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By Raleigh R. Hood and S. Wajih A. Naqvi

The Indian Ocean (IO) remains one of the least studied and most poorly understood ocean basins. The atmospheric circulation in the region has many unique characteristics which stem in large part from the presence of the Asian land mass, and this forcing gives rise to a wide variety of physical, biogeochemical and ecological responses that are not observed in other ocean basins. The monsoonal forcing results in highly seasonal surface oceanic circulations throughout the northern IO, especially in the Arabian Sea (AS). The IO also has a unique equatorial circulation and thermal structure opposite to those found in the Atlantic and Pacific oceans, and as a result there is no strong equatorial upwelling signal or biological response in the east. Moreover, the IO experiences anomalous climatic events and perturbations such as the Madden-Julian Oscillation, Wyrtki jets, and the Indian-Ocean Dipole Zonal Mode. All of these unique forcings have ecological and biogeochemical consequences, however, most of these consequences are not fully understood and many have not yet been characterized. One other unique aspect of the oceanography of the IO is that it contains one of the most intense oxygen minimum zones (OMZs) in the world oceans, but unlike the Atlantic and Pacific oceans, the IO OMZ is located in the north rather than occurring along the eastern boundary. This, again, is due to the unusual geographical setting, climate and circulation of the IO because of which the most intense upwelling anomalously occurs in the northwestern sector (off Oman and Somalia). The resultant higher subsurface respiration rates combine with limited oxygen supply (caused by the lack of local sources of deep waters) to produce near-total oxygen depletion within a 1 km-thick layer in the AS. This, in turn, leads to reducing conditions and several polyvalent elements are biologically transformed into their lower oxidation states. The most important among them is nitrogen, the easily bioavailable “fixed” forms of which (mostly nitrate) are converted to the inert gaseous forms (molecular nitrogen (N_2) and nitrous oxide (N_2O)) by denitrifying bacteria. This makes the AS one of the most important sites of water column denitrification and an important source region of atmospheric N_2O.

Over 200 scientists from all over the world attended the SIBER meeting in Goa.

In an effort to define the existing gaps in our knowledge, the SIBER (Sustained Indian Ocean Biogeochemical and Ecological Research) workshop was convened in Goa, India, October 3-6, 2006. The event, hosted by India's National Institute of Oceanography (NIO), included 4 days of presentations, posters and working group discussions with participation by more than 200 scientists from all over the world. The overarching goals of the workshop were: to review the state of our knowledge of the biogeochemical and ecological dynamics of the Indian Ocean; define the major scientific questions that need to be addressed; and formulate a plan for future international research in the IO. The seven workshop themes were: 1) atmosphere-ocean interactions, 2) nutrient cycling and limitation, 3) biological production and remineralization, 4) pelagic carbon cycling and air-sea exchange, 5) anthropogenic impacts, 6) benthic biogeochemistry and ecology and 7) future plans and technologies. The working groups, which were organized around these themes, were charged with summarizing the information that was presented, identifying scientific questions and making recommendations for future research.

Another important motivation for the SIBER workshop has been the planned implementation of a mooring array in the IO as part of the CLIVAR/GOOS observing system. This basin-wide array is designed to study climate variability and oceanic response, and it will complement existing arrays in the Atlantic and Pacific oceans. This deployment provides a unique opportunity for leveraging long-term meteorological and physical measurements and mooring support cruises for making complementary ecological and biogeochemical measurements.

The presentations and working groups identified numerous gaps in our knowledge and defined several major scientific questions. For example, there is still a pressing need for carrying out first-order basin-wide descriptive science; that is, we need to better characterize and understand the many unique aspects of the IO circulation and the ecological and biogeochemical responses associated with the monsoon forcing and other phenomena like the Indian Ocean Dipole, the Madden-Julian Oscillation, Wyrtki jets, etc. There are major questions and hypotheses that emerged from previous studies (especially from the Joint Global Ocean Flux Study), such as the potential role of mesozooplankton grazing in limiting phytoplankton production during the Southwest Monsoon (SWM) in the AS, that still remain to be tested. This is in contrast to the information from recent field and modeling studies, which suggests that low iron levels in surface waters may limit phytoplankton production during the late SWM in the western AS. Indeed, questions about the role of iron limitation extend over the entire basin; that is, it is probably reasonable to assume that the IO sector of the Southern Ocean is also iron limited, but there is very little information on Fe concentrations and/or Fe limitation further north.

Another interesting observation that is yet to be satisfactorily explained is that while the minimum oxygen concentration in the Bay of Bengal (BoB) is lower by no more than 2 µM than that in the Arabian Sea, the BoB remains precariously poised at the denitrification threshold. What is the relative role of biological oxygen demand versus circulation in maintaining such subtle differences in the oxygen field but large differences in biogeochemical cycling and fluxes in the two basins? Another OMZ-related issue concerns the relative importance of denitrification and the anaerobic ammonium oxidation (anammox) in the production of N_2. Recent results of N_2/Ar measurements show a large excess of N_2 over the amounts expected from the computed 'nitrate deficits'. To what extent this mismatch arises from anammox, degradation of non-Redfieldian organic matter, or other factors is yet to be fully resolved. Also unknown are the contributions of aerobic and anaerobic respirations within continental margin sediments, which according to some preliminary data, might be substantially different from other oceanic margins (e.g., low sulphate reduction rates). There is very little information available on benthic biogeochemical and ecological processes in the northeastern Indian Ocean (BoB and Andaman Sea) where there are broad shelves with high rates of organic matter loading from riverine sources. It must also be pointed out that the bulk (~60%) of the total global oceanic area of the continental margins exposed to natural oxygen deficiency (< 0.5 $mL.L^{-1}$) is found in the Indian Ocean, which in conjunction with the high population density and rapid economic growth in the surrounding countries, makes the coastal environments particularly vulnerable to anthropogenic perturbations. Finally, we still have an extremely poor characterization of rates of open ocean nitrogen fixation. There is tantalizing evidence from satellites, supported by the geochemical signatures (nitrogen isotopes and gas ratios), which suggests that N_2-fixation rates may be very high in the AS, the BoB and the southern IO, but the limited field measurements have shown much lower N_2-fixation than suggested by the isotopic data. Thus, while it is generally agreed that the IO plays an important role in global nitrogen cycle, including modulation of the oceanic nitrogen inventory on the geological time scale, we still do not have enough information to adequately quantify the fluxes involved.

Climate change and the carbon cycle are also major issues. The IO is warming faster than any other ocean basin and may therefore provide a sentinel for ecological and biogeochemical impacts of global warming in other ocean basins. There is also some evidence which suggests that the monsoon winds may be intensifying due to global warming. This is based on the satellite data which indicate that the upwelling and associated phytoplankton blooms during the SWM may be becoming more intense. Moreover, there are still large uncertainties related to the role of the IO in the global carbon cycle. There is insufficient data to fully characterize air-sea CO_2 exchange in the IO basin and there appear to be major discrepancies in some regions of the northern IO basin between the estimated air-sea carbon flux (i.e., CO_2 outgassing) versus the apparent net metabolic balance (i.e., net autotrophy).

Finally, the IO (primarily the BoB and the eastern IO rim) is subject to significant riverine injections, with globally significant annual freshwater discharges. The freshwater is accompanied by terrigenous inputs such as dissolved inorganic nutrients, dissolved and particulate organic carbon and other elements. Some of the highest rates of nutrient export inferred from global models are from watersheds in South Asia, a region that accounts for about 1/5 of the global synthetic nitrogen fertilizer utilization, and where the human population is predicted to increase markedly over the next 50 years. The expected further increases in inputs of N and P to coastal ecosystems and consequent deterioration of coastal water quality will have a large impact on chemical fluxes and ecology of not only the coastal areas but well beyond the continental margins.

The Indian Ocean is, indeed, one of the last great frontiers for ocean biogeochemical and ecological research, and the SIBER workshop has provided crucial information that will allow us to summarize the state of our understanding and define the major questions that need to be addressed. The major planned workshop products will include a special issue and/or a monograph of research and/or overview papers that were presented at the meeting and ultimately a science plan for guiding future research in the IO basin. This plan will be developed with a view toward having SIBER develop as a major regional research program of IMBER.