SIBER and IOP: Joint activities and science results

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1. Introduction to SIBER

The Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program is an emerging basin-wide, international research initiative sponsored jointly by the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project and the Indian Ocean Global Ocean Observing System (IOGOOS) (Hood et al., 2011). The long-term goal of SIBER is to understand the role of the Indian Ocean in global biogeochemical cycles and the interaction between these cycles and marine ecosystem dynamics.

SIBER has been motivated by the deployment of coastal and open-ocean observing systems in the Indian Ocean that have created new opportunities for carrying out biogeochemical and ecological research. As described in Yu et al. (2012), the Indian Ocean Panel (IOP) is coordinating the deployment of a basin-wide observing system in the Indian Ocean (the Indian Ocean Observing System, IndOOS, which includes the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction, RAMA). These deployments, which are already well underway, are accompanied by efforts to maintain the Argo float network and a variety of physical oceanographic survey and mooring support cruises. In addition, several nations in the Indian Ocean are deploying coastal observing systems. These observatories, which are focused primarily on physical measurements, provide foundational infrastructure that can support a wide variety of biogeochemical and ecological studies in both coastal waters and the open ocean. SIBER is a decade-long (Figure 1), multidisciplinary international effort that is designed to leverage these observing systems and other international programs in order to advance our understanding of biogeochemical cycles and ecosystem dynamics of the Indian Ocean in the context of climate and human-driven changes.

2. The emergence of SIBER and its linkage to the IOP

CLIVAR formed IOP in 2004 as an international committee charged with the duty of guiding sustainable ocean observing and climate research in the Indian Ocean: the IOP activities focus primarily on physical processes, e.g., atmosphere and ocean circulation and air-sea exchange at intraseasonal, interannual and multi-decadal time scales. The overarching goal of the IOP is to improve our understanding of the physical dynamics of the Indian Ocean and its teleconnections with the other ocean basins, with a view toward improving models and prediction. The IOP leadership recognized from its start the importance of establishing meaningful interdisciplinary ties and collaborations aimed at understanding how physical processes impact biogeochemical cycles and particularly air-sea CO_2 exchange and carbon export. Toward this end, they established a tradition of inviting chemists, biologists and ecologists to attend their annual panel meetings. The lead author of this article was invited to attend the 2006 IOP meeting in Hawaii. At that time the IOP was planning IndOOS/RAMA. However, in 2006 there was no equivalent panel or committee to act as a compliment to the IOP for guiding biogeochemical and ecological research in the Indian Ocean. The identification of this gap was the motivation for developing the SIBER program, i.e., to address the need for an international committee/program that can guide biogeochemical and ecological research in the Indian Ocean and capitalize on this opportunity to "piggy back" this research on emerging physical oceanographic studies and infrastructure buildup in the basin.

After several years of meetings, planning and negotiation the SIBER program emerged under IMBER and IOGOOS with close ties to the IOP. The connection to the IOP is maintained in two ways. First, cross membership between the IOP and SIBER Scientific Steering Committee (SSC) is arranged to promote continuous communication and exchange between the two groups. Second, the SIBER SSC and the IOP convene back-to-back meetings every year, which include a joint session to explicitly discuss ongoing and potential new interdisciplinary collaborations. Typically, several members of the SIBER SSC (composed mostly of biological, chemical and fisheries oceanographers) attend the entire IOP (composed mostly of physical oceanographers and atmospheric scientists) meeting and vice versa. This co-convening of annual meetings provides an important forum for a group of scientists to learn about ongoing and planned research in the Indian Ocean in disciplines outside their own. Though, perhaps, the most important function of these meetings is to provide an opportunity to get to know one another, which helps to foster long-term interdisciplinary collaborations.

3. Research themes, implementation strategy and timeline

The SIBER Science Plan and Implementation Strategy (Hood et al., 2011) ultimately emerged from concepts that were formulated and discussed at the first SIBER Conference convened in Goa, India in October 2006 (Hood et al., 2007, Hood et al., 2008) involving more than 200 participants, and significantly refined during a second SIBER Workshop convened in Goa, India in November 2007 (Hood et al., 2008) involving 30 participants. Both meetings were interdisciplinary and included scientists from Indian Ocean rim nations, Europe and North America. The information and ideas from these meetings have been condensed into six major research themes, each of which identify key issues and priority questions that need to be addressed in order to improve our understanding of the biogeochemical and ecological dynamics of the Indian Ocean and develop a capability to predict future changes. These themes can be broadly separated into three that are regionally focused and three that address broad scientific questions.

Regional Scientific Themes:

Theme 1: Boundary current dynamics, interactions and impacts *(How are marine biogeochemical cycles and ecosystem processes in the Indian Ocean influenced by boundary current dynamics?)*

Theme 2: Variability of the equatorial zone, southern tropics and Indonesian Throughflow and their impacts on ecological processes and biogeochemical cycling *(How do unique physical dynamics of the equatorial zone of the Indian Ocean impact ecological processes and biogeochemical cycling?)*

Theme 3: Physical, biogeochemical and ecological contrasts between the Arabian Sea and the Bay of Bengal *(How do differences in natural and anthropogenic forcing impact the biogeochemical cycles and ecosystem dynamics of the Arabian Sea and the Bay of Bengal?)*

General Scientific Themes:

Theme 4: Controls and fates of phytoplankton and benthic production in the Indian Ocean *(What are the relative roles of light, nutrient and grazing limitation in controlling phytoplankton production in the Indian Ocean and how do these vary in space and time? What is the fate of this production after it sinks out of the euphotic zone?)*

Theme 5: Climate and anthropogenic impacts on the Indian Ocean and its marginal seas *(How will human-induced changes in climate and nutrient loading impact the marine ecosystem and biogeochemical cycles?)*

Theme 6: The role of higher trophic levels in ecological processes and biogeochemical cycles *(To what extent do higher trophic level species influence lower trophic levels and biogeochemical cycles in the Indian Ocean and how might this be influenced by human impacts, e.g., commercial fishing?)*

The implementation plan for SIBER is divided into three major areas of science activity: 1) remote sensing studies, 2) modeling studies, and 3) in situ observations that all have the potential for leveraging existing physical observational infrastructure (See the SIBER Science Plan and Implementation Strategy for details at http://www.incois.gov.in/Incois/siber/siber.jsp or http://www.imber.info/index.php/Science/Regional-Programmes/SIBER). The timeline for SIBER meetings and symposia that have been convened to date and that are planned for the future are detailed in Figure 1.

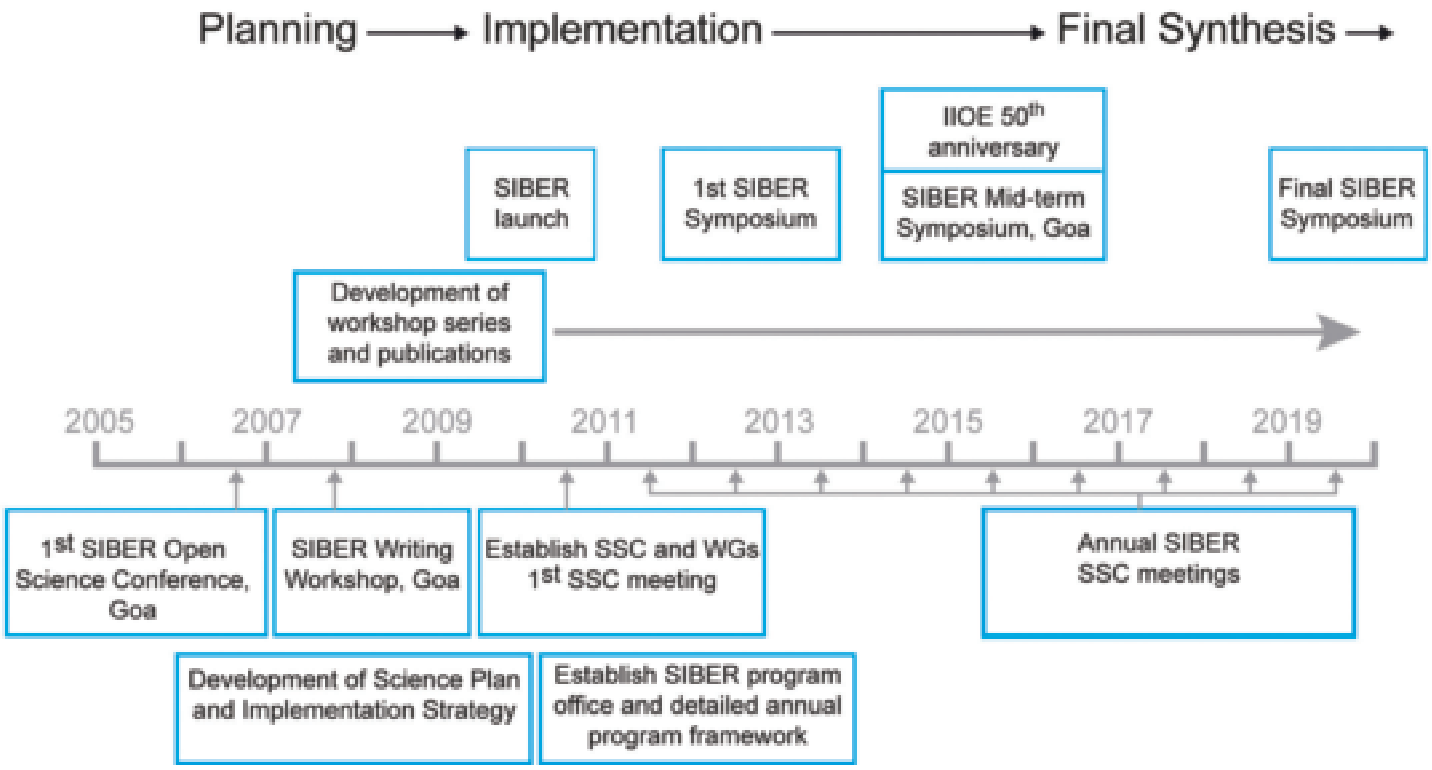

Fig 1: SIBER Program timeline from Hood et al. (2011)

4. Some emerging science activities and results

Several on-going interdisciplinary research activities have been instigated by SIBER and the IOP or have benefited from the programmatic framework that this linkage provides. For example, the 2006 SIBER conference motivated an interdisciplinary modeling study of the physical and biological factors that determine the spatial distribution of the oxygen minimum zone in the Arabian Sea (for a preview of this study see McCreary et al., 2011). The Arabian Sea Oxygen Minimum Zone (OMZ) is one of the most intense open-ocean OMZs in the world, with near-total depletion of oxygen at depths from 200 to 1000 m (e.g., Morrison et al., 1998). Yet, the physical and biological factors that determine the location and intensity of this feature have not been quantified and few, if any, models have successfully reproduced it. Of particular interest is the "eastward shift" of the upper OMZ into the central and eastern basin of the Arabian Sea. This shift is surprising because biological production is the largest in the western basin due to upwelling off Somalia and Oman. McCreary et al. (2011) have succeeded in simulating the major features of the observed oxygen field in the Indian Ocean, including the eastward shift (Figure 2).

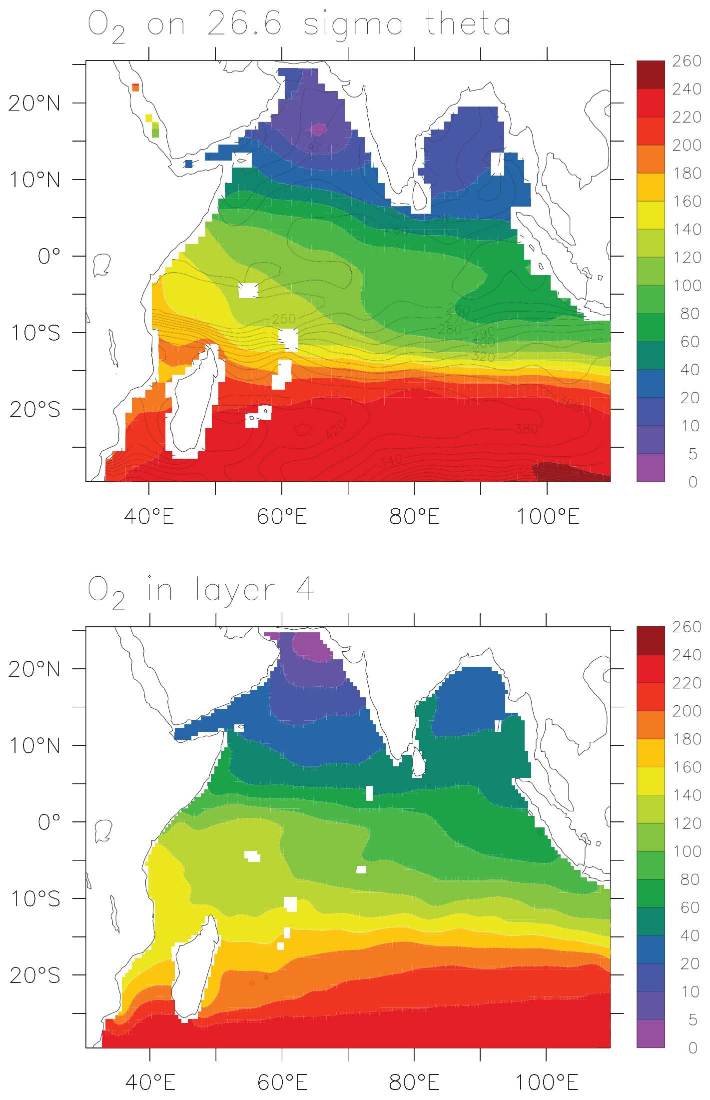

Fig 2: Maps of annual-mean oxygen concentrations from WOA05 on the 26.6-σ_θ surface (top) and from layer 4 (upper OMZ) of the physical model (bottom). Figure and caption modified from McCreary et al. (2011).

Among other things, they concluded that the eastward shift of the upper Arabian Sea OMZ results from two causes: 1) primarily northward advection of oxygenated waters along the western boundary of the basin; and 2) eddy-enhanced horizontal mixing, which is more vigorous along the west coast. In addition, they stressed that the remineralization and sinking rates of detritus must be sufficiently low for these two processes to impact the oxygen budget.

Similarly, exchanges between physical and biological oceanographers at joint SIBER/IOP meetings have led to new interdisciplinary collaborations focusing on the biogeochemical impacts of the Indian Ocean Dipole (IOD) (e.g., Wiggert et al., 2009). There has been a considerable amount of research over the last decade characterizing how the IOD modifies basin-wide physical variability. Along with this physical response, a clear biological impact has been revealed in ocean color data acquired by remote sensing platforms such as SeaWiFS. The signature feature illustrating IOD alteration of chlorophyll variability is the phytoplankton bloom that first appears in September along the eastern boundary of the Indian Ocean in tropical waters that are normally highly oligotrophic (Figure 3). Positive chlorophyll anomalies are also apparent (albeit less consistently) in the southeastern Bay of Bengal, while negative anomalies are observed over much of the Arabian Sea (Figure 3). Despite the clear basinwide influence of IOD events on biological variability, the accompanying influence on biogeochemical cycling that must occur has received little attention. Using a combination of satellite-derived physical and biological measurements (SST, SSH, surface winds, ocean color and primary production) Wiggert et al. (2009) show that there is a profound redistribution of where primary production and carbon uptake occurs in response to IOD events, with the eastern Indian Ocean deriving a significant enhancement at the expense of the western tropical Indian Ocean and to a lesser degree the Arabian Sea.

Several interdisciplinary studies are ongoing that are focused on the southern hemisphere boundary currents in both the western and eastern Indian Ocean and many of these projects fit both into SIBER Theme 1 and are also of considerable interest to the IOP (for an overview of these projects see Beckley, 2011). For example, studies of the transport by the east Madagascar Current, shelf-edge upwelling in northern Mozambique as well as zooplankton and seabirds associated with Mozambique Channel eddies. In the eastern Indian Ocean, much research relating to IOP interest in the physical dynamics of boundary currents and SIBER Theme 1 is ongoing off the west and northwest coast of Australia. Most of this research is multi-disciplinary and has benefitted from considerable governmental investment in Australia's Integrated Marine Observing System (IMOS) through installation of oceanographic moorings, reference stations, coastal radar, acoustic monitoring and deployment of gliders and Argo floats in the region that are being used to provide the physical observational context for biogeochemical and higher trophic level studies. At IMOS reference stations regular biological measurements are being made and the gliders are collecting fluorescence data.

At present, SIBER and IOP efforts are focused on finding the resources needed to deploy biogeochemical sensors on IndOOS/RAMA moorings (see SIBER SPIS, Appendix IV, available at http://www.imber.info/siber.html). The overarching objectives of this effort are to provide data for: 1) Defining biogeochemical variability in key regions of the Indian Ocean and for understanding the physical, biological and chemical processes that govern it; 2) Developing and validating models of ocean-atmosphere-biosphere interactions; and 3) Assessing the impacts of climate change on oceanic primary productivity and air-sea CO_2 exchange. Some preliminary attempts to deploy biogeochemical sensors on RAMA buoys have been carried out. NOAA instrumented a fluorometer at 25 m depth on one of its buoys deployed on 22 May 2010 at location 80.5E, 0N to measure the chlorophyll concentrations. FIO (First Institute of Oceanography, SOA, China) recently deployed its Bailong Buoy equipped with a pCO_2 system to measure the air-sea CO_2 flux at location 100E, 8S on 28 Feb. 2011 (see Yu et al., 2012). Further plans and funding are now in place to deploy multiple biogeochemical sensor packages on RAMA and Indian moorings in the Bay of Bengal with the generous support from the Bay of Bengal Large Marine Ecosystem project (BOBLME, www.boblme.org).

5. Conclusions and legacy

Collaboration between SIBER and IOP offers a unique opportunity to mobilize the multidisciplinary, international research effort that will be required to develop a new level of understanding of the physical, biogeochemical and ecological dynamics of the Indian Ocean in the context of the global ocean and the Earth System. This understanding will be required to predict the impacts of climate change. It also provides an important new model for carrying out basin-scale interdisciplinary research that can lead to the long-term collaborations needed to achieve this goal. The collaboration between SIBER and the IOP has already fostered several new interdisciplinary studies in the Indian Ocean. This model can and should be applied in the other ocean basins.

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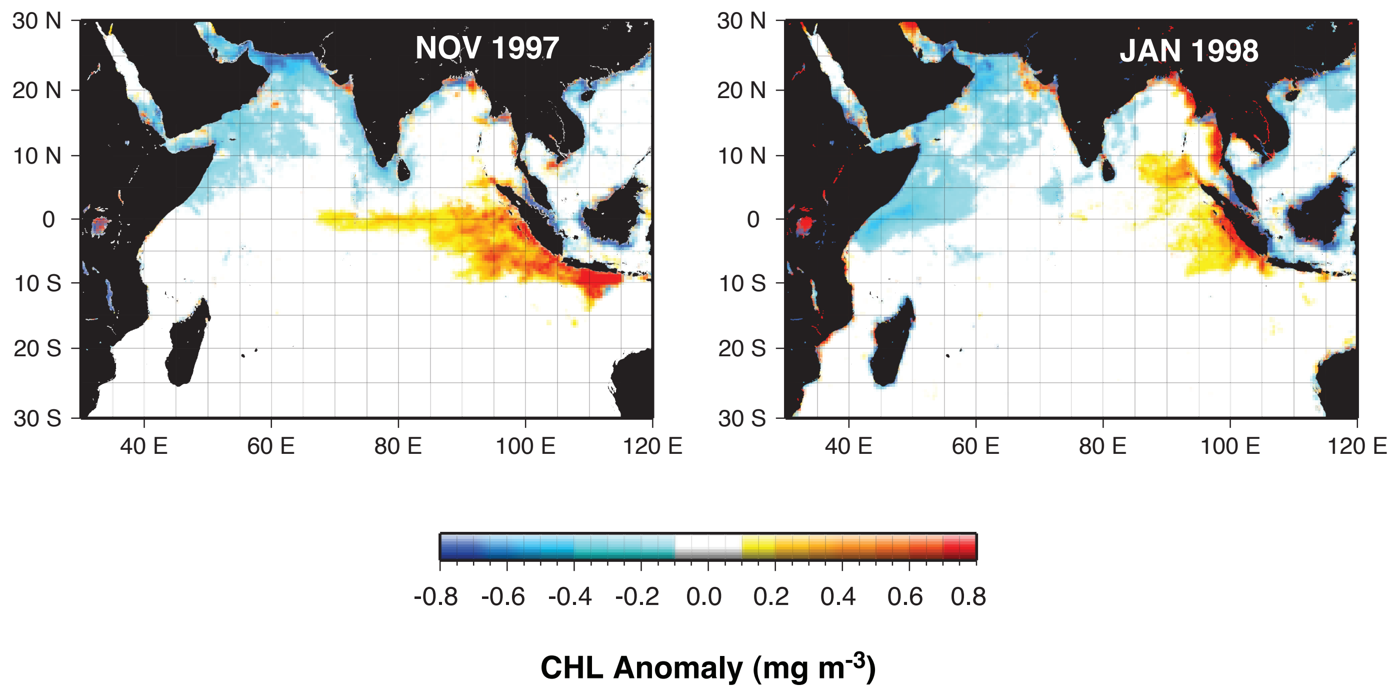

Fig 3: Distribution of chlorophyll anomaly observed by SeaWiFS during the 1997/98 IOD. Values in the range of ffl0.1 mg m^{-3} have been masked in order to highlight the features of interest. Figure and caption modified from Wiggert et al. (2009).