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GRL special section: WOCE Indian Ocean expedition

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The World Ocean Circulation Experiment (WOCE) is the most ambitious global oceanographic program ever undertaken. The program combines *in situ* measurements of unprecedented quality and coverage with state-of-the-art satellite observations and modeling. The Indian Ocean expedition is one part of the WOCE field endeavor, with other expeditions covering the Pacific, Atlantic, and Southern Oceans. Focusing on 1995, the Indian Ocean was intensively sampled by the international oceanographic community using a fleet of oceanographic research vessels and relying on the cooperation and resources of many countries (Figure 1). In technique and scope the expedition far surpasses the last great coordinated Indian Ocean effort, the International Indian Ocean Expedition of the 1960s [*Wyrtki*, 1971].

As with all of the ocean basins, tropical heating of Indian Ocean water must be eventually vented to the atmosphere. In the Atlantic and Pacific Oceans this can be accomplished by advective heat transport to both the northern and southern poleward colder latitudes. The Indian Ocean is unique in that Asia blocks an ocean route to the northern poleward regions. While in the Indian Ocean the Agulhas Current carries heat to the southward poleward latitudes, there is not a northern counterpart, such as the Gulf Stream in the Atlantic Ocean, or the Kuroshio Current in the Pacific Ocean. Without a direct northward route in the Indian Ocean, other mechanisms must help balance the heat (and freshwater) budget.

An overall goal of WOCE is to understand the general circulation of the global ocean well enough to be able to model its present state and predict its evolution in relation to long-term changes in the atmosphere [*WCRP*, 1986; *U.S. WOCE Science Steering Committee*, 1996]. Each of the major oceans is unique and somewhat isolated due to geography. Yet to adequately model and predict the impact of the oceans on climate, our understanding of each ocean - and in particular its unique attributes - must be advanced.

The tropical Indian Ocean is dominated by the Asian monsoon, the singular most important climate feature of the northern Indian Ocean [*Hastenrath and Greischar*, 1993; *Webster*, 1994]. A general issue is how and with what efficiency is the Indian Ocean's monsoon regime north of 10 °S, coupled to the more typical subtropical ocean regime to the south. Possibly, the accumulated tropical ocean heat is removed by the atmosphere rather than being advected to the south by the ocean. For example, the very warm sea surface temperatures may drive more vigorous evaporation that can enhance the strength of the Asian Monsoon. Much of the water lost to evaporation is then returned to the Indian Ocean (Bay of Bengal) as river runoff balancing a large portion of the hydrological cycle. In addition, Ekman wind-driven overturning in the northern regions of the Indian Ocean, primarily in the Arabian Sea, allows cooler subsurface water to reach the surface where it is warmed and spreads southward. However, it is not clear how this shallow overturning cell is coupled with the larger scale requirement for warm water movement to colder southern latitudes.

As in all oceans, the Indian Ocean meridional fluxes involve more than just the upper ocean: The full ocean depth participates in the balancing heat and freshwater fluxes. The source and spreading pattern of deep and bottom water, within and between the many small basins characteristic of the Indian Ocean is more complicated and far less resolved than it is in other oceans [*Warren*, 1994; *Mantyla and Reid*, 1995; *Lee and Marotzke*, 1997]. There is a suggestion that the Indian Ocean's meridional circulation is more vigorous than it is in other oceans. The abundance of Indian Ocean submarine ridges produce a greater ratio of boundary area to ocean volume than in the Atlantic and Pacific Oceans. As ocean mixing may be concentrated at the bottom boundary of the ocean [*Polzin et al.*, 1997], the diapycnal mixing coefficient for the Indian Ocean may be larger, as well as the associated overturning circulation.

Another unique attribute of the Indian Ocean is its access to neighboring oceans. All of the oceans are linked through the deep Antarctic circumpolar belt, but only the Indian Ocean thermocline has open boundaries at temperate and tropical latitudes with both its neighbors: the Pacific Ocean by way of the Indonesian Seas and south of Australia, and the Atlantic Ocean across the Agulhas Retroflection immediately south of Africa. Traces of Pacific water passing through the Indonesian Seas are found across the Indian Ocean within the South Equatorial Current near 12 °S. To balance the global circulation, this water must eventually find its way to the circumpolar belt and return to the Pacific Ocean. Exactly how it does this, and to what extent it involves the Atlantic Ocean and larger scale thermohaline circulation is a point of contention [*Schmitz*, 1995; *MacDonald and Wunsch*, 1996; *Gordon*, 1996]. Nonetheless, these interocean links are important components of the requirement to move equatorially warmed water to poleward latitudes.

This special section on the WOCE Indian Ocean expedition presents an early assessment of some of the interesting attributes of the Indian Ocean. By using observations and models important advances to key research issues of the Indian Ocean are accomplished, improving the description, understanding, and simulation of the Indian Ocean. The special section papers in this *Geophysical Research Letters* issue focus on four areas: the monsoon regime north of 10 °S [*Chereskin et al.*, *Haines et al.*, *Howell et al.*, *Morrison*, *Rhein et al.*, *Schott et al.*], the Indonesian Seas interocean link [*Bray et al.*, *Gordon et al.*, *Jean-Baptiste et al.*], the more typical subtropical ocean regime to the south of 10 °S [*Ffield et al.*, *Karstensen and Tomczak*, *Schodlok and Tomczak*, *Schodlok et al.*, *Talley and Baringer*], and deep and bottom waters [*Hufford et al.*, *McCarthy et al.*, *Quadfasel et al.*].

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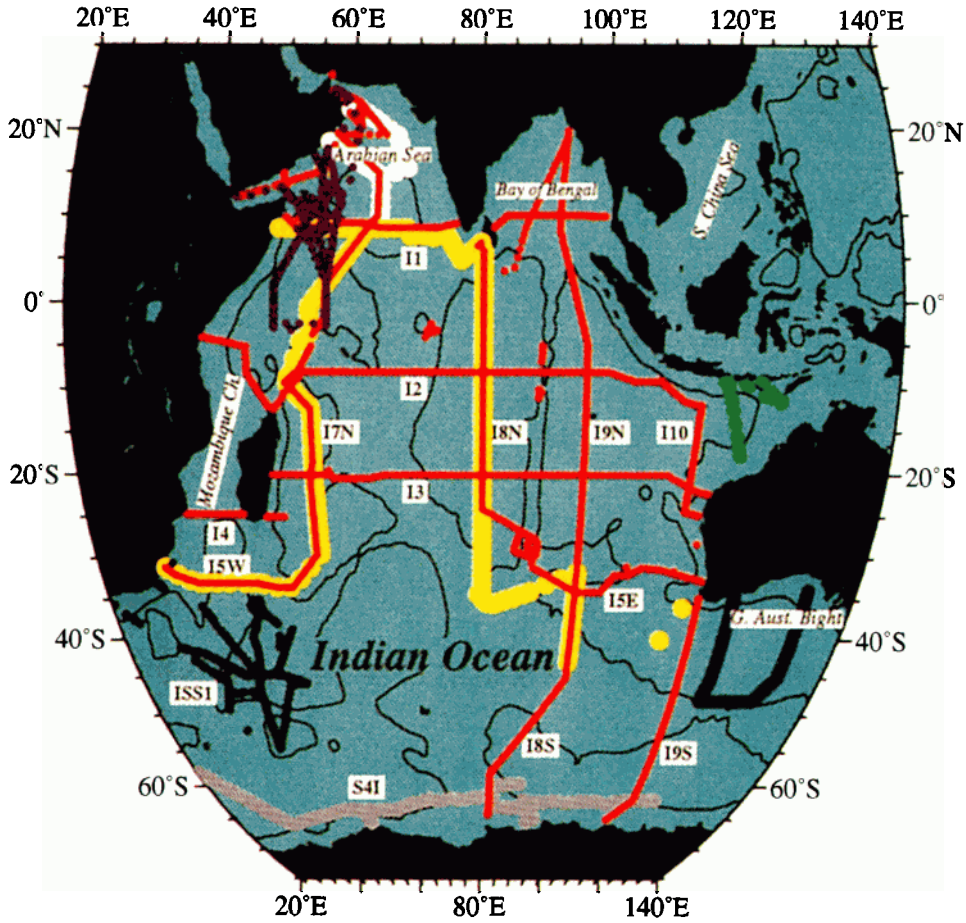

Figure 1. Map of the Indian Ocean showing the location of the WOCE hydrographic stations used in this collection of papers. The stations are coded by research vessel: Discovery, 1993 and 1995 (black); Dufresne, 1989 and 1992 (green); Franklin, 1994 (blue); Meteor, 1995 (purple); Thompson, 1995 (white); Baldrige, 1995 (yellow); Knorr, 1995 (red); and Palmer, 1996 (gray). Thin black lines indicate the smoothed 4000 m bathymetry contours.

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References

Gordon, A. L., Communication between oceans, *Nature*, 382, 399-400, 1996.

Hastenrath, S., and L. Greischar, The monsoonal heat budget of the hydrosphere-atmosphere system in the Indian Ocean sector, *J. Geophys. Res.*, 98, 6869-6881, 1993.

Lee, T., and J. Marotzke, Inferring meridional mass and heat transports of the Indian Ocean by fitting a general circulation model to climatological data, *J. Geophys. Res.*, 102, 10585-10602, 1997.

MacDonald, A. M., and C. Wunsch, An estimate of global ocean circulation and heat fluxes, *Nature*, 382, 436-439, 1996

Mantyla, A. W., and J. L. Reid, On the origins of deep and bottom waters of the Indian Ocean, *J. Geophys. Res.*, 100, 2417-2439, 1995.

Polzin, K. L., J. M. Toole, J. R. Ledwell, and R. W. Schmitt, Spatial variability of turbulent mixing in the abyssal ocean, *Science*, 276, 93-96, 1997.

Schmitz, W. J., On the interbasin-scale thermohaline circulation, *Rev. Geophys*, 33, 151-173, 1995

U.S. WOCE Science Steering Committee, *U.S. WOCE Synthesis Plan*, 18 pp., U.S. WOCE Planning Report Number 16, U.S. WOCE Office, College Station, TX, 1996.

Warren, B. A., Driving the meridional overturning in the Indian Ocean, *Deep-Sea Res.*, 41, 1349-1360, 1994.

Webster, P. J., The role of hydrological processes in ocean-atmosphere interactions, *Rev. Geophys.*, 32, 427-476, 1994.

WCRP, *Scientific plan for the World Ocean Circulation Experiment*, 83 pp., WCRP Publication Series No. 6, WMO/TD-No. 122, 1986.

Wyrtki, K., *Oceanographic atlas of the International Indian Ocean Expedition*, 531 pp., Nat. Sci. Found., Washington, D.C., 1971.

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