



Advancing marine ecological services for the Indian Seas: INCOIS's contribution

S K Baliarsingh*, A Samanta, D M Lal, P C Mohanty, S Raulo, S Giri, B Dash, S Jha, C Sathish,
R Premkumar, Harisha, S Joseph, T M Balakrishnan Nair & T Srinivasa Kumar

Indian National Centre for Ocean Information Services (INCOIS), Ministry of Earth Sciences, Govt. of India,
Hyderabad, Telangana – 500 090, India

*[E-mail ID: baliarsingh.s@incois.gov.in]

Received 09 April 2024; revised 24 May 2024

The seas around India hold immense ecological and economic importance. However, this region experiences adverse effects from climate change, pollution, and overexploitation of marine resources. To tackle these challenges and promote sustainable ocean management and blue economy, the Indian National Centre for Ocean Information Services (INCOIS) offers a suite of marine ecological services on Marine Fisheries Advisory Services (MFAS), Algal Bloom Information Service (ABIS), and Coral Bleaching Alert System (CBAS). The MFAS provides advisories on Potential Fishing Zone (PFZ) and tuna fishery. The PFZ advisories detect major fishing grounds, helping increase catch and reduce fishing costs. ABIS provide information and early warnings of algal blooms. CBAS monitor coral reefs' health by detecting coral bleaching events around major Indian islands and supporting conservation and climate resilience. The Water Quality Now casting System (WQNS) delivers updates on coastal health by disseminating data on multiple water quality parameters. WQNS operates at two key locations, utilising measurements from autonomous water quality observatories onboard moored buoys. This study also highlights the ongoing research towards developing marine ecological services on jellyfish aggregation, species-specific marine fisheries, and front-based PFZ characterization. The Jellyfish Aggregation Advisory Service (JAAS) aims to identify environmental triggers and provide early warnings on jellyfish swarming and beach stranding. Species-specific marine fisheries aim to provide region-specific information on the expected abundance and distribution of specific fish species (Hilsa, Sardine, and Mackerel). Such information will aid the fishing industry and the fishermen in targeting their efforts more effectively and in reducing the environmental impact of fishing.

[**Keywords:** Blue economy, Climate resilience, Environmental stewardship, INCOIS, Marine biodiversity]

Introduction

India's Exclusive Economic Zone (EEZ) comprises diverse geographical features, including a coastline stretching over ~ 11,098 km, dividing the North Indian Ocean into the Arabian Sea and the Bay of Bengal¹⁻³. The Indian EEZ also includes Lakshadweep and Andaman and Nicobar (A&N) islands⁴. India's coastal population relies heavily on marine fisheries for food and livelihoods, with diverse fish species supporting subsistence and commercial fishing activities, boosting local economies and generating employment. India's coral reefs, notably those in the A&N archipelago, are one of the significant biologically diverse ecosystems in the world. They provide vital niches for various species, such as including ichthyic species, crustaceans, and mollusks, while also serving as natural defences that protect from coastline degradation and coastal flooding⁵. The resources from India's marine environment provide a livelihood to more than 3.5 million people through recreation, fishing, and other economic activities⁶.

Despite India's vast oceanic resources, the current contribution of the blue economy to its Gross Domestic Product (GDP) stands at approximately 4 %, which is relatively low considering its extensive coastline and EEZ, comprising about 60 % of the country's total area⁷. Recognising the untapped potential, the government has identified the blue economy as a key factor for economic prospects. With the nation's increasing focus on the ocean for economic opportunities, the imperative for sustainable ocean management comes to the forefront.

On the other hand, India is vulnerable to significant risks from climate change, with rising temperatures, altered precipitation cycles, and an increase in the frequency of tropical cyclones, river floods, heat waves, etc. The aforementioned shifts endanger agricultural productivity, hydrological resources, and the livelihoods of millions. Nearshore regions are especially susceptible to rising sea levels, resulting in land loss and saline water intrusion, which harms agriculture and triggers migrations. Economic losses

from climate-related disasters have increased over the past decade, highlighting the urgent need for resilience measures. Tackling these challenges demands comprehensive policies and international cooperation. India is working towards climate action by targeting net-zero emissions by 2070. Nonetheless, greater efforts are needed to reduce pollution and manage marine resources sustainably for long-term environmental and economic stability. In addition to the impact of climate change, escalating human interventions further stress the coastal milieu through pollution, overfishing, and habitat degradation. Monitoring these ecosystems through marine ecological services offers an important avenue for implementing necessary management strategies. Realising the importance of marine ecological services in the country's economy, the "Indian National Centre for Ocean Information Services (INCOIS)", provides "the best possible ocean information and advisory services to society, industry, government agencies, and the scientific community through sustained ocean observations and constant improvements through systematic and focused research". INCOIS regularly disseminates services on nowcasting of coastal water quality, algal bloom, marine fishery advisories, and coral bleaching alerts (Fig. 1). The marine ecological services are generated using a multitude of data sourced from satellites, models, and *in situ* observation platforms⁸. Presently, advancements in satellite remote sensing technology, characterised by new satellites with higher spatio-temporal resolution, along with

improvements in ocean models and expansion of ocean observation networks through additional moored platforms, present an opportunity to enhance existing operational services and develop new marine ecological services. In this context, INCOIS is actively involved in researching and developing new marine ecological services, particularly focused on events such as jellyfish swarming and advisories/forecasts related to specific fish species like sardines, mackerel, and hilsa (Fig. 1). Continuous research efforts are also directed toward upgrading existing services. This article offers a brief overview of INCOIS's existing operational marine ecological services as well as those under research and development.

Operational marine ecological services

Potential Fishing Zone (PFZ) advisory

Coastal fisheries are a vital component of the country's socio-economy, supporting a large sector of coastal population depending on fishing for their livelihoods⁹. However, locating fish resources often entails significant time and resource investment, reducing profitability and increasing carbon footprint. Recognising these challenges, INCOIS has operationalised the Marine Fisheries Advisory Services (MFAS), specifically catering to the needs of India's fishing communities. This initiative addresses the uncertainties fishermen face daily, aiming to enhance their socio-economic status and also contributes towards resource sustainability.

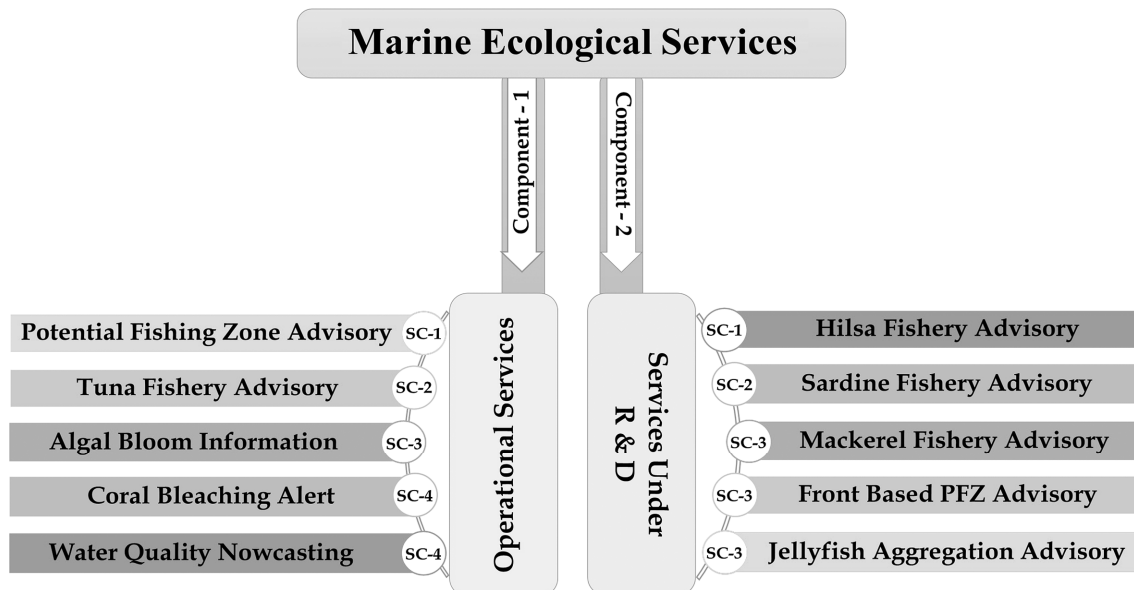


Fig. 1 — Schema showing the components (operation and services under R&D) and sub-components of marine ecological services at INCOIS

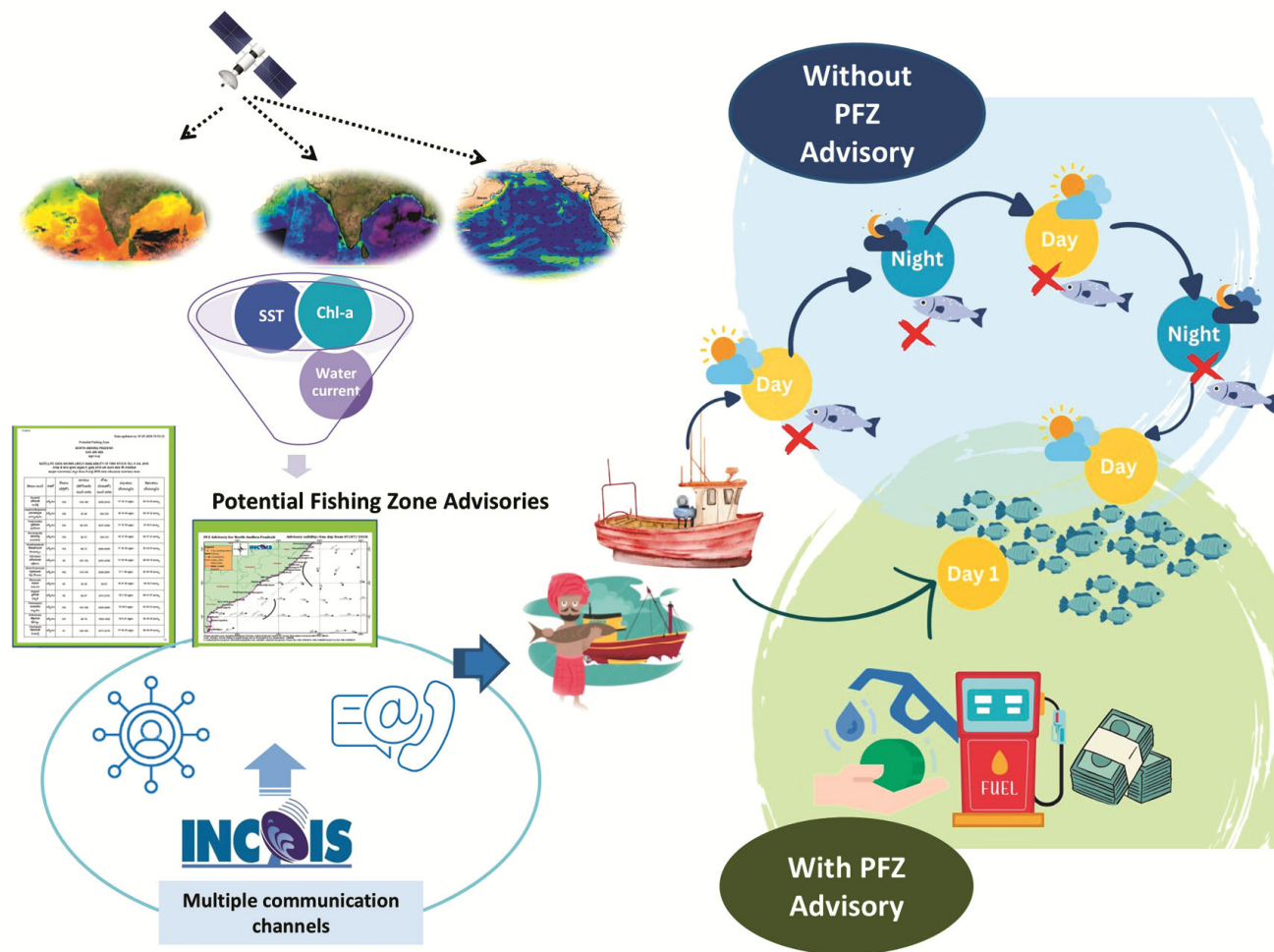


Fig. 2 — Schematic representation of the overview of the end-to-end system of the Potential Fishing Zone (PFZ) advisory service of INCOIS

The foundation of INCOIS's MFAS lies in the Potential Fishing Zone (PFZ) advisories, which have been operational for over two decades. These advisories offer timely and reliable locations of fish availability, bringing numerous benefits to the fishing community. The PFZ advisories are being continuously validated and have been shown to enhance fishermen's Catch Per Unit Effort (CPUE) by minimising the duration of fish finding, thereby consequently saving fuel costs¹⁰⁻¹². Additionally, the use of the PFZ advisories contributes to the reduction of CO₂ emissions from fossil fuel burning.

Being the only such advisory available to the fishing community, PFZ service is instrumental in enhancing their socio-economic well-being. The overview of the end-to-end system of the PFZ advisory service of INCOIS is illustrated in Figure 2. The science behind the PFZ advisories lies in the fish

behaviour and ocean biogeochemical processes¹³. Fish ecology in the marine ecosystem is influenced by a multitude of hydro-biological variables, prompting them to move towards areas with favourable conditions such as aquatic oxygen, temperature, and salinity. Sea Surface Temperature (SST) serves as a key environmental parameter, often correlated with fish availability, particularly pelagic species. The concentration of pelagic fish at frontal zones, specifically in regions of steep surface temperature gradients, underscores the significance of chlorophyll-*a* (proxy of phytoplankton biomass) and SST gradients^{14,15}. The presence/evolution of chlorophyll-*a* indicates food chain development, leading to the availability of fish. Leveraging remotely sensed data on SST and chlorophyll-*a* from satellites like NOAA-AVHRR, Oceansat, VIIRS-SNPP, and/or MODIS-Aqua, INCOIS delivers PFZ advisories to fishermen

daily, operating continuously with the exception of regional capture fishery restriction days. The PFZ advisories are disseminated via various channels such as SMS, village information centers, electronic display boards at fish landing centers, NGO websites, social media platforms and the INCOIS website. The PFZ advisories generated for the Indian coast were found to benefit local fishermen by increasing the CPUE at the PFZ-notified area by 2 – 3 times more than the non-notified area^{10,16,17}.

Looking ahead, the future of MFAS holds exciting prospects for innovation and impact. INCOIS is spearheading efforts to develop species-specific fishery advisories for different fish populations, including tuna, hilsa, sardine, and mackerel. Furthermore, INCOIS is committed to enhancing the accessibility and effectiveness of these advisories by exploring new dissemination channels and integrating biogeochemical data. Through proactive research and stakeholder engagement, INCOIS aims to empower fishermen with the knowledge and tools needed to navigate increasingly dynamic marine ecosystems, fostering a more sustainable and resilient fishing industry.

Tuna fishery advisory

Tuna is a highly migratory species and is important from an economic point of view. On a global scale,

the Pacific Ocean contributes the highest tuna catch (~70.2 %), followed by the Indian Ocean (~20.4 %)¹⁸. The Indian EEZ has a tuna fishery potential of ~213,000 tons, with a contribution of Yellowfin Tuna (YFT) (~54 %), skipjack (~40 %), and big-eye tuna (~6 %). As there were no dedicated vessels for the tuna fishery, the “Marine Products Exports and Development Authority (MPEDA)” has assisted in the transformation of fishing vessels into tuna long-liners since 2006. With the positive response to the transformation of vessels, MPEDA approached INCOIS to develop an advisory service. Due to the increasing demand, INCOIS started hind-cast studies by utilising geo-tagged fish catch and collocated satellite data (*i.e.*, SST, chlorophyll, and K_d490 -a proxy for water clarity) (Fig. 3). The results from the experiments enabled INCOIS to disseminate the advisory on tuna fishery for further validation. After receiving the feedback and validation results, INCOIS operationalised the tuna fishery advisory for a selected group of users and tuna long-liners, since 2010.

In the later phase, INCOS realised the necessity of having information on the migration route and habitat preferences of tuna for better management of the tuna advisory. Therefore, further research and development work, “*Satellite telemetry studies on migration*

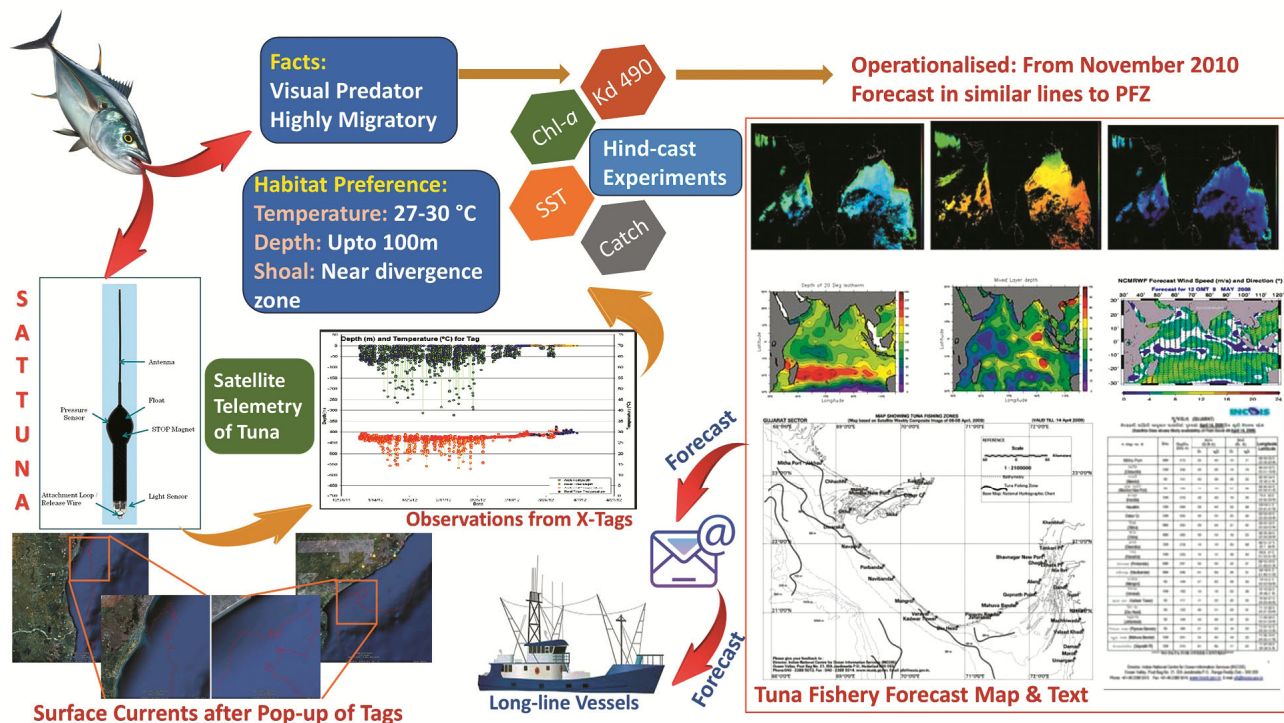


Fig. 3 — Schematic representation of the overview of INCOIS' species-specific advisory service for tuna

patterns of Tunas in Indian Seas (SATTUNA)” was initiated by collaborating with national fisheries institutes (Fig. 3). In this context, INCOIS initiated experiments on YFT (highest contributor to Indian tuna fishery) for India, based on the linkage between their behaviour and preferred ecological conditions. YFT stands as a commercially important fish found in tropic-subtropical oceans worldwide. YFT populations experience high fishing pressure due to its economic importance and demand. The “Indian Ocean Tuna Commission (IOTC)” in 2016 reported chances of ~68 % overfishing of YFT, signifying the necessity of understanding the environmental preferences of YFT in the Indian Ocean to check on the overfishing and decline in population¹⁹. Along with the environmental conditions, the behaviour of the YFT can provide a base for understanding their ecological preferences in the Indian Ocean. Several studies revealed the highly migratory characteristics of tuna due to their high metabolic rates along with their preference to reside within the thermocline^{20,21}. Therefore, temperature is considered the dominant factor controlling the migration and habitat preference of tuna²².

To understand the migration pattern (behaviour) of YFT, rather than the conventional acoustic or archival tagging, Pop-up Satellite Archival Tags (PSATs) were used in the experiment (Fig. 3). The experiment was conducted in coordination with the “Central Marine Fisheries Research Institute (CMFRI)” and the “Fisheries Survey of India (FSI)”. The PSATs (Model X-Tag) are capable of monitoring the behaviour, movement, and environmental preference of tuna²³. During the tagging experiment in the Indian seas, 42 large YFTs were tagged using PSATs from 2011 to 2014 (in two batches). The PSAT tags continuously record data on temperature, depth, and light conditions before detaching from the YFT on a pre-set date. Once they reach the surface, they transmit the observed information to land station^{24,25}.

The observations deciphered that YFT in the Arabian Sea typically prefer depths of around 110 m, while in the Bay of Bengal, they tend to stay in waters less than 100 m deep. Their preferred temperature range was found to be between 25 °C and 30 °C. Overall, the research indicated that YFTs are inhabitants of the studied region and do not undergo extensive seasonal migrations across basins. Consequently, the tagging experiment supported and reinforced the tuna fishery advisory provided by

INCOIS. Subsequently, INCOIS has been disseminating advisories to tuna long-liners via its website and email.

Algal Bloom Information Service (ABIS)

Marine algae are the predominant primary producers in the ocean that sustain the highly diverse food chain and modulate the earth’s climate through photosynthesis, thereby supporting large-scale fisheries. However, sometimes, these algae multiply rapidly over a short period of time, resulting in bloom events. More often, these bloom events exert an adverse impact on the aquatic ecosystem and are then termed “Harmful Algal Bloom (HAB)”, with their occurrence becoming frequent. The adverse effects of the bloom include extensive fish mortality and a decline in dissolved oxygen concentrations, resulting in uninhabitable conditions for the majority of species. Through field-based measurements, it’s not possible to monitor the spatial extent as well as temporal patterns. In this context, satellite remote sensing enables remote detection of algal blooms through its specific spectral signatures²⁶.

Against this backdrop, INCOIS has operationalised Algal Bloom Information Service (ABIS), which uses ocean colour remote sensing technology with a suite of appropriate bio-optical algorithms. ABIS employs environmental indicators to detect and monitor algal blooms. Key indicators include chlorophyll-*a*, representing phytoplankton biomass, SST indicating water column mixing, and a Bloom Index (BI) to determine bloom conditions in optically complex waters^{8,27}. Additionally, ABIS disseminates insights on the responsible phytoplankton like diatoms and *Noctiluca scintillans* (frequent bloom-forming species in Indian waters) and phytoplankton size classes (pico, nano, and micro). ABIS uses satellite-retrieved data from MODIS-Aqua. ABIS service is made available aboard the INCOIS portal for various stakeholders, including the scientific and industrial sectors. Schema of ABIS is illustrated in Figure 4. ABIS also complements other ecological services like the MFAS. Especially, near real-time data on ABIS is very helpful in studying the effect of HAB on the ecosystem as well as human health^{28,29}. A recent study by Samanta *et al.*²⁸ successfully used ABIS to study the spatial-temporal extent of the intense water quality disrupting mixotrophic dinoflagellate bloom events in the coastal waters of Kerala. In another investigation, Srichandan *et al.*²⁹ used ABIS to decipher the long-term trend of chlorophyll-*a* and bacillariophyta

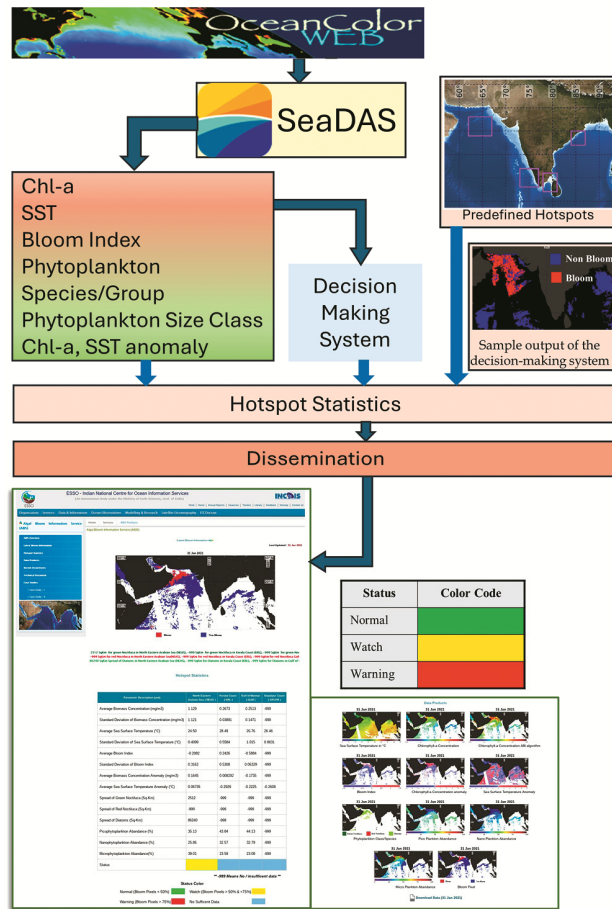


Fig. 4 — Schema showing the overview of INCOIS's Algal Bloom Information Service (ABIS)

distribution in coastal waters off Gopalpur. Apart from sustaining the ABIS, attempts are also underway i) to incorporate new ocean colour satellite sensors into the data processing chain, ii) inclusion of more phytoplankton group/species identifying bio-optical algorithms, and iii) upgradation of the existing information service to a forecast service.

Coral Bleaching Alert System (CBAS)

Coral reefs are among the most diverse marine ecosystems on Earth, boasting a wealth of species interactions³⁰. Despite occupying just a fraction of the ocean floor, merely 0.2 %, they represent the pinnacle of biodiversity underwater³¹. These sprawling reef structures act as natural barriers, safeguarding coastlines spanning thousands of kilometres from the erosive forces of waves. In doing so, they preserve crucial habitats like lagoons and mangroves, which serve as vital nurseries for a myriad of species, both commercially valuable and otherwise³². However, the resilience of coral reefs is delicate and vulnerable to

an array of natural and human-induced disturbances, including global warming, severe storms, overfishing, marine pollution, and other harmful activities. While coral bleaching can occur due to various factors, the widespread occurrence known as 'mass bleaching' typically arises from a combination of intense sunlight and unusually high water temperatures³³. The impacts of rising temperatures due to climate change on coral reefs are unmistakable, extensively recorded, and well-defined³⁴. Even slight temperature increases of 1 – 2 °C above typical summer maxima can disrupt the mutualism of corals with zooxanthellae, leading to bleaching and potentially death. Though corals may recover if the stress is short-lived, prolonged exposure leaves them susceptible to disease and mortality.

Coral reef environments in India significantly contribute to the country's total fish catch and consumed animal protein³⁵. Key coral reef ecosystems in India include the Gulf of Kachchh, Lakshadweep, the Gulf of Mannar, Andaman and Nicobar Islands, and Malvan^{36,37}. Prior to 1998, India had no recorded incidents of coral bleaching until a significant event caused widespread coral loss across major reef areas³⁸. Subsequently, there have been multiple documented instances of coral bleaching³⁷. In response, INCOIS has operationalised the "Coral Bleaching Alert System (CBAS)". This system utilises satellite-derived SST to gauge thermal stress levels in coral environments, providing early indications of bleaching intensity and spatial distribution. The CBAS actively monitors reef zones and raises public awareness, aligning with INCOIS's primary objectives of reef monitoring and early warning for coral bleaching events.

CBAS utilises high-resolution NOAA-AVHRR night-time SST data, with a spatial resolution of 1 km, on a daily basis to generate advisory for coral bleaching in Indian coral reef areas. It employs a climatological reference, the Maximum Monthly Mean (MMM), spanning the last 30 years, to establish threshold limits for coral tolerance before bleaching occurs. Biweekly assessments of positive SST anomaly are conducted against this climatology to identify Hotspots (HS) and Degree of Heating Weeks (DHWs), indicating an increased risk of coral bleaching. HS are determined by SST anomalies greater than 1 °C and are updated biweekly, while DHWs aggregate the cumulative thermal stress over the past 12 weeks, measured in °C-weeks. DHW values up to 4 °C-weeks signify a "Warning" status,

indicating stress on corals, while DHWs between 4 – 8 °C-weeks denote "Alert Level-1," associated with significant coral bleaching. DHWs exceeding 8 °C-weeks represent "Alert Level-2," indicating the potential for widespread bleaching. The methodology outlined in Figure 5 provides a systematic approach for generating coral bleaching alerts, proving valuable for coastal management, ecologists, and researchers in making informed decisions and policies regarding coral ecosystems. Ongoing research aims to enhance the CBAS by evaluating the impact of prolonged anomalous ocean temperatures on coral reefs during past bleaching events^{39,41}. The CBAS was efficient in detecting the coral bleaching events along the Andaman coast triggered by heat stress in the pre-monsoon seasons^{39,42}. Additionally, studies focus on assessing the influence of marine heatwaves on coral bleaching intensity and spectral characteristics, with future projections considering various climate change scenarios⁴³.

Water Quality Nowcasting System (WQNS)

Coastal areas provide a diverse array of ocean value chain services, contributing significantly to the national economy⁴⁴. The Indian coastal waters are increasingly susceptible to human-induced disturbances, including land runoff, industrial wastes, municipal wastes, seaport activities, etc. Both natural and human-induced factors regulate coastal hydro-biology⁴⁵. Studies reveal a notable disparity in nutrient levels compared to standard stoichiometry, rendering the coastal waters of India susceptible to nutrient-induced pollution. This is also evidenced by an increasing number of algal blooms in recent decades and their consequences. Tracking physical, chemical, and meteorological factors associated with marine biology offers crucial insights into coastal environmental dynamics, supporting sustainable resource management and fostering regional economic growth⁴⁶. Against this backdrop, to monitor the water quality at strategic locations of the Indian

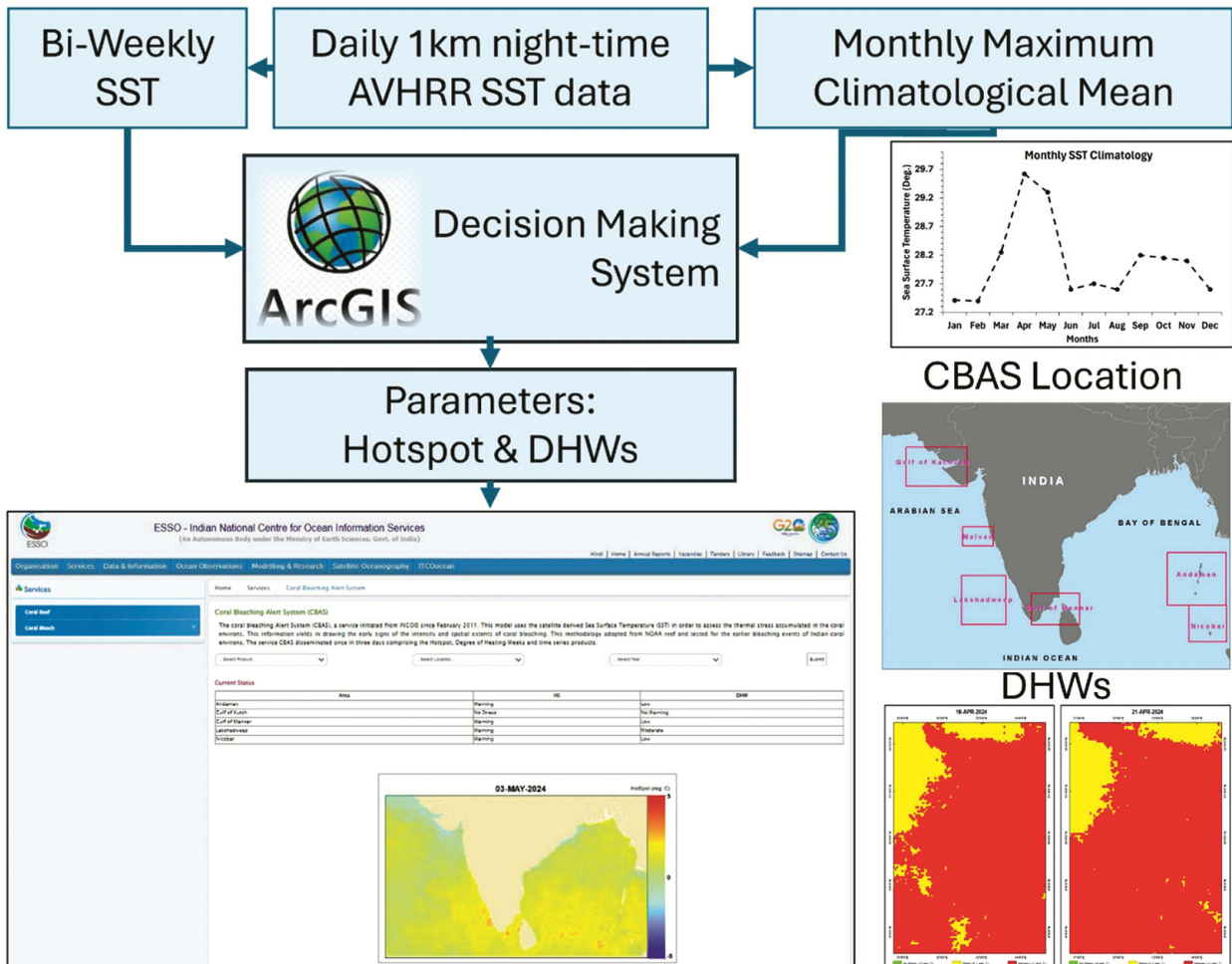


Fig. 5 — Schema showing the operational framework of the Coral Bleaching Alert System (CBAS) of INCOIS

coastal waters, INCOIS has recently operationalised a Water Quality Nowcasting System (WQNS) based on moored buoy-based observatories, initially one for the east coast (Visakhapatnam) and another for the west coast (Kochi). Both locations are major economic hubs influenced by urbanisation, and port activities^{47,48}. They were selected for observatory implementation due to their contributions to the blue economy and differing hydrological characteristics influenced by monsoons and river discharge. Kochi faces seasonal mud banks from river discharge, low primary production from backwater discharge, phytoplankton blooms, and strong CO₂ flux due to monsoon-induced upwelling^{28,49-51}. In contrast, Visakhapatnam experiences seasonal hypoxic conditions due to weaker coastal upwelling from March to May and strong stratification from substantial freshwater flux during the reversing monsoon (October to December)^{52,53}. WQNS consists of a real-time data monitoring mechanism through autonomous water quality observatories, ocean remote sensing data, wireless mediums for transmitting data, a data processing-quality control system, and a web-based data visualisation application (Fig. 6). These observatories are equipped with different physical-biogeochemical sensors, data telemetry systems, and integration with satellite-based observations for real-time data transmission to land. The sensors onboard these buoys continuously measure a suite of water quality parameters, including surface current (speed and direction), salinity, temperature, pH, dissolved oxygen, phycoerythrin, Coloured Dissolved Organic Matter (CDOM), chlorophyll-*a*, turbidity, dissolved methane, hydrocarbon (crude and refined), scattering, pCO₂ (water and air), and inorganic macronutrients. This real-time data is transmitted to a central processing facility at INCOIS, and after necessary quality control, the data is disseminated through the INCOIS website. The development of WQNS is well-detailed in Balakrishnan Nair *et al.*⁴⁸.

The WQNS has proven its capability to identify alterations in water column characteristics caused by episodic events and mesoscale processes. Furthermore, integrating ABIS with WQNS is aimed at understanding the impact of algal blooms on water quality deterioration. Initial findings from the WQNS show encouraging trends, including diurnal patterns of dissolved oxygen at the observatory deployment site in coastal waters of the southeastern Arabian Sea

and signature of water column mixing evidenced by temperature decreases linked to local depressions off Visakhapatnam⁴⁸. INCOIS plans to extend the WQNS network to encompass other regions of biogeochemical significance.

Marine ecological services under research and development

Based on the existing understanding, the success of operational ecological services, the benefits of new satellite and modelled data, and user-specific needs, INCOIS is researching several new marine ecological services. This involves conducting feasibility studies, assessing habitat suitability for target species, identifying data sources, evaluating data availability, and finalising programs/models. The implementation framework is also being considered for the potential development of these services.

Hilsa fishery advisory

Hilsa shad, *Tenualosa ilisha* is among the highly commercially significant anadromous fish of the Indo-Pacific region. The species inhabit the marine, estuarine, and riverine environments at various stages of their life. It has a broad global distribution, especially across Southeast Asian countries, including India, Bangladesh, and Myanmar^{54,55}. In India, approximately 90 % of the total hilsa capture fishery is contributed by the Hugli estuary and adjoining western Bay of Bengal; where hilsa alone constitutes a lucrative fishery and provides livelihood support to millions of coastal fisherfolks^{54,56}. However, in the last two decades, the hilsa population in the Hugli estuary and adjoining the Bay of Bengal is declining steadily. It has been estimated that from 2002 to 2015, the population has decreased by 13 % due to overexploitation, and the present exploitation rate (0.81) surpassed the maximum exploitation limit (0.78)⁵⁷. Therefore, proper conservation and management of hilsa is of paramount importance. The ongoing research on the hilsa fishery advisory development focuses on understanding the spatial variability of the hilsa catch with respect to different environmental drivers that influence its anadromous migration and catch variability. This understanding is aimed at modelling the habitat suitability of hilsa for providing advisory with a sustainable fishing approach.

Based on the extensive literature review, different environmental drivers impacting the hilsa migration

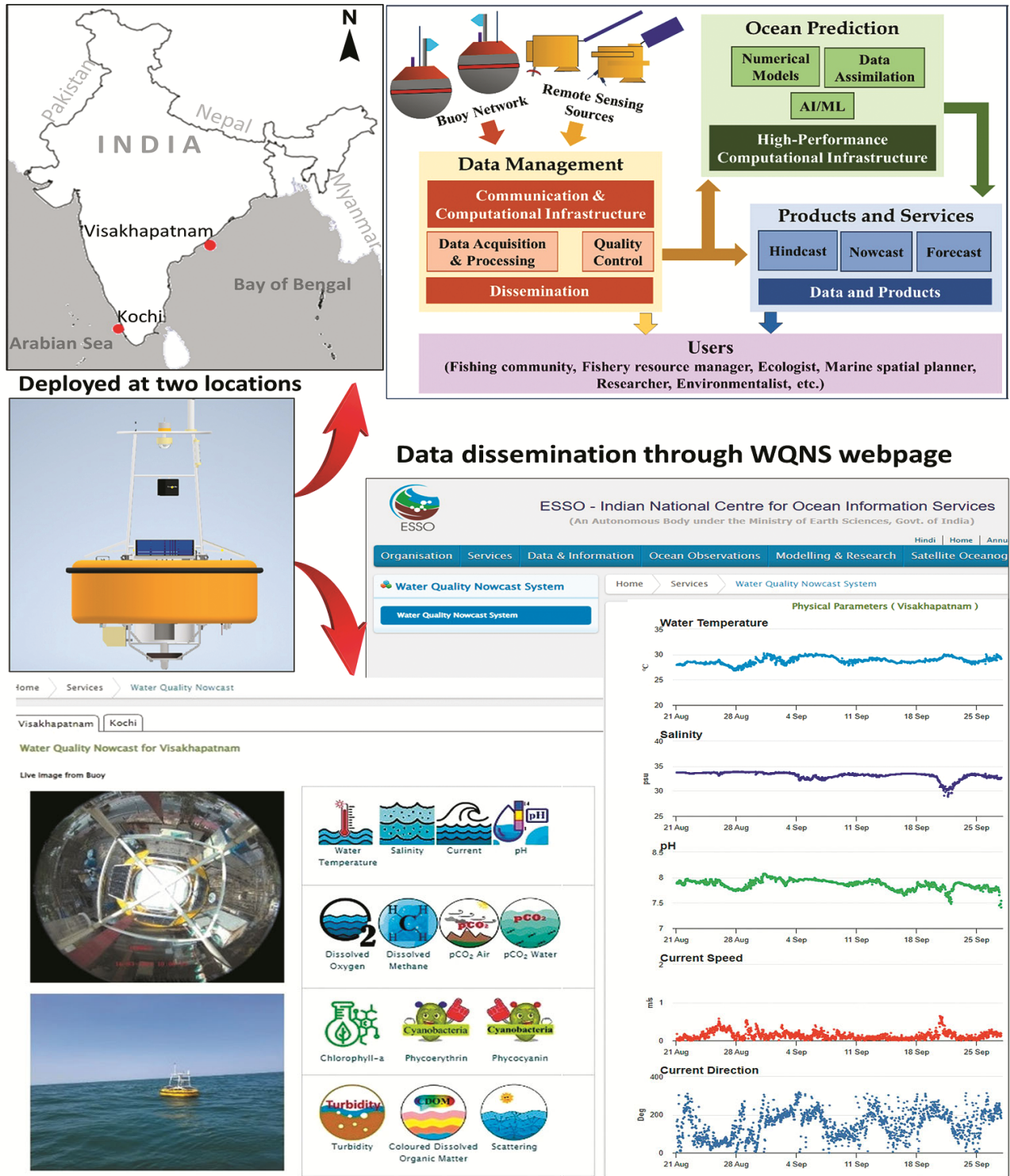


Fig. 6 — Schematic representation of the overview of INCOIS’s Water Quality Nowcasting System (WQNS)⁴⁸. Image reprinted with permission from Elsevier⁴⁸

have been identified, of which salinity, precipitation, SST, and current velocity are reported to have significant impacts^{55,58}. The suitability range of

different parameters has been identified from the literature⁵⁸⁻⁶⁰ and used in the machine learning models along with georeferenced fish catch data to

understand the habitat suitability through spatio-temporal variability of the hilsa catch. Research is underway to transform this understanding towards developing the hilsa fishery advisory on an experimental basis for validation of the model (Fig. 7). This approach would be useful for providing short-term hilsa fishery advisory by INCOIS in the future for proper hilsa fishery management and sustainable fishing approach.

Sardine fishery advisory

Indian oil sardine (*Sardinella longiceps*) holds significant economic value, contributing nearly 17 – 20 % to India's total marine fish landings over the past decade⁶¹. Particularly in Kerala, oil sardine sustain a substantial commercial fishery, serving as a major source of both production and consumption⁶². Despite the economic importance of oil sardines, there has been a notable absence of a successful forecasting system for this species in the Indian context. In response, INCOIS has initiated the research on species-specific advisory for oil sardines,

initially for off Kerala. To predict Indian oil sardine, major environmental predictors have been identified, such as SST, precipitation, salinity, and Mixed Layer Depth (MLD)^{63,64}.

Various datasets, including monthly fish catch data from landing centres and geo-tagged fish catch data from outsourced projects, are under analysis to correlate with environmental proxies for monthly and daily sardine prediction. Additionally, suitable habitat suitability models (regression/ classification, AI/ML) are also under training with the aim of finalising a multi-model approach to locate sardine availability. Modelling algorithms encompass regression techniques such as (i) Generalised Linear Model (GLM), (ii) Generalised Additive Model (GAM), as well as AI/ML-based methods including (iii) Boosted Regression Tree (BRT), and (iv) Random Forest (RF)⁶⁵. Currently, the models are in the process of being trained using multiple datasets with varying periodicity and from different data sources, which is aimed at identifying the optimal approach for predicting conditions in the coastal waters of Kerala.

In a specific case study for off Kerala, the sardine aggregation events termed “Sardine Run” were investigated to provide a plausible scientific basis (Fig. 8). These ‘Sardine Run’ events were backtracked to find the conducive condition(s)⁶⁶. The case study underpinned the interconnected influence of SST, rainfall, water currents, and wind patterns, with the emergence of SST and rainfall as significant factors.

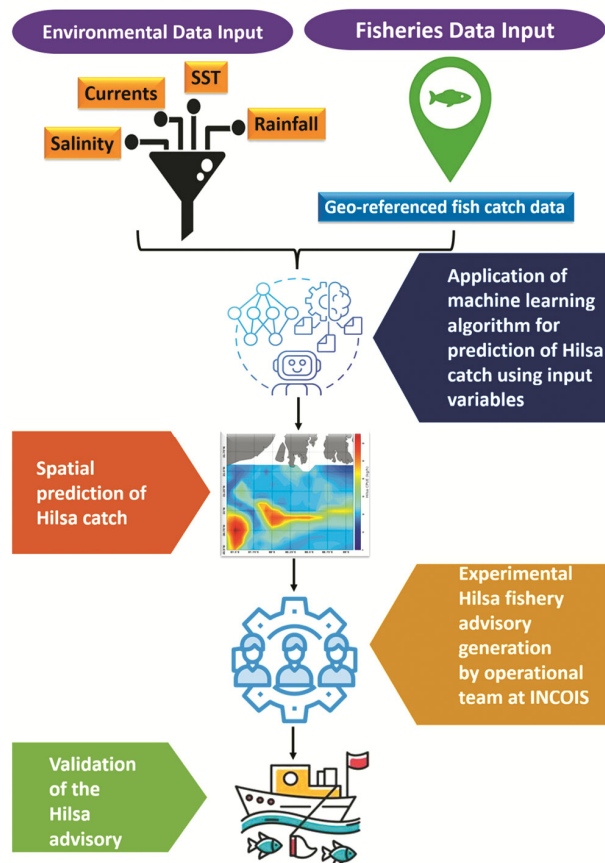


Fig. 7 — Schematic representation of the processes adopted for the development of experimental hilsa fishery advisory

Mackerel fishery advisory

The Indian mackerel plays a crucial role in the marine environment by connecting lower trophic-level producers to higher-level consumers^{67,68}. It is one of the most abundant small pelagic fish in the coastal waters of eastern Arabian Sea. According to FRAEED⁶⁹, in 2022 alone, landings of marine fish along the Indian coast reached 3.49 million tonnes, with Indian mackerel contributing a significant 9.39 % (3.28 lakh tonnes) portion. India accounts for 90 % of global mackerel production, with 77 % originating from the west coast and 23 % from the east coast⁷⁰. However, the knowledge about the species is meagre, with the Data Deficient (DD) status by the IUCN. Juvenile Indian mackerels are often captured alongside anchovies, silverbellies, and other pelagic fishes using various fishing gear commonly used for commercial fisheries.

Due to its dynamic life cycle, numerous efforts to map its habitat and seasonal abundance have been

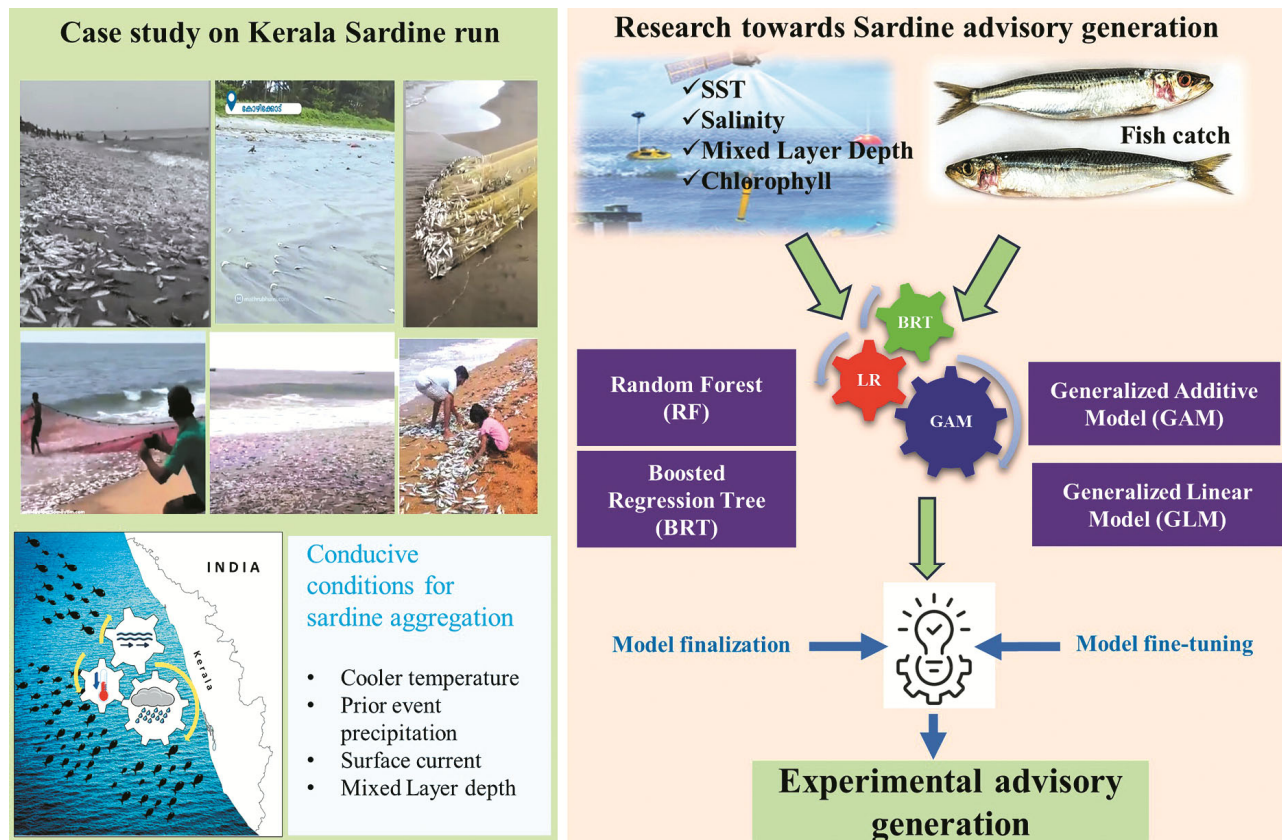


Fig. 8 — Schematic representation of the processes adopted for the development of experimental sardine fishery advisory^{65,66}. Image reprinted with permission from Elsevier⁶⁵ and Springer Nature⁶⁶

unsuccessful. The most effective method for identifying fish-abundant regions involves integrating satellite data, GIS, and statistics with field data on fish aggregations⁷¹. INCOIS has initiated research to address the challenge of modelling mackerel abundance in Indian waters and identify factors that influence their aggregation. Initial time-series analysis using various multiple regressions revealed a strong correlation between rainfall, MLD, seawater temperature at 50 m depth, and PFZ lines with mackerel catches in different time lags. Further investigations are underway with statistical methods (GLM, GAM, etc.) to identify the variables most conducive for mackerel aggregation and their interrelationships. Additionally, machine learning tools and ensemble models are being explored for their ability to predict mackerel availability, potentially leading to abundance forecasting competencies (Fig. 9).

Front-based PFZ advisory

Ocean frontal zones are relatively narrow regions characterised by intensified surface gradients of

physical, chemical, and biological properties that delineate regions with distinct vertical structures⁷². As they typically form at the boundaries between warm and cold water masses, fronts are commonly detected using SST data, which can be monitored via satellites^{10,73}. In the vast oceans, these physical features play crucial roles as habitats for trophic transfer, supporting the reproduction, foraging, and migration of pelagic commercial species⁷⁴.

Currently, INCOIS provides daily advisories on PFZ, utilising satellite-retrieved SST and chlorophyll data. These advisories are generated based on the prescribed methodology, which involves the detection of thermal and chlorophyll fronts^{10,13,75}. These fronts are identified as PFZ because they form at the boundaries between water masses with varying temperatures or densities, often associated with upwelling resulting in increased mixing and biological productivity^{40,76,77}. Consequently, they serve as ideal environments for the growth of phytoplankton, which in turn attracts commercially important species due to greater prey availability⁷⁸.

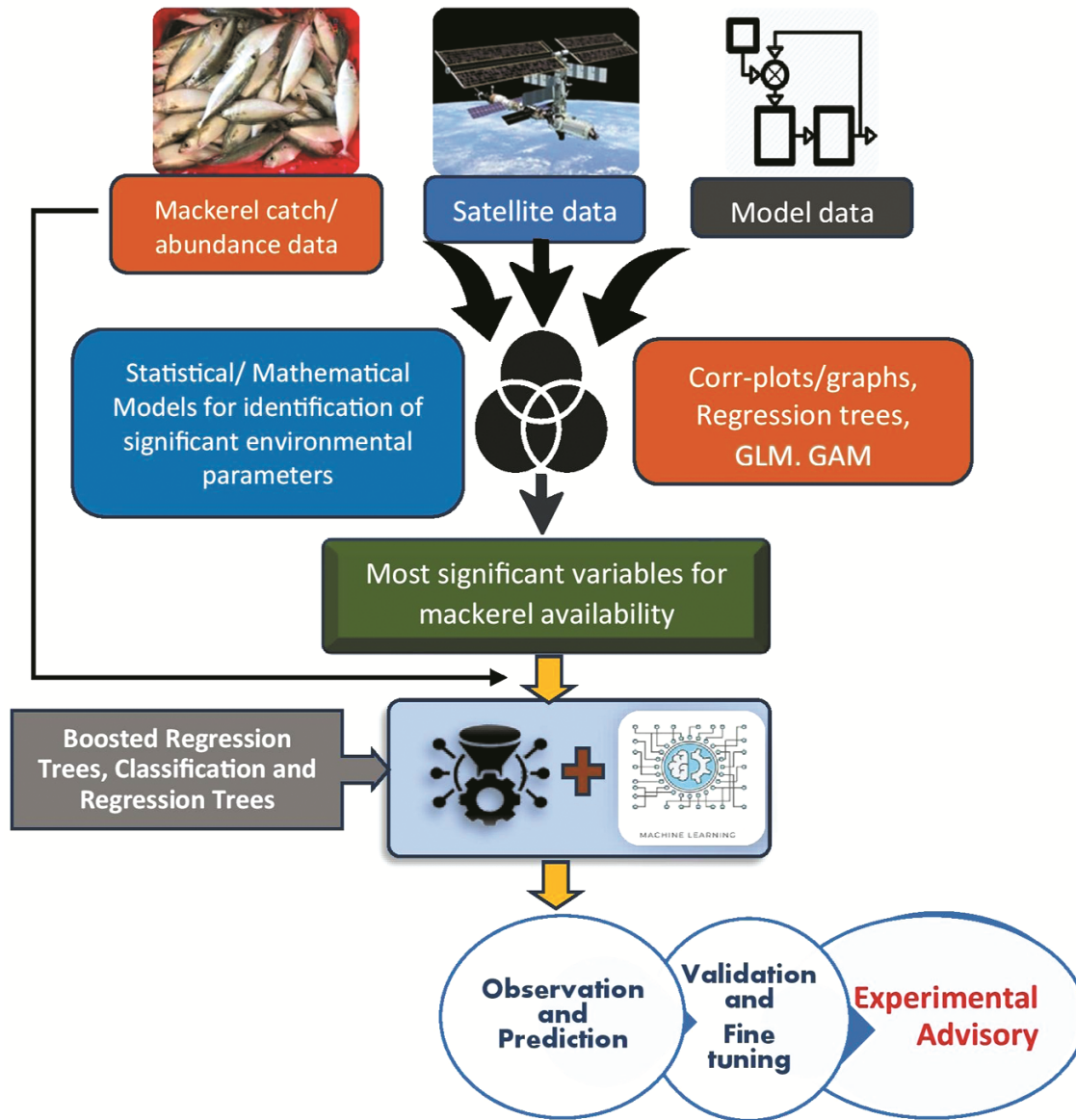


Fig. 9 — Schema showing R&D process of experimental species-specific advisory for Indian mackerel

Recognising the pivotal role of fronts as reliable indicators of fishing grounds, several studies have proposed various factors influencing the dynamics of frontal productivity, including initial background conditions and the persistence and age of the fronts⁷⁹. These factors can significantly influence the nature of the food web that develops near the system and the species likely to aggregate near fronts over time. A comprehensive investigation into environmental variables, encompassing horizontal variabilities, vertical profiles across the fronts, and abundance patterns of organisms from plankton to top predators over persistent thermal fronts, could substantially enhance the predictive capacity of PFZ advisories.

Initiatives in these lines are underway, involving the continuous monitoring of persistent thermal fronts along selected stretches of the Indian coast and field surveys (Fig. 10). The anticipated outcome of this research is to provide more precise predictions and species-specific advisories in the future. When coupled with other environmental and subsurface variables and dynamic modelling tools, the efficacy of this approach is expected to be amplified in the future.

Jellyfish aggregation advisory

In recent decades, jellyfish aggregation events in the form of coastal water swarming and beach strandings have been on the rise. These aggregation

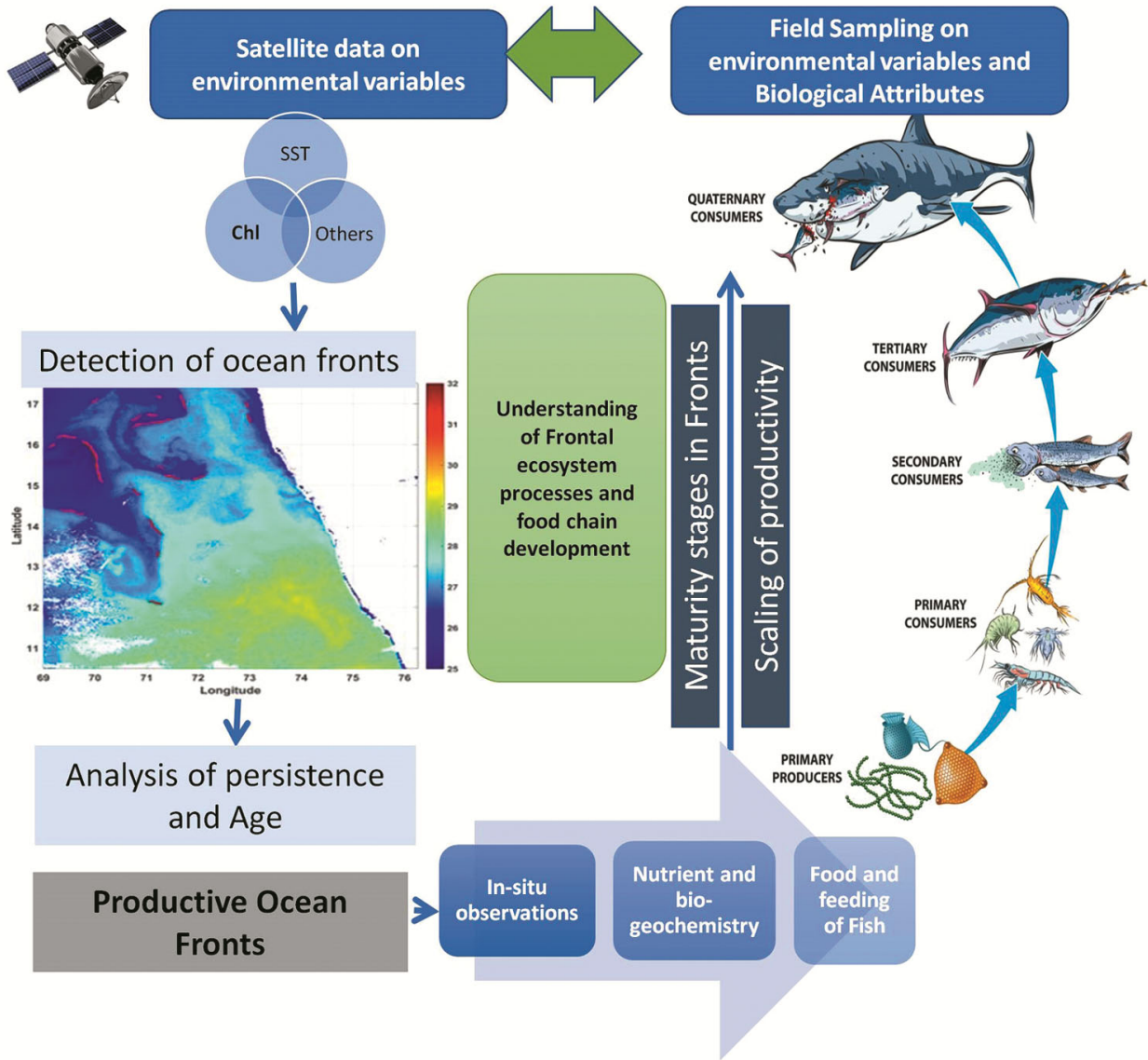


Fig. 10 — Schematic representation of conceptual framework to bridge the gap between oceanic fronts to fish availability towards the development of characterised Potential Fishing Zone (PFZ) advisory

events exert an adverse impact on the function of coastal nuclear power plants by chocking the seawater inlet systems, tourism by decreasing the aesthetic value of the beaches, capture fisheries by chocking the fishing nets, and malfunctioning of the food chain by providing a competitive advantage to other species⁸. On the other hand, at several pockets of the Indian coast, edible jellyfish are harvested and exported to other countries. Therefore, there is a need for the Jellyfish Aggregation Advisory Service (JAAS) to provide information on the swarming events for precautionary measures as well as an alternative fishing opportunity. The potential target

stakeholders of JAAS are tourists, tourism industries, power plants, fishermen, scientists, pollution monitoring agencies, and policymakers. Realising its need and importance, INCOIS has initiated research towards the development of JAAS. A thorough literature review has helped identify the favourable environmental preferences for jellyfish aggregation, leading to the development of a conceptual framework⁸. In the subsequent process, a detailed account of jellyfish aggregation in coastal waters and beaching strandings along the Indian coast has been prepared, and a database is curated, documenting the location, timing, duration, and intensity of the

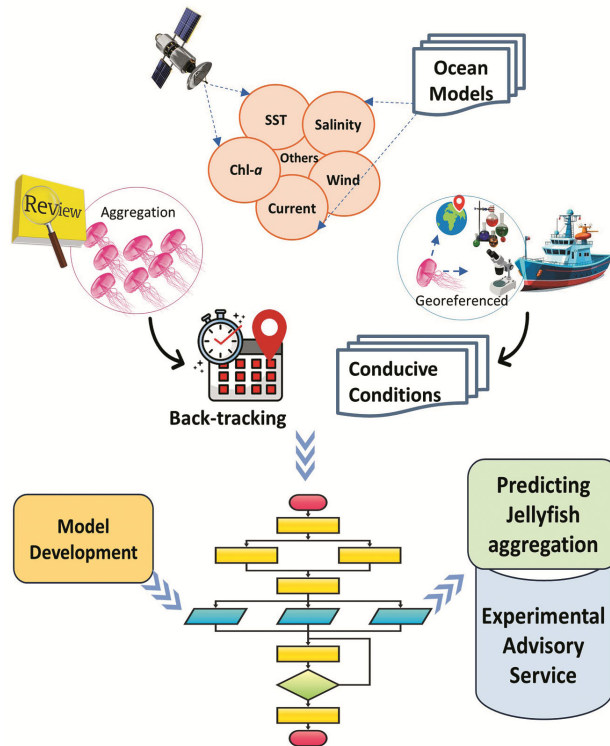


Fig. 11 — R&D process of Jellyfish Aggregation Advisory Service (JAAS)

events⁸⁰. Research is underway to identify the interrelationship of the conducive parameters (operationally available) vis-à-vis jellyfish aggregation events by backtracking the past events. In addition, systematic monitoring programs have been initiated in synergy with coastal laboratories to collect quantitative data on jellyfish abundance, distribution, and behaviour in different regions and seasons. A schematic representation showing the research and development efforts for JAAS is illustrated in Figure 11. Some recent case studies have also highlighted the effectiveness of the conducive parameters, such as water temperature, winds, and currents, in understanding the environment setting facilitating jellyfish aggregation. For instance, Baliarsingh *et al.*⁸¹, highlighted that an increase in SST has been identified as a significant factor leading to fish mass mortality, and this rise in temperature also led to an increase in jellyfish populations, as the depletion of fish resources provided them with a competitive advantage for food. Subsequently, the beaching of the aggregated jellyfish was facilitated by the shoreward currents.

Summary and Conclusion

This study highlights INCOIS's pivotal role in providing indispensable marine ecological services that are crucial for both blue economy and marine ecosystem monitoring and management. By integrating satellite data, models, and *in situ* observations, INCOIS delivers vital services like coastal water quality nowcasting and marine fishery advisories, imperative for effective marine ecosystem management amidst climate change and human activities. The operationalisation of PFZ and tuna advisory services has notably uplifted the socio-economic status of fishermen while promoting resource sustainability. Moreover, INCOIS's ABIS emerges as a critical tool in monitoring algal bloom events, offering timely interventions to safeguard aquatic ecosystems and public health. Similarly, the CBAS and WQNS contribute significantly to coral reef and coastal water quality monitoring, highlighting INCOIS's commitment to advancing sustainable coastal management practices. Beyond operational services, ongoing research and development aim to enhance existing services and introduce new ones, like refining PFZ advisories based on oceanfront maturity levels, providing species-specific advisories for pelagic fishes, and issuing aggregation advisories for jellyfish. INCOIS's ongoing efforts in this direction promise to boost India's regional blue economy and tackle escalating environmental challenges, ensuring the resilience and vitality of marine ecosystems for future generations.

Future research should focus on several key areas to build on the current findings. Comparative studies between INCOIS and similar institutions globally are essential to identify best practices and areas for improvement in marine ecological services. Additionally, exploring new technologies and methodologies will enhance data collection, integration, and analysis capabilities, making these services more accessible and effective worldwide. Investigating adaptive strategies to cope with the uncertainties of climate change is crucial for ensuring the resilience and effectiveness of marine ecological services amidst evolving environmental challenges. Expanding research on the socio-economic aspects of marine ecological services in different communities, particularly in developing regions, will help better understand and maximise the benefits of these services.

Acknowledgments

The authors are thankful to the Ministry of Earth Sciences, Govt. of India, for supporting the marine ecological services and applied research programmes of INCOIS. The authors are also thankful to the organisers of the World Ocean Science Congress 2024 for providing an avenue for this manuscript to be included in the conference's special issue. This is INCOIS's contribution number 533.

Conflict of Interest

The authors declare that there are no conflicts of interest in publishing this manuscript in the Indian Journal of Geo-Marine Sciences.

Author Contributions

SKB: Conceptualisation, data analysis, investigation, visualisation, and writing – original draft. AS, DML, PCM, SR, SG, BD, SJ (Sneha), CS, RP, & Ha: Formal analysis, visualisation and writing – original draft. SJ, TMBN & TSK: Supervision, project administration and writing – review & editing.

References

- TRW: Transport Research Wing, Change in length of coastline of India (Circular), Ministry of Ports, Shipping and Waterways (MoPSW), Government of India, New Delhi, Dated 29 April 2025, 2025, pp. 03. <https://www.shipmin.gov.in/sites/default/files/Length%20of%20Indias%20Coastline%20Circular.pdf>
- Bharti D K, Guizien K, Aswathi-Das M T, Vinayachandran P N & Shanker K, Connectivity networks and delineation of disconnected coastal provinces along the Indian coastline using large-scale Lagrangian transport simulations, *Limnol Oceanogr*, 67 (6) (2022) 1416–1428. <https://doi.org/10.1002/lno.12092>
- MFAHD: Ministry of Fisheries, Animal Husbandry & Dairying, *Sagar Parikrama*, A program by Ministry of Fisheries, Animal Husbandry and Dairying, saluting our great freedom fighters, sailors and fishers, beginning from Gujarat, Posted On: 02 Mar 2022, Press Information Bureau, Government of India, Delhi, 2022, Accessed online at: <https://pib.gov.in/PressReleasePage.aspx?PRID=1802384>, Accessed on 08 May 2024.
- Wafar M, Venkataraman K, Ingole B, Ajmal Khan S & Loka Bharathi P, State of knowledge of coastal and marine biodiversity of Indian Ocean countries, *PLoS one*, 6 (1) (2011) e14613.
- Gibson R N, Atkinson R J A & Gordon J D M (eds), Coral reefs of the Andaman Sea - An integrated perspective, In: *Oceanography and Marine Biology*, Vol 45, 1st edn, (CRC Press, US), 2007, pp. 173–194.
- Nayak S, Coastal zone management in India - Present status and future needs, *Geo-Spat Inf Sci*, 20 (2) (2017) 174–183. <https://doi.org/10.1080/10095020.2017.1333715>
- Shenoi S S C, Nurturing the blue economy: A call for sustainable ocean utilization, *Curr Sci*, 126 (2) (2024) 119–120.
- Baliarsingh S K, Lotliker A A, Srichandan S, Samanta A, Kumar N, *et al.*, A review of jellyfish aggregations, focusing on India's coastal waters, *Ecol Proces*, 9 (2020) 1–9. <https://doi.org/10.1186/s13717-020-00268-z>
- CMFRI, *Marine fisheries census 2010*, Part 1, (Ministry of Agriculture and farmers welfare, Krishi Bhavan, New Delhi & Central Marine Fisheries Research Institute, Kochi), 2012, pp. 110.
- Kumar S, Kumar N, Padmaja N S, Nayak S, Pillai V N, *et al.*, *Validation of Potential Fishing Zone (PFZ) Advisories (2006–2007)*, Technical Report, Report No: INCOIS-ASG-PFZ-TR-08-2007, (Indian National Centre for Ocean Information Services, Cochin), 2007, pp. 27.
- Pillai V N & Nair P G, Potential fishing zone (PFZ) advisories-Are they beneficial to the coastal fisherfolk? A case study along Kerala coast, South India, *Biol Forum*, 2 (2010) 46–55.
- George G, Krishnan P, Dam Roy S, Sarma K, Goutham Bharathi M P, *et al.*, Validation of potential fishing zone (PFZ) forecasts from Andaman and Nicobar Islands, *Fish Technol*, 50 (2013) 1–5.
- Solanki H U, Dwivedi R M, Nayak S R, Naik S K, John M E, *et al.*, Cover: Application of remotely sensed closely coupled biological and physical processes for marine fishery resources exploration, *Int J Remote Sens*, 26 (10) (2005a) 2029–2034. <https://doi.org/10.1080/01431160310001595028>
- McGowan J A, Chelton D B & Conversi A, Plankton patterns, climate, and change in the California Current, *CalCOFI Rep*, 37 (1996) 45–68.
- Lehodey P, Andre J M, Bertignac M, Hampton J, Stoens A, *et al.*, Predicting skipjack tuna forage distributions in the equatorial Pacific using a coupled dynamical bio-geochemical model, *Fish Oceanogr*, 7 (3-4) (1998) 317–325.
- Maity S, Kumar T S, Dutta S, Akhand A & Hazra S, Satellite based integrated potential fishing zone advisories: A feasibility analysis in the coastal water of West Bengal, In: *Proceedings of the Zoological Society*, Vol 68, (Springer, India), 2015, pp. 4–19. <https://doi.org/10.1007/s12595-013-0088-x>
- Chavda V M, Vaghela D T, Parmar H V & Parmar P V, Evaluation of Fish Catch in Potential Fishing Zones (PFZs) off Veraval Coast, Gujarat, *Biol Forum*, 13 (3) (2021) 127–133.
- Abdussamad E M, Indian tuna resources: Distribution, commercial exploitation, utilization and trade, In: *Manual on World Trade Agreements and Indian Fisheries Paradigms: A Policy Outlook*, (Central Marine Fisheries Research Institute, Cochin), 2012, pp. 111–119.
- Myers R A, Hutchings J A & Barrowman N J, Why Do Fish Stocks Collapse? The Example of Cod in Atlantic Canada, *Ecol Appl*, 7 (1) (1997) 91–106.
- Bushnell P G & Brill R W, Oxygen Transport and Cardiovascular Responses in Skipjack Tuna (*Katsuwonus pelamis*) and Yellowfin Tuna (*Thunnus albacares*) Exposed to Acute Hypoxia, *J Comp Physiol B*, 162 (2) (1992) 131–143.

- 21 Block B A, Keen J E, Castillo B, Dewar H, Freund E V, *et al.*, Environmental Preferences of Yellowfin Tuna (*Thunnus albacares*) at the Northern Extent of Its Range, *Mar Biol*, 130 (1) (1997) 119–132.
- 22 Brill R W, A Review of Temperature and Oxygen Tolerance Studies of Tunas Pertinent to Fisheries Oceanography, Movement Models and Stock Assessments, *Fish Oceanogr*, 3 (3) (1994) 204–216.
- 23 Block B A, Dewar H, Farwell C & Prince E D, A New Satellite Technology for Tracking the Movements of Atlantic Bluefin Tuna, *Proc Natl Acad Sci*, 95 (16) (1998) 9384–9389.
- 24 Lutcavage M E, Brill R W, Skomal G B, Chase B C & Howey P W, Results of Pop-up Satellite Tagging of Spawning Size Class Fish in the Gulf of Maine: Do North Atlantic Bluefin Tuna Spawn in the mid-Atlantic? *Can J Fish Aquat Sci*, 56 (2) (1999) 173–177.
- 25 Weng K C, Boustany A M, Pyle P, Anderson S D, Brown A, *et al.*, Migration and Habitat of White Sharks (*Carcharodon Carcharias*) in the Eastern Pacific Ocean, *Mar Biol*, 152 (4) (2007) 877–894. <https://doi.org/10.1007/s00227-007-0739-4>
- 26 Baliarsingh S K, Dwivedi R M, Lotliker A A, Sahu K C, Kumar T S, *et al.*, An optical remote sensing approach for ecological monitoring of red and green *Noctiluca scintillans*, *Environ Monit Assess*, 189 (7) (2017) p. 1-10 (Art No 330). <https://doi.org/10.1007/s10661-017-6037-9>
- 27 Samanta A, Lotliker A, Baliarsingh S K & Nair B, Algal Bloom Information Service, Technical Report No.: ESSO-INCOIS-ISG-TR-01(2019), 2019, pp. 22.
- 28 Samanta A, Baliarsingh S K, Lotliker A A, Joseph S & Nair T B, Satellite-based detection of *Noctiluca* bloom in the coastal waters of the southeastern Arabian Sea: A case study implicating monitoring needs, *Natl Acad Sci Lett*, 46 (2) (2023) 103–107. <https://doi.org/10.1007/s40009-023-01205-2>
- 29 Srichandan S, Baliarsingh S K, Samanta A, Jena A K, Lotliker A A, *et al.*, Satellite-Based Characterization of Phytoplankton Blooms in Coastal Waters of the Northwestern Bay of Bengal, *J Indian Soc Remote Sens*, 50 (11) (2022) 2221–2228. <https://doi.org/10.1007/s12524-022-01597-6>
- 30 Montano S, The extraordinary importance of coral-associated fauna, *Divers*, 12 (9) (2020) 357. <https://doi.org/10.3390/d12090357>
- 31 Reaka-Kudla M L, The global biodiversity of coral reefs: A comparison with rain forests, In: *Biodiversity II: Understanding and protecting our biological resources*, edited by Reaka-Kudla M L, Wilson D E & Wilson E O, (Joseph Henry Press, Washington DC), 1997, pp. 83–108.
- 32 Nagelkerken I, Van der Velde G, Gorissen M W, Meijer G J, Van't Hof T, *et al.*, Importance of mangroves, seagrass beds and the shallow coral reef as a nursery for important coral reef fishes, using a visual census technique, *Estuar Coast Shelf Sci*, 51 (1) (2000) 31–44. <https://doi.org/10.1006/eess.2000.0617>
- 33 Hoegh-Guldberg O, Climate change, coral bleaching and the future of the world's coral reefs, *Mar Fresh Res*, 50 (8) (1999) 839–866.
- 34 Veron J E, Hoegh-Guldberg O, Lenton T M, Lough J M, Obura D O, *et al.*, The coral reef crisis: The critical importance of < 350 ppm CO₂, *Mar Pollut Bull*, 58 (10) (2009) 1428–1436. <https://doi.org/10.1016/j.marpolbul.2009.09.009>
- 35 Raghuraman R, Raghunathan C & Venkataraman K, Present status of coral reefs in India, In: *Ecology and conservation of tropical marine faunal communities*, edited by Venkataraman K, Sivaperuman C & Raghunathan C, (Springer, Berlin, Heidelberg), 2013, pp. 351–379. https://doi.org/10.1007/978-3-642-38200-0_23
- 36 Bhatt J R, Kumar R & Edward J K P, Conservation and management of coral reefs in India, In: *Coral reefs in India-status, threats and conservation measures*, edited by Bhatt J R, Patterson Edward J K, Macintosh D J & Nilaratna B P, (IUCN India), 2012, pp. 1–17.
- 37 Majumdar S D, Hazra S, Giri S, Chanda A, Gupta K, *et al.*, Threats to coral reef diversity of Andaman Islands, India: A review, *Reg Stud Mar Sci*, 24 (2018) 237–250. <https://doi.org/10.1016/j.rsma.2018.08.011>
- 38 Arthur R, Coral bleaching and mortality in three Indian reef regions during an El Niño southern oscillation event, *Curr Sci*, (2000) 1723–1729.
- 39 Mohanty P C, Mahendra R S, Bisoyi H, Tummula S K, Grinson G, *et al.*, Assessment of the coral bleaching during 2005 to decipher the thermal stress in the coral environs of the Andaman Islands using Remote Sensing, *Eur J Remote Sens*, 46 (1) (2013) 417–430. <https://doi.org/10.5721/EuJRS20134624>
- 40 Mohanty P C, Mahendra R S, Nayak R K, Kumar N, Kumar T S, *et al.*, Persistence of productive surface thermal fronts in the northeast Arabian Sea, *Reg Stud Mar Sci*, 16 (2017a) 216–224. <https://doi.org/10.1016/j.rsma.2017.09.010>
- 41 Mahendra R S, Mohanty P C, Bisoyi H & Srinivasa Kumar T, Geospatial assessment of Coral and Mangrove Environs of the Andaman Islands, *Int J Earth Sci Eng*, 7 (1) (2014) 375–379.
- 42 Mohanty P C, Venkateshwaran P, Mahendra R S, Kumar H S, Kumar T S, *et al.*, Coral bleaching along Andaman coast due to thermal stress during summer months of 2016: A geospatial assessment, *Am J Environ Protect*, 6 (1) (2017b) 1–6. <https://doi.org/10.11648/j.ajep.20170601.11>
- 43 Mohanty P C, Kushabaha A, Mahendra R S, Nayak R K, Sahu B K, *et al.*, Persistence of marine heat waves for coral bleaching and their spectral characteristics around Andaman coral reef, *Environ Monit Assess*, 193 (491) (2021) 1–9. <https://doi.org/10.1007/s10661-021-09264-y>
- 44 Costanza R, De Groot R, Sutton P, Van der Ploeg S, Anderson S J, *et al.*, Changes in the global value of ecosystem services, *Global Environ change*, 26 (2014) 152–158. <https://doi.org/10.1016/j.gloenvcha.2014.04.002>
- 45 Mathew T, Prakash S, Baliarsingh S K, Samanta A, Lakshmi R S, *et al.*, Response of phytoplankton biomass to nutrient stoichiometry in coastal waters of the western Bay of Bengal, *Ecol Indic*, 131 (2021) p. 108119. <https://doi.org/10.1016/j.ecolind.2021.108119>
- 46 Christie P, Is integrated coastal management sustainable? *Ocean Coast Manag*, 48 (3–6) (2005) 208–232. <https://doi.org/10.1016/j.ocecoaman.2005.04.002>
- 47 Prasad V R, Srinivas T N R & Sarma V V S S, Influence of river discharge on abundance and dissemination of heterotrophic, indicator and pathogenic bacteria along the east coast of India, *Mar Pollut Bull*, 95 (1) (2015) 115–125. <https://doi.org/10.1016/j.marpolbul.2015.04.032>

- 48 Balakrishnan Nair T M, Sarma V V S S, Lotliker A A, Muraleedharan K R, Samanta A, *et al.*, An integrated buoy-satellite based coastal water quality nowcasting system: India's pioneering efforts towards addressing UN ocean decade challenges, *J Environ Manag*, 354 (2024) p. 120477. <https://doi.org/10.1016/j.jenvman.2024.120477>
- 49 Muraleedharan K R, Dinesh Kumar P K, Prasanna Kumar S, John S, Srijith B, *et al.*, Formation mechanism of mud bank along the Southwest Coast of India, *Estuar Coast*, 41 (2018) 1021–35. <https://doi.org/10.1007/s12237-017-0340-0>
- 50 Seena G, Muraleedharan K R, Revichandran C, Abdul Azeez S & John S, Seasonal spreading and transport of buoyant plumes in the shelf off Kochi, South west coast of India-A modeling approach, *Sci Rep*, 9 (1) (2019) p. 19956. <https://doi.org/10.1038/s41598-019-56103-9>
- 51 Sarma V V S S, Monthly variability in surface $p\text{CO}_2$ and net air-sea CO_2 flux in the Arabian Sea, *J Geophys Res: Oceans*, 108 (C8) (2003) 1-11. <https://doi.org/10.1029/2001JC001062>
- 52 Sarma V V S S, Krishna M S, Viswanadham R, Rao G D, Rao V D, *et al.*, Intensified oxygen minimum zone on the western shelf of Bay of Bengal during summer monsoon: Influence of river discharge, *J Oceanogr*, 69 (2013) 45–55. <https://doi.org/10.1007/s10872-012-0156-2>
- 53 Sarma V V, Desai D V, Patil J S, Khandeparker L, Aparna S G, *et al.*, Ecosystem response in temperature fronts in the northeastern Arabian Sea, *Prog Oceanogr*, 165 (2018) 317–331. <https://doi.org/10.1016/j.pocean.2018.02.004>
- 54 Ahsan D, Naser N, Bhoomik U, Hazra S & Bhattacharya S B, *Migration, spawning patterns and conservation of hilsa shad (Tenualosa ilisha) in Bangladesh and India*, (Academic Foundation, New Delhi), 2014, pp. 97.
- 55 Bhaumik U, Fisheries of Indian Shad (*Tenualosa ilisha*) in the Hooghly–Bhagirathi stretch of the Ganga River system, *Aquat Ecosyst Health Manage*, 20 (1-2) (2017) 130–139. <https://doi.org/10.1080/14634988.2017.1283894>
- 56 Sajina A M, Suresh V R, Sandhya K M, Mukherjee J, Manna R K, *et al.*, Status of hilsa fishery in hooghly-bhagirathi river system and associated coastal waters of northern Bay of Bengal, *Proc Natl Acad Sci India Sect B Biol Sci*, 90 (2020) 647–656. <https://doi.org/10.1007/s40011-019-01140-7>
- 57 Das I, Hazra S, Das S, Giri S, Maity S, *et al.*, Present status of the sustainable fishing limits for Hilsa Shad in the northern Bay of Bengal, India, *Proc Natl Acad Sci, India, Sect B Biol Sci*, 89 (2018) 525–532. <https://doi.org/10.1007/s40011-018-0963-3>
- 58 Hossain M S, Sharifuzzaman S M, Chowdhury S R & Sarker S, Habitats across the life cycle of Hilsa shad (*Tenualosa ilisha*) in aquatic ecosystem of Bangladesh, *Fish Manage Ecol*, 23 (6) (2016) 450–462. <https://doi.org/10.1111/fme.12185>
- 59 Hossain M S, Sarker S, Chowdhury S R & Sharifuzzaman S M, Discovering spawning ground of Hilsa shad (*Tenualosa ilisha*) in the coastal waters of Bangladesh, *Ecol Modell*, 282 (2014) 59–68. <https://doi.org/10.1016/j.ecolmodel.2014.03.001>
- 60 Giri S, Chanda A, Mondal P P, Samanta S, Chakraborty K, *et al.*, Role of biogeochemical parameters in delineating suitable habitats of juvenile Hilsa (*Tenualosa ilisha*) within an estuary, *Environ Biol Fishes*, 104 (9) (2021) 1057–1072. <https://doi.org/10.1007/s10641-021-01134-3>
- 61 Shyam S S, Oil Sardine Landings and Revenue Realization under a Climate Change Regime in India, *J Fish Livest Prod*, 9 (9) (2021) 1–3.
- 62 Natarajan A, Najmudeen T M, Gopalan M K, Kuriakose S, Ratheesan A N, *et al.*, Economic and livelihood impacts of the decline in Indian oil sardine landings in Kerala state, India, *Reg Stud Mar Sci*, 62 (2023) p. 102963. <https://doi.org/10.1016/j.rsma.2023.102963>
- 63 Holmes E E, Smith B R, Nimit K, Maity S, Checkley Jr D M, *et al.*, Improving landings forecasts using environmental covariates: A case study on the Indian oil sardine (*Sardinella longiceps*), *Fish Oceanogr*, 30 (6) (2021) 623–642. <https://doi.org/10.1111/fog.12541>
- 64 Hamza F, Anju M & Valsala V, A bioenergetics model for seasonal growth of Indian oil sardine (*Sardinella longiceps*) in the Indian west coast, *Ecol Modell*, 456 (2021) p. 109661. <https://doi.org/10.1016/j.ecolmodel.2021.109661>
- 65 Dash B, Baliarsingh S K, Samanta A, Sahoo S, Joseph S, *et al.*, Evolution and recent trends of Indian oil sardine research: A review, *Ocean Coast Manag*, 258 (2024) p. 107396. <https://doi.org/10.1016/j.ocecoaman.2024.107396>
- 66 Baliarsingh S K, Dash B, Jena A K, Raulo S, Samanta A, *et al.*, Investigating Indian Oil Sardine aggregation events in coastal waters of the southeastern Arabian Sea, *Environ Sci Pollut Res*, 31 (2024) 34271–34281. <https://doi.org/10.1007/s11356-024-33519-z>
- 67 Sherman K, The large marine ecosystem approach to marine resources assessment and management, In: *The ecosystem approach to fisheries*, edited by Bianchi G & Skjoldal H R, (CAB International and FAO, Rome), 2008, pp. 47–75. <https://doi.org/10.1079/9781845934149.0047>
- 68 Skjoldal H R & Misund O A, Ecosystem approach to management: Definitions, principles and experiences from implementation in the North Sea, In: *The ecosystem approach to fisheries*, edited by Bianchi G & Skjoldal H R, (CAB International and FAO, Rome), 2008, pp. 209–227. <https://doi.org/10.1079/9781845934149.0209>
- 69 FRAEED, CMFRI, *Marine Fish Landings in India-2022*, Technical Report, CMFRI Booklet Series No 31/2023, (ICAR-Central Marine Fisheries Research Institute, Kochi), 2023, pp. 16.
- 70 Bhendarkar M P, Naik S D, Ramteke M H, Raut S M & Swain S, Morphometric and meristic studies of Indian Mackerel, *Rastrelliger kanagurta* (Cuvier, 1817) off Southern Coast of Maharashtra, India, *Ecol Env Cons*, 20 (2014) 1705–1708.
- 71 Wilson C D, Roberts D & Reid N, Applying species distribution modelling to identify areas of high conservation value for endangered species: A case study using *Margaritifera margaritifera* (L), *Biol Conserv*, 144 (2) (2011) 821-829. <https://doi.org/10.1016/j.biocon.2010.11.014>
- 72 Belkin I & Cornillon P, SST fronts of the Pacific coastal and marginal seas, *Pacific Oceanogr*, 1 (2) (2003) 90-113.
- 73 Clayton S, Nagai T & Follows M J, Hydrochemistry and phytoplankton pigments in water samples obtained during R/V Natsushima (JAMSTEC) cruise to the Kuroshio Extension Front in October 2009, Supplement 1, PANGAEA, 2014. <https://doi.org/10.1594/PANGAEA.819108>

- 74 Bakun A, Babcock E A, Lluch-Cota S E, Santora C & Salvadeo C J, Issues of ecosystem-based management of forage fisheries in “open” non-stationary ecosystems: The example of the sardine fishery in the Gulf of California, *Rev Fish Biol Fish*, 20 (2010) 9–29. <https://doi.org/10.1007/s11160-009-9118-1>
- 75 Solanki H U, Mankodi P C, Nayak S R & Somvanshi V S, Evaluation of remote-sensing-based potential fishing zones (PFZs) forecast methodology, *Cont Shelf Res*, 25 (18) (2005b) 2163–2173. <https://doi.org/10.1016/j.csr.2005.08.025>
- 76 Raju R M, Nayak R K, Swapna M, Mohanty P C, Manche S S, *et al.*, Variability of the thermal front and its relationship with Chlorophyll-a in the north Bay of Bengal, *Reg Stud Mar Sci*, 56 (2022) p. 102700. <https://doi.org/10.1016/j.rsma.2022.102700>
- 77 Swapna M, Raju R, Nayak R K, Mohanty P C, Sessa Sai M V R, *et al.*, Spatiotemporal Characteristics of Thermal Fronts in Relation to Potential Fishing Zones in the Continental Shelf Sea Around India, *J Indian Soc Remote Sens*, 51 (2) (2023) 335–348. <https://doi.org/10.1007/s12524-022-01629-1>
- 78 Sund P N, Blackburn M & Williams F, Tunas and their environment in the Pacific Ocean: A review, *Oceanogr Mar Biol Ann Rev*, 19 (1981) 443–512.
- 79 Sarma V V S S, Kumari V R, Srinivas T N R, Krishna M S, Ganapathi P, *et al.*, East India Coastal Current controls the dissolved inorganic carbon in the coastal Bay of Bengal, *Mar Chem*, 205 (2018) 37–47. <https://doi.org/10.1016/j.marchem.2018.07.010>
- 80 Sathish C, Baliarsingh S K, Samanta A, Joseph S & Balakrishnan Nair T M, *7th International Jellyfish Blooms Symposium (JBS7, 2023), Book of Abstracts*, November 21-25, Thiruvananthapuram, India, edited by M Dawson & Kumar A B, Organised by Dept of Aquatic Biology & Fisheries, University of Kerala and ICAR-Central Marine Fisheries Research Institute, India, 2023, pp. 192.
- 81 Baliarsingh S K, Jena A K, Srichandan S, Raulo S, Joseph S, *et al.*, A scientific basis for fish mass mortality and jellyfish beach stranding in relation to cyclone yaas, *J Coast Conserv*, 27 (2) (2023) 1-7 (Art No 15). <https://doi.org/10.1007/s11852-023-00944-0>