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New Indian Ocean Program Builds on a Scientific Legacy

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Prior to the International Geophysical Year (1957–1958) and before the acceptance of ideas about continental drift and the emergence of the theory of plate tectonics, the Indian Ocean was viewed as one of the last great frontiers of Earth exploration. During this post–World War II era, many new technologies were emerging for sampling the ocean and atmosphere and for mapping deep-ocean topography. Yet fundamental descriptive work still remained to be done on oceanic and atmospheric circulation, marine geology, and biological and ecological variability in the Indian Ocean.

Motivated by these technological developments and the opportunity to explore one of the last great frontiers on Earth, the Scientific Committee on Ocean Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) launched one of the greatest oceanographic expeditions of all time: the International Indian Ocean Expedition (IIOE). An interdisciplinary endeavor embracing physical oceanography, chemical oceanography, marine biology, meteorology, and marine geology and geophysics, IIOE was a monumental mid-twentieth-century oceanographic research program that conducted an unprecedented number of hydrographic surveys covering the entire Indian Ocean basin (Figure 1).

Data from these surveys dramatically advanced the understanding of monsoon variability and dynamics and described for the first time the complex surface ocean circulation that emerges in response to monsoon forcing. The data also provided a much more detailed picture of the complex topography of the Indian Ocean basin that helped scientists establish the theory of plate tectonics.

Building from this legacy, SCOR and the IOC are working to stimulate a new phase of coordinated international research focused on the Indian Ocean, beginning in late 2015 and continuing through 2020. This push to motivate a second major international effort to explore the Indian Ocean has been dubbed IIOE-2.

IIOE: 46 Research Vessels Under 14 Flags

IIOE emerged from a remarkable cascade of events. These events included the International Geophysical Year, which showed the value of coordinated multinational efforts in ocean science, and the formation of SCOR, which was dedicated to stimulating international cooperation in ocean sciences.

At its first meeting in 1957, SCOR identified the Indian Ocean as the least known region of the global ocean and envisioned exploration of the Indian Ocean as one of its first tasks [*Deacon*, 1957]. In 1959, after 2 years of dedicated planning, SCOR hired its first project coordinator, Robert G. Snider, to lead the IIOE effort. The IIOE project office, located in New York City, was funded by the U.S. National Science Foundation through the U.S. National Academy of Sciences (NAS) and was overseen by the NAS Committee on Oceanography (one of the predecessors of the current Ocean Studies Board of the National Research Council).

IIOE became the first project of the IOC, which assumed management responsibilities for the project in mid-1962. The project officially continued through 1965, with 46 research vessels participating under 14 different national flags.

Legacies and Challenges

IIOE proved to be a remarkable success, providing much of the scientific foundation for our modern understanding of the Indian Ocean. It led to the publication of the first oceanographic atlas of the basin [*Wyrtki et al.*, 1971] and a detailed map of Indian Ocean bathymetry [*Heezen and Tharp*, 1966] among many other legacies. It also revealed the existence of an equatorial undercurrent in the Indian Ocean [*Knauss and Taft*, 1964] and contributed to the realization that old grid-like traverses of the ocean needed to be complemented with phenomena-based experiment design [*Stommel*, 1963].

The planners of IIOE recognized the importance of data standardization and intercalibration. For example, when collecting zooplankton samples, scientists used what is now called the Indian Ocean Standard Net (IOSN)—a 5-meter-long nylon gauze net with a mesh of 330 micrometers and a mouth of 1 square meter [*Currie*, 1963]. Intercalibration exercises were carried out for other biological and chemical parameters in an attempt to make samples comparable among stations. Although the attempt was not entirely successful, the effort highlighted how IIOE planners wanted to be able to combine data from

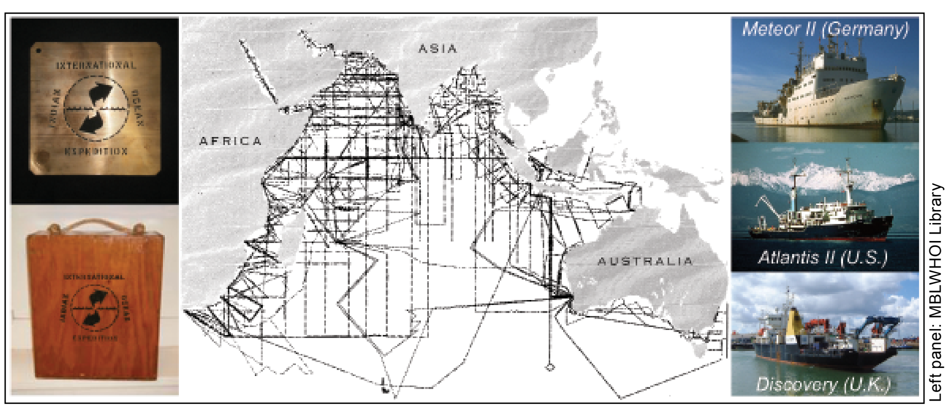

*Fig. 1. (middle) Map of the Indian Ocean showing the cruise tracks of research vessels during the International Indian Ocean Expedition (IIOE), which ran from 1957 to 1965. (left) Stencil and field instrument case from IIOE. (right) Three oceanographic research vessels from Germany (*Meteor II*), the United States (*Atlantis II*), and the United Kingdom (*Discovery II*) that participated in IIOE.*

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different investigators into a data set that could be scrutinized to better understand basin-wide dynamics.

IIOE also led to the development of new scientific capacity in countries surrounding the Indian Ocean basin. For example, the Indian Ocean Biological Centre was established at Cochin, India, to process the biological samples collected with the IOSN. This center later led to the establishment of India's National Institute of Oceanography (NIO) in Goa, which marked the beginning of the development of India's considerable modern-day oceanographic research capacity.

Remarkably, most of the stations occupied during IIOE were positioned on the basis of star sighting and dead reckoning. Navigation was done much the way Captain Cook had done it 2 centuries earlier. Imagine trying to explore the ocean today without GPS, modern weather forecasting, or any satellite remote sensing.

For a popular account of the expedition, including personal reflections of many participants, see *Behrman* [1981].

Advances in Oceanography Since IIOE

The end of 2015 will mark the 50th anniversary of the completion of IIOE. In the years since IIOE, three fundamental changes have taken place in ocean science.

First, the deployment of a broad suite of oceanographic and meteorological sensors on Earth-observing satellites has dramatically improved the characterization of both physical and biological oceanographic variability and the atmospheric forcing of that variability.

Second, new components of the ocean observing system, most notably Argo floats, are now standard tools for data collection. In addition, in the Indian Ocean, the deployment of the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) and the basin-wide tsunami detection network are producing robust data sets.

Third, the development of ocean modeling in all its facets from short-term forecasting to seasonal prediction to climate projections has fundamentally changed our perspectives on ocean variability and its role in climate and biogeochemical cycles.

In addition, improvements in analytical techniques have made new and better measurements possible in all oceanographic disciplines.

Other fundamental changes, not specific to oceanography but nonetheless highly consequential, are the advances in global positioning for precision navigation, real-time data collection and transmission, and new types of communication (e.g., the World Wide Web), which have enormously facilitated data sharing and scientific collaboration. These advances have revolutionized scientists' abilities to measure, model, and understand the oceans.

Moreover, compared with resources available in the IIOE era, which relied almost exclusively on ship-based observations (Figure 1), new measurement technologies, in combination with targeted and well-coordinated field programs, provide the capacity for a much more integrated picture of Indian Ocean variability.

Thanks to these technological developments, scientists can now study how the ocean changes across a wide range of spatial and temporal scales and how these fluctuations are coupled to the atmosphere. Thanks to these advances, the time is ripe for a new focus on the Indian Ocean: IIOE-2.

IIOE-2: The Indian Ocean's Role in a Bigger Picture

The overarching goals of IIOE-2 are to advance scientific understanding of interactions between geological, ocean, and atmospheric processes that give rise to the complex physical dynamics of the Indian Ocean region and to determine how those dynamics affect climate, extreme events, marine biogeochemical cycles, ecosystems, and human populations. This understanding is required to predict the impacts of climate change, eutrophication, acidification, and increased fish harvesting in the Indian Ocean and to know how the Indian Ocean interacts with other components of the Earth System. New understanding is also fundamental to policy makers for the development of comprehensive coastal zone, ecosystem, and fisheries management strategies for the Indian Ocean.

Other goals of IIOE-2 include helping to build research capacity in Indian Ocean rim nations and motivating efforts to make oceanographic data from the region discoverable and widely accessible.

Organizational Framework

A large part of IIOE-2, which is planned for 2015–2020, involves organizing ongoing research and stimulating new initiatives as part of a larger sustained expedition to the Indian Ocean. International programs that have research and observations ongoing or planned in the Indian Ocean during this time include the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, the Climate and Ocean Variability, Predictability and Change (CLIVAR) project, the Indian Ocean component of the Global Ocean Observing System (IOGOOS), GEOTRACES (a global survey of trace elements and isotopes in the ocean), and the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP). Many countries, including Australia, China, Germany, India, Indonesia, Japan, the United Kingdom, and the United States, are planning research in the IIOE-2 time frame as well.

To help organize these efforts, the IOC convened three planning workshops. The first, at which the framework for a plan was developed, was held in May 2013 in Hyderabad, India. The second meeting was convened in November 2013 in Qingdao, China, and focused on identifying the high-level science and societal drivers for IIOE-2. The third workshop, which occurred in March 2014 in Mauritius, focused on engaging the research community of the southwestern Indian Ocean region in this new initiative. The reports from these meetings are available at http://iocperth.org.

SCOR subsequently formed an IIOE-2 Science Plan Development Committee (SCOR SPDC) that has been tasked with reviewing the information gathered from these workshops and other national planning efforts and distilling them into a compelling science plan for IIOE-2.

Research Themes

The domain of the expedition will be basin-wide, extending to and considering interactions with the Southern Ocean. Using input from the workshops and national planning efforts, the SCOR SPDC has grouped pressing research questions into six main research themes for IIOE-2.

Anthropogenic impacts: How are human-induced ocean stressors (e.g., warming, sea level rise, deoxygenation, acidification, eutrophication, atmospheric and plastic pollution, coastal erosion, and overfishing) impacting the biogeochemistry and ecology of the Indian Ocean? How, in turn, are these impacts affecting human populations in Indian Ocean rim nations?

Boundary current dynamics, upwelling variability, and ecosystem impacts: How are marine biogeochemical cycles, ecosystem processes, and fisheries in the Indian Ocean influenced by boundary currents, eddies, and upwelling? How does the interaction between local and remote forcing influence these currents and upwelling variability in the Indian Ocean? How have these processes (and their influence on local weather and climate) changed in the past, and how will they change in the future?

Monsoon variability and ecosystem response: What factors control present, past, and future monsoon variability? How does this variability impact ocean physics, chemistry, and biogeochemistry in the Indian Ocean? What is the effect on ecosystem response, fisheries, and human populations?

Circulation, climate variability, and climate change: How has the atmospheric and ocean circulation of the Indian Ocean changed in the past, and how will it change in the future? How do these changes relate to topography and connectivity with the Pacific, Atlantic, and Southern oceans? What impact do these changes have on biological productivity and fisheries?

Extreme events and their impacts on ecosystems and human populations: How do extreme events in the Indian Ocean impact coastal and open ocean ecosystems? How will climate change impact the frequency and/or severity of extreme weather events, tropical cyclones, and natural modes of climate variability in the Indian Ocean? What are the threats of extreme weather events, volcanic eruptions, and tsunamis, combined with sea level rise, to human populations in low-lying coastal zones and small-island nations of the Indian Ocean region?

Unique geological, physical, biogeochemical, and ecological features of the Indian Ocean: What processes control the present, past, and future oxygen dynamics of the Indian Ocean, and how do they impact biogeochemical cycles and ecosystem dynamics? How do the physical characteristics of the southern Indian Ocean gyre system influence the biogeochemistry and ecology of the Indian Ocean? How do the complex tectonic and geologic processes and topography of the Indian Ocean influence circulation, mixing, and chemistry and therefore biogeochemical and ecological processes?

In addition to the surface and atmospheric circulations, IIOE-2 will promote further exploration of deep circulation and deep-sea ecosystems in the Indian Ocean along with tectonic processes and ocean–solid Earth interactions that support them. Assimilation of data into oceanic and atmospheric analyses and reanalyses will also be important research topics under IIOE-2.

Next Steps

An IOC resolution supporting IIOE-2 was endorsed at the 47th meeting of IOC's executive council in July 2014. This resolution will help motivate participation and action by IOC member states.

In the meantime, the SCOR SPDC is forging ahead with the development of an IIOE-2 science plan based on the planning workshops and national meetings that have been convened to date. The draft plan will be circulated for comment to the scientific community and IOC before final adoption. As with the original IIOE, the scientific communities and governments in the Indian Ocean region and beyond will engage in this important new activity through the combination of nongovernmental and intergovernmental ocean science organizations.

The success of IIOE-2 will be gauged not just by how much it advances understanding of the complex and dynamic Indian Ocean system but also by how it contributes to sustainable development of marine resources, environmental stewardship, ocean and climate forecasting, and the training of the next generation of ocean scientists from the region. If this vision of success is realized, IIOE-2 will leave a legacy as rich as the original expedition.

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