



Sustenance of Indian Moored Buoy Network During COVID-19 Pandemic – A Saga of Perseverance

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The moored buoy network in the Indian Ocean revolutionized the observational programs with systematic time-series measurement of *in situ* data sets from remote marine locations. The real-time meteorological and oceanographic data sets significantly improved the weather forecast and warning services particularly during extreme events since its inception in 1997. The sustenance of the network requires persistent efforts to overcome the multitude of challenges such as vandalism, biofouling, rough weather, corrosion, ship time availability, and telemetry issues, among others. Besides these, the COVID-19 pandemic constrained the normal functioning of activities, mainly by delaying the maintenance of the network that resulted in losing a few expensive buoy system components and precious data sets. However, the improvements in the buoy system, in-house developed data acquisition system, and efforts in ensuring the quality of measurements together with “best practice methods” enabled 73% of the buoy network to be functional even when the cruises were reduced to 33% during the COVID-19 lockdown in 2020. The moored buoys equipped with an Indian buoy data acquisition system triggered high-frequency transmission during the Super cyclone Amphan in May 2020, which greatly helped the cyclone early warning services during the COVID-19 pandemic. The COVID-19 lockdown points toward the reliability and enhanced utility of moored buoy observations particularly when other modes of measurements are limited and necessitates more such platforms to better predict the weather systems. The present study analyzed the enhancement of the buoy program and improvisation of the buoy system that extended the life beyond the stipulated duration and enabled the high-frequency data transmission during cyclones amid the COVID-19 lockdown. The recommendations to better manage the remote platforms specifically in the event of a pandemic based on the operational experience of more than two decades were also presented.

Keywords: moored buoy, ocean observation, marine sensor, cyclone, COVID-19, North Indian Ocean

INTRODUCTION

The unprecedented spread of COVID-19 has taken the world by storm with significant socio-economic impact besides a large number of casualties and severe disruption of daily life. The Covid pandemic revealed that the world is ill-equipped to make real-time measurements of economic activity and its immediate consequences. The pandemic demonstrated the urgent need for improved data, models and analysis to understand and correct those deficiencies (Difffenbaugh et al., 2020). The immediate impact of the pandemic associated lockdown is also reported with some positive changes such as an abrupt 8.8% decrease in global CO₂ emissions in the first half of 2020 compared to the same period in 2019 (Liu et al., 2020), decrease in NO₂ in seven cities in India during the 2020 lockdown period (Vadrevu et al., 2020), and substantial reduction in pollutant concentrations in the industrial cities of Western India (Nigam et al., 2021). Similarly, the significant reduction in marine traffic (March et al., 2021) across the globe during the COVID-19 lockdown resulted in a substantial reduction in marine noise (Thomson and Barclay, 2020). The consequences of the COVID-19 situation are likely to persist for a longer duration with a significant impact on the socio-economic and scientific realm across the globe. Adapting to the COVID-19 situation necessitates better assessment, which is severely impaired by the inoperative measurement systems specifically the remote ocean platforms.

As the nations struggled to control the spread of the COVID-19 pandemic, the impact on the environment particularly the marine environment is less addressed. Perhaps one of those strongly affected by the pandemic are the ocean observation systems such as moored buoys, drifting buoys, Argo floats, and radars, to name a few. Even though these systems are robust and capable of operating autonomously for years, regular deployment and refurbishment are required for the upkeep of the resilient network (Heslop et al., 2020). Sustained ocean observations are necessary to meet the growing demand for weather and climate services whereas pandemic-associated slowdown in maintenance activities have adversely affected the data return (Viglione, 2020). The decline in the data flow can adversely affect the reliability of the weather forecast particularly during extreme events with potentially devastating consequences such as the propagation of the possible errors caused by the gap in the measurements. The survey conducted by the Global Ocean Observation System (GOOS) in April 2020 on the immediate impact of COVID-19 on ocean observations indicate a possible impact on 30–50% of the moorings, pausing a threat of losing the crucial data sets and even the equipment (Heslop et al., 2020). Prioritizing the maintenance activities under essential service is suggested considering the importance of ocean observations in weather services and long-term climate change.

The Indian Ocean plays a vital role in better understanding the global climate and is significantly inter-connected and impacted by the El-Niño and La-Niña phenomena. Two decades ago, the Indian Ocean was significantly under-sampled compared to other tropical oceans. The available information was mostly based on numerical models, ship-based observations, and few specific scientific experiments such as the International Indian

Ocean Experiment (IIOE), Arabian Sea Monsoon Experiment (ARMEX), and Bay of Bengal Monsoon Experiment (BOBMEX), among others. The inception of the moored buoy program by the National Institute of Ocean Technology (NIOT) under the aegis of the Ministry of Earth Sciences (erstwhile Department of Ocean Development) in August 1997, earmarked a new era of systematic collection of meteorological and oceanographic parameters in the North Indian Ocean. This network is operational now, for more than two decades, transmitting uninterrupted meteorological and oceanographic observations in real-time at selected strategic locations despite innumerable challenges (Venkatesan et al., 2016). The long term moored buoy measurements of surface meteorological as well as subsurface oceanic parameters provided many new insights into the ocean dynamics of the North Indian Ocean such as the barrier layer dynamics in the Bay of Bengal (BoB), characteristics of warm pool in the Arabian Sea (AS), significant monsoon intraseasonal oscillations in BoB and complex air-sea flux exchange, to name a few. The predictive capability of cyclone track and intensity is significantly improved with the incorporation of the crucial upper ocean measurements such as temperature profile, salinity profile, and Tropical Cyclone Heat Potential (TCHP) in real-time during the passage of cyclones (Venkatesan et al., 2014, 2020; Navaneeth et al., 2019). The moored buoys captured the signals of more than 30 low-pressure systems and withstood the fury of intense cyclones such as Phailin in October 2013, Ockhi in December 2017, and Amphan in May 2020 showing the success of the engineering design as well as transmitted uninterrupted high-frequency data as per the rapid mode algorithm implemented by NIOT.

The maintenance activities and data services of the moored buoy network in the Indian Seas are also impacted by pandemic restrictions. However, the experience in maintaining the moored buoy network over two decades by overcoming various challenges helped to disseminate the critical real-time met-ocean observations amid the COVID-19 pandemic. The challenges faced in general and particularly during the lockdown in 2020 never deterred the program from providing its services to the end-users, particularly during extreme events. The present study detailed the evolution of moored buoy network, the impact of pandemic restrictions on data return, enhanced support during cyclones amid the COVID-19 lockdown during the year 2020, and the specific challenges during the pandemic. The recommendations for better maintenance of a remote platform based on the operational experience for more than two decades specifically during the pandemic were also presented.

ESTABLISHMENT AND ENHANCEMENT OF THE MOORED BUOY NETWORK IN THE INDIAN OCEAN

The “Indian moored buoy network,” the first of its kind in the Indian Seas, was established with the primary objective of supporting the cyclone and tsunami early warning services in the North Indian Ocean. The present buoy network (**Figure 1**) includes 12 Ocean Moored buoy Network for the Northern Indian Ocean (OMNI) buoys with profile measurements (seven

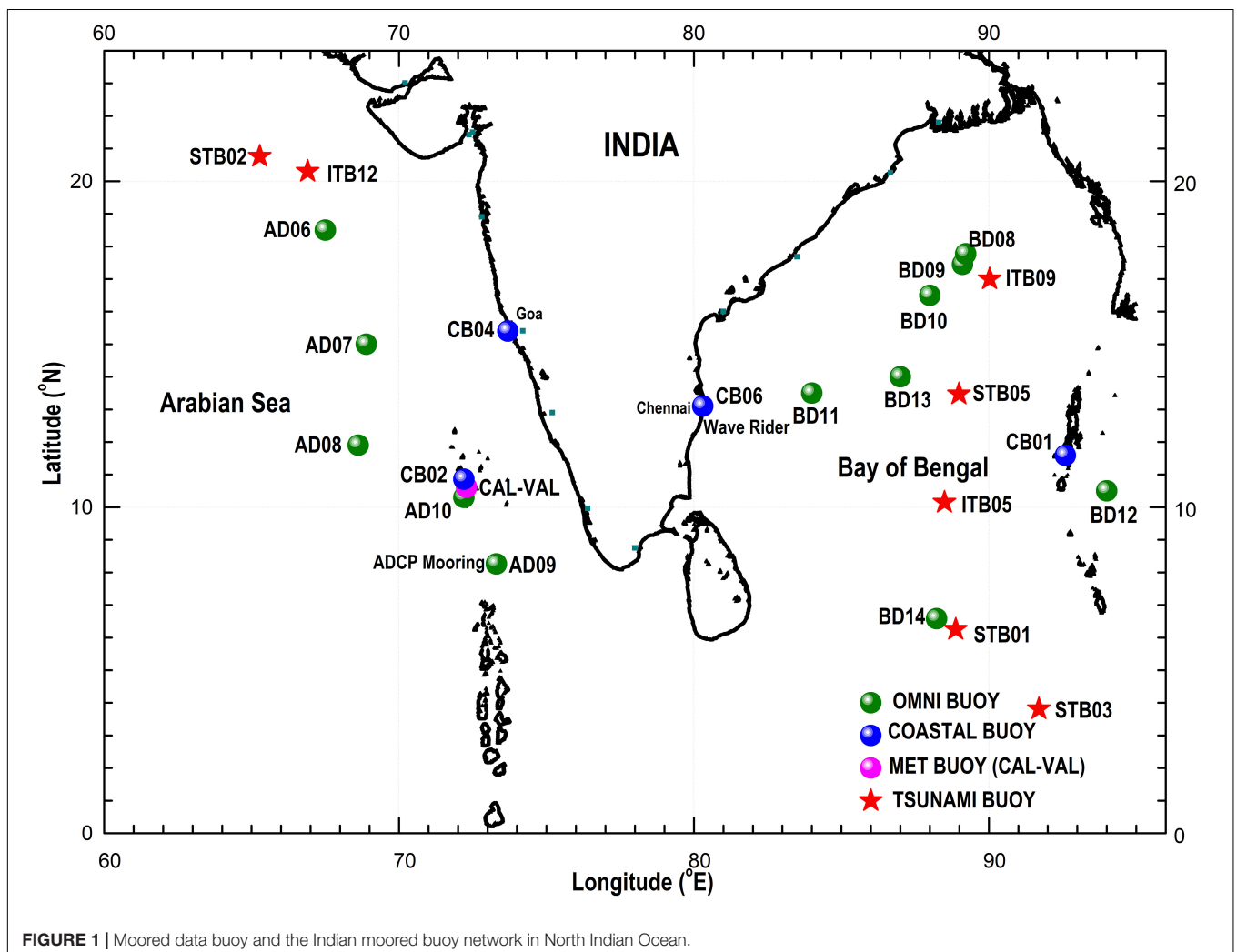
in the BoB and five in the AS) in deep waters, four coastal buoys, three tsunami buoys (one in AS and two in BoB) and one CALibration and VALidation (CAL-VAL) buoy, which is specifically deployed for the validation of satellite data. In addition, Indian Arctic (IndARC) buoy has been maintained in Arctic region since July 2014.

Instrumentation

The moored buoy program was initiated with sensors to measure the meteorological and surface oceanographic parameters such as air temperature, relative humidity, wind, sea level pressure, wave, sea surface temperature, sea surface salinity, and surface current. Furthermore, additional sensors for measuring shortwave radiation, longwave radiation, precipitation, Conductivity-Temperature (CT) sensors at discrete depths (1, 5, 10, 15, 20, 30, 50, 75, 100, 200, and 500 m) for subsurface temperature and salinity measurements and Acoustic Doppler Current Profiler (ADCP) for subsurface current measurements up to 150 m were introduced to the existing buoys in 2010. The meteorological sensors are fitted on the mast at 3 m above the mean sea level as per the recommendations of the World Meteorological

Organization (Jarraud, 2008) whereas the downward-looking ADCP is connected at 5 m depth in the mooring line. The measurements are carried out at specified intervals as suggested for data collection and dissemination by GOOS. The moored data buoys transmit data every 3 h, whereas the high-frequency internal data is made available after the retrieval of the mooring.

The selection of the communication method largely depends on how far the buoy is from shore and the data bandwidth required, though other factors such as timeliness, cost, and energy requirements also play a role (Venkatesan et al., 2013). The moored buoy close to shore utilizes both general packet radio service (GPRS) and satellite communication whereas the offshore platforms depend only on satellite communication. The communication with the buoy is a bi-directional link based on the Inmarsat-C satellite system, which also includes a global positioning system (GPS) receiver providing position information. The redundant position indicating facility incorporated using Argo satellite/Indian National Satellite (INSAT) telemetry helped in tracking the vandalized buoys during COVID-19 lockdown. The in-house developed coastal buoys, except sensors, with GPRS telemetry helped in extending



the period of operation, particularly during COVID-19 lockdown by significantly reducing energy consumption.

Regular calibration of sensors and data acquisition system (DAS) electronics are done at periodic intervals to ensure the quality of the data. In-house calibration facility for precipitation sensor, humidity sensor, DAS, and air pressure sensor helped in cost savings and delay in sending the sensor to original equipment manufacturer (OEM) for calibration. Apart from the efforts taken in ensuring the continuity of data, the quality of the data is ensured by comparing with other standard reference platform/systems.

Marine biofouling is a serious issue in tropical waters with hundreds of organisms that can get attached to the buoy system and mooring. Various methods of anti-fouling approaches are used in sub-surface oceanographic sensors including copper guard protection, protective sensor casing, and anti-fouling paints, to name a few (Venkatesan et al., 2017). Zinc oxide cream (Desitin) and silicone-based grease which were applied to the sensing parts of the ADCP were found to control the biological growth (Bigorre and Galbraith, 2018). The highest drift reported in the conductivity cell is reduced by installing the anti-fouling device impregnated with tributyltin oxide (TBTO) on each end of the conductivity cell in CT sensors (Sea-Bird Electronics, 2016). Efforts in reducing the biofouling along with the regular refurbishment and calibration of the sensors ensured sustained data collection, which was well paid off during the extended period of operation during the COVID-19 pandemic.

Moored Buoy Data Center

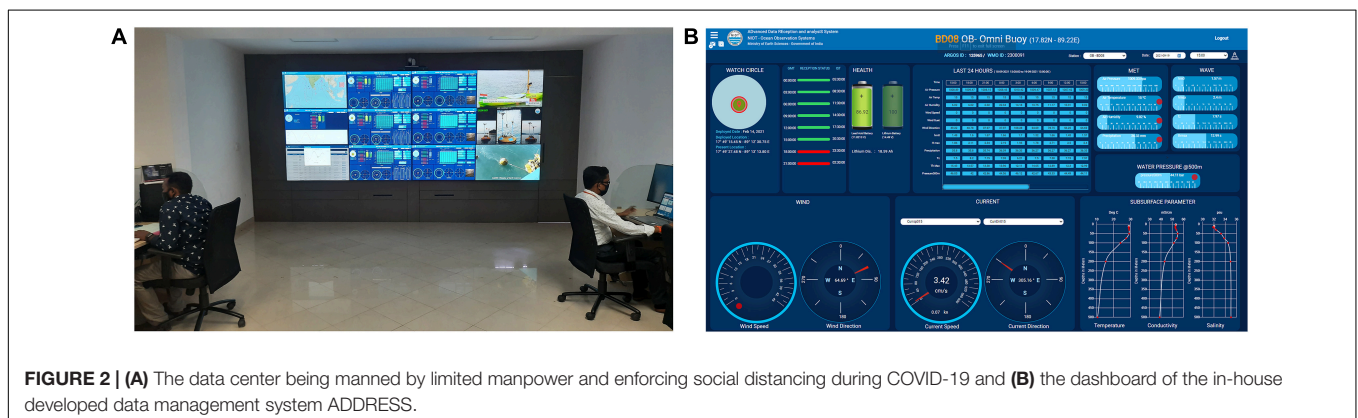
The moored buoy data center plays a vital role as a nerve center, hosting a suite of IT infrastructure facilities to receive, process, visualize, monitor, and manage the data from buoy networks around Indian Seas (Figure 2A). This facility is strategically important with round-the-clock support and acts as the nodal point for dissemination of real-time data to the Indian National Center for Ocean Information Services (INCOIS), Hyderabad who in turn work with the National Disaster Management Authorities for the promulgation of alerts and warnings to the countrymen. The data center established in 1997 has undergone significant improvements with customized tools to suit the

requirement evolved over a period of more than two decades of operational experience. ADvanced Data REception and Analysis System (ADDRESS) is a customized software solution developed in-house for information sharing and process automation across organizational needs (Figure 2B). It facilitates the monitoring of data reception from remote ocean platforms and endurance of individual buoys systems such as buoy drift, sensor stoppage and is aimed at eliminating the practical difficulties in data visualization/analysis and maintaining inventory of equipment/items used in the buoy systems.

Advanced data reception and analysis system is incorporated with QC procedures for automatically assessing the quality of data received from buoys and presents data quality metrics to ensure the normal functioning of the sensors. The sensor malfunctioning, drift in measurements, sensor stoppage, transmission issues, and buoy drift, among others, are monitored regularly. ADDRESS also provides the deployment details along with the metadata that encompasses instrument descriptions, manufacturer details, calibration details, and detailed information on the suite of sensors attached to specific buoy systems, to name a few. The up-gradation of the data reception center in October 2018 with a suite of high-tech IT infrastructure facilities to meet the processing demands, growing storage requirements, and to enhance the data services greatly helped in the uninterrupted data reception and dissemination during the COVID-19 lockdown.

Optimized Mooring Design

The buoy system mooring in general is designed based on the depth of the deployment location, characteristics of the ocean current, wind, and wave during extreme storm events and fatigue cycles. The NIOT moored buoy system consists of a hull, instrument container, mast assembly, keel weight, and keel frame. The buoy hulls are disc shaped to have good wave following capability and also acts as a buoyancy module. A keel weight is attached at the bottom of the instrument container of the surface buoy to prevent the capsizing of the hull and a keel frame to install near-surface sensors. A water-tight instrument container made up of marine-grade aluminum alloy is used to position electronics and batteries. It is also facilitated with safety features like a vent valve for the ventilation of batteries



and a pressure relief valve. The lid lock bolts are used to lock the lid over the instrument container and are designed with a central pin and a special key to dismantling the bolt as an anti-vandalism measure. The inverse catenary configuration with a mooring scope of 1.2 reduces the static as well as dynamic loading that helps to withstand the intense cyclones. Inductive cable is used in the top 500 m with CT/ Conductivity, Temperature, and Depth (CTD) sensors connected at selected depths through which data is transferred to facilitate real-time transmission. The preventive measures taken to safeguard the mooring from threats like vandalism, corrosion, biofouling, and fatigue were decisive in extending the operational period amid intense cyclones and COVID-19 lockdown.

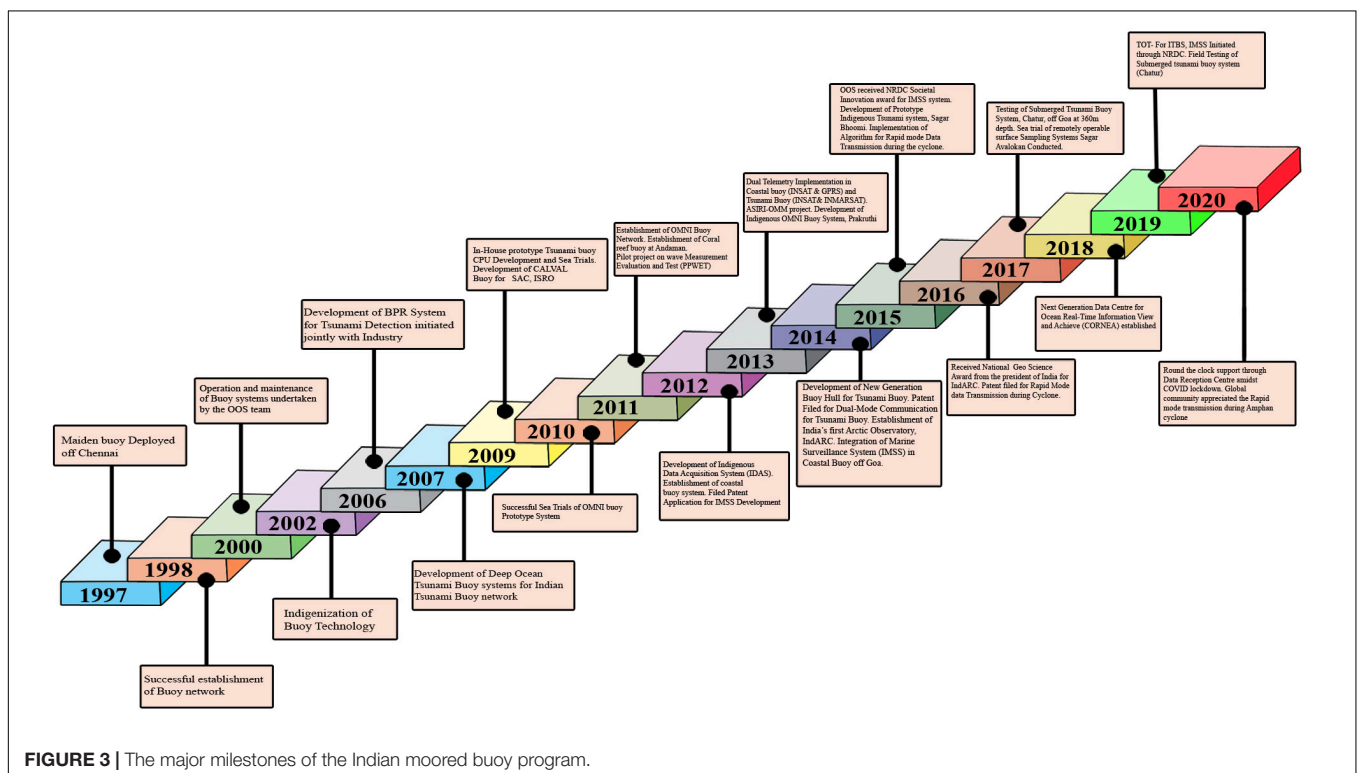
Technology Developments

The development of the Indian DAS (IDAS) “Hrudaya” and the incorporation of an intelligent power management system (PMS) were the major developments that helped in sustaining the buoy network during the pandemic. Data acquisition, processing, storage, and transmission are the key functions of the DAS (Meindl, 1996). IDAS is meticulously designed in-house to work in marine conditions, activates the respective sensors at pre-determined intervals, and logs the received data. The raw data is processed, encrypted, and is sent through the satellite to the shore-based data reception center and stores high-frequency data (Venkatesan et al., 2018a). The reduced power processor with sleep mode provisions and multi-level watchdog timers protect the IDAS from software hang-ups and ensured higher endurance.

The development of controlled high-frequency transmission was initiated to support the weather and early warning services, particularly during cyclone passages. The algorithm incorporated in the IDAS in coastal and deep ocean buoys successfully triggered rapid mode in the vicinity of a low-pressure system and resumed normal mode after the passage of the cyclone. This enabled the real-time availability of critical met-ocean data set at higher frequency during the cyclone passages amid the COVID-19 lockdown.

The incorporation of a Hybrid charge controller has enabled NIOT buoy systems to work for a longer period of more than a year. The intelligent PMS controls the charging and discharging of the batteries, distributes the power to the connected loads, provides power system status information to the IDAS, and provides a constant voltage to the sensor irrespective of the changes in the battery voltage. The primary source of power is the lead-acid battery charged by the solar panel, and the secondary source is the primary lithium thionyl chloride battery (Linden and Thomas, 2002; Gordon and Deines, 2011). The initial power to the entire buoy system is supplied by the primary source. The PMS monitors and switches the buoy power to the secondary source when there is an outage of the primary source. The underwater sensors are self-powered with redundant power from the main power source of the buoy, which enhanced the endurance of the sensor operation.

The steady and sustained growth of the moored buoy program over the years is depicted in Figure 3. The program started with the deployment of the first buoy in August 1997 off Chennai in BoB, made its presence felt year after year by its strong commitment to the scientific community. The



network got inducted with tsunami buoys in 2004 and got revamped in 2010 with additional surface and subsurface sensors. The buoy program had advanced measurement capabilities with a multifaceted approach to new observational techniques, technology developments, state of art data reception centers, research dimensions on new scientific areas, and international collaborative projects.

MOORED BUOY PROGRAM DURING COVID-19 LOCKDOWN IN 2020

Working remotely or work from home has become a new normal due to pandemic lockdown affecting every possible realm, which brought new challenges to the moored buoy program, and the regular operations got impacted the most. Maximum efforts were put forward to ensure the continuity of data by formulating a mitigation plan by prioritizing the tasks, ensuring the 24/7 support of the data center, and by extending the operational period of buoys in the field. The

data reception center continued to operate 24x7 with skeletal manpower and ensured uninterrupted real-time dissemination of buoy data to the end-users during the unprecedented and challenging times amidst lockdown. COVID-19 protocols and safety measures were strictly followed by ensuring the quarantine, social distancing, sanitization, and safety gears apart from the regular monitoring of the temperature and oxygen levels. The majority of the data reception systems were automated with minimal manual intervention and the software tool ADDRESS with automated quality control and visual representation greatly helped in uninterrupted data dissemination to end-users.

Performance and Maintenance of the Buoy Network

The sustenance of the moored buoy network has never been an easy task that required perseverance and dedicated effort as evident from the operational statistics (Figure 4A). The annual schedule includes four deep-sea cruises (two each in AS and BoB)

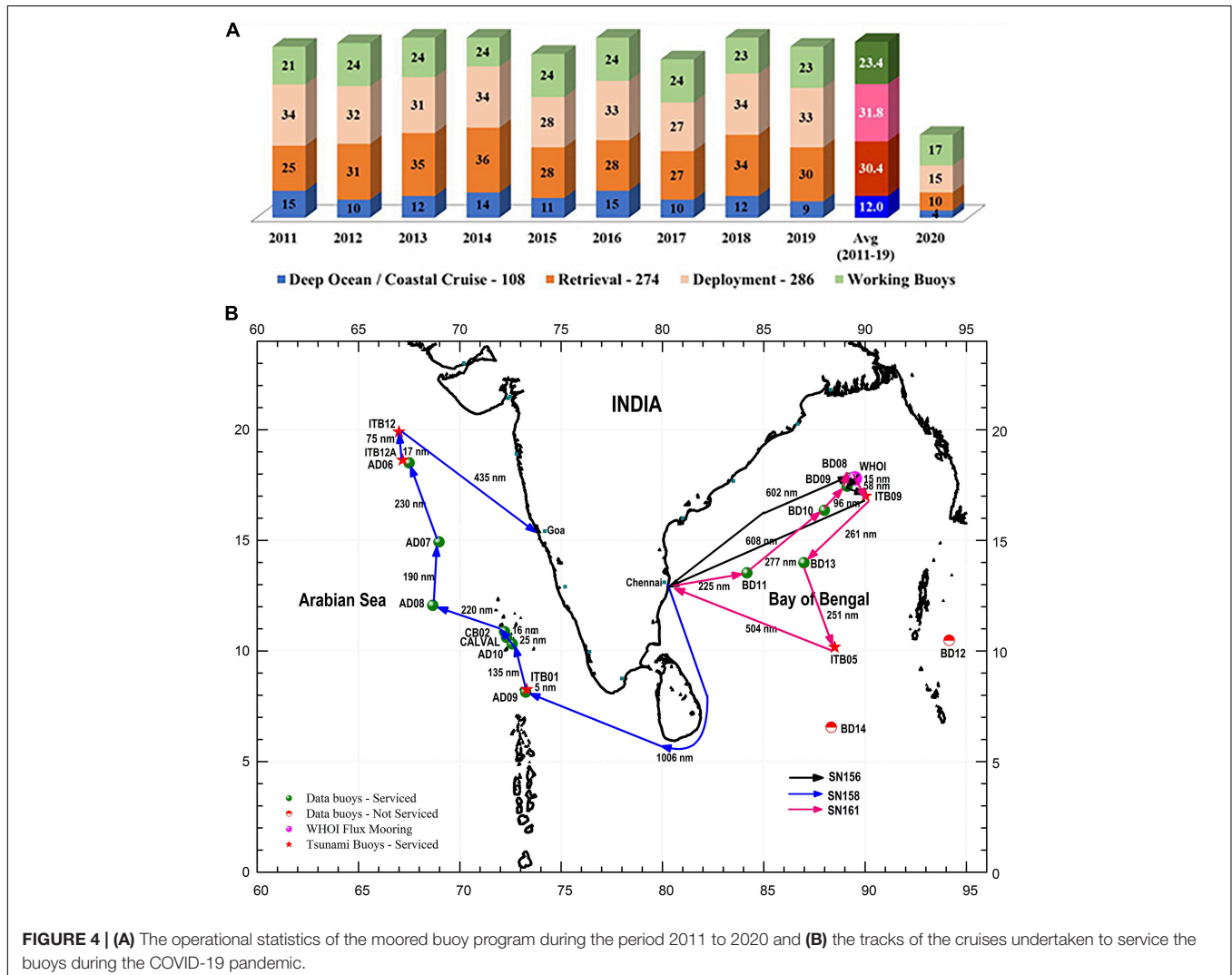


FIGURE 4 | (A) The operational statistics of the moored buoy program during the period 2011 to 2020 and **(B)** the tracks of the cruises undertaken to service the buoys during the COVID-19 pandemic.

comprising of approximately 30 days each and 3–4 coastal cruises apart from the additional cruises to deploy/retrieve the buoys that are stopped/drifted/vandalized. There were 108 cruises spanning 1,445 man-days sailing over 1,36,038 nm to carry out 286 deployments and 274 retrievals over the period from 2011 to 2019 that accounts for an approximate annual average of 12 deep ocean/coastal cruises with 32 deployments and 30 retrievals traversing 15,115 nm with 161 man-days (Figure 4A).

The year 2020 indicates minimum cruises and field operations due to the ongoing COVID-19 pandemic, which substantially affected the buoy maintenance operations leading to a significant reduction in the overall performance of the network. The cruises planned from March to May 2020 to service the moored buoy network in AS and BoB and all the fieldwork from March to September were canceled due to the COVID-19 lockdown, whereas the cruises which were scheduled from September to December 2020 were partially carried out.

National Institute of Ocean Technology has undertaken three cruises immediately after the relaxation in lockdown to service the buoys which have already crossed the expected period of operation, to replace the buoys which were vandalized and the ones which stopped transmission. The first cruise was undertaken onboard ORV Sagar Nidhi from 29 September to 14 October to retrieve INCOIS Flux mooring (Figure 4B), which was due in May 2020. The vandalized buoy BD09 (89.1°E/17.5°N) in northern BoB was also retrieved and deployed a new buoy system. The AS cruise was followed immediately (November 2 to December 3, 2020) again onboard ORV Sagar Nidhi, which carried out a total of 48 operations including eight buoy deployments, 10 retrievals, 13 CTD operations apart from the samples collected for scientific research. The BoB cruise in February 2021, was mainly focusing on the replacement of buoy systems, which have already crossed the expected period of operation due to the long gap of 14 months between the services (Figure 4B).

Data Return From Buoy Network During COVID-19 Pandemic

Quality data return with a minimum gap is the key target of the moored buoy program wherein the efforts are undertaken to ensure the quality as well as quantity. However, the COVID-19 pandemic has affected the ocean observation network globally as reported by GOOS with a significant reduction in data return. It is worth noting that 73% of the Indian buoy network was functional during the pandemic in 2020 even when the cruises were reduced to 33% (Table 1). The deployments during the corresponding period were 47%, whereas the retrievals were only 33%. The substantial reduction of cruises resulted in the loss of buoy systems as reflected in the reduction of retrievals.

The AS buoys recorded higher data return (>80%) from air temperature, air pressure, wind, and rainfall sensors even during the COVID-19 pandemic, whereas the humidity and radiation sensors recorded comparatively less data return (~55%) owing to the sensor damage/drift over a longer period of operation

TABLE 1 | The performance of the moored buoy network during the year 2020 amid COVID-19 pandemic.

Network statistics	Average (2011–2019)	Performance during 2020
Working Buoys	23.4	17 (72.65%)
Deployments	31.8	15 (47.17%)
Retrievals	30.4	10 (32.89%)
Cruise/Field trips	12	4 (33.33%)

(Figure 5A). The average data return of surface meteorological parameters in BoB is significantly impacted due to the loss of buoy systems and vandalized meteorological sensors (Figure 5B). The impact of the COVID-19 pandemic was visible in the significant reduction (~50%) of data return in BoB, compared to an average data return of 97.9% for the meteorological parameters (Venkatesan et al., 2018b) during two decades of operation. The wave data and CT profiles reported high data return in AS and BoB, which was recovered after the retrieval of the buoy system, including the ones which stopped real-time transmission. The self-powered underwater sensors, ADCP, and CT profiles with self-recording facility provided 93.3% and 80% of data return in AS, whereas the corresponding figures in BoB are 58.3% and 85.7%, respectively. The importance of independent power sources and redundant storage in increasing data return is evident from the higher data return in ADCP and CT profiles, which was recovered from the internal storage of the sensor even when the surface buoy system was lost.

Challenges

The maintenance of the moored buoy network involves the execution of a large number of cruises huge inventories of sensors and buoy systems, logistics related to re-calibration, and purchase of sensors apart from the regular monitoring, archiving, quality control, and dissemination of data sets. The availability of ship time and sensors, unresponsive weather conditions, the continuous menace due to corrosion, biofouling, piracy in AS, and vandalism, to name a few, are the major challenges in sustaining the moored buoy program. Even after extensive efforts made over several years, in particular in sensitizing fishing communities, vandalism remains a significant problem. The awareness campaigns on the application and importance of these data buoys, through direct discussions, and the distributions of multi-lingual brochures, among others, were carried out but have met with only limited success.

The cruises were carried out by following the COVID-19 protocol and guidelines (Figure 6A). The cruise participants were quarantined before boarding the vessel and ensured, social distancing, hygiene, whereby carrying out the buoy maintenance activities. During the pandemic, the guidelines issued by Port Health officials (PHO) and linked activities required additional days for quarantine and more funds for the related works.

The delay in service has resulted in significant loss, wherein two vandalized buoys could not be retrieved in time. The surface buoy system along with meteorological components and data logger drifted away and was lost at the BD10 (88°E/16.3°N)

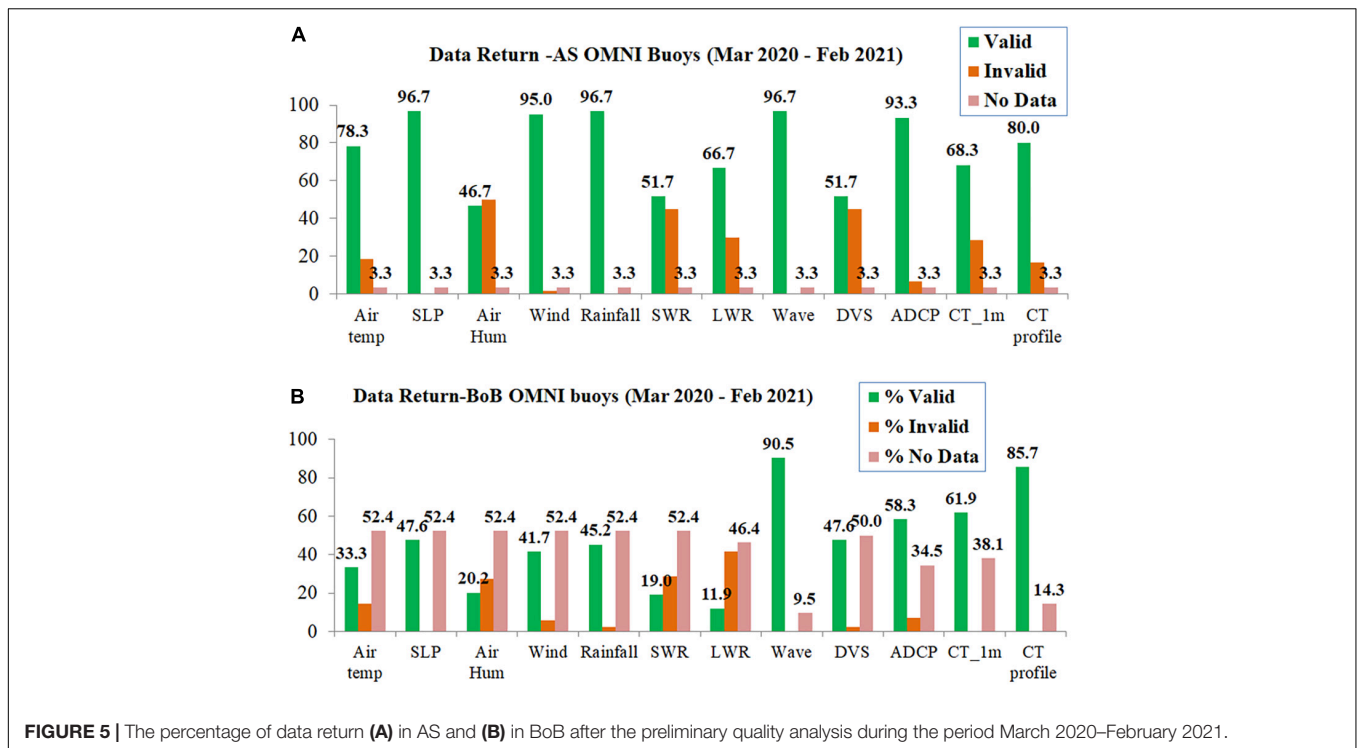


FIGURE 5 | The percentage of data return (A) in AS and (B) in BoB after the preliminary quality analysis during the period March 2020–February 2021.

location in BoB. However, the subsurface sensors were retrieved with the entangled fish net from the seabed after a comprehensive search near the anchor drop location (Figure 6C). The vandalized surface buoy AD06 was drifting in AS and was retrieved by the cruise team, with a damaged mast where the meteorological sensors were missing (Figure 6B). The subsurface sensors along with the measured data set and mooring components could not be retrieved from the AD06 location. The BD13 buoy (14N/87E) in BoB, which stopped transmitting data after the passage of the cyclone Amphan in May 2020, could not be traced even after an extensive search in the location around the last transmitted position. The program suffered significant losses in terms of money and precious data, particularly the high-frequency data set. The delay in service also caused significant issues due to the biofouling of subsurface sensors and drift in measured data. Timely service could have reduced the loss of vandalized sensors, buoy systems, and high-frequency data.

Moored Buoy Observations During the Cyclones Amid the COVID-19 Pandemic

The impact of COVID lock down on the functioning of moored buoys beyond the service period is visible in the status of the network during the passage of cyclones Amphan (May 2020), Nisarga (June 2020) and Nivar (November 2020) as shown in Figure 7. Substantial reduction in the number of working buoys towards the fag end of 2020 during Nivar (Figure 7C) is evident.

The moored buoy network except for BD10 in BoB was fully operational at the beginning of the COVID-19 lockdown in March 2020. These buoys were serviced during October–December 2019 and the regular maintenance cruises were

scheduled during April–May 2020. Even though the intelligent PMS can power the buoy for more than a year, the possible drift in the sensors, specifically the biofouling in underwater conductivity

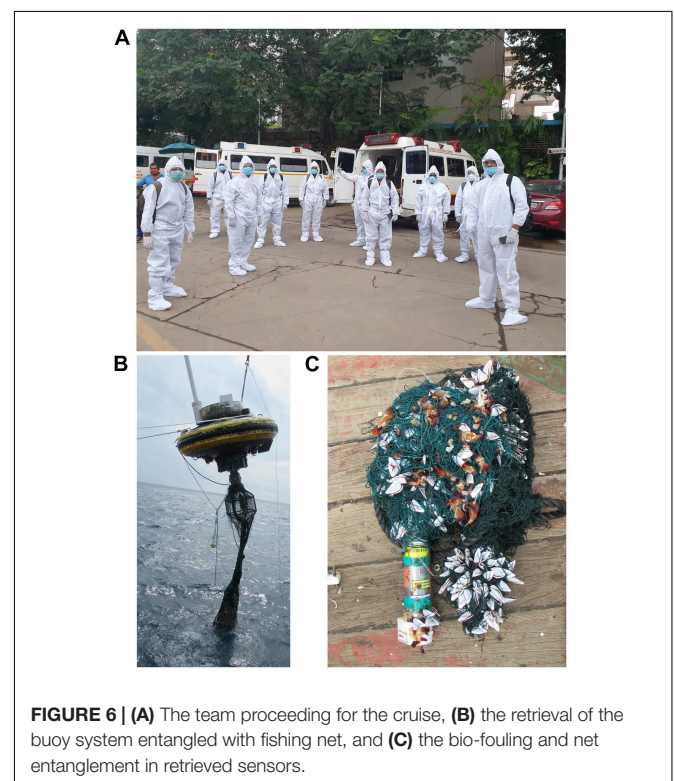
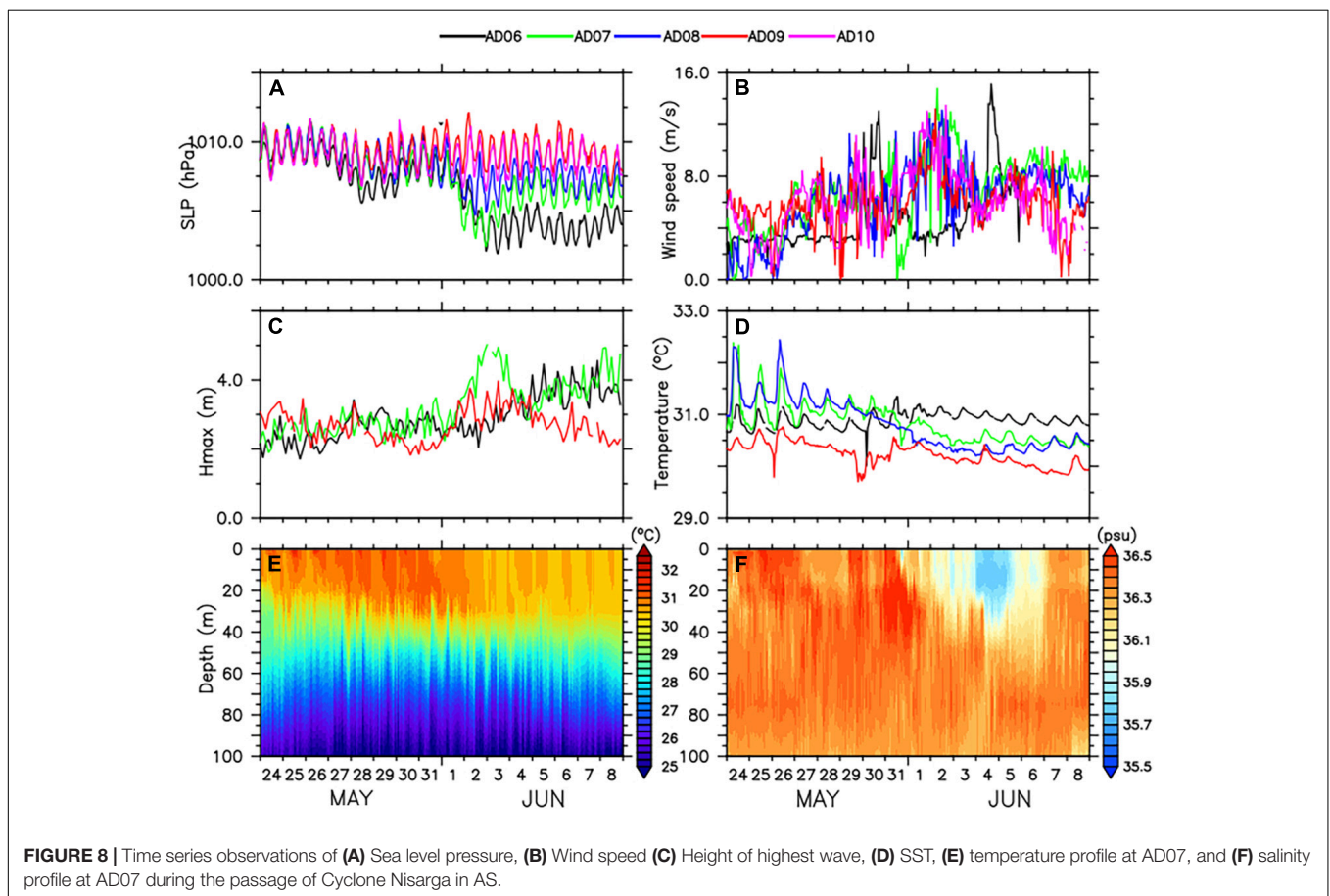
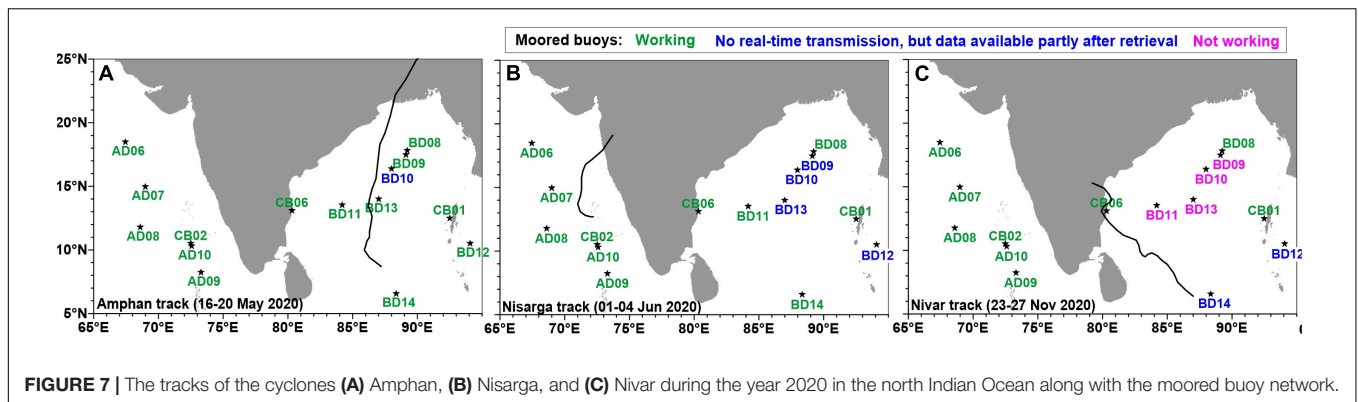


FIGURE 6 | (A) The team proceeding for the cruise, (B) the retrieval of the buoy system entangled with fishing net, and (C) the bio-fouling and net entanglement in retrieved sensors.



sensors necessitated the service at an interval of 6 months to ensure the quality data return.

The moored buoy network captured the signals of the cyclones as well as transmitted high-frequency data during the year 2020 amid COVID-19 lockdown. The cyclone season in the North Indian Ocean started with the Super cyclone Amphan in May 2020, which was the highest intensity cyclone ever recorded in BoB during the pre-monsoon season (Figure 7A). The severity of oceanic response was recorded in moored buoys as the significant drop in sea-level pressure (SLP), rapid increase in wind speed and wave height, and substantial drop in temperature and salinity.

Some components of moored buoys BD09 (89°E/18°N) and BD13 (14°N/87°E) in the proximity of cyclone were damaged due to the extreme wind and stopped transmission on May 19 and May 24, 2020, respectively.

During the passage of the cyclone Nisarga, all the OMNI buoys in the Arabian Sea were operational (Figure 7B). Severe Cyclonic Storm Nisarga was the first cyclonic storm over the AS during 2020 amid the COVID-19 pandemic and ongoing restrictions in sailing. The network of five OMNI buoys in AS captured the signals of the cyclone at various stages from its genesis till the landfall (Figure 8). The impact of cyclone Nisarga was observed

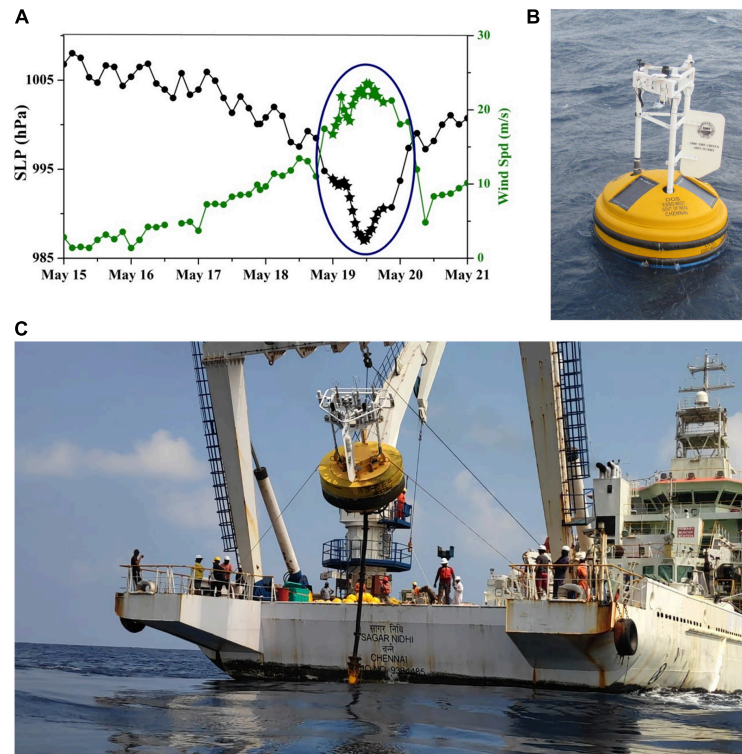


FIGURE 9 | (A) Time-series observations of air pressure and wind speed with high-frequency real-time data during cyclone AMPHAN in BoB, **(B)** the Indian buoy system with tripod mast deployed in AS, and **(C)** retrieval of the INCOIS flux mooring.

in the surface parameters of OMNI buoys particularly in AD06 ($67.5^{\circ}\text{E}/18.5^{\circ}\text{N}$) and AD07 ($68.97^{\circ}\text{E}/14.9^{\circ}\text{N}$) in the central AS.

The maximum drop in SLP at $\sim 1,002$ hPa was observed in AD06 and AD07 (**Figure 8A**) which were at a distance of 280 and 225 nm from the cyclone track, respectively. The wind speed of 13.8 m/s was recorded in AD07 (**Figure 8B**) with a corresponding wave height of 5 m on 3 June (**Figure 8C**). Significant variability in SLP, wind speed, and temperature were observed in AD08 ($68.6^{\circ}\text{E}/12.0^{\circ}\text{N}$) whereas minor response was recorded in AD09 ($73.3^{\circ}\text{E}/8.1^{\circ}\text{N}$) and AD10 ($72.6^{\circ}\text{E}/10.3^{\circ}\text{N}$) which were located south of the cyclone genesis areas in southern AS.

Prominent diurnal oscillation in SST was observed at all buoy locations before the cyclone followed by a considerable drop at AD07 and AD08 locations after the cyclone passage (**Figure 8D**). Significant pre-cyclone diurnal warming was observed in the shallow mixed layer in which the cooling associated with cyclone passage was limited to the upper few meters for a period of 3–4 days. Substantial freshening of ~ 1.2 psu was observed in the upper mixed layer during the cyclone passage. It was observed that the response to the cyclone was significant only in the upper mixed layer at AD07 (**Figures 8E,F**), which was located at a considerable distance of 225 nm on the left side of the track.

Even though the buoys in AS were fully operational, two coastal buoys and one OMNI buoy were only operational in BoB during the passage of the cyclones Nivar in November 2020 and Burevi in December 2020 resulting in the non-availability of real-time data from the rest of the buoys. The buoys in the AS were

serviced during November 2020 whereas that of BoB was carried out in February 2021. Even though the real-time data was not available, the high-frequency data sets were recovered from the buoys after the retrieval of the buoy system.

Achievements

The efforts to upkeep the moored buoy network operational during the COVID-19 pandemic also resulted in achieving a few significant tasks such as the deployment of indigenous tripod buoy system, OceanSITES mooring in AS, and BoB, and Rapid Transmission during cyclones, among others. The development and implementation of rapid mode transmission in moored buoys was a major achievement, which greatly helped the early warning services with the high-frequency transmission during many cyclones since its incorporation in 2016, including the cyclones in 2020 amid the COVID-19 pandemic (**Figure 9A**). The moored buoys incorporated with IDAS such as BD09 during Cyclone Amphan in May 2020, CAL-VAL buoy ($72.3^{\circ}\text{E}/10.6^{\circ}\text{N}$) during the cyclone Nisarga in June 2020, and CB06 ($80.3^{\circ}\text{E}/13.1^{\circ}\text{N}$) during the cyclone Nivar in November 2020 triggered high-frequency transmission, among which the rapid transmission in BD09 during the Super Cyclone Amphan was widely appreciated. The OMNI buoy BD09 triggered high-frequency data transmission on 19 May 2020 as the Amphan cyclone approached the buoy. The buoy transmitted data at 1-h interval, while the normal transmission was at every 3 h. BD09 recorded minimum air pressure of 988 hPa on May 12

at 12:00 p.m. (**Figure 9**), while transmitting at rapid mode and continued for 17 h by providing 11 additional real-time data sets. The CAL-VAL buoy (72.3°E/10.6°N) and CB06 (80.3E/13.1N) buoy were incorporated with a refined algorithm and provided high-frequency transmission at an interval of 30 min during the cyclone Nisarga in June 2020 and Nivar in November 2020, respectively. The rapid mode algorithm enabled the buoy system to provide the critical met-ocean data sets to stakeholders with higher frequency in real-time, during the devastating cyclones amid the COVID-19 pandemic.

The buoy system design was updated with a target to extend the endurance and accommodate redundant sensors. The cylindrical-shaped buoy hull with more reserve buoyancy and tripod mast helps to accommodate more sensors and ensures ease of maintenance. The enlarged instrument container with a protective hood and more space for batteries can extend the endurance for 2 years. The wind vane aligns the buoy and anemometer in the direction of wind whereas the existing buoy aligns the buoy with the surface current. Orienting buoy and anemometer in the direction of wind ensure that measured wind data is not obstructed by other components on the sensor arm. The wind vane has an area of 0.57 m² and it experiences 35.6 kg of wind load at 30 m/s for the alignment. The mooring part for this buoy system remains the same as the existing buoy system. This updated buoy system was successfully deployed at AD08 location at a depth of 4,300 m during the AS cruise in November 2020 (**Figure 9B**).

The existing OceanSITES mooring at AD07 location in AS is retrieved and redeployed a new buoy system during the AS cruise in November 2020. The OceanSITES location in BoB was established at BD11 (13.6°N/ 84.1°E) and deployment of hydrophone for acoustic applications was carried out during the cruise in February 2021. The retrieval of the Flux mooring in BoB (**Figure 9C**), the maintenance of the tsunami buoys in AS and BoB, and extensive sample collection for the studies on microplastics in the marine environment was also successfully carried out during the COVID-19 pandemic.

RECOMMENDATIONS

The OMNI buoy network has proven its mettle in serving the society during COVID-19 pandemic. The pandemic served as a learning experience and helped in identifying the gaps as well as the strengths in sustaining the network. The refinement of the buoy system along with the efforts in extending the deployment period tremendously helped during the pandemic. The recommendation for the better management of remote platforms based on the experience in managing the OMNI network for more than two decades specifically during the COVID-19 pandemic are listed below:

- (a) **Self-Sustainable Data Center:** The shore-based data center plays a vital role in any remote data acquisition network being the hub between remote platforms and the end-users. Ideally, these centers should be designed for automated data reception, quality control, data dissemination, and data archival with minimum human intervention. The necessity for manual intervention will be challenging during a pandemic or similar extreme events. The critical weather services and early warning applications requiring real-time data from these platforms should also be well connected. State of the art, fully dedicated hardware, software, network, and power backup facility with redundancy is essential to support during any casualties. It is proposed to locate an independent and easily accessible facility well protected from the possible impacts of natural disasters such as floods, cyclones, tsunamis, and earthquakes, among others. The well-equipped data reception center with customized, fully automated data reception and dissemination facility enabled the uninterrupted real-time dissemination of OMNI buoy data during the COVID-19 pandemic.
- (b) **Customized Data Acquisition System:** Data acquisition system that caters to the key functions of data acquisition, processing, storage, and transmission plays a decisive role in the successful operation of moored data buoys. Customization of the DAS to suit the operational efficacy and user requirement has a substantial impact on the endurance and data return of the remote platforms. The IDAS with hybrid charge controller, redundant telemetry, and rapid data transmission facilitated the real-time transmission for an extended period.
- (c) **Intelligent Power Management System:** The power source of the remote platforms should be capable enough to deliver an uninterrupted supply beyond the normal working period when the regular servicing is delayed due to unanticipated issues. Reduced power processor with sleep mode provisions along with hybrid charge controller, considerably enhanced the endurance of the OMNI buoy system and made it operational for more than a year during the COVID-19 Pandemic.
- (d) **Enhancement of Sensors:** Ocean observation platforms need to be strengthened with smart sensors with independent power sources and self-recording facilities that can operate for a longer duration. This will avoid the loss of data due to snapped connection with the buoy CPU, which had been reported on many occasions including the COVID-19 pandemic. Redundant sensors are suggested to ensure continuity and to assess the quality/drift of the data over a longer period. It is recommended to focus on the refinement of sensors that can self-calibrate at the field. This will avoid spurious data when the working period extends beyond the expected time.
- (e) **Local Calibration Facility:** Regular calibration, ideally after each retrieval of sensors is required to ensure the quality and reliability of the measurements. The absence of a local calibration facility leads to a long waiting period for the calibration of the sensors at overseas facilities, particularly for conductivity and temperature sensors which are prone to biofouling. The in-house facility at NIOT to calibrate air humidity, air temperature, air pressure, and precipitation sensors has greatly helped in executing the maintenance cruises during the Pandemic.

- (f) **Optimized Telemetry:** Real-time transmission of data sets from remote platforms is an important feature that supports weather services. Two-way communications with the buoy system will sort out a lot of issues. Dual telemetry is recommended to overcome the issues associated with satellite communication. Additional GPRS-based communication is suggested for coastal moorings and redundant satellite communication for offshore platforms. Apart from this, an additional position indicating facility using Argo was found to be critical in providing the location information during buoy stoppage and drifting, particularly in vandalized buoys.
- (g) **Robust Mooring System:** The mooring components selected should be capable of working for a longer period withstanding the dynamic loads and mooring motions, in order to hold the system in the deployed location. The major loss of buoy system and components were attributed to vandalism during the pandemic period that necessitates strengthening the anti-vandalism measures.
- (h) **Best Practice Methods:** The endurance and performance of remote platforms in the harsh marine environment can be optimally maximized by following the best-practice methods without compromising the quality of the system. The quality of measurement is ensured in NIOT-OMNI buoys by following the best-practice methods (Venkatesan et al., 2018a) evolved over the years of services in maintaining the moored buoy network in the Indian Seas.
- (i) **Rapid Data Transmission:** The remote ocean observation platforms are in general configured to acquire data at a higher frequency, i.e., at 1 min, which is stored internally and transmit at a lower frequency, i.e., at 3 h. The high-frequency data is available after the retrieval of the buoy system, which varies between 6 months to more than a year. Vandalism or delay in maintenance may lead to the loss of the buoy system or the sensors, which in turn results in the total loss of the critical high-frequency data as reported during the COVID-19 pandemic. The rapid data transmission during cyclones in NIOT buoys was a boon to the end-users amid the pandemic associated data loss. An extension of the algorithm to trigger high-frequency transmission at periodic intervals or event-based can save the critical data sets.
- (j) **Open Data Policy:** The COVID-19 pandemic has significantly affected the data return from remote ocean platforms that can significantly affect the weather services and climate studies. The pandemic point toward the necessity to share the available data sets to meet the growing need of weather and climate studies. The OMNI-RAMA data portal, wherein the moored buoy data from OMNI as well as RAMA buoys are made available for the public is a major milestone toward open data policy. It is highly recommended to follow the open data policy in all remote platforms, which can fuel scientific research across the globe.
- (k) **International Co-operation:** The pandemic has severely affected the field trips and cruises to service the remote platforms owing to limited resources, travel restrictions,

fund cuts, and safety measures, which necessitates sharing the facilities with national and international organizations. The existing memorandum of understanding (MoU) between the Ministry of Earth Sciences (MoES)-India and National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory (NOAA/PMEL), United States has eased out the many obstacles in maintaining the RAMA network and serves as a good example of resource sharing. The support extended by the Indian Navy and Coast Guard have greatly contributed to maintaining the buoy network particularly during the buoy stoppage/drifting/vandalism.

SUMMARY

Sustaining the observational program and ensuring high-quality data with minimal data gap amidst the multitude of challenges require enormous vision and teamwork. Apart from the regular challenges such as vandalism, biofouling, rough weather, and limited ship time availability, the COVID-19 lockdown has added the risk of delay in servicing the buoys in remote marine environments. The recent increase in the frequency and intensity of cyclones in AS and BoB, demands enhanced observational capability and improved collaborations across the globe. The present-day moored buoy system is the result of incessant research and technological developments over two decades. Continuous improvements in various aspects such as buoy system components, state-of-the-art data reception facility, reliability checks, and best practice methods, along with the untiring efforts of the team were rewarded by providing continuous data during the devastating cyclones during COVID-19 lockdown, where the other modes of measurement were interrupted.

Adapting to the present COVID-19 situation particularly the field operation is necessary to ensure the continuity of measurements. The expected impacts of the pandemic in the coming years, necessitate collective efforts and better collaboration among the scientific and user community across the political boundaries to achieve a resilient system. The COVID-19 lockdown has proved the increasingly significant role of remote observational platforms, which necessitates integrated efforts to evolve revised observational requirements to realize a sustainable ocean observation network.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

RV and KJJ conceived the manuscript, provided the guidance to co-authors, and coordinated the author contributions. CAP and MK contributed to preparing the activities during the COVID-19 pandemic, reviewed and edited the manuscript. MAM, BK,

BH, GV, KR, and AT contributed to the technology developments and field operations/cruises. PM, KT, and PS contributed to the mooring design, cruise details, and challenges. SRS, RSu, MK, MVM, KN, and CAP carried out the data processing and analysis. RSr, SJ, CM, NS, and MS supported in data collection. All the authors contributed to the article and approved the submitted version.

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