Gulf of Aden eddies and their impact on Red Sea Water

Amy S. Bower and David M. Fratantoni
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

William E. Johns and Hartmut Peters
Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA

Received 17 April 2002; accepted 19 August 2002; published 8 November 2002.

[1] New oceanographic observations in the Gulf of Aden in the northwestern Indian Ocean have revealed large, energetic, deep-reaching mesoscale eddies that fundamentally influence the spreading rates and pathways of intermediate-depth Red Sea Water (RSW). Three eddies were sampled in February 2001, two cyclonic and one anticyclonic, with diameters 150–250 km. Both cyclones had surface-intensified velocity structure with maxima $\sim$0.5 m s^{-1}, while the equally-energetic anticyclone appeared to be decoupled from the surface circulation. All three eddies reached nearly to the 1000–2000 m deep sea floor, with speeds as high as 0.2–0.3 m s^{-1} extending through the depth range of RSW. Comparison of salinity and direct velocity measurements indicates that the eddies advect and stir RSW through the Gulf of Aden. Anomalous water properties in the center of the anticyclonic eddy point to a possible formation site in the Somali Current System. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4536 Oceanography: Physical: Hydrography; 4512 Oceanography: Physical: Currents. **Citation:** Bower, A. S., D. M. Fratantoni, W. E. Johns, and H. Peters, Gulf of Aden eddies and their impact on Red Sea Water, *Geophys. Res. Lett.*, *29*(21), 2025, doi:10.1029/2002GL015342, 2002.

1. Introduction

[2] The Gulf of Aden is the receiving basin for the dense, saline overflow of Red Sea Water (RSW). The overflow results from an excess of evaporation over precipitation in the Red Sea, estimated to be about 2 m yr^{-1} [*Morcos*, 1970]. Unlike many other marginal sea overflows, the Red Sea outflow transport is strongly seasonal due to monsoon winds and variations in buoyancy fluxes, with a winter maximum of 0.6 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) and a summer minimum of 0.05 Sv [*Murray and Johns*, 1997]. The dense Red Sea outflow water descends from sill depth ($\sim$150 m) in Bab el Mandeb Strait (BAM), entrains less dense, fresher Gulf of Aden water, and reaches neutral buoyancy in the western Gulf of Aden in multiple, intermediate-depth, high-salinity layers centered around 600 m. It then spreads laterally through the gulf [*Siedler*, 1968; *Bower et al.*, 2000]. The mixing and stirring processes that take place in the Gulf of Aden set the properties of RSW before it spreads farther into the open Indian Ocean, where it is a major intermediate water mass [*Wyrtki*, 1971; *Beal et al.*, 2000].

Copyright 2002 by the American Geophysical Union.
0094-8276/02/2002GL015342$05.00

[3] Our general understanding of the physical oceanography of the Gulf of Aden has been severely limited by the lack of modern in situ observations. A major field program, called Red Sea Outflow Experiment (REDSOX) was recently undertaken to observe the mixing and spreading of RSW in the Gulf of Aden. During two research cruises in 2001, we obtained the first three-dimensional description of the hydrographic and velocity structure of the descending and equilibrated RSW in winter and summer. These measurements have revealed new large, energetic, deep-reaching eddies in the Gulf of Aden that fundamentally influence the spreading of RSW, and are the subject of this note.

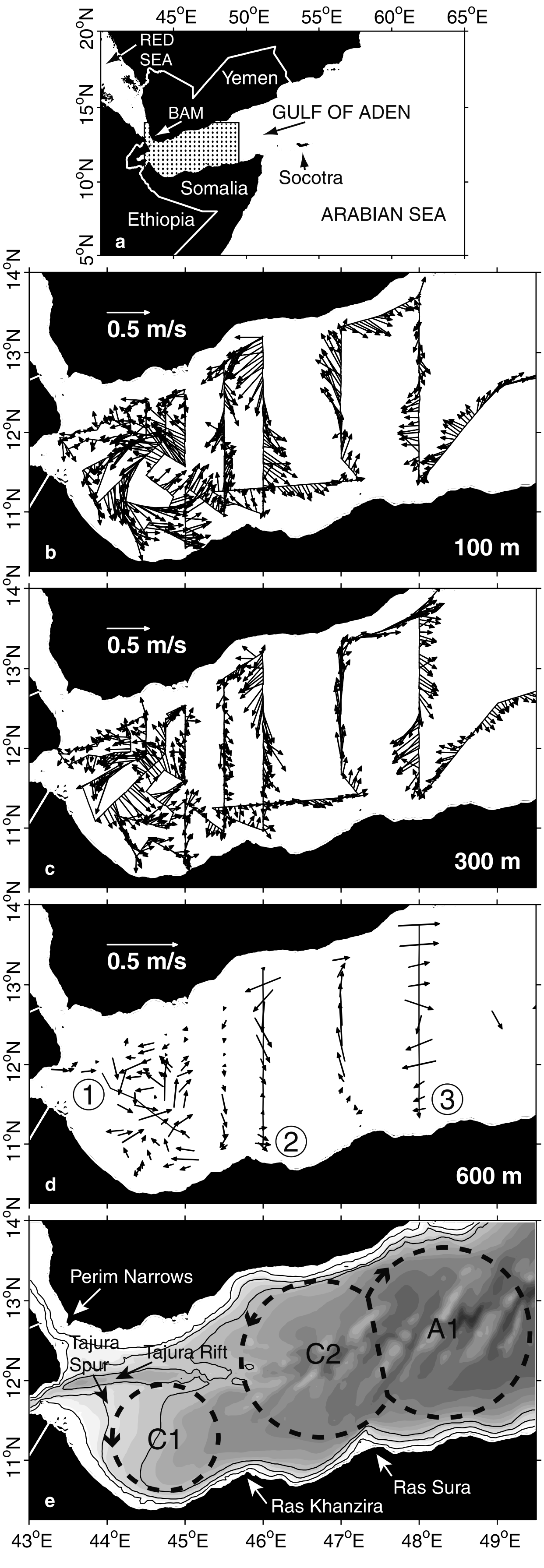
2. Observations

[4] The observations discussed here were collected during the winter REDSOX cruise on board the *R/V Knorr* (KN-216) from 11 February–15 March 2001, i.e., during the season of maximum outflow transport. A total of 238 Conductivity-Temperature-Depth-O_2/Lowered Acoustic Doppler Current Profiler (CTDO_2/LADCP) full-water column profiles were obtained (stippled area in Figure 1a) [*Johns et al.*, 2001]. The shipboard ADCP (SADCP) was used to collect upper-ocean velocity profiles continuously along the ship track from the surface to 350 m depth. The LADCP profiles discussed here were mostly referenced using the ship's navigation, and are accurate to about ±0.03 m s^{-1}.

3. Results

3.1. Horizontal Velocity Structure

[5] The SADCP measurements at 100 and 300 m (Figures 1b and 1c) reveal that currents in the Gulf of Aden were strong and organized into coherent eddy structures in February 2001. The most conspicuous feature is an energetic cyclonic eddy adjacent to the Somali coast in the southwestern part of the gulf (henceforth C1, see Figure 1e for schematic representation). This feature was about 150 km in diameter at 100 m, and somewhat smaller at 300 m. Maximum azimuthal speeds were $\sim$0.4–0.5 m s^{-1}. Farther east, there is an indication of another cyclonic circulation, centered between 46° and 47°E, and at about 12° 15′N (C2). Larger than C1, this eddy spans much of the width of the gulf, with a diameter of $\sim$225 km. Maximum speeds reached 0.4 m s^{-1}. Immediately east of C2, there is a hint of an anticyclonic circulation at 100 m, which is much more apparent at 300 m and deeper (A1). This eddy has a diameter of $\sim$250 km and similar maximum swirl speeds to C2, $\sim$0.4 m s^{-1}.



[6] The LADCP measurements reveal that these eddies are deep-reaching, extending to 600 m and deeper, i.e., through all the depths where RSW is found (Figure 1d). The diameter of C1 is reduced by about 30% at 600 m depth compared to shallower depths, and swirl speeds have decreased by a similar fraction with maximum $\sim$0.25 m s^{-1}. Eddies C2 and A1 have a similar size at this depth as they do at 300 m, and peak speeds are nearly as high, reaching a maximum of $\sim$0.3 m s^{-1}.

3.2. Vertical Structure

[7] Figure 2 shows vertical sections of salinity and density (upper panels) and LADCP velocity (lower panels) along three sections crossing the eddies (see Figure 1d for section locations). In Section 1 across C1, relatively undiluted RSW is apparent, with salinities up to 37.4 in multiple layers between σ_θ = 27.0–27.5. The deeper isopycnals dome upward by $\sim$100-m, centered at station 143, consistent with a cyclonic geostrophic circulation. Cross-section are considerably more surface-intensified where the flow is over shallower topography. The eddy circulation clearly extends to the sloping bottom.

[8] Section 2 (Figure 2b) illustrates the large horizontal scale of C2 and its deep penetration. The RSW salinity is much reduced here, probably reflecting the rapid stirring and mixing of recently-injected outflow water. Density surfaces are shallowest at stations 181 and 182, where the zonal velocity is zero. Like C1, the velocity structure is surface-intensified. Speeds greater than 0.1 m s^{-1} extend to at least 700 m.

[9] A1 fills nearly the entire width of the gulf at all depths below $\sim$100 m (Figure 2c). Salinity in the RSW layer is even lower, not exceeding 36.3. Consistent with the anticyclonic flow, the deeper density surfaces dip down by about 50–100 m in the middle of the section, centered at station 219. The velocity structure contrasts noticeably from that of both of the cyclones in that it is not surface-intensified. In fact, the eastward flow associated with the eddy at the northern (left) half of the section is entirely subsurface, (see also Figure 1). The eddy velocity extends to near the now deeper, $\sim$2000 m deep sea floor, with speeds > 0.1 m s^{-1} down to 1000 m.

3.3. Impact of Eddies on RSW Spreading Pathways

[10] The eddies described above strongly influence the spreading pathways of RSW in the Gulf of Aden. This is illustrated in Figure 3, which shows salinity on three density surfaces that correspond to the three depths in Figure 1 (note color scale difference in each panel). These depths/densities correspond to layers of equilibrated RSW (salinity maxima). The two shallow salinity maxima equilibrate at or upstream of Perim Narrows, probably due to mixing within the strait.

Figure 1. (opposite) (a) Map showing location of the Gulf of Aden as well as study region during February 2001 REDSOX cruise (stippled area). (b, c) 15-minute average velocity vectors at 100 and 300 m from shipboard ADCP. (d) LADCP velocity vectors at 600 m. Sections numbered 1–3 are shown in Figure 2. (e) Schematic diagram of three large eddies observed during February 2001, cyclones C1 and C2, and anticyclone A1. Bathymetry is shaded in 200-m intervals, and contoured at 100, 500 and 1000 m.

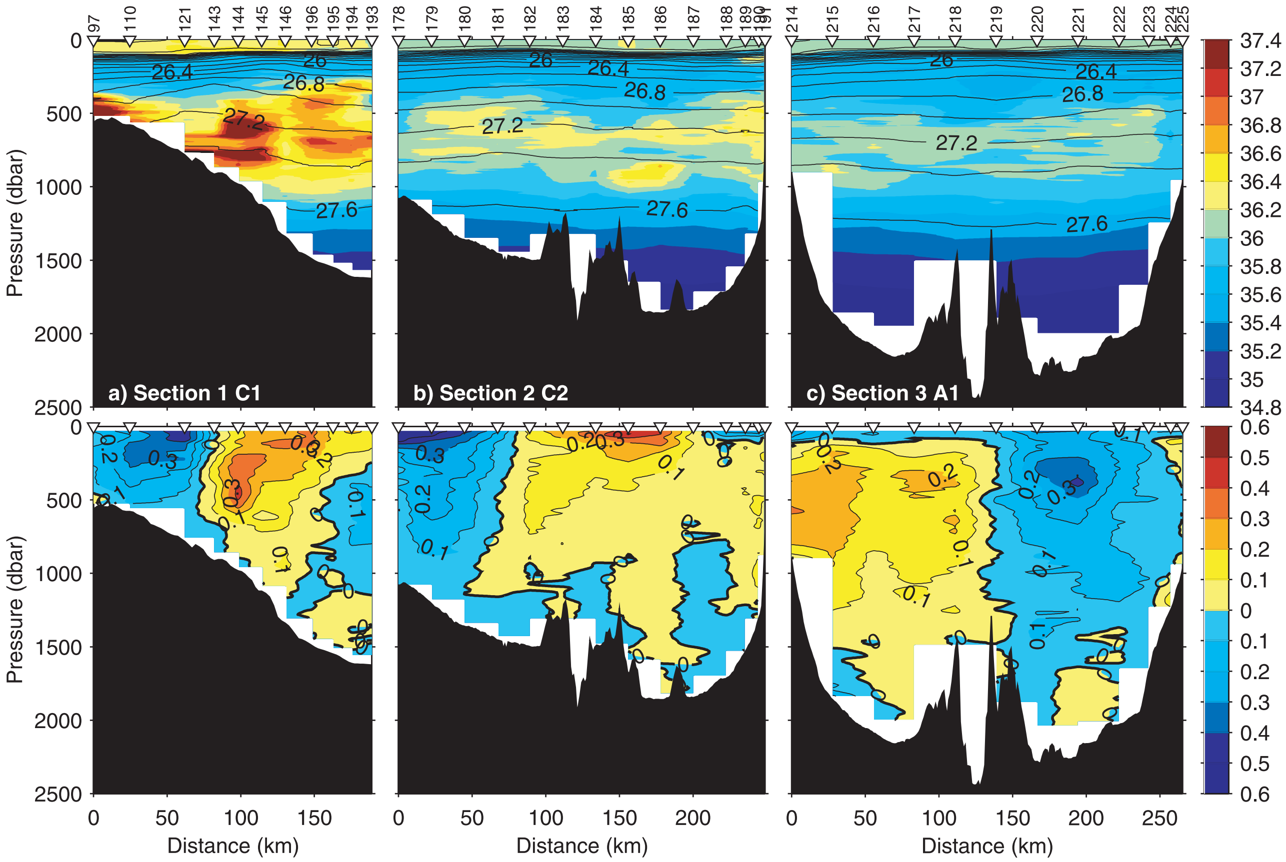


Figure 2. Vertical sections of (upper panels) salinity (color shading) and density (σ_θ; contours) and (lower panels) cross-section component of LADCP velocity (in m s^{-1}) for the three eddies as shown in Figure 1. North end of each section is on left. Station locations and numbers are indicated along top axes.

The deep salinity maximum in Figure 3 is that typically used to trace RSW throughout the Indian Ocean [*Wyrtki*, 1971].

[11] Figure 3a reveals a narrow, barely-resolved vein of high-salinity water along the southern boundary of the gulf, extending to 47°E. Comparison with the SADCP vectors at the same level (Figure 1b) shows that this vein was initially advected by the flow around the southern rim of C1. At Ras Khanzira, the high-salinity vein appears to be caught in the strong shear between C1 and C2, being stretched offshore as well as eastward. Farther north, there is an isolated blob of somewhat less saline water that also appears sheared by the two eddies. The strong shear and dilution of RSW near Ras Khanzira suggest that this may be a region of significant mixing. The salinity field east of this cape is consistent with the advection of diluted shallow RSW (>35.6) along the southern rim of C2 and then northward along 47°E between C2 and A1.

[12] At the middle density surface (Figure 3b), salty is also advected around the southern rim of C1, and a patch is pulled offshore just west of Ras Khanzira, consistent with the smaller diameter of C1 at this depth. A more diluted patch is present north of the cape, also along the rim of C1. The pathways of RSW east of the cape are not clear at this depth.

[13] At $\sigma_\theta = 27.2$, RSW in the far western gulf is confined by the narrow Tajura Rift (Figure 3c). A strong salinity gradient at the mouth of the rift and the narrow confinement of the saltiest water against the Tajura Spur results from the cyclonic circulation around C1, which sweeps the escaping RSW southward. The salty vein is again advected around C1, but in a much tighter loop owing to the smaller diameter of C1 at this depth (see Figure 1d). East of 46°E, the salinity is low and more.

4. Discussion and Summary

[14] One of the specific objectives of REDSOX was to determine if RSW is advected through the Gulf of Aden in a long, narrow boundary undercurrent, like for example the Mediterranean Undercurrent in the Gulf of Cadiz [*Medalian*, 1970]. This had been suggested by [*Bower et al.*, 2000] based on limited historical hydrographic data. The REDSOX salinity and direct velocity measurements indicate however that energetic mesoscale eddies dominated in the spreading of RSW in February 2001. The overwhelming impact of the eddies is highlighted by azimuthal volume transport around, for example, eddy A1, estimated from the LADCP data to be about 21 Sv (about 8.5 Sv in the 400–800 m RSW layer). These eddy transports are at least an order of magnitude larger than the RSW outflow transport in winter.

[15] Our investigation suggests that these eddies may originate in the highly energetic and eddy-rich Somali

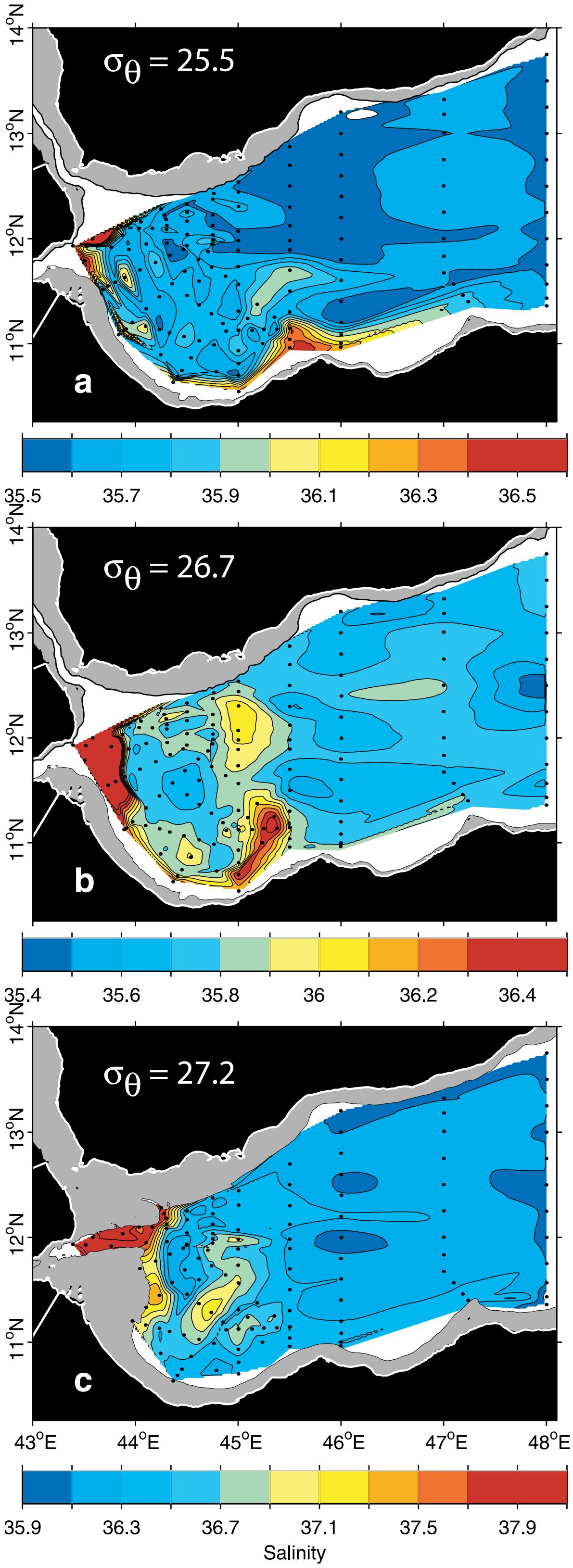


Figure 3. Salinity distribution in the western Gulf of Aden on three density surfaces, σ_θ = 25.5, 26.7 and 27.2, at nominal depths of 100, 300 and 600 m. Note that the salinity range and contour interval in (c) are twice that in (a) and (b).

Current System in the northwestern Indian Ocean. Anticyclone A1 has a core layer centered at σ_θ = 26.7 that is anomalously low in salinity (stations 218–220 in Figures 2c and 3b) and high in dissolved oxygen (not shown). Water with these characteristics is formed in the South Indian Ocean at the subtropical-subpolar transition and advected northward in the Somali Current during the summer monsoon [*Schott et al.*, 1990; *Fischer et al.*, 1996]. *Fratantoni et al.* [2002] remotely observed the generation and westward translation of anticyclonic eddies shed from a portion of the Somali Current near the mouth of the Gulf of Aden. The anomalous water in the core of A1 could have remained trapped as the eddy translated through the gulf since the maximum azimuthal velocity at 300 m (0.2–0.3 m s^{-1}, Figure 2c) is much larger than typical eddy translation speeds of 0.05–0.08 m s^{-1} [*Fratantoni et al.*, 2002]. Ongoing analysis of the REDSOX data sets will further our understanding of the kinematics and dynamics of these large-scale ocean eddies and their role in RSW spreading.

[16] **Acknowledgments.** The authors gratefully acknowledge the crew of the *R/V Knorr* and the technical and research associates for their skill and dedication in carrying out this challenging project. This work was funded by the U.S. National Science Foundation under Grants No. OCE-9818464 (WHOI) and OCE-9819506 (RSMAS) and the U.S. Office of Naval Research under Grant No. N00014-00-1-0688 (WHOI). This is WHOI Contribution Number 10732.

References

Beal, L. M., A. Field, and A. L. Gordon, Spreading of Red Sea overflow waters in the Indian Ocean, *J. Geophys. Res*, *105*(C4), 8537–8548, 2000.

Bower, A. S., H. D. Hunt, and J. F. Price, Character and dynamics of the Red Sea and Persian Gulf outflows, *J. Geophys. Res.*, *105*(C3), 6387–6414, 2000.

Fischer, J., F. Schott, and L. Stramma, Currents and transports of the Great Whirl-Socotra Gyre system during the summer monsoon, August 1993, *J. Geophys. Res.*, *101*(C2), 3573–3587, 1996.

Fratantoni, D., D. Glickson, and A. Bower. Generation of translating Somali Current rings during the southwest monsoon, poster presented at 2002 Ocean Sciences Meeting of the American Geophysical Union, Honolulu, HI, 2002.

Johns, W., H. Peters, R. Zantopp, A. Bower, D. Fratantoni. CTD/O2 measurements collected aboard the R/V Knorr, February–March 2001: REDSOX-1, Technical Report 2001-01, University of Miami, Miami, Florida, 10 pp. plus appendices, 2001.

Madelain, E., Influence de la topographic du fond sur l'écoulement méditerraneen entre le Détroit de Gibraltar et le Cap Saint-Vincent, *Cah. Océanogr.*, *22*(1), 43–61, 1970.

Morcos, S. A., Physical and chemical oceanography of the Red Sea, *Oceanography Marine Biology Annual Review*, *8*, 73–202, 1970.

Murray, S. P., and W. Johns, Direct observations of seasonal exchange through the Bab el Mandab Strait, *Geophys. Res. Let.*, *24*, 2557–2560, 1997.

Schott, F., J. C. Swallow, and M. Fieux, The Somali Current at the equator: Annual cycle of currents and transports in the upper 1000 m and connection to neighbouring latitudes, *Deep-Sea Res.*, *37*(12), 1825–1848, 1990.

Siedler, G., Schichtungs- und Bewegungsverhältnisse am Südausgang des Roten Merres, "Meteor" Forschungsergebn, *Reihe*, *A*(4), 1–76, 1968.

Wyrtki, K., Oceanographic Atlas of the International Indian Ocean Expedition, National Science Foundation, Washington, D. C., 1971.

A. Bower and D. Fratantoni, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA. (abower@whoi.edu)

W. Johns and H. Peters, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149, USA.