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Two decades of operating the Indian moored buoy network: significance and impact

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ABSTRACT
Ocean–atmosphere interactions in the North Indian Ocean play a vital role in the onset, progression and withdrawal of the Indian monsoon. This paper describes the Ocean Observation System (OOS), an operational observational programme of the Earth System Science Organization and the National Institute of Ocean Technology (ESSO-NIOT) under India’s Ministry of Earth Sciences (MoES). Since 1997 it has provided oceanographic and surface meteorological data in real time for weather forecasting, climate research and several other applications. The programme focuses on understanding the phenomenon of the mean seasonal cycle of the Indian monsoon, the intra-seasonal to intra-decadal oscillations of air–sea interactions, trends that are related to tropical cyclones and the annual cycle balance in the exchange of waters between the two limbs of North Indian Ocean, i.e. the Arabian Sea and the Bay of Bengal. \textit{In situ} observations are also used to develop, initialise and validate regional forecast models that provide high resolution data. There is also a growing need to understand the spatial phenomenon of oceans using satellite observations, wherein the quality of data needs to be validated and verified carefully. This paper also provides an overview of the scientific and societal impact of the Indian moored buoy network over two decades of operation.

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1. Introduction
The North Indian Ocean circulation and Indian monsoon are two inter-related and important dynamical processes for which oceanic and atmospheric coupling plays a key role. The western and eastern areas of the North Indian Ocean are the Arabian Sea and the Bay of Bengal, respectively; they demonstrate contrasting physical oceanographic conditions with respect to thermo-haline structure and circulation, primarily due to the differences they experience in boundary forcing that is caused by the monsoons. The Summer Monsoon Current (May to September) and Winter Monsoon Current (November to February) maintains balance over an annual cycle by exchanging waters between the Arabian Sea and the Bay of Bengal. Among the world’s oceans, the Bay of Bengal is one region that is very strongly influenced by freshwater forcing, which is caused by large amounts of rainfall from monsoons and tropical cyclones in combination with the associated river discharges from the surrounding landmasses. Marginal seas such as the Red Sea and the Persian Gulf exhibit a significant influence on the Arabian Sea. The Indonesian Throughflow brings waters from the south-western tropical Pacific Ocean, which has an impact on the heat and salt budgets of the tropical Indian Ocean – and hence on the monsoon climate. The Indian Ocean Dipole (IOD) is a unique phenomenon that occurs in the tropical Indian Ocean periodically, with contrasting anomalies in the near-surface thermo-haline structures of the eastern and western equatorial Indian Ocean. The hallmark of Indian Ocean properties and processes is time dependency, which needs to be understood for the improved prediction of the monsoon–ocean coupled system. \textit{In-situ} observations play an important role in providing information about the monsoon onset, propagation, withdrawal and its active/break spells. This paper describes the importance of the ocean observation network in the North Indian Ocean, which provides oceanic and atmospheric time series real-time data from fixed stations.

2. Scientific observations in the North Indian Ocean
Historically, ocean surface measurements have been made via ships of opportunity, cargo vessels that sail the oceans to conduct maritime trade. These measurements were made for the safety of the ships’ navigation,
so they are mostly confined to shipping lanes and have bias for fair weather conditions. Similar measurements have also been made using fishing and naval vessels. Research vessels, though relatively few in number, are deployed to carry out systematic surface and water column measurements during scientific cruises in specific geographic regions, making them very helpful for mapping the characteristics of the seas and understanding their governing mechanisms. Data collected on the Indian monsoon has contributed significantly to the understanding of air–sea interactions. Among all the scientific cruises that have taken place, the Arabian Sea Monsoon Experiment (ARMEX) and the Bay of Bengal Monsoon Experiment (BOBMEX) have been two of the most important expeditions, carried out as part of the Indian Climate Research Programme (ICRP), coordinated by India’s Department of Science and Technology. The result of these studies have led to a new understanding ocean–atmosphere coupling (Hareesh Kumar et al. 2001; Bhat & Narasimha 2007).

In addition to scientific experiments, the need for ongoing systematic time series observations are required in order to study the air–sea interactions and ocean circulation of the Indian Ocean. With this in mind, the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) was established (McPhaden et al. 2009). RAMA provides high-quality time series data throughout the Indian Ocean tropics and gives a crucial insight into understanding and predicting East African, Asian and Australian monsoons, as well as the variability of the Indian Ocean climate and its atmospheric teleconnections with other major large-scale oceanic and atmospheric phenomena.

3. Objectives

Air–sea parameters and their variability in both time and space are crucially important for the synoptic analysis of weather and forecasting. The Indian moored buoy network (Figure 1) is designed for understanding the dynamics of air–sea interactions and ocean circulation in the North Indian Ocean. The network is mainly concentrated in areas wherein rich oceanic and atmospheric dynamic processes occur. As the Indian monsoon variability is directly related to the socio-economic relations of its surrounding countries, the observations from the

![Figure 1](image-url)
network are important factors for understanding the regional circulation and ocean–atmosphere interactions.

The continuous time series observations provided by the Indian moored buoy systems in the eastern Arabian Sea and the Bay of Bengal have provided openings for comparative studies, incorporating ship of opportunity expendable conductivity, temperature and depth profiling systems, the Argo array and surface drifting buoy programmes. Moored buoys are of particular value in providing in situ observations for limited-duration research experiments, such as ARMEX and BOBMEX, the Indian Ocean Experiment (INDOEEX) and the Joint Air–Sea Monsoon Interaction Experiment (JASMINE). RAMA in the Indian Ocean has been providing new data that has added great value to our understanding of the relations between oceans, monsoons and cyclones on different timescales (McPhaden et al. 2010). The Indian moored buoy system continuously records vertical profiles of temperature, salinity and currents, which supplements RAMA. The moored buoy programme and RAMA provide continuous measurements in the historically data-sparse North Indian Ocean for studying large-scale ocean–atmosphere interactions, mixed-layer dynamics and ocean circulation related to monsoons on intra-seasonal to inter-annual timescales (McPhaden et al. 2009; Venkatesan et al. 2013). The Earth System Science Organisation’s National Institute of Ocean Technology (ESSO-NIOT) cruises also provide an opportunity to deploy instruments for other national and international programmes.

4. Application

4.1. Intra-seasonal and diurnal variability studies

The summer monsoon rainfall distribution on the Indian subcontinent is related to the variation of the convection over the Bay of Bengal (Gadgil 2000). Hence, for understanding intra-seasonal oscillations (ISOs) of the monsoon it is very important to understand the processes that determine the variability of organised convection over the bay. Active and weak spells of convection which occur over the Bay of Bengal give an insight into understanding the nature of the feedback between the atmospheric convection and the surface conditions of the bay. Simultaneous time series observations in the northern and southern bay from moored buoys and ships during the summer monsoon have revealed that the dominant intra-seasonal timescale of the variation of wind and sea surface temperature (SST) is in the order of three to four weeks (Bhat et al. 2001; Bhat & Narasimha 2007). During the summer of 1999, the data collected on the Indian naval ship INS Sagardwani and via in situ observations from the Indian moored buoy network show that the oceanographic and meteorological parameters exhibited intra-seasonal, inertial, diurnal and semi-diurnal oscillations (Hareesh Kumar et al. 2001). However, the low period oscillations of 8 to 16 days reflected in the tropical rainfall measuring mission microwave imager (TMI) SSTs during monsoon season were not observed in the buoy SSTs due to strong stratification in the Bay of Bengal (Parekh et al. 2004). The amplitude of the ISOs of SSTs in the Bay of Bengal is large (1°C to 2°C), mainly because of the shallow mixed layer in that region, due to Fresh water flux from the rivers and rain makes a very shallow mixed layer in the Bay of Bengal and that brings high amplitude oscillations of SST in the region (Sengupta & Ravichandran 2001).

The SST anomalies in the bay propagate northward in response to northward-moving, alternative positive and negative anomalies of net heat flux with a speed of about 1.8 m/s (Sengupta et al. 2001). One of the important satellite-derived parameters which can determine the variability of the SST is the outgoing long-wave radiation (OLR). It is found that changes in the OLR can lead to changes in the SST over a period of a few days (Premkumar et al. 2000; Bhat 2003). The moored buoy observations show high seasonality in the magnitudes of the diurnal range of SSTs (ΔSST) in the North Indian Ocean (Shenoi et al. 2009). During the summer monsoon, the winds are strong over the North Indian Ocean and the cloudy skies suppress the solar radiation arriving at the surface. Both of these factors favour a reduction in ΔSST. On the other hand, during spring, the winds are weaker and the solar radiation is higher due to the absence of clouds. Both of these factors promote a large degree of diurnal warming. The depth dependence of ΔSST is also highest during the spring and lowest during the summer monsoon. Even though the diurnal range of the SST during the summer monsoon in the Bay of Bengal is low, the diurnal cycle has a significant influence in maintaining the observed amplitude of the ISOs (Mujumdar et al. 2011). One of the important air–sea interaction parameters that can influence the SST and ocean thermal structure is the drag coefficient. Parekh et al. (2011) developed an accurate method for estimating the drag coefficient over the North Indian Ocean using buoy wind and other boundary layer parameters.

4.2. Cyclone studies

The first glimpse of the ocean response to cyclonic forcing was captured by the moored buoy deployed in the
Bay of Bengal during the Odisha super cyclone in 1999. Two cyclones hit the Odisha coast at Gopalpur and Paradip during 15 to 31 October 1999. Both cyclones marked their presence in the Bay of Bengal by showing variations in SST, air temperature, wind speed and surface currents, as recorded by moored buoys (Chinthalu et al. 2001). The buoy data has reflected various extreme events during the course of its operation since 1997. During 3 to 7 November 2010, cyclone Jal traversed between two buoys in the Ocean Moored Buoy Network for the Northern Indian Ocean (OMNI) in the Bay of Bengal at a wind speed of 16 m/s. The subsurface temperature showed near-surface cooling and deepening of the mixed layer (Venkatesan et al. 2013). The mixed layer heat budget analysis showed that vertical processes were the dominant contributors towards the observed cooling (Girishkumar et al. 2014).

In 2013, five cyclones developed over the Bay of Bengal for the first time since 1987. The post-monsoon season featured a lot of activity in the Bay of Bengal, with the formation of three very severe cyclonic storms (VSCSs) and one severe cyclonic storm (SCS). The observed cyclone tracks from May to December 2013 are shown in Figure 2. During VSCS Phailin, the buoy design withstood the rough sea, though one of the buoys moved in a clockwise direction with inertial oscillation triggered by the cyclone. The buoy near the eye of the cyclone recorded an air pressure of 920 hPa, the lowest value recorded in the North Indian Ocean to date (Venkatesan et al. 2014). The buoy data are also used for cyclone tracking and intensity prediction by the ESSO-India Meteorological Department (IMD). The SST data are used by the ESSO-IMD as the initial indicators for the monsoon forecast, as well as the ocean state forecast given by the ESSO-Indian National Centre for Ocean Information Services (ESSO-INCOIS) and the weather forecast given via global data assimilation system. Figure 3 shows an example of the OMNI buoys’ air pressure and wind speed data during tropical cyclones.

4.3. Arabian Sea mini warm pool study

The SST data from the moored buoys in the south-eastern Arabian Sea, close to Minicoy, reveal ISOs that contribute to better understanding the physical processes governing the warming and cooling phases of the Arabian Sea warm pool. Surface heat flux terms and horizontal advection terms were estimated by using three-hourly buoy data (Sengupta et al. 2008). The mechanism of springtime SST cooling in the south-eastern Arabian Sea appears to differ from that forced by the monsoon ISOs. The data collected by the moored buoys suggest that a typical pre-monsoon intra-seasonal SST cooling event occurs under clear skies when the ocean is gaining heat. In the warming phase, the SST rises mainly due to the heat absorbed within the mixed layer, while during the cooling phase the SST cools rapidly because of the large penetrative flux of solar radiation at the base of the mixed layer, and the advective cooling caused by the upper ocean currents. However, if the mixed layer is very shallow then the penetrative short-wave radiation flux at the base of the mixed layer will be high and can lead to cool SSTs even if the net surface short-wave radiation is high (Sengupta et al. 2002).

4.4. Satellite validation and inter-comparison studies

The satellite systems rely on complicated algorithms to convert measurements of electromagnetic radiation into meaningful geophysical variables. Satellite data must be calibrated and validated with in situ observations in order to detect and remove the potential biases induced by atmospheric effects and orbital and instrumental errors (McPhaden et al. 1998).

The SST and wind speed are important surface parameters that determine air–sea interactions in the tropics. The availability of good quality SST and wind speed data is central to studying the tropical climate and its variability. The quality of the SSTs derived from the TMI was evaluated by Bhat et al. (2004) using buoy data from the Bay of Bengal. A comparison between buoy observations, TMI SSTs and National Centres for Environmental Predictions (NCEP) weekly SSTs in the Bay of Bengal revealed that the TMI gives the most reliable and accurate SST data set for the study of intra-seasonal space-time variability in the cloudy and humid conditions of the summer monsoon (Senan et al. 2001; Sengupta et al. 2001; Sengupta & Ravichandran 2001). More recently, Vaid et al. (2011) have observed the intra-seasonal signals in both the TMI SSTs and the daily high-resolution blended Reynolds SSTs.

Goswami and Sengupta (2003) compared the NCEP and Quick Scatterometer (QuikSCAT) surface winds with moored buoy data collected in the Arabian Sea and the Bay of Bengal and showed that QuikSCAT represents the observed surface winds better than the NCEP. Sathesan et al. (2007) carried out a comparative study of QuikSCAT-derived wind speed and direction with a large sample of buoy measurements. The other study also indicated that the air–sea temperature difference, which shows seasonal variations in the North Indian
Ocean (Bhat 2002), can influence the magnitude of the wind residuals.

The validation of the SST and wind speed derived from the multi-frequency scanning microwave radiometer (MSMR) onboard the Oceansat-I (Muraleedharan et al. 2004) demonstrated that the correlation of the moored buoy SSTs is better during the night, but during the daytime the correlation only peaks during high winds. Further, the study proved that, compared to autonomous weather stations and ships, moored buoys are a better platform for validating satellite-derived wind speeds. By using a standard multiple linear regression analysis between the buoy wind speed and the MSMR brightness temperature, Parekh et al. (2005) developed a regional empirical algorithm for the retrieval of surface winds from the MSMR over the Arabian Sea. Parekh et al. (2007) carried out a study comparing the MSMR surface wind speed with buoy data and showed that the MSMR overestimates the entire range of wind speeds (by 0–18 m/s), and that the retrieval of low wind speeds from the MSMR is not possible also. They also concluded that one of the advantages of the MSMR over the TMI is its ability to retrieve more accurate daytime SSTs. With the help of the surface wind speed and wave data measured by the moored buoys in the Arabian Sea and the Bay of Bengal, Bhatt et al. (2004) carried out an experiment with the Global Data Assimilation System (GDAS) at the National Centre for Medium Range Weather Forecasting (NCMRWF), and the results show that the inclusion of MSMR winds in the model results in a remarkable improvement in the quality of the model’s output.

A comparison of the model simulations (Modular Ocean Model, v4) with observations from the moored buoys demonstrated that the model can reproduce the seasonal evolution of temperature structure in the Arabian Sea and the Bay of Bengal (Bijoy et al. 2008). The most widely used flux products in the

Figure 2. Observed cyclone tracks in the Bay of Bengal, May to December 2013.
forcing of ocean general circulation models (OGCMs) are those provided by NCEP reanalysis. However, a comparison of the NCEP latent heat flux and sensible heat flux with those of the buoys showed that they are largely underestimated during monsoons (Swain et al. 2009). ESSO-NIOT deployed a pair of buoys, MET (meteorological), OPTICAL (optical) and CAL-VAL (calibration and validation), at Kavaratti, Lakshadweep in the Arabian Sea. The in situ data collected by the buoy system were used for the calibration of the satellite sensor ocean colour monitor (Shukla et al. 2013).

4.5. Ocean wave studies

Surface wave information is highly significant for any marine activity. Effective planning, the design of ports, harbours, coastal and offshore engineering applications and the design of ships and other ocean-going vessels require accurate information on waves. Measurements of wave parameters either in shallow or deep waters are difficult, especially during bad weather. Historically, visual observations made from ships have been the main source of wave information. These observations often lack extreme wave data as they tend to avoid stormy areas. In this scenario, wave observations from fixed platforms and moored buoys are the main source of extreme wave information (Joao Cruz 2008). OMNI buoys are equipped with motion reference unit (MRUs) which measure heave, roll and pitch. These data are recorded at a rate of 1 Hz for 17 min at 3-h intervals. Vimala et al. (2014a) reported that wave spectra generated in the Bay of Bengal show dominant peaks at 0.08 Hz to 0.1 Hz and multi-peak spectrum energy is distributed within a wide range of 0.05 Hz to 0.25 Hz. They also presented the Joint North Sea Wave Project (JONSWAP) spectrum, which mostly coincides with the buoy-measured wave spectrum during windy sea conditions. Real-time wave forecasts were made using moored buoy wave data (Jain & Deo 2007; Vimala et al. 2014b). The significant wave height derived from the moored buoys is useful for validating the wave forecast and different model outputs, such as the Wave Model (WAM), the Simulating Waves Nearshore (SWAN) model and the Nested SWAN model (Muraleedharan et al. 2006; Vimala et al. 2014c).

Figure 3. Response of Indian moored buoy data during tropical cyclone events: (a) air pressure and (b) wind speed.
5. Data management and user outreach

The Indian moored data buoy system features a suite of sensors configured to collect 106 parameters and transmit through satellite telemetry at either 1-h or 3-h intervals. During data transmission the buoy hardware establishes a link with the satellite and transmits the collected data to the Mission Control Centre (MCC). Further, a large amount of data are archived and stored at the MCC and disseminated in near-real-time to ESSO-INCOIS (Figure 4). Due to the voluminous inflow of data, the manual mode of data management, quality control (QC) mechanism and inventory management faced a lot of challenges and required high levels of human intervention. To overcome these issues, an integrated tool called the Advanced Data Reception & Analysis System (ADDRESS; Venkatesan et al. 2015) was developed for the buoy system, data, inventory, cruise and operation management. While developing this tool, key areas such as ocean data management, QC methodologies, QC standards (global, climatologic and local), metadata, visualisation tools and communication systems were focused on. To achieve a user-friendly system, an additional focus was placed on creating an integrated approach, so current and traditional data management schemes were referenced in order to solve daunting problems. The tool allows the homogenisation of all data files received from different buoy variants and provides an easy-to-use graphical user interface whose functionality extends not only to importing but also to filtering, concatenating, visualising and exporting data. Through this functionality, the tool should guarantee a common framework for data file manipulation, aiding scientists, researchers and technicians in handling data files from different sources. The use of information technology is envisioned to increase information quality and improve overall efficiency and effectiveness in buoy data management.

6. New technologies, challenges and limitations

The Ocean Observation System (OOS) has provided technical expertise for the handling of different sensors – meteorological and oceanographic, surface and subsurface, analog and digital – and the testing of multisensory data, as well as its integration. One major breakthrough is the development of the indigenous Data Acquisition System (DAS) for moored buoys. The DAS has the capability to monitor, acquire, record and transmit data and communicate with multiple sensors (Venkatesan et al. 2013). The Integrated Marine Surveillance System (IMSS) implemented in the Indian moored buoy programme is the first of its kind, using an approach that provides real-time meteorological and oceanographic data via 3G telemetry and/or general packet radio service (GPRS; Venkatesan 2014). An uninterrupted power source is required to run all the sensors working at sea, which are unattended for long periods; with this in mind, NIOT developed wind-powered buoys (Kesavakumar et al. 2013). To study Polar–Indian monsoon teleconnections, a multi-sensor moored observatory was deployed in the Arctic region (PIB Gol 2014). To understand high-frequency events like internal waves and turbulence, it is necessary to sample the ocean parameters over short timescales. In addition, an algorithm has been developed and implemented in the Indian moored buoy system for collecting high-frequency data during cyclonic events. These scientific requirements are addressed by newer technological advancements and are being adopted by the Indian moored buoy network.

The OOS has successfully enabled significant advances over the past 17 years; however, there are some challenges with regard to maintaining the highest standard of data quality in the network. One of the major challenges is ship availability; specialised ships with deep sea mooring capabilities are required for retrieval and deployment operations. The buoys should be recovered and redeployed at least once per year to ensure continuous data transmission, and this requirement has been successfully met during the last few years. Vandalism of buoys is a global phenomenon and an international issue that every country is trying to minimise. In the past few years, the issue of data buoy vandalism has been raised in a number of different international fora: the Intergovernmental Oceanographic Commission (IOC), the UN General Assembly (UNGA), the Western and Central Pacific Fisheries Commission (WCPFC) and the Indian Ocean Tuna Commission (IOTC). Tampering with buoys, both deliberate and accidental, and problems linked with fishing are major threats to the existence of buoy networks in the open ocean. Moreover, vandalism causes the loss of significant scientific data collected by buoys. Another major challenge is overcoming the sensor fouling to ensure that reliable data is provided. The anti-fouling methods adopted for the open ocean environment can ensure data returns of good quality (Senthil et al. 2015).

Hundreds of kB of data can be transferred via cable communications; however, Indian moored buoys are using real-time satellite telemetry which is limited to 1 MB/s with present technology (Venkatesan 2014). It is quite often observed that buoys drift out of satellite footprints due to tampering; thus, a well-developed communication system is required to track the buoys.
7. International collaboration

The OOS programme is associated with the Global Ocean Observing System (GOOS), the Data Buoy Corporation Panel (DBCP), the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), the World Meteorological Organization (WMO) and the IOC, along with regional bodies such as Bay of Bengal Programme – Intergovernmental Organization (BOBP-IGO) and the Bay of Bengal Large Marine Ecosystem (BOBLME). The OOS programme is also collaborating with the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) to use facilities and equipment to conduct joint research survey activities, to develop sensors, tools, calibration facilities and standardisation and to build expertise in the field of ocean science and technology. The moored buoy network meets sensor standardisation according to WMO standards. Sensor selection is based on the recommendation of an expert committee and sensors used by other global operators such as the National Oceanic and Atmospheric Administration (NOAA), the Woods Hole Oceanographic Institute (WHOI) and JAMSTEC in order to meet data uniformity. In addition, the OOS is involved in a joint programme between India and the United States (US), the Air–Sea Interaction Research Initiative (ASIRI) under the National Monsoon Mission to study the air–sea interactions in the Bay of Bengal region.

8. Future work

Deficiencies in in situ data are obstructive to developing a more proficient understanding of weather and climate. More detailed, frequent and accurate in situ observations are required for developing better models and enhancing existing ones, thus improving the accuracy of predictions.
and forecasts (Fousiya et al. 2015). There is growing interest in continuous multidisciplinary observations of the oceans from the regional scale all the way up to the global scale. Biogeochemical sensors and bio-optical sensors are becoming highly valued, as they are needed to monitor the causes and effects of global climate change and the capability of the oceans to act as a sink for CO2 and other greenhouse gases and heat (Dickey & Moore 2003).

At present, high temporal resolution measurements of biogeochemical and bio-optical parameters are not available from the Arabian Sea and the Bay of Bengal. Given this, the OOS is likely to expand its moored network throughout the Indian Ocean and important oceanic regions. The OOS is planning to deploy specially designed moored systems with sensors for measuring variables such as the partial pressure of CO2, sea water pH and dissolved oxygen. Deep sea current metre mooring, installation of underwater cameras in moored systems and satellite validation studies through collaboration with the Space Applications Centre (SAC) are the major future objectives of the moored buoy programme. The OOS is also working in collaboration with ESSO-National Centre for Antarctic and Ocean Research (NCAOR) on the design and deployment of surface and subsurface mooring systems in the South Indian Ocean to collect data on various parameters such as ocean currents, temperature, dissolved oxygen, partial pressure of CO2 gas dissolved in the water, photo-synthetically active radiation data and sediment traps, in order to measure the quantity of sinking particulate organic material.

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Disclosure statement

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