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A hydrographic section across the subtropical South Indian Ocean

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Abstract—Features of the water-property and circulation fields at the southern limit of the continentally bounded Indian Ocean are described on the basis of a transoceanic hydrographic section occupied along roughly Lat. 32°S by the R.R.S. *Charles Darwin* in November–December 1987. Primary observations consisted of 106 full-depth CTD/O_2 stations with discrete measurements of the concentrations of dissolved silica, phosphate and nitrate. The section lies in the southern part of the South Indian subtropical gyre; water-property features in the upper kilometer indicate that the northward interior flow is predominantly in the eastern half of the ocean there, consistent with the forcing pattern of wind-stress curl. The southward return flow is the Agulhas Current, whose transport at Lats 31–32°S is estimated as 85×10^6 m^3 s^{-1}. Circumpolar Deep Water flows northward to fill the greater deep Indian Ocean by means of western-boundary currents in the Crozet Basin, Central Indian Basin and Perth Basin. North Atlantic Deep Water entering directly from the mid-latitude South Atlantic is almost entirely confined to the southwestern Indian Ocean (Mozambique Basin, Natal Valley) by the topography of the Madagascar Ridge and Mozambique Channel.

Geostrophic transport figures are presented based on a zero-velocity surface constructed along the section from the tracer-property evidence of where deep water was moving northward and where southward. Ekman transport, deduced from shipboard acoustic-Doppler profiler measurements, as well as synoptic and historical wind stress data, is found to be small (about 1×10^6 m^3 s^{-1} northward). Net transport (geostrophic and Ekman) across the section is estimated to be 7×10^6 m^3 s^{-1} southward, which implies a similarly sized Indonesia throughflow. Ambiguity in the geostrophic referencing scheme, and the magnitude of baroclinic eddy noise on the section, suggest this figure is uncertain by at least $\pm 10 \times 10^6$ m^3 s^{-1}. The calculations obtain a figure for net transport of water below 2000 dbars of 27×10^6 m^3 s^{-1} northward, which specifies an average upwelling speed at the 2-km level north of 30°S of 6.9×10^{-5} cm s^{-1}. This estimate, perhaps uncertain by 20–30%, nonetheless contributes to growing evidence for an anomalously vigorous meridional circulation in the Indian Ocean. The associated calculations of heat and fresh water flux divergences demonstrate that the Indian Ocean thermohaline circulation essentially expresses a conversion of bottom and deep water to mid-depth thermocline, and near-surface water.

1. INTRODUCTION

EQUATORWARD of approximately Lat. 35°S, the South Indian Ocean is confined by the continents of Africa and Australia. The average wind stress, which is predominantly eastward south of 32°S and westward farther north (e.g. HELLERMAN and ROSENSTEIN, 1983), acts on these waters to drive a strong subtropical circulation consisting of an

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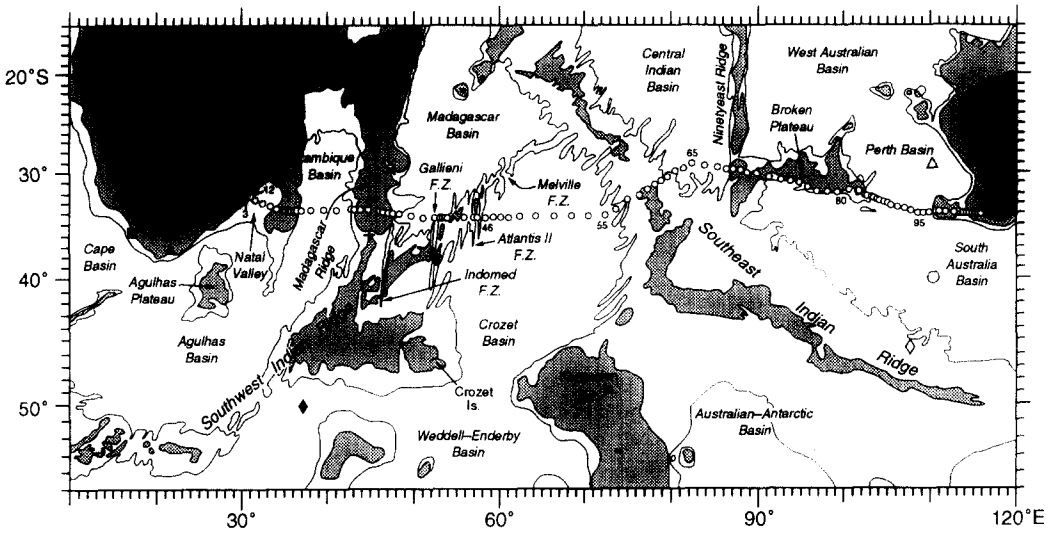

Fig. 1. Index map for the South Indian Ocean identifying geographical features mentioned in text and showing positions of hydrographic stations cited. Isobaths of 3 and 4 km simplified after GEBCO Sheet 5.00; areas shallower than 3 km are stippled. Small open circles designate positions of Stas 3–109, R.R.S. *Charles Darwin* Cruise 29, 13 November–16 December 1987. Other stations are coded as: Ajax Sta. 61 (■); *Conrad* Cruise 17, Stas 269 (▲), 282 (◆); GEOSECS Stas 434 (◇), 435 (○), 436 (△); *Discovery II* Cruise 164, Stas 11404 (×), 11411 (+), 11451 (*).

equatorward interior flow and a poleward western-boundary current. The boundary flow in this case is the Agulhas Current, which rivals the Gulf Stream of the Atlantic in terms of total volume transport (GRÜNDLINGH, 1980). Unlike the Atlantic, however, the Indian Ocean is essentially closed to the north at tropical latitudes. A net gain of heat (HASTENRATH and LAMB, 1979) and buoyancy is thus experienced by this ocean. As a consequence, no convectively generated deep or bottom waters are produced in the Indian Ocean. Rather, these waters are imported from other basins (specifically the Atlantic and Southern Oceans) or formed *in situ* by mixing. The thermohaline circulation of the Indian Ocean thus represents a conversion of these imported cold, dense waters to warmer waters, just the opposite of the North Atlantic in which thermocline waters are converted to deep water (e.g. HALL and BRYDEN, 1982).

In order to document the net water-mass property exchanges of the Indian Ocean with the rest of the world's oceans, and to quantify the strengths of the currents that effect those exchanges, we occupied a hydrographic section between Africa and Australia along approximately 32°S (Fig. 1). The section, conducted from the R.R.S. *Charles Darwin* during Cruise 29 in November–December 1987, Durban to Fremantle, consists of 106 full-ocean-depth stations. This paper will present a general description of those observations with reference to profile plots of temperature, salinity, and the concentrations of dissolved oxygen, silica, phosphate, and nitrate (Fig. 2a–f). In doing so, repeated reference will be made here to a companion transindian section at 18°S that was occupied in 1976 (WARREN, 1981), and the Oceanographic Atlas of the International Indian Ocean Expedition (WYRTKI, 1971).