

ships of opportunity, and biogeochemical sensors on the basin-scale mooring array and Argo floats.

Clearly, full implementation of IndOOS will require a well-coordinated, international effort of large magnitude. One or just a few nations cannot carry the full investment of resources. The implementation plan includes a set of principles that is

meant to encourage broad international participation and rapid transition of measurements to societal benefit. Chief among the principles is the need to distributed data openly in a timely manner. There is a preference for communication of data in real time to make it available at climate analysis and prediction centers. This is essential to demonstrate the value of IndOOS and capture the potential societal benefits.

Development of an Indian Ocean Moored Buoy Array for Climate Studies

McPhaden M.J.¹, Y. Kuroda² and V. S. N. Murty³,

¹NOAA/Pacific Marine Environmental Laboratory, USA, ²Japan Marine–Earth Science and Technology Agency, Japan, ³National Institute of Oceanography, Goa, India

Corresponding author: Michael.J.Mcphaden@noaa.gov

1. Introduction

The Indian Ocean is unique among the three tropical ocean basins in that it is blocked at 25°N by the Asian land mass. Seasonal heating over this land mass sets the stage for dramatic monsoon wind reversals and intense summer rains over the Indian subcontinent and adjoining areas of Southeast Asia. Recurrence of these summer monsoon rains is critical to agricultural production that provides life-sustaining support for hundreds of millions of people in the region. The reversing monsoon winds also generate a unique system of currents unlike those observed in the tropical Atlantic and Pacific, which are under the influence of steadier trade winds. Blocked by Asia, these currents cannot export heat to the northern subtropics. The resulting oceanic thermal structure produces feedbacks to the overlying atmosphere that affect not only the monsoon circulation and rainfall patterns, but also weather and climate in remote parts of the globe through atmospheric teleconnections.

Despite the importance of the Indian Ocean in the regional and global climate system, it is the most poorly observed and least well understood of the three tropical oceans. To remedy this situation, the Indian Ocean Panel, sponsored by the Climate Variability and Predictability Program (CLIVAR) and the Global Ocean Observing System (GOOS), has developed a plan for systematic, sustained, and comprehensive in situ observations in the Indian Ocean to complement both present and planned space-based satellite measurements. The plan (available at http://eprints.soton.ac.uk/20357/01/IOP_Impl_Plan.pdf) describes the scientific rationale, design criteria and implementation strategies for each of the observing system components. These include Argo floats, drifting buoys, tide gauge stations, ship-of-opportunity expendable bathythermograph (XBT) lines, a basin scale moored buoy array, and specialized measurement programs for the Indonesian Throughflow and western boundary currents. India also maintains a regional national buoy program in the Bay of Bengal and Arabian Sea. The totality of these efforts is referred to as the Indian Ocean Observing System (IndOOS) (Meyers and Boscolo, this issue). This article focuses on specific issues related to design and implementation of the basin scale moored buoy array component of IndOOS.

2. Scientific Rationale and Design Goals

Mooring programs have been implemented in the Indian Ocean in the past as part of CLIVAR, the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux (JGOFS) experiment, and various national initiatives. In most cases though, these programs were relatively short term and/or focused on a particular region. Missing until recently was a plan for a coordinated, multi-national, basin-scale sustained mooring array like the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) in the Pacific

and the Pilot Research Moored Array in the Tropical Atlantic (PIRATA).

The CLIVAR/GOOS Indian Ocean Panel moored buoy array is designed to resolve the most energetic variations in the open ocean away from the western boundary. Like the Pacific TAO/TRITON array, it is intended to be marginally coherent in latitude and longitude for defining the evolution of large-scale intraseasonal-to-interannual wind, sea surface temperature (SST), upper-ocean temperature and salinity variations. It is essential for understanding the role of the ocean in variability related to the Madden-Julian Oscillation (MJO) and other high frequency phenomena, for understanding mixed-layer dynamics, and for understanding interactions between the ocean and atmosphere. The data will also support development of operational climate forecast models, weather and climate prediction, ocean-state estimation, reanalysis efforts, and satellite validation.

The array (Figure 1, page 15) consists of 39 surface moorings for measurement of temperature, salinity, mixed layer currents, and basic meteorological variables. Four subsurface Acoustic Doppler Current Profiler (ADCP) moorings are located along the equator where geostrophy breaks down and direct current measurements are necessary. A fifth ADCP mooring is also located in the upwelling zone off the Island of Java where the SST dipole/zonal mode first develops. This mooring is near the northern terminus of the frequently repeated XBT line IX1 between Australia and Indonesia. In addition to the 39 surface and 5 ADCP moorings, three subsurface moorings maintained by India's National Institute of Oceanography (NIO) along the equator at 77°E, 83°E, and 93°E are designed to monitor deep ocean currents.

The array is intended to cover the major regions of ocean–atmosphere interaction in the tropical Indian Ocean. These regions include the Arabian Sea, the Bay of Bengal, and the equatorial waveguide, where wind-forced intraseasonal and semi-annual current variation is prominent; the eastern and western poles of the Indian Ocean SST dipole/zonal mode; the thermocline ridge near 10°S, where wind-induced upwelling and Rossby waves in the thermocline affect SST; the southwestern tropical Indian Ocean, where ocean dynamics and air–sea interaction affect cyclone formation (Xie et al., 2002); and the southeastern basin where water masses are subducted into the upper pycnocline as part of the cross equatorial circulation cell between the subtropics and the tropics (Schott et al, 2004). Numerical model design studies have assessed the adequacy of the array to achieve its purposes in the context of other observing system components. Alternative sampling strategies have also been evaluated with the conclusion that the present array configuration is scientifically sound and cost-effective (Vecchi and Harrison, 2006; Oke and Schiller, 2006).

The entire array will contribute to the objectives of the OceanSITES program (<http://www.oceansites.org/>). In addition, eight specially enhanced flux reference sites will provide instrumentation to estimate all components of surface heat, moisture and momentum fluxes. These enhanced moorings are located in different climatic zones where climatologies are poorly known or where surface fluxes are critical for understanding climate variability (Yu et al, 2006).

3. Status of Implementation

The Japan Marine-Earth Science and Technology Agency (JAMSTEC) pioneered the deployment of long-term moorings for studies of ocean-atmosphere interactions in the Indian Ocean with an ADCP mooring at 0°, 90°E in 2000 (Masumoto et al, 2005) and two TRITON moorings at 1.5°S, 90°E and 5°S, 95°E in 2001 (Figure 2, page 15). Deep ocean subsurface moorings were also initiated by NIO in 2000 (Sengupta et al, 2004). These JAMSTEC and NIO moorings have been continuously maintained since then. In October-November 2004, NOAA's Pacific Marine Environmental Laboratory (PMEL) in collaboration with NIO and the Indian Department of Ocean Development (DOD) deployed 4 ATLAS moorings and 1 ADCP mooring between 80°-90°E from the Ocean Research Vessel Sagar Kanya. These five mooring sites were serviced and one additional site was initiated on a cruise of the Sagar Kanya in August-September 2006. PMEL is also working with Indonesian agencies to occupy two new locations at 4°N and 8°N along 90°E using the research vessel Baruna Jaya I in late 2006 or early 2007. The French research vessel Suroit will deploy an ATLAS mooring in the southwest Indian Ocean in January 2007. Discussions are underway between PMEL and the First Institute of Oceanography in China to jointly maintain the ADCP mooring off the coast of Java. The status of existing and planned sites for 2006-07 is shown in Figure 3 (page 15).

Securing adequate ship time to implement and sustain the array is a major issue. Making reasonable assumptions about ship speeds, carrying capacity, and ports of call around the Indian Ocean, it is estimated that a minimum of 142 days of ship time per year will be required to maintain the full array (Figure 4). This minimum assumes that cruises are dedicated only to mooring work and that other activities will not consume ship time. The minimum is likely to be exceeded, since research cruises in the region are generally multi-purpose.

A five-year implementation plan, ramping up from the current 11 sites to full implementation in 2010, is shown in Figure 4. The array will require multi-national support and a reliable, regular supply of ship time. The greatest impediment to implementation, assuming adequate financial resources and ship time can be found, is vandalism by fishing vessels. Fishing vandalism is not unique to the Indian Ocean as it also affects TAO/TRITON in the Pacific and PIRATA in the Atlantic. Unfortunately, the problem is already apparent in data and equipment losses at some of the active surface mooring sites in Figure 3.

4. Data Availability

ATLAS and TRITON mooring data are transmitted to shore in real-time via Service Argos satellite relay. Service Argos places a significant portion of these data on the Global Telecommunications System for worldwide dissemination in order to support operational climate analyses and forecasts. In addition, PMEL hosts a website where ATLAS and TRITON mooring data are freely available (<http://www.pmel.noaa.gov/tao/disdell/>). JAMSTEC maintains a website where TRITON mooring data are freely available (<http://www.jamstec.go.jp/jamstec/TRITON/>). NIO hosts a website for access to data from its deep ocean moorings (<http://www.nio.org/>

[/data_info/deep-sea_mooring/oos-deep-sea-currentmeter-moorings.htm](http://www.nio.org/data_info/deep-sea_mooring/oos-deep-sea-currentmeter-moorings.htm)).

5. Coordination with Other Programs

The moored buoy array, in addition to being coordinated with other elements of the IndOOS, is capable of accommodating biogeochemical sensors to support programs such as the Surface Ocean Lower Atmosphere Study (SOLAS), the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), and the International Ocean Carbon Coordination Project (IOCCP). In the wake of the Asian tsunami on 26 December 2004, discussions are also underway with organizations involved in developing the Indian Ocean tsunami warning system on how best to coordinate implementation efforts with IndOOS. It would be advantageous for example to coordinate IndOOS and tsunami mooring deployment cruises and to consider development of a multi-hazard moored buoy platform for both tsunami warnings and climate studies.

The CLIVAR/GOOS moored buoy array provides context for the development of process studies like the Mirai Indian Ocean cruise for the Study of the MJO convection Onset (MISMO; see Yoneyama et al, this issue) centered around 0°, 80°E in October-December 2006 and the French-lead VASCO-CIRENE (Duval and Vialard, 2006) project in the southwest Indian Ocean in January-February 2007. Both these process studies will examine ocean-atmosphere interactions associated with the MJO for which the high resolution moored time series data are especially valuable. VASCO-CIRENE also provides the opportunity to deploy a flux reference site mooring at 8°S, 67°E as an element of the sustained observing system. New knowledge gained from programs like MISMO and VASCO-CIRENE can feedback into design modifications to optimize the array for scientific purposes.

6. Concluding Remarks

The moored array component of IndOOS has been endorsed by CLIVAR and GOOS and is being implemented through multi-national cooperative efforts. Continued commitment of financial, human, and ship time resources from several nations

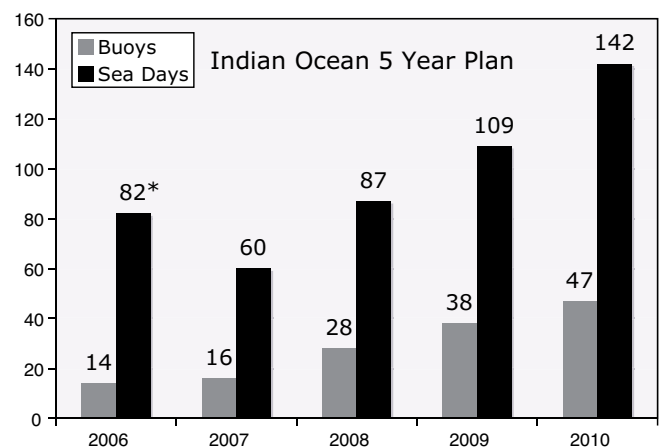


Figure 4. Implementation schedule and ship time requirements (in sea days) for establishing the moored buoy array. Ship time in 2006 (highlighted by an asterisk) is an estimate of the actual amount that will be used on mooring deployment cruises. Ship time estimates for 2007-2010 represent minimum requirements based on the assumption that cruises are dedicated solely to servicing to buoys of the array with ports of call around the Indian Ocean. In arriving at the 2007-2010 estimates, hypothetical cruise tracks were developed allowing for sufficient station time and assuming that ships typically cruise at 10 knot speeds

will be required to fully establish this key element of the observing system over the next few years. Once completed, the array will significantly advance our understanding and ability to predict the monsoons and related climate phenomena in much the same way as TAO/TRITON and PIRATA have advanced studies of ENSO and Tropical Atlantic climate variability.

Acknowledgments

The authors would like to thank the CLIVAR/GOOS Indian Ocean Panel, chaired by Gary Meyers, for its contributions to design of the Indian Ocean moored buoy array; the Indian Department of Ocean Development, especially M. Sudharkar of DOD's National Center for Antarctic and Ocean Research, for assistance with logistic support; NOAA's Office of Climate Observation for financial support; and JAMSTEC for its support of the TRITON mooring program.

References

Duval, J.P. and J. Vialard, 2006: The VASCO-CIRENE experiment. Proc 27th AMS Conference on Hurricanes and Tropical Meteorology, April 2006 (<http://ams.confex.com/ams/pdfpapers/108726.pdf>)

Masumoto, Y., H. Hase, Y. Kuroda, H. Matsuura, and K. Takeuchi, 2005: Intraseasonal variability in the upper layer

currents observed in the eastern equatorial Indian Ocean. *Geophys. Res. Lett.*, **32**, L02607, doi:10.1029/2004GL021896.

Oke, P. R., and A. Schiller, 2006: A model-based assessment and design of a tropical Indian Ocean mooring array. *J. Climate*, in press.

Schott, F. A., J. P. McCreary, and G. C. Johnson, 2004: Shallow over-turning circulations of the tropical-subtropical oceans. In *Earth Climate: The Ocean-Atmosphere Interaction*. C. Wang, S.-P. Xie, and J. Carton (eds.), *Geophys. Monograph*, **147**, AGU, Washington, D.C.

Sengupta, D., R. Senan, V. S. N. Murty and V. Fernando, 2004: A biweekly mode in the equatorial Indian Ocean. *J. Geophys. Res.*, **109**, C10003, doi:10.1029/2004JC002329.

Vecchi, G.A. and M.J. Harrison, 2006: An Observing System Simulation Experiment for the Indian Ocean, *J. Climate*, in press.

Xie, S.-P., H. Annamalai, F.A. Schott, and J.P. McCreary, 2002: Structure and mechanisms of South Indian Ocean climate variability, *J. Climate*, **15**, 864–878.

Yu, L., J. Xiangze, and R. A. Weller, 2006: Annual, Seasonal, and Interannual Variability of Air-Sea Heat Fluxes in the Indian Ocean. *J. Climate*, in press.

Indian Moorings: Deep-sea current meter moorings in the Eastern Equatorial Indian Ocean

Murty, V.S.N.¹, M.S.S. Sarma¹, A. Suryanarayana¹, D. Sengupta², A. S. Unnikrishnan¹, V. Fernando¹, A. Almeida¹, S. Khalap¹, A. Sardar¹, K. Somasundar³ and M. Ravichandran⁴

¹National Institute of Oceanography, Goa India. ²Center for Atmospheric and Oceanic Sciences, Indian Institute of Sciences, Bangalore, India. ³Ministry of Ocean Development, New Delhi, India. ⁴Indian National Centre for Ocean Information Services, Hyderabad, India

Corresponding author: vsnmurty@nio.org

1. Introduction

The Ministry of Ocean Development (MOD), Government of India, initiated the Ocean Observing System (OOS) programme in 1997 for long-term current measurements in the equatorial Indian Ocean. Under the OOS program, 3 locations at 93°E, 83°E and 76°E (Fig. 1) were selected along the equator for deploying the current meter moorings (Murty et al., 2002). The National Institute of Oceanography (NIO), Goa, took the responsibility of executing the project. This project started in 2002 after developing a suitable mooring design with current meters and relevant hardware. The designed I-type mooring is basically of subsurface mooring with 6 Recording Current Meters (RCMs) at six nominal depths of 100m, 300m, 500m, 1000m, 2000m and 4000m. The main objective of the project is to generate long-term time series of current data from the equatorial Indian Ocean to understand the dynamics of currents in the equatorial Indian Ocean in relation to climate variability and change. The depths of the RCMs were designed to obtain information on currents in the upper thermocline, main thermocline, intermediate, deeper and near-bottom depth ranges. The central and eastern equatorial Indian Ocean comes under the influence of the warm pool with the sea surface temperatures >28°C during most of the year (Vinayachandran and Shetye, 1991). McPhaden (1982) presented the analysis of the long-time series of current data obtained from a station near Gan Island in the equatorial Indian Ocean. Unnikrishnan et al. (1997) showed that the seasonal cycle of climatological temperature at 100 m depth in the tropical Indian Ocean is dominated by semi-annual variability in the equatorial region and annual variability elsewhere. Reppin et al. (1999) presented the analysis of time series current data from moored ADCP (Acoustic Doppler Current Profiler) and current meters at the equator and 80.5°E. Prasanna Kumar et al. (2005) in their analysis of high-resolution of Ocean General Circulation

Model (OGCM) simulations showed strong seasonality (largest spatial extent during April–May, and least in December) in the time-evolution of the warm pool. These authors report that the upper ocean heat budget in the equatorial Indian Ocean is largely controlled by advection, rather than the net heat flux alone. From the theoretical considerations, Gent et al (1983) examined the semi-annual variation of zonal currents in the equatorial Indian Ocean. In this article, the authors present brief information on the Indian current meter moorings along the equator and some preliminary results.

2. Status of the data and methods of analysis

The first deep-sea current meter mooring was deployed successfully in February 2000 at the equator, 93°E on board ORV Sagar Kanya. This mooring was successfully recovered

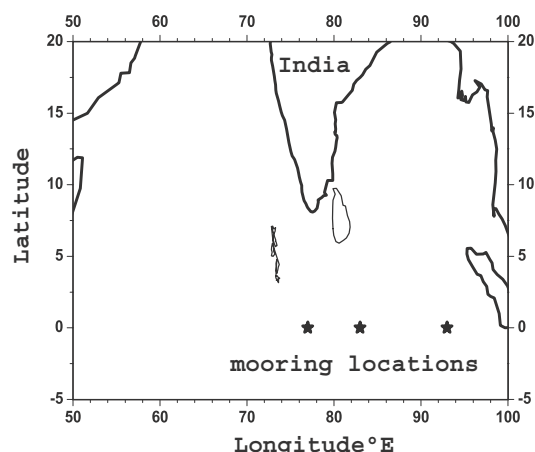


Figure 1. Study area and the locations of the Indian deep-sea current meter moorings in the equatorial Indian Ocean.