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A numerical study of the circulation in the northwestern Weddell Sea

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Abstract

An eddy-permitting simulation is used to study the circulation of the northwestern Weddell Sea and its interaction with the Scotia Sea. The analysis focuses on the circulation pathways, associated stratification, and volume transports. Comparison between model results and observations show reasonable agreements with respect to the modeled thermohaline stratification and circulation such as export of Weddell Sea Deep Water through the Weddell–Scotia Confluence region. Using the model results, we estimated the relative contributions of the two main routes of escape of the Weddell Sea deep waters into the Scotia Sea and the South Sandwich Trench. The main route for inter-basin exchange is found to be through the Scotia Sea (via the South Orkney Passage and the Bransfield Strait). Our simulation does not show advective transport of deep or bottom waters through the South Sandwich Trench, and Lagrangian analysis of float trajectories indicates that the fluxes in this region are more likely related to eddy-driven mixing than to mean flow advection. The model shows, in addition, some sub-basin scale features that have not been reported in the observations. The Weddell western boundary current is seen as a diffuse, filamentous feature. A south-flowing jet was present over the outer shelf off the Antarctic Peninsula. Retroflection and return southward flow is seen for from the South Sandwich Trench, and there was a small inflow of Scotia Sea waters into the Powell Basin.

1. Introduction and background

Although the origins of the Southern Ocean water masses have been the subject of extensive studies, their rates of formation and contributions to global ocean ventilation are still a matter of debate. Ganachaud and Wunsch (2000) suggested that the outflow of deep waters from the Southern Ocean might be comparable in magnitude to formation rates in the North Atlantic i.e. a volume flux ranging between 15 and 20 Sv. The Weddell Sea is thought to be the main contributor to this ventilation outflow. The formation of dense waters in the Weddell basin starts with the entrainment of relatively warm and salty Circumpolar Deep Waters (CDW) into the northern limb of the Weddell gyre. The CDW are carried eastward by the cyclonic gyre, then south to the continental

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margins where the loss of buoyancy associated with ice formation generates down-slope plumes of dense waters. These dense-water plumes feed the deep western boundary current that flows from the Filchner Depression area to the tip of the Antarctic Peninsula (Deacon, 1979; Orsi et al., 1993; Fahrbach et al., 1994). From there the deep waters flow eastward, within the northern limb of the Weddell Gyre, along the northern Weddell and southern Scotia seas. (Locarnini et al., 1993; Gordon, 1988), eventually spreading into the world ocean as Antarctic Bottom Water. The importance of the spreading of these waters to the ocean ventilation was highlighted in Locarnini's (1994) estimate that more than half of the Antarctic water that ventilates the deep ocean originates in the Weddell Sea.

There are numerous modeling studies of the Southern Ocean dynamics; however, only two have been focused on the large-scale circulation of the Weddell Sea. Gordon et al. (1981) used a Sverdrup-type model over a flat bottom to estimate the circulation patterns and volume transports associated with wind-stress forcing over the Weddell–Enderby basin. Their calculation resulted in a cyclonic gyre centered near 55°S with a maximum western boundary transport of approximately 78 Sv. More recently, Beckmann et al. (1999) simulated the regional circulation using a primitive equation model in a realistic basin setting that was coupled to an ice-shelf cavities model. Their experiments revealed that the sub-ice cavities contribute significantly to deep- and bottom-water formation along the continental slope and impact water-mass characteristics throughout the entire basin.

In this study we use a primitive equation numerical model to describe and analyze the Weddell Gyre circulation. The relatively high resolution of the model grid allows us to make direct comparisons between model results and observations (both from historical data and those collected during the DOVETAIL field program; Muench and Hellmer (2002) in a number of important areas of the basin. This model, however, does not include direct ice forcing and is therefore unsuited to study the seasonal variability of the gyre. The focus instead is on the mean circulation patterns and the general interaction between the wind-driven flows and the bottom topography. Comparison between model results and observations show reasonable agreement between mass structures and circulation patterns.

2. Model set-up

The model used in our numerical experiments is the Modular Ocean Model (MOM, version 2). A detailed description of the MOM equations and their numerical implementation can be found in Pacanowski (1995). The model was set-up in a circumpolar grid extending from 75°S to 35°S. The model's resolution is a constant 0.2° in the meridional direction and varies in the zonal direction from 0.2° (from 80°W to 70°E) to 0.8° elsewhere. To avoid the diffusive effects associated with sudden changes of grid resolution the coarse- and high-resolution regions were bridged by a buffer zone of 10° of longitude in which the resolution follows a cosine function. In the vertical, the model included 30 levels of variable thickness. The bottom topography was derived from the data set compiled by Smith and Sandwell (1997). The experiments were initialized with temperature and salinity values derived from the Levitus and Boyer (1994) climatology, and forced at the sea surface with wind stresses obtained by averaging winds derived from the ECMWF climatology from 1979 to 1998. The heat and salt surface fluxes were parameterized using a relaxation to annual mean climatological values using a 30-day time period. The ocean model was not initially coupled to an ice model, and we plan process studies that will allow us to investigate the contribution of ice-thermodynamics to the mean circulation and variability of the Weddell gyre.

The spin-up of the model was accomplished in two phases. First we integrated the model for a 10-year period using a Laplacian formulation for the horizontal mixing. This approach allows the model's density field to adjust to the bottom topography and eliminates most of the large-scale discontinuities caused by the initially unadjusted fields. After the initial integration period we switched our horizontal mixing parameterization to a more scale-selective biharmonic operator,

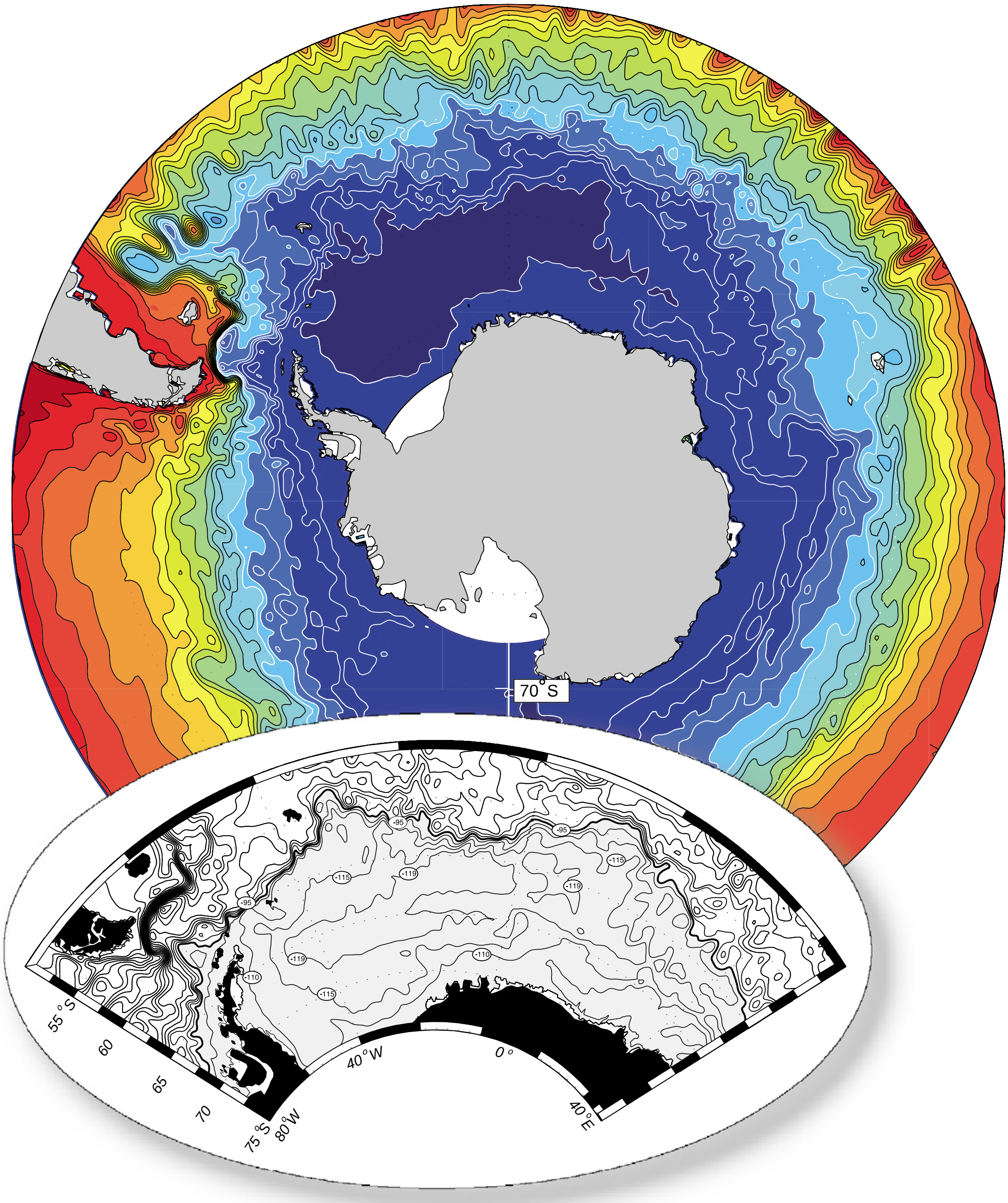


Fig. 1. Snapshot of the sea-surface height (SSH, in cm) at the end of the bi-harmonic simulation. The inset figure shows the SSH distribution within the Weddell basin.

which allows the development of a highly energetic, mesoscale variability (Fig. 1). Within the Weddell basin the circulation is characterized by a cyclonic gyre closed to the west by a weak and filamentous western boundary current. The two best-developed fronts between South America and the Antarctic continent are the sub-polar front, in the northern Drake Passage, and the Weddell/Scotia Confluence to the south.

3. Results

Our discussion of the numerical results will be divided into an overview of the large-scale circulation within the Weddell basin, and a more in-depth discussion of circulation in the north-western region. For the qualitative description of the circulation, we will use snapshots of the model velocities or sea-surface heights (SSHs) instead of long-term averages. Although the model's resolution allows the development of eddy activity, most of it is concentrated along the boundary between the northern limb of the Weddell gyre and the southern branch of the Antarctic Circumpolar Current (ACC) not in the interior of the gyre, the circulation patterns are remarkably steady. A snapshot, therefore, reflects the long-term patterns of the interior circulation and, at the same time, shows those regions that are strongly influenced by eddy variability. For quantitative estimates (e.g., volume fluxes) we will use long-term averages of the model variables.

3.1. The Weddell gyre

The Weddell gyre extends from the Antarctic Peninsula to approximately 40°E (Orsi et al., 1993; Gordon, 1998). To the north it is bounded by the ACC and to the south by the Antarctic continent (Fig. 1). Since the vertical density gradient in the Weddell Sea is relatively small ($N^2 \sim O[10^{-6}\,s^{-2}]$), the model simulated sea-surface height (SSH) fields (Fig. 2) can be used to describe depth-integrated flow, while the particulars of the gyre outflows can be characterized with the velocity fields at 2000 m depth (Fig. 2).

After passing through the Drake Passage, the northernmost branch of the ACC, which carries the bulk of the transport, is diverted to the north by bottom topography (Fig. 3). The southernmost branch of the ACC, which accounts for less than 20% of the total transport, flows along the northward limits of the Weddell Gyre (Fig. 2). The area between the ACC and the Weddell gyre is a frontal zone known as the Weddell–Scotia Confluence (WSC, Gordon, 1967; Patterson and Sievers, 1980; Whitworth et al., 1994). The WSC

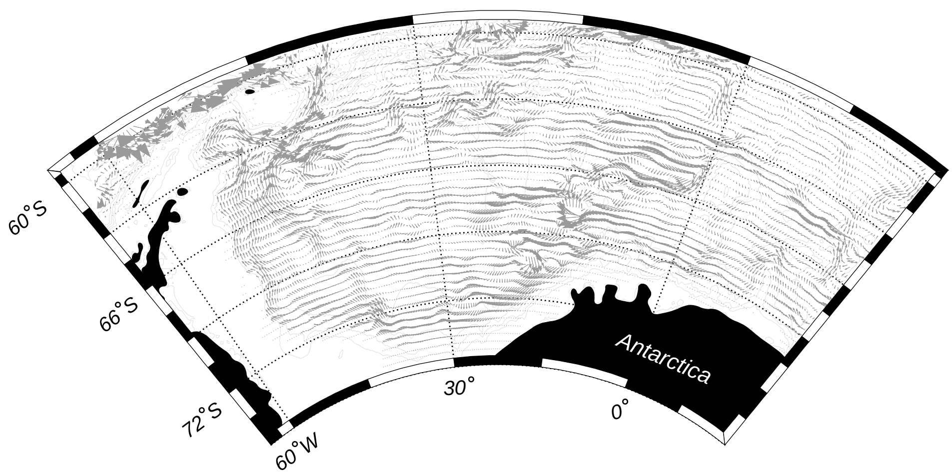


Fig. 2. Snapshot of the model velocities at 2000 m.

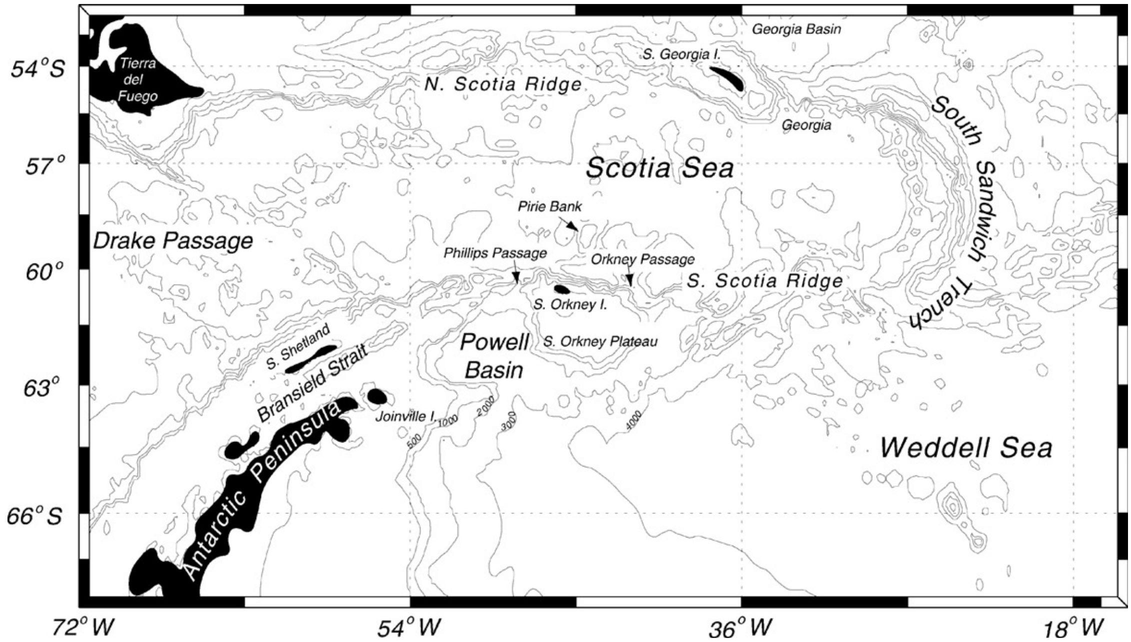


Fig. 3. Bottom topography of the northwestern Weddell Sea and the Scotia Sea.

reaches its northernmost extension at approximately 30°W, where the deep passage of the South Sandwich Trench (Fig. 3) allows a northward penetration of the gyre. East of the Greenwich meridian, the northern limb of the gyre veers south then continues until it reaches the Antarctic continent at which time it turns to the west and joins the Antarctic coastal current.

In contrast to mid-latitude gyres, the Weddell Sea gyre does not display the marked crowding of SSH contours in the region that is associated with a swift boundary current (Fig. 2). Orsi et al. (1993) noted a similar broad horizontal structure in the dynamic topography of this region and attributed it to an eastward shift of the western boundary current system. The velocity fields depicted in Fig. 2, however, indicate that in the numerical experiments there is no zonal shift of a single current, but rather several filaments that appear to be trapped by depth contours. This structure is better defined south of 65°S. North of 65°S the filaments merge into a broad western boundary current, though some multi-axis distinction remains. Near 63°S the western boundary current veers east to feed the northern limb of the Weddell gyre. Thus the northern limb of the Weddell gyre is fed both from the immediate western boundary and from the interior of the basin. Portions of this current divert to the north at South Orkney Passage and at South Sandwich Trench where they exit the Weddell basin.

The central portion of the Weddell gyre is characterized by two SSH minima separated by a weak saddle point (Fig. 2). A similar double cell structure has been identified in observations (Orsi et al., 1993; Bagriantsev et al., 1989). Beckmann et al. (1999) reported a similar structure in their numerical simulation and noted that although it persists throughout the year it is more pronounced during the austral winter. The origins of these minima are not clear. Treshnikov (1964) speculated that the sub-gyres were an oceanic response to stationary cyclones. In our numerical experiments the double-cell structure appears to be related to topographic steering of the northern limb of the gyre. Near the Greenwich meridian, the eastward limb of the Weddell gyre reaches the deep plateau of the Weddell basin and is bathymetrically constrained to turn to the southeast, creating a closed recirculation cell. The fact that the effect of bottom topography is more pronounced in deeper layers explains Orsi's et al. (1993) observation that the double-cell structure is better defined in deep layers.

To describe the mass structure of the simulated Weddell gyre, Fig. 4 shows a section of temperature and salinity near the Greenwich meridian. The Antarctic surface waters are the coldest ($\theta < -1.0$°C), freshest (salinities <34.6), and most ventilated waters of the gyre. Below lies a core of CDW that is characterized by temperatures greater than 0°C and salinities greater than 34.6. CDW is the only one of these water masses that is not formed within the Weddell basin but, rather, it is advected from the north through a discontinuity in the Southwest Indian Ridge (Deacon, 1979). Below the CDW lie the two densest water masses of the Weddell gyre: WSDW (-0.7°$C < \Theta < 0$°C) and WSBW ($\Theta < -0.7$°C). WSBW are mostly formed along the southern and western continental shelves through interaction between locally produced shelf waters and CDW advected from the east. Recently formed WSBW sinks to the deepest layers, whence it slowly upwells to replenish the stock of WSDW that is entrained into upper layers or that exits the basin to the north. The water mass structure depicted in Fig. 4 closely resembles a similar section discussed by Orsi et al. (1993, their Fig. 3a). The largest difference between model results and the Orsi et al. (1993) observations is that the coldest WSBW in the model is slightly warmer ($\sim$0.05°C) than the observed.

Since the model's temperatures and salinities compare well with observations, we can use the model predicted velocities, which are in quasi-geostrophic balance with this mass structure, to calculate volume transports and extend our comparisons with observations. Before doing that, however, it should be noted that it is not possible to make a strict comparison between model results and observations because of the different time scales that they represent. In fact, while most observational estimates are derived

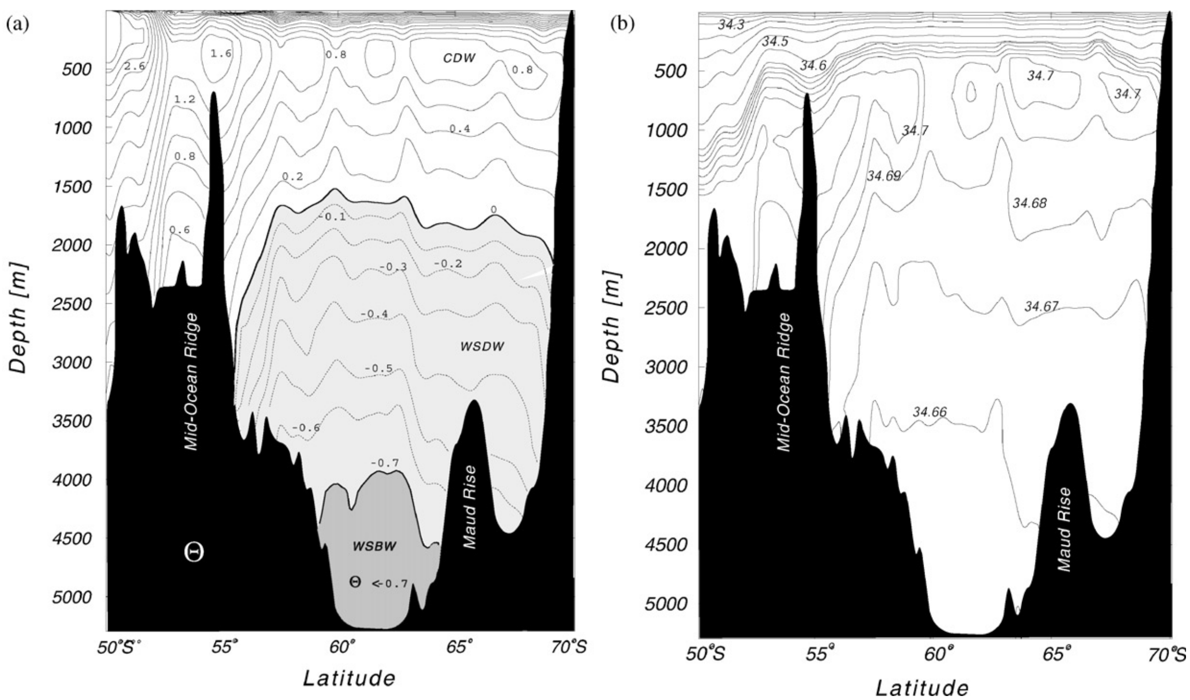


Fig. 4. Meridional sections of: (a) potential temperature (°C); (b) salinity (ppt), at the Greenwich meridian. The water masses depicted are Circumpolar Deep Water (CDW), Weddell Sea Deep Water (WSDW), and Weddell Sea Bottom Water (WSBW).

from short-time records (the several days required to occupy an ocean transect from a surface vessel) the model estimates represent only the long-term, mean values. Modeled transport estimates are presented with these caveats in mind (Fig. 5).

To the north, the ACC has a mean transport of 165 Sv, roughly half of which (80 Sv) is funneled to the north while the remainder splits into narrow jets flowing eastward. The southernmost of these jets, which downstream will form the northern limit of the WSC, has a mean transport of 28 Sv. The ACC transport calculated here is higher than the average value estimated by Nowlin and Klinck (1986) of 132 ± 14 Sv, but is closer to the most recent estimates of Stevens et al. (1999) of 161 Sv. Agreements notwithstanding, it shall be noted that the absolute value of the ACC transport is not well determined and is subject to uncertainties of tens of Sverdrups.

At the continental margin of the Antarctic Peninsula the model yielded a western boundary transport of 18 Sv. Western boundary transports derived from data obtained near the northern end of the Antarctic Peninsula during the 1992 winter drifting ice station experiment were about 28 Sv (Muench and Gordon, 1995). Of this, 5–6 Sv were associated with a bottom-trapped flow of WSBW. These measurements reflected winter conditions. Similar transports were derived by Fahrbach et al. (1994) based on time series of current-meter observations. The western boundary values estimated by the model and derived from observations are substantially smaller than the 78 Sv derived by Gordon et al. (1981) from the Sverdrup relation. These differences reflect the effect of the bottom topography on the Weddell Sea circulation, since the Sverdrup estimate is strictly valid only for a flat-bottomed basin, or an ocean with a strong thermocline that isolates upper from deeper layers. Neither of these conditions is valid in the Weddell gyre, where the westward propagation of the wind's energy input is trapped along topographic

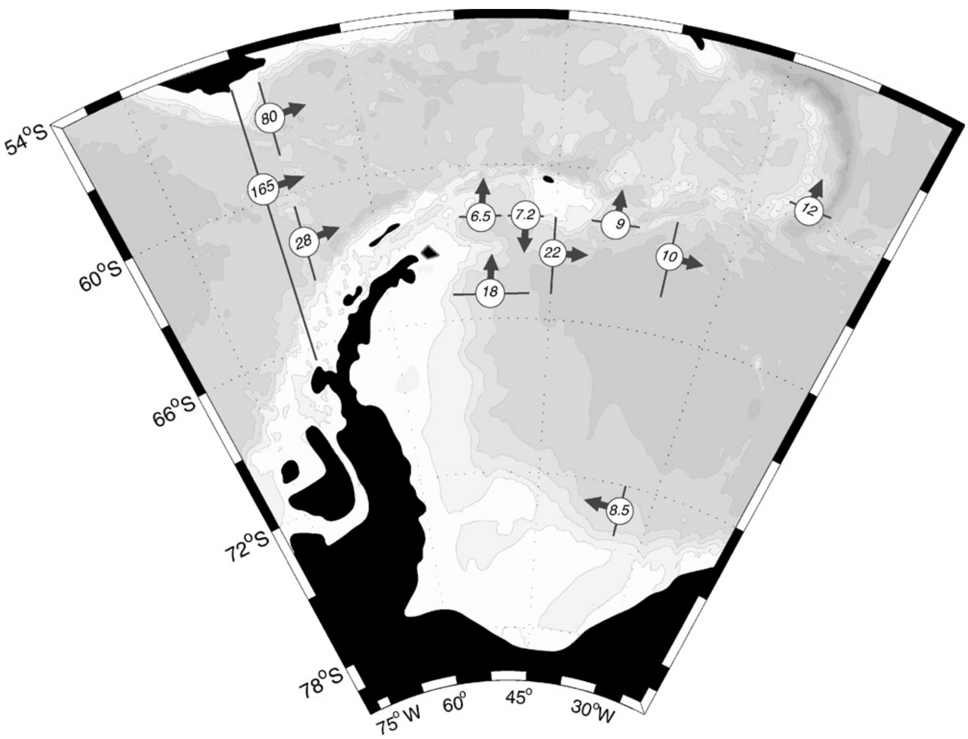


Fig. 5. Depth integrated volume fluxes across different sections of the Southern Ocean. The fluxes values are quoted in Sverdrups ($1\,Sv = 10^6\,m^3\,s^{-1}$).

discontinuities, creating the diffuse, topographic jet-like structure discussed previously. Although approximately half of the transport of the western boundary current is supplied from the south (~8.5 Sv), filaments from the interior of the basin contribute the other half. To the east, and south of the South Orkney Plateau, the northern limb of the Weddell gyre has a mean modeled transport of 22 Sv. These 22 Sv contain 18 Sv coming from the western boundary, 3 Sv from the interior of the basin, and approximately 1 Sv from the shelf region through the Powell Basin. From a CTD/LADCP data set obtained during the DOVETAIL experiment Gordon et al. (2001) estimated an eastward transport south of the South Orkney Plateau, of 40 Sv. Gordon et al. (2001) observed that half of this transport is re-circulated water that exits the Powell Basin.

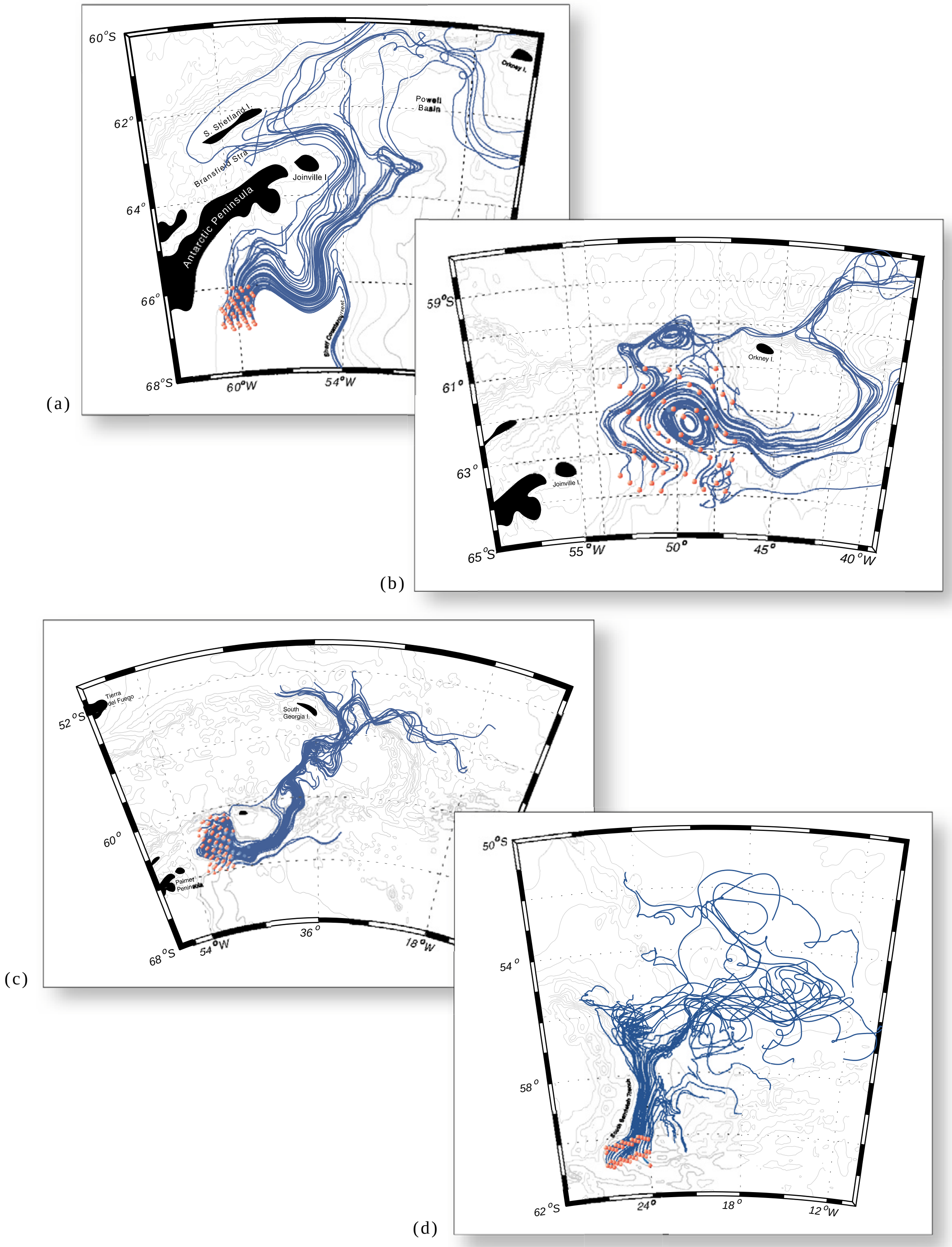
East of the South Orkney Plateau, 9 Sv escape the basin to the north and enters the Scotia Sea. Farther downstream, the eastward transport of the northern limb decreases to 10 Sv. East of the South Scotia Ridge the eastward transport is augmented by 2 Sv of recirculated water, which generates a net northward outflow of 12 Sv. Although the South Scotia Trench has been thought of as the main gateway for deep-water flow, our simulation indicates that none of these 12 Sv flows directly out of the basin. In fact, farther north the total transport is *southward*, as the ACC forces a return of this deep flow. In the following sections we will discuss these matters in more detail.

3.2. The northwestern region

The wide continental shelf region surrounding the eastern flank of the Antarctic Peninsula, and the model's relatively high resolution, allow depiction of circulation patterns over the continental shelf, a region often beyond the resolving capability of large-scale models. Shelf waters contribute to the T–S characteristics of the deep circulation; therefore, it is of interest to determine their circulation patterns and the sites for offshore flow. To investigate these matters we seeded the southwestern region of the model with 500 floats, which were uniformly distributed between 50 and 200 m, and followed their trajectories during a 3-year period (Fig. 6a shows the floats trajectories as well as the position of their launching). The floats are advected with the three components of the velocity field and therefore can move vertically within the water column while following the horizontal flow. The density stratification in the shelf region, however, is nearly homogenous, and the floats tend to move along isobars following the bottom topography. The general circulation pattern consists of a broad northward flow, which, after reaching the tip of the Antarctic Peninsula, turns west to Bransfield Strait. Narrowing of the continental shelf north of 66°S forces some of the floats offshore where they are entrained into the western boundary current. Those floats are then advected to the north, into the Powell Basin, and eventually exported into the Scotia Sea through the South Orkney Passage (~38°W). There is approximately 1 Sv of shelf water outflow into the deeper ocean. Although this value is small compared to the total transport of the western boundary current, it is nonetheless important because of its role in ventilating the waters of the basin's interior (Gordon et al., 2001). The remaining floats continue north and, after rounding Joinville Island, flow west into Bransfield Strait. The floats that reach Bransfield Strait recirculate back to the east to pass over the northern rim of the Powell Basin, with some of them escaping into the southern branch of the ACC.

Observations over the shelf region are adequate for only a regional comparison between model and observations. The trajectories of the floats around Joinville Island and into Bransfield Strait appear to be in agreement with the circulation patterns derived by Gordon et al. (2000) and the velocity measurements described by von Gyldenfeldt et al. (2002). We have found no observational evidence

Fig. 6. Trajectories of Lagrangian floats launched in different regions of the Weddell Sea. The location where the floats were launched is marked by the red dots. These floats were tracked during a time span of 6 years. The underlying contours correspond to the bottom topography of the basin. (a) Continental shelf of the northwestern Weddell Sea, (b) Powell Basin close-up; (c) Powell Basin long-term integration; (d) South Sandwich Trench.


60°S
62°
64°
66°
68°S
60°W
54°W
Orkney I.
Powell Basin
S. Shetland I.
Bransfield Stra
Joinville I.
Antarctic Peninsula
(a)
59°S
61°
63°
65°S
55°W
50°
45°
40°W
Orkney I.
Joinville I.
(b)
52°S
60°
68°S
54°W
36°
18°W
Tierra del Fuego
South Georgia I.
Palmer Peninsula
(c)
50°S
54°
58°
62°S
24°
18°
12°W
(d)

for the existence of the shelf countercurrent simulated near the slope region (Fig. 6a). This countercurrent is generated by direct wind forcing over closed f/H contours (Fig. 7). The model results are robust in the sense that they were reproduced using the original ETOPO5 data set and its improved version by Smith and Sandwell (1997). We note, though, that the topography of this region is quite poorly documented. Existence of the shelf countercurrent cannot be discounted on account of lack of observational evidence since, according to the model results, it is a narrow feature and therefore may not have been sampled by the limited regional observations.

Seaward of the coastal region, circulation is dominated by the northward-flowing western boundary current (Fig. 2). Near 64°S this boundary current splits into two branches; one located over the slope region and the other bordering the deep basin near the eastern limit of the slope. The westernmost branch enters Powell Basin and flows cyclonically before exiting it near the southwestern corner of the South Orkney Plateau. The offshore branch hugs the outer limit of the continental slope and flows eastward into the basin's interior.

In order to investigate transport into and circulation within Powell Basin, we seeded the model with floats that were uniformly distributed between 500 and 3000 m depth, and tracked their displacements during a 5-year interval (Fig 7b). The trajectories within Powell Basin indicate a high degree of renewal of the waters near the edges, and a longer residence time toward the center of the basin. The circulation pattern revealed by the trajectories and the velocity vectors (not shown) are in general agreement with the observations except near the Phillip Passage. There, the model results show a relatively small (less than 1 Sv, Fig. 7) entrainment of Scotia Sea waters into Powell Basin. We have found no observational confirmation of this inflow. In fact, existing observations suggest that the dominant circulation in this is an outflow (Nowlin and Zenk, 1988; von Gyldenfeldt et al., 2002). Direct velocity measurements in this region are scarce, and even the LADCP velocity data collected during DOVETAIL and reported by Gordon et al. (2001) are ambiguous in the sense that near the northeastern passage it shows velocity vectors pointing both to the north and to the south. Observations (Naveira Garabato et al., 2002) and the model results of Schodlok et al. (2002) show an outflow with a weak recirculation, although not as well defined as in the other passages.

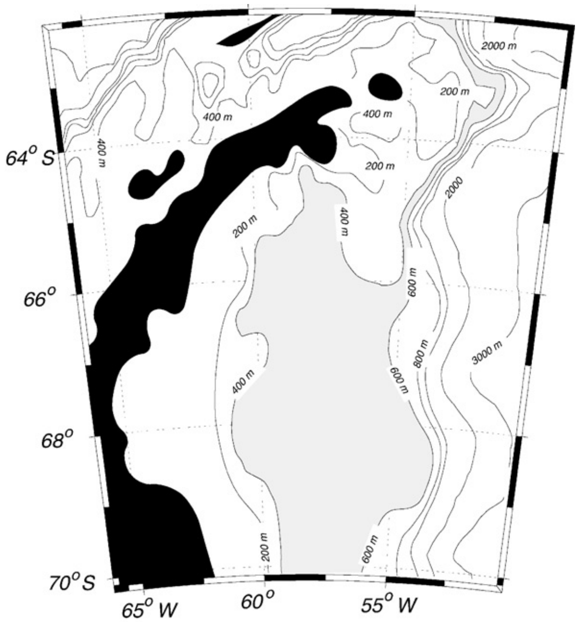


Fig. 7. Bottom topography of the western Weddell Sea continental shelf. Depths are given in m. Shaded contours mark region of quasi-uniform planetary vorticity.

Most of the floats that escape Powell Basin round the South Orkney Plateau to its south and leave the Weddell Sea at the Orkney Passage flowing westward along the northern margin of the South Orkney Plateau. The South Orkney's outflow, however, does not reach the Drake Passage as indicated by the observations (e.g., Naveira Garabato et al., 2002), but is entrained into the ACC and advected northeast into the Georgia Basin (Fig. 6c). Since the general circulation in this region is strongly influenced by the eastward flow of the ACC, it seems reasonable to surmise that any *westward* flow is likely to be a relatively narrow boundary current that is not resolved by the model's grid step. In these regards it should be noted that, although Naveira Garabato et al. (2002) made no estimate of the transport associated with the westward flow, they implicitly noted that it may be relatively small.

According to observations, the deep and bottom waters of the northwestern Weddell Sea flow eastward within the northern limb of the Weddell Gyre. However, a branch of WSDW is diverted into the Scotia Sea through a 3200 m deep passage cutting through the South Scotia Ridge near 38°W, east of the South Orkney Plateau (Gordon et al., 2001). The overflow from the South Orkney Passage is the source of the coldest bottom water observed within the Scotia Sea. From the South Orkney passage, the Weddell overflow spreads westward along the southern boundary of the Scotia Sea, retroflecting back into the Scotia Sea in the southern Drake Passage (Gordon, 1966; Nowlin and Zenk, 1988; Locarnini et al., 1993; Gordon et al., 2001; Naveira Garabato et al., 2002). There is no sign of WSDW overflow into the Scotia Sea west of South Orkney Plateau, though an isolated deep basin within the South Scotia Ridge (the Hesperides Trough) is filled with WSDW derived from an 1800-m deep connection to the Weddell Sea (Gordon et al., 2001). At depths above the Weddell Sea deep water there is observational evidence for the transfer of Pacific water into the Weddell Sea along a pathway west of the South Orkney Plateau, as suggested by the model results (Fig. 6a). The salinity within the pycnocline (50–250 m) of the Weddell Sea is more saline than that of the Pacific pycnocline water within the Scotia Sea south of the Polar Front. The Bransfield Strait pycnocline, representing a mixture of Weddell and Pacific water, is intermediate in salinity (Fig. 8; Gordon et al., 2000). The Bransfield Strait intermediate salinity pycnocline is observed to spread along the South Scotia Ridge, turning southward to follow the southern rim of the South Orkney Plateau. Over the South Orkney Plateau, the very low salinity pycnocline water may be drawn directly from the Pacific pycnocline which shifted southward with the Bransfield Strait water.

A meridional section of potential temperature, from the model, at 44°W illustrates the characteristics of the outflow through Orkney Passage (Fig. 9). This section crosses the South Orkney Plateau which separates the Scotia Sea to the north from the Weddell Sea to the south, and it can be directly compared with the recent DOVETAIL section published by Gordon et al. (2001). The upper layers of the Weddell sector are marked by a temperature maximum of 0.6°C that corresponds to Weddell Deep Waters (WDW), a remnant of the CDW that enters the Weddell Gyre at the eastern margin (Orsi et al., 1993) and is advected west by the southern limb of the gyre. Farther north, the upper layers of the Scotia Sea show a temperature maximum that is associated with the eastward advection of CDW from the Pacific Ocean. Below the upper layers, there is gradual decrease of temperature with increasing depth in both basins. Below 1500 m the Weddell sector is dominated by deep and bottom waters. To the north of the South Orkney Plateau the only deep waters are located in the South Orkney Trough, a deep channel separating the South Orkney Plateau from the Pirie Bank. The deep waters in the South Orkney Trough are advected from the Weddell Sea through the Orkney Passage.

The vertical distribution of temperature (Fig. 9) bears a reasonable resemblance to the CTD "snapshot" captured during the winter 1997 DOVETAIL cruise (Gordon et al., 2001). In the Scotia Sea, temperature gradients in the modeled upper ocean are similar to those in the observations, although below 1000 m the modeled temperatures are approximately 0.5°C warmer than the observations. In the Weddell sector the most notable difference between the model and the observations is the absence of the two relatively small cores of ventilated WSDW and WSBW that were observed during the 1997 DOVETAIL cruise. Gordon et al. (2001) speculated that these cores form from low-salinity, high-oxygen shelf water and descend to levels where they interleave isopycnally and mix with the resident WSDW and WSBW. These relatively small-scale cores of ventilated waters are not in the original Levitus data set and, since the model has no seasonal forcing, it is unable to reproduce them.

3.3. The Weddell–Scotia confluence

The WSC is the frontal region that separates the ACC to the north from the Weddell Gyre to the south, and it is locked in position by the South

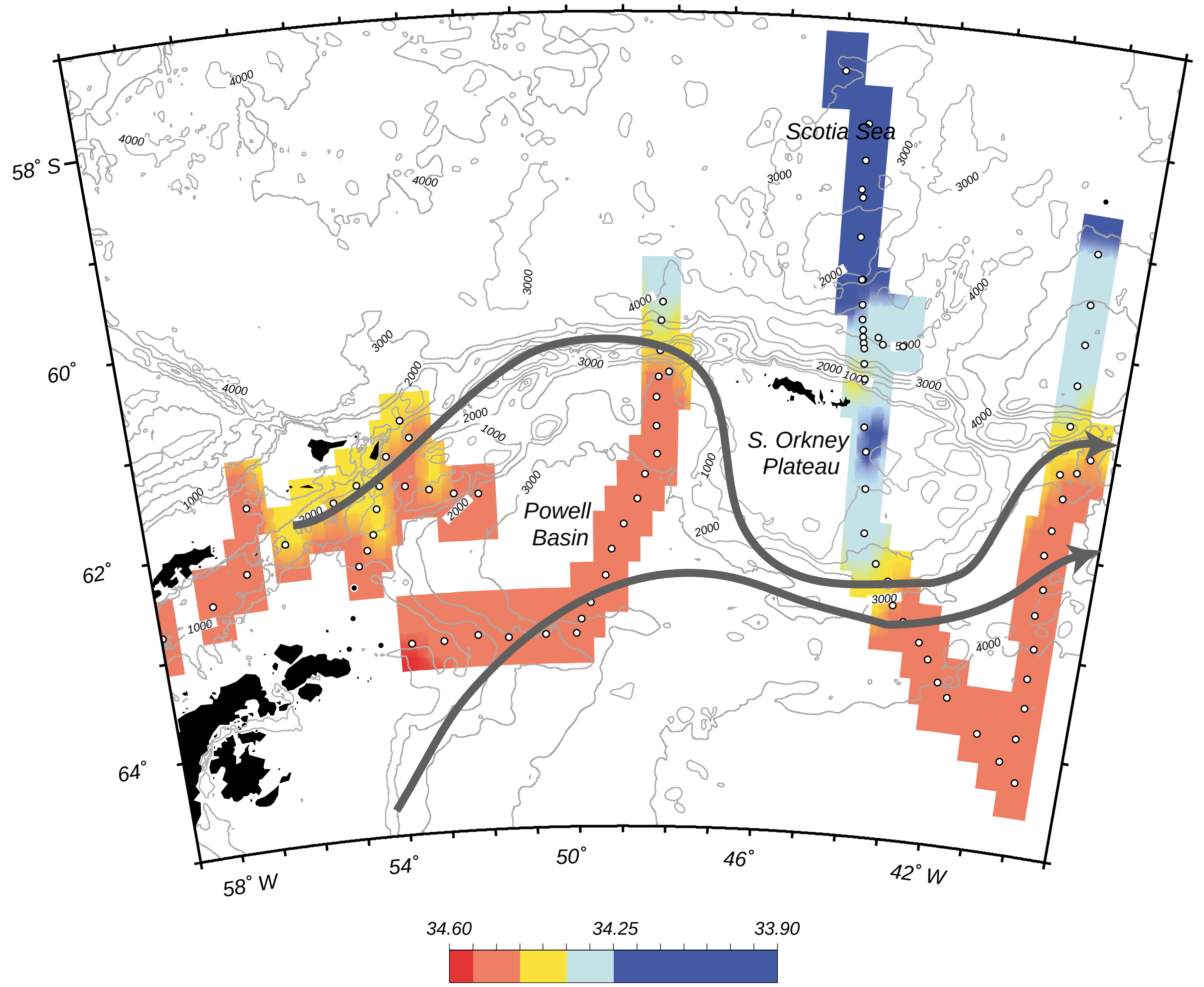


Fig. 8. Mean salinity within the temperature interval –0.9°C to –1.1°C during August 1997 (data collected during the U.S DOVETAIL field experiment).

Scotia Ridge (Fig. 10). The meridional exchanges across the WSC are so restricted by the bottom topography that earlier descriptions of the regional circulation surmised that the preferred route of escape of WSDW was located to the east of the South Sandwich Arc. There, a deep canyon connects the abyssal plains of the Weddell Sea with the Georgia Basin (Wust, 1933). More recently Locarnini et al. (1993) concluded, based upon a reanalysis of historical hydrographic data, that most of the South Sandwich Trench outflow is re-circulated to the south and that the bulk of the inter-basin exchange occurs farther west, in the narrow passages connecting the Weddell with the Scotia seas.

In our simulation there is a well-defined, northward flow of Weddell Sea waters along the South Sandwich Trench. The same results, however, indicate that none of these waters continues into the Georgia Basin. In fact, transport calculations near the tip of the trench show *southward* volume flux in this region. These results agree with the earlier conclusions of Locarnini et al. (1993) who observed that the northward transit of Weddell Sea waters in this region is inhibited by the ACC. To further investigate these matters we seeded the

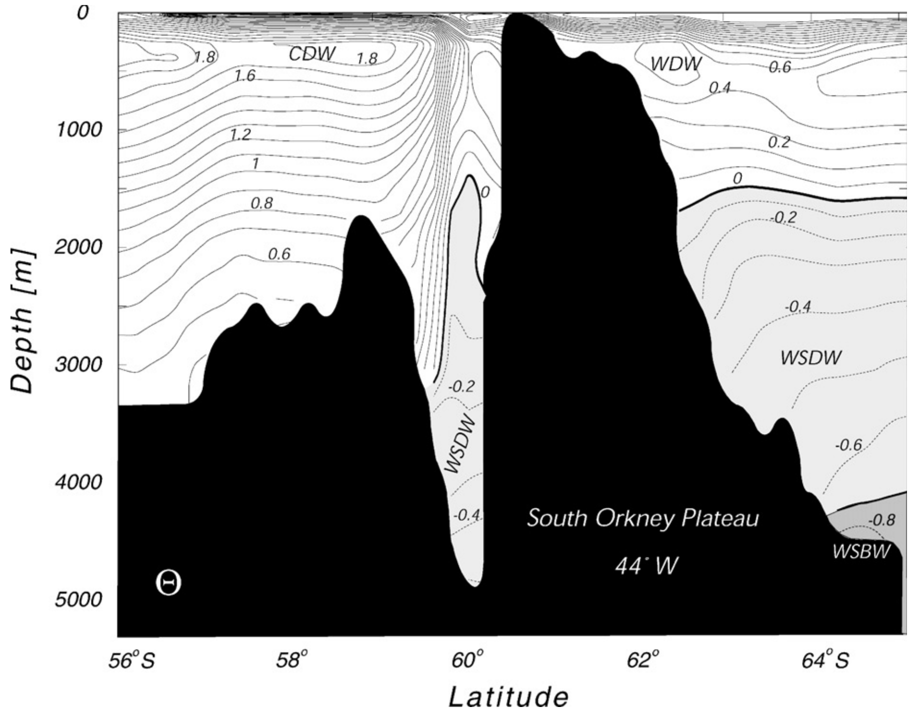


Fig. 9. Meridional section of potential temperature at 44°W. The shadow regions mark the limits of Weddell Sea Deep Water (WSDW), and Weddell Sea Bottom Water (WSBW).

model with Lagrangian floats, uniformly distributed between 3000 and 5000 m depth, and initially located near the base of the trench (Fig. 6d). In spite of the large flow variability in this region the float trajectories can be easily reconciled with the velocity patterns depicted in Fig. 10. At the western flank of the trench, the closely packed trajectories of the floats reflect the well-defined structure of the boundary current. Farther north, however, the float trajectories start to spread to the east as they become advected by the ACC. Although the large variability of the circulation in this region obscures the magnitude of the meridional mass exchanges, the float trajectories show the linkages between the Weddell Sea and the Georgia Basin. The convoluted shapes of these trajectories, however, indicate that northward displacement of the floats is not associated with a steady, well-defined current but rather with the more turbulent motion generated by eddies or meanders of the mean circulation. In summary, although our simulation shows no direct, advective outflow of Weddell Sea water east of the Orkney Passage, it suggests an eddy-driven exchange of mass and other properties between the Weddell and the Georgia basins.

It is not possible to quantitatively estimate the magnitude of these eddy-fluxes from this simulation, because the steady forcing applied to our model will tend to underestimate the magnitude of the eddy variability. We plan future experiments to investigate the magnitude of these inter-basin exchanges and their sensitivity to the applied atmospheric forcing and model resolution. The model is in agreement with observations (Gordon et al., 2001) by showing that most of the Weddell water exported into the Scotia Sea through the South Orkney Passage is well-ventilated and has passed through Powell Basin. The water that flows north through the South Sandwich Trench, however, is mostly drawn from the offshore western boundary current, lacking ventilation at the northern end of Antarctic Peninsula.

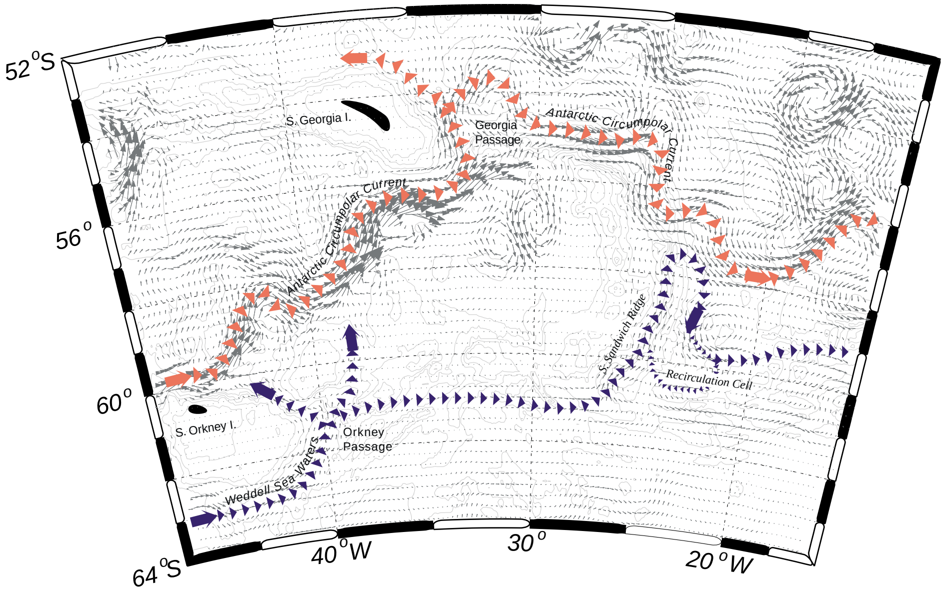


Fig. 10. Model velocities at 2000 m depth in the northwestern Weddell and Scotia seas. The underlying contours correspond to the bottom topography and the overlying arrows mark the path of the main currents.

The present analysis has focused on those aspects of the model simulation that we deem robust, i.e. results that do not change significantly with small variations of the model parameters. There are, however, certain aspects of the Weddell Sea circulation that, although obviously related to the topics of our interest, have not been included in the discussion because of the limitations of the model configuration. These limitations include a lack of coupling to a sea-ice model, and a poor representation of bottom boundary layer processes that is typical of most z-level models (Griffies et al., 2000). For a discussion of these aspects of the Weddell Sea circulation the reader is referred to the articles of Beckmann et al. (1999) and Schodlok et al. (2002). The focus of our study, instead, has been the dynamical processes involved in the mass exchanges between the Weddell Sea and the ACC, and it is in these regards that the model results are considered robust. In fact, our main conclusion, that the bulk of the Weddell Sea outflow is confined to the deep passages that lead to the Scotia Sea, is unlikely to be changed by refinements of the experimental setting such as inclusion of sea-ice effects or bottom boundary layer processes. Such refinements might lead to quantitative differences in the estimated outflows, but are unlikely to change in their relative importance with respect to the overall balance. Z-level models like MOM may suffer from a poor representation of bottom topography yet it can be argued that, at $1/5^\circ$ resolution, the model provides a reasonable resolution of the most important passages between the Weddell and the Scotia seas.

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