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Reversing bottom circulation in the Somali Basin

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Abstract. Two sets of direct velocity measurements were taken, concurrent with hydrographic data, in the bottom waters of the northern Somali Basin in June and September, 1995. The velocities indicate a temporal flow reversal in the bottom circulation, which is consistent with the changing density structure between the sections. In June, there is evidence of a southward Deep Western Boundary Current with a transport of 5 Sv. By September, flow close to the boundary is northward, with a transport of 2.6 Sv. Furthermore, the deep density gradient across the interior of the Somali Basin also changes between occupations, implying a cyclonic circulation in June and anticyclonic flow in September. Rossby wave activity is high in this region during the southwest monsoon, yet there is also evidence of a strong barotropic component to the Great Whirl in September, which may cause the reversal in the abyssal circulation.

Introduction

The Somali Basin is bounded in the west by Africa, in the east by the Carlsberg Ridge and in the north by the continental shelf surrounding the island of Socotra (Figure 1). The Carlsberg Ridge separates the Somali Basin from the Arabian Basin, which has no waters denser than neutral density $\gamma = 28.115$, corresponding to a sill depth between the basins of 3800 m. There is no production of bottom waters in the Arabian Basin and as a result, bottom water crosses the sill into the Arabian Basin, with a return of lighter, less deep waters into the Somali Basin [*Quadfasel et al.*, 1997]. Thus, below density $\gamma = 28.115$ the Somali Basin is enclosed, except to a single supply of bottom waters from the south. Approximately 1-1.7 Sv of Circumpolar Deep Water enters the Basin through the Amirante Passage at 8°S [*Johnson et al.*, 1998].

The character of the abyssal circulation is generally assumed to follow the theoretical model of *Stommel-Arons* [1960] where, in the simplest case, the assumption of uniform upwelling over a flat-bottomed basin drives a poleward interior flow, through the conservation of potential vorticity. Further, from considerations of lateral friction and conservation of mass, a return flow is implied at the western boundary. Applying such a model to the Somali Basin, adding representative geometry and a southern water source, *Johnson et al.* [1991] predicted that a northward deep western boundary current (DWBC) feeds southern source waters into the basin interior until its transport is diminished to zero at 4°N. At greater latitudes, there is a predicted southward DWBC and a cyclonic recirculation of bottom waters.

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Previous observations of deep currents in the northern Somali Basin have been hampered by weak density structure [*Warren et al.*, 1966] and by lack of guidance in the tracer fields for setting a zero velocity surface (ZVS) [*Johnson et al.*, 1991], thus the circulation is far from clear. During the southwest monsoon of 1964 *Warren et al.* [1966] inferred northward flow along the Somali continental slope below 2500 m depth between 3 and 8°N, from marginally lower salinities (0.005) next to the slope. In contrast, *Fieux et al.* [1986] found evidence of higher salinities next to the boundary and anticlockwise geostrophic currents off Somalia at 3°N in April 1985, implying a weak southward flow at the boundary. On the equator a single current record from 3000 m depth revealed a seasonal cycle, with weak southward flow during the northeast monsoon and northward flow during the southwest monsoon [*Schott et al.*, 1989]. The geostrophic transport of deep waters into the Arabian Basin was also found to be modulated seasonally *Quadfasel et al.* [1997]. These data suggest that monsoon forcing may dominate over the steady abyssal circulation. However, observations reported by *Johnson et al.* [1991] from the heights of two subsequent monsoons in the 1986/87 seasons revealed a steady northward boundary current at 3°S and weak circulation in the north, consistent with the Stommel-Arons dynamics of their model described above.

In this note we use direct velocity profiles of the bottom currents in the northern Somali Basin to enhance measurements of the density and property fields and clarify the boundary flow, the sense of the circulation, and its temporal variability.

Data

In June 1995, RV *Malcolm Baldridge* crossed the Somali Basin along 8.5°N, as part of the World Ocean Circulation Experiment (WOCE) repeat line IR1. Three months later in September, RV *Knorr* re-occupied the same line, plus a short section over a WOCE mooring line between 11 and 9.5°N (Figure 1). This time the line was sampled perpendicular to the topography of the continental slope before turning due east at 53°E, 8.5°N. At each station pressure, temperature, salinity and oxygen were measured using a CTD, and velocities were profiled using a Lowered Acoustic Doppler Current Profiler (LADCP). Salinity and oxygen concentrations from each cruise were calibrated to WOCE standards, with accuracies nominally ±0.002 for salinity and ±0.5% for oxygen. Neutral density surfaces were calculated using the algorithm from *Jackett and McDougall* [1997]. On I1 at stations 906, 907 and 908 LADCP problems caused a data drop out below 1200 m depth and a back-up instrument was installed by station 909.

It is difficult to quantify uncertainties in LADCP velocities, since there are several independent errors related to instrumental limitations [*Firing*, 1998], as well as issues related to high frequency motions captured in the measure-

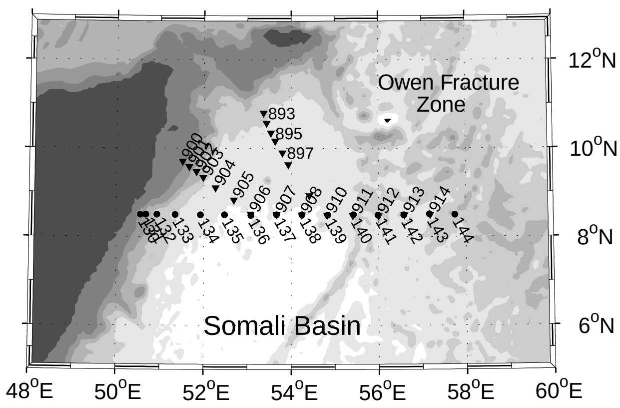

Figure 1. Positions of stations from cruise IR1 in June 1995 (130 to 144) and I1 in September 1995 (893-915). Shading represents bathymetry from 0 (dark gray) to 5000 m (white) in isobaths of 1000 m. The index map (with 3800 m isobath) indicates the region of the Indian Ocean covered in the main figure

ments. For a thorough description of the potential errors see *Firing* [1998]. Two of the most relevant errors are discussed here. First, since we are studying deep currents we must be concerned with the bottom interference layer, which occurs between about 600 and 700 m above the sea bed and results in a gap in the processed velocity profile and therefore an uncertain offset. A staggered ping instrument was used on stations prior to 909 during I1, avoiding this problem entirely, but remaining data are contaminated, resulting in a probable offset of a few $cm\ s^{-1}$. Second, tides and inertial oscillations superimposed on the geostrophic circulation are a concern. Barotropic tides of no more than 2 $cm\ s^{-1}$ were estimated using a global model of ocean tides [*Egbert et al.*, 1994] and removed from the LADCP velocities. The closest WOCE mooring at 6°N, 54.48°E and 4020 m depth shows that during the southwest monsoon, internal waves are dominated by near-inertial oscillations of amplitude 2-3 $cm\ s^{-1}$ (M. Dengler, personal communication).

Results

The density structure in the deep waters changes markedly between June and September (Figure 2). In June, neutral density surfaces trend upward throughout the deep layer over the continental slope, and upward towards the Carlsberg Ridge in the interior. This is suggestive of a southward flowing DWBC with northward interior flow, assuming a mid-depth reference level. In September the case is less clear, perhaps obscured by deep eddies, and flow directionality is hard to guess. In each section there are no isopycnal gradients of either salinity or oxygen and hence the property fields provide no evidence of flow direction, or even of the existence of a boundary current. Neither is there a significant change in properties along density surfaces between June and September. Therefore, any temporal change of property distribution in pressure space would appear to be

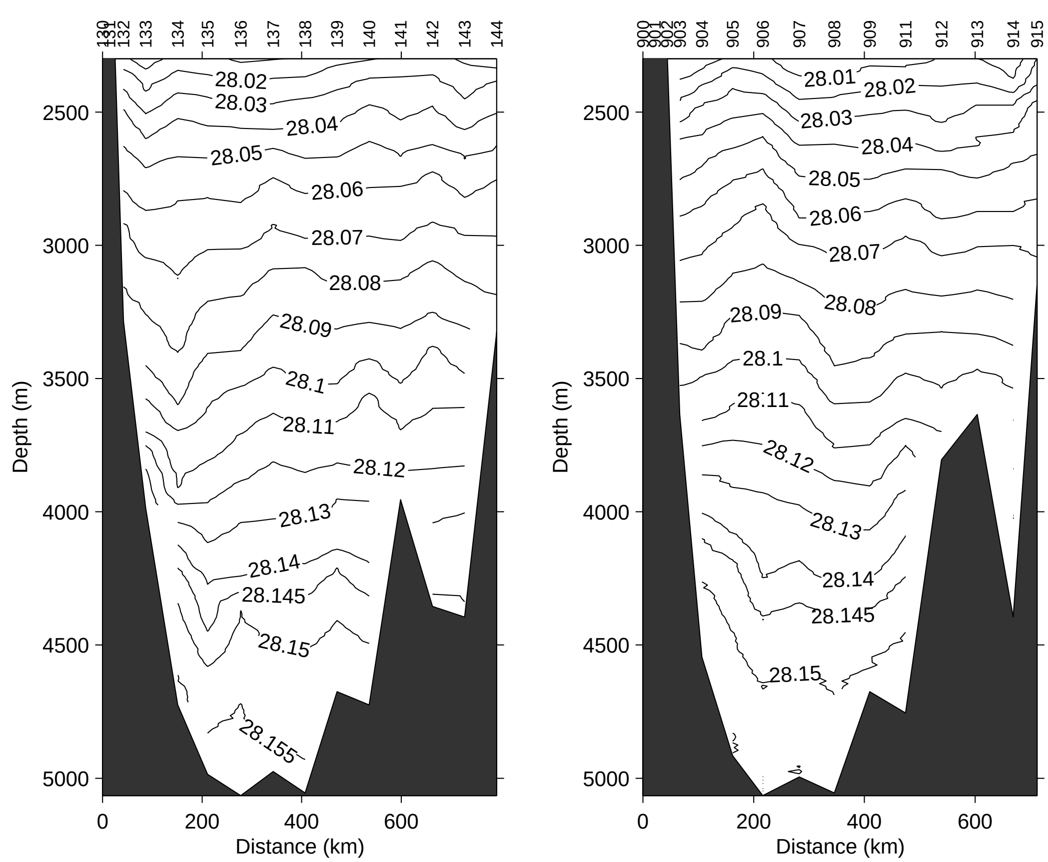

Figure 2. Vertical sections of neutral density surfaces below 2300 m, from June (left) and September (right) 1995. Topography is shaded, the Somali continental slope in the west and the Chain and Carlsberg Ridges in the east.

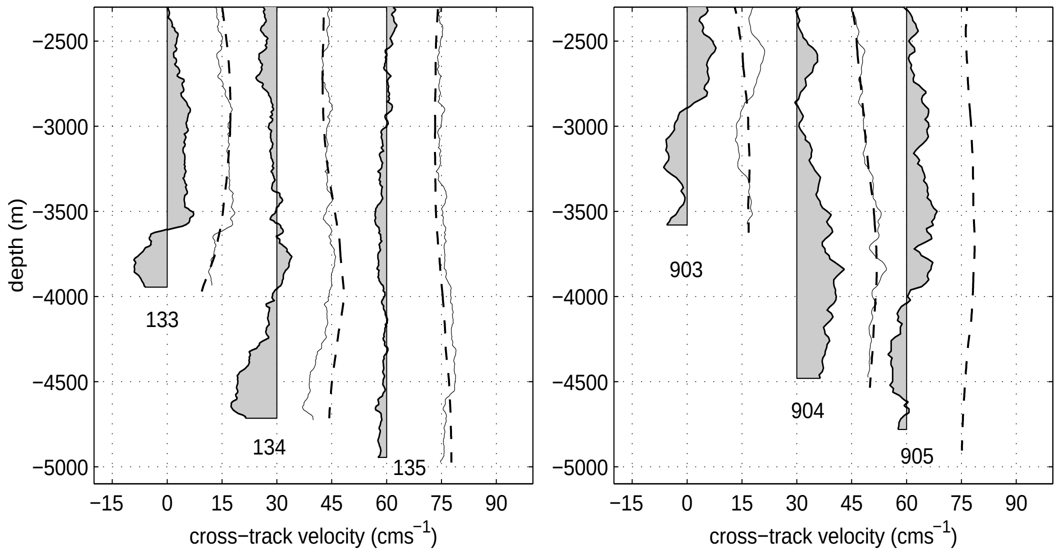

Figure 3. Deep velocity profiles from LADCP (shaded), geostrophic approximation (dashed), and LADCP averaged onto station-pairs (thin lines) over the Somali continental slope in (a) June, and (b) September 1995. Each profile is successively offset by 15 cm s^{-1}.

a result of the movement of isopycnal surfaces, rather than a reflection of modified water masses being advected onto the section. This is suggestive of a change in density structure in response to local dynamical adjustment.

Figure 3 shows cross-track LADCP and geostrophic profiles deeper than 3000 m over the continental slope, in June and September. Geostrophy is referenced to LADCP profiles averaged onto station pairs, by finding the depth-mean difference below 200 m, that is, below the Ekman layer [*Chereskin et al.*, 1997], and adjusting the geostrophic velocities accordingly. Looking first at the velocities in June (Figure 3a) we see a distinct bottom-intensified current on LADCP profiles 133 and 134, with southward velocities up to 13 $cm\ s^{-1}$. The geostrophic velocity gradients suggestive of this DWBC are weak. In September (Figure 3b) there is no longer southward bottom-intensified flow and in fact, on station 904 the currents are northward at the bottom, with velocities up to 7 $cm\ s^{-1}$. Again, the deep geostrophic shear is weak and here gives little suggestion of flow directionality. The geostrophic shear profiles do not capture the bottom boundary flows well for two reasons. First there is no measure of the density gradient below the deepest common level of each station pair and on sloping topography this results in a substantial data gap or bottom triangle. Second, and less important, narrow bottom trapped flows on sloping topography are smeared and diminished by the geostrophic method, which integrates along pressure horizons.

To represent the flow of the enclosed layer of bottom waters in the Somali Basin direct velocity vectors are averaged below $\gamma = 28.115$. Figure 4 shows these vectors for June (black) and September (white). Despite lower signal to noise away from the boundary, the direct velocities are showing a relatively consistent picture within the interior. Not only has the flow at the western boundary switched direction between June and September, but so too has the interior flow. In June the sense of rotation within the bottom waters of the basin is cyclonic. By September it is anticyclonic, as supported by both the repeated section and the short section to the north along the WOCE moorings. The density gradients across the basin are consistent with these findings (Figure 2). Following linear vorticity [*Stommel and Arons*, 1960] theory as applied to the Somali Basin by *Johnson et al.* [1991], this switch may imply that the vertical velocity into the bottom layer has also reversed, from an upward pumping of bottom waters out of the layer in June, to a downward pumping at the top of the layer in September.

To best compare the intensity of the two circulations we have estimated the transport at the western boundary using LADCP data, and the interior transport using geostrophy referenced to a standard pressure (2000 db). In this way we can directly compare the direction and magnitude of the interior circulation between June and September, assuming a constant ZVS. Also, the LADCP velocities better sample the flow in the DWBC and can provide us with an absolute estimate of its transport. All transports are integrated for the density layer $\gamma > 28.115$. The boundary current regime is considered to be stations out to 135 on IR1, and to 905 on I1. The meridional component of DWBC transport is cal-

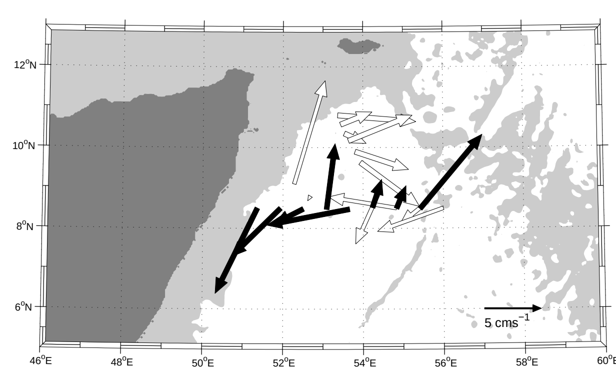

Figure 4. LADCP velocity vectors averaged below 3800 m, from June (black) and September (white) 1995. Bathymetry is shaded above 3800 m.

culated for I1, to be consistent with geostrophic velocities across the rest of the section, and with section IR1. The direct volume transport estimate for the boundary flow is 4.9 Sv southward in June, and 2.6 Sv northward in September. Geostrophic transports integrated across the interior switch from 5.0 Sv northward in June to 4.5 Sv southward in September. Rather fortuitously, the DWBC transport and subjectively referenced interior transport balance very closely in June. It is instructive to note that just -0.5 Sv of the June DWBC transport is captured by geostrophy, and that the dominant reason for this, outweighing the arbitrary choice of reference level, is the missing density gradients within the bottom triangles.

Discussion and Conclusions

Direct measurements of ocean velocity are especially useful for resolving the features of a boundary current [*Beal and Bryden*, 1997]. In narrow boundary flows the geostrophic method can significantly under-estimate the peak velocities and total transport, primarily due to the lack of a horizontal density gradient below the deepest common level of each station pair. Furthermore, in this case, using geostrophy alone with no property anomaly patterns and very little guidance for placement of a ZVS, it was not possible to discern even the direction of the flow with certainty.

Previous studies [*Warren et al.,* 1966; *Fieux et al.,* 1986] inferred the presence of a DWBC through isothermic salinity difference, albeit a weak signal of O(0.005). Is it surprising then, that we see no such signatures in the WOCE data? Perhaps not, since our analysis is farther poleward and deeper than these studies. There is no introduction of bottom waters in the northern basin, and thus water circulating north in the interior in June has little chance for modification by diapycnal processes before it intensifies at the boundary and flows back southward. Nevertheless, without the additional evidence of water mass anomalies, it is possible that the abyssal flow reversal we have seen is not representative of a seasonal modulation. In fact, it may be due to Rossby waves. Eddy kinetic energies from the closest WOCE mooring at 4020 m depth (none are in the DWBC) are on average 11.2 $cm^2 s^{-2}$ during the southwest monsoon (up to 42.8 $cm^2 s^{-2}$) and there is no evidence of flow seasonality (M. Dengler, personal communication). Moreover, the wavelength of these Rossby waves appears comparable to the basin width at this latitude and could perhaps explain a switch in the circulation (Figure 4). On the other hand, LADCP profiles show that in the period from June to September the Great Whirl, directly above these abyssal currents, doubles in intensity and width. There is evidence that a strong barotropic response is associated with much of this spin up, since the LADCP shows speeds greater than 10 $cm\ s^{-1}$ at 3000 m depth in September. We speculate that a barotropic response to the monsoon wind forcing could result in a reversal of the abyssal circulation. Further analysis of the full-depth velocity field is the subject of future work.

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References

Beal, L. M. and H. L. Bryden, Observations of an Agulhas Undercurrent, *Deep-Sea Res., 44,* 1715-1724, 1997.

Chereskin, T. K., W. D. Wilson, H. L. Bryden, A. Ffield and J. Morrison, Observations of the Ekman balance at 8°30′N in the Arabian Sea during the 1995 southwest monsoon, *Geophys. Res. Lett., 24,* 2541-2544, 1997.

Egbert, G. D., A. F. Bennett, and M. G. G. Foreman, TOPEX/POSEIDON tides estimated using a global inverse model, *J. Geophys. Res., 99,* 24,821-24,852, 1994.

Fieux, M., F. Schott and J. C. Swallow, Deep boundary currents in the western Indian Ocean revisited, Deep-Sea Res. *33,* 415-426, 1986.

Firing, E., Erratum, International WOCE Newsletter, *31,* 20, 1998.

Jackett, D. R. and T. J. McDougall, A neutral density variable for the world's oceans, *J. Phys. Oceanogr., 27,* 237-263, 1997.

Johnson, G. C., D. L. Musgrave, B. A. Warren and D. B. Olson, Flow of the bottom and deep water in the Amirante Passage and Mascarene Basin, *J. Geophys. Res.,* , *103,* 30,973-30,984, 1998.

Johnson, G. C., B. A. Warren and D. B. Olson, Flow of bottom water in the Somali Basin, Deep-Sea Res. *38,* 637-652, 1991.

Quadfasel, D., J. Fischer, F. Schott and L. Stramma, Deep water exchange through the Owen Fracture Zone in the Arabian Sea, *Geophys. Res. Lett., 24,* 2805-2808, 1997.

Schott, F., J. C. Swallow, and M. Fieux, Deep currents underneath the Somali Current, Deep-Sea Res., *36,* 1191-1199, 1989.

Stommel, H. and A. B. Arons, On the abyssal circulation of the world ocean - 1. Stationary planetary flow patterns on a sphere, Deep-Sea Res. *6,* 140-154, 1960.

Warren, B., H. Stommel and J. C. Swallow, Water masses and patterns of flow in the Somali Basin during the southwest monsoon of 1964, Deep-Sea Res. *13,* 825-860, 1966.

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