricted in the deeper levels. The main boundaries of where the particles could have come from in a 1-, 2- or 3-month period superimposed on the FRAM trajectories are illustrated in Fig. 10b. It is not possible to absolutely identify a specific region where the tracers would have originated because of the vertical and interannual variation. However, on the basis of the flow indicated by the FRAM tracks, the OCCAM analyses indicate that particles would be transported from the central-southern Scotia Sea regions to the South Georgia area in a 2–3 month period.

The period of the transect survey was the 26th-29th December 2000, so a 2–3 month transport time indicates that particles that occurred on the north coast of South Georgia at the end of December would have been in the central southern Scotia Sea during October 2000. This region, from about 58°S to 60°S and 38°W to 42°W, is in the vicinity of the SACCF and was under sea-ice (>15% ice concentration) until November (Fig. 10b).

5. Conclusion

Questions relating to the balance between locally derived and advected production in the seas around South Georgia are only just beginning to be addressed. The timescales of phytoplankton bloom development suggest the importance of local factors for primary producers, but the longer generation times of copepods and krill in relation to likely residence times around the island imply that advection may largely predominate (Atkinson et al., 2001). This study has highlighted the importance of a frontal zone in introducing enhanced levels of both primary and secondary production into the region. The close coupling of biology and physics over the timescale indicated establishes a clear link between the island and the krill rich regions in the southern and western parts of the ACC and the northern extent of the ice edge in winter (Murphy et al., 1998). The region lying between the SACCF (corresponding to Marr's definition of the northern influence of Weddell water) and the SACCB, particularly west of 45°W, is important both in terms of its associated high krill biomass and as a major site of krill reproduction (Marr, 1962; Spirodonov, 1995; Murphy et al., 1998; Hofmann et al., 1998). On our crossing of the SACCF the majority of krill biomass lay between it and the SACCB, and on the outward survey in particular, a major concentration was present within the front. Therefore the presence of the retroreflecting SACCF close to
the northern shelf of South Georgia has important implications for the transport and delivery of production (krill and other zooplankton) into the region (Murphy et al., 1998). Smaller size classes of krill often occur at the eastern end of the island compared to the west. It is unclear whether the differences are the result of changes in the distribution of krill with age or are the result of input of different sized krill. Smaller krill may originate from the ice edge and the Weddell Sea and larger ones offshore of the Antarctic Peninsula (Watkins et al., 1999; Murphy et al., 1998). Our study highlights that the SACCF may have a crucial role in the input of smaller krill into the South Georgia region at the eastern end of the island. It remains to be seen how fluctuations in the position of the SACCF are related to the variable environmental conditions experienced around South Georgia and large scale changes in krill biomass (Murphy, 1995, 1998, 2001; Fedoulov et al., 1996; Whitehouse et al., 1996; Shreeve et al., 2002).

Acknowledgements

We thank the officers and crew of RRS James Clark Ross for support at sea and all associated with BAS field operations and logistics for making cruise JR57 happen. We also thank the SeaWiFS Project (Code 970.2) and the Distributed Active Archive Center (Code 902) at the Goddard Space Flight Center, Greenbelt, MD 20771, for the production and distribution of the SeaWiFS data. These activities are sponsored by NASA’s Mission to Planet Earth Program.

References


