Tropical Indian Ocean mooring array: Present status and future plans

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1. Introduction

Despite the importance of the Indian Ocean in the global climate system, the tropical Indian Ocean is known as a region where in situ data are quite sparse both in time and space. Development of a systematic observing system in the tropical Indian Ocean is well behind those in the tropical Pacific and Atlantic Oceans, though some progress has been achieved for observations at the regional level. Among various methods of the ocean observing techniques, mooring lines have a big advantage for measuring time series of several variables with fine temporal resolution. The significant role of a mooring array in monitoring the variations in the upper ocean and in understanding the associated mechanisms has already been demonstrated by the success of TAO/TRITON array in the tropical Pacific Ocean (McPhaden et al, 2001). In this presentation, we review the scientific basis for mooring observations in the Indian Ocean and discuss the present status and future perspectives of the mooring array in the tropical Indian Ocean.

2. Scientific interests in the tropical Indian Ocean

The Indian Ocean strongly affects and is affected by the Asian-Australian-African monsoons. Large amplitude seasonal variability of the upper-layer circulation of the Indian Ocean is a manifestation of this air-sea-land coupled system, and it has been studied for a long time, using both the observed data and numerical models. The eastern tropical Indian Ocean is characterized by a surface warm water pool, where the sea surface temperature (SST) is greater than 28°C. Small changes in SST lead to a significant response in the overlying atmosphere, resulting in the global and regional climate changes through the atmospheric teleconnections. Although there were several recent attempts to measure the air-sea interactions that affect SST variability in the warm water pool region (e.g., Webster et al., 2000), the detailed mechanisms responsible for the SST changes are not well understood due to the lack of in situ observations.

Eastward zonal jets, known as the Wyrtki jets (Wyrtki, 1973), appear semiannually in the upper-layer along the equator, and they contribute to the redistribution of mass and heat between the eastern and the western equatorial regions. The ensuing coastal Kelvin waves and the reflected Rossby waves affect upper ocean conditions elsewhere remotely by changing the thermocline depth. In addition, shorter time scale variability, associated with the equatorially trapped waves excited by the atmospheric disturbances and by the oceanic instabilities, is also expected to be a major cause of the variations in the tropical Indian Ocean.

Recent observations have identified the importance of intraseasonal variability in the tropical Indian Ocean. At intraseasonal time scales the boreal summer monsoon oscillates between active and break periods during its onset and evolution (Webster et al., 1998). The intraseasonal oscillations form in the central Indian Ocean, propagate eastwards, bifurcate along the equator and propagate poleward to the north and south as distinct vortices in the Bay of Bengal sector. The northward (and strongest) mode brings active periods of the monsoon to South Asia. The active periods are associated with strong winds, heavy precipitation, and cool SST anomalies. The recent BOBMEX (Bhat et al., 2001) and JASMINE (Webster et al., 2000) projects are studying the intraseasonal modes, and are attempting to quantify how the modes are coupled to annual and interannual variability, and to determine the degree to which the modes are the result of coupled ocean/atmosphere processes. A long term time-series array is needed to quantify this process.

The value of long time-series of high quality air-sea fluxes and upper ocean observations has been demonstrated in the tropical Indian Ocean (Weller et al., 1998). Such observations are needed as part of a moored array effort to evaluate climatologies, air-sea flux products derived from operational models and satellite products. The recent volume, "Observing the Oceans in the 21st Century", identifies the needs and plans for surface flux reference sites (Taylor et al., 2001) and ocean time-series sites (Send et al., 2001) for the tropical Indian Ocean.

The WHP (WOCE Hydrography Program) expedition in the Indian Ocean provided high quality temperature, salinity and velocity data along several sections (Ffield, 1997). As an example in the Bay of Bengal sector, the data, together with model results, provided quasi-synoptic snapshots of the vigorous circulation pathways and upper ocean temperature and salinity structure (Hacker et al., 1998) including previously unobserved detail. Such data provide essential information for the meridional distribution of the moored array.

For better understanding of subsurface variability, time-series measurements of the temperature, salinity, and currents have been made at several locations since 1970s. The multi-year time series of current and temperature profiles collected near Gan Island revealed rich variability in upper ocean velocity and thermal structure in the central equatorial Indian Ocean (Knox, 1976; McPhaden, 1982). Another observation using the current meter mooring array was made south of Sri Lanka along 80.5°E during early 1990s, under the World Ocean Circulation Experiment (WOCE) (Schott et al., 1994; Reppin et al., 1999). The data indicates the important processes for the water exchange between the Arabian Sea and Bay of Bengal on seasonal and interannual time-scales.

In addition, recent comprehensive analyses of observed data and results from numerical models increase our knowledge on the interannual variations of the SST anomaly in the tropical Indian Ocean. It has been known that the ENSO affects the SST over the wide area of the Indian Ocean through a change in the surface heat flux. Saji et al. (1999) and Webster et al. (1999), however, indicate the dipole structure in the SST anomaly is strongly related to atmospheric variations over the tropical Indian Ocean, suggesting the possibility regional air-sea coupled processes may be important. Xie et al. (2001) demonstrated that the SST in the southwestern tropical Indian Ocean is sensitive to the upper-layer thickness, which is controlled by the wave propagation in the tropical regions. Modeling studies confirm that propagation of the equatorially trapped Kelvin and Rossby waves govern the dynamics of the equatorial Indian Ocean (McCreary et al., 1993; Sengupta et al., 2001). However, to detect these waves in the subsurface data is quite difficult at present, considering the sparseness of the in situ observations.

Indonesian throughflow (ITF), flow between the Pacific and the Indian Oceans, plays an important role in the circulation of the Indian Ocean as the largest input of water to the tropical region. Although direct observations of the ITF have been done at several locations within the Indonesian Seas (Murray and Arief, 1988; Molcard et al., 1996; Gordon et al., 1999), details on the mean magnitude of the ITF and characteristics of the variability have not clearly understood from the sporadic observational data. A systematic observation with long-term time series measurements of the currents within the Indonesian archipelago is required.

The deep-sea current observations in the equatorial Indian Ocean are equally essential to understand the nature and structure of the deep-flows across the equator, in relation to the meridional overturning circulation (MOC) in the Indian Ocean. Toole and Warren (1993) estimated a large net northward transport of 27×10^6 m^3/s below 2000 m across the 32°S hydrographic section. However, the way by which the large transport crosses the equator to the northern Indian Ocean is still not clear. Better understanding of the strength of the meridional overturning and its pathway is one of the important issues for climatic variability studies.

In order to understand further the above variability in the tropical Indian Ocean and the mutual relations among the phenomena in the different time scales, a basin wide array of the mooring lines is required. We could for example envision a fully developed array ten years from now consisting of about 30 moorings, with lines spaced 15 degrees apart in longitude (4 or 5 sections) and with elements located on the equator and at 2, 5, 10 degrees latitude in both hemispheres. To detect the interannual signals and decadal/interdecadal variations, such a mooring array should be maintained for at least ten years. The data from the array will also be useful for validating the remote sensing satellite data and the results of Ocean General Circulation Model (OGCM) simulations.

3. Present status of mooring programs

As of September 2002, there are six open ocean moorings in the Indian Ocean to obtain the time series of the velocity, temperature, salinity, and atmospheric variables in the central and the eastern equatorial regions (Figure 1). Three current meter moorings are located along the equator at 93°E, 83°E, and 76°E, under the Indian National Program for an Ocean Observing System (OOS). Each mooring consists of 6 recording current meters at 6 depths, covering the upper and lower thermocline, intermediate, deep and near-bottom levels. The data has been obtained so far for two years at 93°E and for one year at 83°E. All three moorings are in place presently.

One upward-looking ADCP mooring is located on the equator at 90°E, observing the variability in the upper-layer velocity above the depth of about 400 m. This mooring was first deployed in November 2000, and the data for about two years until July 2002 has been obtained. Another ADCP mooring was placed at (5°S, 95°E) for one year from November 2000 to October 2001. Two TRITON buoys are deployed at (1.5°S, 90°E) and (5°S, 95°E) in October 2001, with real-time data transmission system via the satellite. The TRITON buoy can observe temperature and salinity in the upper 750 m of the ocean, currents at 10 m depth, wind vector, incoming solar radiation, relative humidity, air temperature, air pressure, and precipitation. The ADCP mooring and the TRITON buoy observations are a part of OASIS (Observational Activities for the Study of the Indian ocean climate System) program of JAMSTEC/FORSGC.

In addition, Indian scientists have been maintaining coastal mooring buoys. Five deep sea stations, located at (15.6°N, 69.2°E), (10.6°N, 72.5°E), (12.1°N, 90.8°E), (18.5°N, 87.6°E), and (14.0°N, 83.2°E), and four shallow water stations at (15.4°N, 73.8°E), (12.9°N, 74.7°E), (8.7°N,

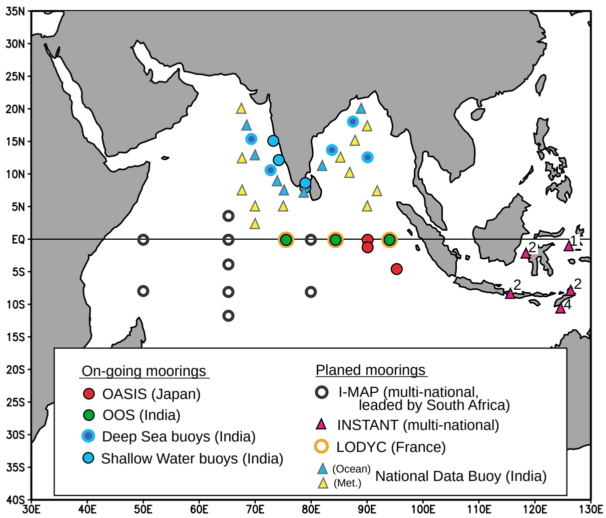

Figure1: Locations of the on-going and planed mooring lines. Suffixes for INSTANT buoys indicate the number of moorings nearby.

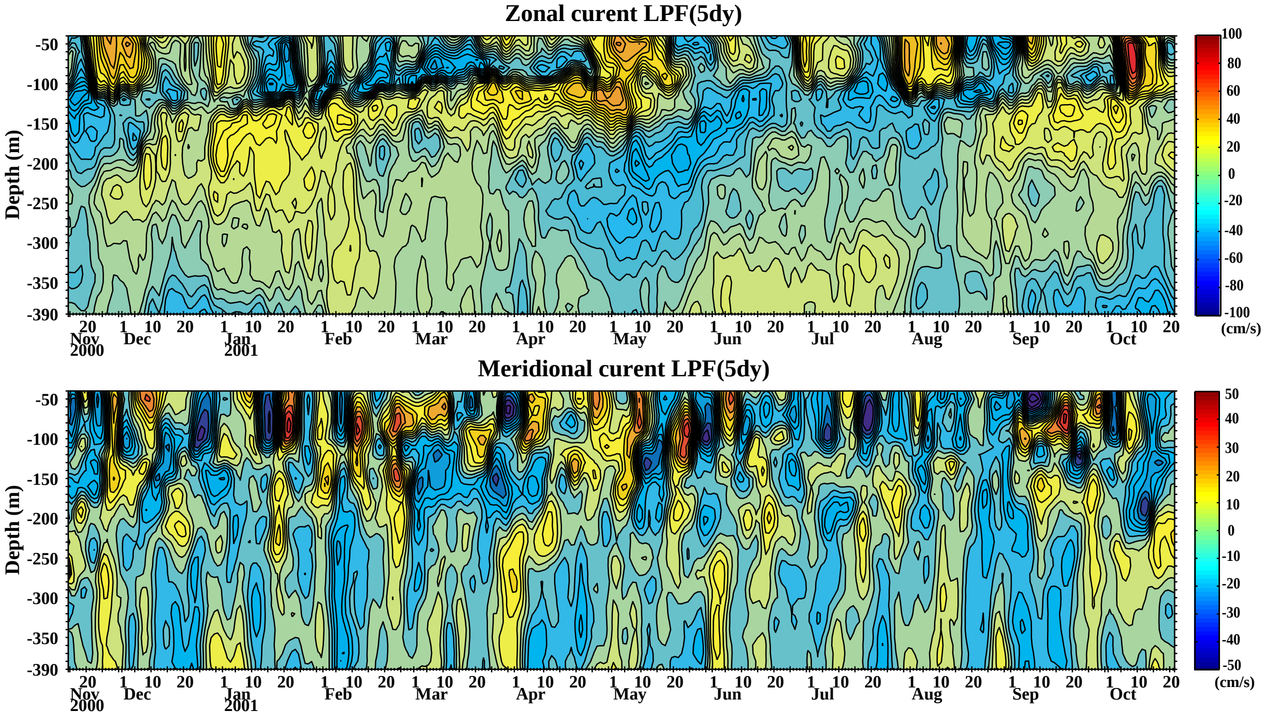

Figure 2: Time-depth sections of the zonal and meridional currents at 90°E on the equator. Five-day low-passed filter was applied to the original data.

78.4°E) and (8.2°N, 78.6°E) are currently operating. The deep sea stations measure the SST, wave height, air pressure, air temperature, and surface winds, while the shallow water stations observe the wave height, currents, air pressure, air temperature and surface winds

4. Preliminary results from recent equatorial mooring deployments

The moorings introduced in the previous section can be considered as pilot experiments for a future tropical mooring array. Preliminary results from these moorings provide us valuable information on the variability in the tropical Indian Ocean and can be used as a basis for an expanded and improved future mooring array. One of the most interesting outcomes from the recent available mooring data is the existence of strong intraseasonal variability in the eastern equatorial Indian Ocean. The observed current variability in the upper 400 m depth at 90°E on the equator from November 2000 to October 2001 is shown in Figure 2. The zonal currents shallower than about 100 m depth demonstrate the strong intraseasonal signal with a typical period of 30 days. The meridional component of the upper-layer velocity also exhibits a strong intraseasonal variability, though the dominant time-scale of 5 to 12 days is shorter than for zonal current. This variability can be seen throughout the record . Similar results, with additional spectral energy peak in the 10 to 20-day period in meridional current variability, are also obtained from the current meters at 93°E and model results (Sengupta et al., 2001). The intraseasonal variability can also be observed at deeper levels (1996 m and 3995 m) at 93°E. It turns out that the 30 day variations in zonal current are associated with the atmospheric intraseasonal oscillations and that the semiannual Wyrtki jets consist of several intraseasonal pulses of the zonal jet.

The two-year data set from the current meter mooring at 93°E clearly indicates large amplitude interannual variation in the eastern equatorial Indian Ocean (Figure 3). The current meter at 135 m depth observed strong eastward flow up to 30 cm/s from mid-April to end of June 2000 (top panel), representing the part of the flow associated with the spring Wyrtki jet. Relatively weaker eastward flow of 20 cm/s due to the fall Wyrtki jet is also appeared in October. The currents at

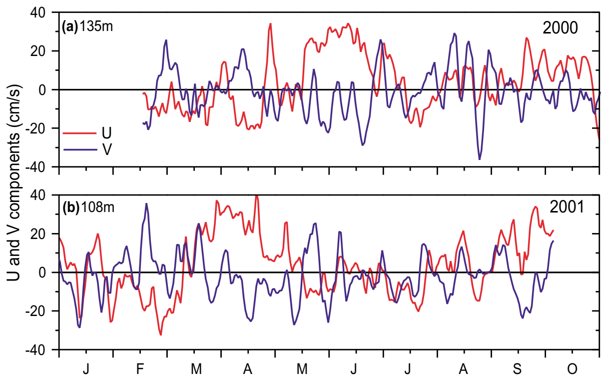

Figure 3: Temporal variation of Zonal & Meridional components (de-tided and daily averaged)at first level from current meter moorings at equator, 93°E during January-October 2000 and 2001

108 m depth at the same location in 2001, however, indicate early occurrence of the spring jet during March to mid-May (lower panel). It is interesting to note that, in the thermocline around 100 m depth at 93°E, the Wyrtki jets appear to be more purely semiannual instead of a series of the intraseasonal events as observed at 90°E.

5. Future prospects for a tropical Indian Ocean mooring array

The above preliminary results highlight the importance of the mooring observations to obtain clear descriptions of the variability and to have insights into the mechanisms responsible for variability in the tropical Indian Ocean. However, the locations of the moorings operating presently are of limited spatial coverage. To observe the details of the variability associated with the basin scale phenomena, such as the IOD and/or the response to the ENSO, the existing mooring systems should be expanded both longitudinally and latitudinally

There are several on-going and planned national/ international projects, which are briefly summarized below (see Figure 1).

(1) The Indian National OOS
The OOS will keep the three current meter moorings at 93°E, 83°E, and 76°E and is planning to deploy an additional mooring at 64°E. This OOS program is expected to continue for another five years, i.e. till March 2007 for the maintenance of these moorings with funding support from Department of Ocean Development (DOD), Govt. of India. The maintenance of the moorings for some more years would give detailed information on the seasonal and interannual variability in the currents at the equator in the Indian Ocean.

(2) OASIS (Observational Activities for the Study of the Indian ocean climate System)
The ADCP mooring at 90°E on the equator and two TRITON buoys will be maintained at least two more years to obtain longer time-series that can be used for the study of interannual variations in the eastern equatorial Indian Ocean. There is a possibility to move one TRITON buoy deployed at (1.5°S, 90°E) to a location much closer to the equator in the next year.

(3) I-MAP (Indian Ocean Moored Array Project)
I-MAP is a multi-national project coordinated by South African scientists to investigate ocean conditions in the tropical western Indian Ocean. An array of nine TAO-like buoys in the western and the central tropical Indian Ocean is planed as I-MAP. The locations of the array will be 50, 65, and 80°E on the equator at the initial phase, and expand to off-equatorial regions afterwards. Five-year observations are expected.

(4) French mooring observation
The LODYC group is planning to install one mooring, equipped with an ADCP, current meters and a thermistance chain at 76°E. This will be done at the beginning of 2005, and will be continued for two to three years. In collaboration with the Indian OOS project, the French ADCP might be deployed on the top of one of the Indian OOS moorings. Depending on the availability of instruments, additional ADCPs might be installed either on the top of other OOS buoys (83°E and 93°E) or on two independent moorings at 2°N, 76°E and 2°S, 76°E.

(5) U.S. observation
No specific US plans exist yet, but at least one organization (NOAA/PMEL) is interested in an initial array focused on the equator for the purposes of studying intraseasonal-to-interannual time scale variations involving ocean dynamics, surface layer heat and fresh water budgets, and ocean-atmosphere interactions. The initial scope of the effort is envisioned to consist of a modest zonal array spanning the basin with a small number of off-equatorial elements to provide an indication of the latitudinal coherence of observed variability. This array would need to be coordinated with other mooring programs and observing system efforts, and would be viewed as an initial step towards the development of a more comprehensive multi-national sustained ocean observing system in the Indian Ocean.

(6) INSTANT (International Nusantara Stratification and Transport)
INSTANT is a coordinated international effort to measure the flow of water between the Pacific and Indian Oceans via the Seas of Indonesia. The objective is to understand the broad spectrum of variability in the Indonesian throughflow, and the role of regional oceanography in establishing the transfer function between the Pacific inflow and the outflow into the Indian Ocean. Eleven moorings, of which 4 are located in Timor Strait in the eastern Indian Ocean, are planned for deployment for three years beginning in 2003.

(7) Indian National Data Buoy Program
India has a plan to deploy 40 moored surface buoys in the region around India. Twelve buoys out of the 40 buoys are classified as ocean buoy, which measures temperature, salinity, currents and wave spectrum at the sea surface and subsurface temperature profile, together with basic atmospheric variables. Another twelve buoys are meteorological buoys and only observe air temperature, pressure, winds, relative humidity and SST. Remaining 16 buoys are coastal and environmental buoys. These buoys are an extension of the present deep-sea and shallow-water buoys near Indian, and will be deployed from 2003 through 2007.

Although the main objectives for each project are different, it is necessary to coordinate these observational efforts as much as possible. Sharing of resources such as ship time should be encouraged. Also, a policy of free and open data access should be incorporated into the development of the observing system from the beginning. Finally, where feasible, data should be transmitted to shore in real-time so as to support operational weather, climate, and ocean analysis and forecasting efforts.

6. Recommendations for Workshop action

This paper has provided an overview of scientific issues and ongoing and planned observation efforts. The vision for the Workshop is to develop an implementation strategy to achieve the required tropical moored array for the Indian Ocean. The array needs to span the full equatorial band from the western to the eastern boundaries, and needs to extend north and south of the Equator as needed to capture the important variability which can be most efficiently measured by moorings. The mooring array should be implemented in coordination with Argo and other in situ observation plans. The recent WOCE, BOBMEX and JASMINE observations, together with monthly climatologies, ongoing satellite observations, and high-resolution model simulations, provide new detail on the ocean circulation pathways and the resulting transport of heat and freshwater, and provide a relatively firm basis for the design of a tropical moored array.

A possible implementation strategy is to identify regional and process sub-elements of the overall array, identify the important science that the sub-elements address, identify the significant implementation issues (funds, shiptime, infrastructure development), and develop a draft implementation plan for those sub-elements. The sub-elements could be national, bilateral, or multinational efforts. Possible sub-elements include: the along equator moorings; the I-MAP moorings; the 80°E moorings; the Bay of Bengal sector moorings; and the eastern Indian Ocean moorings.

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