

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.

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

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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

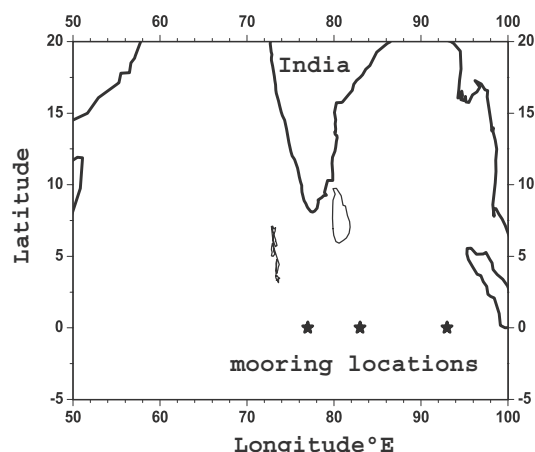


Figure 1. Study area and the locations of the Indian deep-sea current meter moorings in the equatorial Indian Ocean.

in December 2000 and data were obtained from all the RCMs. The mooring was redeployed and the second mooring was deployed at the equator, 83°E in December 2000. In March 2002, these two moorings were recovered and data were obtained. While redeploying these moorings at the same locations, a third mooring was deployed at the equator, 76°E. In October 2003, all the three moorings were recovered and redeployed for one more year, but the mooring at 76°E was shifted to 77°E. While deploying the mooring at 77°E, an upward-looking Acoustic Doppler Current Profiler (ADCP) was placed at 100 m depth on the top of the mooring. In October 2004, all the three moorings were recovered and deployed for another year. One upward-looking ADCP was placed at 100 m on top of each mooring. This project will continue till March 2007 with funding support from the MOD, and might be extended possibly for another 5 years through 2012. Though there is no human-vandalism for the moorings, we often found heaps of Tuna-fishing nets around the top current meter, particularly at the 93°E mooring location. The time-series currents data are available from the NIO website (http://www.nio.org/data_info/deep-sea_mooring/oos-deep-sea-currentmeter-moorings.htm) and are submitted to the Indian National Center for Ocean Information System (INCOIS), Hyderabad for display at INCOIS website. The moorings will be recovered in August – September 2006 and will be redeployed at the same locations for another year. Table 1 shows the status of the current data available as of July 2006.

In this article, the authors present some of the results obtained from the analysis of the time series current data from the Indian deep-sea current meter moorings. Both semi-diurnal and diurnal tides were removed from the time series of zonal (u) and meridional (v) current data using a 49 hour moving average. The residual time series data were used for spectral analysis (Murty et al., 2002; Emery and Thomson, 1997). The upward-looking ADCP (300 kHz, RD Instruments Make, USA) provided data of zonal (u) and meridional (v) current velocity and pressure (at the depth of the ADCP) in the upper 100 m. Due to mooring motion there were data gaps in the first top bins. The data were acquired at 15 minute intervals at 4m bins and all data were daily averaged to obtain the daily mean profiles of u and v for the period of September 2003 to October 2004.

3. Intraseasonal variability of measured currents

Murty et al. (2002) reported the first results of the Indian current meter moorings and described the variability of current structure at 93°E. They showed that there exists considerable meso-scale variability in the measured currents, comprising of intraseasonal oscillations of period 10-20 days and 30-50 day periods. Senguta et al. (2004) modelled successfully the observed biweekly mode (10-20 day period) variability in the equatorial Indian Ocean using an Ocean General Circulation Model (OGCM) forced by the daily averaged QuikSCAT surface winds. They demonstrated that the biweekly mode is due to the propagation of Mixed Rossby Gravity (MRG) waves generated

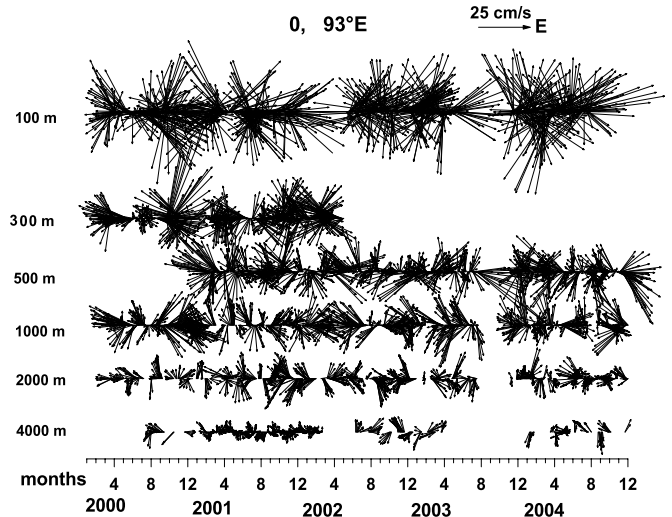


Figure 2. Long-term variability of current vectors at the nominal depths of the Indian deep-sea current meter mooring at the equator, 93°E during April 2000 – December 2004

by the intraseasonal winds over the equatorial Indian Ocean, and that the energy of bi-weekly wave intensifies eastward with depth. Sengupta et al. (2004) compared the simulated u and v components with those observed at 83°E and 93°E during 2000-2001. They reported that the biweekly wave has a wavelength of about 3000 km. Reppin et al. (1999) reported the spectral peak at 15 day period in the zonal component of velocity off the equator, 80.5°E and in the meridional velocity at the equator. Figure 2 shows the vertical structure of current vectors at six depths at the equator, 93°E during February 2000 – December 2004. It should be noted that the mean depths of the data are different in each deployment year (Table 1), and there are data gaps as the moorings' recovery was carried out after 13 to 15 months of deployment. Also some RCMs did not record the data due to loss of rotors. At this location, the vectors show considerable intraseasonal variability. Figure 3 (page 8) shows the long-term temporal variability of u and v at the uppermost depth of each mooring at the equator, 93°E during 2000-2004. The zonal velocity (top panel in Figure 3) shows the dominant seasonal variation superimposed with intraseasonal variation. Figure 3 also shows the dominant intraseasonal variability in the meridional velocity of period 10-20 day (bottom panel in Fig. 3) that has been compared well with model simulated meridional velocity (Sengupta et al. 2004). At the shallowest depth level of the RCM (e.g., 2001-2003 and 2003-04 deployments at 93°E), the zonal velocity is eastward both during April-May and September-October, coinciding with the semi-annual occurrence of equatorial Wyrтки jets (Wyrтки, 1973). During winter and summer monsoon periods, the zonal velocity is towards the west along the equator. The upward-looking ADCP-obtained meridional velocity in the upper 100 m at 77°E also clearly shows a banded structure with change of velocity at intraseasonal period of 10-20 days (Figure 4 page 15).

Each zonal velocity time series dataset is fitted with the semi-annual harmonics (thick curve in the top panel of Figure 3) obtained by the least square method. The phase of the semi-annual wave is referenced from January 1 for each time series. The amplitude of the semi-annual wave is large (14 cm/s) during the 2003-04 deployment when the mean depth of the RCM is as shallow as 106 m, and the amplitude decreases as the mean depth of the RCM increases. Table 2 presents the amplitude and phase of the semi-annual wave fitted to the time series of u and v components at 93°E, 83°E and 76°E.

Station No.	Mean depths of RCMs (obtained from Pressure sensors in each RCM)				
	2000	2000-02	2002-03	2003-04	2004-05
EQCM 1 [Equator, 93°E]	156, 290, 484, 991, 2004, 3995	139, 275, 470, 981, 1962, 3971	106, 344, 529, 1024, 2004, 4015	76, 312, 501, 996, 1981, 3991	To be recovered
EQCM 2 [Equator, 83°E]	----	ND, 397, 604, 1093, 2100, 4100	141, 342, 538, 1032, 2026, 4008	139, 339, 534, ND, 2022, 4000	To be recovered
EQCM 3 [Equator, 76°E]	----	----	418, 645, 821, 1314, 2311, 4122	----	----
EQCM 3A [Equator, 77°E]	----	----	----	168, 389, 568, 1059, 2101, 4084	To be recovered

ND: No data available

Table 1. Mean depths of RCMs in the deep-sea current meter moorings during each deployment.

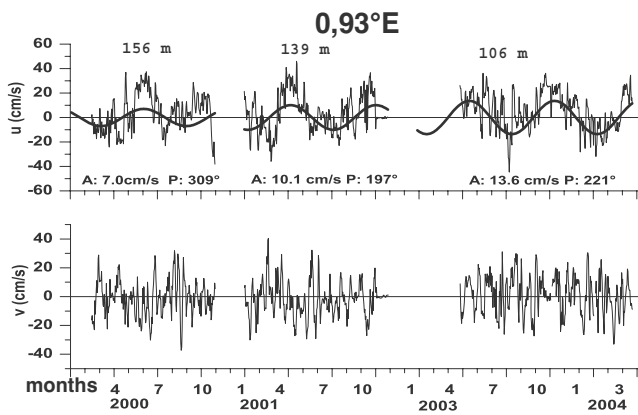


Figure 3. Long-term variability of zonal (top panel) and meridional (bottom panel) components of current velocity (cm/s) at the equator, 93°E during February 2000 – April 2004.

During the 2002-03 deployments at 83°E and 76°E locations, the amplitude of the semi-annual wave decreases with depth with highest amplitude of 29 cm/s at 141 m depth at 83°E and lowest amplitude of 10.2 cm/s at 1032 m at 83°E (Table 2). The amplitudes of the semi-annual wave are lower at the 93°E location (during all the 3 deployments), compared to those at the 83°E and 76°E locations. At the 83°E and 76°E locations, one can notice the upward increase of phase from about 800 m to towards surface, indicating the downward propagation of energy associated with the semi-annual wave. This upward phase propagation is clear at 93°E only during January – October 2001 deployment (Table 2). The amplitude and phases of the semi-annual wave fitted to the meridional velocity are also shown in Table 2. The amplitudes are in general smaller compared to the zonal velocity amplitudes, while the phases do not show any trend. The phase of the semi-annual wave fitted to the meridional velocity is almost constant for the 83°E deployment during 2002-03. For the deployment period of 2002-03, the zonal phase increased eastward from 186° at 83°E to 221° at 93°E at the uppermost depth level. This yields an eastward phase velocity of about 80 cm/s which is closer to the speed of the semi-annual Kelvin wave. The depth penetration of the semi-annual wave appears to be deeper at 76°E/77°E and 83°E locations and shallower at 93°E. Further observations and modeling studies are essential to understand this behavior of the semi-annual wave along the equator of the Indian Ocean.

The daily averaged time series of zonal and meridional velocity data at 76°E, 77°E, 83°E and 93°E locations were analysed using the Fast Fourier Transformation (FFT) technique (Emery and Thomson, 1997). Figure 5 shows the spectra of the zonal and meridional velocity at the topmost level respectively at 77°E, 83°E and 93°E from different deployment periods. The zonal velocity shows the dominant 170 day and 64 day periods at all the three locations, corresponding to the semi-annual period of Kelvin Wave and Madden-Julian oscillations respectively. The spectra for the meridional velocity, however, show the dominant intraseasonal variability with periods between 15 and 24 day at the three locations. It may be noted that the spectra are shown for periods above 10 days.

4. Conclusions

The status of Indian deep-sea current meter moorings along the equator is presented along with the brief results. The observations showed the presence of intraseasonal variability of 10-20 day period. It is noticed that the semi-annual variability is dominant in the central equatorial Indian Ocean and penetrates

to deeper depths, compared to that at 93°E. Further studies are being carried out to analyze the long-term measured current data with various model simulations to identify the variability associated with the Indian Ocean Dipole (Saji et al., 1999).

5. Acknowledgements

The Indian moorings program is funded by the Ministry of Ocean Development (MOD) and the moorings operations were carried out onboard the ORV Sagar Kanya. This is the NIO contribution No. 4188.

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Mooring duration	Mooring Location	Mean depth (m)	Zonal velocity (u)		Meridional velocity (v)	
			Amplitude (cm/s)	Phase	Amplitude (cm/s)	Phase
Jan/2000 – Dec/2000	93°E	156	7.0	309	3.5	22
		290	9.8	39	2.4	61
		991	4.6	108	1.4	20
Jan/2001 – Oct/2001	93°E	139	10.1	197	2.4	110
		275	6.7	22	1.1	86
		470	3.2	307	2.8	137
Apr/2002 – Mar/2003	93°E	106	13.6	221	1.5	290
		83°E	141	29.2	186	1.1
Apr/2002 – Mar/2003	83°E	342	13.2	76	2.1	245
		538	21.0	44	3.7	244
		1032	10.2	334	0.3	79
		76°E	418	13.4	101	2.7
Aug/2002 – Mar/2003	76°E	645	17.7	97	2.5	159
		821	14.6	72	2.2	277

Table 2: The amplitude and phase of the semi-annual variation of zonal and meridional velocity at the mean depths of Recording Current Meters at 93°, 83° and 76°E during 2000-03 in the equatorial Indian Ocean. The phase is referenced from January 1.

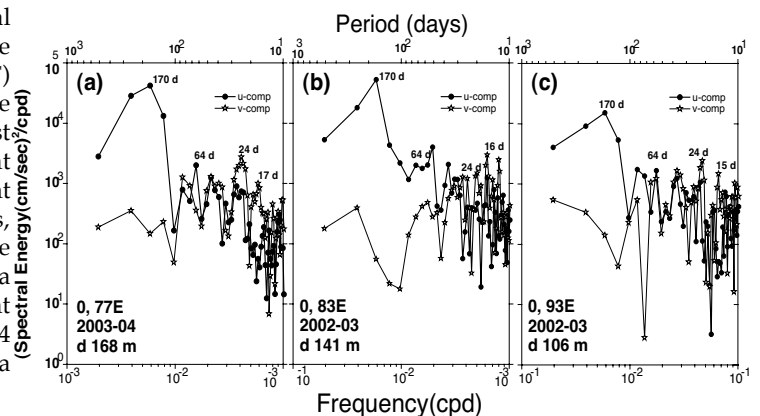


Figure 5. Spectra of zonal (filled circles) and meridional velocity (open stars) at the depths of uppermost Recording Current Meter (RCM) in the moorings at (a) 77°E, (b) 83°E and (c) 93°E. The mean-depth of RCM and the period of deployment are given in the figures. Spectra for periods below 10 days are not shown.

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MISMO : MIRAI Indian Ocean cruise for the Study of the MJO-convection Onset

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1. Introduction

The Madden-Julian Oscillation (MJO, Madden and Julian 1971, 1972) is known as dominant intraseasonal variability in the tropics. The MJO is an eastward propagating disturbance, occurring primarily during the boreal winter-spring season, with strong atmospheric convection which usually appears at first in the central-eastern equatorial Indian Ocean. Influences of the MJO spread not only within the tropical region but also to the atmospheric and oceanic conditions over the world through interactions with the monsoon (e.g., Yasunari 1979), El Niño (e.g., McPhaden 1999), tropical cyclones (e.g., Maloney and Hartmann 2001), and others. Although previous studies have revealed the various aspects of the MJO, so far there is no definitive explanation on the onset of the MJO convection over the Indian Ocean and associated upper-ocean variability.

As for the atmospheric convection itself, recent studies have suggested several key components that have to be clarified by observations. For example, Johnson et al. (1999) demonstrated the trimodal cloud distribution (cumulus, congestus, and cumulonimbus) in the tropics. In particular, it was shown that congestus clouds developed during the suppressed phase of the MJO moistened the mid-troposphere and preconditioned for the active phase with deep convection (Johnson et al. 1999, Kikuchi and Takayabu 2004). Furthermore, the large diurnal cycle in the sea surface temperature in a light wind condition seems to be crucial for the initiation of shallow cumuli and congestus clouds, suggesting the important role of coupling between the atmosphere and the upper ocean in the MJO-convection onset (Slingo et al. 2003). These studies suggest that fine-scale observation from the ocean surface to the entire troposphere is required for better understanding of MJO-convection. The TOGA COARE program in the tropical western Pacific during 1992 and 1993 (Webster and Lukas 1992) was one such observational effort. There are no intensive observations, however, in the Indian Ocean, though fine-scale observations are strongly desired for the study on the initiation of the MJO convection there.

For the upper-ocean variability in the central-eastern tropical Indian Ocean, it has been well known that a strong zonal jet and associated thermocline displacement appear twice

a year during the monsoon transition periods (April-May, and October-November). These are known as the Wyrtki jets (Wyrtki 1973). Using current data from an ADCP mooring at 0°, 90°E, Masumoto et al. (2005), however, demonstrate that intraseasonal disturbances with the 30-50 days period dominate the zonal current in the eastern equatorial Indian Ocean. From their coherence analysis, the intraseasonal variability of zonal currents is considered to be induced by the wind stress between 80°E and 90°E at the periods of 30-50 days. However, details of generation mechanisms for the intraseasonal variability remain unsolved. Thus, it is important to obtain fine resolution data sets to reveal the air-sea interaction processes at the intraseasonal time scale. The data will also be able to be used for validating numerical models and satellite observations, and in turn the models will help in understanding the complex physical processes.

Based on these recent areas of progress, an observational cruise by the R/V Mirai named as MISMO (Mirai Indian Ocean cruise for the Study of the MJO-convection Onset), has been designed to conduct the needed intensive atmospheric and oceanic observations. In the following sections, basic information on the MISMO project will be briefly described.

2. Objectives

The aim of MISMO is to reveal the atmospheric and oceanic features of the central-eastern equatorial Indian Ocean in November, where and when the convection in the MJO is often initiated. Special emphases are put on the following issues:

- a. *Vertical structure of the atmosphere*
 - Moisture convergence in the lower troposphere
 - Variation of vertical profile of atmospheric parameters such as water vapor, divergence field, and clouds
 - Development of cumulus convection
- b. *Role of the air-sea interaction*
 - Diurnal cycle of SST and its difference in behavior before / after the onset of the MJO
 - Variation of ocean surface heat flux
- c. *Oceanic responses to the MJO*
 - Variation of ocean surface currents accompanied with westerly wind bursts
 - Evaluation of warm water and salinity transports