Pathways of Weddell Sea Deep Water in the Argentine Basin Examined Using a Primitive Equation Model

J. A. Murphy, D. P. Stevens, and G. R. Bigg, University of East Anglia, Norwich, UK. j.murphy@uea.ac.uk

The Drake Passage (see Fig. 1) prescribes the densest water that can enter the South Atlantic. The Antarctic Circumpolar Current (ACC) at Drake Passage can only supply temperatures greater than 0.2°C; so within the Argentine Basin the source of waters colder than 0.2°C must be from the Weddell Sea. Water with potential temperature $-0.7°C<\theta<-0.2°C$ will be defined as Weddell Sea Deep Water (WSDW). New WSDW can enter the Argentine Basin through the Georgia Basin, or through the passage situated between the Islas Orcadas Rise and the Mid-Atlantic Ridge. According to Stommel and Arons' (1960) theory it should flow in a deep boundary current towards the coast of South America and then north along the western boundary of the Argentine Basin. Since water colder than -0.2°C does not escape the Basin, the coldest water in the boundary current should return to the south-east as part of an interior flow regime.

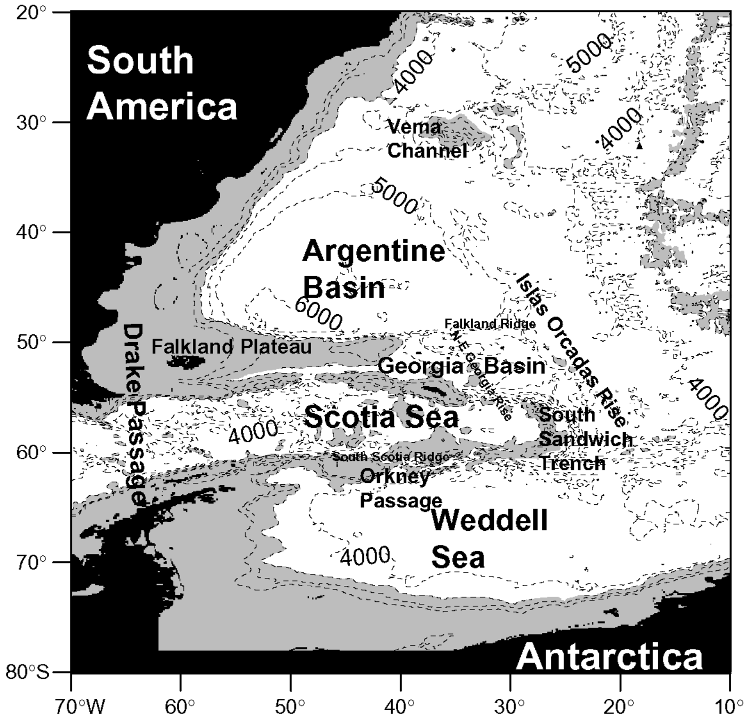

Figure 1. Bathymetry of the South Atlantic. Depths less than 3000 m are shaded.

Traditional tracer measurements cannot distinguish new WSDW from water that has been circulating for some time. CFC data however should be able to provide some insight into the relative ages of the deep and bottom waters of the Argentine Basin. CFCs have been introduced to the atmosphere only recently so we expect the highest signal to be in the deep boundary current predicted by Stommel and Arons (1960), and for there to be substantially lower concentrations in the rest of the basin, which comprises the slower-moving interior recirculation. However, interior waters with low-CFC concentrations are not found in the south-east Argentine Basin. Warner et al. (1990) and Weiss et al. (1990) show CFC distributions from the SAVE leg-E cruise (nominally at 45°S). Some higher concentrations were found on the western boundary, and lower concentrations were found in the interior of the south-west region of the Argentine Basin. But, there was a sharp increase in CFCs just north of the Georgia Basin that persisted eastwards to the Mid-Atlantic Ridge.

Pathways of Antarctic Bottom Water in the South Atlantic

We use a numerical model to look at the arrival of WSDW in the Argentine Basin and to examine its route north once there. The area to be modelled is shown in Fig. 1. The model domain is limited to 70°W–20°E, 20°S–75°S. Exchanges with other oceans are accounted for by having active open boundaries at the Drake Passage, at 20°S, and between Africa and Antarctica at 20°E. In the vertical we have 32 model levels and a horizontal resolution of approximately 55 km. Monthly Levitus temperature and salinity data and Hellerman-Rosenstein winds were used to force the model. The use of idealised tracers in the numerical model may help us to shed some light on the problem. Following England (1995) we use a transient dye tracer. The concentration of dye (D) is governed by the standard tracer conservation equation:

$$\frac{dD}{dt}+(u\cdot\nabla)D+w\frac{\delta D}{\delta z}=F^D+S^D,$$

where D obeys the following boundary condition:

$$D(x,y,z)=1\,\text{unit m}^{-3}$$

over the considered source water volume V_s, and initial condition:

$$D(x,y,z)=0\,\text{unit m}^{-3}\ \text{for all}\ (x,y,z)\notin V_s.$$

u is the horizontal velocity, w the vertical velocity, F^D represents the diffusion and S^D the source. As such, water in direct contact with the source, has a concentration of 1 unit m^{-3} throughout the integration, whereas interior grid boxes are gradually filled with the dye. The dye tracer provides useful information on the pathways taken by the water masses.

The source volume chosen initially was within WSDW south of 60°S and above the level of the Orkney Passage (near 40°W) at 3500 metres; this was denoted WSDW1. The other source volume chosen was WSDW below 3500 m and south of 60°S and this was denoted WSDW2.

Routes north out of the Weddell Sea

The ocean bathymetry constrains WSDW to enter the Argentine Basin from either the Georgia Basin or east of the Islas Orcadas Rise. WSDW may reach these locations through:

1. The South Sandwich Trench Route (Georgi, 1981). We will refer to the water following this route as T-WSDW.
2. The Scotia Sea Route (Locarnini et al., 1993). This route was first established by Locarnini et al. (1993), henceforth L93, as an alternative to the traditional South Sandwich Trench route, although it was previously identified by Hollister and Elder (1969). The water following this route will be called S-WSDW herein.

In the model the T-WSDW can reach the Georgia Basin at least as fast as the S-WSDW, but it is the S-WSDW that fills the south-east Scotia Sea and enters the Georgia Basin. L93 and Weiss et al. (1990) show high CFCs throughout the south-east Scotia Sea and in the deep waters the high CFC signal can be traced northeast through the Scotia Sea as far as the Georgia Basin.

Entry of WSDW to the Georgia Basin

After flowing into the Georgia Basin the S-WSDW meets with the T-WSDW above the northern end of the South Sandwich Trench. The WSDW tracer distributions suggest that only the S-WSDW flows significantly to the south of the North-East Georgia Rise into the western part of the Georgia Basin. Water as cold as -0.5°C can enter the northern part of the basin from the east, north of the North-East Georgia Rise, in accordance with maps of bottom temperature shown by Whitworth et al. (1991), henceforth W91, and L93. This water is T-WSDW. In the model the lowest temperature involved in the S-WSDW route is $\theta \sim -0.2$°C. Fig. 2 shows that it is the WSDW2 (the cooler part of the T-WSDW) which dominates the Georgia Basin at this level.

WSDW between the Islas Orcadas Rise and the Mid-Atlantic Ridge

Model results showing the deep velocity vectors (Fig. 3 shows those from 4336 metres) indicate a path northwards from the Weddell Sea flowing to the east of the Islas Orcadas Rise. Arhan et al. (1997), using data from the eastern leg of SAVE-5, calculates a transport of 0.68 Sv for WSDW (-0.2°C$<\theta<0.2$°C) on the northern side of the Falkland Ridge which must have passed around the Islas Orcadas Rise. This is consistent with the model results showing water from east of the Islas Orcadas joining the

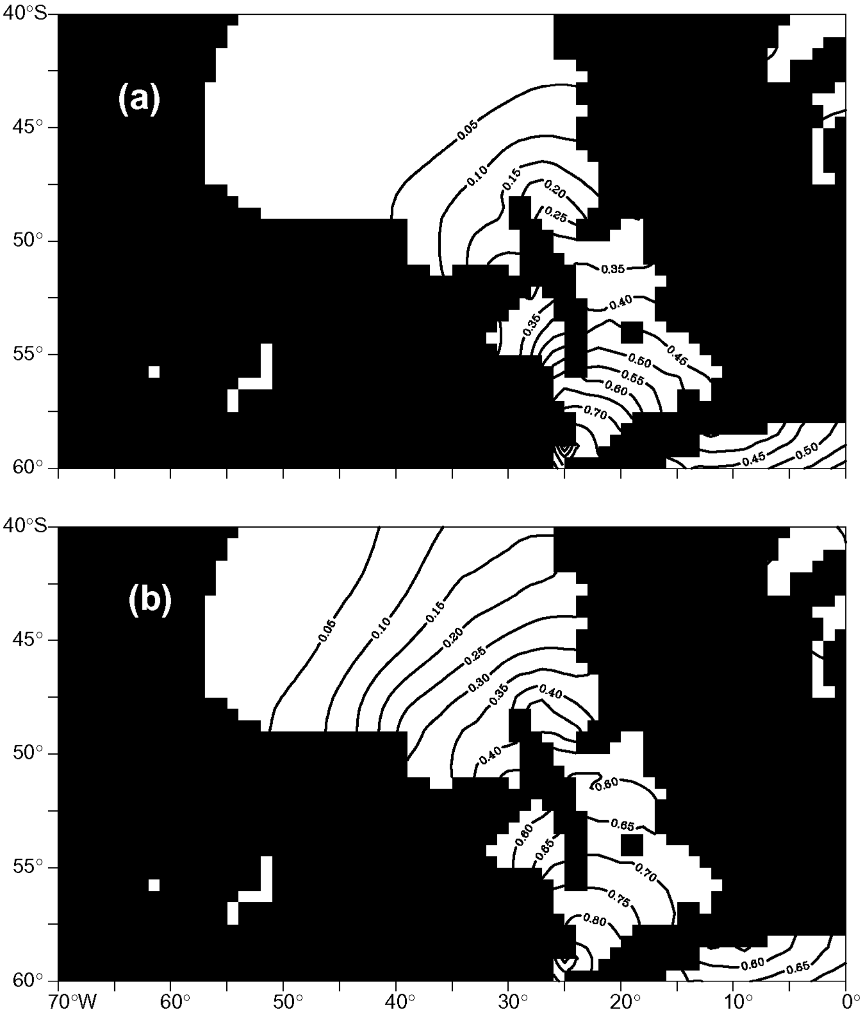

Figure 2. Deep WSDW model tracer distributions at 4336 m, (a) after 10 years of integration, (b) after 20 years of integration.

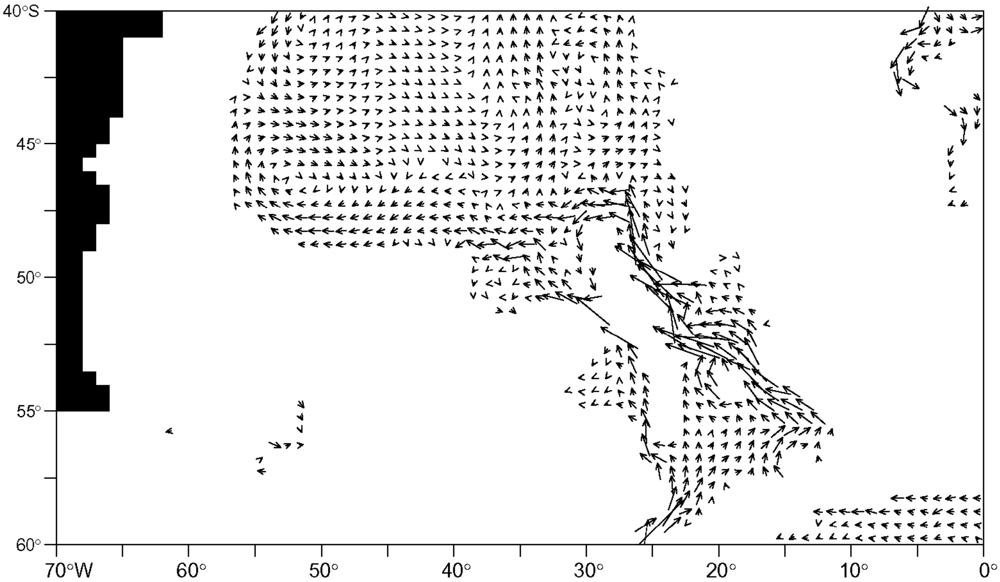

Figure 3. Model velocity vectors from 4336 m depth after 20 years of model integration.

deep boundary current north of the Falkland Ridge and travelling westwards.

The model transports at 43°W, north of the Falkland Plateau, compare favourably with W91. The model prescribes 3.04 Sv of WSDW net westward transport (1.9 Sv in W91) of which 1.84 Sv is "new" WSDW according to W91 terminology (1.2 Sv in W91). The model proportions of water in different temperature ranges is similar.

Flow of WSDW in the Argentine Basin

CFC data does not appear to agree with a simple Stommel and Arons circulation scheme with high-CFC values being found at the eastern side of the Argentine Basin. Warner et al. (1990) suggest that these high CFCs are consistent with a separate cyclonic gyre in the abyssal circulation. W91 pose an alternative involving entrainment and eastward advection of water from the Georgia Basin within the ACC. They showed evidence that the entry of deep waters from the Georgia Basin to the Argentine Basin is related to the meandering of the Subantarctic and Polar fronts. They suggest that water thus entrained by the ACC is carried eastwards with the propagating meander at a rate that exceeds its northward diffusion into the open Argentine Basin to the north. This process would limit the influence of high CFC concentrations to regions downstream (east) of the source region and one meander amplitude north of the source region. We do not believe this story is sufficient.

Results from the idealised tracers

The lighter WSDW spills over the South Scotia Ridge, especially at the Orkney Passage, and fills the south-east Scotia Sea by turning eastwards under the influence of the ACC. WSDW has also travelled north via the South Sandwich Trench route (east of the South Sandwich Arc). The deeper WSDW (WSDW2) shown in Fig. 2a has left the Weddell Sea via the South Sandwich Trench and then entered the eastern side of the deep Georgia Basin as well as travelling to the east of the Islas Orcadas. Some of the lighter WSDW dye has also reached this level but the signature of the deeper WSDW is much stronger.

From Fig. 2b we see that WSDW2 does enter the deep boundary current, as is evident from Fig. 3, but it also appears to spread primarily from the south-east part of the Argentine Basin, northward from the Georgia Basin and from between the Islas Orcadas Rise and the Mid-Atlantic Ridge. The high WSDW2 signal does not penetrate rapidly into the deep boundary current of the Argentine Basin as can be seen from Fig. 2. This behaviour is reminiscent of the CFC signal in the data of W91. We suggest that the deep boundary current is strongly affected by the deep-reaching ACC and that this is causing the rapid recirculation which limits the very high-CFC value waters to the area east and north of the Islas Orcadas Rise region. It may be that part of the boundary current is becoming entrained in the ACC, and it is being advected eastwards to the north of the main boundary current. A zonal picture of the deeper WSDW tracer WSDW2 from 45°S (Fig. 4, page 22) shows a remarkably similar distribution to the SAVE CFC data (Weiss et al., 1990) and to that of A11 (Smythe-Wright and Boswell, 1995) with very high concentrations along the western flank of the Mid-Atlantic Ridge, low-CFC interior waters in the south-western basin and an increase in the westernmost part of the basin in the deep boundary current.

This picture is different to that offered by W91, which suggests that meanders of the ACC capture blobs of WSDW and advect them to the east faster than they can diffuse north. It is unlikely that this scenario can produce the high-CFC signal as far north as 42°S (A11 data) and data with the same high volume (the high-CFC area is quite large). We suggest that a more continuous entrainment by the ACC results in the eastward advection of high-CFC water and that when this water arrives at the Mid-Atlantic Ridge it turns north. This schematic produces an approach for the Vema Channel from the south-east consistent with Flood and Shor (1988) and Hogg et al. (1982).

Acknowledgements

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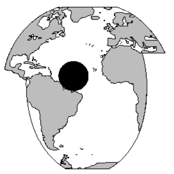
Deep Circulation in the Western Tropical Atlantic Inferred from CFCs and L-ADCP Measurements During ETAMBOT Cruises



C. Andrié, LODYC, ORSTOM/CNRS/Université Pierre et Marie Curie, Paris, France; Y. Gouriou, B. Bourlès and C. Oudot, ORSTOM Brest, France; J. F. Ternon, ORSTOM Cayenne, French Guiana. andrie@lodyc.jussieu.fr

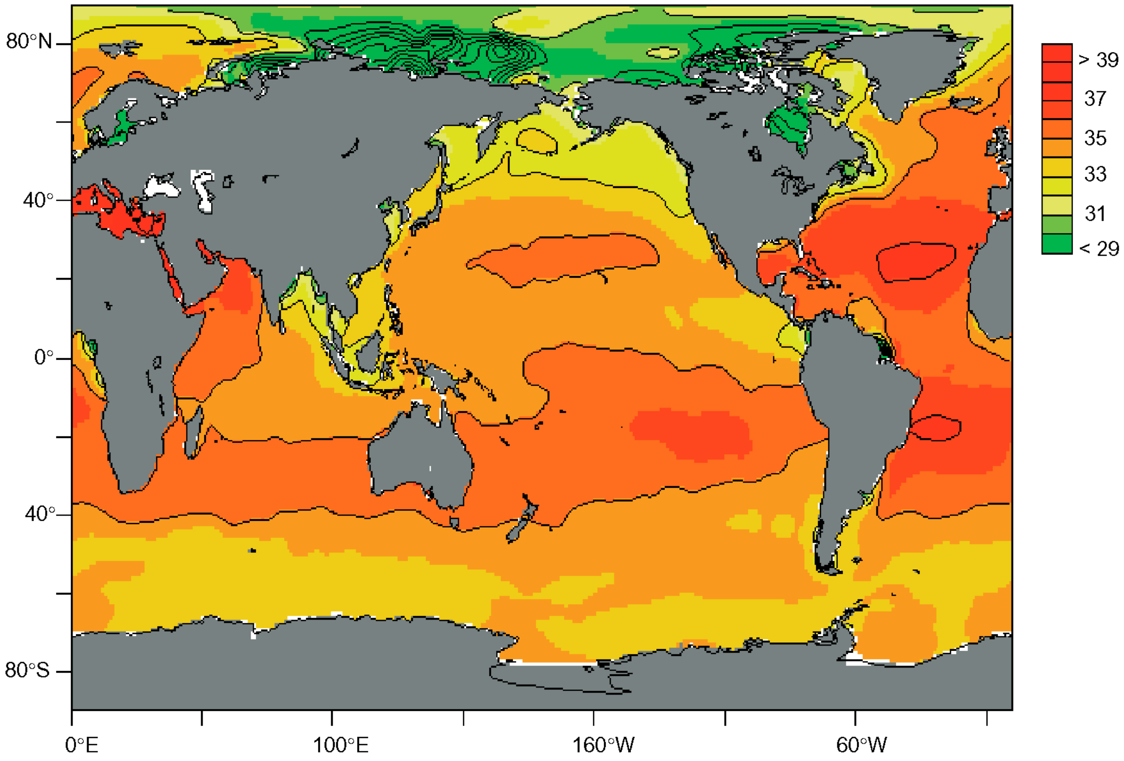
Direct velocity measurements have pointed out the complexity of the deep circulation in the western tropical Atlantic (Johns et al., 1993; Schott et al., 1993; Colin et al., 1994; Hall et al., 1994; Rhein et al., 1995; Fischer and Schott, 1997). The estimation of the net southward transport of the Deep Western Boundary Current (DWBC), which flows along the continental margin of the American continent, is complicated by the recirculations and their associated variability. The fate of the DWBC at the equator is of fundamental importance for the south Atlantic budget. SOFAR floats have shown that zonal flow, with strong variability, exists at depth along the equator (Richardson and Schmitz, 1993; Richardson, 1994). To address those questions, transient tracers, such as CFCs, are particularly useful in identifying the water masses. They have been measured during recent equatorial cruises: along repeated sections at 44°W and 35°W during Meteor cruises from 1990 to 1994 (Rhein et al., 1995; Rhein et al., 1996), and during the WOCE CITHER 1 cruise (along 7°30'N and 4°30'S, and at 35°W and 4°W in between) (Andrié et al., 1996).

In this context, one of the main objectives of the ETAMBOT programme was to study the western equatorial circulation between the American continent and the Mid Atlantic Ridge (MAR). The two cruises which have been carried out during the ETAMBOT programme took place during opposite seasons: ETAMBOT 1 in September–October 1995 and ETAMBOT 2 in April–May 1996. Both cruises followed the same tracks. The cruise tracklines (Fig. 1) consist of three sections, along 7°30'N between the coast and 35°W, along 35°W from 7°30'N to 5°S, and a slanted section crossing the Ceara rise, off Brazil. During those cruises, direct measurements of current were made from the surface to the bottom with a L-ADCP, Acoustic Doppler Current Profiler, attached to the rosette. During the ETAMBOT 1 cruise, profiles of current could only be made for the first 33 stations, between the coast and 37°W, at 7°30'N. During the ETAMBOT 2 cruise, profiles of current were made at every station. The data have been processed following the method described in details by Fischer and Visbeck (1993).

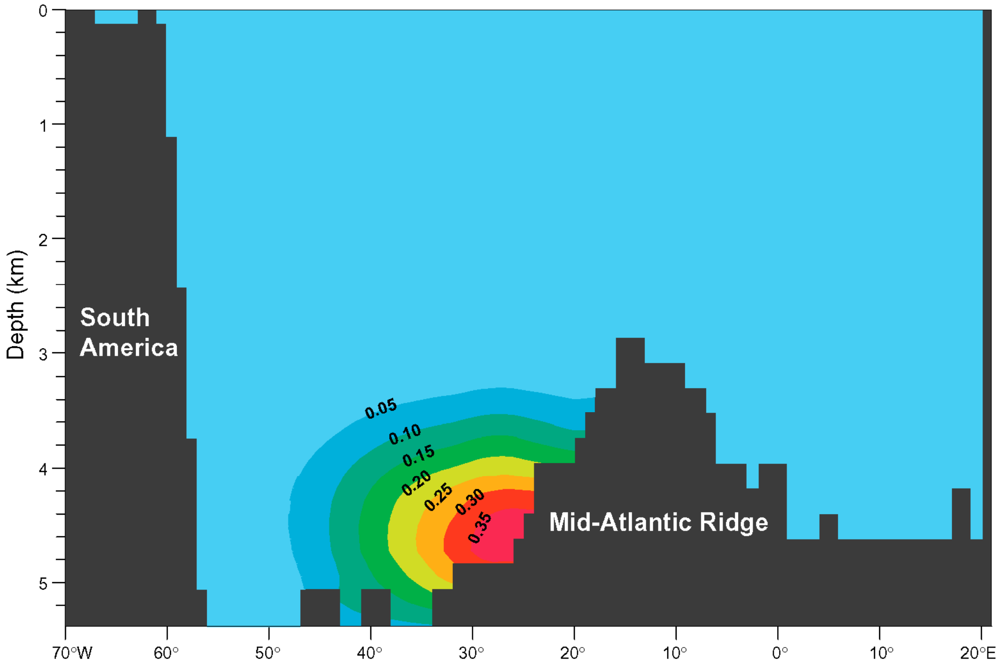
Here, we focus principally on the circulation features inferred from CFC-11 and L-ADCP measurements performed during the ETAMBOT 1 and 2 cruises.

ETAMBOT 1 - 7°30'N section

Figs. 2a and 2b display the CFC-11 and L-ADCP measurements obtained during the ETAMBOT 1 cruise (in September 1995) along 7°30'N, from the coast to 35°W. At the coast, the two maxima of CFC-11, which characterise the North Atlantic Deep Water (NADW), are clearly visible around 1700 m and 3900 m. The upper core (1500 m–1800 m) originates from the Labrador Sea. The vertical extension of that core is limited, presumably because of the weakness of the convection processes in the Labrador Sea



Gordon, page 37, *Figure 1. Annual mean salinity (psu) at the sea surface (from Levitus et al., 1994 (http://ferret.wrc.noaa.gov/fbin/climate.server). The Atlantic Ocean surface water north of 30°S is more saline than that of the Pacific and Indian Oceans. The contrast is most striking in the northern hemisphere, where the Atlantic and Pacific salinity difference in the subtropical region is approximately 2.0 psu and even larger differences occur within the eastern half of the temperate and subpolar regions. This difference is closely linked to the formation of North Atlantic Deep Water and is an integral part of the global-scale thermohaline circulation.*



Murphy et al., page 10, *Figure 4. Zonal distribution of the model's deep WSDW tracer at 45°S.*