GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 22, PAGES 2789-2792, NOVEMBER 15, 1997

Preliminary results from WOCE hydrographic sections at 80°E and 32°S in the Central Indian Ocean

Lynne D. Talley
Scripps Institution of Oceanography, La Jolla, CA

Molly O. Baringer
NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

Abstract. The hydrographic properties and circulation along sections at 80°E and 32°S in March, 1995, in the Indian Ocean are described very briefly. A halocline was well-developed in the tropics. A westward coastal jet of fresh Bay of Bengal water was present at the sea surface at Sri Lanka with eastward flow of saline Arabian Sea water below. The Equatorial Undercurrent was well developed as were the deep equatorial jets. The Indonesian throughflow jet presented a large dynamic signature at 10 to 14°S coinciding with a strong front in all properties to great depth. Its mid-depth salinity minimum is separated from that of the Antarctic Intermediate Water. The Subantarctic Mode Water of the southeastern Indian Ocean imparts its high oxygen ventilation signature to the whole of the transects, including the tropical portion. The deepest water in the Central Indian Basin is pooled in the center of the basin, and its principal source appears to be the sill at 11°S through the Ninetyeast Ridge. Northward deep water transports across the 32°S section were similar to those observed in 1987 but the deep water was lower in oxygen and fresher than in 1987. Upper ocean waters at 32°S were more saline and warmer in 1995.

1. Introduction

Hydrographic work was carried out along WOCE sections I8N along 80°E and I5E along 32°S from March 10, 1995 to April 15, 1995 (Fig. 1 in the overview, Ffield, 1997). The meridional section I8N crossed the Central Indian Basin. The zonal section I5E partially repeated the 1987 crossing of the northward deep water flow west of Australia (Toole and Warren, 1993). A small source of Central Indian Basin deep water at a gap in the Ninetyeast Ridge near 28°S was surveyed and is described by McCarthy et al. (1997) .

All stations were to within 10 meters of the bottom and included a 36-bottle rosette/CTD cast with a lowered acoustic doppler current profiler (ADCP). A ship-mounted ADCP was operated throughout. Basic station spacing was 30 nm, and was reduced at the equator, Sri Lankan and Australian coasts and crossings of the NinetyEast and Broken Ridges. The CTD data stream consisted of elapsed time, pressure, two temperature channels, conductivity, oxygen, altimeter and transmissometer signals. Salinty, oxygen, and nutrients were measured at all stations and bottles. Samples for other chemical tracers were collected on numerous selected stations. Comparisons with preliminary data from the other WOCE legs and with earlier data show that the WOCE data are of uniform accuracy. Significant differences from Geosecs salinity and phosphate are attributable to improved measurement accuracy in the WOCE data.

Potential temperature and salinity (Fig.1) are a good basis for describing the basic features. A more complete description including oxygen, nutrients and ADCP velocity measurements is not possible in this limited space. Velocity estimates are based on geostrophy except as noted, and are preliminary as no attempt has been made to balance mass. Unless otherwise stated, a reference level of zero velocity at the bottom is used. This reference level yields reasonable velocities and transports for a first cut. Transports are reported in Sverdrups (1 Sv = $1x10^6 m^3/sec$).

2. Tropical halocline, Sri Lankan coastal jet and equatorial currents

The meridional section crossed the tropical Indian Ocean squarely in the middle, at its narrowest northern hemisphere location, separating the Bay of Bengal to the east from the Arabian Sea to the west. Surface water in the Bay of Bengal is relatively fresh due to large river runoff. In the Arabian Sea it is saline due to large evaporation. A front between the two waters lies near southern India/Sri Lanka, with large seasonal dependence in its location. On our March section south of Sri Lanka, the surface water was from the Bay of Bengal (salinity < 33.3), overlying saline water from the Arabian Sea (salinity > 35.3). An intense halocline centered at 60 m separated the two waters with approximately a 1.1 salinity change over 10 m. The halocline was deepest off the Sri Lankan coast, associated with a narrow westward coastal jet in the surface layer ($>$ 40 cm/sec, geostrophic) and a narrow eastward jet in the saline layer below. The seasonal westward surface flow is referred to variously as the Northeast Monsoon Current (Schott et al., 1994) or the North Equatorial Current (Tomczak and Godfrey, 1994). Westward transport in the surface jet relative to zero velocity at the bottom is 6 Sv. This estimate is lower than the 10-13 Sv estimated by Schott et al. (1994) from direct velocity observations during the winter months when the current is more intense. The intense portion of the eastward undercurrent, with velocities in excess of 10 cm/sec, extended down to 450 m and coincided with the high salinity core of Arabian Sea origin. The overall subsurface eastward flow between 200 and 2200 meters carried a transport of 26 Sv relative to the bottom. Concurrent LADCP pro-

Paper number 97GL02657.
0094-8534/97/97GL-02657$05.00

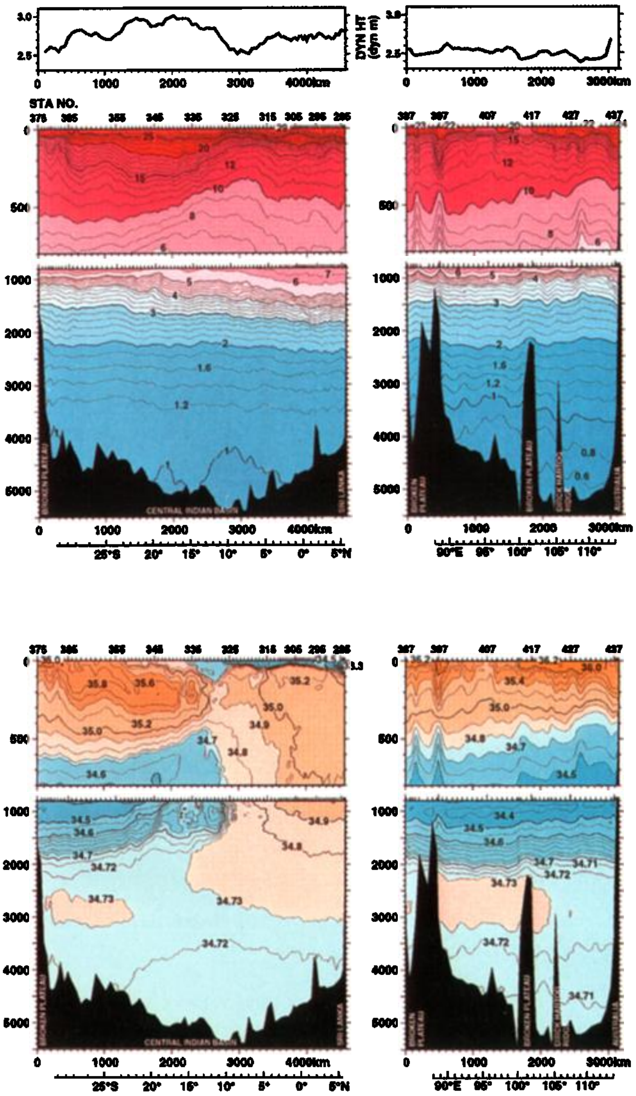

Figure 1. (a) Dynamic height at the sea surface relative to 3000 dbar (dyn m) along I8N at 80°E (left) and I5E at 32°S (right). (b) Potential temperature along I8N at 80°E (left) and I5E at 32°S (right). (c) Salinity along I8N at 80°E (left) and I5E at 32°S (right). Station positions are shown in the map of the Indian Ocean WOCE expedition contained in this issue (Ffield, 1997).

files suggest that the eastward flow might not be this deep so the transport might be overestimated.

The tropical mixed layer temperature sometimes exceeded 31°C in the daytime. Thus the section was within the Pacific/Indian warm pool. Except for a marked diurnal surface heating which affected the upper 10 meters, the surface layer was relatively well mixed to the top of the halocline. Winds were light in this region. On some occasions, when the diurnal heating had produced a thin, warm layer at the top, it was also relatively salty, suggesting that evaporation might contribute to maintaining the vertical uniformity of the mixed layer.

At the equator, surface current velocities were about 70 cm/sec westward. Temperature/salinity/density indicate an eastward undercurrent centered at about 80 m on this March section, in accord with seasonal climatology (Knox and Anderson, 1985). The equatorial currents were confined between fronts at 4°N and 4°S. The freshest surface water lay just outside this equatorial band and the halocline was most intense within the equatorial band. These may be consistent with upwelling of saline water. Brunt-Vaisala frequency and LADCP profiles (neither shown) have short vertical scales to the ocean bottom within 3 degrees of the equator as in the Pacific and Atlantic Oceans, indicating the presence of the stacked equatorial jets (Luyten and Swallow, 1976). Just south of the equator was an eastward equatorial countercurrent, with surface velocities > 70 cm/sec based on both ADCP and geostrophic shear. This current extended to about 1100 m; its eastward transport was about 55 Sv, with 18 Sv in the upper 100 m.

3. The 10°S front and the Indonesian throughflow

A front at about 10°S separates the tropical waters from the Indonesian throughflow jet. The throughflow jet lies between 10 and 14°S, extending zonally westward from Java, carrying a surface-to-intermediate layer of relatively fresh water (Gordon et al., 1997). Oxygen and nutrients in the jet are similar to those of the tropical Indian Ocean. On the southern side of the jet is a major front in oxygen and nutrients, with oxygen increasing towards the south from 2.5 ml/l to 4.5 ml/l at 400 m across 1 degree latitude. The low salinity extends down to about 1200 m and is clearly separated from the Antarctic Intermediate Water (AAIW) core whose salinity minimum is well-developed south of 18°S. We identify the 10-14°S core as being of throughflow rather than AAIW origin because of its low oxygen and higher density and large-scale property maps (not shown). Fieux et al. (1994) observed properties similar to the jet core near Java and concluded that it was a mixture of low oxygen North Indian Deep Water and Banda Sea Intermediate Water. The throughflow jet has the largest surface dynamic height signature for the whole cruise (Fig. 1a), with a 50 cm change and westward surface geostrophic velocities > 30 cm/sec; the ADCP suggests 70 cm/sec (not shown). Geostrophic transport is 21 Sv westward in the top 1500 m, with 6 Sv in the upper 100 m relative to the ocean bottom.

4. Subtropical gyre

South of 14°S lies the oxygen-rich subtropical gyre. An oxygen maximum is apparent to the south along the I8N and I5E sections (Fig. 2) centered at 26.8 σ_θ; this is the northward extension of the Subantarctic Mode Water (SAMW) which is ventilated in the southeastern Indian Ocean (McCartney, 1982). A weak oxygen maximum at the same density extends well north of 14°S. This is the densest water which ventilates the subtropical gyre in the Indian Ocean. Along the I5E section the SAMW is also marked by a potential vorticity minimum, reflecting its origin as a deep convective layer north of the Subantarctic Front (Fig. 2).

The upper subtropical gyre contains the saline Subtropical Underwater extending equatorward from the subtropical evaporation cell. South of a front at 24°S, the highest salinity is at the surface, and rises to greater

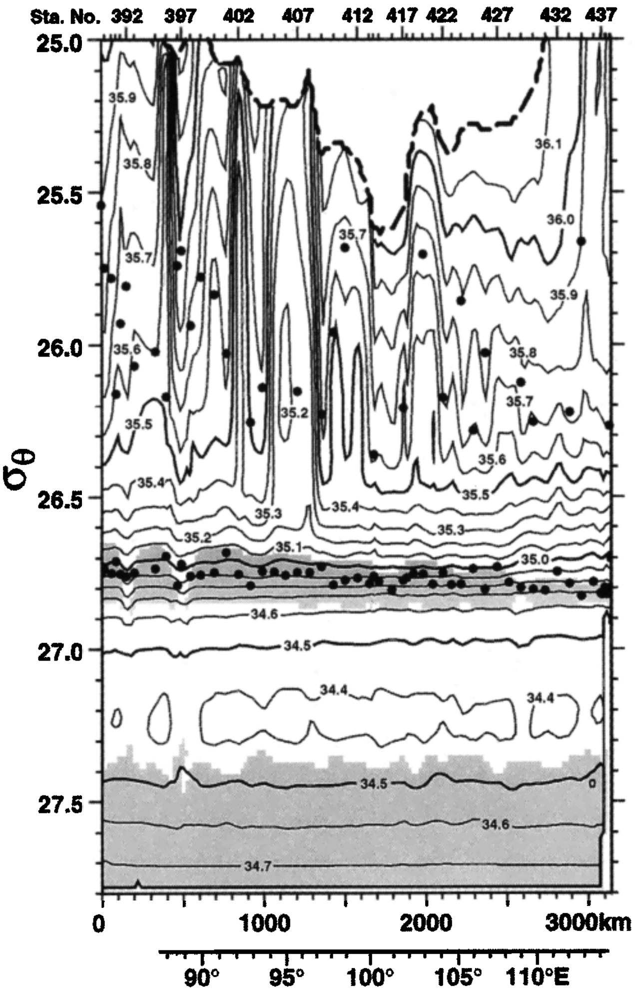

Figure 2. Salinity along the 1995 I5E section with σ_θ as the vertical coordinate. Dots represent the oxygen maximum, marking more recently ventilated waters. Planetary potential vorticity with values less than $60x10^{-14}(cms)^{-1}$ is shaded. The low potential vorticity centered at 26.8 σ_θ, containing an oxygen maximum, is the Subantarctic Mode Water.

than 36.1 psu east of 100°E. Properties are nearly uniform along the isopycnals which lie between 100m depth (26.5 σ_θ) and the AAIW salinity minimum at 27.2 σ_θ, where there is slightly lower salinity between 90°E and 110°E (Fig. 2) .

The intermediate depths are dominated by AAIW, which extends northward to about 24°S before truncation north of 18°S by the throughflow jet and by the saline Indian Ocean Deep Water extending southward from its origin in the north (Red/Arabian Sea).

5. Central Indian Basin deep water

The bottommost water of the Central Indian Basin is fed from the West Australia Basin through gaps in the Ninety-East Ridge (Warren, 1981, 1982). Warren (1982) showed the importance of a sill at 11°S, compared with a smaller sill at 5°S. Toole and Warren (1993) showed a small leakage around 28°S which we sampled in detail (McCarthy et al., 1997). At 80°E the largest bottom puddle of water at 80°E with temperature less than 1°C is centered at 9°S, accompanied by large deep isopycnal slopes, suggesting an 11°S source (Fig. 1b). A secondary bottom pool of cold water lies at 18°S; this is likely a southward extension of the 11°S bottom water (Warren, 1982). The mounding of the Central Indian Basin's deep waters in the middle is characteristic of bottom waters in almost all deep basins of the world ocean except in the presence of strong boundary currents or the ACC. The geostrophic shear is cyclonic within the deep basin (anticyclonic flow around the ridges) relative to the bottom.

The deep water in the layer above the bottommost water enters the Central Indian Basin directly from the south across a broad saddle at about 35°S. The 1987 section (Toole and Warren, 1993) shows the high salinity and high oxygen of this northward-moving Circumpolar Water layer, centered at 3000-3500 m. This layer was evident on our meridional section (salinity maximum at 3000 m south of 21°S in Fig. 1c).

6. Comparison with the 1987 32°S section

East of Broken Ridge, the zonal 32°S section (I5E) crossed the major source of deep water for the eastern Indian Ocean. It crisscrossed the zonal 1987 section (Toole and Warren, 1993; Robbins and Toole, 1997). Property distributions on both the 1987 and 1995 sections show the most saline and highest oxygen deep waters banked to the west against Broken Plateau with fresher and lower oxygen waters to the east (Fig. 1c for 1995). This suggests that the newer water to the west and northward flow there. Salinity, oxygen and nutrients from the 1995 section show the northward 2000-

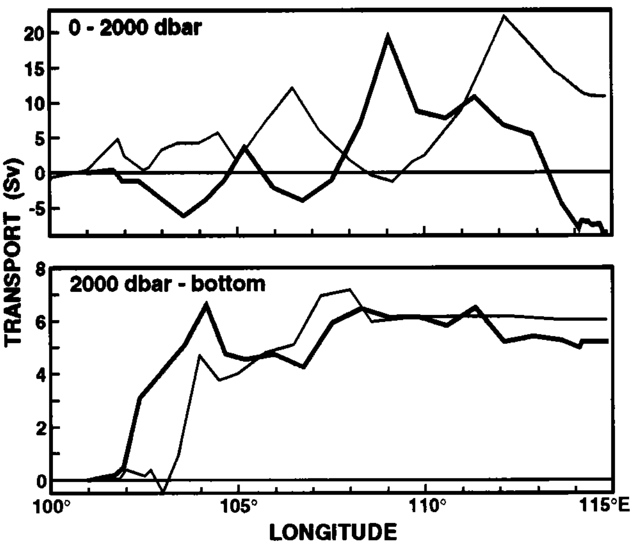

Figure 3. Cumulative geostrophic transport into the Perth Basin integrated from west to east (positive values are northward): (a) above 2000 dbar and (b) below 2000 dbar for the 1995 32°S section (heavy) and the 1987 32°S section (light). Reference levels chosen are described in this text and follow Toole and Warren (1993).

4000 dbar flow confined west of the narrow Dirck Hartog Ridge (DHR) at 106°E.

Preliminary transport calculations (Fig. 3) follow Toole and Warren's (1993) velocity referencing, and rely on water mass identification using silica (not shown here). Between Broken Plateau and the DHR, a shallow zero velocity level above the relatively high salinity near the top of Broken Plateau in the 2000-3000 m range (Fig. 1d) results in northward flow of the deep water. Just west of the DHR, where salinity drops below 34.73, lower salinity and higher silica suggest northern water and the reference is moved deeper to 3000 and 4000 m. Immediately east of the DHR, a reference near 2500 m resulted in small southward transport. Farther east of the DHR, deep isopycnals slope downward into the Australian coast (see the deepest isotherms in Fig. 1b), as also in 1987. To produce deep southward flow in this region, a reference level of 4000 m was chosen except near the Australian coast where the deep isopycnals abruptly rise into the coast (also in 1987) where a 3000m reference level was chosen. The net northward flow is 5.2 Sv below 2000 dbar (6.6 Sv northward in the western boundary current at Broken Plateau; 1.4 Sv southward in the interior) (Fig. 3). Toole and Warren (1993) and Warren (1981) both obtained a net northward flow of 6 Sv (7 Sv boundary current; 1 Sv southward return flow). The general location and magnitude of the deep flows are remarkably similar. One small difference is that the northward flow just east of the DHR was right at the ridge in 1987 but away from ridge in 1995.

Upper ocean transports, above 2000 m, differ strikingly from those in 1987. Toole and Warren (1993) found a net northward flow of surface waters closing the subtropical circulation (> 10 Sv above 2000 m). However the 1995 section shows a net southward flow of surface laters (> 8.5 Sv above 2000m) east of 109°E. The 1987 section showed a net eastward rise of intermediate isopycnals not seen in the 1995 section; in 1987 the 26.8 and 27.26 σ_θ isopycnals rose from 540 to 380 dbar and 1025 to 850 dbar respectively between 100 and 115°E. This large 1987-1995 difference may reflect seasonality in the Leeuwin current, which has maximum southward flow during March-April (Smith et al. 1991). We found 5.8 Sv of southward near surface flow above 150 dbar, similar to the 6.2-6.8 Sv found during March-June 1987 by Smith et al. (1991), while Toole and Warren report only 0.7 Sv southward during the opposite season.

Isopycnal salinities and potential temperatures in and above the SAMW (26.6-26.8 σ_θ) were higher by about 0.05 psu and 0.3°C in 1995 compared with 1987. Silica was about 0.5 umol/kg higher and oxygen was about the same. At higher densities, from the core of the AAIW down to above the high salinity Circumpolar Water, salinity and potential temperature in 1995 were about 0.01 psu and 0.1°C higher than in 1987. Silica was about 5 umol/kg higher and oxygen 0.1 to 0.2 ml/l lower in 1995 compared with 1987.

The core of the saline Circumpolar Water (high salinity at 2500-3500 m in Fig. 1c) and the waters below to the bottom were fresher by about 0.003 to 0.005 psu, silica was 5 umol/kg higher, and oxygen was 0.1 ml/l lower in 1995 compared with 1987. If these two sets of measurements are comparable in accuracy, and it is expected that they are, then it appears the waters measured in 1995 were older than in 1987 from the AAIW down to the bottom.

Acknowledgments. This work was funded by the National Science Foundation Ocean Sciences grant OCE-9413160. Data were collected and processed by the Scripps Oceanographic Institution's Oceanographic Data Facility. We thank the captain and crew of the R/V Knorr for their support.

References

Fieux, M., C. Andre, P. Delecluse, A.G. Ilahude, A. Kartavtseff, F. Mantisi, R. Molcard, and J.C. Swallow, Measurements within the Pacific-Indian oceans throughflow region, *Deep-Sea Res.*, *41*, 1091-1130, 1994.

Ffield, A., WOCE Indian Ocean expedition, *Geophys. Res. Lett.*, *this issue*, 1997.

Gordon, A.L., S. Ma, P. Hacker, L.D. Talley, D.B. Olson, A. Ffield, and D. Wilson, Advection and diffusion of Indonesion Throughflow within the Indian Ocean South Equatorial Current, *Geophys. Res. Lett.*, *this issue*, 1997.

Knox, R.A., and D.L.T. Anderson, Recent advances in the study of the low-latitude ocean circulation, *Prog. Oceanogr.*, *14*, 259-317, 1985.

Luyten, J.R., and J.C. Swallow, Equatorial undercurrents, *Deep-Sea Res.*, *23*, 999-1001, 1976.

McCarthy, M.C., L.D. Talley, and M.O. Baringer, Deep Upwelling and Diffusivity in the southern Central Indian Basin, *Geophy. Res. Lett.*, *this issue*, 1997.

McCartney, M.S., Subtropical recirculation of mode waters, *J. Mar. Res.*, *40(Suppl)*, 1982.

Robbins, P.E. and J.M. Toole, The dissolved silica budget as a constraint on the meridional overturning circulation of the Indian Ocean, *Deep-Sea Res.*, *in press*, 1997.

Schott, F., J. Reppin, J. Fischer, and D. Quadfasel, Currents and transports of the monsoon current south of Sri Lanka, *J. Geophys. Res.*, *99*, 25127-25141, 1994.

Smith, R.L., A. Huyer, J.S. Godfrey, and J.A. Church, The Leeuwin Current off Western Australia, 1986-1987, *J. Phys. Oceanogr.*, *21*, 323-345, 1991.

Tomczak, M. and J.S. Godfrey, Regional Oceanography: an Introduction, Pergamon Press, 422 pp, 1994.

Toole, J.M., and B.A. Warren, A hydrographic section across the subtropical South Indian Ocean, *Deep-Sea Res.*, *40*, 1973-2019, 1993.

Warren, B.A., Deep circulation of the World Ocean, Evolution of Physical Oceanography, MIT Press, 6-41, 1981.

Warren, B.A., The deep water of the Central Indian Basin, *J. Mar. Res.*, *40(Suppl)*, 823-860, 1982.

Lynne D. Talley, Scripps Institution of Oceanography, La Jolla, CA 92093-0230 USA (e-mail: ltalley@ucsd.edu)

Molly O. Baringer, NOAA/AOML, Miami, FL 33149 USA (e-mail: baringer@aoml.noaa.gov)

(Received April 28, 1997; revised July 11, 1997;
accepted August 25, 1997.)