Reports

Deep Western Boundary Current in the Eastern Indian Ocean

Abstract. *Historical temperature data suggest that the deep circulation of the eastern Indian Ocean is a system separate from that in the west, with its water being supplied directly from the south. If so, then circulation theory would require that the northward flow take the form of a narrow western boundary current along the Ninetyeast Ridge. Recent observations demonstrate the existence of this current, and indicate a volume transport for it of about 4 × 10^6 cubic meters per second.*

Circulation theory (*1*) requires that western boundary currents transport deep water away from its high-latitude sources and refill the major ocean basins from their western sides. In the western Indian Ocean such a current, about 400 km wide and lying below a depth of 3000 m, has been located in the Madagascar and Mascarene basins close against Madagascar (*2*). It represents a northward flow of cold deep water from the Antarctic, apparently passing through the Crozet Basin en route to the Madagascar Basin (Fig. 1). At the 4000-m level the potential temperature increases gradually toward the equator along this path, and it continues to do so north of Madagascar, through the Somali and Arabian basins (*3*), which is consistent with replenishment of the deep water in those basins by the deep Madagascar current.

To the east of the Mid-Indian Ridge, however, the 4000-m potential temperature is markedly lower in the Central Indian Basin than in the Arabian Basin and probably lower than in the Somali Basin; farther east, beyond the Ninetyeast Ridge, it is distinctly lower in the West Australian Basin than in any of the other three (*3*). This eastward decrease of temperature is not easily rationalized with a deep eastward flow away from a cold-water source; it suggests instead that water from the deep Madagascar current may be blocked by the ridge system and limited to the western Indian Ocean. Indeed, although the deep Central Indian Basin appears to be closed off to the south, the West Australian Basin is open to the Antarctic at depths greater than 5000 m near longitude 106°E (*3*), and there is no kinematic reason why deep water could not enter the West Australian Basin directly from the south rather than from the west. If such a northward flow occurs, then the dynamical arguments of deep circulation theory (*1*) would require that it take the form of a narrow current along the Ninetyeast Ridge—the western boundary of the West Australian Basin. Unfortunately, historical data have been much too widely scattered (*3*) to tell whether (or not) such a current exists.

An opportunity to settle the point was provided recently while carrying out a hydrographic section along latitude 18°S from Madagascar to Australia aboard R.V. *Atlantis II* (7 July to 19 August 1976). On the eastern flank of the Ninetyeast Ridge, and in the western part of the West Australian Basin, deep stations were occupied at intervals of 15 to 200 km, depending on bottom depth and proximity to the ridge; the observations were generally made 200 to 300 m apart vertically (never more than 400 m) and always within 100 m of the bottom. Properties measured were temperature, salinity, and the concentrations of dissolved oxygen, silica, phosphate, and nitrate.

Below about 4500 m, the water in the West Australian Basin was found to be nearly homogeneous, but at depths between 3 and 4 km and in a zone extending 600 km from the Ninetyeast Ridge (about one-quarter the width of the basin) the isotherms slope downward to the east, the 1.2°C isotherm, for example, descending from 3500 to 4200 m. By the thermal-wind relation, the direction of the associated horizontal density gradient requires northward movement of the deep water in this zone relative to that at mid-depths. Farther to the east, the temperature field is comparatively feature-

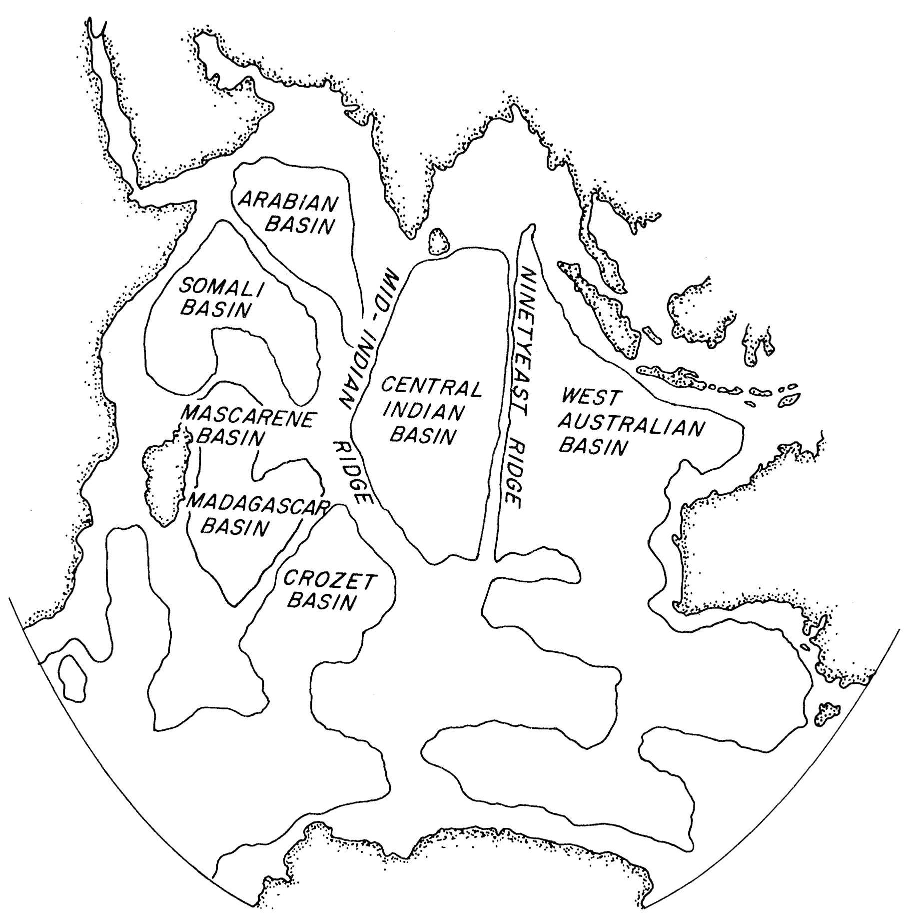

Fig. 1. Index map of the Indian Ocean, identifying basins and ridges mentioned in the text. A coarse representation of the 4-km isobath is also included.

less, and the deep western boundary current therefore stands out clearly. Within the current itself there is evidently a concentration of flow very close to the ridge, because the isotherms descend 200 to 300 m within about 30 km of it—and this is virtually the total depth change for isotherms in the interval 3000 to 3500 m.

Of the other properties measured, the silica values most usefully supplement and clarify the temperature structure. In the western part of the West Australian Basin a slight silica maximum was generally found in the depth interval 3 to 4 km, the maximum values being about 130 μg-atom/liter or a little greater, as contrasted with values of 120 to 125 μg-atom/liter in the bottom water. Immediately adjacent to the Ninetyeast Ridge, however, where the isotherms descend so abruptly, the values in the interval 3 to 4 km are lower and the maximum is absent. This pattern is strikingly like that observed in the deep western boundary current of the subtropical South Pacific (*4*), although on a reduced scale. The latter distribution has been explained (*5*) in terms of a boundary-current field having (i) a concentrated northward flow close to the western boundary from about 2000 m to the bottom, carrying water from the Antarctic with a relatively low silica concentration; and (ii) a weaker flow farther to the east that is northward at great depth but southward above about 3600 m, transporting water with a relatively high silica concentration from the North Pacific in the interval 2000 to 3600 m. Since the deep northern Indian Ocean, like the North Pacific, is a source of high-silica water (*3*), the silica distribution observed in the West Australian Basin suggests a qualitatively similar velocity structure for the Ninetyeast Ridge current.

Geostrophic estimates of the volume transport of the current depend, of course, on the choice of a "level of no motion." If the meridional velocity component is assumed to be zero at 3000 m, just above the levels where isotherms slope downward to the east, then the density field gives a net transport of 7×10^6 m^3/sec northward, through a section extending from 3000 m to the bottom, and 600 km to the east of the ridge. The silica distribution, however, suggests a more likely surface of zero velocity as lying at 3000 m within about 30 km of the ridge and at 3700 m (just below the silica maximum) farther to the east. Calculated on this basis, the net transport below the zero-velocity surface, and, again, within 600 km of the ridge, works out to be 4×10^6 m^3/sec (northward). Both figures are comparable to previous estimates (*2*) of the transport of the deep Madagascar current: 4 to 5×10^6 m^3/sec. The maximum calculated speed in the Ninetyeast Ridge current is found at the base of the zone of steeply sloping isotherms adjacent to the ridge and is 6 cm/sec.

The scheme of deep circulation originally proposed by Stommel and Arons (*1*) postulated boundary currents only along the western sides of oceans because, for simplicity, it disregarded the ridge systems that divide oceans into multiple basins. If these ridges rise high enough above the ocean floor, however, they can prevent deep flow between the basins and require separate circulation systems in them. It is then a consistent refinement of the theory that each such basin should have its own western boundary current; and the Ninetyeast Ridge current, supplying the deep water of the West Australian Basin, is clearly one. Whether the Central Indian Basin is also supplied by that current—some part of it perhaps passing across the Ninetyeast Ridge—is not yet clear.

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References and Notes

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Wood Versus Fossil Fuel as a Source of Excess Carbon Dioxide in the Atmosphere: A Preliminary Report

Abstract. *If the amounts of wood consumed in deforestation to increase agricultural land and as firewood in underindustrialized countries are added to the amount consumed by the money economies as forest products, the estimates of the net amount of wood removed from the biosphere in this century should be revised upward. The per capita ratio of the weight of carbon from net wood burned to the weight of carbon from fossil fuel burned in this century has been at least 0.1 and may have approached 1.0.*

The recent reports of a worldwide shortage of firewood (*1*) led to the suggestion that the amount of wood burned may have been underestimated; particularly questionable is the conclusion that the combustion of fossil fuel was the major cause of the buildup of CO_2 in the atmosphere (*2*, *3*). Garrels *et al.* (*4*, p. 308) have recently reviewed the CO_2 cycle through geologic time, stating that "we hope someday to be able to simulate the real world with a model sufficiently complex that the results obtained from it will have some valid predictive value." Even the primary production of the biosphere is not sufficiently well understood (*5*). A preliminary reexamination of the scant data available on deforestation indicates that there has been a substantial underestimation of the net CO_2 produced from deforestation. This underestimate arises from an overemphasis on data from routine economic statistics and an inaccurate extrapolation to the whole world of the more comprehensive data from the few highly industrialized countries with money economies.

Table 1 contrasts the annual per capita consumption of fossil fuels and wood in the United States and Brazil for 1970. The direct commercial usage estimates in the money economies are well documented (*6*, *7*). In the United States the net loss of forest land to agricultural purposes in the period from 1962 to 1970 was estimated by the U.S. Forest Service to be 500,000 acres (2000 km^2) per year (*6*). The forest land lost to urbanization, the construction of highways and reservoirs, and the increased recreational uses of forests is as difficult to estimate as the amount of wood cut and burned by the rural poor, including moonshine distillers. At the upper limit, we estimate that, excluding the commercial forest products industry in the United States, some 0.2 metric ton of carbon in wood are lost annually per capita in clearing and noncommercial activities. If we take this upper limit of 0.2 ton per capita and assume that the managed forests in the United States are near a steady-state condition (plantings equal cuttings plus losses), it would appear that the carbon from net wood loss in the United States is at most only 2 percent or so of that from fossil fuels. Such, however, is not the case in most of the world.

In Brazil (see Table 1), at least 75 percent of the direct cutting is for firewood