Preliminary Results From a WHP Section in the Central Indian Ocean

Lynne D. Talley, Scripps Institution of Oceanography, La Jolla, CA 92093-0230, USA, and Molly Baringer, NOAA/AOML, 4301 Rickenbacker Causeway, Miami, FL 33149

Work carried out along WOCE section I8N/I5E occupied on RV Knorr (10 March 1995 to 15 April 1995), was described briefly in Talley (1995). The section crossed the centre of the Central Indian Basin and repeated the 1987 crossing of northward deep water flow west of Australia (Toole and Warren, 1993). A small source of Central Indian Basin deep water was surveyed. The cruise track, Columbo south along 80°E (I8N) then east along 32°S (I5E), was shown in the September issue of the newsletter; updated versions are available through netscape or ftp (ftp://nemo.ucsd.edu/woce/plots, click on woceind_label.gif). A cruise report and vertical sections are available from Talley (ltalley@ucsd.edu) and a condensed version of this note with additional figures can be found at http://www.aoml.noaa.gov/general/project/phodmob4.html.

Potential temperature was shown in the previous issue (Talley, 1995); salinity along the 80°E and 82°S sections (Figs. 1a and b) is a good basis for description of the basic features. Velocity/transport estimates listed below 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.

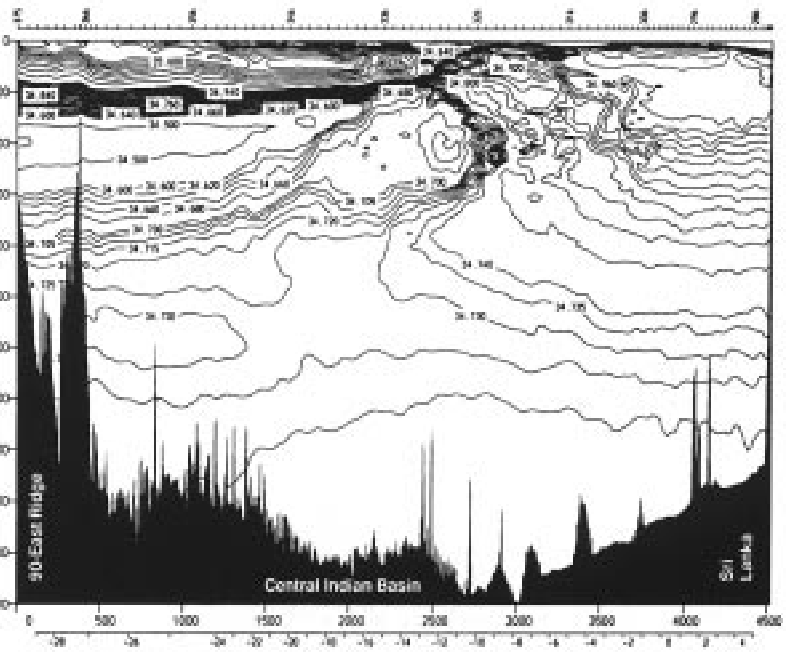

Figure 1a. Salinity along I8N at 80°E.

Surface and intermediate water masses and geostrophic currents

Fresh surface water (<33.3 off Sri Lanka and <34.2 at 5°S) extends southward from Sri Lanka to a front at 10°S and originates in the north-eastern Indian Ocean. Below the fresh surface water lies an intense halocline centred mostly around 60 m depth with approximately a 1.1 psu change over 10 m. The saline water (>35.3) just below the halocline is of Arabian Sea origin. The halocline is deepest off the Sri Lankan coast, where there appears a narrow westward coastal jet in the surface layer (>40 cm s^{-1}), and a narrow eastward jet in the saline layer below down to 400 m (>10 cm s^{-1}); the eastward flow appears to extend as deep as 2200 m. Westward transport in the surface jet may be 6 Sv; eastward transport below is about 30 Sv.

Temperature/salinity/density indicate an equatorial undercurrent centred at about 80 m on this March section, in accord with climatology (Knox and Anderson, 1985). The westward surface current has velocities of about 70 cm s^{-1}. The equatorial currents are confined between fronts at 4°N and 4°S, and the low salinity surface water is higher than north and south of this equatorial channel; the halocline is also more intense at the equator. Brunt-Väisälä frequency and LADCP profiles show short vertical scales

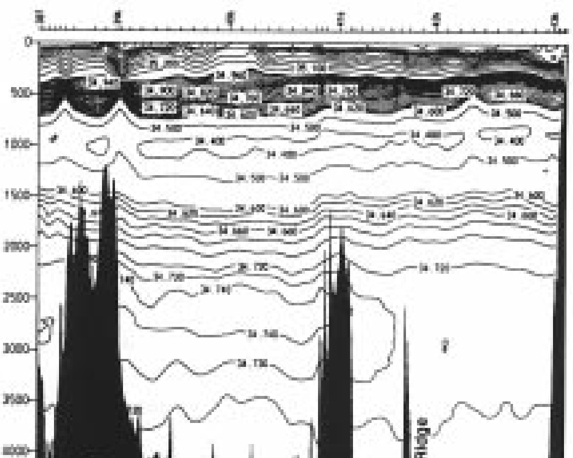

Figure 1b. Salinity along I5E at 32°S.

to the ocean bottom within 3 degrees of the equator like in the Pacific and Atlantic Oceans, suggesting stacked equatorial jets (Luyten and Swallow, 1976). Just south of the equator is a strong eastward equatorial countercurrent, with surface velocities >70 cm s^{-1} based on both ADCP and geostrophic shear. This current extends to about 1100 m; its eastward transport is about 55 Sv, with 18 Sv in the upper 100 m.

A strong front at about 10°S separates the tropical waters from the Indonesian throughflow jet. This jet lies between 10° and 14°S and appears to extend zonally westward from Java, carrying a surface-to-intermediate layer of relatively fresh water. Oxygen and nutrients in the jet are similar to those of the tropical Indian Ocean. On the southern side of the jet is a marked 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 through the Antarctic Intermediate Water (AAIW) level, although the jet's low salinity core is separated from the fresh AAIW core south of 18°S. We identify the core as being of throughflow rather than AAIW origin because of its low oxygen and higher density. 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 on both sections, with a 50 cm increase and westward surface geostrophic velocities >30 cm s^{-1}; the ADCP suggests 70 cm s^{-1}. Geostrophic transport is 21 Sv westward in the top 1500 m, with 6 Sv in the upper 100 m.

South of 14°S lies the subtropical gyre. A strong oxygen maximum exists to the south along I8N and I5E sections centred at 26.8σ_θ; this is the northward extension of the Subantarctic Mode Water (SAMW) which is ventilated in the southeastern Indian Ocean. A weak O_2 minimum 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 Sub-antarctic Front.

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 than 36.1 psu east of 100°E. Below 100 m along I5E there is almost no variation in water properties on isopycnals down to the AAIW core, which has very slightly lower salinity east of 90°E (Fig. 2).

On the eastern end of the I5E section is the southward-flowing Leeuwin Current. Net transport relative to the bottom is 12 Sv, and is confined to within 2–3 degrees of the coast and to the upper 1200 m. Beneath it the flow is weak (Fig. 3).

The intermediate depths are dominated by AAIW, which extends northward to about 24°S before truncating north of 20°S by the throughflow jet and by the saline Indian Ocean Deep Water extending southward from its origin in the north (Red/Arabian Sea). The global distribution and importance of the tropical boundary near 20°S for AAIW are being described elsewhere.

Sources of deep water for the Central Indian Basin

The Central Indian Basin is far removed from the southern bottom water source since its bottommost water is fed from the east across 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 that there could be a small leakage into the Central Indian Basin around 28°S. Our section confirms the importance of the 11°S sill – the largest puddle of water at 80°E with temperature <1°C is centred at 9°S (Talley, 1995), accompanied by the largest deep isopycnal slopes, suggests an 11°S source. A secondary bottom puddle of cold water lies at 18°S; this is probably 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 (anti-

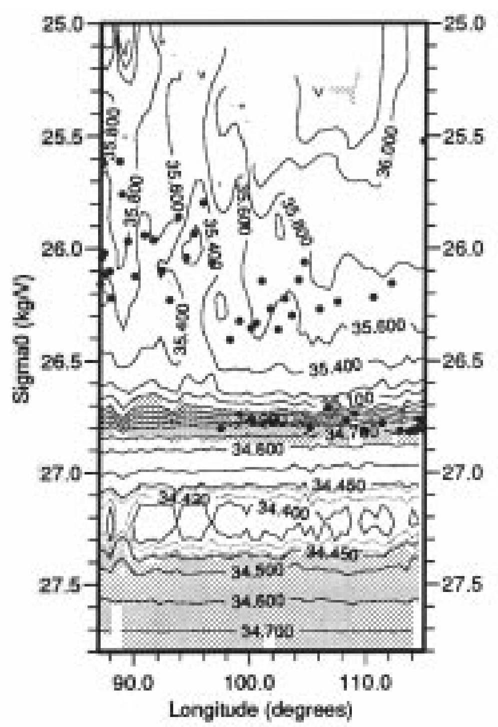

Figure 2. Salinity along the 1995 I5E section with sigma theta as the vertical coordinate. Dots represent the O_2 maximum, marking more recently ventilated waters. Planetary potential vorticity with values less than 60 E-14 $(cm\ s)^{-1}$ are shaded, also marking waters of convective origin.

cyclonic flow around the ridges) relative to the bottom.

We found clear evidence of westward flow of bottom water through the 28°S sill into the Central Indian Basin, where it turns to the south. A preliminary, heuristic combination of geostrophic shear and LADCP velocities from the three sill sections suggests a bottom flow on the north side of the central section (probably due to a northern location of the deep channel to the east); the deep flow was 3200 to 4000 m deep, 30 km wide, and 10 cm s^{-1}. An origin east of the Ninety-East Ridge and north of Broken Plateau is indicated by the properties; the layer is colder than 1.2°C, fresher than 34.725 psu and denser than 45.89σ_4. The net transport appears to be about 2 to 2.5 Sv.

The deep water lying above the bottom water does not follow such a circuitous route from the south, but rather enters the Central Indian Basin directly across a saddle at about 35°S. The 1987 section (Toole and Warren, 1993) shows its high salinity and high oxygen, centred at 3000–3500 m.

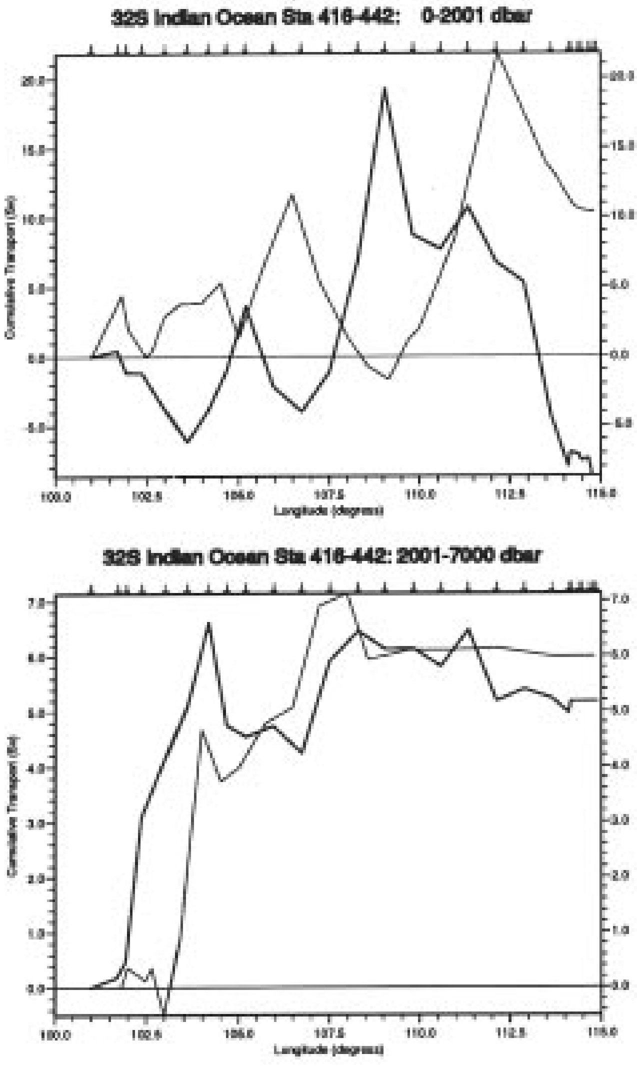

Figure 3. Cumulative geostrophic transport into the Perth Basin (positive values are northward), (a) above 2000 dbar and (b) below 2000 dbar for the 1995 I5E section (heavy) and the 1987 I5 section (light). Reference levels chosen are described in this text and follow Toole and Warren (1993).

Comparison with the 1987 occupation of I5E

The eastward leg of our cruise (Fig. 1b) criss-crossed the 1987 section (Toole and Warren, 1993). The deep flow is northward just east of Broken Ridge on both sections, and southward farther to the east up to Australia, based on property distributions, which show the newest deep and bottom waters banked to the west against Broken Ridge with older waters to the east. Oxygen and nutrients from the new 1995 section show that the northward 2000–4000 dbar flow is confined west of the small Dirck Hartog Ridge. They also show that the deep water which flows north into the Perth Basin is not as new as the deep water which remains south of Broken Plateau.

Preliminary transport calculations follow the spirit of Toole and Warren (1993). Unlike the 1987 section, the deep flow does not narrow significantly with depth. A shallow zero velocity level above the high silica west of the Dirck Hartog Ridge sends this flow northward. Following the break to high silica values the reference is moved deeper to 3000 and 4000 m at Stas 422 and 423. Immediately next to the Ridge a shallower reference near 2500 m reduced the unresolved deep flows to small southward values. To the east of the Ridge deep isopycnals generally slope downward into the Australian coast as was seen in the 1987 section. To produce deep southward flow, a reference level of 4000 m was chosen except near the Australian coast where the deep isopycnals abruptly rise into the coast (also seen in the 1987 section) where a 3000 m reference level was chosen. The net northward flow is 5.2 Sv below 2000 dbar (6.6 Sv northward in the boundary current; 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. Note that at about 107°E Toole and Warren show the last of their boundary current flowing north while the 1995 section shows a northward deep flow of a similar 1.5 to 2 Sv, distinctly separated from the boundary current proper.

The most striking difference between the 1987 and 1995 transports lies above 2000 m. 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 waters (>8.5 Sv above 2000 m) east of 109°E. The 1987 section showed a net rise of intermediate isopycnals not seen in the 1995 section: the 26.8 and 27.26σ_θ isopycnals rose from 540 to 380 dbar and 1025 to 850 dbar respectively between 100° and 115°E. The 1995 section shows no net rise of these isopycnals (435 and 970 dbar, respectively). This large difference may reflect seasonal variability in the

Leeuwin current transport, which has a 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 (1993) report only 0.7 Sv southward during the opposite season.

Isopycnal salinities in and above the SAMW (26.6–26.8σ_θ) were higher by about 0.05 psu in 1995 compared with 1987. Silica was about 3 umol/kg higher and oxygen was about the same. At greater densities, from the core of the AAIW down to just above the high salinity Circumpolar Water, salinity in 1995 was about 0.01 psu 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 CPW 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 that from the AAIW down to the bottom, the waters measured in 1995 were older than in 1987.

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Maurice Ewing Symposium on 'Applications of Trace Substance Measurements to Oceanographic Problems'

Peter Schlosser, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964-8000, USA

In mid-October 65 scientists from seven countries met at the seventh Maurice Ewing symposium to consider the applications of the measurement of trace substances to oceanography. Anticipating the acquisition of the management of Biosphere 2, Columbia University scientists Schlosser, Smethie and Broecker decided to use this symposium to assess the potential of this site for scientific meetings. The organizers were pleased with the results. Not only were the participants wowed by the host of new results and challenged by syntheses of existing tracer data sets but they were captivated by the beauty of the site, the friendliness of its personnel, and the mystique of the Biosphere itself. The meeting was a great success.

Wally Broecker, a pioneer in this field, was particularly pleased to see that tracer oceanography was at last coming of age. For too long it had remained a prodigal son not fully embraced by the physical oceanographic community. The blossoming of this field awaited the development of numerical models capable of simulating tracer fields. This effort has its roots over a decade ago in work by the modelling groups at Princeton and at Hamburg, but only in the last few years has the interplay between observation and models become a two-way street. Modellers are making use of tracers to verify and improve their simulations, and observationalists are taking note of the power of the models in designing strategies for future tracer measurements. Long convinced that the power of tracer measurements lay primarily in its application to basin and larger scale oceanographic processes, the organizers were pleased to note the greater emphasis being placed on this way of looking at the results.

The meeting topics included global circulation, thermocline ventilation, deep water formation, boundary currents, oceanic variability, integration of tracers in models, tracer release experiments, ocean/atmosphere gas exchange, tracers as proxies for anthropogenic CO_2, and new technologies and methodologies. It was clear that the production of the WOCE data set, which will provide the first 'complete' global tracer survey with high spatial resolution, is well underway. WOCE tracer data are available in the community and are already widely used, especially by a new generation of young scientists who are educated in physical oceanography or ocean modelling. Faster delivery of tracer data to the WOCE data centres was strongly encouraged as a means to efficiently integrate these data into a larger synthesis effort.

Coloured maps of the Helium and Tritium distribution in the Pacific are available on the World Wide Web:
http://kopernik.whoi.edu/wpac/wpac.html