SAtellite-based Marine Process Understanding, Development, Research and Applications for Blue Economy (SAMUDRA): A Technology Demonstration Program in the Bay of Bengal

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RESEARCH ARTICLE

SAtellite-based Marine Process Understanding, Development, Research and Applications for Blue Economy (SAMUDRA): A Technology Demonstration Program in the Bay of Bengal

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Abstract

SAtellite-based Marine Process Understanding, Development, Research and Applications (SAMUDRA) for blue economy, a technology development program of the Space Applications Centre, is an umbrella program covering research and applications geared toward physical and biological oceanography making use of current and future satellite observations for developing the nation's blue economy. The main motivation behind this project was to develop satellite and numerical model-based information and value-added products and to demonstrate the implementation of developed applications for operational requirements. The program also aimed at improving existing methodologies for various applications by utilizing space-based inputs. Several field campaigns with the use of NavIC-enabled instruments and NABH-MITRA were conducted for measuring biophysical parameters and validation of developed applications in the coastal regions. One of the key aspects of this project was development of web-based customized tools/dissemination system for providing the information to the end users. Some of the key/notable achievements of SAMUDRA were development of a portal OceanEye (tailor-made web-portal for Shipping Corporation of India), storm-surge/inundation system, oil-spill trajectory modeling, level-next potential fishing zone algorithm and rip current alert system.

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Introduction

Warm and salinity stratified basin, Bay of Bengal has caught the attention of researchers from time immemorial because of the strong air–sea interaction, and ocean processes occurring at different temporal and spatial scales, that affects the southwest monsoon and cyclones (Wijesekera et al, 2016, Gordon et al. 2020). Some of the notable programs which have specifically catered to this basin for unraveling hidden processes are the Bay of Bengal Monsoon Experiment (BOBMEX) during July–August 1999 (Bhat et al., 2001), Ocean Mixing and Monsoon (OMM) during 2013–17 (Sharma et al., 2016; Wijesekera et al, 2016) and Bay of Bengal Boundary Layer Experiment (BoBBLE) carried out during the summer monsoon June–July 2016 (Vinayachandran et al., 2018). All these experiments were largely focused on intense ocean observations collected using ships, buoys, gliders, etc., for addressing unresolved key science processes. None of these programs were dedicatedly meant to demonstrate utilization of satellite data for developing "blue economy," that integrates harnessing the living and non-living resources with a sense of social inclusion and environment issues. Inspired by Gunter Pauli's book "The Blue Economy: 10 years, 100 innovations, 100 million jobs (2010)," SAtellite-based Marine Process Understanding, Development, Research and Applications for blue economy (SAMUDRA) was conceptualized by Space Applications Centre, ISRO, in the year 2017 for the Indian Ocean to exhibit the full potential of remote sensing observations. It was expected to provide a large canvas for demonstrating ocean applications (hazard/disasters, safe navigation, potential fishing zone identification, ocean energy, etc.), using the data from ISRO's missions like INSAT-3D/R, OCEANSAT-2, SARAL/AltiKa, SCATSAT-1 and other global Earth Observing (EO). Focus of the project was to develop newer applications and generation of satellite-based value added products, with major emphasis on web-based dissemination to various users/stakeholders in order to provide end-to-end solution.

As a proof of concept, the SAMUDRA program was planned to be executed as a Technology Demonstration Program (TDP) encompassing certain specific objectives mainly focusing in the Bay of Bengal (BoB) region of the Indian Ocean (IO). The project started in July 2017, and the first phase ended in March 2021. During the project period, capital investment toward infrastructure and technology development were toward realizing SAMUDRA's long-term objectives beyond the stated period. With the involvement of several national institutions/academic centers, we could achieve the stated goals in a much meaningful manner to meet the needs of the users. This paper presents goals and objectives of the project along with salient achievements made under various themes. Details of the individual components under SAMUDRA are published as separate publications, and they are extensively referred in this manuscript. At the end, we provide a section on summary, gaps in the existing satellite data for oceanographic studies and way forward.

Application and Research Themes under SAMUDRA

High-Resolution Satellite Data Assimilative Ocean State Analysis/Forecasting System—Observing System Experiments

Prior to SAMUDRA, the ocean forecasting system set up by SAC used Princeton Ocean Model (POM) (Ratheesh et al., 2014) for ocean circulation forecasting and Simulating WAve Near-shore model (SWAN) (Suchandra et al., 2015) for wave forecasting. Both the models provided information at 50 km x 50 km horizontal resolution. These models were capable of capturing the large-scale variations in the ocean; however, smaller scales ($\sim$ 10 km – 50 km) were completely missed. With technological advancement at SAC after the procurement of high-performance computing system in 2016, high-resolution versions of ocean circulation and wave models were configured to meet the user demand of providing fine scale information. Specific objective under this theme was to develop satellite data assimilation modules toward carrying out observing system experiments (OSE). Toward this, it was required to upgrade the existing ocean state analysis/forecasting system in terms of generating information at a higher spatial resolution. Another aim was the development of ultra-high-resolution site-specific ocean state forecasting system for special events like satellite recovery experiments and for any strategic applications.

Data Assimilation for Wave Forecasting System

For wave forecasting the spectral wave model, WAVEWATCH-III (WW3DG, 2016) was configured with four nested domains with ultra-high-resolution coastal domain covering the entire Exclusive Economic Zone of India. Details of the model configuration are provided in Seemanth et al. (2021). The forecasting system uses 10-m analysis and forecast wind components obtained from the National Centre for Medium Range Weather Forecasting (NCMRWF) Unified Model (NCUM; Sumit Kumar et al., 2020), which are available at 25 km horizontal resolution. In order to improve the predicting capability of the model, significant wave height observations from SARAL/AltiKa, Jason2, Jason3 and Sentinel3 altimeters are assimilated into the model using optimal interpolation technique (Seemanth et al., 2021). The assimilation algorithm, so developed to ingest satellite data, has been integrated in the INCOIS operational wave forecasting system.

Data Assimilation in Ocean General Circulation Model

To develop the assimilation algorithm and test the efficacy of satellite data impact on ocean state, the modified version of the Modular Ocean Model version 3.0 (hereafter referred to as MVMOM3, Mallick et al., 2018, 2019, 2020) was configured for an extended domain (27 E–142 E, 35 S–26 N) covering the entire Indian Ocean (IO) with a variable horizontal and vertical resolution. Further details of this configuration are provided in Mallick et al. (2020). The model is forced by atmospheric forecast of air temperature, specific humidity, winds, radiation and precipitation, obtained in near real time from National Centre for Medium Range Weather Forecasting (NCMRWF). Track observations of sea level anomaly (SLA) from altimeter are assimilated using Ensemble Optimal Interpolation technique (Agarwal et al. 2021). Model simulated SST is moderately nudged toward Group of high-resolution SST (GHRSST). No in situ observations are currently assimilated in this model. This operational ocean circulation model provides forecasts of sea level anomaly and 3D fields of temperature, salinity and ocean currents for the Indian Ocean.

The new ocean state forecasting (OSF) system is designed in such a way that it assimilates most of the space-based observations for improved predictions using high-resolution versions of wave (up to 2.5 km) and circulation (up to 10 km) models. The entire ocean state forecasting system, comprising the circulation and the wave models, was installed at the NODPAC and a dedicated web-portal named "Ocean Eye" and an automated email-based forecast disseminating system has been developed by the MOSDAC team. "Ocean Eye" web-portal disseminates 3–5 days forecast of sea surface currents, wave height, wind speed and sea level pressure for the entire Indian Ocean. Apart from this, information on ship avoidance zones is also provided during cyclones. An automated email-based forecast requesting system is developed in which a ship that sends an email with information of its coordinates receives forecast of that location for next 3–5 days. Figure 1 shows an illustration of the results of this component.

Coastal Vulnerability

Coast is one of the vulnerable regions affected by both natural (extreme wave conditions) and anthropogenic factors. Under this theme, four key aspects were taken up: (i) real-time prediction of storm surge and coastal inundation, (ii) development of an automated rip current prediction system for rip currents, (iii) development of regional algorithm to identify probable regions of deposition and quantify the sediment dynamics and (iv) studies on short-term and long-term shoreline changes using modeling, satellite observations and beach-profile data. All these parts involved numerical modeling, satellite data application and field data for model/algorithm development and validation.

Storm Surge and Coastal Inundation

Coastal inundation due to cyclones is simulated using the state-of-the-art Advanced Circulation (ADCIRC) model coupled with Simulating Waves Nearshore (SWAN) model along the east coast of India (Bhaskaran et al., 2014; Dietrich et al., 2012; Mandal et al., 2020). Bathymetry of the computational domain is prepared by integrating data from digital coastal bathymetric chart with global digital elevation model (DEM) ETOPO-2. Astronomical tides are prescribed as open ocean boundary condition to ADCIRC model. Total 13 harmonic tidal constituents (K1, O1, P1, Q1, M2, N2, S2, K2, L2, 2N2, MU2, NU2 and T2) were taken from Le Provost tidal database (Provost et al., 1998). The major shortcomings of coastal inundation simulation due to inaccurate representation of intricate networks of river, creeks and lagoons have been overcome by careful description of the critical coastal wetland features influencing the landward inundation of storm surge in the present work. Experimental simulation of storm surge induced coastal inundation is carried out for the Thane (2011), Phailin (2013), Hudhud (2014) and Vardah (2016) cyclones. Modified Jelesnianski wind scheme (Pandey & Rao, 2018) has been used to prepare wind forcing from best track data provided by Indian Meteorological Department (IMD). The computed surge residual for Thane, Phailin, Hudhud and Vardah is compared with available tide-gauge observations, which have resulted in root mean square error (RMSE) of 0.08 m, 0.06 m 0.11 and 0.01 m, respectively. The model set up is then used to generate coastal inundation forecast due to Titli cyclone using weather research and forecasting (WRF) wind forecast fields, with a lead

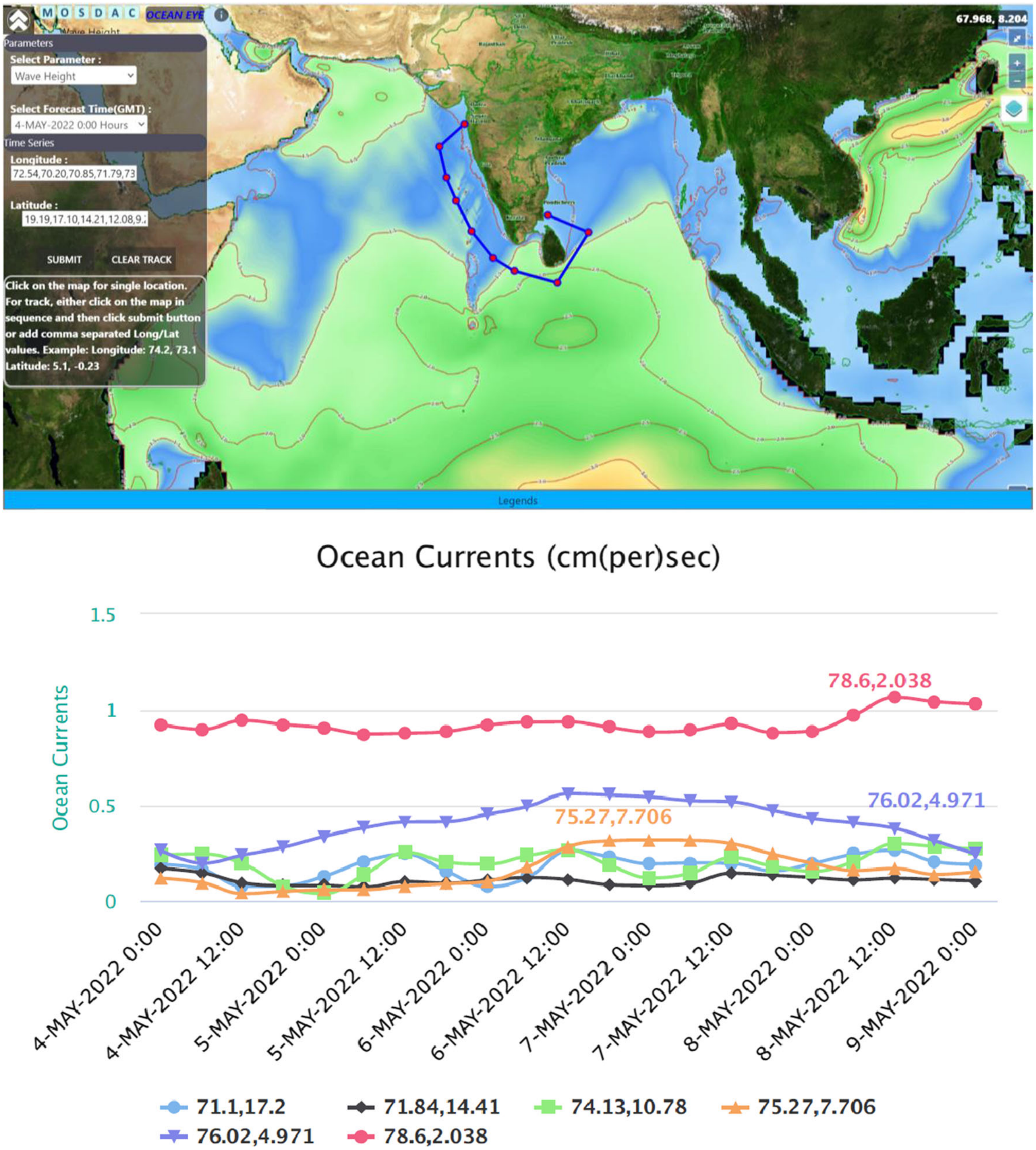

Fig. 1 (Upper Panel) Snapshot of Ocean Eye web portal displaying the forecast map of significant wave height for a particular day. Blue line indicate the track of ship, which can be overlaid using tools provided ocean eye web portal. (Lower Panel)The chart shows the time-series plots of forecast wind, wave height, currents and sea level pressure for the track points selected on the ocean eye web portal. Different line color indicates forecast on the selected locations

period of 48 h (Mandal et al., 2020). Sample result of coastal inundation and its validation with satellite image is shown in Fig. 2. The storm surge and coastal inundation model has been made operational on Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC), and products are hosted during the event of a cyclone.

Rip Currents Prediction and Monitoring

Under SAMUDRA, a new rip current likelihood-forecasting model using modeling and satellite data has been developed. Hindcast model outputs from a WAVEWATCH III (WW3) model and predicted tides from Finite Element System-FES2014 global tidal model have been

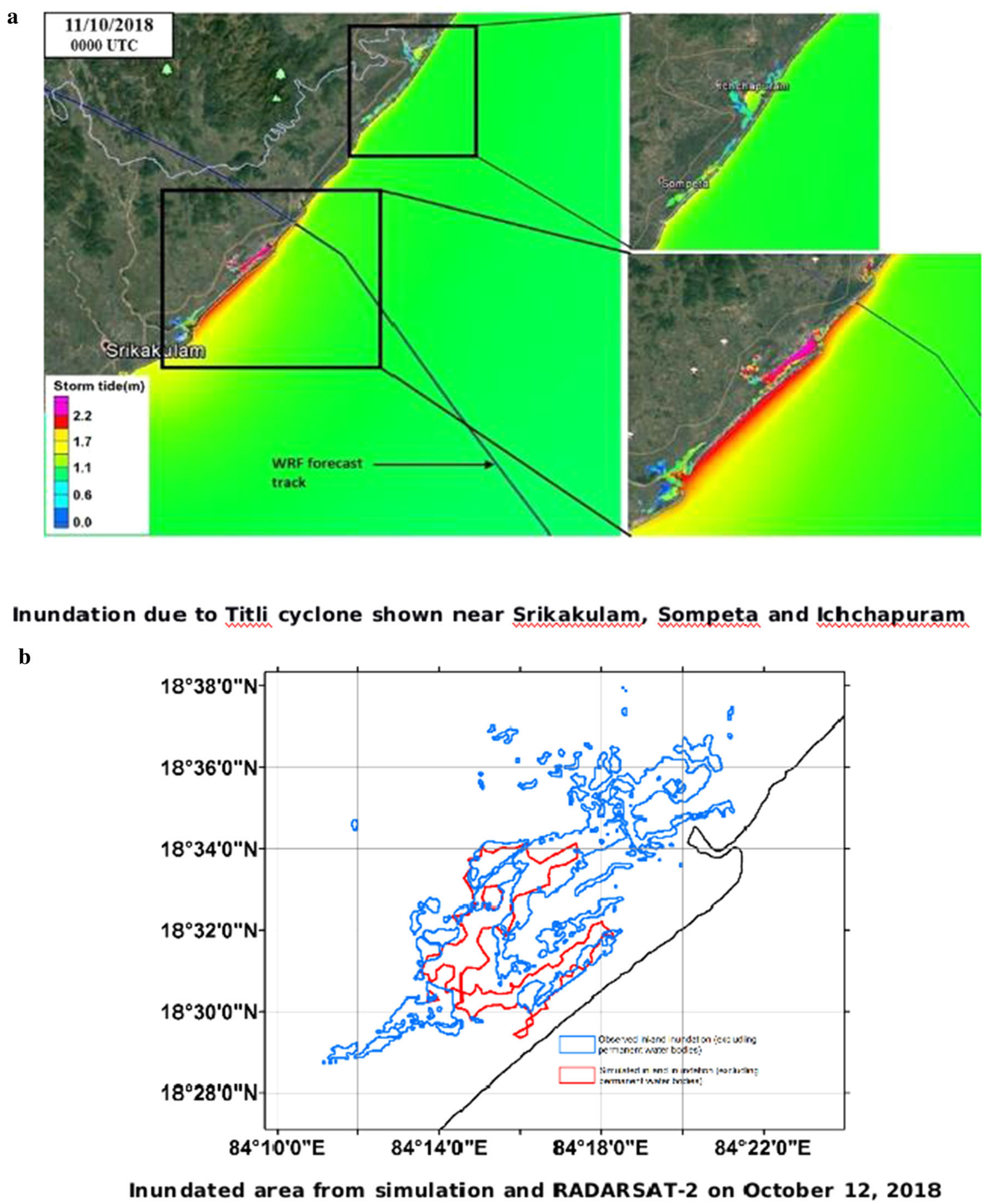

Fig. 2 **a** Inundation due to Titli cyclone shown near Srikakulam, Sompeta and Ichchapuram **b** Inundated area from simulation and RADARSAT-2 on October 12, 2018

utilized. Modeled waves and tides were validated with the wave buoys and tide gauges' data, respectively. A logistic regression formulation was used between lifeguard reports from the Goa beaches and modeled wave and tide parameters. Three different schemes have been chosen for rip current prediction in hindcast mode, and the one with seven predictors was found to be outperforming in predicting the rip current activity with a lowest Brier Score of 0.19, the probability of detection (POD) of 0.61 and false alarm rate (FAR) of 0.39, respectively (Surisetty et al. 2019a). Later, the same scheme was chosen for forecasting rip current likelihood using altimeter assimilated WAVEWATCH III forecast for the next 5 days and implemented on MOSDAC through a dedicated portal (Fig. 3a). Detailed results on the

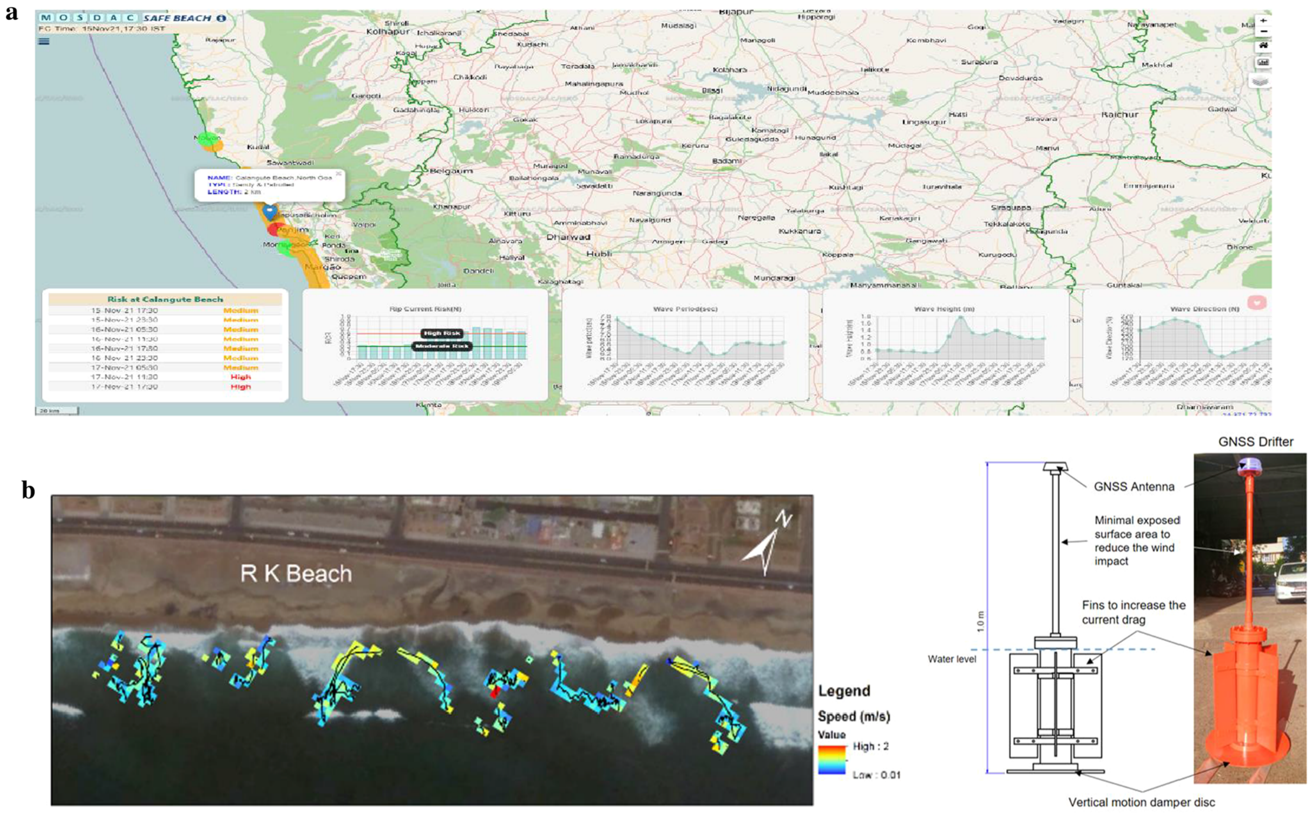

Fig. 3 **a** Rip current forecast webpage hosted on MOSDAC, SAC (https://www.mosdac.gov.in/rip/). **b** 5 × 5 m bin averaged measured speeds (left pane) in the surf zone using two GNSS drifters (right panel) on 14 May 2018 at RK Beach, Visakhapatnam

validation using low-cost GNSS/NavIC (Fig. 3b)-based drifters are given in Surisetty et al. 2020a; 2021a. Techniques have been developed to obtain high-resolution nearshore bathymetry from satellite imageries and in situ data obtained from modified Jet Ski (Surisetty et al. 2021b; 2020c) to utilize for numerical modeling.

Sediment Dynamics

Using satellite observations, the regions of deposition and erosion and estimation of the quantities of change from in situ measurements at the selected locations of the Godavari delta region have been identified.Using In situ data collected from Laser In Situ Scattering and Transmissometry (LISST) instrument, suspended sediment concentration was computed. This was then used to derive the algorithm for deriving SSC from Advanced Wide Field sensor (AWIFS) data. The satellite data analysis suggests that the high erosion trend of the coast has turned to less and stable coast by 2019, where the shoreline is evolving to better condition in spite of the extreme events. However, the stations located near to the river mouth are observed to undergo severe erosion. A regional algorithm to estimate total suspended matter from AWIFS data for the Godavari delta region have been developed. The proposed regional algorithm was able to capture both spatial and temporal variations of sediment concentrations (Murali et al. 2020).

Coastal Erosion Modeling

In the present study, an approach has been developed toward predicting the beach erosion at Rama Krishna (RK) Beach, Visakhapatnam using XBeach modeling system. The approach is similar to one used by Ramakrishnan et al. (2018). We created a simulation domain represented in 580 alongshore and 170 across-shore rectangular grids with 5 m spatial resolution. The geodetic measurements along RK beach were taken with the help of dual frequency LEICA GPS500 Instrument with SR520 receiver. The differential global positioning system (DGPS) observations were made on May 14, 2018, and September 30, 2018, along Ramakrishna beach at Visakhapatnam. The DGPS profiles of RK beach measured during March 14, 2018, are used to create the initial beach topography through series of interpolation techniques. We collected the receiver independent exchange format (RINEX) data of IGS station and precise ephemeris from Scripps Orbit and Permanent Array Centre (www.sopac.ucsd.edu). The beach profile global navigation satellite system (GNSS) observable was synchronized with reference station over epoch period of 1 s data were collected.

Using various forcing parameters, the forecast of beach erosion for 10 June is provided on 1 June, which corresponds to a lead period of 10 days and such beach erosion forecast is provided for alternate 10 days up to September 30, 2018, spanning the monsoon season over the Indian Peninsula. The observed beach profiles and DGPS observations are used to validate the model performance. Area under erosion observed from the model result is in homologous with the in situ observations. Figure 4 shows illustration of the results of this component. The beach was observed to have a gradual erosion along the entire length, which is maximum at the central sector, where the simulation shows an erosion of about 50 to 60 m from the initial shoreline. The beaches along the northern sector are simulated to have an erosion of about 40–50 m, while the erosion is in patches in the southern sector which extends a maximum to about 30–40 m from the initial shoreline.

Fish Track Taking Potential Fishing Zone (PFZ) Activity to Level-Next

In India, PFZ identification, mapping and forecasting is done using satellite-based chlorophyll and SST information (Solanki et.al. 2001, 2003, 2005) and the advisory is operationally provided by INCOIS, MoES. While the methodology is extremely useful for the fishermen, it had its own limitations due to non-availability of high-resolution satellite observations under cloudy conditions. Under SAMUDRA, a refinement in the already existing operational PFZ procedure was sought to (i) develop fish track module based on feature propagation of ocean parameters such as SST fronts, chlorophyll and ocean surface currents, and (ii) verification of the forecasted PFZ locations with fish catch data from field surveys in real time.

We developed a new potential fishing zone advisory algorithm using multiple satellite observations such as sea surface temperature (SST), chlorophyll, SLA, ocean surface wind and currents data. The conceptual flowchart is shown in Fig. 5a, and the detailed methodology is provided by Jishad et al. (2019). The possible propagation of PFZ regions has been identified using relative wind (ocean surface wind field minus surface current) field. The relative wind fields and the corresponding Ekman transport are used for the computation of persistence.

The quantity of fish catch from the identified PFZ locations and the non-PFZ locations is shown in Fig. 5b. The forecast and its persistence for about 3–4 days have been validated by the collaborators using field-based trawl

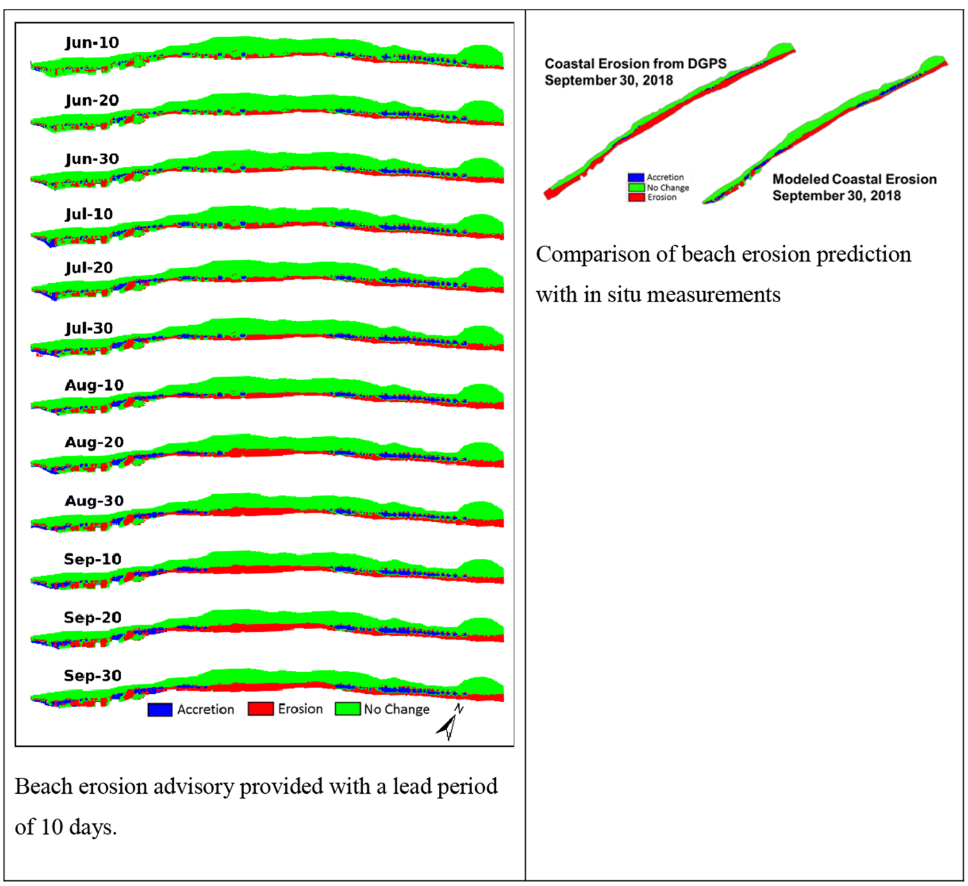

Fig. 4 Schematic diagram showing the PFZ forecast methodology

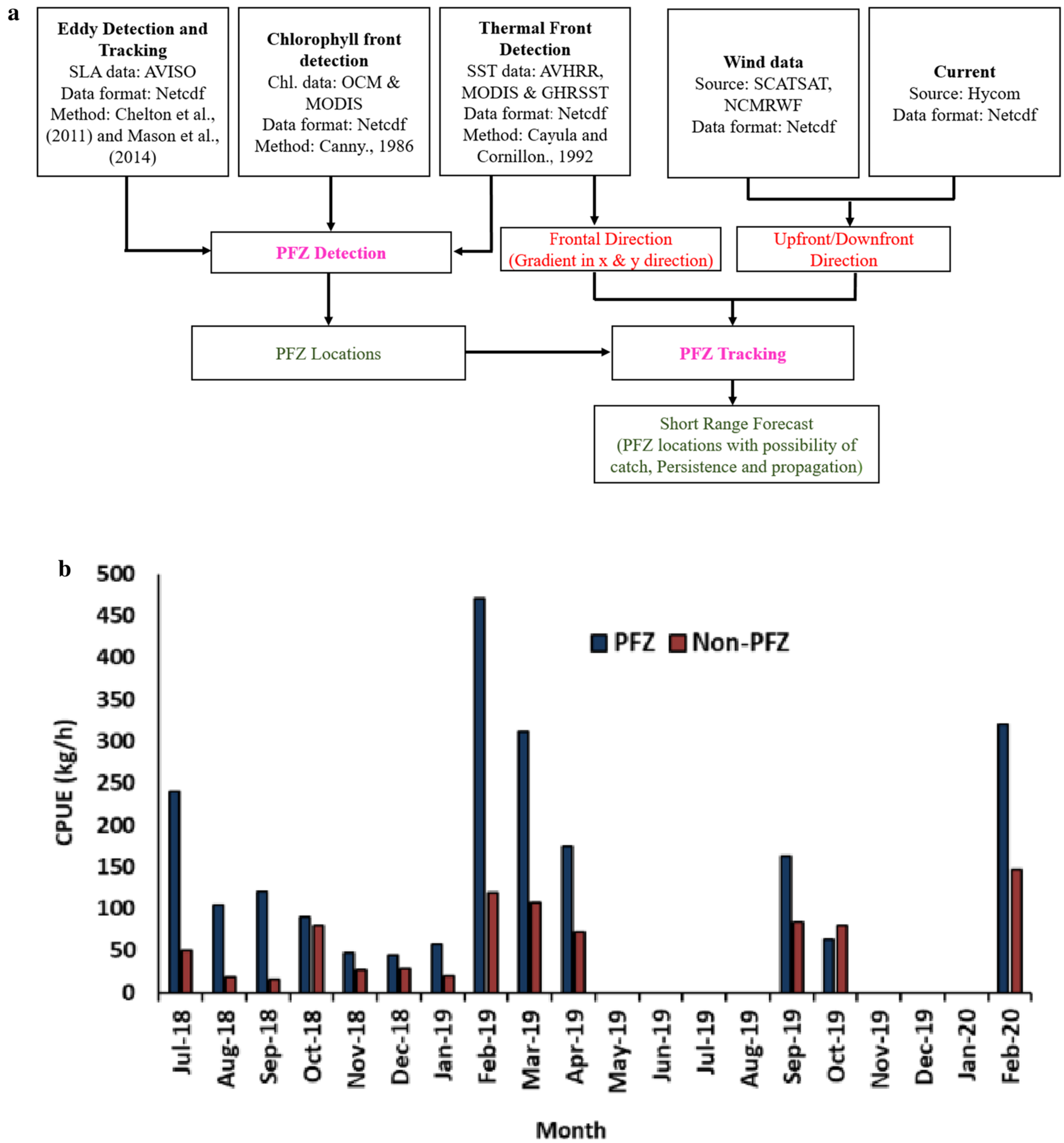

Fig. 5 **a** Conceptual flow chart for the advanced PFZ advisory algorithm. **b** CPUE in both PFZ and non-PFZ locations

nets estimated catch per unit effort (CPUE) and longlines based hook rate and gill nets datasets Bay of Bengal waters off Tamil Nadu, Andhra Pradesh and Odisha coast during 2016–2020. The validation exercise used in-house developed NABMITRA system which was equipped with NavIC. The validation is observed to be working satisfactory for the PFZ locations and in parallel this has been tested in non-PFZ locations as well (Jishad et al, 2019; Manigandan et al, 2020). The cost benefit analysis has been attempted and found that the forecasted locations and related expenditure-cum-CPUE rate were better than non-forecasted catches.

This new method has advantage during the cloudy days as it provides information on wind and current-based features movement, which was difficult to obtain from only chlorophyll and SST information.

Satellite-based Ocean Analysis

Analyzed fields of sea surface wind are available at 25 km horizontal resolution from scatterometer missions (Chakraborty et al. (2019); however, there was a need to generate this information at a higher spatial resolution and therefore this possibility was explored under this theme. Satellite observations of sea surface (SST, SLA, Winds, SSS) were used and possibility of retrieving oceanic subsurface information, which is very crucial for naval applications, was also envisaged. Chlorophyll concentration data from satellites are also available since long (Garnesson et al. 2019). Ocean Color Monitor onboard Oceansat series of satellites has been continuously gathering the information since last two decades. Spatial and temporal continuity of these data has always been challenging under cloudy conditions; hence, an attempt was made to utilize ocean color data from all available sensors and generate ocean color merged product.

Under this theme, three products, viz. (i) scatterometer-based daily global high-resolution analyzed ocean surface winds, (ii) vertical profiles of density and velocity anomaly fields reconstructed from satellite observations and (iii) merged chlorophyll fields from different satellites, were envisaged.

Analyzed Wind Vector field: In order to generate daily high-resolution (0.0625° × 0.0625°) analyzed winds over the global oceans, Level-4HB data from SCATSAT-1 scatterometer are utilized. The swath-based scatterometer wind products are first projected on to the global geographical grid with specific resolution (0.0625°) and subsequently interpolated component-wise to using box-averaging method. This is an iterative process, and thus, an optimum number of iterations are chosen to fill each and every missing grid over the global oceans. The details of the methodology are presented in Chakraborty et al. (2019). An illustration of the swath based wind product (Level-4HB) and its corresponding analyzed product (Level-4AW_625) is shown in Fig. 6. The generated global analyzed products are validated using observations from global moored buoys and the results are promising. The high-resolution analyzed wind product is available on MOSDAC.

Vertical Density and Velocity Anomaly fields: Vertical structure of density and velocity anomaly fields have been derived using satellite-based sea surface height anomaly, sea surface temperature and sea surface salinity observations for the Bay of Bengal. Interior + Surface Quasi Geostrophic (ISQG) approach has been used to generate these profiles. Detailed methodology can be referred from Mandal et al. (2021), Liu et al (2014) and Wand et al. (2013). First, the applicability of ISQG via identical twin experiments using numerical ocean model outputs was explored. After establishing the methodology was applied to satellite datasets. The entire Bay of Bengal was divided into several boxes of size 5° × 5°, and later the outputs were merged. The method was found to work nicely in the regions of low eddy activity and during some specific seasons. The product was validated using Rama buoy observations and has been hosted on MOSDAC website. Figure 7 shows illustration of the methodology and its sample output presented on MOSDAC.

Satellite-based Merged Chlorophyll fields: For merging data from the two different sensors, the topmost requirement is similarity in datasets. Thus, for OCM-2 merging with MODIS Aqua and NPP VIIRS, the data from all the three sensors were investigated at eight-day interval for the entire globe in total and Arabian Sea in particular, for 2016 and 2017. The investigations revealed that the chlorophyll concentration from MODIS Aqua and NPP VIIRS match to a certain limit (MODIS and VIIRS datasets match closely in low-chlorophyll-a regions while not in higher value such as the coastal and algal bloom affected regions), but there were large differences in the OCM data. Consequently, biases were generated and their spatial and temporal variations have been studied in detail. Algorithm for Chl- ‘a’ merging is ready and will be used once data from EOS-6/ Oceansat-3 become available.

OilTrack: Tracking of Oil Spill

The focus of this component was to develop a methodology to detect and track the trajectory of hazardous tracers, in this case, the oil spill, and to possibly identify the source of the spill.

Oil-spill detection and oil spill pathways/prediction was attempted under this theme using the state-of-art technique based on advanced Lagrangian coherence structure (LCS) in the North Indian Ocean region. The remote sensing satellite such as SAR was used to detect the instantaneous oil-spills occurring over the oceans. For nowcasting of the oil spill trajectories, technique involving computation of LCS-Cores (Olascoaga and Haller 2012) was used. A numerical model-based approach was also used to compliment the LCS-based nowcasting approach. A 2-dimensional, advective–diffusive model for providing oil spill trajectory nowcasting was developed in-house using the inputs such as currents, winds, waves and tides from numerical models.

One of the case studies taken up in this study was the Chennai oil spill during January 2017. Figure 8 (a) shows the actual clean up area as blue lines, and Fig. 8 (b) shows detected oil spill from SAR as green polygon and the trajectories from advective diffusive model using numerical model forecasts as red lines. In yet another study, Suneel et al. (2019) used remote sensing data, chemical fingerprinting techniques as well as numerical modeling for identifying the amount and sources of oil spill and tar-balls at Easter Arabian Sea. Repeated occurrences of the spills in the SAR data for 2017 were confirmed to be from the oil platforms. Backward trajectory simulations using numerical model as well as chemical fingerprinting analysis and compound specific isotope analysis conform that the source

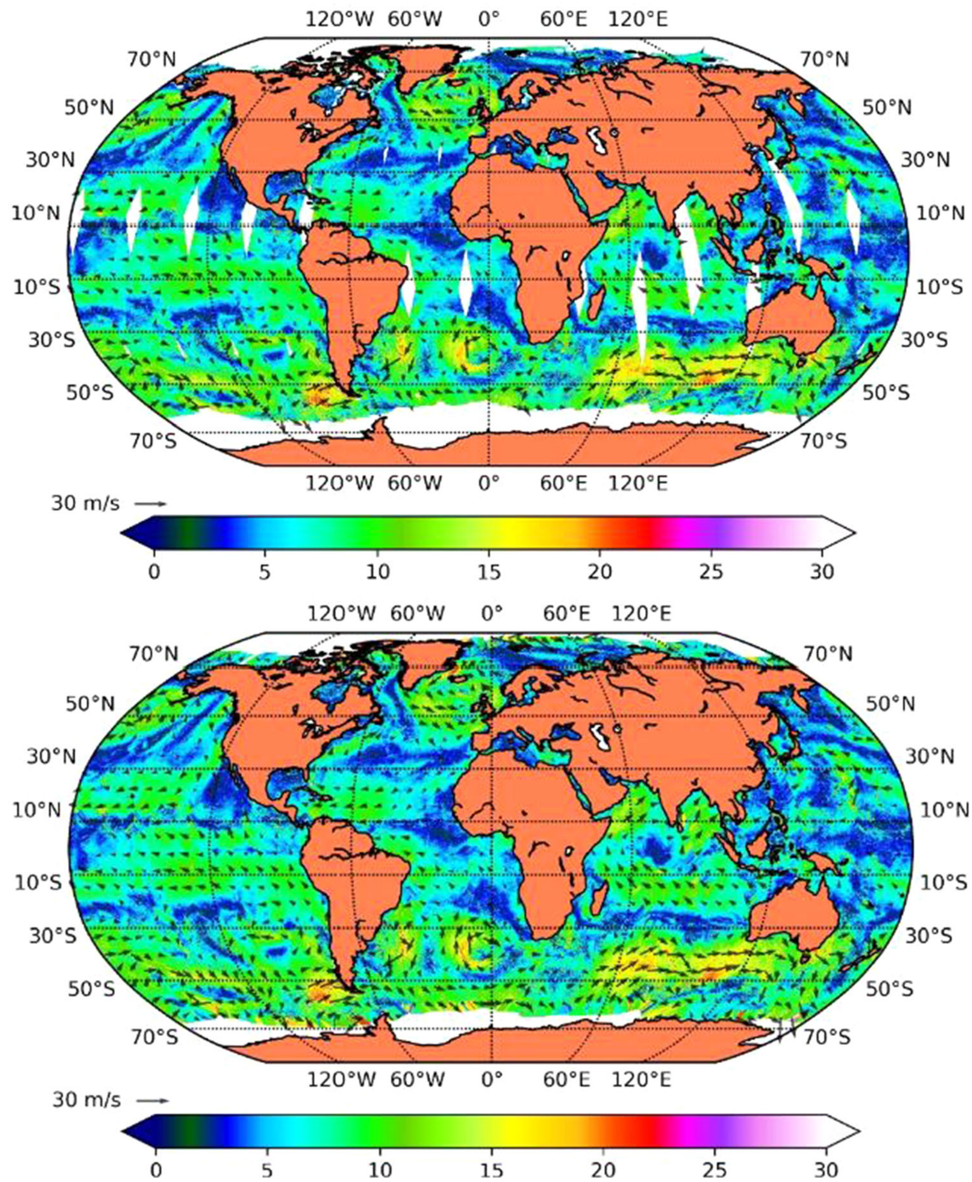

Fig. 6 Scatsat-1 Level-4HW swath winds (in m/s, top panel) and the corresponding analyzed winds (in m/s, bottom panel) on July 29, 2018

of the tar-balls off Goa coast to be of the Bombay High platforms. However, the oil-spills found at the Kutch and the Mangalore coast were found to be caused by ships.

A graphical user interface (GUI) for altimeter-based LCS technique developed for nowcasting of oil spill trajectory is hosted on MOSDAC (Fig. 8(c)).

Ocean Energy from Satellites

The exclusive economic zone (EEZ) surrounding the Indian coastal states is still unexplored in terms of renewable resources. This component has explored the possibility of energy availability along Indian coastal region using space-based microwave radars and its possible validation using in situ measurements.

The study revealed that the combined scatterometer datasets would help in the accurate assessments of wind resource rather than a single scatterometer. Further, considering the available area after exclusions, conflict regions due to shipping, visual and avian exclusions, India have a net power production of 364 GW (3190 TWh/yr) for V112 3 M and 516 GW (4522 TWh/yr) for G128 5 M turbines at 80 m hub height (Surisetty et al. 2020b). Figure 9a shows an illustration of the results of this component. Based on this analysis, offshore wind farm site suitability and assessment has been done along Tamilnadu coastal region by considering many factors such as earthquake prone, shipping conflict, avian, visual exclusion, nearness to the Ports and availability of transmission lines (Surisetty et al. 2019c).

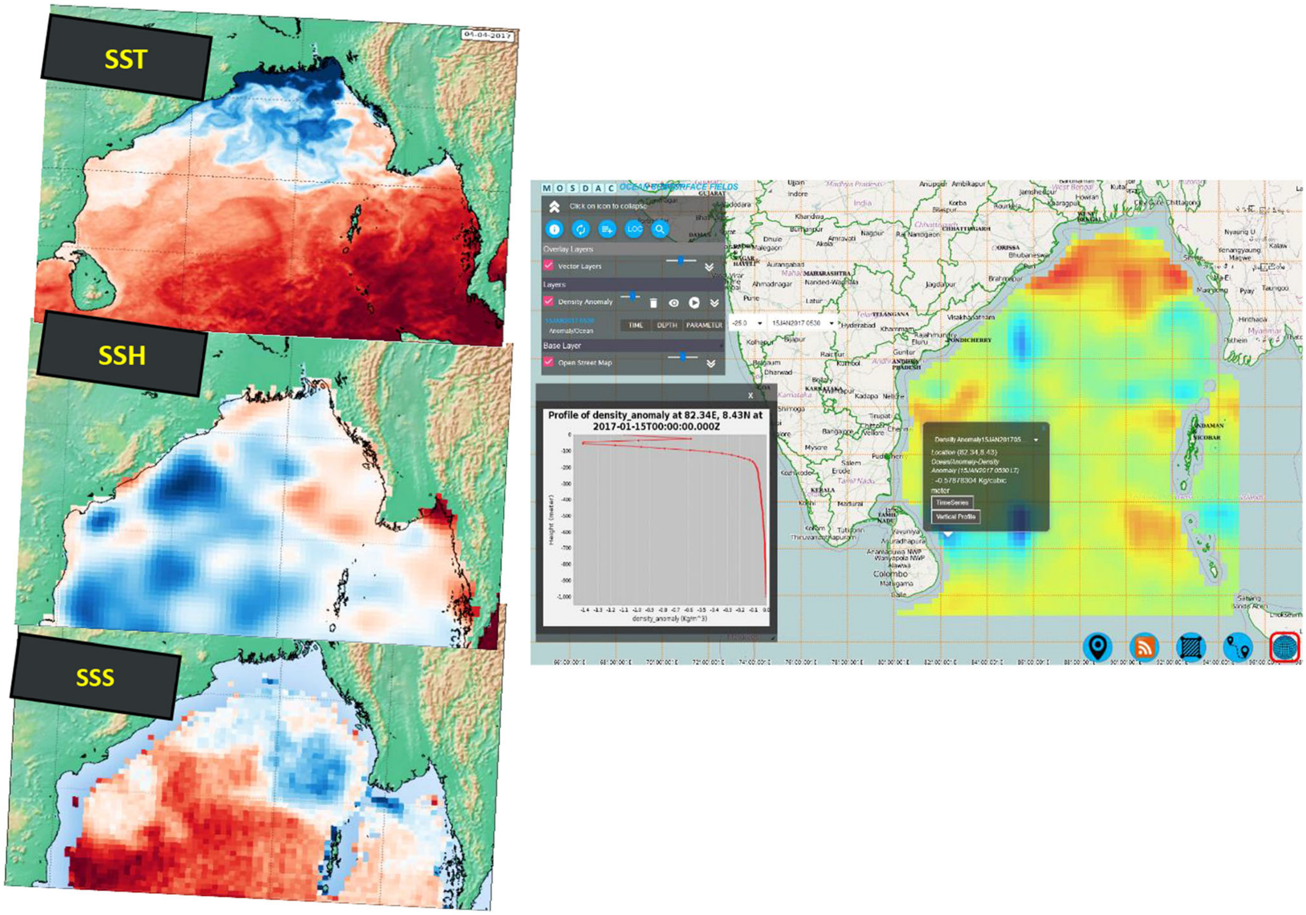

Fig. 7 (Left panels) Satellite derived SST, SSS and SSH used for generating subsurface density and velocity anomaly fields using isQG approach. (Right panel) Sample output of the product hosted on MOSDAC

Wave resource assessment in the Indian exclusive economic zone has been performed using 19 years (2000 to 2018) of wave hindcast by the spectral wave model WAVEWATCH-III. Our study shows the peak mean wave energy flux (9–12 kW/m) is concentrated in the offshore region of the western coast. Monsoon is the most energetic season among all four seasons with maximum potential exceeds 30 kW/m during the month of June, July and August. Four hotspots are identified based on local maxima of OHI value within 100-m-depth region of the eligible area. Economic analysis is performed using available data of four WECs: Wavedragon, Pelamis, Oceantec and Aquabuoy. Oceantec exhibits the lowest LOCE between 346 and 505 €/MWh (Patel et al., 2020). Figure 9b shows an illustration of the results of this component.

Optimization of Model Parameters and Ocean Flux Estimates

This component was purely research and development part for improving the numerical ocean model used in the advanced ocean state analysis/forecast system for carrying out observing system simulation studies toward satellite senor definition studies. The component involved several sensitivity experiments making use of numerical model to fine tune some of the physical parameterizations related to flux computations. Such refinements were carried out in the past as well, however, with the coarser version of the numerical models (Agarwal et al., 2008). With the increase in the model resolution and availability of better parameterization methods for the computation of fluxes in the ocean model, testing and suitable modifications in the updated version were required.

Under this theme, several sensitivity studies of numerical ocean model simulations with regard to changes in the momentum, heat and freshwater flux parameterizations were carried out. The work component included the development and implementation of an alternate, TOGA COARE-based flux formulation in the numerical ocean model and carry out yearlong simulations for inter-comparison of the outputs with the simulations of numerical model having a slightly older bulk formulation. Both the simulations were also compared with the observations. The results were mixed, there was 10–30% improvement in

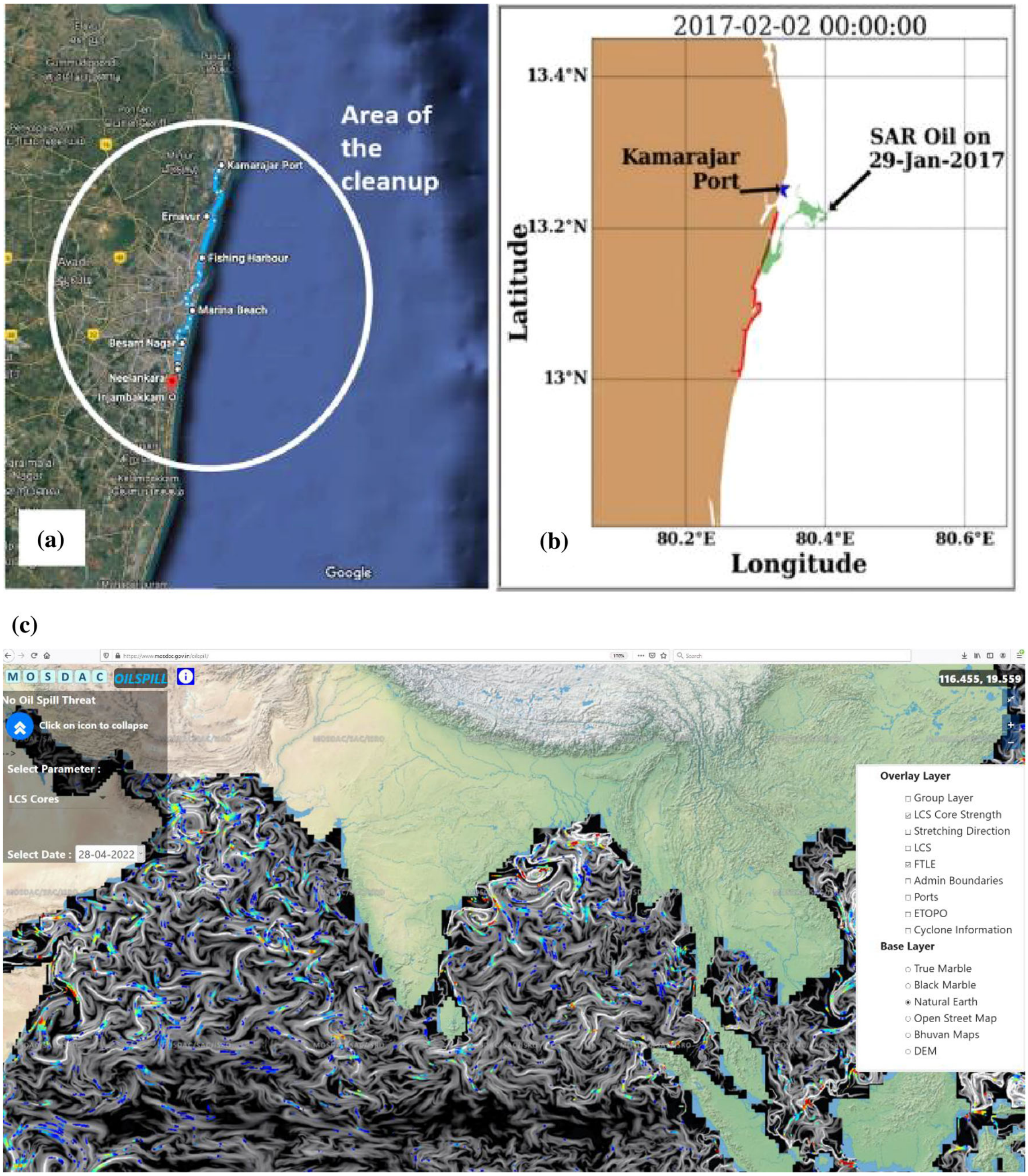

Fig. 8 **a** Blue line showing the cleanup activities as reported by the newspaper. **b** Red color shows beached oil as per our oil spill model simulations Green colored patch is the oil-spill detected by the SAR satellite. **c** Graphical User Interface for providing daily now-cast of the oil-spill trajectories computed from the daily altimeter based currents

many physical parameters such as surface temperature and vertical thermal structure regions in the open ocean, however, there are regions, specifically near the coast, that show deterioration in simulations after using the TOGA COARE flux algorithm. Details of the sensitivity experiments and results are provided in Mallick et al., (2018, 2019 and 2020). Effect of sea surface salinity assimilation in numerical model was also demonstrated under this theme. The assimilation of salinity improved upper ocean stratification in the Bay of Bengal region. Figure 10 (a-l) shows an illustration of the results of this component.

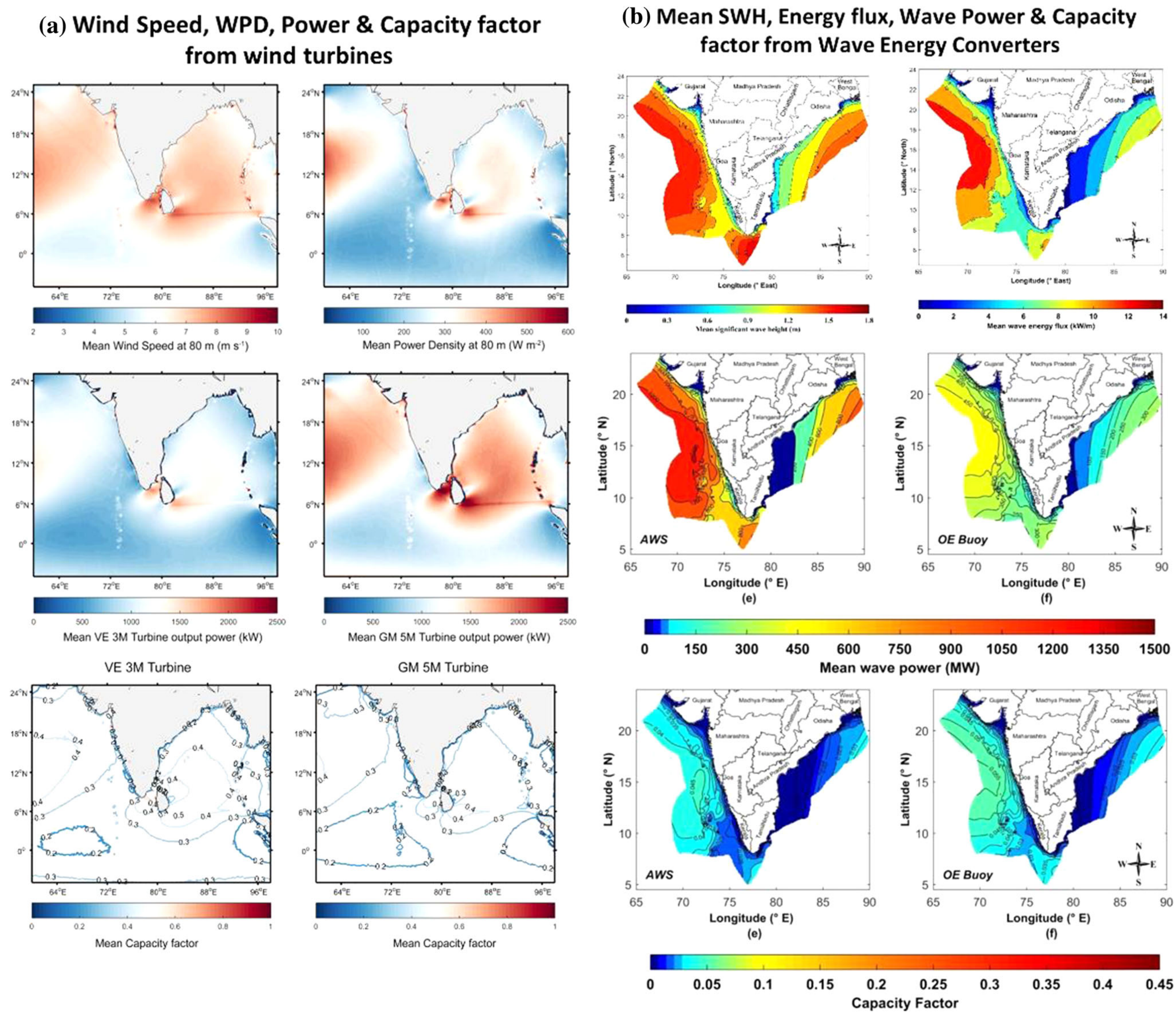

Fig. 9 **a** Wind speed, WPD, Power and Capacity factor from wind turbines as derived from multiple scatterometer data and **b** Mean SWH, Energy flux, wave power and capacity factor from wave energy converters

Major Outcomes, Deliverables and Infrastructure Development

Many applications related to the themes discussed in Sect. 2 were developed and tested for operational use under the program. The ultimate goal of transferring some these developed and demonstrated applications to user agencies for their operational requirements was envisaged. Some of the applications such as high-resolution data assimilative AOSF system development and forecast dissemination through ocean eye web-portal coastal inundation forecast due to storm tide, altimeter-based LCS for oil spill trajectory nowcast, outlook on RIP current for various beaches in India, and wind wave energy estimates are hosted and regularly updated on MOSDAC/VEDAS. In addition to the above operational applications, value-added products generated during the program, such as the high-resolution analyzed wind vector fields and vertical density and velocity anomaly profiles are kept on the MOSDAC server available for use by the scientific community.

One of the major success stories of SAMUDRA was the transferring of technology to the operational agencies. The applications that were transferred to INCOIS included coastal erosion model that was developed and validated, a novel technique for the identification of potential fishing zones, satellite and buoy data assimilation modules for their operational wave forecasting system. The data assimilative advanced ocean state forecasting system was installed at NODPAC for their operational use.

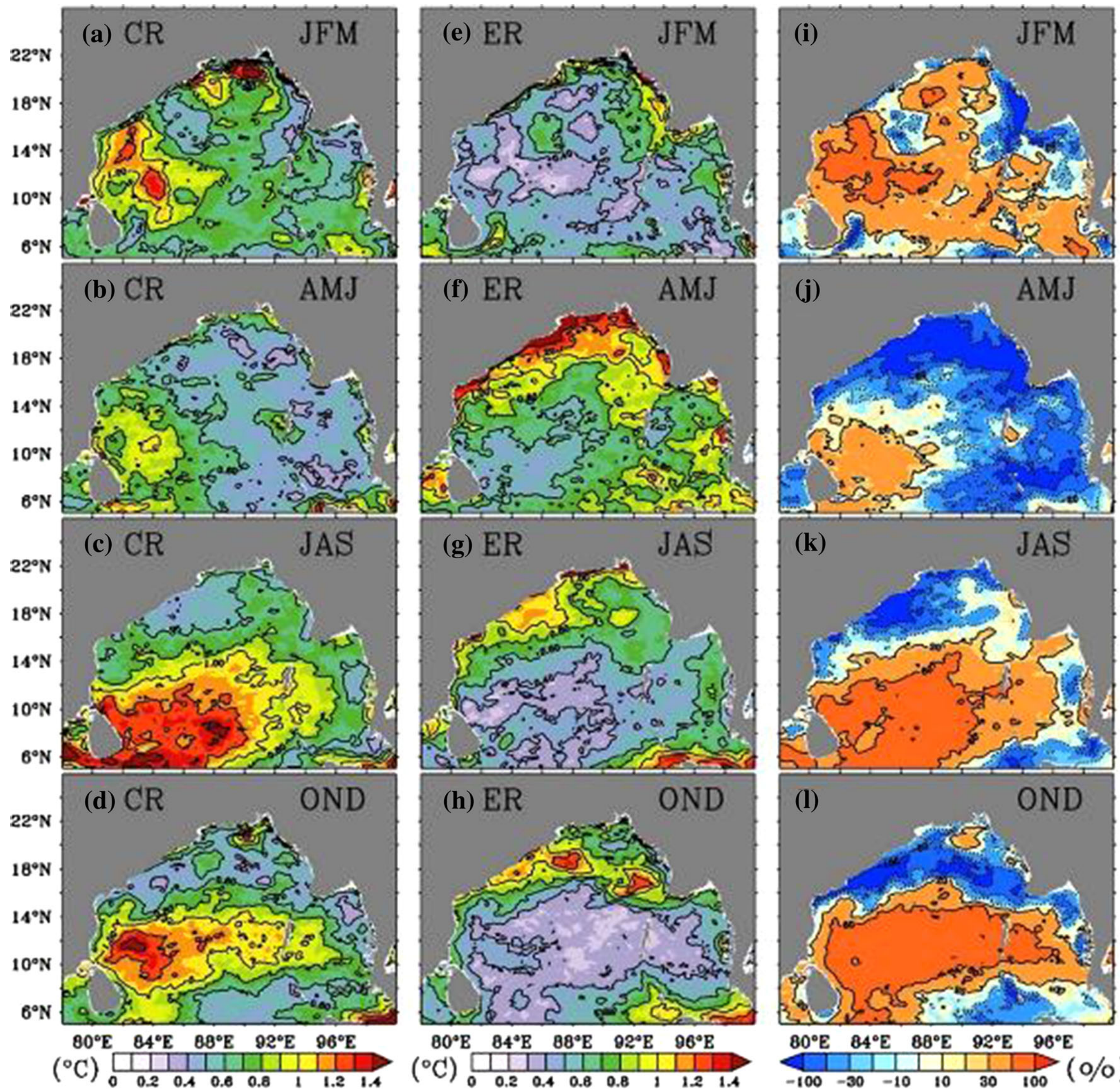

Fig. 10 Seasonal SST error (*C*) plot between the CR **a–e**, ER **e–h** and the percentage of improvement in SST error in the ER over the CR **i**–l for the year 2015

Most applications that were developed under SAMUDRA fitted well under the various components in the blue economy concept of UN laid sustainable development goals (Table 1).

In order to work on various objectives and for collecting observations with the active involvement of various collaborators, instruments such as acoustic Doppler velocity profiler (ADCP), directional wave and tide recorder (DWTR), echo sounder, submersible particle size analyzer and isotope ratio mass spectrometer (IRMS) with elemental analyzer were procured. Apart from the above an IRMS laboratory was developed, mainly to analyze the water samples collected during the various field campaigns.

Future Observational Requirements

One of the major offshoots of SAMUDRA program has been the identification of observational gaps, which will be a very useful input to those who plan and design the future observing systems. Some of the critical challenges due to lack of observations that were experienced while the execution of the project was the availability of reliable coastal observations, high-resolution (both spatial and temporal) fields of coastal currents, chlorophyll, sea level, winds and waves.

Numerical models have improved significantly by constraining them with satellite observations of sea surface temperature, sea surface salinity (SSS), significant wave height and SLA. While sea surface temperature observations are available in abundance from space, there are

Table 1 Components of Blue Economy and related applications developed under SAMUDRA

Components of blue economy		Status under SAMUDRA	Remarks
Harvesting and trade of marine living resources		Developed a novel PFZ identification approach	Technology transferred to INCOIS
Use of renewable non-exhaustible natural forces (wind, wave, and tidal energy)		Hot Spots Energy zones in the Indian Coastal regions identified using Satellite based wind, wave energy. Based on this analysis, the energy availability in these zones has also been quantified	The data base is available on VEDAS
Commerce and trade in and around the oceans	Transport and trade	Satellite data assimilative advanced ocean state forecasting system developed mainly for the Indian Navy and Shipping corporation	Data disseminated through MOSDAC "ocean eye' and email based automatic system Data assimilative modules installed at INCOIS Entire forecasting system installed at NODPAC
	Coastal development	Coastal Erosion model configured Storm surge inundation model developed and operationalised	Coastal Erosion model transferred to INCOIS
	Tourism and recreation	Mechanism for RIP Current forecast developed	Storm surge inundation forecast available through MOSDAC
			RIP Current outlook available on MOSDAC
Indirect contribution to economic activities and environments	Coastal Protection	Oil spill trajectory model developed	Source of tar balls found at Goa beach traced. LCS based oil spill trajectory nowcast available at MOSDAC

several challenges with regard to space-based observations for SSS and SLA. Spatio-temporal resolution of SSS is still inadequate to address the space time variability at smaller scales. A constellation of salinity sensors and continuity with salinity mission is of utmost important. SLA from satellites is available since last three decades, however these are one dimensional observations along the track of the satellite. While these observations from multiple platforms have played a significant role in the advancement of operational oceanography, two-dimensional information of SLA has always been a problem. Upcoming SWOT mission (Marrow et al. 2019), which is due to launch in 2022 is expected to provide a two-dimensional coverage of the dynamical ocean topography at high spatial resolution of 2 km. This along with the currently available nadir altimeters should be able to resolve some of the unsolved mysteries of the ocean, specifically in the Bay of Bengal.

In the case of rip currents that are quasi-permanent in nature and occur at small scales, monitoring through satellites requires very high-resolution cameras with frequent revisit. Presently, none of the high-resolution satellites have diurnal coverage over any beach. Field measurements within rip currents are quite dangerous due to risk of life. GNSS drifters partly help in resolving the rip currents over temporal and spatial scale. However, a greater number of such drifters are required for detailed structure of rips. Apart from that, surf zone bathymetry needs to be surveyed frequently, which is not possible with the present echo sounding technology. Therefore, a shore camera/video-based bathymetry retrieval techniques need to be explored.

The coastal regions are subjected to dynamical changes that affect the bathymetry. Unavailability of updated bathymetry is a major shortcoming with respect to numerical simulation of coastal processes. Accurate estimation of sediment concentration from satellite images along the coastal region is still challenging owing to the optical complexity in the coastal waters. Space borne hyperspectral remote sensing observations and a robust algorithm are the need to overcome the concerns in the estimation of satellite derived suspended sediment concentrations. In the coastal region, sediment dynamics are highly influenced by the tides and the present space born observations in the polar orbits are insufficient to resolve the sediment dynamics driven by the varying tidal currents. Satellite observations from geosynchronous platform with high temporal resolution will have the ability to resolve the tidal dynamics.

The major challenge that remain till date over the Indian Ocean Region is the availability of continuous high-resolution observations of chlorophyll concentration, which are crucial for PFZ identification. Cloud contamination is the biggest hindrance in maintaining the continuity. High repeat coverage of the region by means of sensors mounted over the geostationary platform (such as GOCI) would help in providing cloud free images several times during the day (Agarwal et al., 2019).

Sea surface wind observations available from Ku band microwave radiometer (like Scatsat) are prone to large uncertainties in the low wind conditions. While for high winds, C band scatterometers are available and their continuity must be ensured, for low winds, high-frequency scatterometers (Ka band) may be explored. Temporal frequency of the winds from space must also be increased so that the diurnal variability may be captured.

Summary and Way Forward

SAMUDRA TDP was taken up to demonstrate applications utilizing satellite data, ground-based observations along with numerical models for coastal vulnerability, PFZ, advanced ocean state forecast, satellite-based ocean analysis and ocean-based energy mainly in the Bay of Bengal region. The idea was in line with ISRO's vision of use of space technology for the benefit of the common man. Most of the objectives were successfully achieved within the project period of 4 years. Under this program, many applications were demonstrated and subsequently transferred to the user agencies for operational purpose. Some of the developed and tested applications are also hosted on MOSDAC and are catering to the user requirements. Ocean eye, storm surge-induced coastal inundation prediction, Rip current warning system, oil spill trajectory nowcasting, PFZ identification and monitoring system, generation of high resolution analyzed wind vector and identification of ocean energy hot spot regions and their techno-economic feasibility analysis were some of the major achievements that were made under this program. Apart from these many other applications were developed, demonstrated and operationalized in order to be used by various user agencies and stake holders.

Contribution made by collaborating agencies in the success of SAMUDRA program needs special mention. They helped in accomplishing various components of the proposed objectives, in particular, taking field measurements, which were necessary for building, testing and validation of the developed algorithms.

SAMUDRA TDP was a feasibility study, a subset of the bigger SAMUDRA program, which was envisaged. In the next phase of SAMUDRA, new avenues will be pursued as a natural extension of SAMUDRA-TDP in which the scope and domain will be further expanded. Future research will also focus toward the utilization of ISROs upcoming missions such as Oceansat-3, which will have ocean color monitor, sea surface temperature monitor (SSTM) and a scatterometer, INSAT future generation satellites, NISAR. Some of the objectives that will be targeted during the next phase of SAMUDRA are related to future oceanographic sensor definition, continuing with the generation of value-added products, very high-resolution data assimilative, relocatable grid modeling for region/event specific, and monitoring the marine litter and their pathways using satellite and numerical models. Focus will also be toward monitoring and analyzing regional climate change trends from satellite observations.

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Declarations

Conflict of interest "The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper."

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