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The Conrad Rise as an obstruction to the Antarctic Circumpolar Current

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[1] The Antarctic Circumpolar Current (ACC) carries water freely around the whole continent of Antarctica, but not without obstructions. Some, such as the Drake Passage, constrict its path, while others, such as mid-ocean ridges, may induce meandering in the current's cores and may cause the genesis of mesoscale turbulence. It has recently been demonstrated that some regions that are only relatively shallow may also have a major effect on the flow patterns of the ACC. This is here shown to be particularly true for the Conrad Rise. Using the trajectories of surface drifters, altimetry and the simulated velocities from a numerical model, we show that the ACC bifurcates at the western side of this Rise. In this process it forms two intense jets at the two meridional extremities of the Rise with a relatively stagnant water body over the Rise itself. Preliminary results from a recent cruise provide compelling support for this portrayal.

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1. Introduction

[2] Flow in the Antarctic Circumpolar Current is concentrated at the nearly zonal fronts that form a prominent part of the hydrography of the Southern Ocean [*Whitworth and Nowlin*, 1987]. Using a statistical analysis of hydrographic data [*Lutjeharms and Baker*, 1980], the movements of surface drifters [*Daniault and Menard*, 1985] as well as altimetric observations [e.g., *Cheney et al.*, 1983; *Nerem et al.*, 1994; *Gille et al.*, 2000], it has been demonstrated that mesoscale turbulence in the Southern Ocean is largely concentrated at these fronts. The most prominent of these is the Subtropical Convergence in the South-West Indian Ocean sector of the Southern Ocean [e.g., *Chelton et al.*, 1990]. From these observations as well as other studies [*Marshall*, 1995; *Gille*, 2003], it is also clear that a secondary set of regions of high mesoscale turbulence in the Southern Ocean consists of locations where the ACC crosses prominent features in the bottom topography. A particularly well-developed one is at the South-West Indian Ridge.

[3] At this ridge a substantial part of the ACC is funneled through the Andrew Bain Fracture Zone [*Craneguy and Park*, 1999; *Pollard and Read*, 2001] in consequence of which about 3 eddies per annum are formed [*Ansorge and Lutjeharms*, 2003, 2005]. These eddies, both cyclonic and anti-cyclonic, drift roughly parallel to the eastern side of the Ridge and pass the Prince Edward Islands before they dissipate about 7–11 months later. Apart from their impact on the meridional heat transport [*Ansorge et al.*, 2006], the eddies produced by this disruption to the flow of the ACC also have a noticeable impact on the biogeography of the region around the Prince Edward Islands [*Bernard et al.*, 2007; *Ansorge et al.*, 2008] and on the behavior of local top predators [e.g., *Nel et al.*, 2001]. Other bathymetric features have a different influence on the structure of the ACC.

[4] A recent investigation of the Crozet Plateau and its direct environment [*Pollard et al.*, 2007a] has demonstrated that its topography has a major effect on the disposition of the ACC and that this also has a biological influence [*Pollard et al.*, 2007b]. Subsurface floats do not cross the Plateau, but are steered both north and south of this feature that is less than 2000 m deep. Perhaps unexpectedly, surface drifters behave in a very analogous way, with very few crossing the Plateau [*Pollard et al.*, 2007b]. The Conrad Rise is a similar, relatively shallow feature lying between latitudes 52 and 54°S (Figure 1). The greater area of the Rise is shallower than 3500 m, therefore considerably deeper than the Crozet Plateau. The Conrad Rise has not been extensively investigated to date, most of the cruises to the region having been Russian fisheries surveys which focused on the Ob and Lena seamounts [e.g., *Pakhomov*, 1993; *Pakhomov and Semelkina*, 1995]. As part of the SWINDEX survey [*Pollard and Read*, 2001], two near-meridional sections were undertaken on the equatorward side of the Rise. Our investigation describes the flow patterns at the topographic feature using remote sensing products, telemetered observations and modeling. Recently, we undertook the first large scale hydrographic survey of the Conrad Rise region and we present some preliminary results.

2. Data and Methods

[5] Drifter data for the area between 48 to 58°S and between 33 to 52°E came from the WOCE-GDP assemblage of the Data Assemblage Center of the Atlantic Oceanographic and Meteorology Laboratory of NOAA where they undergo careful quality control. The data are interpolated into 6-hour intervals. The average, absolute geostrophic velocity (see Figure 2) was calculated for the years 2000 – 2004 based on the delayed-time altimetry merged from TOPEX/Poseidon and ERS, or Jason-1 and Envisat. Details on the websites for these data can be found in the acknowledgments.

[6] Model data were obtained from ORCA025, an eddy-permitting (i.e., with a nominal resolution of $^1/_4$° resolving mesoscale eddies at low and mid-latitudes) global ocean-sea

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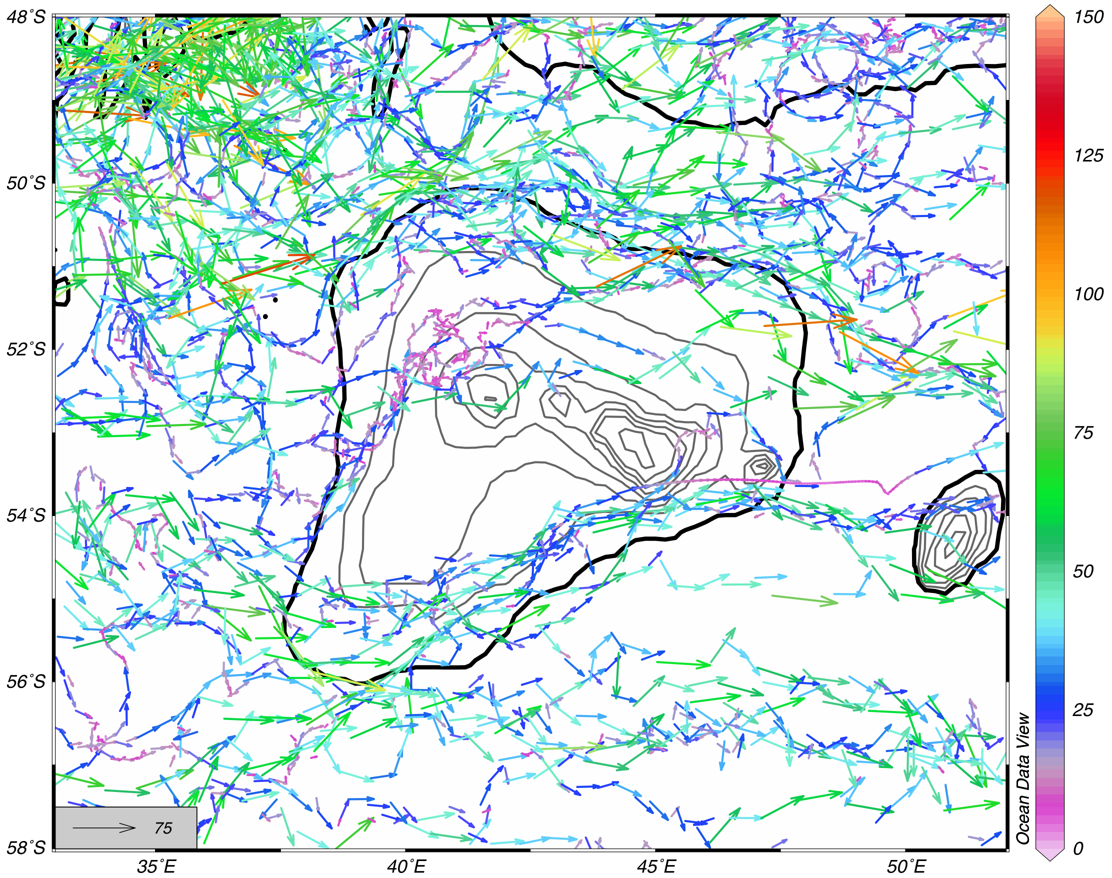

Figure 1. Velocity vectors (in cm s^{-1}) derived from the motion of surface drifters in the vicinity of the Conrad Rise. Arrows are daily positions (6-hour average). Color coding as well as arrow size represent the speeds of the drifters The scale for speed is given in the left, bottom corner of the diagram in cm s^{-1}. Bathymetry less than 4000 m is given in 500 m intervals with the 4000 m isobath contoured with a thick black line. Two intensified current jets are evident; one to the north and one to the south of the Rise.

ice model commonly used by *The DRAKKAR Group* [2007] and based on the NEMO code [*Madec*, 2006]. The bathymetry is derived from a 2-minute resolution (ETOPO2) bathymetry dataset of the National Geophysical Data Center. With partially filled bottom cells, 46 vertical levels ranging from 6 m near the surface to 250 m at the bottom, and advanced advection schemes, the model has been demonstrated to successfully simulate crucial elements of the large-scale circulation [*Barnier et al.*, 2005]. The model is forced by a consistent dataset [*Large and Yeager*, 2004] of daily inter-annually varying wind and thermohaline forcing fields over the period 1958–2004.

[7] The first hydrographic survey of the Conrad Rise was carried out in April 2008 where three meridional transects along 38, 44 and 48°E, comprising of 41 CTD casts extending to 2000 m, were undertaken with latitudinal resolution of 0.5°. Furthermore, a fourth line crossing the rise was done with the aim to study the physical environment of the Ob and Lena seamounts. At each CTD station, Seabird SBE 9/11 sensors measured temperature, salinity, oxygen and pressure.

3. Results and Discussion

[8] The motion of surface drifters for the years 1987 – 2005 for the general region of the Conrad Rise in the Southern Ocean is given in Figure 1. Each arrow represents a daily position (6-hour average). Speeds vary from about 5 to 100 cm s^{-1}. Particularly noticeable is the pattern of avoidance of the Conrad Rise. Whereas most drifters exhibit a direction between north-east and south-east over the whole region, very few cross those parts of the Conrad Rise shallower than 3500 m. A concentrated path is evident poleward of the Rise, over the region between 3500 to 4000 m deep. In this particular dataset a slightly less conspicuous path is found at the same depth interval equatorward of the Rise. A more concentrated flow path seems to lie roughly at the 4000 isobath. However it is clear that eastward moving drifters between 52 and 55°S are forced to move in an equatorward direction when they approach the Conrad Rise at about 39°E. Moreover, subsurface floats - parked at depth of about 1000 – 2000 m (not given here) - have been shown also to exhibit this particular flow pattern. A number of tracks of floats approaching the Rise from the west between the latitudes 51 and 55°S show distinct meridional movements in order not to pass directly over the Rise.

[9] A dataset with considerably better statistical significance would be one derived from regular satellite remote sensing such as altimetry. This is shown in Figure 2. The absolute geostrophic velocities for a 5-year period indicate that there is a major difference in the calculated speeds on the Conrad Rise and those at its northern and southern

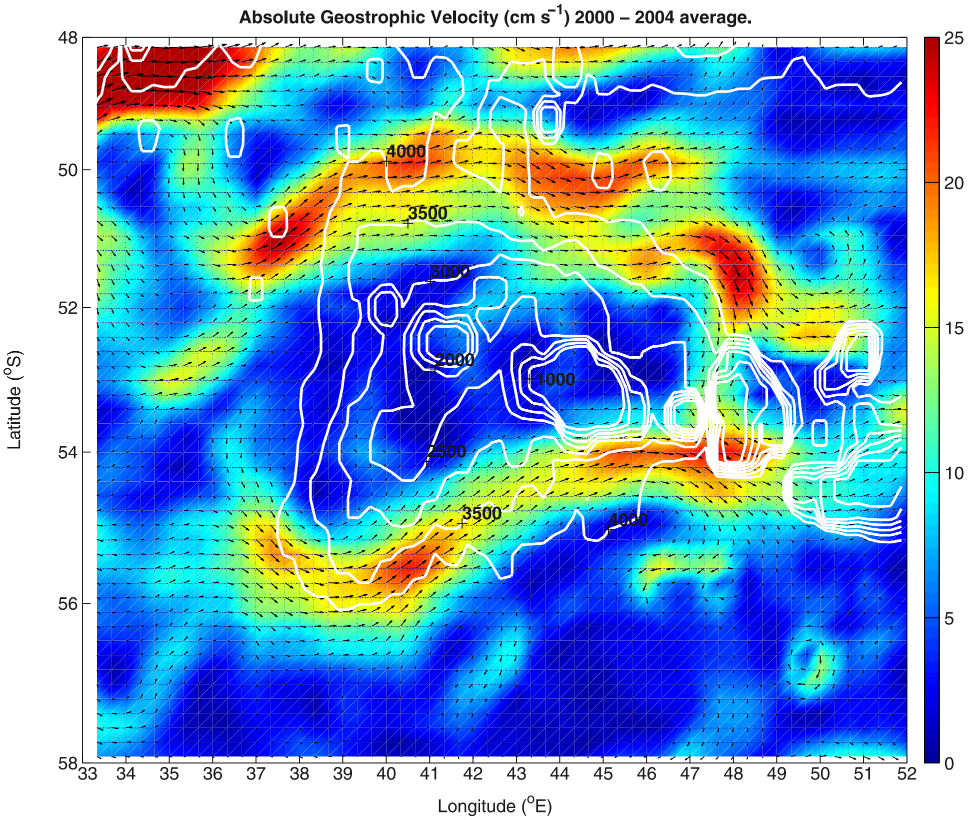

Figure 2. The absolute geostrophic speed (in cm s^{-1}, color bar) and directions derived from altimetry and averaged over a period of 5 years (from 2000 to 2004) at the Conrad Rise. Bathymetry shallower than 4000 m is shown by isobaths in white, at 500 m intervals.

edges. Whereas speeds of 0 – 5 cm s^{-1} are prevalent over the Rise itself the average speeds on either side of it can be up to 25 cm s^{-1}. Average approaching speeds do not exceed 17 cm s^{-1}. It is noticeable that shallower features of more limited lateral extent, that are found on the eastern side of the Conrad Rise, do not seem to form strong obstruction to the average flow. This is not in conflict with the drifter pathways of Figure 1. The average of the absolute geostrophic velocity seems to indicate that the flow adjacent to the Conrad Rise consists of intensified zonal jets. It would be profitable to see if this specific current configuration will also be reproduced by a numerical model. This is given in Figure 3.

[10] The plan view of the velocities, integrated over the top 500 m, is shown in Figure 3a. As in the average geostrophic velocities, shown in Figure 2, the simulated movement on the Rise is weak to stagnant, hardly anywhere exceeding 4 cm s^{-1}. The jet currents evident in those data are also seen in the simulated currents, with the cores of the jets lying roughly over the regions where the depth is 3000 to 3500 m. There is an indication that the core of the northern jet lies over slightly shallower water (viz. Figure 3b). It is clear from the depiction of the currents directly west of the Rise that they follow the isobaths north- and southwards, speeding up in the process of avoiding the shallower sections of the Rise. Note that these are currents shallower than 500 m avoiding an obstacle shallower than 2500 m. The vertical structure of the simulated jets is shown in Figure 3b. The core speeds of the currents at the surface are 18 cm s^{-1} decreasing to between 2 and 6 cm s^{-1} at a depth of 3500 m. Hereby, the southern core has higher surface speeds (cf. Figure 3a), but especially represents a more barotropic nature of the flow compared to the northern core. The model also portrays the southern branch to be more variable over the full depth, while the northern branch appears to be more stable. The core widths are slightly in excess of about 1° latitude. The full-depth volume transport associated with the southern (between 53 and 55.5°S) and northern (between 50.5 and 53°S) portions of the flow around the Rise are approximately 35 Sv and 22 Sv respectively. *Pollard and Read* [2001] reported an average transport of 35 Sv along the equatorward flank of the Rise. Offshore to both cores one can identify weak re-circulations to the west.

[11] To verify the above results, a dedicated and comprehensive cruise was designed to survey the large-scale circulation at the Conrad Rise in April 2008. Figure 4a shows the integrated, zonal geostrophic speeds averaged over the top 519 m along three sections occupied during the cruise. A substantially enhanced flow was indeed observed on either side of the Rise. On the equatorward side, the jet was ~1.5° of latitude wide, while the southern jet was narrower and weaker (as also seen in drift tracks and averaged altimetry). Speeds were remarkably similar to those modeled and derived from remote sensing and in some cases exceeded 20 cm s^{-1}. While the current directions were predominantly eastward, some westward circulation was observed over the Rise. The northern jet had a

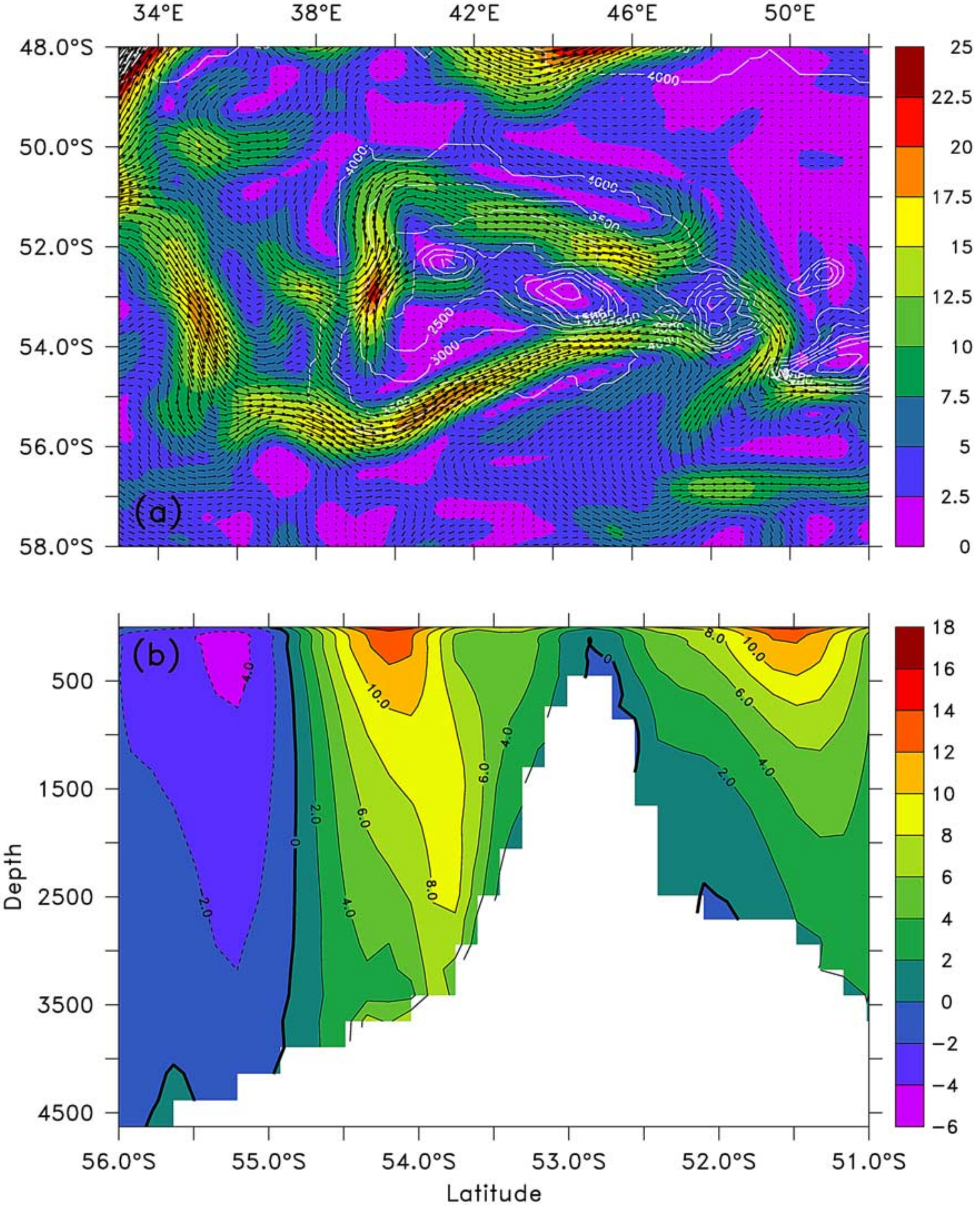

Figure 3. (a) Current speed and direction at the Conrad Rise simulated by ORCA025 ($^1/_4$° nominal resolution), averaged for the years 2000–2004 and over the top 500 m. Bathymetry shallower than 4000 m is shown by isobaths at 500 m intervals. The speed scale is in cm s^{-1}. (b) Zonal velocity (positive values are eastward, in cm s^{-1}) along a vertical section at 44°E. Bottom topography is indicated by the white region.

speed of 10 – 15 cm s^{-1} which corroborates measurements made by *Pollard and Read* [2001] at similar depths. The vertical structure of the zonal geostrophic velocities (with 2000 m reference level) along 44°E is shown in Figure 4b and may be compared with the model results (see Figure 3b). There were indications of shear edge eddies adjacent to the main current jets on this occasion, but these might be transient and thus would not feature in long-term means (e.g., Figures 2 and 3). Nevertheless, the remarkable consistency between long term current averages and this first hydrographic cruise give us considerable confidence that the jet-like currents are a permanent feature of the circulation at the Conrad Rise.

4. Conclusions

[12] Although it has previously been shown, not entirely unexpectedly, that the Conrad Rise strongly affects the flow

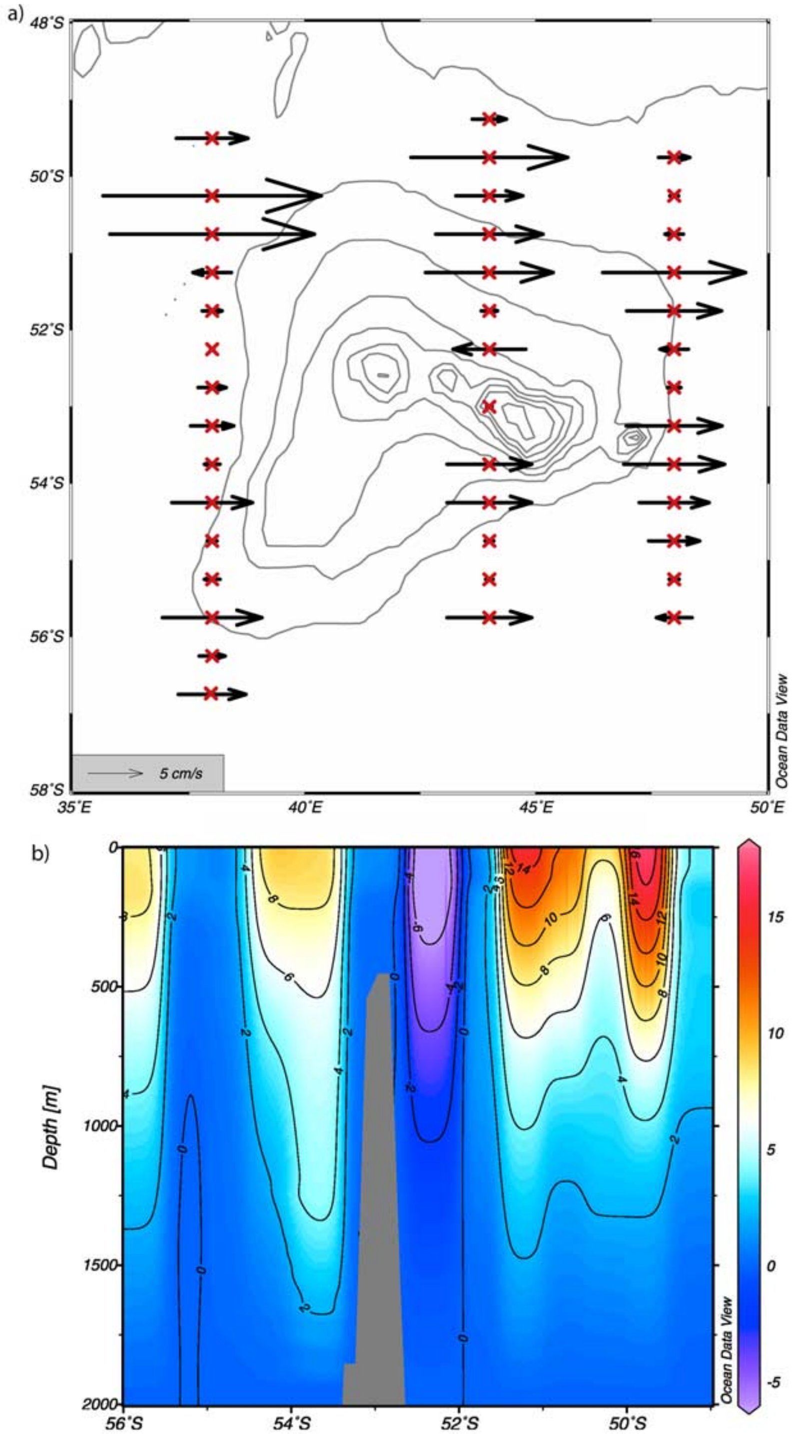

Figure 4. Geostrophic speeds (cm s^{-1}) calculated with a reference level of 2000 m (a) Zonal speeds integrated over the top 519 m along the three sections undertaken during a cruise. Red crosses indicate the station positions and bathymetry shallower than 4000 m is shown by isobaths at 500 m intervals. (b) Eastward component of the geostrophic flow along 44°E. Bottom topography is indicated by the grey region.

of bottom water [*Boswell and Smythe-Wright*, 2002], no other thorough hydrographic investigations have to date been undertaken in the region. The tracks of subsurface floats and surface drifters as well as new hydrographic observations now demonstrate convincingly that this Rise forms a substantial barrier to the eastward movement of Antarctic water masses at all depths. The similarity of the movement at various depths, even at depths substantially shallower than most of the Rise, effectively illustrates the barotropic component of the Antarctic Circumpolar Current.

[13] The intensified flow to either side of the Conrad Rise of 15 cm s^{-1} or more forms what may be considered as two

jets of higher velocity, extending all the way to the sea floor. It is conceivable that these jets act as substantial barriers to ambient water masses thus causing the relative isolation of the waters over an extensive part of the Rise itself. The possible effect of this seclusion on the resident biota is not known yet. Enhanced plankton activities have been observed in the vicinity of the Ob and Lena seamounts [*Pakhomov*, 1993; *Pakhomov and Semelkina*, 1995]. A detailed survey around the seamounts was also undertaken during the cruise in April 2008. The reported abundance of biota close to the seamounts may be linked to trapped circulations that exist over the mounts. Further research is underway to closely investigate the movement on, and adjacent to, the Rise and the influence of these movements on the local ecosystem.

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