Antarctic Largescale Box Analysis and The Rôle Of the Scotia Sea - ALBATROSS

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Summary

This proposal seeks support for a study of the influence of the Scotia Sea on global ocean circulation. During a 35 day research cruise using *RRS James Clark Ross*, we shall undertake a high quality hydrographic and tracer survey of the southwest Atlantic in the form of an enclosed box. This box incorporates repeats of three hydrographic sections completed during the last decade, so we shall detect any changes in water mass properties. It crosses the Antarctic Circumpolar Current (ACC) twice and so enables us to quantify its transport. The Scotia Sea is a region believed to exhibit intense water mass modification. Deep waters from the Weddell Sea escape through narrow passages into the Argentine Basin and are also entrained into the eastward flowing ACC. Deep waters flowing east through Drake Passage are believed to undergo freshening and cooling in the Scotia Sea. When taken together with previous hydrographic sections, our survey will complete a set of boxes, so we shall use inverse techniques to determine horizontal and surface fluxes of heat and freshwater in the Weddell Sea, Scotia Sea and Southwest Atlantic. Thus we shall quantify the rôle of the Scotia Sea in the ocean-atmosphere climate system.

1. Background

The Scotia Sea occupies the region between Drake Passage in the west, the Falkland Plateau in the north, the South Sandwich Islands in the east, and the South Scotia Ridge to the south. The Scotia Sea and its bathymetry are illustrated in Figure 1. The Sea is traversed by the Antarctic Circumpolar Current (ACC). The Scotia Sea also provides a pathway through which Weddell Sea Deep Water (WSDW) can influence the thermohaline circulation of the world ocean.

Negative heat fluxes over the Weddell Sea lead to deep water production, primarily in the western Weddell Sea (Fahrbach *et al.*, 1994). WSDW is found in both the Atlantic and Indian Oceans. Additionally a small amount of WSDW may enter the Pacific through the Drake Passage (Nowlin and Zenk,1988; Roether *et al.*, 1993). WSDW enters the Indian Ocean between Crozet and Kerguelen (Mantyla and Reid, 1995). A component of WSDW that enters the Atlantic passes to the east of the South Sandwich Arc, however there is also a component that takes a route through the Scotia Sea (Locarnini *et al.*, 1993). The water that takes this route can enter the Scotia Sea through deep narrow passageways in the South Scotia ridge. The deepest gap is the narrow Orkney Passage with a sill depth of about 3500 m (LaBrecque *et al.*, 1981), although there are other shallower gaps through which some WSDW may flow (Gordon, 1966; Nowlin and Zenk, 1988). It is also possible that recently ventilated waters can spill over the South Scotia Ridge along its entire length (Weiss and Bullister, 1984). There are two possible routes for WSDW to enter the Argentine Basin from the Scotia Sea. Wittstock and Zenk (1983) report a northwestward flow of cold bottom water through Shag Rocks Passage. From there the Malvinas Chasm provides a route to the Georgia Basin and Argentine Basin. The minimum sill depth along this route is 3200 m. However Locarnini *et al.* (1993) discount this possibility and suggest that WSDW in the Malvinas Chasm is supplied from the east as a branch of the cyclonic abyssal circulation in the Georgia Basin. They also suggest that a more plausible route for WSDW to leave the Scotia Sea is via the Georgia Passage (sill depth 3200 m; LaBrecque *et al.*, 1981). Furthermore they speculate that the flow through the Georgia Passage can supply an important portion of the WSDW entering the deep western boundary current in the Argentine Basin.

As well as this direct influence, WSDW may also have an indirect effect on the global thermohaline circulation. The main component of abyssal waters renewing most of the world oceans via deep boundary currents is Circumpolar Deep Water (CDW) of the ACC (Mantyla and Reid, 1983). Locarnini *et al.* (1993) suggest that as the ACC passes through the Scotia Sea, its most voluminous water mass, CDW, is cooled and freshened by WSDW. Thus, as a result of this ventilation, the Scotia Sea provides an effective link between the waters of the Weddell Sea and the rest of the world abyssal ocean.

Southeast Pacific Deep Water (SPDW) is observed passing through Drake Passage (Sievers and Nowlin, 1984). Based on a comparison of data from World Ocean Circulation Experiment (WOCE) cruises A17 and A23 Arhan *et al.* (1998) propose a deep circulation scheme in which SPDW and CDW both overflow the Falkland Plateau. This is because SPDW is observed on A17 but not on A23. However the location of the overflow is unknown.

The ACC comprises a number of narrow jets associated with density fronts, the Subantarctic Front, the Polar Front and the Southern Antarctic Circumpolar Current Front (Orsi *et al.*, 1995). The transport of the ACC at Drake Passage has been variously estimated between 15 Sv westwards and 237 Sv eastwards (Johnson and Bryden, 1989). Most recent publications suggest that a value of about 130 Sv eastwards is most appropriate (Nowlin and Klinck, 1986; Peterson and Stramma, 1991). On leaving Drake Passage the fronts diverge (Peterson and Stramma, 1991). The Subantarctic Front turns abruptly northward and forms the Falkland Current. The Polar Front takes a more northeasterly path across the Falkland Plateau. The Southern Antarctic Circumpolar Current Front follows a more zonal route along the northern edge of the South Scotia Ridge (here identified as the Scotia Front), before leaving the Scotia Sea between South Georgia and the South Sandwich Islands.

There has been considerable debate as to the dynamical mechanism governing the ACC. Munk and Palmén (1951) suggested that since no continents block the circumpolar path around the Southern Ocean, the transport of the ACC should be directly proportional to the wind stress. They outlined a mechanism by which surface wind stress should be balanced by topographic form stress caused by pressure gradients across ocean ridges. In contrast with Munk and Palmén's emphasis on form stress governing ACC transport, Stommel (1957) noted that the ACC spirals southward along its circumpolar path, returning northward sharply at Drake Passage. Therefore he suggested that the current might be thought of as a Sverdrup interior flow, driven southward by the wind stress curl with a western boundary current return flow at Drake Passage. In a recent paper, Warren *et al.* (1996) have revived Stommel's suggestion, arguing that because the steady state equations describing form stress do not limit the zonal transport of the ACC, instead the vorticity constraints imposed by Sverdrup dynamics must define ACC transport. However in response Hughes (1997) suggested that the irrelevance of form drag is clearly an overstatement.

The ACC plays an important rôle in the Earth's climate system, because it serves as the major conduit carrying water mass, heat, and fresh water between the Atlantic, Indian, and Pacific Oceans. The southern Indian and Pacific Oceans export heat southwards whereas the South Atlantic carries heat northwards (Macdonald and Wunsch, 1996), with the Southern Ocean providing a link. Some of the waters that pass through Drake Passage may participate in the cold water return route (CWRR) of the North Atlantic Conveyor Belt Circulation (Rintoul, 1991). If this is the case, the surface and intermediate waters need to gain buoyancy (heat) as they return northward. An alternative view put forward by Gordon (1986), the warm water return route (WWRR), is based on North Atlantic Deep Water (NADW) upwelling in the Pacific and Indian Oceans, then flowing westward (with water from the Pacific entering the Indian Ocean through the Indonesian Passages), and completing its circuit back into the Atlantic via the Agulhas Retroflection zone. Later Gordon *et al.* (1992) proposed a modification in which the CWRR makes an excursion into the Indian Ocean (gaining heat) and passes into the Atlantic via the Agulhas region. The relative importance of each of these routes is as yet uncertain and is a central question in the Climate Variability and Predictability (CLIVAR) implementation plan. Modelling studies have been inconclusive with some supporting the CWRR (e.g. Drijfhout *et al.*, 1996) and others the WWRR (e.g. Thompson *et al.*, 1997).

During the observational phase of WOCE (1990-1997), hydrographic sections were undertaken across each of the major ocean basins. Although each section had unprecedented resolution along the cruise track, distances between adjacent sections were of necessity many thousands of kilometres. Our cruise will complement the WOCE 'snapshot', by answering questions which those sections have prompted, and by repeating some sections. Long term monitoring is important in detecting natural and anthropogenic climate change. Hydrographic sections of relevance to this proposal include S1, undertaken by German WOCE in 1990 which included a full suite of chemical tracers, and its repeat SR1, occupied almost annually by Brian King and colleagues at the Southampton Oceanography Centre, slightly to the east of S1 and with no tracers. We shall also make use of data from two WOCE One-Time hydrographic sections, A11 and A23, both completed through the UK WOCE programme. A11 was a zonal section along 45°S in 1992-93, and A23 was a meridional section completed in 1995 along 35°W. Both include chlorofluorocarbons (CFCs), and for A23 helium, tritium and oxygen isotope data are also available. In addition to the WOCE sections, the British Antarctic Survey (BAS) occupy annually a short section from the Maurice Ewing Bank to South Georgia led by Mark Brandon, although these stations are generally only to a depth of 1000 m and there are no tracers.

2. Objectives

Our objective is to undertake a detailed hydrographic survey of a box surrounding the Scotia Sea. As well as traditional measurements of temperature, salinity and oxygen we shall sample CFCs, oxygen isotopes, tritium, helium and nutrients. The aims of the survey are as follows:

(i) To determine the pathways of Weddell Sea Deep Water as it enters and leaves the Scotia Sea.

(ii) To quantify the cooling and freshening of Circumpolar Deep Water as it crosses the Scotia Sea.

(iii) To determine the pathway and transport of Southeast Pacific Deep Water across the Falkland Plateau.

(iv) To measure the transport of the Falkland Current and compare with the transport of the wind stress curl forced western boundary current.

(v) To compute heat, fresh water and other tracer budgets for the Scotia Sea, southwestern Atlantic and western Weddell Sea.

(vi) To calculate the transport and characterise the fronts associated with the ACC as it enters and leaves the Scotia Sea.

(vii) To determine the interannual variability of the transport and water mass properties of the ACC at Drake Passage. Thus continuing the U.K.'s rôle in monitoring this important choke point.

(viii) To determine temporal changes to the water masses of the Scotia Sea and the extent to which recently ventilated deep waters may have been affected by possible climate change.

The planned cruise track is shown in Figure 1. Stations will be undertaken throughout the cruise except where crossing shallow topography and where territorial waters preclude it. The track will be tightly determined by the bottom topography, and will complete a synoptic box around the Scotia Sea. We shall commence from the Falkland Islands southwards and westwards to the northern Drake Passage. This is on the continental shelf so little transport flows over it. During the steam we shall occupy a deep CTD station to test the systems and determine CFC bottle blanks. CTD stations will be occupied across Drake Passage repeating the S1 section from 1990. We shall then work east along the crest of the topography, past the Antarctic Peninsula. Following the South Scotia Ridge enables us to determine whether water masses are able to overflow the ridge. We shall carefully place closely spaced stations in any gaps through the ridge to detect throughflow of deep waters. At 31°W we shall meet the A23 cruise track just south of the Weddell Scotia Confluence, and here we turn northwards to repeat the A23 stations to South Georgia. In A23 these stations have been particularly enlightening in tracing the path of the deep waters (Arhan *et al.*, 1998) and are being studied by PhD students at UEA to determine the rôle of the Weddell Scotia Confluence in ventilation From South Georgia we shall occupy the section to the Maurice Ewing Bank previously studied by BAS; this will be the first time that this section has been competed with full depth stations with lowered ADCP and tracers. The final section from the Maurice Ewing Bank to the Falkland islands is a section which has never been occupied before; the 1994 World Ocean Atlas (Levitus and Boyer, 1994) is devoid of deep data along the Falkland Plateau.

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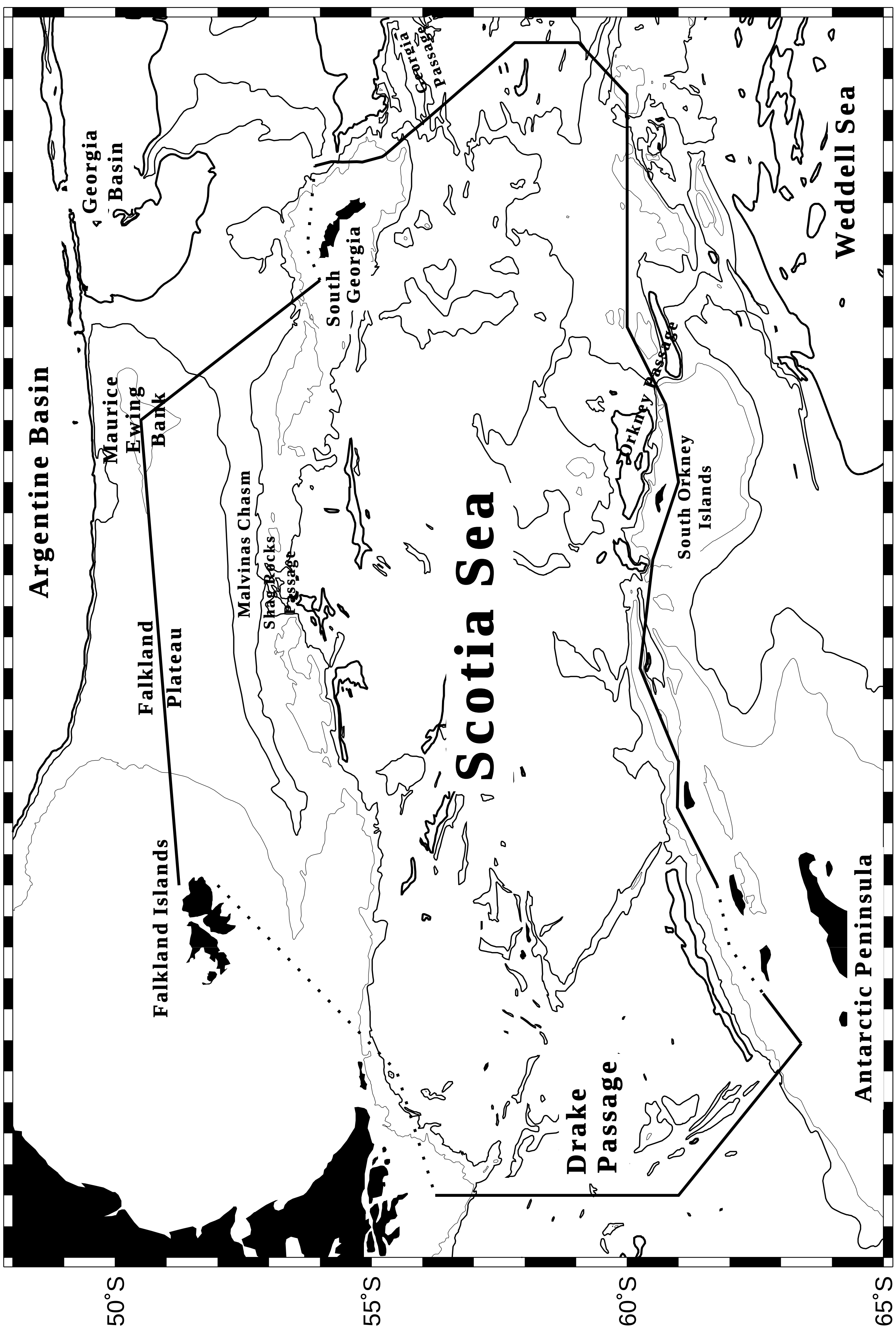

Figure 1: The topography of the Scotia Sea region and proposed cruise track. The light, medium and heavy contours indicate the 1500 m, 3000 m and 4500 m isobaths, respectively. Stations will be undertaken where the cruise track is marked by a solid line. Dotted sections denote steaming legs.

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