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RESEARCH

Multiple ocean parameter-based potential fishing zone (PFZ) location generation and validation in the Western Bay of Bengal

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Abstract A new conceptual framework based on satellite data, including chlorophyll (CHL), sea surface temperature (SST) fronts, relative winds, current vectors, Ekman transport, and eddies, has been developed to identify potential fishing zones (PFZ) in the Bay of Bengal (BoB). The framework aims to provide persistent forecasts, even under cloudy conditions, based on feature propagation. The validation of the PFZ was carried out using fish catch data collected by the Fishery Survey of India (FSI) between 2016 and 2018. Hooking rates (HR) from longlines and catch per unit effort (CPUE) from trawl nets were used to analyse the data points in hook rate categories (1.0–3.0 and > 3.0) and CPUE categories (50–100 kg and > 100 kg) and interpret them with the PFZ maps. The analysis showed that the high fish catch locations were consistent with persisting features in the BoB, such as high chlorophyll patches, SST fronts, and cyclonic eddies. The high fish catch locations based on hook rate and high CPUE were found to be collocated with the high chlorophyll persisting features and thermal gradients in the BoB. The regression analysis shows that availability of the food (CHL) had the strongest correlation with fish catch, followed by the comfort condition (fronts and eddies).

Keywords PFZ · Validation · Ocean features · Bay of Bengal · CPUE · Hook rates

Introduction

More than 30% of the India's population lives along its more than 7500-km-long coastline. Fishing is a major economic activity and India is the third largest producer of fish and second largest producer of inland fish. Locating and catching fish in coastal and deep waters is always a challenging task. Indian scientists dealing with marine sciences, remote sensing, and fishery science have collaborated to develop a technique to use the satellite and model-based datasets to identify the locations of fish aggregation. The potential fishing zone (PFZ) as a proxy to potential shoals of fish aggregation will benefit the fishing community to reduce the time and effort spent in searching the shoals of fish, thus improving the profitability

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and hence, the socio-economic status. Conventional means of sampling and monitoring the ocean using oceanographic research vessels are limited in both time and space-scales of coverage, making it difficult to study the entire ecosystem. Since the advent of satellite remote sensing, particularly remote sensing of ocean colour, it has become possible to sample the global ocean on synoptic scales at a relatively high temporal resolution of about a day. Ocean-colour radiometry is the only means of quantifying the base of the marine food chain (i.e. phytoplankton biomass) on a global scale, providing a synoptic-scale window into the pelagic ecosystem (Platt & Sathyendranath, 2008). Earth observation from satellites has revolutionised our view of the oceans and offers vast potential for fisheries applications, including marine resource management, stock assessment, marine aquaculture, and fish harvesting. Increasingly, the satellite datasets have been utilised for operational fisheries applications. For example, in India, satellite data from the Indian satellite IRS-P4 Ocean Colour Monitor (OCM) sensor, in combination with National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) SST data are used to generate potential fishing zone (PFZ) advisories. These advisories have helped artisanal fishers reduce search time by up to 70% and have increased significantly the catch per unit effort (Solanki et al., 2003b).

Applications in fisheries by remote sensing lie mostly in measuring characteristics of the physical and biological environment at the sea surface. The first application of satellite remote sensing in fisheries advisory in the USA was in 1971 (Laurs, 1993). This application has had a tremendous impact on the efficiency of American tuna fleets, often reducing search times by 25 to 40% (Simpson, 1992). Tuna fish aggregation has been observed near thermal fronts (Fiedler & Bernard, 1987). Phenomena such as upwelling areas, ocean colour, and the presence of large amounts of chlorophyll in the water have been found as indicators of areas of fish stock congregations and fish stock migration (Mansor et al., 2001). Variations in ocean conditions play a key role in natural fluctuations of fish stocks and in their vulnerability to harvesting. In addition, thermal gradient has been included in some studies as an indicator of thermal fronts and upwelling areas, which are highly productive areas that sustain fish populations (Fiedler & Bernard, 1987; Podesta et al., 1993). Studies on tuna, and related scombroid fishes, indicate the existence of distinct physical and biological boundaries that promote or inhibit major abundances or aggregations of schools, individuals, or some size groups, which depend on ocean processes such as fronts, thermoclines, and productive regions of the oceans (Glantz & Feingold, 1990).

Ocean thermal fronts are the areas which are well known for upwelling and for having high chlorophyll contents (Owen, 1981; Reese et al., 2011). Elevated chlorophyll structures associated with fronts are reported for the study area, BoB and high concentrations of chlorophyll are mostly associated with cool waters (low SST) of ocean, mainly induced from upwelling (Abbott & Zion, 1985; Chavez et al., 1999), and they are the indicators of the fish populations (Carpenter et al., 1985; Sissenwine, 1984). Hence, identifying thermal fronts are wind-induced features is the crucial components in PFZ algorithm and has been used in PFZ monitoring (Ardianto et al., 2017; Nayak et al., 2003; Solanki et al., 2003b). The cloud cover mostly contaminates the satellite data for SST and chlorophyll. Continuous availability of satellite-based high-resolution SST and chlorophyll is therefore a major challenge, especially in the BoB, which is cloudy almost throughout the year (Zuidema, 2003)**.** Hence, it becomes quite essential to explore additional parameters from satellite and identify some features that are secondary in the formation of PFZ, e.g. mesoscale eddies, has a significant role in modulating the distribution of chlorophyll and nutrient cycling in the ocean (Mahadevan, 2014; Singh et al., 2015) and upwelling zones. Other ocean parameters such as location and evolution of frontal boundaries, upwelling zones, currents, and eddies are important in defining marine fish habitats (Balaguru et al., 2014). Fishes are known to respond well with changes in temperature and they congregate around the upwelling boundaries of cold deep waters rich of phytoplankton (Belkin et al., 2009; Choudhury et al., 2007). The validation of PFZ with the utilisation of satellite data (SST and chlorophyll) and derived feature-based forecast have been attempted in Indian waters with in situ catch data (Dutta et al., 2016; George, 2014; George et al., 2013; Kizhakudan, 2014; Madhupratap et al., 2001; Nammalwar et al., 2013; Solanki et al., 2003a; Sreekanth et al., 2016) and some research institutions are generating PFZ advisory using SST and CHL only. There has been enough scope to improve the methods of ocean feature extraction and forecast with the utilisation of optical, thermal infrared, and microwave satellite datasets, even in partially cloudy/cloudy conditions. Hence, proper utilisation of all these ocean features is essential for the efficient monitoring of PFZ. The current study is focussed on to validate our new PFZ algorithm using various ocean parameters such as fronts, mesoscale eddies, winds, and ocean surface currents for the proper monitoring and forecasting of PFZ in the Bay of Bengal (BoB) water.

Data and methodology

The feature-based PFZ tracking methodology (Jishad et al., 2021) has been utilised to generate PFZ advisory within exclusive economic zone (EEZ) regions in BoB (longitude: 78°E–95°E and latitude: 5°N–23°N). This methodology incorporates all the suitable oceanic- and atmospheric-derived parameters such as chlorophyll concentration, thermal fronts based on SST gradients, locations of cyclonic and anti-cyclonic eddies, and relative wind (from wind and current vectors). The chlorophyll and SST data from Moderate Resolution Imaging Spectroradiometer (MODIS) (1 km) (*http://www.oceancolor.gsfc.nasa.gov*), ocean surface winds from Indian Space Research Organisation (ISRO) launched scatterometer, SCATSAT-1 (6.25km) (*http://www.mosdac.gov.in*), Hycom model current data of 9.1-km resolution (*http://www.hycom.org*), and Sea surface height (SSH) at 25 km by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) (http://www.aviso.oceanobs.com) are used for this study. The daily chlorophyll data has been averaged for 3 days and composites have been used to reduce the cloud cover. These parameters were resampled using bilinear interpolation approach to bring to uniform resolution of 4-km pixels.

The first part of the methodology involves the identification and tracking of the thermal fronts using Cayula & Cornillon, (1992) method, which is better than gradient approach suggested by Kostianoy et al., (2004) (Jishad & Agarwal, 2022). The chlorophyll fronts were detected using Canny algorithm (Canny, 1986). Detection of mesoscale eddies using methodology explained by Chelton et al., (2011) and Mason et al., (2014) using fixed threshold for maximum size (400 km) and lower amplitude (5 cm) (Jayan et al., 2023). The PFZ advisory is generated based on the presence of thermal/chlorophyll fronts, eddy, and chlorophyll concentration and more weightage is given to the regions encompassing high chlorophyll concentration, thermal fronts, and cold core eddies. The possible propagation of PFZ features has been identified using relative wind (ocean surface wind field minus surface current) field. The relative wind fields and the corresponding Ekman transport for the day t_0 have been obtained.

To validate the authenticity of the feature-based PFZ forecast, the hind cast data from Fishery Survey of India (FSI), Mumbai (https://fsi.gov.in) for 2016, 2017, and 2018 is used. The fish catch data in hook rate and CPUE is mainly from long line based hooks (from Drishti Vessel) and bottom trawl gear (from Samudrika Vessel), respectively. For trawl net operations, the CPUE is calculated as the total fish catch in respective number of hours during a single haul operation during the trip using a single boat (total fish catch/number of hours). For the long line operation in the deeper waters, the hook rate is computed using ‘Number of fish *100 / total number of hooks’ (Prince et al., 2002).

Several PFZ validation campaigns were conducted with the help of collaborating agencies between 2016 and 2018, covering a broad range of catches, from a few kilogrammes to hundreds of kilogrammes for trawl net fishing and thousands of kilogrammes for deep/longline fishing. The catch per unit effort (CPUE) approach is used for trawl net data, while the hook rate approach is used for deep catch, as trawler operations are carried out in coastal waters with a maximum depth of 120 m, while open ocean catches are made using hooks at depths of 100–3200 m. PFZ forecasts are divided into three categories based on the availability of single, double, or all three parameters from C, F, and E. A single parameter (either one) indicates lower possibility, two parameters (either two) suggest medium possibility, and three parameters are considered a higher possibility of fish catch. PFZ forecasts are provided based on the availability of high chlorophyll (> 0.1 mg/m^3), thermal fronts, and cyclonic eddies.

The hook catch was mainly consisting of pelagic fishes includes different types of *Tunas*, *Chorinemus*, *Sail fish*, *Sword fish*, *Black Marlin*, and *Ray fishes*.

These fish are known for their ability to swim long distances and their adaptability to the ever-changing environment of the open ocean. They are a diverse group of species that can vary greatly in size, shape, and behaviour. One of the challenges of living in the open ocean is finding food. Pelagic fish are typically opportunistic feeders, meaning they will eat whatever prey is available at the time. Some species, such as tuna, feed primarily on small fish and squid, while others, such as billfish, feed on larger prey such as mackerel and other pelagic fish. So, these fishes are easily caught using hooks and prey. The quantity of fish and its species is varying day by day and daily spatial distribution is shown in Fig. 1.

Trawler nets are used by commercial fishing vessels to catch fish on a large scale. Overfishing, bycatch, and damage to the seafloor are all concerns associated with trawling operations. The bottom catch mainly includes demersal fishes, which are a group of fish species that live near or on the bottom of the ocean or other bodies of water. However, overfishing and habitat destruction are major threats to many demersal fish populations. Sustainable fishing practices, such as using selective fishing gear and protecting critical habitats, can help to ensure that these fish species continue to thrive in the future. Trawler nets were mainly consisting of *Ribbon fish*, *Pomfret*, *Nemipterids*, *Leiognathids*, *Squids*, *Caranx*, *Mackerel*, and *Perches* and species distribution and catch weight were different in each day. The daily distribution of the fish catch locations using trawler net for 2016–2018 is shown in Fig. 2.

The validation of deep water fish catch data has been carried out using the fish catch data from both fishing trawlers and hooks for 2016, 2017, and 2018. The deep-water catches (hook rate) were classified into low (< 1.0), medium (1.0–3.0), and high (> 3.0) and the coastal catch from trawler is also classified as low

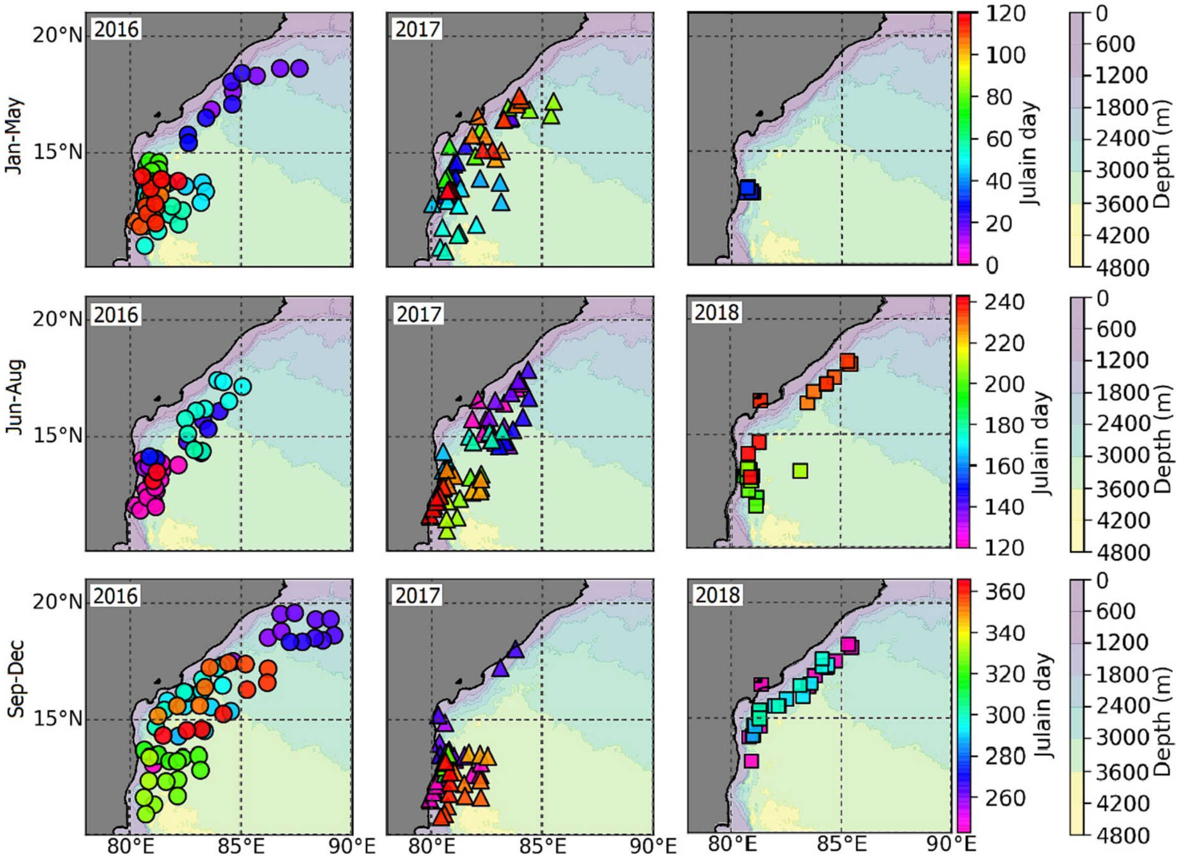


Fig. 1 The bathymetry is overlaid with the hook line fish catch locations using circle, triangle, and square for 2016, 2017, and 2018, respectively. Different colours are indicating the Julian day

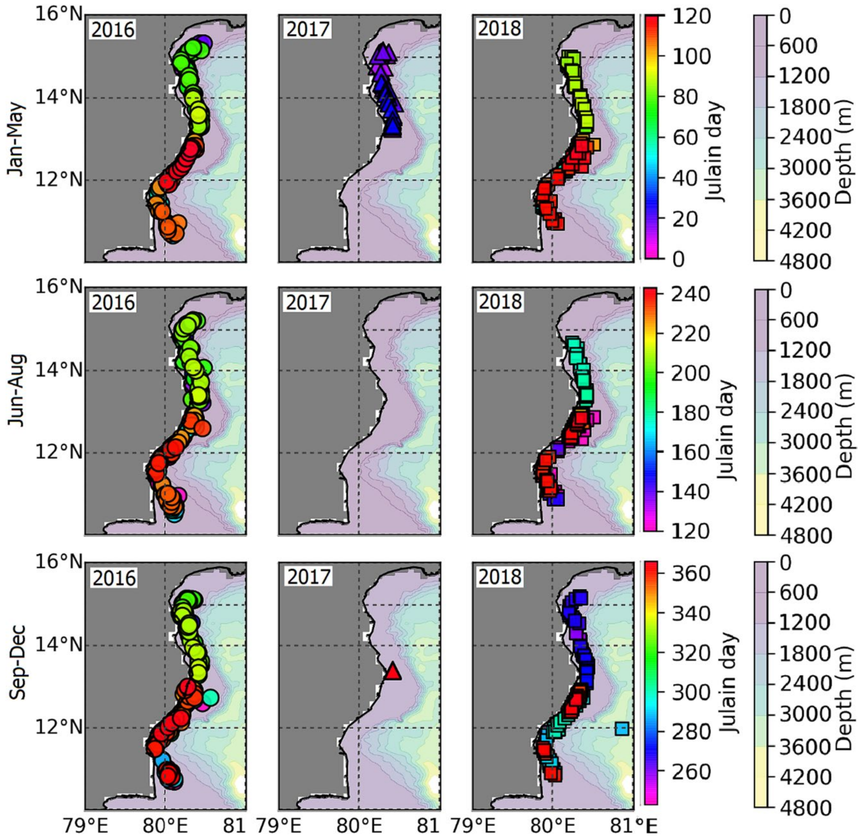


Fig. 2 The bathymetry is overlaid with the trawler net fish catch locations using circle, triangle, and square for 2016, 2017, and 2018, respectively. Different colours are indicating the Julian day

(0–50 kg), moderate (50–100 kg), and high (> 100 kg) fish catch based on CPUE.

The PFZ advisory has been provided to collaborating agencies (CAs) and the near real-time validations were conducted using the help of fishers. In few cases, a satellite-based location-tracking terminal was used to mark the locations where PFZ validation was carried out. This terminal acquires its current location from Global Positioning System (GPS) and transmits it periodically via Geosynchronous Satellite System (GSAT-6 satellite) to Central Hub located at Space Applications Centre (SAC), Ahmedabad. This location tracking information is processed using a data processing software located at Hub. Nabhmitra, a web-based software, was used to view the live location of fishing vessel and plot the entire track of the points.

Results and discussion

A feature-based algorithm has been used to generate PFZ maps for both coastal (bottom trawl operation) and deep (long line operation) fishing locations based on catch data dates. The presence of high chlorophyll concentrations (C) along with thermal fronts (F) and/or cold core eddies (E) are considered to be the best regions for potential fish catch. The PFZ maps identify high chlorophyll patches, SST fronts, and eddies, and compare them with in situ fish catch data, including quantity and geotagged locations obtained from fishing vessels. However, accurate PFZ advisories are difficult to provide during cloudy skies as the infrared and visible channels cannot penetrate through clouds.

Validation of deep water catch data from hooks (Dristi vessel data)

The hook rate (HR) is the measure of the total number fish caught per total number of hooks used, where the high hook rates indicate a good catch. The HR shown in Fig. 3a with different colours for each month during 2016–2018, along with the corresponding PFZ forecast for 2016–2018, obtained from deep fishing conducted continuously for 15–20 days each time. The hook rates are represented with colours overlaid with the generated PFZ advisory. The single, double, and triple dots in the PFZ advisory indicate the availability of high chlorophyll (C), thermal front (F), and cyclonic eddy (E), respectively. Figure 3b shows the average chlorophyll (mg/m^3) overlaid with the eddy periphery (solid line) for the period of October 13–27, 2016. Corresponding fish catch locations with hook rates are shown using different coloured circles in Fig. 3c.

On September 22, 2016, the HR was about 3.87, which coincided with a high chlorophyll (CHL) patch in northwest BoB. On October 19 and 27, there was a high fish catch with a hook rate of 4.29 and 3.33, respectively, observed off central Andhra coast, where CHL in surrounding water was 0.5 mg/m^3. There was persistence of cyclonic eddy in the same region for a month. The HR were very high during December 23–29, when the cyclonic eddy and thermal front were present long with the high CHL on December 23 and 24, respectively.

The thermal gradient and Ekman transport vectors were in the same direction, indicating that cool water was moving to this location, and the persistence of these features resulted in high HR of 3.33, 4.60, 4.92, and 9.52 on December 23, 24, 27, and 29, respectively. The species classification data showed the dominance of yellowfin tuna fish in the deeper waters (3138 m). On August 26, 2018, the catch (230 kg) was very high (HR = 6.19) and coincided with

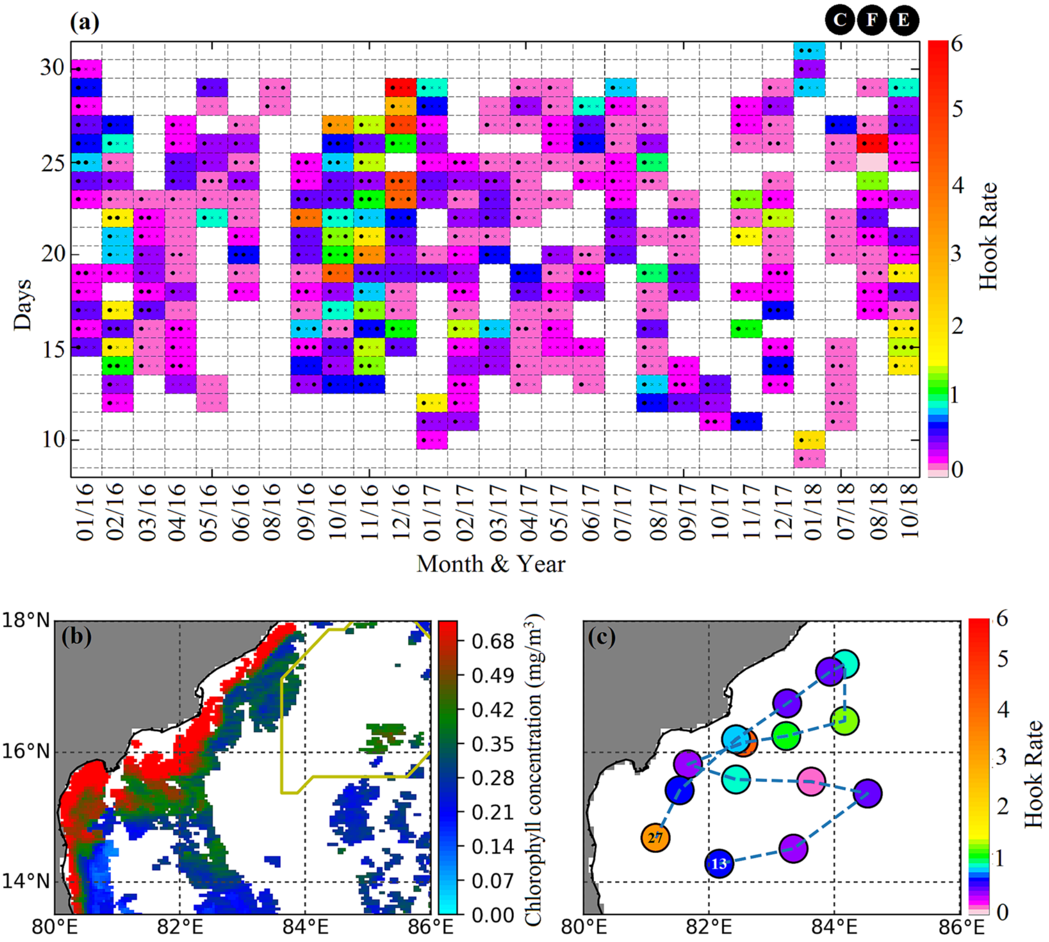


Fig. 3 **a** The hook rate shown in different colours for each month during 2016–2018 with the corresponding PFZ forecast; the C, F, and E are showing the presence of CHL, front, and cyclonic eddy, respectively. **b** The average chlorophyll (mg/m^3) overlaid with eddy periphery (solid line) for October 13–27, 2016, and **c** the fish catch locations with hook rate shown using different colour circle form longline-based deep water fish catch for October 13–27, 2016

high CHL. HR between 1 and 3 is classified as moderate catch, and during February 14, 15, 17, and 22 and October 20–22, 2016, the fish catch was in the moderate range. The high CHL was present in all the cases along with the thermal fronts (on February 22, 2016) and cyclonic eddy (on February 20–22, 2016) on isolated days. Moderate catch was also obtained in 7 days of November, where high CHL and thermal fronts were present on November 14 and 23. The fish catch was quantified as HR = 1.27 and HR = 1.11 for November 14 and 23, respectively. Medium fish catch is listed around 6 days from 2017 to 2018, where only high CHL was present in the catch location except 2 days. No parameters were present on August 24, 2018, and all the parameters were present on November 15, 2018.

About 87% of the total number observation (309) were classified as low catch (HR < 1), and about 31% were observed as zero catch. Only 13% of the total number observations (309) were classified as medium and high catch, which is very less compared to the observation.

Validation of coastal catch data (Samudrika vessel data)

The CPUE is the standard unit for quantifying the amount of fish got from the fishing nets, and the coastal catch is classified into 0–50, 50–100, and > 100 kg (Fig. 4a). Due to the course resolution of the Sea Level Anomaly (SLA) data, and since all the data was collected from the coast, eddy data was not available for the coastal fishing locations. The average chlorophyll (Fig. 4b) and the fishing locations with CPUE (Fig. 4c, d, and e) shown using different

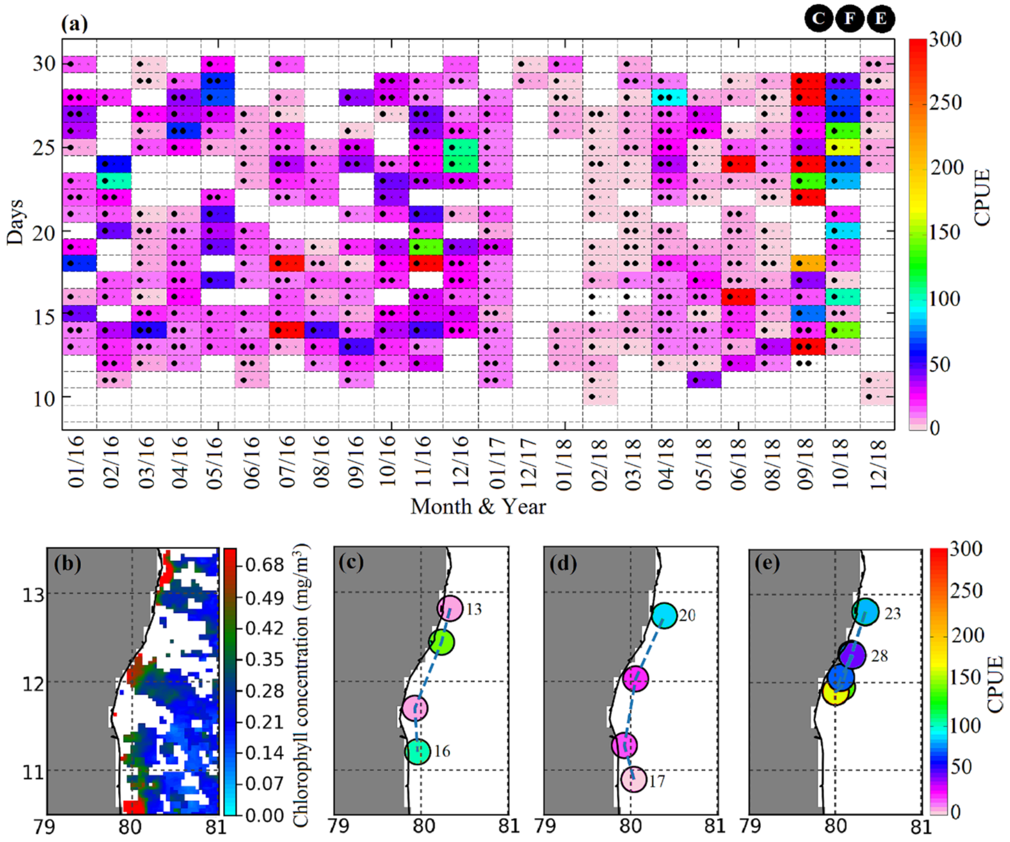


Fig. 4 **a** The CPUE shown in different colours for each month during 2016–2018 with the corresponding PFZ forecast, **b** the average chlorophyll, and **c**, **d**, **e** the fishing locations with CPUE shown using different colour circle form trawl net-based coastal water fish catch for October 13–28, 2018

coloured circle form trawl net-based coastal water fish catch for 13–28 Oct 2018.

About 152 kg (CPUE of 101.33), 438 kg (CPUE of 292), and 746 kg (CPUE of 497.33) were recorded with high CHL on February 23 and July 13 and 18, 2016, respectively. On November 18, the fish catch was very high (706 kg with CPUE 170.67) also coincided with high CHL. On December 24 and 25, very high and dense CHL patches (concentration > 0.7 mg/m^3) were observed along the Tamil Nadu coastal waters, where the total catch was 171 and 162 kg with CPUE of 114 and 108, respectively. On June 16, 2018, high catch of 1000 kg with CPUE 666.67 was observed and was a corresponding high CHL patch in the satellite observations. Similar observations were recorded on June 24, when the catch was ~ 1500 kg with a CPUE 1000.0, consisting large amount of jellyfish.

During September 13 to 29, there were observations of very high catch in the Andhra Pradesh and Tamil Nadu coastal water. These locations were dominated by high chlorophyll and the temperature gradient, and these conditions might have triggered suitable conditions for high fish catch during the period of the next 15 days; the observed catch range was 201 to 2000 kg with a variation in CPUE range of 134 to 1334. During the period October 14–26, 2018, the total catch range was 166 to 243 kg with CPUE ranging in between 104 and 162 from Andhra Pradesh coastal water, where the CHL concentration was very high.

When the CPUE is 50–100 kg, the catch is classified as moderate catch. In 2016, there was very high CHL concentration in the coastal regions of the south of Krishna River on January 18th, 2016 and the total catch weight was 94 kg with CPUE of 62.67. On February 24, 2016, there was high CHL concentration in ranging from 0.6 to 0.7 mg/m^3, and the fish catch was about 90 kg with CPUE of 60 kg. On May 28, 2016, there was an observation of SST fronts and high CHL in this coastal water zone, where the total catch weight was 101 kg with CPUE of 67.33. Subsequently, on the same day, there was an observation of high catch of 86 kg in surrounding water with CPUE of 57.67. On November 14, 2016, the CHL concentration was high (> 0.60 mg/m^3) and 77 kg of fish was caught with CPUE of 81.33. On December 24, there were very high CHL concentration patches (> 0.7 mg/m^3) along the coastal waters, and the total catch was 126 kg with CPUE of 84. On December 25, catch was high, 76 kg with CPUE of 50.67. On April 28, 2018, strong thermal fronts and high CHL patches were observed, and a high catch of 141 kg was obtained from the location with CPUE of 94.0. On September 15 and 18, the catch weight was 95 kg and 75 kg, respectively, and the locations coincide with the high CHL concentrations. There were high CHL features seen on October 16, 20, and 23, in the coastal waters, and got high catch from these locations.

Near real-time validation of the PFZ advisory

The near real-time forecast was generated using the oceanic and atmospheric parameters and sent to collaborators. It is a mandatory to conduct cost-benefit analysis using the real-time fish catch data from a fishing vessel. Collaborating agencies conducted PFZ validation campaigns during 2018–2020.

As explained in the "Data and methodology" section, the PFZ forecast was generated for March 8th, 2019, off the coast of Chennai (Parangipettai). Initially, the forecast provided by ESSO-INCOIS (the yellow lines in Fig. 5a) is checked for March 8th, 2019, which is generated using only SST and CHL. The outputs from feature-based algorithm marked with blue dots in Fig. 5b are compared with operational forecast for off the coast of Chennai (Parangipettai). The PFZ locations are identified and using the information of eddies, SST fronts, Ekman transport vectors, and chlorophyll images to detect is shown in Fig. 5c. Initially, the SST data was used to compute thermal gradients and fronts, forming the initial layer (the black pixels in Fig. 5c). This information gives an indication of the suitability of the fishing grounds for the fishing school. Secondly, the chlorophyll data was checked for the primary productivity as a food source (shaded plot in Fig. 5c). The presence of cyclonic eddy provides additional favo*u*rable information to confirm the PFZ (yellow contour in Fig. 5c). Bottom trawling operations were carried out for both identified PFZ and non-PFZ locations near to 11.5°N and 80°E (those that were not reported by INCOIS).

The satellite-based location-tracking terminal were used for the live location and the fishing vessel track on March 8th, 2019 (Fig. 5d and e). The position of the fishing vessel was continuously monitored using in-house GPS receiver and NABHMITRA web page

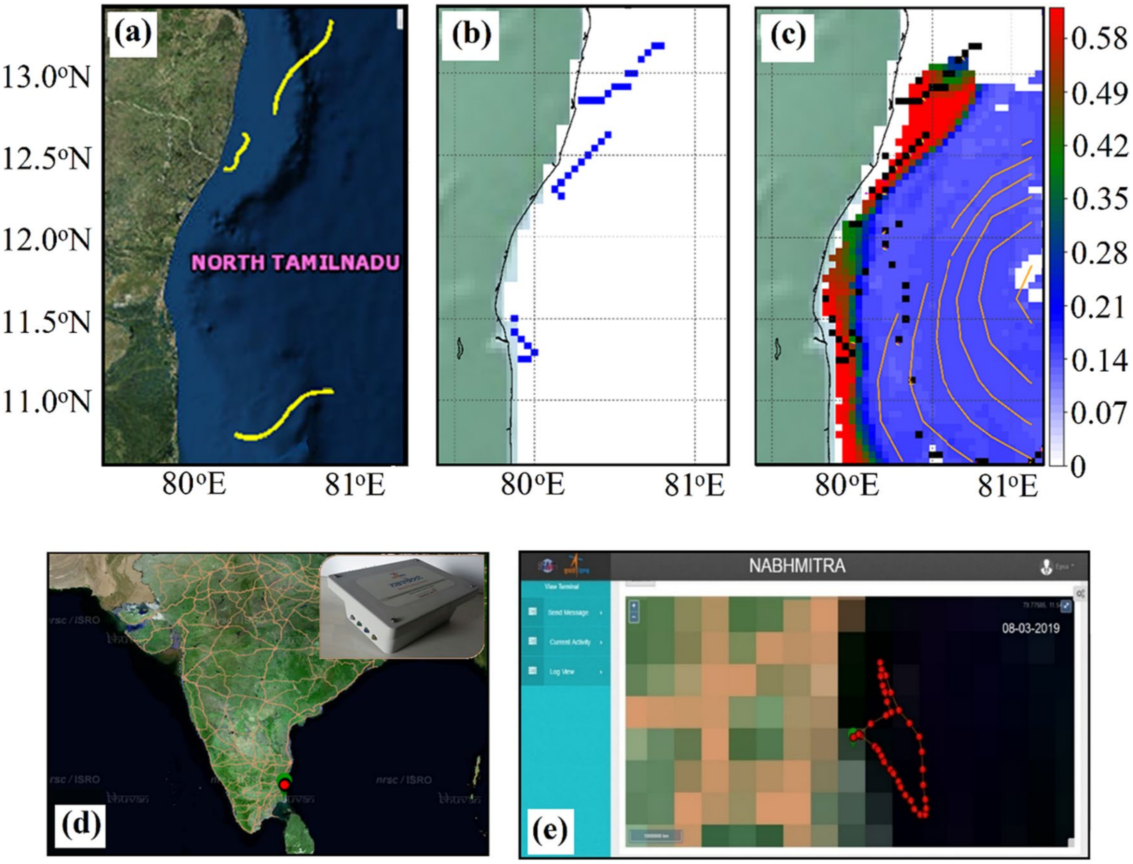


Fig. 5 **a** The operational PFZ forecast given by ESSO-INCOIS for 08-03-2019. **b** Operational forecast generated using multiple ocean and atmospheric parameters by SAC-ISRO. **c** Comprehensive image of the input parameters such as eddies, SST fronts, Ekman transport vectors, upwelling zones, and chlorophyll images to detect and forecast PFZ. **d** The screenshot of the Nabhmitra web page showing the satellite-based location of the tracking terminal, and **e** the zoomed image showing the live location of the boat while doing validation

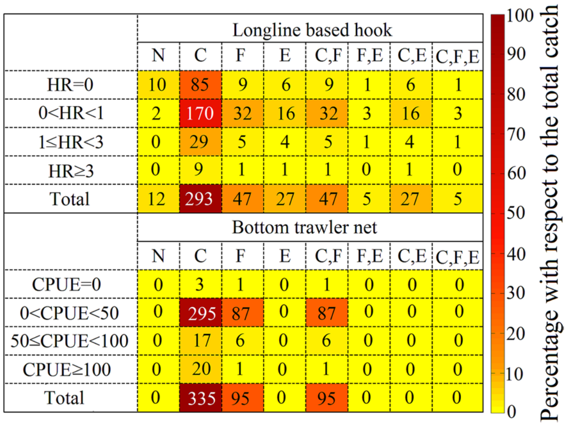
(https://nabhmitra.sac.gov.in/). The vessel's position (latitude and longitude) was updated in every 15 min to the base station.

Initially, the fishing operations were started in the PFZ region and later the experiment was extended to the non-PFZ region. At non-PFZ locations, about six species were found and the total weight was very less (97.83 kg) compared to the adjacent PFZ location (224.9 kg). The major species was cephalopod species (*Loligo vulgaris*) weighing around 7.8 kg. Total 16 species comprised of both finfish and shellfish weighing around 224.9 kg along with trash fishes were caught from the identified PFZ location. The hauling time for the cruise conducted for PFZ location was estimated to be around 2.30 h. The fish species that predominantly contributed in total weight and CPUE were identified as *Loligo vulgaris*, *Selar crumenophthalmus*, *Leiognathus berbis*, *Johnius carouna*, *Mene maculata*, *Stolepherous* spp., *Chelon Parsia*, and *Sepia* sp. The survey conducted at both PFZ and non-PFZ location on the same day revealed the fish composition and total catch seems to have significant variation in both fish species composition and total weight. The CPUE of all the species collected from PFZ and non-PFZ region were observed as 41.6 kg/h and 32.0 kg/h, respectively. The same experiment was repeated on March 12, 2019, using gill nets and line operations at the forecasted PFZ locations near to Parangipettai. The catches were quite significant for all the days and consist of *Sardinella longiceps* (145 kg), *Muraenesox bagio* (50 kg), *Scomberomorous lineolatus* (30 kg), and *Rastrelliger kanagurta* (35 kg).

Daily PFZ forecast advisory has been provided to the Central Marine Fishery Research Institute, Chennai base (CMFRI) during July 2018 to February 2020 for BoB along northern Tamil Nadu and Pondicherry coastal waters. Figure 6 shows the monthly averaged CPUE/fish catch distribution in the PFZ and non-PFZ locations, which clearly depicts the potential of the method in harvesting the fishery resources in BoB using the feature-based method.

Relation between fish catch and algorithm input parameters

The fish catch data points have been correlated with the fishing ground parameters, mainly SST, CHL, and eddy. The study used catch datasets from bottom trawl (336 days) and hook (309 days) between 2016 and 2018. The distribution of catch was analysed for different conditions, such as the absence (N) and presence of only chlorophyll (C), front (F), cyclonic eddy (E), and the possible combinations of C, F, and E for different range of catch (Figure 7). The maximum high catch was obtained when they fishing locations were coincided with the high CHL patch (170 out of 293 for hook and 295 out of 335 days for trawler). The next important parameter is the fronts. The results show the high correlation between catch and CHL, followed by front. The fish catch was maximum when there was a high chlorophyll patch (Fig. 7). Eddy data is available for long line-based hook and is one of the important parameters after CHL and front. Fishing schools prefer (CHL) followed by a comfortable habitat (cold core eddy and thermal front) to sustain. The dependence between fish catch and the number of parameters is shown in Fig. 8. Only a single parameter (either E or F or C) was available in 40% and 60% of the total days for longline and hook, respectively. Two parameters (out of E, F, and C) were available in 13% and 25 %. Not all the three parameters were present in shallow water catch, and eddy data was not available in the coastal waters. However, all parameters were available in 5



	Longline based hook							
	N	C	F	E	C,F	F,E	C,E	C,F,E
HR=0	10	85	9	6	9	1	6	1
0<HR<1	2	170	32	16	32	3	16	3
1≤HR<3	0	29	5	4	5	1	4	1
HR≥3	0	9	1	1	1	0	1	0
Total	12	293	47	27	47	5	27	5
	Bottom trawler net							
	N	C	F	E	C,F	F,E	C,E	C,F,E
CPUE=0	0	3	1	0	1	0	0	0
0<CPUE<50	0	295	87	0	87	0	0	0
50≤CPUE<100	0	17	6	0	6	0	0	0
CPUE≥100	0	20	1	0	1	0	0	0
Total	0	335	95	0	95	0	0	0

Fig. 7 The distribution of catch in the presence of chlorophyll (C), front (F), cyclonic eddy (E) and the possible combinations of C, F and E and absence of any parameter (N) for different range of catch. The colour is showing the percentage of the number of catch with respect to the total number of catch

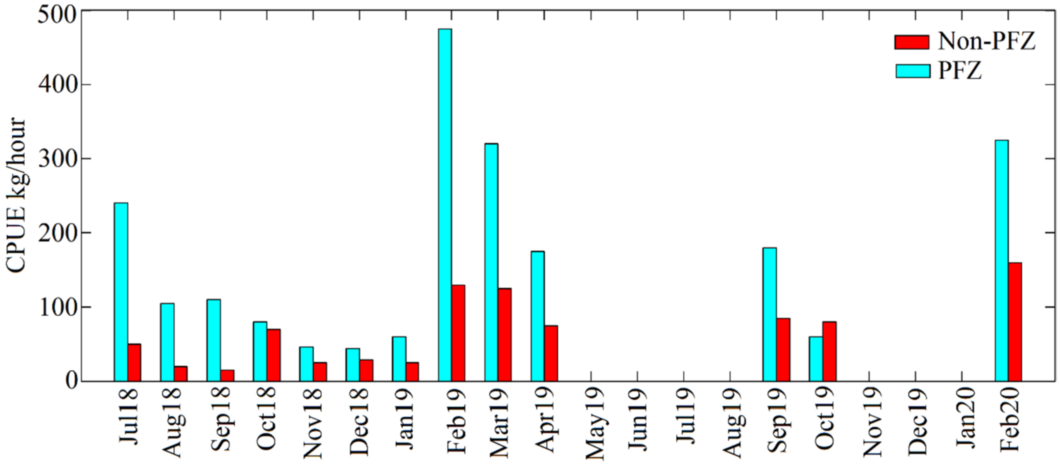
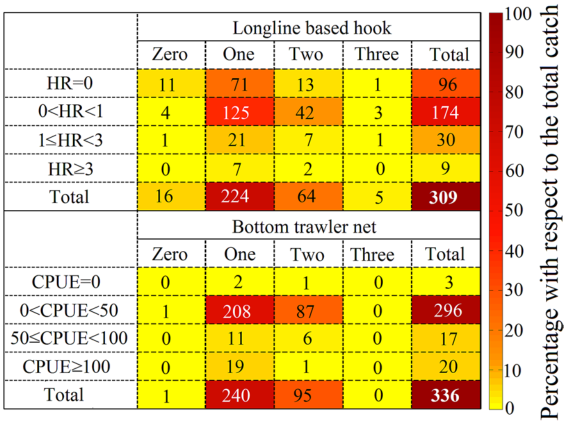


Fig. 6 CPUE in both PFZ and non-PFZ locations in southwest BoB coastal water



	Longline based hook				
	Zero	One	Two	Three	Total
HR=0	11	71	13	1	96
0<HR<1	4	125	42	3	174
1≤HR<3	1	21	7	1	30
HR≥3	0	7	2	0	9
Total	16	224	64	5	**309**
	Bottom trawler net				
	Zero	One	Two	Three	Total
CPUE=0	0	2	1	0	3
0<CPUE<50	1	208	87	0	296
50≤CPUE<100	0	11	6	0	17
CPUE≥100	0	19	1	0	20
Total	1	240	95	0	**336**

Fig. 8 The catch distribution is depicted under various conditions: zero parameters, one parameter, two parameters, and all three parameters from chlorophyll, front, and cyclonic eddy. The color indicates the percentage of catches relative to the total catch, across different catch ranges

days for long line catch. Figure 8 shows the possibility of getting the parameters to give the forecast. Chances of getting all the three parameters are very less, almost zero in the coastal water. The PFZ forecast generated using single or double parameter good enough to forecast the medium catch. This analysis shows the importance of each parameter in the PFZ forecasting system and their relation with the fishing grounds.

The study found an increase in fishery and catch in coastal and deep regions in BoB due to the persistence of high chlorophyll features, which were regulated by wind speed and currents. The decrease in SST and its reducing gradient played crucial role in the catch enhancement. The current study also linked to the observation of eddies in the BoB coastal and deep waters, which seems an important physical oceanographic parameter enhancing the water column productivity. The cyclonic eddy is the cold core eddy, where the central part of the eddy observed to be cooler and highly productive water as compared to peripheral waters. The study observed several mesoscale eddies in the BoB water, which surround fish catch location and were identified as the potential fishing zone locations. Hence, this study has new concepts over the earlier existing PFZ methodologies and validation works for the BoB. This validation shows the efficiency of the PFZ algorithm in monitoring possible fish catch locations. This study proves the significance of satellite images in exposing the multifarious dynamics of PFZ by exploring various ocean conditions that favour fish availability.

Regression analysis between fish catch and algorithm input parameters

To confirm the contribution of each parameter and their relationship with the catch, a regression analysis is carried out with the input parameters. The results confirm the clear pathway of the food, comfort zone, and persistence. The fishes are highly attracted by the food, and the presence of CHL has high weightage with fish catch. The SST, thermal front, and Eddy are other parameters which are directly influenced to the fish catch and CHL. The analysis was conducted for four different categories of the catch datasets of bottom trawl and hook datasets during 2016–2018. The multiple regression (Fig. 9) of above parameters with the HR $>$ 1.0 and CPUE $>$50 category points depicted the high correlation (0.608 and 0.498 for hooks and trawler, respectively); hence, this relationship can be used to forecast the PFZ locations with high catch. The multiple regression for other categories (HR $<$ 1.0, CPUE $<$ 50) in between model and predicted are 0.0712 and 0.118 for hooks and trawler, respectively. This result is also evident in regression analysis (Fig. 9). Although getting very high catch is very rare in the ocean, this study is confirming the applicability of the forecasting method for medium catch.

Conclusion

In the present study, the feature-based PFZ algorithm developed was validated with hindcast datasets obtained from FSI and CMFRI, which proved useful in monitoring and identifying PFZ regions in the BoB over different months and seasons. This algorithm is a modified method compared to the conventional approach that uses satellite-derived SST and chlorophyll. The study aimed to establish a link between fish catch availability and various ocean parameters available from satellites, such as chlorophyll, SST, SST gradients, SSHA, ocean surface currents, and wind vectors. The study inferred about the identification of productive zones based

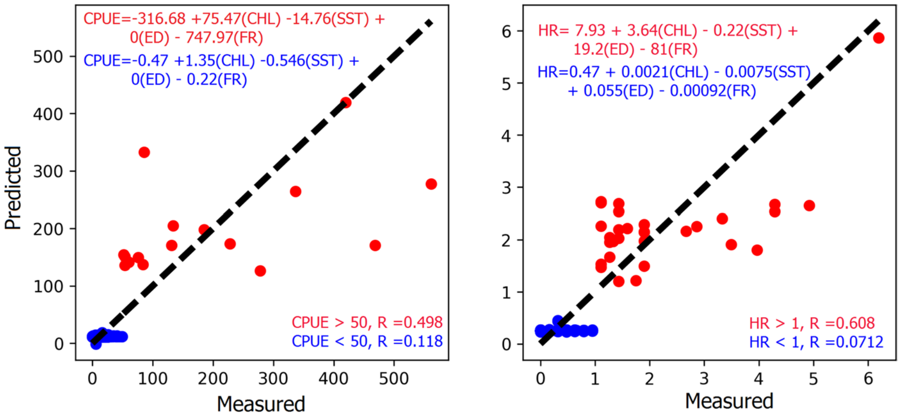


Fig. 9 Regression results of fish catch data from hook and trawler with the prediction for HR > 1, HR < 1, CPUE > 50, and CPUE < 50 for BoB

on prevalent eddy information along with SST fronts and chlorophyll. The current data provides valuable information on the persistence of productive features in the sea and their propagation. High fish catch rates based on hook rate and high CPUE have been observed in BoB catch locations that are relatively well-matched and collocated with high chlorophyll persisting features and thermal gradients. The catch has a high relationship with the availability of the food (CHL) followed by comfort condition (fronts and eddy). These results are confirmed using regression analysis. The high catch PFZ locations can be predicted using the SST, CHL, thermal fronts, and eddy information. This method-based validation has advantages over previous approaches that only use SST and chlorophyll, as here the wind and current-derived data could locate PFZ persistent features for 2 to 3 days, and high fish catches observed in the forecasted locations, and even in cloudy regions, have been successfully validated.

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Data availability The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Ethics approval and consent to participate Nothing to declare

Consent for publication All authors agree on submitting the present version.

Competing interests The authors declare no competing interests.

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