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Deep water exchange through the Owen Fracture Zone in the Arabian Sea

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Abstract. From geostrophic calculations the exchange of deep water from the Somali into the Arabian Basin through the Owen Fracture Zone has been estimated to be about 2 Sv, with a seasonal modulation of the same magnitude. After leaving the Fracture Zone, the flow bifurcates into a northern and a southern branch, each closely following the slope of the Carlsberg Ridge. The weaker vertical gradients of the hydrographic properties in the deep Arabian Basin are consistent with enhanced vertical mixing at the rugged topography over the Carlsberg Ridge.

Introduction

The deep Arabian Basin is a cul-de-sac for spreading of lower Circumpolar Water in the western Indian Ocean [*Warren*, 1981a]. It is fed mainly by an inflow from the Somali Basin through the Owen Fracture Zone, a gap in the Carlsberg Ridge near 11° N, 57° E (Figure 1). From comparing the temperature stratification in both basins, *Wyrtki* [1971] concluded that the sill for the overflow lies at about 3800 m depth. The deep Somali Basin, in turn, is ventilated from the Mascarene Basin in the southern hemisphere through the Amirante Passage about half-way between the island of Madagascar and the Seychelles Plateau. Geostrophic calculations based on hydrographic observations have fairly well established the structure of the deep flow in the Mascarene Basin as well as its transport [*Warren*, 1974; *Warren*, 1981b; *Fieux et al.*, 1986; *Swallow and Pollard*, 1988]. For the boundary current along the east coast of Madagascar, estimates range between 3 and 5 Sv (1 Sv = 10^6 m^3s^{-1}), of which 1 to 4 Sv continue into the Somali Basin via the Amirante Passage [*Fieux and Swallow*, 1988; *Barton and Hill*, 1989].

In contrast, the circulation in the deep Somali Basin is far from clear. From water-mass analysis, *Warren et al.* [1966] inferred a northward spreading of the low-salinity water along the Somali continental slope into the northern basin. The data they used were collected during the height of the SW Monsoon. From similarly spaced observations in April, *Fieux et al.* [1986] did not find such a boundary current, but rather inferred a weak southward flow. A single current record from an instrument moored at 3000 m depth at the equator revealed a seasonal modulation of the current, with weak southward flow during the winter monsoon and a northward, albeit stronger, flow in summer [*Schott et al.*, 1989]. This supports *Fieux et al.'s* [1986] view that the monsoon response may dominate over the mean thermohaline-driven deep circulation.

During two hydrographic surveys at the respective heights of the monsoon seasons, *Johnson et al.* [1991a] found a steady northward boundary current at 3° S, which appeared to turn offshore at the equator, feeding the northern Somali Basin from

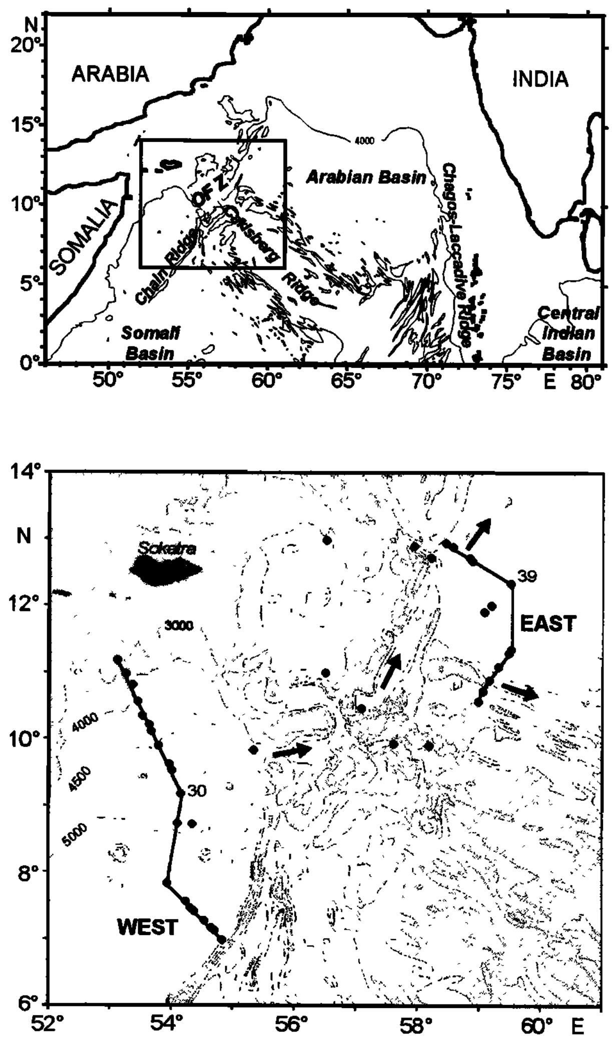

Figure 1. (a) Location of the study area in the northern Indian Ocean. Topography (4000 m isobath) is taken from *GEBCO* [1979]. (b) Location of the hydrographic stations in the northern Somali and western Arabian basins. Depths less than 4000 m are shaded. Also indicated are the paths of the mean flow.

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the interior rather than via a boundary current. In the northern Somali Basin they found only weak flows, consistent with Stommel-Arons dynamics. In the Arabian Basin, east of the Carlsberg Ridge, the same authors [*Johnson et al.*, 1991b] found a southwestward boundary current, also consistent with Stommel-Arons dynamics, if the basin is indeed dominantly supplied through the Owen Fracture Zone rather than through gaps in the Chagos-Laccadive chain.

As part of the WOCE 1995 expedition, R/V *Meteor* repeatedly covered two sections east and west of the Owen Fracture Zone between April and September with CTD measurements (Figure 1). The observations were made before the onset of the SW Monsoon in April, during the monsoon (June) and at the end (September) of this season [*Schott et al.*, 1996]. In addition several stations were run in the deep passages of the Owen Fracture Zone itself.

Hydrographic observations

The deep water in the Arabian Basin is warmer, saltier and less oxygenated than that of the Somali Basin. These basic differences between the hydrographic properties in the two basins are illustrated in Figure 2, showing a composite of all hydrographic profiles from east and west of the Carlsberg Ridge (Figure 1). The two sets of profiles bifurcate at around 3700 m, the bottom water of the Arabian Basin corresponding to that at 4000 m depth in the Somali Basin. This is somewhat deeper than the sill depth of 3800 m inferred by *Wyrtki* [1971] from temperature data alone. But also above these levels the profiles show substantial differences, most clearly seen in the two profiles from each side of the ridge during April (Figure 2). Here, at mid-depth, the gradient between the two basins is reversed, with the waters of the Arabian Basin being cooler, less saline and more oxygenated. The profiles taken within the fracture zone at the center of the ridge are very similar to those in the Arabian Basin. The sill limiting the exchange of deep waters has thus to be at the western side of the Carlsberg Ridge.

The vertical distributions of temperature, salinity and dissolved oxygen content along the eastern sections are shown in Figure 3. The sections start and end at the flank of the Carlsberg Ridge and encompass the eastern exit of the Owen Fracture Zone (Figure 1). In all three surveys the isotherms slope upward towards the south. This indicates an overall geostrophic transport out of the box spanned by the sections, which is consistent with an inflow from the Owen Fracture Zone. Oxygen concentrations strongly decrease towards the north, reflecting the large-scale gradient towards the oxygen minimum zone in the northern Arabian Sea. Close to the bottom, however, the situation is different. The lowest bottom temperatures and the highest oxygen concentrations are found at the flank of the ridge, both to the north and to the south of the Owen Fracture Zone's exit. The bottom water characteristics of the three surveys also differ. In April bottom temperatures were above 1.4° C and oxygen concentrations below 170 μmol/l. In June cold (<1.4° C) and oxygen-rich (>170 μmol/l) bottom water covered almost the whole section, while in September it was only found at the northern end.

Mixing

As mentioned above, the hydrographic profiles from the deep Somali and Arabian basins intersect at about 3700 m depth (Figure 2). The weaker vertical gradients in all water mass components in the western Arabian Basin suggests either stronger upwelling or enhanced vertical mixing, making the layer above this depth cooler, less salty and more oxygenated than at the corresponding depths in the Somali Basin. Enhanced vertical mixing can be caused by the rugged topography of the Carlsberg Ridge, which exerts friction on the mean flow. Figure 4 shows a histogram of the roughness of the topography in the area of the Owen Fracture Zone. We have taken the digitized 5' x 5' topography and simply counted the number of depth changes occurring on this grid. The counting was done for layers of 10 m thickness, which is basically a measure of the chance of a water parcel bumping into a vertical wall on the passage between the two basins. The highest values lie between 2500 m and 4500 m depth, which is also where the largest deviations between the Somali and the Arabian Sea profiles are found (Figure 2). Near-bottom mixing over the Carlsberg Ridge thus seems to be capable of changing the vertical structure of the water column over a layer more than 1000 m thick.

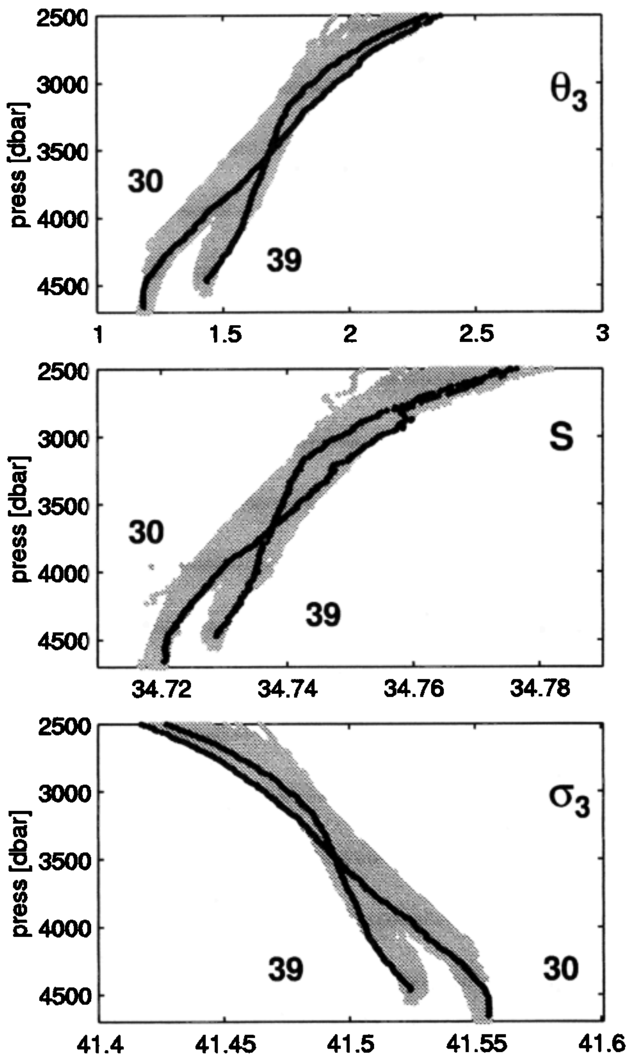

Figure 2. Composite of all hydrographic profiles from east and west of the Carlsberg Ridge, potential temperature referred to 3000 dbar, salinity, and potential density σ_3. See Figure 1 for station location. Two stations (Nos. 30 and 39) from the Somali and Arabian basins, respectively, taken during April 1995, are highlighted by heavy lines.

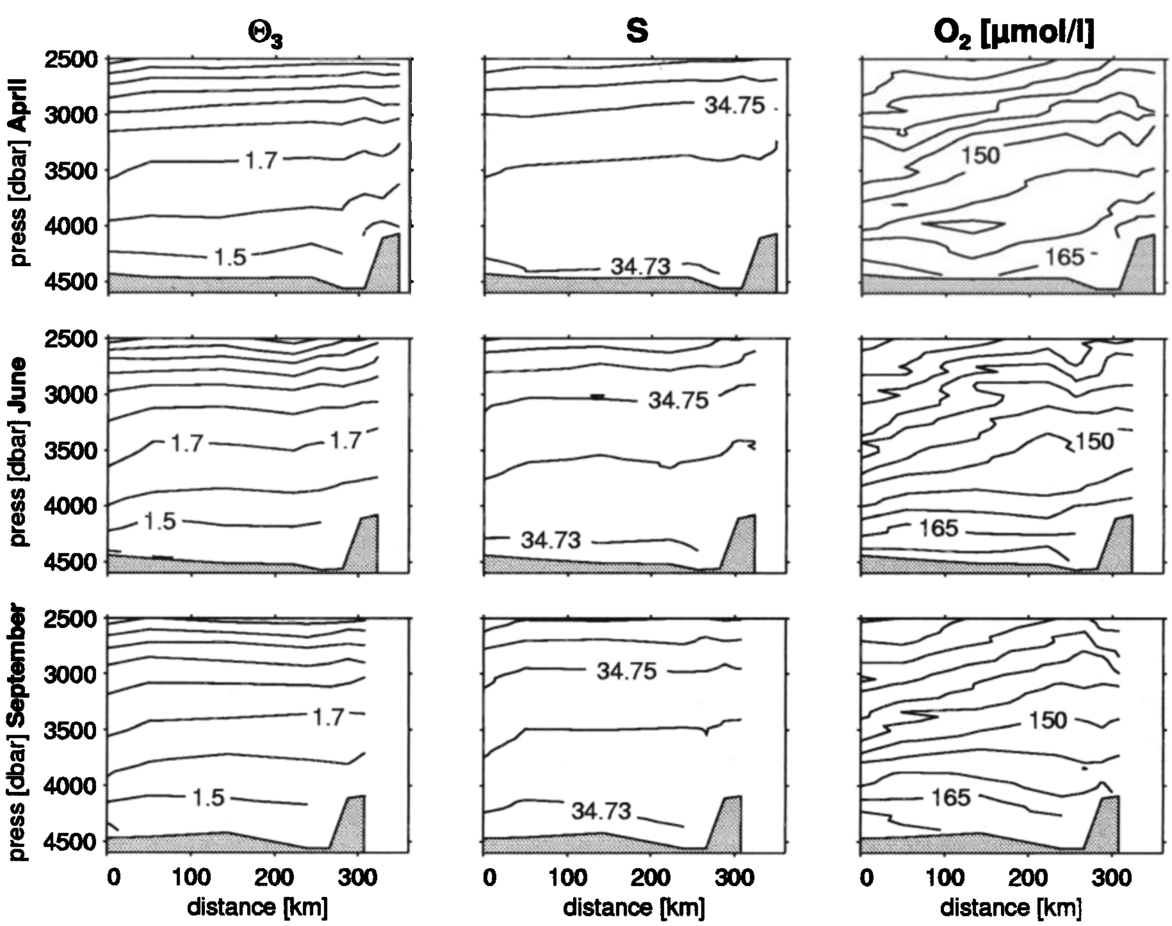

Figure 3. Vertical distribution of potential temperature referred to 3000 dbar, salinity, and dissolved oxygen content during April 1995, June 1995, and September 1995 of the eastern sections. Contour intervals are 0.1° C, 0.01 psu and 5 µmol/l respectively.

Transports

Geostrophic transports for the eastern section were calculated relative to a reference level of 3000 dbar, which is close to the 1.7° C potential temperature surface (referred to zero pressure) used by other authors [e.g. *Johnson et al.*, 1991b]. The transports are summarized in Table 1. Taking a shallower reference level of 2500 dbar changes these figures by less than 20%.

All three surveys found consistent boundary flows, northward at the northern part and southward at the southern part of the sections. The northern transport stays fairly constant at 0.9-1.4 Sv, but the southern transport decreases from 1.8 to 0.3 Sv between April and September. This change dominates the decrease of the total outflow from the section, which goes from 3.2 to 1.2 Sv during the same time period. These numbers may be

Table 1. Geostrophic transports (in Sv) for the range 3000 dbar to the bottom in the eastern box in the Arabian Basin. A layer of no motion at 3000 dbar is assumed. Positive transports are out of the box. For location see Figure 1.

	North	Central	South	Total
April 1995	0.86	0.59	1.75	3.2
June 1995	1.40	-0.65	1.49	2.3
September 1995	1.07	-0.18	0.33	1.2

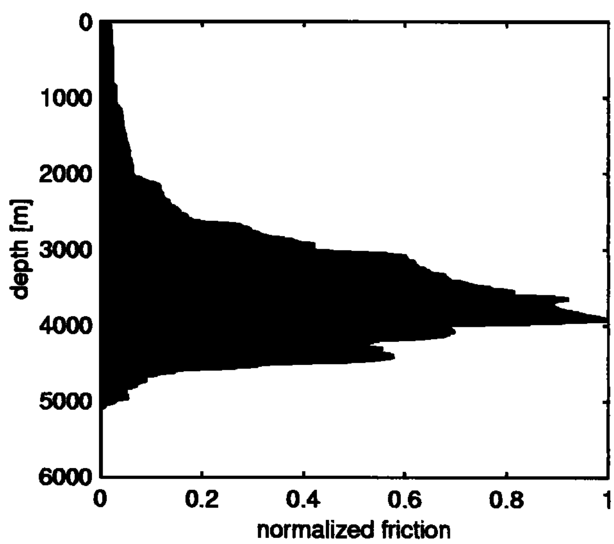

Figure 4. Vertical distribution of the roughness of the topography in the area 8° - 13° N, 54° - 61° E, based on digitized 5' x 5' topography. This covers the northern part of the Carlsberg Ridge with the Owen Fracture Zone. For depth levels spaced at 10 m intervals the number of depth jumps across that level have been counted.

compared with *Johnson et al.'s* [1991b] transport estimates, based on data collected in the deep boundary current near 7° N. In December, during the height of the NE Monsoon they found a southeastward transport of 4.8 Sv, while during the SW Monsoon in August the mean current had reversed, with a transport of only 0.5 Sv.

One might be tempted to infer from these five transport figures that the boundary current, and therefore the exchange through the Owen Fracture Zone, modulates seasonally. Transport fluctuations at the source travel along the boundary in the form of internal Kelvin waves, and thus on the seasonal time scale the transports at the 7° N sections can be treated as being in phase with the source. Our hydrographic observations along the eastern section do indeed support such a view. Of the three surveys, the bottom waters were warmest and least oxygenated in April and showed the strongest overflow characteristics in June. As water-mass properties travel with the mean flow - which is here of order 1-3 cm/s - it will thus take one to three months for the water-mass fluctuations of the source to show up in the section. The integral effect of the overflow is largest a quarter of a cycle after the strongest transport. This phase lag, together with the propagation time of the water mass in the mean currents, adds up to 4-6 months, explaining why the thickest bottom water layer is found in June rather than earlier after the peak of the NE Monsoon.

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