# Operational oceanographic services for the growth of blue economy in India

**T. Srinivasa Kumar* and P. A. Francis**

Indian National Centre for Ocean Information Services, Hyderabad 500 090, India

**Advisories and forecasts of ocean state, circulation, warnings on marine hazards, and information on living and non-living resources are essential for safe operations and increased productivity in the marine environment. These contribute to the growth of blue economy in India. For the past several years, the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad has been providing services such as ocean state forecasts, potential fishing zone advisories, marine hazard warnings and operation-specific advisories/forecasts/ information to the stakeholders. The economic benefits of these services are found to be substantial. This article outlines the major services provided by INCOIS which support the blue economy sectors in India.**

**Keywords:** Blue economy, marine hazard early warning services, ocean state forecast, operational oceanography, potential fishing zone advisories.

## Introduction

TRADITIONALLY, the dependence of humans on the oceans is mainly for food and the transportation of goods. As the excessive use of energy from non-renewable sources led to catastrophic impacts on the Earth's climate and resources on the land started depleting at a faster rate, our dependence on the oceans for clean energy and resources started increasing. Several countries with access to maritime resources are now nurturing blue economy (BE) to boost their economic growth[1]. As more than 40% of Earth's population lives along the coastal regions and their life is linked to the oceans in one way or another, the growth in BE essentially has direct implications on the socio-economic well-being of these communities. While oceans are expected to play a critical role in economic growth, any adverse impact on the coastal regions due to marine hazards and climate change is a challenge with far-reaching implications that cannot be ignored.

India has a unique maritime position with its ~7500 km long coastline home to nine coastal states and 1382 islands. About 30% of the country's population lives in the coastal regions. There are 18 major ports and about 200 minor ports which handle about 95% of India's trade by volume. The country's exclusive economic zone (EEZ) of over 2 million km$^2$ is rich in living and non-living resources. Fisheries is one of the major livelihoods of millions in India. Yet, the share of the maritime sector is estimated to be only around 4% of the country's GDP (https://incois.gov.in/documents/Blue_Economy_policy.pdf). To ensure that the contribution of BE to total GDP increases many-fold, the Government of India (GoI) has recently outlined the Blue Economy Policy (https://incois.gov.in/documents/Blue_Economy_policy.pdf).

Major thrust areas identified in India's BE Policy are (a) energy, (b) food, (c) tourism, (d) transport, (e) resources, (f) freshwater and (g) strategy. All these sectors, which operate mainly in the coastal and high seas, require accurate and timely predictions/projections of ocean parameters, both physical and of the ecosystem, in different timescales ranging from a few days to a few decades. These predictions are essential for making policies, planning, infrastructure development and operational facilities. The forecasts are required not only to ensure safe operations in the sea, but also to optimize the resources required for operations and hence maximize the revenue. Worldwide, operational oceanography centres support these activities by providing the required services based on systematic ocean observations and numerical ocean models equipped with data assimilation capabilities[2]. The major operational oceanographic systems in the world are Mercator Ocean International (MOi) of Copernicus Marine Environment Monitoring Service (CMEMS); Real Time Ocean Forecast System (RTOFS) of the National Oceanographic and Atmospheric Administration (NOAA), USA; Ocean Model, Analysis and Prediction System (OceanMAPS) of Australia and Forecast Ocean Assimilation Model (FOAM) of the UK MetOffice. All these systems which are based on numerical ocean circulation models assimilate *in situ* and remote sensing data into the numerical models and provide ocean analysis as well as short-term forecasts of the ocean parameters. In India, Indian National Centre for Ocean Information Services (INCOIS), Hyderabad, provides ocean analysis and operational forecasts of several ocean state and circulation parameters 5–10 days in advance every day. In addition, it also plays a pivotal role in national and regional maritime disaster mitigation activities by providing timely and accurate advisories and warnings on several oceanogenic hazards such as tsunamis, storm surges, wave surges, etc. to the stakeholders. INCOIS's Ocean State Forecast (OSF) and marine hazard advisories are strongly supported by focused research

*For correspondence. (e-mail: srinivas@incois.gov.in)

in ocean modelling, data assimilation and ocean observations, and are continuously verified using both *in situ* and remote sensing data. The operational oceanographic services generated by INCOIS are provided to many countries in the Indian Ocean Rim through bilateral and multilateral platforms. The services provided by INCOIS to support the BE sectors and the research and development efforts to support these services are discussed briefly in this article.

## Operational oceanographic services provided by INCOIS

Presently, the most important BE sectors in India are the marine fisheries and shipping industries. The requirements of these sectors can be broadly divided into operational and safety-related. While the former requirement is unique to each sector, the safety aspects in marine operations are common across all sectors. For example, while the operational requirement of the marine fisheries sector is advisories on the possible locations for fish aggregation, that for the shipping and offshore industries is the information on surface/subsurface currents, winds, waves, tides, etc. In addition, both sectors require accurate predictions of sea state and predictions of marine hazards like cyclones, tsunamis, etc. for safe operations. The recent accident in the Bombay High region during the passage of cyclone Tautae in June 2021, which claimed the lives of several people, underlines the urgency to have a fool-proof forecast system while aspiring to enhance the BE-related activities. In addition, to ensure that engagement with the oceans for the socio-economic well-being is sustainable, it is necessary to protect the marine ecosystem from exploitation and pollution. With the growing economic interests, it is also important to ensure that 'maritime security' and 'blue diplomacy' are supported with adequate information.

The operational oceanographic services provided by INCOIS to cater to the diverse needs of stakeholders can be broadly categorized as: (i) ocean state forecast services, (ii) marine fisheries advisory services, and (iii) early warning services. The economic implications of these services are found to be substantial[3]. Some details of these services provided by INCOIS are briefly discussed below. All of them support various sectors of the blue economy in one way or the other.

### *Ocean state forecasts*

Oceans are rich in resources and opportunities, but the working environment is challenging and could become hostile at times when the sea gets rough. Hence, to protect life and property, during operations at sea, accurate and timely forecasts of the sea state are important. INCOIS addresses this by providing operational forecasts of winds, waves, tides, currents, etc. with lead times of up to 7 days for the entire Indian Ocean region[4–8] (Figure 1). In addition to these general forecasts, customized forecasts for specific users such as ports and harbours, maritime boards, Indian Coast Guard (ICG), boats/ships, offshore industries, Indian Navy, etc. are also provided. It is estimated that the economic benefit of OSF services could be Rs 25,800 crores for a period of 25 years[9], which is a substantial contribution to the economic growth of the country.

The specialized services provided for ports and harbours, and maritime boards include inland vessel limits (IVLs) essential to determine how far the smaller vessels/boats can go and transfer the cargo on-board large ships safely. This information is derived from the climatology of the wind–wave characteristics together with the local forecasts of the ocean state. In addition, such information also helps in limiting the extent of small vessels at the sea for various operations. The masters of the vessels can access the ocean state forecasts in real time along the ship routes from the INCOIS website (https://sarat.incois.gov.in/shipforecast/Login.jsp) and alter the ship's speed and bearing, if necessary. In addition, ocean state forecasts are also available for the standard waypoints along standard shipping routes such as Chennai – Port Blair and Kolkata – Port Blair.

Considering that several small boats of varying size and class operate in the Indian waters and often get toppled or sunk in the sea during rough wave/weather conditions, INCOIS has devised an impact-based forecast service called 'Small Vessel Advisory Services System' (SVAS)[10]. This service provides the 'Boat Safety Index (BSI)', which indicates whether the particular boat is safe during the prevailing or forecasted wave conditions. BSI is derived based on the beam size, category of the vessel, significant wave height, wave steepness, directional spread and rapid changes in the sea state[10]. This service is particularly useful for small fishing boats and country craft (Figure 2).

Oil spills are a threat to the marine environment. The spill, once occurred, moves under the action of wind and surface currents. It often beaches and affect the flora and fauna in the marine ecosystem[11]. The oil spills also adversely affect fishery in an area and the livelihood of fishermen. Most oil spills in the Indian seas are due to accidents involving ships or due to bilge wash, which is a clear violation of maritime law. ICG, the agency designated to monitor and contain oil spills in the Indian seas, requires accurate forecasts on the movement of these spills to minimize their adverse impacts. INCOIS has set up an on-line Oil Spill Advisory Service (OOSA) to support the requirement of ICG by predicting the trajectory of oil spills and the percentage quantum of oil carried along as the spill moves from its original location[12]. This helps ICG track the oil spill movement and take necessary action/s for its clean-up and mitigation (Figure 2).

INCOIS also provides a specialized service called Search and Rescue Aid Tool (SARAT), to aid search operations at sea. The vastness of the oceans and the constant movement of persons/objects fallen in the water due to ocean

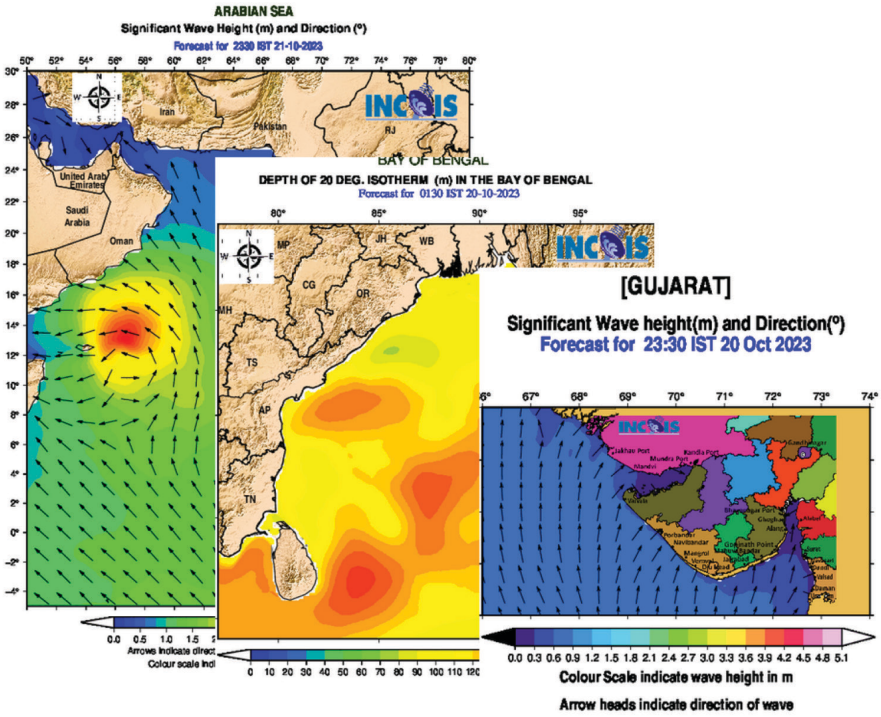


**Figure 1.** Depiction of various ocean state forecasts provided by INCOIS to the public on 20 October 2023.

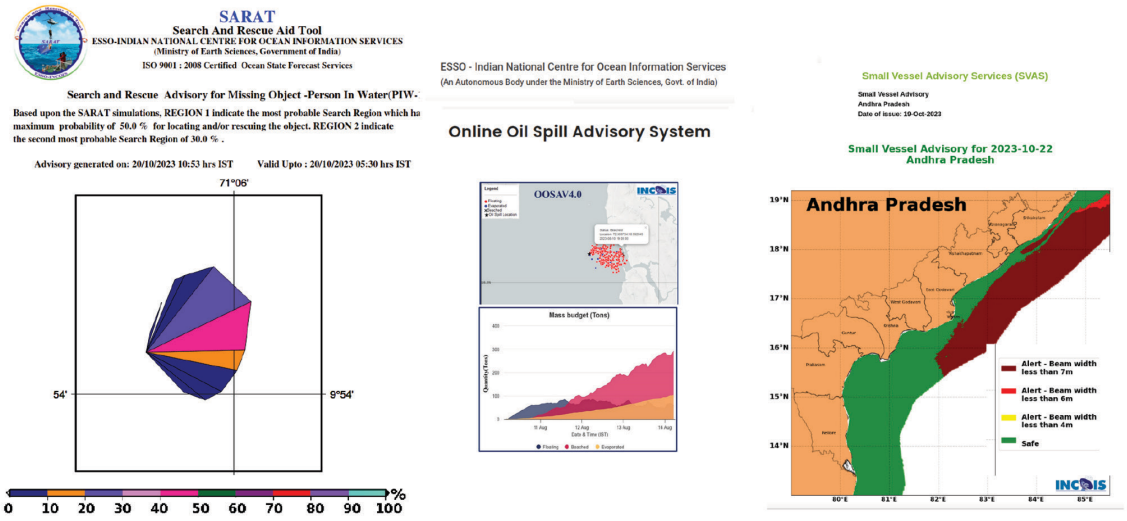


**Figure 2.** Images depicting the specialized advisories. (Left) Search and Rescue advisory, (middle) oil spill advisory and (right) small vessel advisory.

currents and winds make it difficult to locate and rescue/retrieve them under adverse weather and sea state. SARAT makes use of forecasted winds and currents at the location and its surroundings, and narrows down the search area by calculating millions of probable movements of particles using a Monte-Carlo model[5]. The probabilistic distribution, represented on a map, identifies a cone of the search area where the missing person/object could drift due to the action of wind and current (Figure 2). This is extremely useful as it reduces the search area considerably. However, the accuracy of the cone depends on the accuracy of position and time of the person/object fallen in the water.

### *Marine fisheries forecast service*

Fisheries is one of the most important sources of income for many families living along the coast of India. It is estimated that there are around 4 million fishers and one million active fishermen in the country. The marine fishery sector is poised to expand significantly and boost the BE

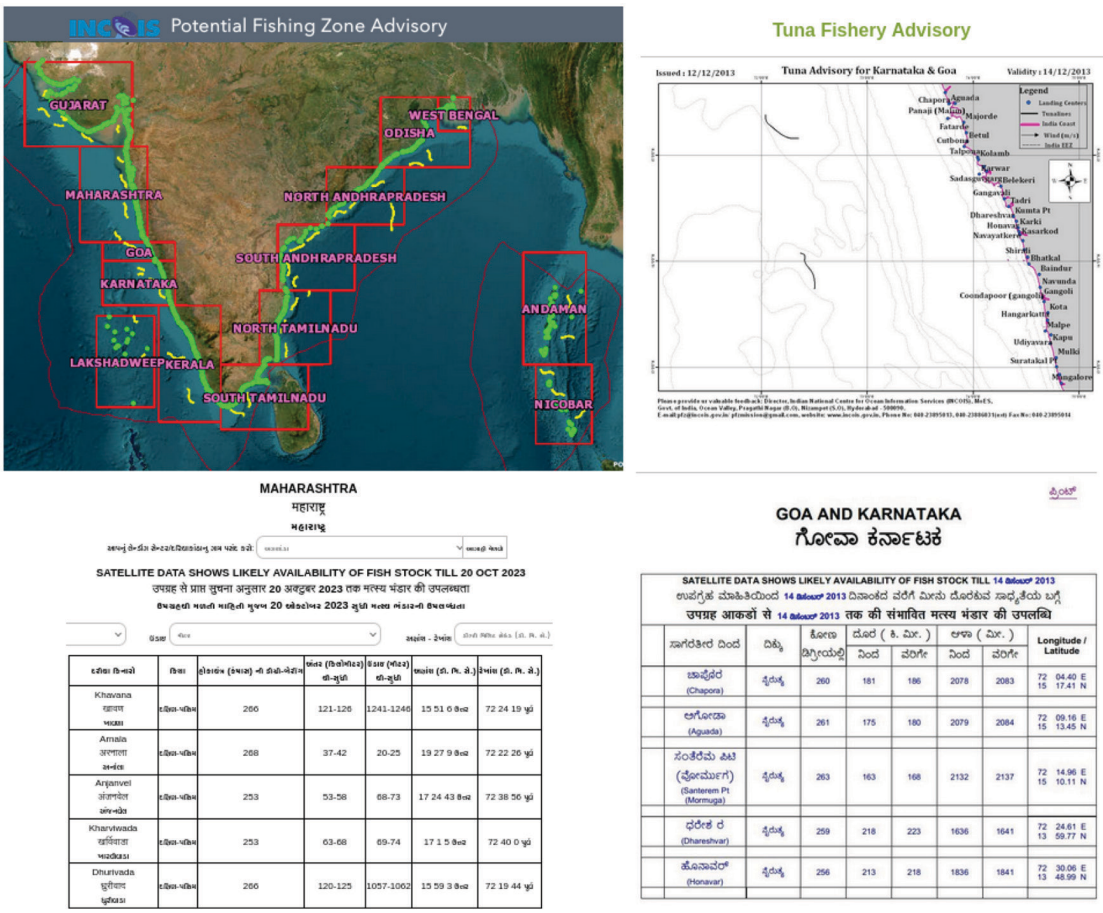


**Figure 3.** Sample advisories on potential fishing zone (left) and tuna PFZ (right).

of India. INCOIS has been supporting the fisheries sector by providing the PFZ advisory services for the past several years[13]. The sea surface temperature (SST) gradients and chlorophyll concentration, measured by remote sensing satellites, are used to prepare the PFZ advisories[14]. The underlying principle is that the frontal regions with sharp gradients in SST and high chlorophyll concentration could be the preferred habitats of fish[15]. The data on SST and chlorophyll concentration, retrieved regularly from the thermal-infrared channels of NOAA-AVHRR and Eumetsat's Met-Op series satellites along with optical bands of Oceansat-II and MODIS Aqua satellites, are used for the identification of PFZ. At present, the PFZ advisories are provided to all the major fish landing centres India in map and text form in local languages (Figure 3), and to individual fishermen via SMS and mobile-based apps. The advisories are valid for three days. The PFZ advisories are not provided during the fishing ban periods and on the days of adverse sea state to ensure that the resources are not extracted unsustainably and the fishing operations are not done under unsafe sea conditions. INCOIS also provides advisories on the occurrences of harmful algal blooms (HABs), which can adversely affect marine fisheries. The presence of HABs is detected using ocean colour remote sensing[16] and their movement pathways are predicted based on the environmental conditions.

INCOIS also provides an advisory on the availability of tuna, which has a high commercial value. The habitat preferences of yellowfin tuna were studied using data collected by tagging them with sensors that can record temperature, water clarity and position[17]. Yellowfin tuna were caught unharmed and pop-up satellite archival tags were attached to record the environmental parameters as they moved preferentially. Based on the understanding gained through this study, daily tuna advisories are being prepared using satellite observations of SST, chlorophyll and water clarity, and disseminated to the fishermen using different modes of communication. Similar research efforts are also being made to develop species-specific advisories for other commercially important fishes such as hilsa and oil sardine.

According to a recent survey by the National Council for Applied Economic Research (NCAER), additional income for the fishers due to the use of the PFZ service could be as much as Rs 3,000 crores annully[9]. Also, for every litre of diesel saved by the fishermen due to the use of PFZ advisories (reduction in the search time), there could be a reduction of about 2.63 kg of carbon dioxide. Hence this service also has large positive environmental implications.

The reduction of $CO_2$ can be turned into carbon credits, which can be traded internationally. The estimated carbon credit per year due to PFZ advisories is ~Rs 36,200 crores (ref. 9).

### *Early warning services*

While the OSF services provided by INCIOS give general outlooks on the sea state conditions, specific early warnings on impending oceanogenic hazards issued by it are extremely important for the safety of millions who live along the coastal regions of India. Hence, these early warning services are essential for the sustained growth of the BE sectors. After the devastating Indian Ocean tsunami on 26 December 2004, INCOIS set up the National Tsunami and Storm Surge Early Warning Centre, which was later recognized as the Regional Tsunami Service Provider for the Indian Ocean Rim countries by the IOC-UNESCO[18]. At present, the Indian Tsunami Early Warning Centre (ITEWC) is issuing warnings within 15 min following the occurrence of tsunamigenic earthquake in the Indian Ocean. The service provided by ITEWC is known for its accuracy and the absence of false alarms[18]. As the occurrence of tsunamis is rare in the Indian Ocean, INCOIS ensures that the communication channels to disseminate the warnings are always kept alive by conducting periodic communication tests. Also, the coastal communities, including the public and disaster response authorities, are kept ready through periodic tsunami mock drills. INCOIS, in association with the Odisha State Disaster Management Authority, has taken up the 'Tsunami Ready' programme of the IOC, which envisages complete preparedness of the coastal communities to respond fast to tsunami warnings.

Tropical cyclones and the associated storm surges are frequent on the Indian coastline compared to tsunamis. Hence, INCOIS also provides predictions on storm surges and high waves associated with tropical cyclones to the public through cyclone warning bulletins issued by India Meteorological Department. The storm surge warnings provided by INCOIS are found to be useful in mitigating coastal inundation during tropical cyclones[19]. In addition, the swells (long period waves >10–15 min) which originate in the Southern Ocean due to low-pressure systems or cyclones arrive at the Indian coast, particularly the southwest coast, and inundate the low-lying areas[20–22]. These unexpected high waves and associated inundations create unexpected flooding and damage in the coastal regions. INCOIS has devised a swell surge prediction system to forewarn the public of the possibility of such swell surges well in advance.

The accurate and timely early warnings and advisories on the hazards of marine origin provided by INCOIS have immense socio-economic benefits, though it is difficult to make quantitative estimates. These early warnings save precious lives and livelihood of several affected people. Also, these advisories with a proven track record of 'no-false alarm', help the authorities to avoid unnecessary evacuations and the associated expenditure. For example, considering the expenditure of Rs 3500 crores incurred for the evacuation and relocation of people affected due to cyclone Phailin in 2013 on the coast of Odisha, NCAER estimated that the cumulative economic benefits of the 23 'no tsunami threat' messages issued by INCOIS for the period 2007–14 would amount to Rs 80,500 crores[9]. In addition to the tsunami early warnings, advisories provided by INCOIS on high waves, swells, storm surges, perigean, tides, etc. also have large economic implications as their occurrences often damage the livelihood of fishermen.

## R&D activities to support the operational oceanographic services

Numerical ocean models and ocean observation networks are the two pillars of operational oceanographic services. While the ocean models forecast evolving oceanographic parameters, ocean observations provide the required data to generate the advisories, validate the numerical models, verify the predictions, prepare the required error statistics, and assimilate in the numerical models for correcting errors in the initial conditions of the numerical models. The backend of INCOIS operational ocean forecast services are High-resolution Operational Ocean Forecast and reanalysis System (HOOFS)[5] and Indian Ocean Forecast System[4]. HOOFS is based on the Regional Ocean Modelling System (ROMS 3.6), which is configured at two horizontal resolutions – 1/12 degree for the entire Indian Ocean (IO-HOOFS) and 1/48 degree for the northern Indian Ocean (NIO-HOOFS). Temperature and salinity profiles measured by Argo floats and moored buoy network, as well as satellite-observed SST and sea surface height (SSH), are assimilated in HOOFS using a Local Ensemble Kalman Filter (LETKF)-based data assimilation system. INCOIS-Global Ocean Data Assimilation System (INCOIS-GODAS), based on the Modular Ocean Model (MOM4) with 3D-VAR data assimilation system is used for preparing the global ocean analysis[23]. GODAS provides lateral boundary conditions for IO-HOOFS, which in turn provides lateral boundary conditions for NIO-HOOFS. The global to regional wind–wave forecasts are generated using a multi-grid Wavewatch-III model, which progressively increases horizontal resolution from global (1 degree) to the northern Indian Ocean (~4 km). The Wavewatch III model assimilates satellite observations of significant wave height to reduce errors in the initial conditions[24]. The Tunami N2 model has been configured for generating scenarios of tsunami wave propagation for different combinations of source characteristics. These scenarios are used in early warning decision support system[18]. The storm surge and associated inundation warnings are generated using the ADCIRC model[19].

INCOIS maintains a network of ocean observation platforms to support its operational activities[25] (Figure 4). Argo floats, tide gauges, wave rider buoys, GNSS network, bottom

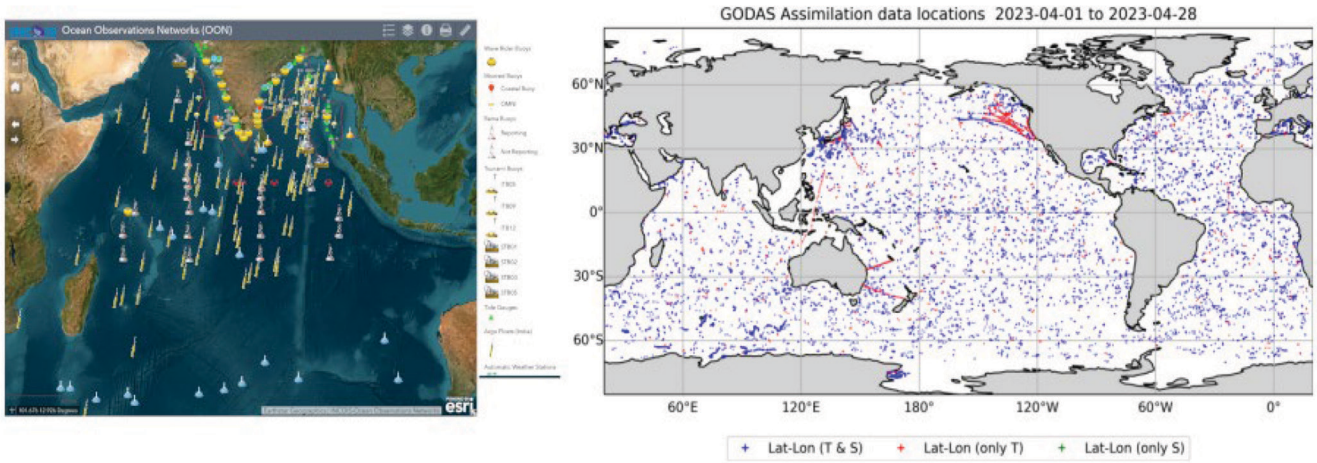


**Figure 4.** (Left) Ocean observation network in the Indian Ocean as of 20 October 2023. (Right) Locations of temperature and salinity profile data assimilated into the INCOIS-Global Ocean Data Assimilation System during 1–28 April 2023.

pressure recorders, surface drifters, ship-mounted AWS network and coastal water quality observation buoys deployed and maintained by INCOIS, coastal Acoustic Doppler Current Profilers (ADCPs) deploy and maintained by the National Institute of Oceanography, Goa, and the moored buoy network maintained by National Institute of Ocean Technology (NIOT), Chennai and PMEL/NOAA (RAMA network) are the most important sources of *in situ* ocean observations for data assimilation, verification and validation of operational forecasts and warnings issued by the INCOIS. In addition, satellite observations of SST and ocean colour are also being received and processed at the INCOIS ground station for operational uses. As INCOIS is the National Ocean Data Centre (NODC), all *in situ* and remote sensing data received by it are quality-controlled and archived. In addition, the oceanographic data collected by all centres of Ministry of Earth Sciences, GoI, are also archived and distributed by INCOIS.

## Future plans of INCOIS to support the blue economy sectors

Most of the users of operational services of INCOIS such as fisheries, shipping, oil exploration industries, etc. operate in shallow waters (<100 m) in the coastal waters. The most important requirement of such users is an accurate, timely and highly localized prediction of coastal currents, waves and tides at timescales of 5–7 days. The present accuracy level of operational ocean predictions in such a short time- and spacescales is not enough to meet the requirements of the users. A major difficulty in improving the accuracy of the short-term forecasts of coastal currents is the lack of understanding of the processes involved in the short-term variation of the coastal currents and their driving mechanism, and the inability of numerical models to predict them. Hence, it is important to gain deep insights into such processes to improve the quality of models used for the predictions. INCOIS has now taken up this research on a priority basis.

The contributions of marine tourism, energy, freshwater and non-living resource sectors to BE are now increasing rapidly. Further, the existing major BE sectors such as transport and fisheries are also growing at a faster pace. With such expansion of BE activities and in the changing climate scenario, the operational ocean service providers will have to gear up to meet the growing and emerging requirements of the industry. For example, it is expected that the energy sector will look for renewable energy sources such as waves, currents and tides, and suitable sites to establish wind and solar power plants in the coastal waters to harness uninterrupted energy. Such activities will demand more accurate predictions and projections of ocean conditions in different time- and spacescales. The growing tourism sector will demand predictions of water quality on the beaches to ensure suitability for recreation. Predictions of rip currents, surf zones, etc. are the other requirements of this sector. Specific forecasts and advisories on habitat suitability for marine capture fisheries will be a requirement in the future. Long-term projections on the rising sea-level, identification of coastal regions which can get inundated due to sea-level rise, long-term changes in the occurrence of hazards of marine origin in the climate change scenario are also important for making policies on coastal zone management and planning the coastal infrastructure. INCOIS envisages expanding the operational oceanographic services by taking these factors into account. Development of a unified ocean modelling system, projections of changes in sea level and extreme waves and storm surges, establishment of an optimal ocean observation network and water quality monitoring systems and developing impact-based ocean forecast and advisory services are some of the initiatives towards achieving these goals.

## Summary

Supporting safe operations in the marine environment with sustainable practices is the primary responsibility of operational oceanography centres such as INCOIS. OSF, PFZ advisory services and early warning services are the three flagship programmes of INCOIS that support the blue economy sectors directly. The economic benefits of INCOIS forecast and advisory services are estimated to be Rs 23,800 crores for 25 years[4]. The economic benefits of INCOIS services will increase multifold when they are expanded to other sectors of the blue economy in future. INCOIS is now gearing up to cater to the growing requirements of the industry, public and policy makers in the backdrop of climate change.

1. Martínez-Vázquez, R. M., Milán-García, J. and de Pablo Valenciano, J., Challenges of the blue economy: evidence and research trends. *Environ. Sci. Eur.*, 2021, **33**, 61; https://doi.org/10.1186/s12302-021-00502-1.
2. Tonani, M. *et al.*, Status and future of global and regional ocean prediction systems. *J. Oper. Oceanogr.*, 2015, **8**, 201–220; doi:10.1080/1755876X.2015.1049892.
3. Balakrishnan Nair, T. M. *et al.*, Advances in ocean state forecasting and marine fishery advisory services for the Indian Ocean Region. In *Social and Economic Impact of Earth Sciences* (ed. Gahalaut, V. K. and Rajeevan, M.), Springer, Singapore, 2022; https://doi.org/10.1007/978-981-19-6929-4_11.
4. Balakrishnan Nair, T. M. *et al.*, Performance of the ocean state forecast system at Indian National Centre for Ocean Information Services. *Curr. Sci*., 2013, **105**(2), 175–181.
5. Francis, P. A., Vinayachandran, P. N. and Shenoi, S. S. C., The Indian Ocean Forecast System. *Curr. Sci.*, 2013, **104**(10), 1354–1368.
6. Sandhya, K. G., Balakrishnan Nair, T. M., Bhaskaran, P. K., Sabique, L., Arun, N. and Jeykumar, K., Wave forecasting system for operational use and its validation at coastal Puducherry, east coast of India. *Ocean. Eng*., 2014, **80**, 64–72
7. Francis, P. A. *et al*., High-resolution operational ocean forecast and reanalysis system for the Indian Ocean. *Bull. Am. Meteorol. Soc*., 2020, **101**(8), E1340–E1356; https://doi.org/10.1175/BAMS-D-19-0083.1.
8. Remya, P. G., Rabi Ranjan, T., Sirisha, P., Harikumar, R. and Balakrishnan Nair, T. M., Indian Ocean wave forecasting system for wind waves: development and its validation. *J. Oper. Oceanogr.*, 2022, **15**(1), 1–16; doi:10.1080/1755876X.2020.177181.
9. National Council for Applied Economic Research Report, economic benefits of dynamic weather and ocean information and advisory services in India and cost and pricing of customized products and services of ESSO-NCMRWF and ESSO-INCOIS, NCAER, New Delhi, 2015, p. 137.
10. Aditya, N. D., Sandhya, K. G., Harikumar, R. and Balakrishnan Nair, T. M., Development of small vessel advisory and forecast services system for safe navigation and operations at sea. *J. Oper. Oceanogr.*, 2022, **15**(1), 52–67; doi:10.1080/1755876X.2020.1846267.
11. Guzman, H. M., Kaiser, S. and Weil, E., Assessing the long-term effects of a catastrophic oil spill on sub tidal coral reef communities off the Caribbean coast of Panama (1985–2017). *Mar. Biodivers.*, 2020, **50**, 28; https://doi.org/10.1007/s12526-020-01057-9.
12. Prasad, S. J. *et al.*, Simulating the spatial and temporal distribution of oil spill over the coral reef environs along the southeast coast of Mauritius: a case study on *MV Wakashio* vessel wreckage, August 2020. *J. Earth. Syst. Sci.*, 2022, **131**, 42; https://doi.org/10.1007/s12040-021-01791-z.
13. Nayak, S., Kumar, T. S. and Kumar, M. N., Satellite based fishery service in India. Full Picture, 2007, pp. 256–257.
14. Solanki, H. U., Dwivedi, R. M. Nayakm S. R., Naik, S. K., John, M. E. and Somvanshi, V. S., Application of remotely sensed closely coupled biological and physical processes for marine fishery resources exploration. *Int. J. Remote Sensing*, 2005, **26**, 2029–2034.
15. Laurs, R. M., Fiedler, P. C. and Montgomery, D. R., Albacore tuna catch distributions relative to environmental features observed from satellites. *Deep Sea Res*., 1984, **31**(9), 1085–1099.
16. Tang, D. L., Kawamura, H., Doan-Nhu, H. and Takahashi, W., Remote sensing oceanography of a harmful algal bloom (HAB) off the coast of southeastern Vietnam. *J. Geophys. Res*., 2004, **109**, 1–7.
17. Kumar, N. *et al.*, Oceanographic preferences of yellowfin tuna (*Thunnus albacares*) in warm stratified oceans: a remote sensing approach. *Int. J. Remote Sensing*, 2020, **41**(15), 5785–5805; doi:10.1080/01431161.2019.1707903.
18. Srinivasa Kumar, T., Patanjali Kumar, Ch. and Nayak, S., Performance of the Indian tsunami early warning system. *Int. Arch. Photogramm. Remote Sensing Spat. Inf. Sci.*, 2010, **XXXVII**(8), 271–274; ISSN 1682-1750.
19. Murty, P. L. N. *et al.*, A coupled hydrodynamic modeling system for Phailin cyclone in the Bay of Bengal. *Coast. Eng*., 2014, **93**, 71–81.
20. Sabique, L., Annapurnaiah, K., Balakrishnan Nair, T. M. and Srinivas, K., Contribution of Southern Indian Ocean swells on the wave heights in the northern Indian Ocean: a modeling study. *Ocean Eng.*, 2012, **43**, 113–120.
21. Sandhya, K. G., Remya, P. G., Balakrishnan Nair, T. M. and Arun, N., On the co-existence of high-energy low-frequency waves and locally-generated cyclone waves off the Indian east coast. *Ocean Eng.*, 2015, **111**, 148–154.
22. Remya, P. G., Vishnu, S., Praveen Kumar, B., Balakrishnan Nair, T. M. and Rohith, B., Teleconnection between the north Indian Ocean high swell events and meteorological conditions over the Southern Indian Ocean. *J. Geophys. Res.: Oceans*, 2016, **121**, 7476–7494.
23. Ravichandran, M., Behringer, D., Sivareddy, S., Girishkumar, M., Chacko, N. and Harikumar, R., Evaluation of the global ocean data assimilation system at INCOIS: the tropical Indian Ocean. *Ocean Model*., 2013, **69**, 123–135.
24. Seemanth, M., Remya, P. G., Bhowmick, S. A., Sharma, R., Balakrishnan Nair, T. M., Kumar, R. and Chakraborty, A., Implementation of altimeter data assimilation on a regional wave forecasting system and its impact on wave and swell surge forecast in the Indian Ocean. *Ocean Eng*., 2021, **237**, 109585.1–109585.12.
25. Beal, L. M. *et al.*, A road map to IndOOS-2: better observations of the rapidly warming Indian Ocean. *Bull. Am. Meteorol. Soc.*, 2020, **101**(11), E1891–E1913.

ACKNOWLEDGEMENTS. The figures in this article are taken from the web-pages of the respective operational oceanographic services of INCOIS. We thank the Group Directors, respective Division Heads and concerned scientific and technical staff for their efforts to make them available for public use. We also thank the Guest Editor of this special issue, Dr S. S. C. Shenoi and the anonymous reviewer for their valuable suggestions and comments which helped improve the manuscript. This article has an INCOIS contribution number 506.

doi: 10.18520/cs/v126/i2/208-214