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TECHNICAL REPORT

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201309, INDIA

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Contents

Abstract

Near real-time monitoring of Indian buoy observations is pivotal in weather forecasting and understanding severe weather events, especially cyclonic storms. This report presents the development of an in-house monitoring package for the Indian buoy observations at the National Centre for Medium Range Weather Forecasting (NCMRWF). This indigenous package is designed to continuously monitor the buoy data received at NCMRWF through the GTS from the Indian buoys, deployed by the Indian National Centre for Ocean Information Services (INCOIS) and the National Institute of Ocean Technology (NIOT), for their assimilation in the NCMRWF global and regional numerical weather prediction (NWP) models. The package automates the reception, quality control, and visualization of buoy data, generating heatmaps and time series plots for key meteorological variables such as sea level pressure, wind speed, wind direction and temperature. These visual tools provide crucial insights into the reception status and reliability of the Indian buoy observations. Importance of the buoy observations in the vicinity of cyclonic storm in the estimation of track and intensity is demonstrated through the case study of cyclone REMAL formed over the Bay of Bengal in May 2024.

Keywords: Buoy; GTS; IMD; INCOIS; NIOT; WMO; Monitoring.

सारांश

भारतीय ब्वॉय अवलोकनों की वास्तविक समय की निगरानी मौसम के पूर्वानुमान और गंभीर मौसम की घटनाओं, विशेष रूप से चक्रवाती तूफानों को समझने में महत्वपूर्ण है। इस रिपोर्ट में राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केन्द्र (रा. म. अ. मौ. पू. के.) में भारतीय ब्वॉय प्रेक्षणों के लिए एक स्वदेशी मॉनीटरिंग पैकेज के विकास को प्रस्तुत किया गया है। इस स्वदेशी पैकेज को रा. म. अ. मौ. पू. के. में प्राप्त ब्वॉय आंकड़ों को भारतीय ब्वॉयों से ग्लोबल टेलीकम्युनिकेशन सिस्टम (जीटीएस) के माध्यम से प्राप्त ब्वॉय आंकड़ों की निरंतर मॉनीटरिंग करने के लिए डिजाइन किया गया है, जिन्हें भारतीय राष्ट्रीय महासागर सूचना सेवा केन्द्र (इंकॉइस) और राष्ट्रीय समुद्र प्रौद्योगिकी संस्थान (एनआईओटी) द्वारा रा. म. अ. मौ. पू. के. वैश्विक एवं क्षेत्रीय संख्यात्मक मौसम पूर्वानुमान (एनडब्ल्यूपी) मॉडलों में आत्मसात करने के लिए लगाया गया है। यह पैकेज ब्वॉय डेटा की प्राप्ति, गुणवत्ता नियंत्रण और दृश्यांकन को स्वचालित करता है, और समुद्र स्तर का दबाव, वायु गति, वायु दिशा और तापमान जैसे प्रमुख मौसम विज्ञान चर के लिए हीटमैप और समय-श्रृंखला ग्राफ तैयार करता है। ये दृश्यात्मक उपकरण भारतीय बुआ अवलोकनों की प्राप्ति की स्थिति और विश्वसनीयता के बारे में महत्वपूर्ण जानकारी प्रदान करते हैं। चक्रवात REMAL, जो मई 2024 में बंगाल की खाड़ी में बना था, के अध्ययन के माध्यम से चक्रवातीय तूफान के निकट क्षेत्र में बुआ अवलोकनों की ट्रैक और तीव्रता के अनुमान में भूमिका को प्रदर्शित किया गया है।

कुंजी शब्द: Buoy; GTS; IMD; INCOIS; NIOT; WMO; Monitoring.

1. Introduction

In recent decades, ocean observation systems have gained significant importance due to their role in improving weather forecasts, climate studies, and oceanographic research. One of the key components of ocean observation systems is the deployment of buoys, which collect critical data on ocean conditions such as sea surface temperature, salinity, ocean currents, and meteorological variables like sea level pressure, temperature, wind speed and wind direction. Buoy networks provide continuous, high-resolution oceanic and atmospheric data, vital for short-term weather forecasting and long-term climate monitoring. India maintains a vast network of buoys across the Indian Ocean, with a specific focus on the Bay of Bengal and Arabian Sea regions. These buoys are classified into two categories: moored buoys and drifting buoys, which play an instrumental role in observing the conditions in the Indian Ocean for improving the accuracy of monsoon predictions, cyclone tracking, and marine operations in the Bay of Bengal and the Arabian Sea (Venkatesan et al., 2018). The ability of buoys to continuously collect and transmit data in near-realtime and delayed time (late arrival) makes them an indispensable part of ocean observation systems. Both near-realtime and delayed time datasets are used in operational oceanography, where the near-realtime data is important for operational ocean forecasting activities while the delayed information is crucial for preparing the reanalysis and monitoring (and predicting) the seasonal and climate variability. These datasets provide more accurate, location-specific data than satellites, which can have limitations in resolution and coverage in certain regions. Hence, buoy observations have been critical in cyclone monitoring in the Indian Ocean. The real-time data from moored and drifting buoys provide essential information on sea surface conditions, such as temperature, wind speed, and air pressure, which are key indicators of cyclone development and intensification. The study by Akhter et al. (2022) highlighted the role of moored buoys in tracking the genesis and evolution of tropical cyclones in the Bay of Bengal. The buoy data played a crucial role in monitoring cyclone Phailin (2013) and Vardah (2016), where timely and accurate data contributed to improving the forecast models (Mohapatra and Sharma, 2019). Study by Wei-Dong et al. (2012), have shown that the assimilation of buoy data significantly improves the accuracy of predicting monsoon onset, duration, and intensity. Moreover, buoy observations are also critical for marine forecasting. Real-time data on wave heights, currents, and SST are used to provide daily marine forecasts, particularly for the safety of fishermen and maritime industries. Coastal zone management also benefits from buoy observations, particularly in predicting storm surges and sea level rise events (Venkatesan et al., 2018). This report explores the process of receiving Indian buoy data at NCMRWF, its archival, and the near real-time monitoring of these observations. The buoy observations are essential in tracking and monitoring the intensity of cyclones, which is demonstrated through the case study of REMAL cyclone formed over the Bay of Bengal in May 2024.

2. Brief description of Indian Buoy Data and its reception at NCMRWF

Two premier institutes of India, the Indian National Centre for Ocean Information Services (INCOIS) and the National Institute of Ocean Technology (NIOT), are responsible for deploying, operating and maintaining the moored and drifter buoy systems. Moored buoys are stationary buoys tethered to the ocean floor, continuously collecting data from a fixed position, while Drifter buoys are free-floating buoys that drift with ocean currents, recording data along their trajectory. The Global Drifter Program (GDP) has been instrumental in deploying drifter buoys worldwide, including in the Indian Ocean. Studies have shown that all these buoys are critical for capturing the oceanic processes that precede monsoon onset, which helps in improving the accuracy of monsoon prediction models (Pradhan et al., 2021). Drifting buoys provide critical data on upper ocean currents and surface temperature variations, which are important for understanding the heat budget of the Indian Ocean and its impact on monsoonal rainfall (Shetye and Michael, 1988). Thus, the moored buoys provide long-term, consistent data for a particular region, while drifter buoys provide a broader spatial coverage by moving with ocean currents. Indian buoy networks are part of a larger Integrated Ocean Observation System (IOOS) that includes satellite observations, Argo floats, and ship-based observations. This integrated approach allows for a comprehensive understanding of ocean-atmosphere interactions in the Indian Ocean (McPhaden et al., 2024). Figure 1 depicts the coverage of Indian Buoy Observation Network over the Bay of Bengal and Arabian Sea. There are 15 Indian buoys currently operational in this region and Table 1 indicates its detailed metadata information.

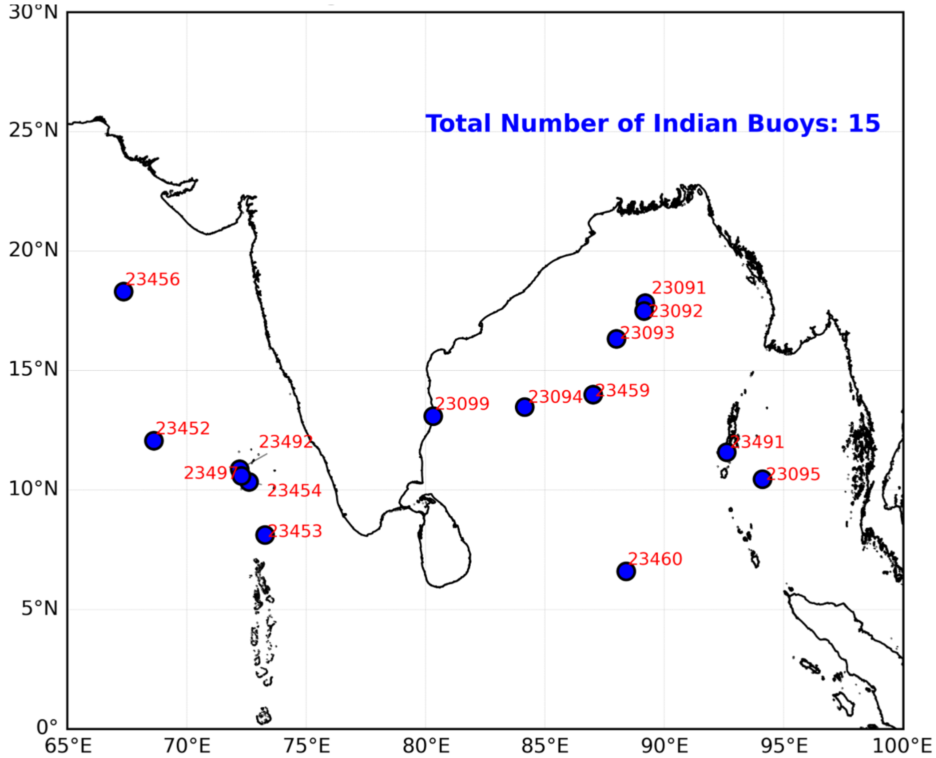


Figure 1. *Coverage of Indian Buoy Network deployed over the Bay of Bengal and Arabian Sea.*

The buoy data collected by INCOIS and NIOT is transmitted via satellite to receiving stations and are transmitted through the GTS. NCMRWF receives the Indian Buoy data through the GTS and also directly from the INCOIS. These observations are particularly important for improving the accuracy of numerical weather prediction (NWP) models run by the National Centre for Medium Range Weather Forecasting (NCMRWF). The real-time buoy data provides crucial insights into oceanic conditions, which in turn aids in more accurate forecasts of monsoons, cyclones, and marine operations.

Table 1. Detailed metadata information of Indian Buoy Network:

Buoy ID	LAT (°N)	LON (°E)	Buoy Type	Category	Deployed at	Data Interval
23091	17.83	89.19	Moored	OMNI	Bay of Bengal	3-Hourly
23092	17.49	89.14	Moored	OMNI	Bay of Bengal	3-Hourly
23093	16.33	87.99	Moored	OMNI	Bay of Bengal	3-Hourly
23094	13.48	84.14	Drifter	OMNI	Bay of Bengal	3-Hourly
23095	10.45	94.10	Drifter	OMNI	Bay of Bengal	3-Hourly
23099	13.09	80.31	Moored	Met-Ocean	Bay of Bengal	Hourly
23452	12.07	68.62	Moored	OMNI	Arabian Sea	3-Hourly
23453	8.12	73.28	Moored	OMNI	Arabian Sea	3-Hourly
23454	10.34	72.61	Moored	OMNI	Arabian Sea	3-Hourly
23456	18.31	67.35	Moored	OMNI	Arabian Sea	3-Hourly
23459	14.00	87.01	Moored	OMNI	Bay of Bengal	3-Hourly
23460	6.60	88.40	Moored	OMNI	Bay of Bengal	3-Hourly
23491	11.59	92.60	Moored	Met-Ocean	Bay of Bengal	Hourly
23492	10.87	72.21	Moored	Met-Ocean	Arabian Sea	3-Hourly
23497	10.59	72.29	Moored	Met-Ocean (CALVAL)	Arabian Sea	3-Hourly

3. Archival of Buoy Observations at NCMRWF

Upon receiving the Indian buoy (moored and drifter) data at NCMRWF, the information is automatically ingested into the high-performance computing system (MIHIR) for processing and assimilation into NWP models. NCMRWF obtains access to the Global Telecommunication System (GTS) through the Regional Telecommunication Hub (RTH)-New Delhi via National Knowledge Network (NKN) connectivity, with standard internet FTP access serving as a backup. The GTS data arrives at NCMRWF in two continuous message formats: the Traditional Alphanumeric Code (TAC) and the Binary Universal Form for the Representation of meteorological data (BUFR). Both formats begin with an “abbreviated header” and follow a fixed structure. Detailed information about the GTS structure and header is available in Prasad (2020). RTH-New Delhi continually transmits GTS data in two streams—ASCII and binary—through both FTP and NKN links to the respective servers at NCMRWF. The buoy data is received in BUFR, TAC, or both formats. These directories are synchronized with the Mihir HPCS, ensuring that GTS files are automatically transferred to designated temporary directories. The received files are processed based on the GTS message structure and separated into individual bulletins. Each file is named using the bulletin header, serial number, and a ".bul" suffix, and archived in a subdirectory named after the first two letters of the header [e.g., SS (for TAC bulletins) or IO (for BUFR bulletins)]. These subdirectories are organized by the date of the bulletin's origin (in YYYYMMDD format) and are stored in the directory structure "/scratch/gfsprod/data/gts" on the Mihir HPCS (e.g., for a TAC bulletin: "/scratch/gfsprod/data/gts/YYYYMMDD/SS/SSVX01_DEMS_180046_589.bul" and for a BUFR bulletin: "/scratch/gfsprod/data/gts/YYYYMMDD/IO/IOBX01_DEMS_180047_968.bul"). It should be noted that Indian buoys are transmitted under the DEMS code, which is the international four-letter location indicator of the originating station or center. The NCEP decoders are employed to decode the GTS buoy datasets and are being stored in "bufrtank" area. Then NCMRWF-GFS (NGFS) dump program generates the "dump file" corresponding to the assimilation cycles (± 3 hours). Now, observation monitoring package scripts generate the ASCII output in the "/home/gfsprod/data/OBS_MON/output/" directory for the "Early run" and in the "/home/gfsprod/data/OBS_MON/output_update/" directory for the "Update run". These directories are organized by date (YYYYMMDD) and cycle (00, 06, 12, 18) within the Mihir HPCS, and the output files are named as sufbuy_CYCz.out (e.g., /home/gfsprod/data/OBS_MON/output/YYYYMMDD/CYC/sufbuy_CYCz.out), where CYC is the assimilation cycle.

4. Near Real-time monitoring of Indian Buoy Observations

Before the buoy data is utilized in operational forecasting, it undergoes a comprehensive series of quality control (QC) checks within global or regional model systems to ensure accuracy. This includes verifying the consistency of the buoy data.

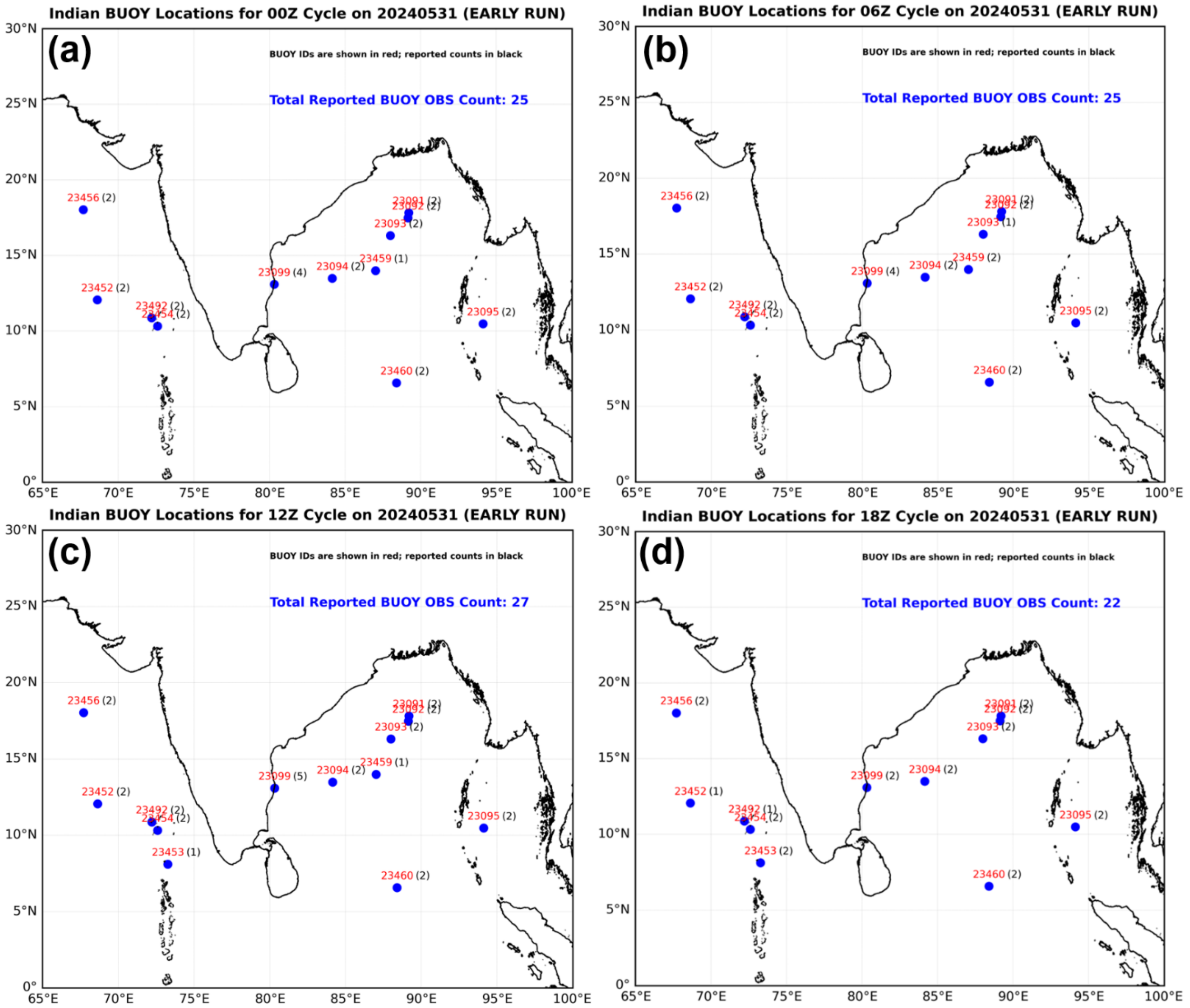


Figure 2. (a-d) *Spatial coverage of reported Indian buoy observations at different cycles during Early run.*

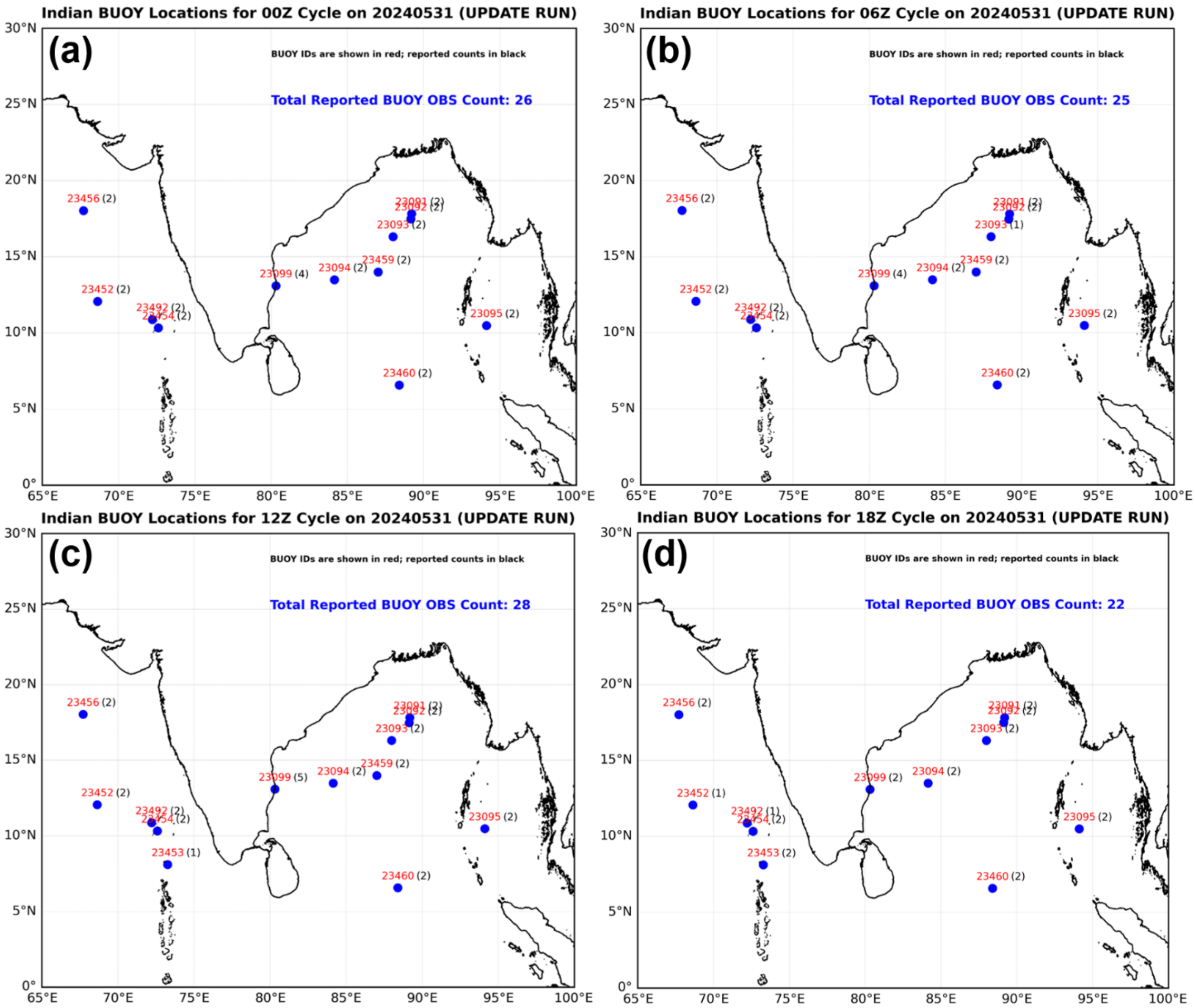


Figure 3. (a-d) *Spatial coverage of reported Indian buoy observations at different cycles during Update run.*

NCMRWF has developed an in-house, indigenous software package to monitor buoy data in near real-time. This system is supported by visualization tools that display buoy data in real-time for the four assimilation cycles (00, 06, 12, and 18 UTC). The tools provide spatial coverage of buoy locations, heatmaps showing observation counts for various meteorological variables such as Mean Sea Level Pressure (MSLP), Temperature, Wind Speed, and Wind Direction, as well as 10-day time series plots of these variables. The plots are stored on the Mihir system at the following path: "/scratch/gfsprod/data/OBS_MON". Figures 2 and 3 illustrate the spatial coverage monitoring of

Indian buoy observations across the Bay of Bengal and Arabian Sea during the Early and Update runs on May 31, 2024. On that day, 12 active buoys provided an average of 25 observations per cycle, equating to at least two observations per buoy per cycle. It is important to note that some Indian buoys report data hourly, while others report every three hours (refer to Table 1). Therefore, buoys reporting hourly can provide up to six observations per cycle, while those reporting every three hours can deliver a maximum of two observations per cycle.

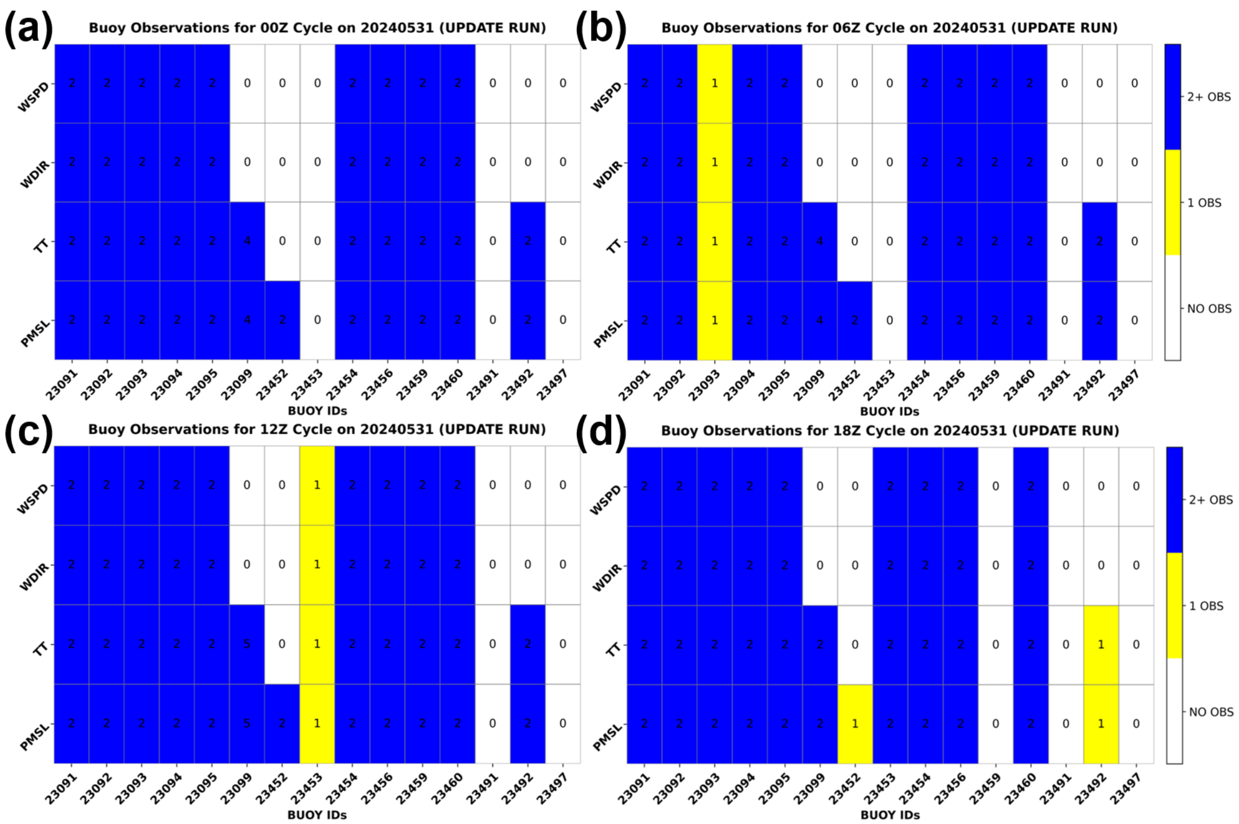


Figure 4. (a-d) *Count of buoy observations, such as Mean Sea Level Pressure (PMSL), Temperature (TT), Wind Direction (WDIR) and Wind Speed (WSPD) during four update assimilation cycles of 31 May 2024.*

The package also includes the functionality to automatically generate heatmaps that visualize the number of valid observations recorded by Indian buoys for various meteorological variables [such as Mean Sea Level Pressure (PMSL), Temperature (TT), Wind Direction (WDIR) and Wind Speed (WSPD)] during a specific cycle. This visualization is a valuable tool for monitoring the completeness of buoy data and comparing the frequency of observations between different buoy data formats (TAC or BUFR). Figure 4 illustrates the count of observations made by the Indian buoy network for meteorological variables during different cycles of the Update run on May 31, 2024. Similar visualizations are produced daily for the Early run. The heatmap generation process starts by initializing a data frame to store observation counts for each buoy (rows) and the respective reported variables (columns) (as seen in Figure 4). Initially, this data frame is populated with counts from buoys that reported only in the TAC format. Since the same buoy report can be transmitted in TAC, BUFR or both, the monitoring package has been automated to handle the duplicate/original BUFR reports. If the BUFR-report from a particular buoy is identical to the TAC-report from the same buoy, it is considered as duplicate data and excluded from further analysis. However, if the buoy reports only in BUFR (i.e., one that does not have a corresponding TAC buoy reporting in that cycle), its counts are added to the respective TAC buoy's tally. As shown in Figure 4, each buoy reports a maximum of two observations per variable. If no observations are recorded, the heatmap will highlight that the buoy did not report for those specific variables during that cycle. Through this process, the heatmap effectively visualizes the number of valid observations made by each buoy, integrating TAC and BUFR buoy data while accounting for duplicates.

The buoy data monitoring system includes a comprehensive process for generating and visualizing time series data from meteorological observations at each buoy station. It automatically retrieves buoy observation data in TAC and BUFR formats for the last 10 days, organizing the data by Buoy IDs. The system processes the extracted data, removes duplicates, and saves it into CSV files containing meteorological variables such as, mean sea level pressure, temperature, wind speed, and wind direction. These CSV files are then used to generate the time series plots for specified dates and cycles. The system distinguishes between hourly and three-hourly reporting buoys and visualizes key meteorological variables accordingly. Time series are plotted for the past 10 days, with built-in capabilities to manage any data gaps. Figure 5 displays time series plots of various meteorological variables (in panels) for the Buoy (ID-23091) during different assimilation cycles (00, 06, 12, and 18 UTC) on 31 May 2024 Update runs. Similar figures are automatically generated for other Buoy IDs during both the Early and Update runs. As seen in Figure 5, this particular buoy (ID: 23091) consistently reported two maximum observations for each cycle across nearly all 10 days. These plots provide a visual summary of the weather conditions at buoy locations, aiding in the analysis of short-term atmospheric and oceanic trends.

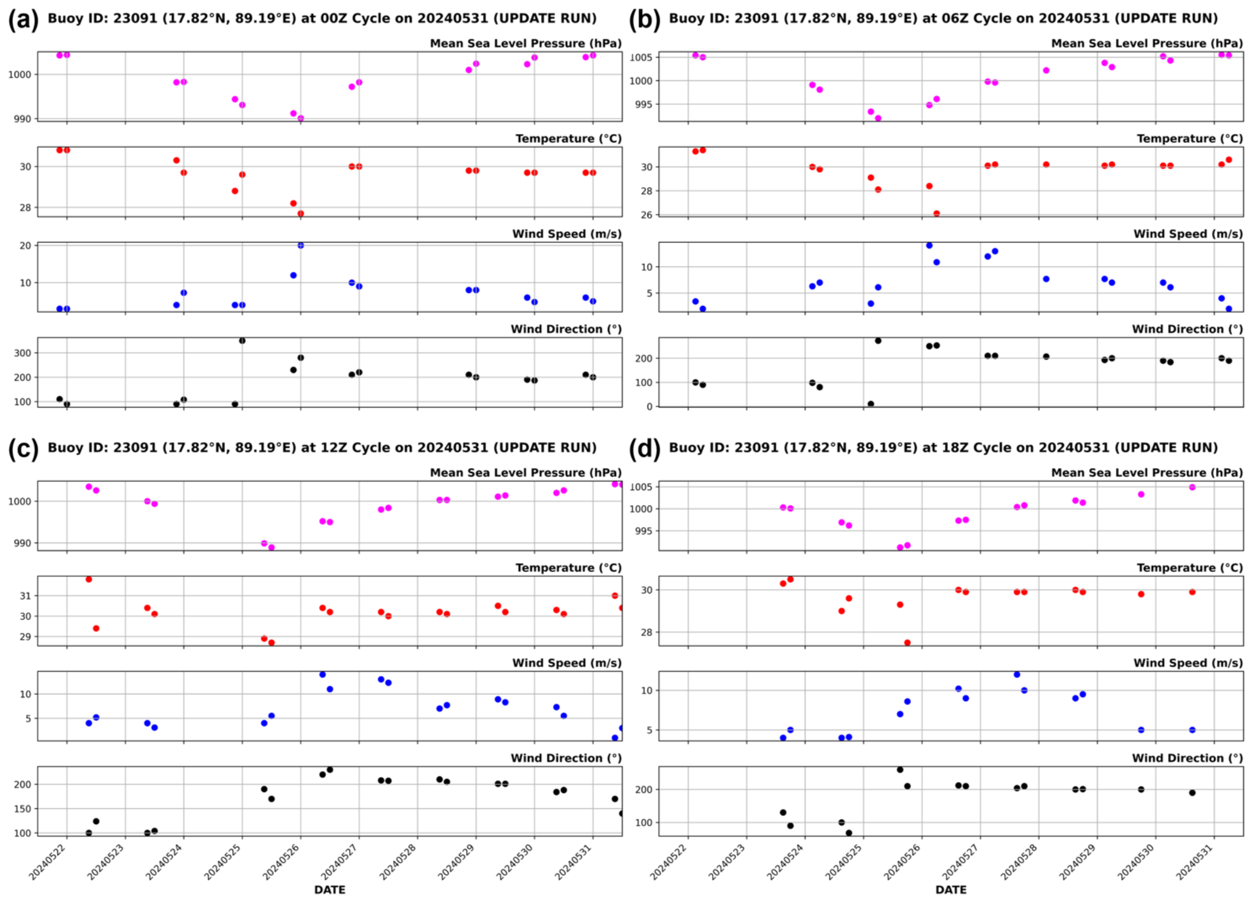
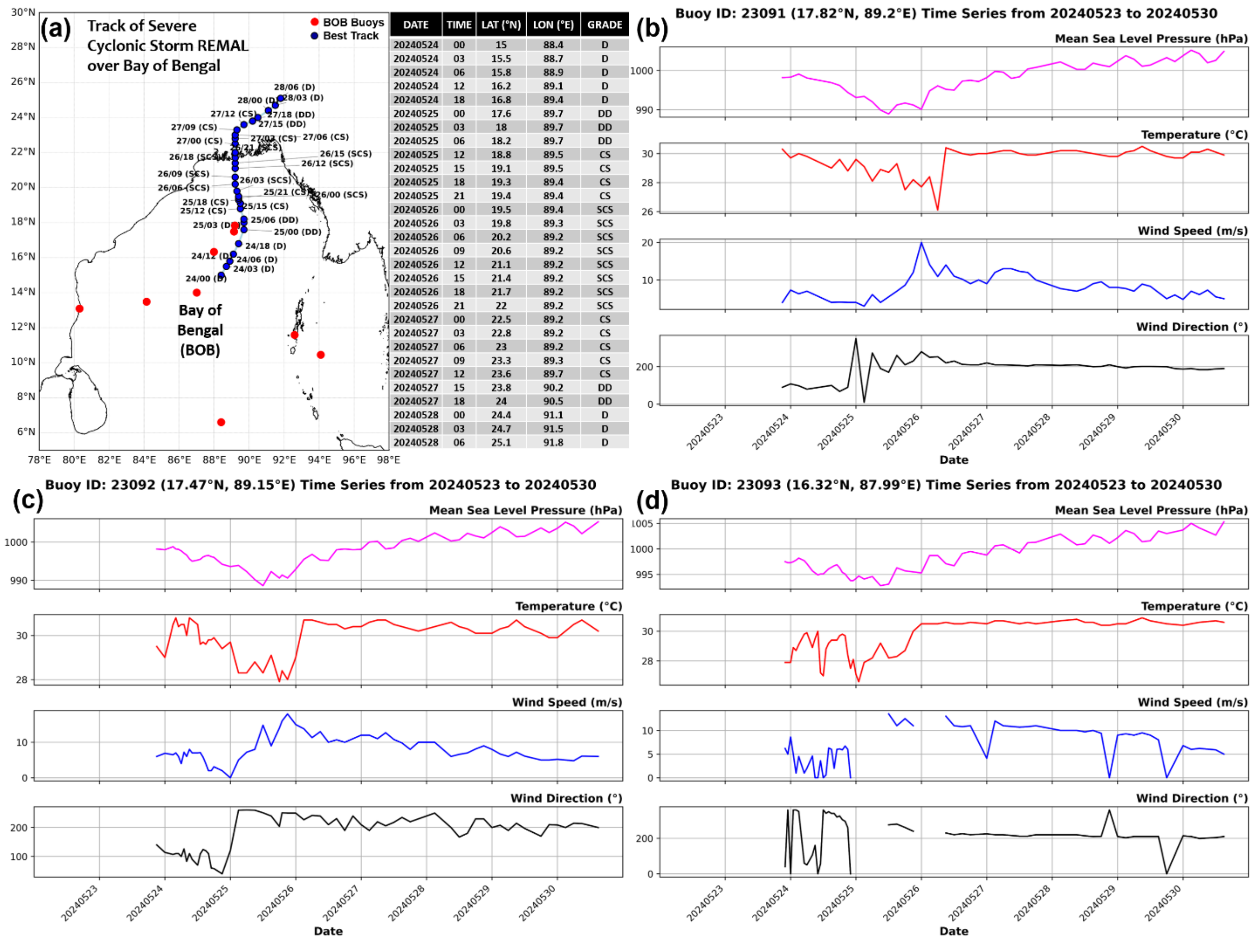


Figure 5. (a-d) *Time series plots of different meteorological variables (in panels) at different cycles during Update run by the Buoy ID-23091.*

5. Applications of monitoring buoy observations in near real-time: A case study

The near real-time monitoring of Indian buoy observations is crucial in advancing our understanding and forecasting of severe weather phenomena, particularly cyclonic storms. A prominent example is the Severe Cyclonic Storm (SCS) REMAL over the Bay of Bengal, which occurred from May 24-28, 2024. According to the India Meteorological Department (IMD), an upper-air cyclonic circulation developed at lower tropospheric levels over the southwest Bay of Bengal early in the morning of May 21, 2024 (0530 IST/0000 UTC), prior to the onset of the southwest monsoon in the region. This circulation led to the formation of a low-pressure area over the southwest and adjoining west-central Bay of Bengal on the morning of May 22, 2024 (0530 IST/0000 UTC). By May 23, it had evolved into a well-marked low-pressure area over the west-central and southern Bay of Bengal (0830 IST/0300 UTC). It subsequently intensified into a depression over the central Bay of Bengal by the morning of May 24, 2024 (0530 IST/0000 UTC). Moving northward, it strengthened into a deep depression on May 25, 2024 (0530 IST/0000 UTC), and later the same day, it developed into Cyclonic Storm "REMAL" over the north and adjoining east-central Bay of Bengal (1730 IST/1200 UTC). Continuing on its northward trajectory, REMAL intensified into a severe cyclonic storm over the northern Bay of Bengal on the morning of May 26, 2024 (0530 IST/0000 UTC). It subsequently made landfall between Sagar Islands, India, and Khepupara, Bangladesh, southwest of Mongla near 21.75°N latitude and 89.2°E longitude, between 2230 IST on May 26 and 0030 IST on May 27, 2024 (i.e. between 1700-1900 UTC on May 26), with wind speeds reaching 110-120 km/h, gusting up to 135 km/h (60-70 knots) (IMD, 2024). The best track of SCS REMAL is illustrated in Figure 6a, which also shows the locations of moored buoys (Buoy IDs 23091, 23092, 23093) positioned along the storm's path (indicated by red dots). These buoys recorded significant oceanic changes, such as a sharp decline in mean sea level pressure (falling below 990 hPa) and increased wind speeds (exceeding 20 m/s or 38 knots, as shown in Figures 6b-d), indicating the rapid intensification of the storm.



DATE	TIME	LAT (°N)	LON (°E)	GRADE
20240524	00	15	88.4	D
20240524	03	15.5	88.7	D
20240524	06	15.8	88.9	D
20240524	12	16.2	89.1	D
20240524	18	16.8	89.4	D
20240525	00	17.6	89.7	DD
20240525	03	18	89.7	DD
20240525	06	18.2	89.7	DD
20240525	12	18.8	89.5	CS
20240525	15	19.1	89.5	CS
20240525	18	19.3	89.4	CS
20240525	21	19.4	89.4	CS
20240526	00	19.5	89.4	SCS
20240526	03	19.8	89.3	SCS
20240526	06	20.2	89.2	SCS
20240526	09	20.6	89.2	SCS
20240526	12	21.1	89.2	SCS
20240526	15	21.4	89.2	SCS
20240526	18	21.7	89.2	SCS
20240526	21	22	89.2	SCS
20240527	00	22.5	89.2	CS
20240527	03	22.8	89.2	CS
20240527	06	23	89.2	CS
20240527	09	23.3	89.3	CS
20240527	12	23.6	89.7	CS
20240527	15	23.8	90.2	DD
20240527	18	24	90.5	DD
20240528	00	24.4	91.1	D
20240528	03	24.7	91.5	D
20240528	06	25.1	91.8	D

Figure 6. (a) *Best track of severe cyclonic storm (SCS) REMAL as provided by IMD, New Delhi (https://rsmcnewdelhi.imd.gov.in/download.php?path=uploads/report/33/33_6ff195_BestTrack_2024.pdf). (b-d) Time series for the different meteorological variables during the period of SCS REMAL (24-28 May 2024) from the Buoy with IDs 23091, 23092 and 23093 respectively.*

The continuous data stream provided by INCOIS and NIOT buoys plays a pivotal role in the timely assimilation of information into global and regional Numerical Weather Prediction (NWP) models operated by the National Centre for Medium Range Weather Forecasting (NCMRWF). This real-time data assimilation significantly improves the accuracy of cyclonic event forecasts, reducing uncertainties in both track and intensity predictions. The case of REMAL exemplifies how near real-time Indian buoy observations contribute substantially to early warning systems and disaster preparedness, ultimately saving lives and mitigating potential damage.

6. Conclusions

The near real-time monitoring of buoy data from the Indian Moored and Drifter Buoy Network, operated by INCOIS and NIOT, plays a critical role in enhancing the accuracy and reliability of weather forecasting, particularly for severe weather events like cyclonic storms. The indigenous buoy monitoring package developed at NCMRWF ensures the regular monitoring of the consistency of buoy data providing visualization tools, such as spatial coverage maps, heatmaps and time series plots, that enable real-time tracking of key meteorological variables. This real-time monitoring system enables to monitor the timely data reception at NCMRWF for their real-time assimilation in the NCMRWF global and regional models. It also allows feedback to the data providers if there are any issues.

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Author Contributions

Upal Saha: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Visualization, Writing – Original Draft, Writing – Review & Editing.

S. Indira Rani: Conceptualization, Methodology, Data Curation, Supervision, Writing – Review & Editing.

D. Srinivas: Resources, Data Curation.

V. S. Prasad: Resources, Data Curation, Project administration.

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