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Impact of sea surface temperature fronts on the spatial distribution of jellyfish in the northern Arabian sea

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ABSTRACT

Identifying the spatial distribution of species and their relationship with environmental factors is crucial for conservation and management efforts. In Pakistan, jellyfish are economically significant and serves as an important fishery resource. This study utilized both *in-situ* and satellite data to investigate the relationship between fish catch and sea surface temperature (SST) gradient magnitude (GM). Notably, an unusually high subsurface Chlorophyll *a* (Chl-a) level (~1.5 mg/m^3) was observed, significantly higher than surrounding waters (~0.5 mgm^{-3}). Additionally, on October 27 at station 6, a high SST GM of 0.097 °C km^{-1} was recorded alongside an elevated subsurface Chl-a of 1.24 mg/m^3. Low salinity levels (<36.2 psμ) were detected in areas with strong frontal activity, while higher levels (>36.7 psμ) were observed in the surrounding regions. Moreover, a high wind stress curl (>0.4 N/m^3) was noted in regions with strong SST fronts along coastal and offshore areas of Balochistan and Sindh. A strong correlation ($R^2 = 0.987$) was identified between annual fish catch and catch per unit effort (CPUE). The study revealed a significant fish catch (>200 kg) along the Balochistan coast and the Indus River estuary, with the exception of one offshore catch station. Results also indicated a strong correlated ($R^2 = 0.73$, $p < 0.001$) between SST GM and fish catch in the upper layer (<50 m depth). By establishing a GM threshold at 0.06 °C km^{-1}, there was an 80% likelihood of achieving a high catch within the upper 50 m layer. These findings enhance our understanding of how SST fronts influence the spatial distribution of jellyfish and improve our ability to forecast jellyfish fishing grounds in the northern Arabian Sea.

1. Introduction

Marine fisheries are complex and dynamic ecosystems that play a crucial role as source of income and employment worldwide (FAO, 2023). However, many global fisheries resources are either fully exploited or overexploited (FAO, 2010). Understanding oceanic parameters is essential for assessing their impact on fish populations and ensuring sustainable management. Satellite remote sensing serves as a powerful tool for observing large-scale oceanic processes, offering extensive spatial coverage and high temporal resolution. By monitoring the ocean surface through satellite remote sensing yields valuable data on various factors that influence fish habitat suitability. Ocean dynamics significantly affect the habitats of fish and squid, promoting these species to migrate to areas that are provide optimal conditions for shelter, reproduction, and feeding (Olson, 2002; Palacios et al., 2006). Therefore, changes in oceanic properties can act as indicators of the abundance and distribution of fish stocks in specific regions (Solanki et al., 2003; Zainuddin et al., 2006).

Jellyfish, belonging to the phylum Cnidaria and class Scyphozoa, are primarily pelagic species that have gained increasing attention due to

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their interactions with human activities, including fisheries, aquaculture, and tourism (Lucas et al., 2014). They can be easily harvested using various fishing methods, such as dip-netting, drift netting, hand nets, gill netting, and purse seining (Brotz et al., 2017). Among these, dip-netting is particularly effective for capturing jellyfish, as it minimizes bycatch and reduces environmental impact (Brotz et al., 2017). Beyond their ecological significance, jellyfish are a traditional food in Chinese cuisine and are gaining popularity in other countries, driven by high commercial demand (Hsieh and Rudloe, 1994; Li and Hsieh, 2004; Kingsford et al., 2000; Nishikawa et al., 2008; Kitamura and Omori, 2010). They are migratory species predominantly found in the tropical and subtropical waters of the Indian and Indo-Pacific regions. Their fishing grounds are influenced by environmental factors, which in turn affect their vertical and horizontal migration patterns (Graham et al., 2001). In Pakistan, jellyfish are considered commercially important fishery resources that contribute to the national economy. Number of studies have focused on the stock assessment of different fish species, indicating over-exploitation in Pakistani waters (Kalhoro et al., 2014a, 2014b, 2015a, 2015b, 2017, 2018, 2024a,b). The decline in stocks of other valuable fish species since 1999 has further highlighted the significance of jellyfish in the region (Graham et al., 2001). Two edible jellyfish species, *Catostylus perezi* (Ranson, 1945), and *Rhopilema hispidum* (Vanhöffen, 1888), are particularly important and commonly harvested in Pakistani waters (FAO, 2009; Gul et al., 2015). Among marine invertebrates, jellyfish are one of the least-studied groups. Despite their seemingly simple biology, they possess a remarkable ability to survive, and their populations have been steadily increased in recent decades (Williams, 2015). No specific studies have been conducted in Pakistan to determine the optimal temperature range for jellyfish or the impact of oceanic parameters on their distribution. Most catches of *Catostylus perezi* and *Rhopilema hispidum* have been observed in Indian waters, the offshore areas of Balochistan, and the inshore waters of Sindh, particularly from March to May and October to December, as well as in July and August (Gul et al., 2015; Kumawat et al., 2023). However, jellyfish are generally found within a narrow temperature range of 26–30 °C (Mills, 2001).

Sea surface fronts are critical to oceanic processes and productivity, playing a significant role in fish ecology. Sea surface temperature (SST) fronts are defined as boundary layers between two distinct water masses that facilitate nutrient exchange, enhance primary production, and contribute to the accumulation of marine organisms (Chen et al., 2009; Belkin et al., 2009). These fronts are characterized by abrupt changes in salinity, temperature, and Chlorophyll-a concentration (Chl-a) (Belkin et al., 2009), and can form as a result of wind-driven upwelling, tidal currents, or freshwater discharge from rivers. SST fronts exhibits strong vertical motions on both sides, leading to intensive mixing that increases phytoplankton biomass. Depending on their location, SST fronts can be categorized as open water, shelf, or coastal fronts (Yanagi and Koike, 1987). They can be classified by their duration as permanent, occasional, or seasonal fronts (Ye et al., 2017).

Fishery scientists have extensively studied oceanic fronts globally, hypothesizing that fish biomass is more abundant near these fronts due to elevated nutrient levels and enhanced primary productivity (Tang et al., 2002; Tseng et al., 2014; Alemany et al., 2014). The physical processes associated with SST fronts are closely linked to productive fish habitat (Block et al., 2002; Munk et al., 2009). As a result, identifying the spatial distribution of species and their relationship with environmental factors is essential for conservation and sustainable management. Commonly utilized ocean satellite observations include SST, SST fronts, Chl-a and Chl-a fronts, all of which directly impact fish habitats. Other important oceanic observations include wind speed, ocean currents, upwelling zones, frontal boundaries, and various oceanographic phenomena. Sea surface fronts can be instrumental in detecting pelagic fish habitats, identifying biological hotspots (Worm et al., 2003; Bakun, 2006), and prioritizing marine conservation efforts (Yen et al., 2004; Etnoyer et al., 2004). SST fronts, generated by various oceanographic processes, serve as a crucial indicator of these dynamic and productive marine environments.

Several studies have been published on identifying potential fishing zones using various methods, often employing satellite and remote sensing technologies (Solanki et al., 2010; Choudhury et al., 2007; Bhaware et al., 2013). However, there is limited literature validating potential fishing zones, particularly concerning SST gradient magnitude (GM). Pelagic fisheries typically migrate in response to changes in physicochemical and biological parameters. In Pakistan, where the fisheries sector is vital to the national economy and employment, traditional shipborne research surveys to identify fishing ground can be prohibitively expensive. Remote sensing offers a cost-effective alternative for studying vast oceanic regions, aiding in fisheries management, and providing valuable guidance to fishermen to enhance their catch efficiency. This study is the first of its kind to utilize both *in-situ* and ocean color data to identify potential fishing zones in northern Arabian Sea, Pakistan.

There have been no previous studies examining the relationship between SST GM and the spatial and temporal variation of pelagic fisheries, such as jellyfish, in Pakistani waters, northern Arabian Sea. This study aims to establish the connection between SST fronts and the spatial distribution of jellyfish. By utilizing *in-situ* data (temperature, salinity and Chlorophyll-a) along with SST and SST GM derived from MODIS Aqua satellite, as well as Chl-a, and wind stress curl (WSC) data from Copernicus Marine and Environment Monitoring Service. This research seeks to predict and provide insights into suitable jellyfish habitats in the northern Arabian Sea. This study reveals important connection between jellyfish distribution and SST GM, along with the effects of other ocean conditions. These findings elucidate how SST fronts impact oceanic environment and, ultimately, the distribution of fish species. By improving fish catch predictions, this research offers valuable benefits for both fishermen and fisheries management.

2. Study area

Pakistani waters are located in the northern part of the Arabian Sea, bordered by northwest Iran and southwest India. The Arabian Sea has long been recognized as a focal point for scientific research, recognized as one of the most complex marine regions in the world (Smith et al., 2006). This area is highly productive, attracting scientific interest (Madhupratap et al., 1996), and characterized by intricate flow patterns, including multiple eddies (Böhm et al., 1999). A prominent seasonal shift in monsoonal circulation occurs, featuring a strong southwest jet during summer and cool, dry northeasterly winds in winter (Shukla and Misra, 1977). The primary production of Chl-a is associated with the deepening of the mixed layer (Prasanth et al., 2021). During the summer monsoon, coastal upwelling occurs along the eastern and western boundaries of the Arabian Sea (Brock et al., 1991). In winter, vertical mixing driven by northeast monsoonal winds significantly effects both costal and open ocean upwelling, leading to phytoplankton biomass (Shafeeque et al., 2021). Numerous studies have emphasized the productivity of the Arabian Sea, particularly examining the impact of cyclones on Chl-a and Chl-a frontal eddies (Tang et al., 2002; Sravanthi et al., 2017; Kalhoro et al., 2024c). Pakistan coastline, which stretches for approximately 1001 km long, is divided into two main regions: Sindh and Balochistan. The Sindh coast spans about 266.5 km and receives substantial freshwater inflow from the Indus River, fostering a rich mangrove ecosystem with numerous creeks. In contrast, the Balochistan coast extends about 734.5 km and features a sharply defined continental shelf with an uneven, generally rocky seabed. This region included notable bays, such as Sonmiani, Ormara, Pasni, Gwadar, and Giwani. Additionally, Pakistani waters encompass a 250, 000 km^2 Exclusive Economic Zone (EEZ) that borders with Iran, Oman, and India. This offering opportunities for the exploration and exploitation of marine resources (see Fig. 1).

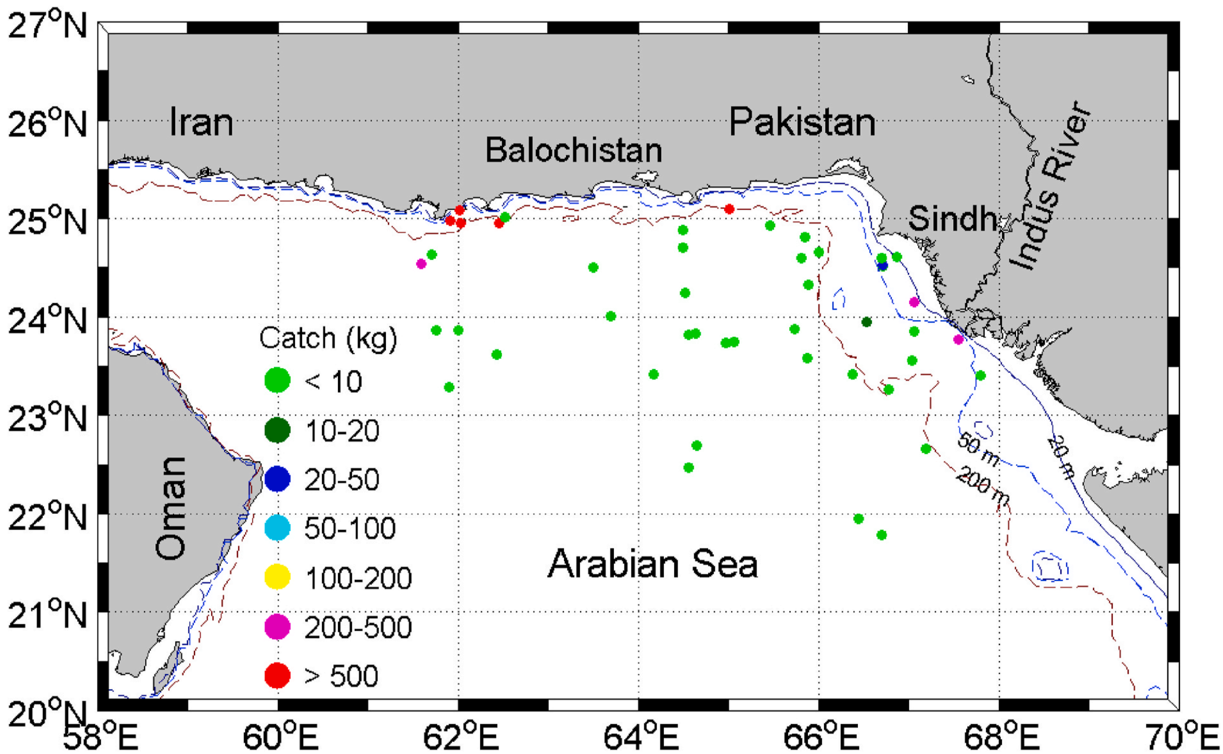

Fig. 1. Spatial distribution of jellyfish catch rate showing in different color circles in northern Arabian Sea, Pakistan. Green dot: <10 kg, dark green dot: 10–20 kg, dark blue dot: 20–50 kg, light blue dot: 50–100 kg, yellow dot: 100–200 kg, pink dot: 200–500 kg, red dot: >500 kg. The blue line, dashed blue line and red dot line showing the isobaths of 20 m, 50 m, and 200 m, respectively (The data collected during a research survey and plotted using MATLAB v.R2020a in present study). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Materials and methods

3.1. Fish catch data

Daily jellyfish catch data was obtained from a fishery resources survey conducted by Food and Agriculture Organization (FAO) and the Marine Fisheries Department (MFD), Karachi, Pakistan. The survey utilized the Norwegian research vessel *Dr. Fridtjof Nansen* and the fishing boat *Mahboob-e-Madina*. A total of 49 fishing trawl stations were surveyed, with jellyfish being caught at 36 of these stations (73.47%). Each trawl lasted approximately 30 min, traveled at 3.5 knots, and covered a distance of about 1.75 nautical miles. During each trawl, time, date, and position were meticulously recorded (Fig. 1). All species caught during research survey were identified, and their weight and number were recorded. Two edible jellyfish species, *Catostylus perezi* and *Rhopilema hispidum* were identified; however, during survey, the jellyfish were generally referred to as both species. Additionally, annual catch data in metric tons (mt) and effort (number of fishing boasts) for jellyfish from 2007 to 2021 were obtained from handbook of fisheries statistics of Pakistan, compiled by MFD, Karachi, Pakistan.

3.2. In-situ oceanographic observations

In-situ oceanographic observations were conducted using, conductivity, temperature, and depth (CTD) measurement collected from 45 hydro-stations in October. A Seabird 911+ CTD probe was utilized to record vertical profile of temperature (°C), salinity (psu), and Chlorophyll-a (Chl-a) concentration (mg/m^3).

3.3. Satellite observation

Daily multiscale ultrahigh resolution (MUR) SST analysis data, with a spatial resolution of 0.011°, are available from June 2002. This dataset is produced by merging data from MODIS, AMSR-E, and AVHRR and can be assessed from the NASA Jet Propulsion Laboratory (http://data.nodc.noaa.gov/ghrsst/L4/GLOB/JPL/MUR/). For this study, daily MUR SST data from August to November 2010 was retrieved to analyzed the SST gradient magnitude (GM). Daily GlobColour-merged Chlorophyll-a products based on satellite observation, was derived from Copernicus Marine and Environment Monitoring Service (CMEMS-https://data.marine.copernicus.eu/product/OCEANCOLOUR_GLO_BGC_L4_MY_009_104/description) with a spatial resolution of 4 × 4 km. Daily wind stress curl (WSC) was derived from Copernicus Marine and Environment Monitoring Service (CMEMS- https://data.marine.copernicus.eu/product/WIND_GLO_PHY_L4_MY_012_006/description), with spatial resolution of 0.125° × 0.125°.

3.4. SST GM detection

Various methods for detecting oceanographic fronts from satellite imagery utilize a range of algorithms from simple to complex (Belkin and O'Reilly, 2009; Lan et al., 2009; Huang et al., 2010). In this study, a straightforward method based on SST gradient magnitude (GM) method was utilized. The intensity of the SST front was quantitatively assessed using the SST GM for each geo-referenced grid. The SST GM at a given pixel is defined as:

$$GM = \sqrt{(\partial T/\partial x)^2 + (\partial T/\partial y)^2} \Big/ 1.2\ (^\circ\mathrm{C\ km^{-1}}) \tag{1}$$

$$D = \sqrt{(\Delta x + \Delta y)^2} \tag{2}$$

In equation (1), where T represent SST, and the x and y axes are directed toward the east and north, respectively. The GM was computed at all pixels for each image. Note that, the MUR data has a spatial resolution of 0.011° × 0.011° (≈ 1.2 km × 1.2 km), the SST GM values were divided by 1.2 in the upper equation. While equation (2), where D denotes the distance between catch location and the nearest SST GM. The gradient threshold was set at 0.06 °C km^{-1} (Saraceno et al., 2005; Ye et al., 2017), and only regions with GM values exceeding this threshold were defined as fronts and identified as potential fishing zones.

3.5. *Flowchart to define the methodology*

The flowchart (Fig. 2) outlines the research methodology employed to analyze the impact of SST fronts on jellyfish distribution. It details the processes of data acquisition and validation using satellite remote sensing data (SST, SST GM, and Chl-a), derived from MODIS and CMEMS, complemented by *in-situ* oceanographic and fish catch data. This validated dataset is then utilized to predict how SST fronts influence jellyfish distribution, enabling the identification and mapping of potential jellyfish hotspots within the study area. The flowchart ultimately guides the visualization of predicted zones where jellyfish are most likely to occur, providing valuable insights for ecological monitoring and management. This research also assists fishery managers in understanding the importance of oceanographic parameters on the spatial distribution of fish species. Furthermore, it assists policymakers in recognizing the need to enhance the capacity of fishery-related institutions by conducting a series of research surveys and utilizing satellite remote sensing observations for the continues monitoring of fisheries resources.

4. Results

4.1. *Spatial distribution of jellyfish in the northern Arabian sea*

The spatial distribution of jellyfish in the northern Arabian Sea, Pakistan, was analyzed using short-term satellite and *in-situ* data from

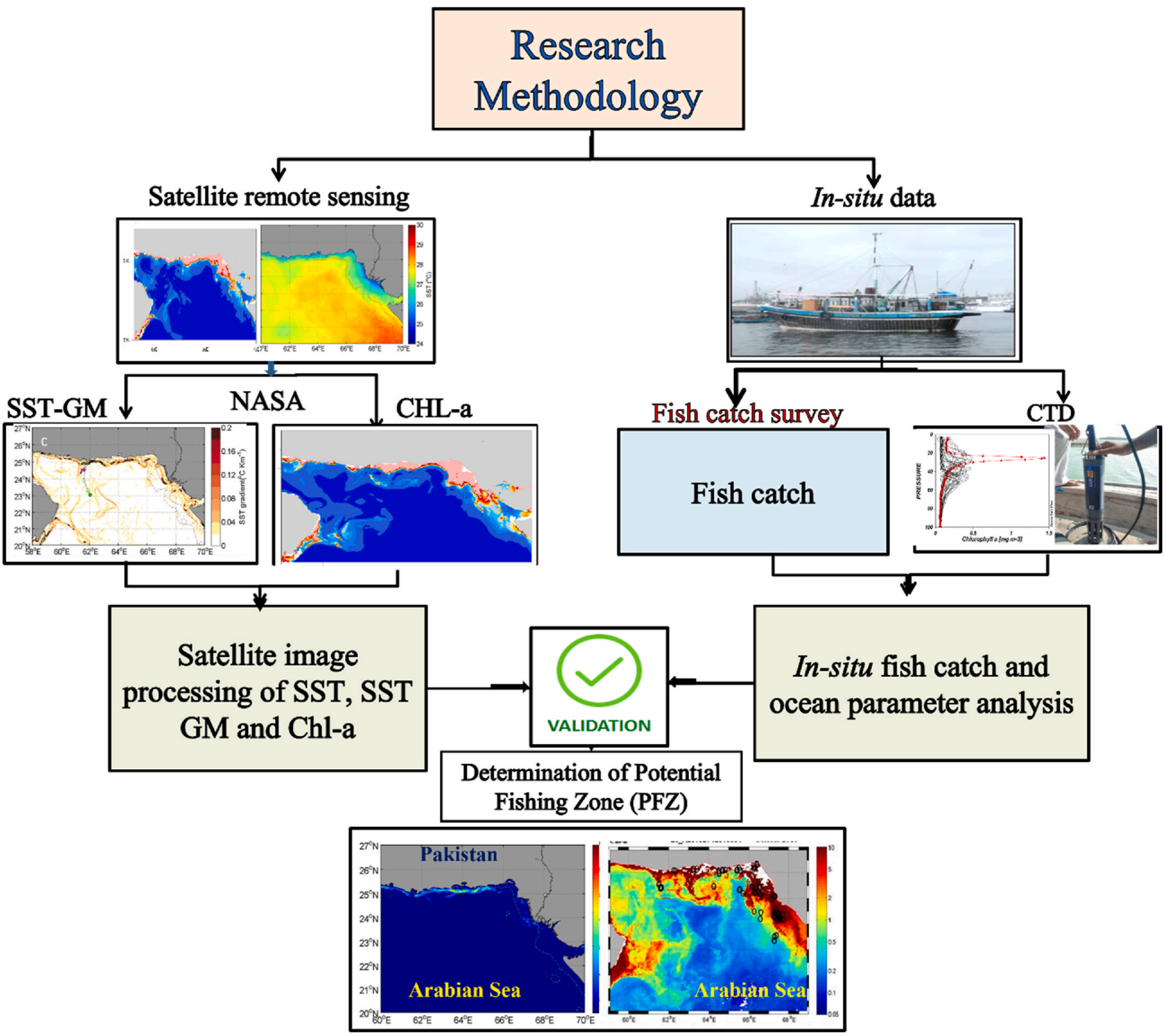

Fig. 2. Flowchart (adopted in present study) illustrate the steps involved in research methodology for current study in Arabian Sea. Images used in this flowchart are: Satellite SST-GM, CHL-a used in present flowchart were retrieved using MODIS (http://data.nodc.noaa.gov/ghrsst/L4/GLOB/JPL/MUR/), and Copernicus Marine and Environment Monitoring Service (CMEMS), (https://data.marine.copernicus.eu/product/OCEANCOLOUR_GLO_BGC_L4_MY_009_104/des), and plotted using MATLAB v.R2020a, and *In-situ* CTD profile graph plotted using Ocean Data View (ODV) open source software, and instrument used in flowchart were taken during research survey. Fishing boat namely *Mahboob-e-Madina* used during present survey and taken during present research survey.

October 2010. Fig. 1 illustrates the distribution of jellyfish catches, revealing generally low catch rates (<10 kg) in the offshore waters of Balochistan and Sindh beyond the 200 m isobaths. The highest catch rates were observed within the 200 m isobaths along the Balochistan coast and between the 20 m and 200 m isobaths in the Indus River estuary. Approximately 90.6 % of the high jellyfish catches were recorded along the 200 m isobath off Balochistan and between the 20 m and 50 m isobaths off the Sindh coast (Fig. 1). Notably, high catches (indicated by pink dot, >200 kg) were recorded near the Indus River estuary along the 20 m and 50 m isobaths off Sindh. While, the highest catches (indicated red dot, >500 kg) were found along the 200 m isobath off the Balochistan coast. An exceptional catch (>350 kg) was recorded on 27 October at 61.5°E, 24.54°N in the offshore waters along the Balochistan coast (Fig. 1).

4.2. Annual catch of jellyfish fishery

The analysis of catch and effort date for the jellyfish fishery in Pakistan from 2007 to 2021 is presented in Fig. 3. This data includes catch weight in metric tons (mt) and effort, representing by the number of fishing boats. The highest catches were recorded in 2019, 2020 and 2021, with the overall catch trends closely following the catch per unit effort (CPUE) (Fig. 3a). Notably, annual jellyfish catches have increased in recent years, underscoring the growing importance of the jellyfish fishery in Pakistan. The average annual landing of jellyfish was 3060 mt, with an average CPUE of 0.161. A strong correlation was found between annual jellyfish catch and CPUE, with an $R^2 = 0.987$, $p > 0.001$ (Fig. 3b). This significant correlation indicates the increased fishing effort is likely to lead to higher jellyfish catches in the region.

4.3. In situ CTD observation

During the fish catch survey, 45 hydro stations were conducted throughout Pakistan EEZ (Fig. 4). The vertical profiles of temperature (^{o}C), salinity (psu) and Chl-a (mg/m^3) from the offshore hydro stations are shown in Figs. 4 and 5. Notably, station A was surveyed on October 19, while stations 1–7 were surveyed on October 26–27. These stations are significant as they were located within or near areas of SST fronts. At most stations, high salinity levels (>36.7 psμ) were observed in the upper 50 m depth layer, with the exception of station A, 1, and 6. High Chl-a concentration (~0.5 mg/m^3) were noted at the subsurface layer (at 50 m depth), while exceptionally high Chl-a levels were observed in the upper layer (<50 m) at stations A and 6. The vertical profiles indicated high temperatures in the surface water, except at stations A, 1, and 6. It is important to note that the high jellyfish catch in offshore waters on October 27 may be linked to the high SST GM observed on October 26. These specific cases are discussed in detail.

4.4. Case 1: October 19, 2010

The vertical profiles of temperature, salinity, and Chl-a at station A, located in offshore waters and surveyed on October 19 (Fig. 4a). The observations revealed a notable lower surface temperature (~28 °C) at station A compared to the surrounding waters (>29 °C) (Fig. 4d). Additionally, the salinity at station A was recorded at 36.2 psμ in the upper layer, showing a slight decrease to 36.1 psμ at 100 m, which is an unusual phenomenon (Fig. 4e). Furthermore, a very high Chl-a concentration (~1.5 mg/m^3) was observed in the surface waters (20–30 m depth), significantly higher than the surrounding waters, where Chl-a were below 0.5 mg/m^3 (Fig. 4f).

These *in-situ* observations at station A align with the satellite SST imagery, which also indicated a lower temperature of approximately 28 °C (Fig. 4b). This temperature anomaly may be attributed to a strong SST GM (~0.06 °C km^{-1}) likely caused by upwelling on October 19, which brought colder, Chl-a-rich subsurface waters to the surface (Fig. 4c). The elevated Chl-a levels were similarly detected through satellite observations at same location (Fig. 4g). The *in-situ* data corroborate the impact of SST GM and the increase in high Chl-a levels on the alteration of oceanic properties. A high wind stress curl (WSC) of >0.4 N/m^3 was noted in the region of strong SST fronts along the costal and offshore areas of Balochistan (Fig. 4h). However, strong WSC was only observed in the coastal region of Sindh. (Fig. 4h). This supports the notion that SST fronts induce discontinuities in physical and biological properties between different water masses. Similar observations of low temperature and high Chl-a at station 1 on October 26 were also captured by satellite images (Fig. 4).

4.5. Case 2: October 26–27, 2010

The *in-situ* vertical profiles of temperature, salinity, and Chl-a were recorded at stations 1–7 on October 26–27, 2010 (Fig. 5). The observations revealed low temperatures and salinities in the upper layers at station 1, alongside a shallower depth of high Chl-a concentration, indicating recent mixing and upwelling events. At station 6, the vertical profile showed a low temperature of 26.96 °C and salinity of 36.40 psμ in the upper layer (Fig. 5a and b). In contrast, station 5 exhibited higher temperatures at 28.71 °C and salinities at 36.63 psμ. The distance between these two stations was approximately 18 km, leading to a calculated SST GM of about 0.097 °C km^{-1}, which was also observed in the satellite data for October 26 (Fig. 6c). The waters at station 6 were characterized by an unusually high subsurface Chl-a concentration of 1.24 mg/m^3 at 15 m, compared to other stations where Chl-a levels were below 0.5 mg/m^{-3} at similar depths (Fig. 5c).

The presence of a low SST patch (<27.5 °C) and an occasional SST front (GM > 0.06 °C km^{-1}) observed near station 4 on October 26–27 (Fig. 6a,b,c,d) suggests that nutrient-rich and Chl-a-rich subsurface waters were uplifted to the surface due to mixing and upwelling (Fig. 6e and f). Additionally, a high wind stress curl (WSC) of >0.4 N/m^3 was noted in regions with strong SST fronts along the coastal and offshore areas of Balochistan, compared to the surrounding waters (Fig. 6g and h). This phenomenon likely contributed to the high jellyfish catch recorded on October 27 (indicated in pink in Fig. 5). Satellite observations of Chl-a confirm that the high concentrations were found in the same locations where low SST and strong SST GM were observed on October 26 and 27. The distance between the SST GM and the station with high jellyfish catch was approximately 19 km.

4.6. SST GM and their relation to jellyfish distribution

The impact of SST GM on jellyfish distribution was analyzed in this study. Fig. 7 displays a scatter plot demonstrating a strong correlation between jellyfish catches and SST GM, with the maximum GM recorded within 19 km of the catch stations. A significant correlation was found between jellyfish catch and SST GM, with $R^2 = 0.58$, $p < 0.001$ (black line). Further analysis of catches in the upper layer (depths <50 m) revealed an even stronger correlation with SST GM, with $R^2 = 0.73$, $p > 0.001$. When applying a threshold of SST GM > 0.06 °C km^{-1}, there is an 80 % probability of high jellyfish catches occurring in the upper layer compared to areas with lower SST GM. This suggests that regions with higher SST GM are more likely to produce substantial jellyfish catches in the upper water column.

5. Discussion

SST fronts significantly enhance Chl-a concentration compared to surrounding waters, attracting fish and increasing biodiversity. Chl-a is a key indicator of phytoplankton production and is essential for assessing aquatic health and function (Smith, 2006; Werdell et al., 2009; Zhao and Zhang, 2014). However, its distribution is mainly regulated by ocean dynamics (Signorini et al., 2015). Previous studies have confirmed that both coastal and offshore SST fronts, whether permanent or occasional, can elevate Chl-a levels due to increased nutrient availability and

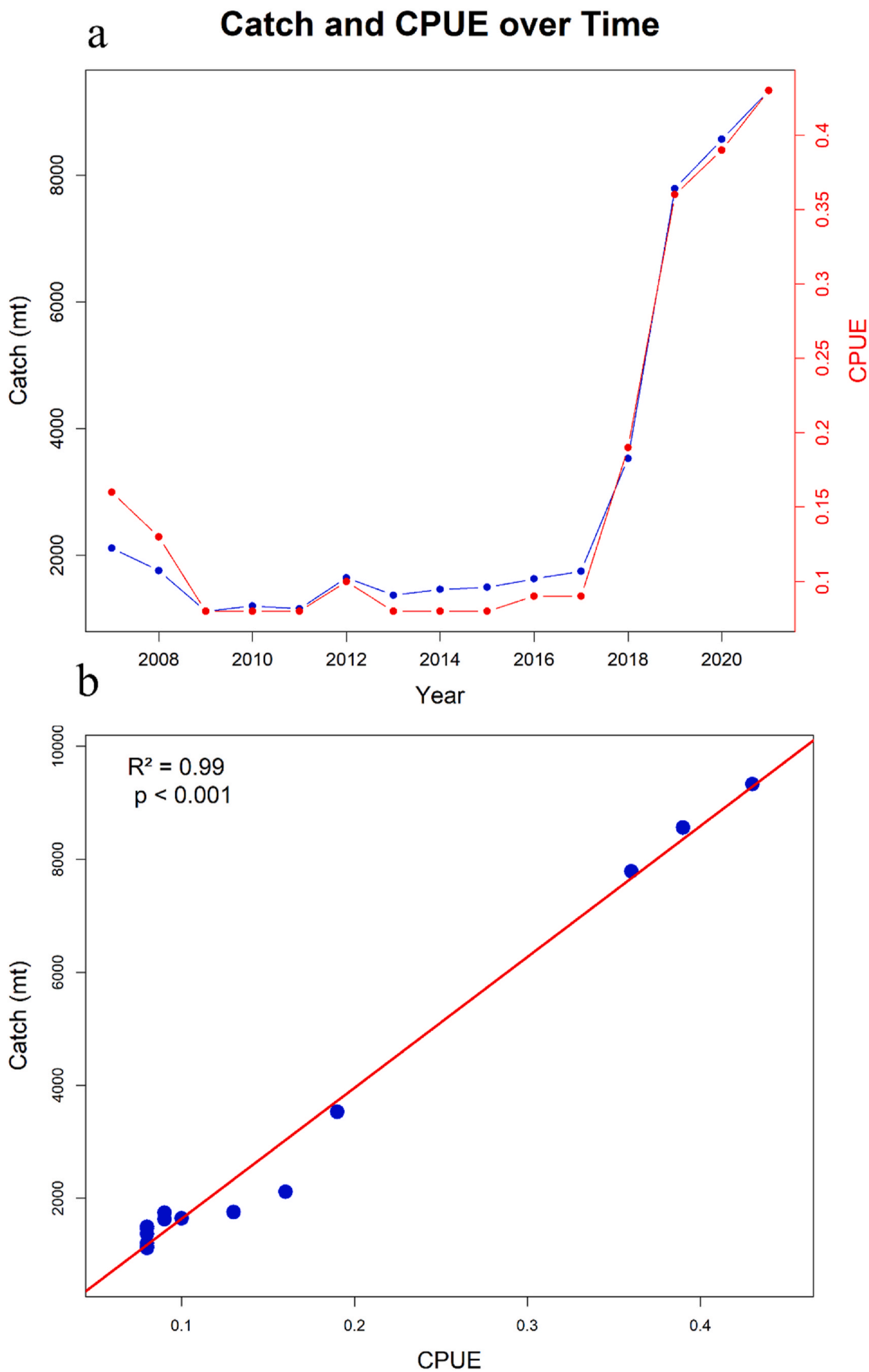

Fig. 3. Catch and effort date series of jellyfish fishery in the Pakistan from 2007 to 2021. The catch is weight in metric tons (mt) and efforts representing the number of fishing boats (a). The annual jellyfish catch and CPUE is highly correlated as $R^2 = 0.987$, $p > 0.001$ (b).

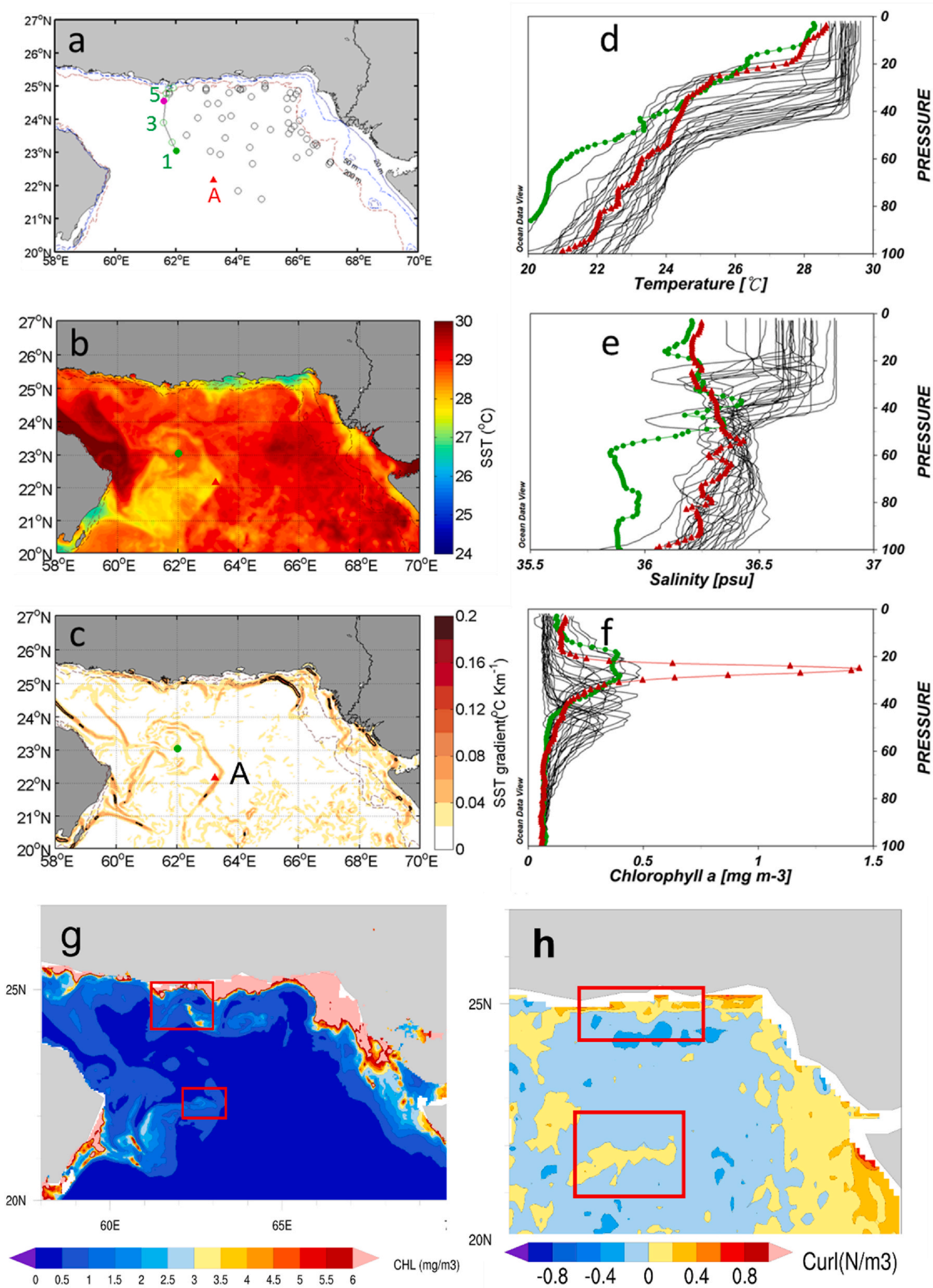

Fig. 4. Locations of the hydro-stations conducted during the survey (a). The red triangle represents station A, surveyed on October 19, while the green dots and circles represent stations 1–7, surveyed on October 26–27, 2010. The pink dot represents the high fish catch on October 27, 2010. Daily SST (b), and SST GM (c), and Chl-a (g), and SWC (h) map on October 19, 2010. The SST GM stronger than 0.06 °C km^{-1} was indicated by black contours. The Vertical profile of temperature (d), salinity (e), and Chlorophyll-a concentration (f) from the offshore hydro-stations. The red triangle and green dot represent station A and 1. (The satellite data was presented using MATLAB v.R2020a and *in-situ* observations were plotted using open-source software: Ocean Data View.v.4 (ODV). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

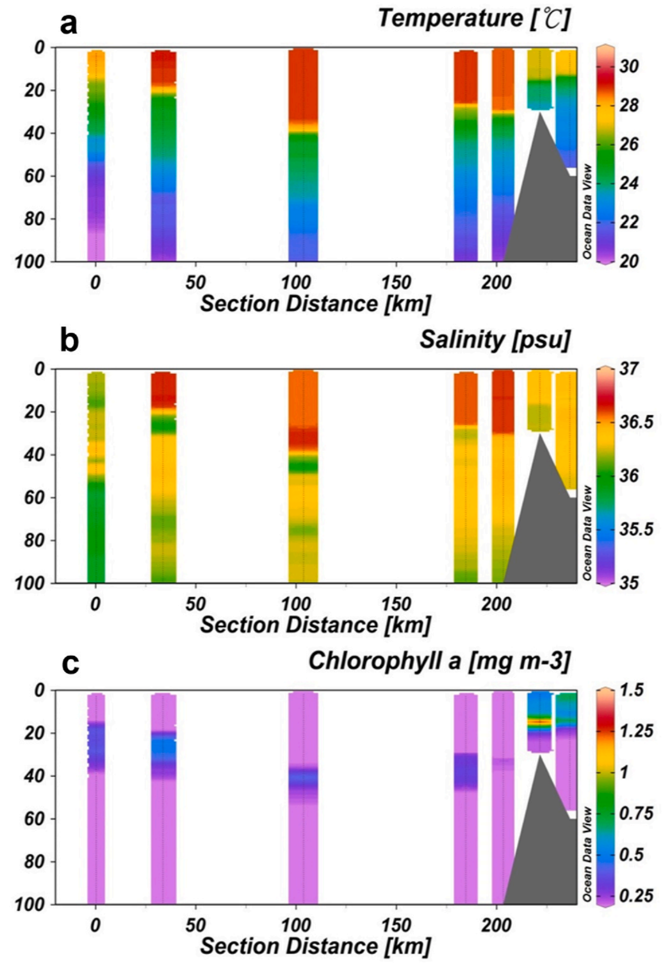

Fig. 5. Vertical profiles of temperature (a), salinity (b), and Chl-a (c) which were measured at stations 1–7 on October 26–27, 2010.

primary productivity (Vipin et al., 2015; Ye et al., 2017; Kalhoro et al., 2024c). This study corroborates those findings, showing consistently high Chl-a concentrations in the upper layers near or within SST fronts areas compared to adjacent waters (Fig. 4a and b and Fig. 5). Case 1 (October 19, 2010), the vertical profile from station A revealed unusually low SST (~28C) and salinity (36.2 psμ) at the surface, accompanied by a high Chl-a concentration (~1.5 mg/m^3), compared to surrounding waters (<0.5 mg/m^3) (Fig. 4). The SST GM of 0.06 °C km^{-1} indicated strong upwelling that brought nutrient-rich, Chl-a-rich subsurface water to the surface. In case 2 (26–27 October 2010), low temperature and salinities were observed in the upper layers at stations 1 and 6, with significant variations in Chl-a concentration (Fig. 5). The high SST GM (0.097 °C km^{-1}) between stations 5 and 6, along with elevated Chl-a levels, suggests that SST fronts facilitate upwelling and mixing processes that transport nutrient-rich waters to the surface (Fig. 5). This phenomenon highlights the role of SST GM in influencing the distribution and productivity of marine organisms. The upwelling process driven by SST fronts transports nutrients to the surface, boosting productivity in the Arabian Sea (Smitha et al., 2008). Numerous studies have explored the impact of coastal and offshore fronts on increasing Chl-a through mixing and upwelling process (Lee et al., 2015; Jing et al., 2016; Ye et al., 2017).

The highest concentrations of Chl-a typically occur in the subsurface layer, a common feature in open waters (Ye et al., 2013). This upwelling enhances primary productivity, leading to rich fish production and playing a crucial role in the carbon cycle (Hu et al., 2021). At stations A and 6, pronounced SST GM likely caused the uplift od nutrient-rich, cold, low-salinity subsurface waters to the surface. This phenomenon underscores the influence of SST GM on the disruption of water properties and highlight its role in modulating oceanographic conditions. The distribution of fish species is shaped by various oceanographic parameters, including physicochemical and biological factors. Sharp changes in these parameters can significantly impact oceanic phenomena and biological productivity (Laevastu and Hayes, 1981). Features such as upwelling, eddies, and fronts can concentrate phytoplankton, which in turn attracts larger fishes (Royer et al., 2004; Tittensor et al., 2010). Frontogenesis, the dynamic process by which oceanic fronts regions characterized by sharp gradient in temperature, salinity, or nutrient content, are formed and intensified, plays a critical role in marine ecosystems (Belkin and O'Reilly, 2009). Oceanic fronts can be characterized into coastal, shelf, and offshore types, each exerting distinct ecological effects (Yanagi and Koike, 1987). Chl-a and SST are pivotal factors influencing ocean primary productivity, with their variations often governed by water currents, eddies, and fronts (Tang et al., 2002). Research has shown that SST fronts formed through frontogenesis can significantly alter phytoplankton communities, leading to elevated Chl-a concentrations. Additionally, high SWC detected in strong SST front regions along the Balochistan and Sindh coast. This strong SWC pumping will caused the nutrient uplift, generating robust SST fronts that enhance surface Chl-a levels. The freshwater inflow from the Indus River contributes the formation of these SST fronts and promotes upwelling, brining nutrient-rich waters to the surface. The relatively shallow continental shelf off the Balochistan coast (Fig. 1) enhance intense coastal upwelling, leading to increased nutrient levels and Chl-a concentrations compared to other regions. This study clearly demonstrates these phenomena through both *in-situ* and satellite observations. The resulting biogeochemical enrichment enhances prey availability for fish populations, supporting their growth, reproduction, and population dynamics (Vipin et al., 2015; Taylor et al., 2012). The spatial and seasonal distribution of fish is largely driven by food availability (Platt et al., 2003). Sudden changes in water properties due to SST fronts can affect the recruitment of small fish populations (Watanabe, 2009). For instance, at station 6 on October 27, high SST GM (0.097 °C km^{-1}) correlated with elevated Chl-a concentration, leading to a substantial jellyfish catch (>200 kg). This observation indicates that areas with strong SST fronts exhibit high primary productivity, enhancing food availability and support the aggregation of various fish species (Reese et al., 2011; Nieto et al., 2017; Xu et al., 2017).

Jellyfish catch rates increases as the distance to the nearest SST front decreases. This study found the highest catches along the 200 m isobaths off the Balochistan coast. On October 27, a notable increase in jellyfish catch was recorded in offshore waters, likely near a strong SST GM area. An offshore SST front formed on October 26 and weakened over the next two days, possibly explaining the high catch recorded on October 27. While previous research has focused on SST fronts affecting pelagic fish species like tuna and Pacific saury in the Pacific Ocean (Tseng et al., 2014; Nieto et al., 2017; Xu et al., 2017), no focused studies have investigated the impact of SST fronts on jellyfish distribution in northern Arabian Sea. This study identified both coastal and offshore SST fronts in the northern Arabian Sea, with strong SST GM observed along the Sindh and Balochistan coasts (Figs. 4 and 6). This phenomenon is attributed to the freshwater inflow from the Indus River in Sindh and intense upwelling and downwelling along the sharp continental shelf of Balochistan (Figs. 4 and 6). Strong SST GM was identified along the 200 m isobath off the Balochistan coast, while weaker SST GM was observed near the 20 and 50 m isobaths off the Sindh coast during October–November. High jellyfish catches were recorded near station 4, coinciding with a strong SST GM (0.09 °C km^{-1}) (Fig. 6). Similar findings by Tseng et al. (2014), Xu et al. (2017) and Nieto et al. (2017) showed that the highest catches were occur in or near the SST front areas. The high catch was found at nearest distance to SST front area (Xu et al., 2017). The distance between high fish catches locations and the SST fronts ranged from 20 to 70 km (Tseng et al., 2014), with Nieto et al. (2017) noting

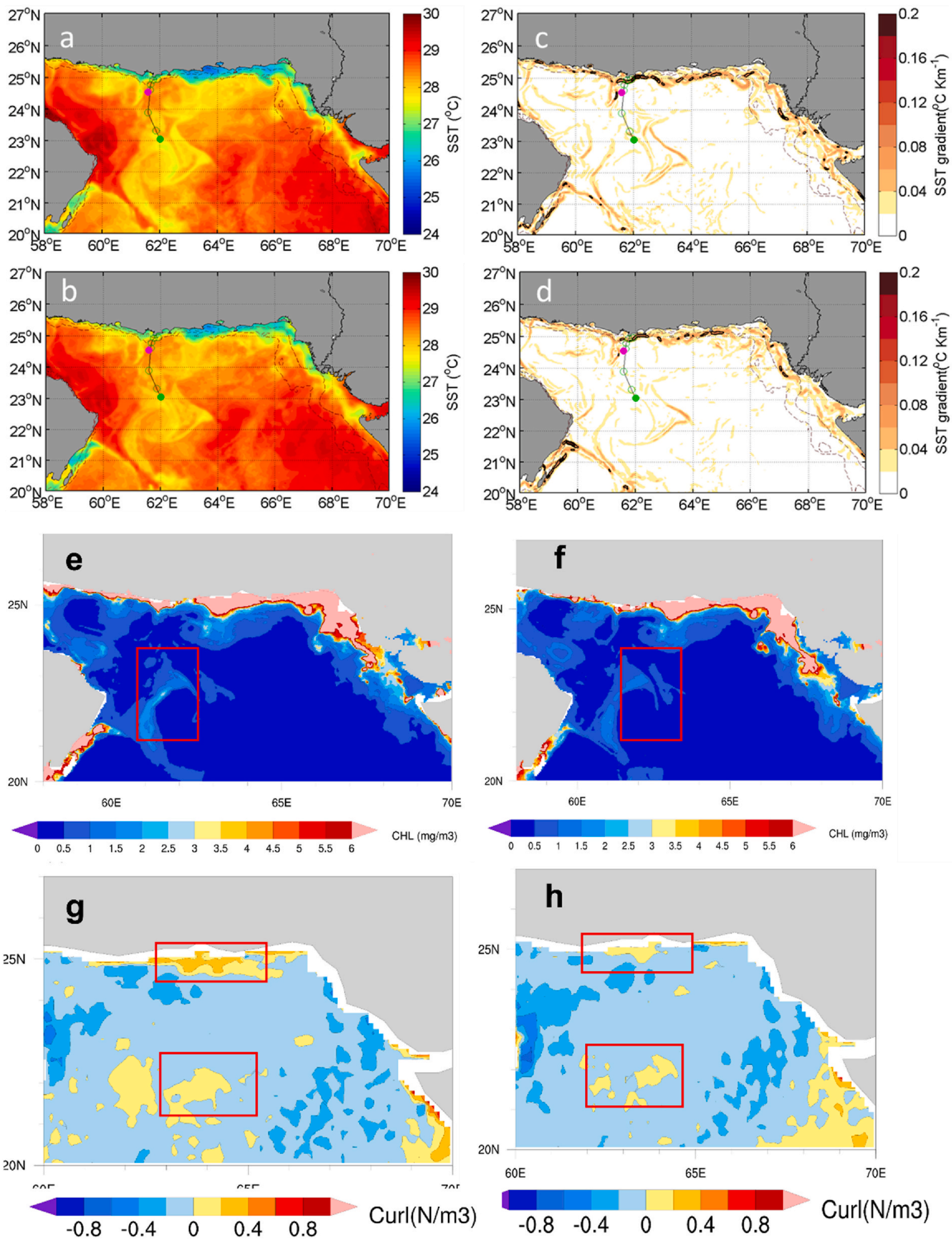

Fig. 6. The daily SST (left panel) and SST GM (right panel) map on October 26 (upper panel) and October 27, 2010 (low panel). The blue dot and circles represent stations 1–7 were conducted on October 26–27, 2010. The pink dot represents the high fish catch on October 27, 2010. The SST GM stronger than 0.06 °C km^{-1} was indicated by black contours. The satellite Chl-a levels on October 26 and 27, also indicates the high concentrations at low SST and strong SST GM area. SWC also indicating the Ekman pumping at strong SST fronts region (The satellite data was presented using MATLAB v.R2020a). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

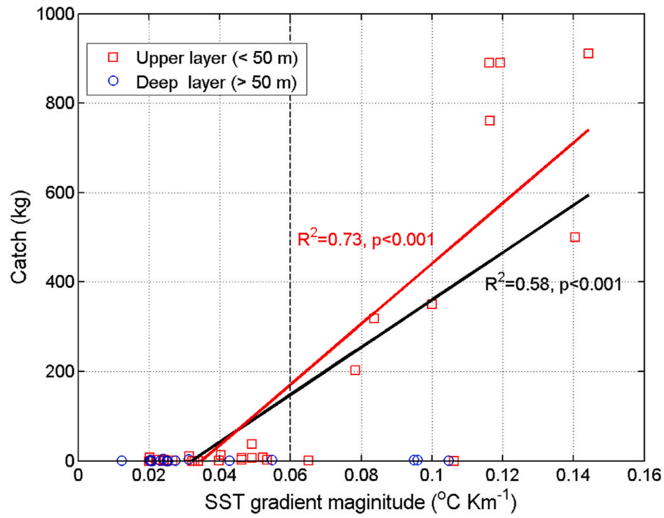

Fig. 7. Scatter plot illustrating the relationship between jellyfish catch and SST GM, with SST GM data from one day prior to the catch. The plot shows a high probability (80 %) of significant jellyfish catches in the upper layer (<50 m depth) where SST GM exceeds 0.06 °C km^{-1}. Red squares represent catches in the upper layer, which show a strong correlation with jellyfish catch ($R^2 = 0.73$, $p > 0.001$). Blue circles denote catches in the deep layer (>50 m), where the overall relationship with SST GM is also significant ($R^2 = 0.58$, $p < 0.001$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

that high tuna catches were found within 50 km of the nearest SST front. Similar patterns have been observed in other regions, such as Arabian Sea, South Atlantic, California current, and China (Ye et al., 2017; Saraceno et al., 2005; Vipin et al., 2015; Kahru et al., 2012). These frontal zones are associated with high nutrient levels and increased Chl-a concentrations (Hu et al., 2003; Greer et al., 2015). Our study corroborates these observations, showing that the highest jellyfish catch occurring approximately 18 km from the SST front. A strong correlation ($R^2 = 0.73$, $p < 0.001$) was observed between SST GM, measured one day prior, and jellyfish catches in the upper layer (<50 m depth) (Fig. 7). To predict potential jellyfish, catch zones, and SST front probability map was created, identifying areas with SST GM > 0.06 °C km^{-1}. Remote sensing studies on SST fronts in various regions, including the Arabian Sea (Vipin et al., 2015), indicate they can alter phytoplankton community structures (Taylor et al., 2012). Thus, frontogenesis is directly linked to the spatial and temporal distribution of jellyfish, as the formation of SST fronts creates environments that foster their growth and population expansion through enhanced biological productivity (Tseng et al., 2014; Alemany et al., 2014). Research showed that SST gradients can enhance Chl-a concentrations, helping aggregate zooplankton and other species, including jellyfish. Satellite-derived fishery zone forecasts have been shown to reduce search time by 25–50% and increase catches compared to non-forecast areas (Laurs et al., 1984). In thus study, high SST GM (0.06 °C km^{-1}) was observed between at 63.5°E, 24.8°N to 65.8°E, 25.0°N off the Balochistan coast, while weaker SST GM was detected off the Sindh coast (Fig. 8).

Fig. 3 demonstrates a significant correlation between jellyfish catch and CPUE ($R^2 = 0.987$, $p > 0.001$), indicating that jellyfish catches increase with fishing effort. The recent increase in jellyfish catches highlight the growing importance of this fishery in Pakistani waters (Fig. 3). The correlation between daily catch data and satellite SST GM suggests that high jellyfish catches in various sites along the Balocistan coast (e.g., Damb, Kalmat, Hingol, Ormara and Pasni) and the Indus River estuary in Sindh are associated with areas of high SST GM off the Balochistan coast and lower SST GM off the Sindh coast (Gul et al., 2015). In the Indian Ocean, high SST correlates with low Chl-a levels, while low SST is associated with higher Chla levels (Tang et al., 2011; Roxy et al., 2016). Since jellyfish are pelagic species that primarily feeding on plankton, which aggregate at frontal zones, the SST fronts uplift nutrient-rich, high-Chl-a waters to the surface, enhancing primary productivity. It is widely recognized that SST is crucial environmental determinant for fish habitats (Tseng et al., 2014). Approximately 80% of high catches occurred in areas with SST GM > 0.06 °C km^{-1} and in the upper layer (<50 m depth). These findings suggest that high jellyfish catch areas are likely located near SST front regions. These frontal zones create high nutrient levels associated with elevated of Chl-a (Hu et al., 2003; Greer et al., 2015). The satellite observation particularly capturing SST with high spatial and temporal resolution, can be utilized to identify zones of significant fishing activity and analyze relationship between oceanographic parameters and fish aggregation (Zainuddin et al., 2006; Tang et al., 2011). It is known that the physical processes associated with frontal zones create highly productive habitats (Munk et al., 2009). Present study identifies a high Chl-a zones associated with elevated SST GM, which attracts fish aggregation. Fishermen have long utilized SST imagery to optimize fishing decisions (Nieto et al., 2017). In light of this study, it is recommended that fishermen focus their activities at or near SST fronts to reduce search time and increase catch compared to non-forecast zones.

6. Conclusion

SST fronts are recognized for their high productivity and prey availability, attracting diverse marine ecosystems. Our study found a significant correlation ($R^2 = 0.73$, $p < 0.001$) between jellyfish catches in the upper layer (<50 m) and SST GM, consistent with previous research that highlights high catches in SST frontal zones. Effective monitoring and management of marine resources require a comprehensive understanding of the entire ecosystem, rather than focusing solely on exploited fish stocks. Traditional vessel-based methods for such studies can be challenging and time-consuming. In contrast, satellite remote sensing provides a valuable alternative, enabling the

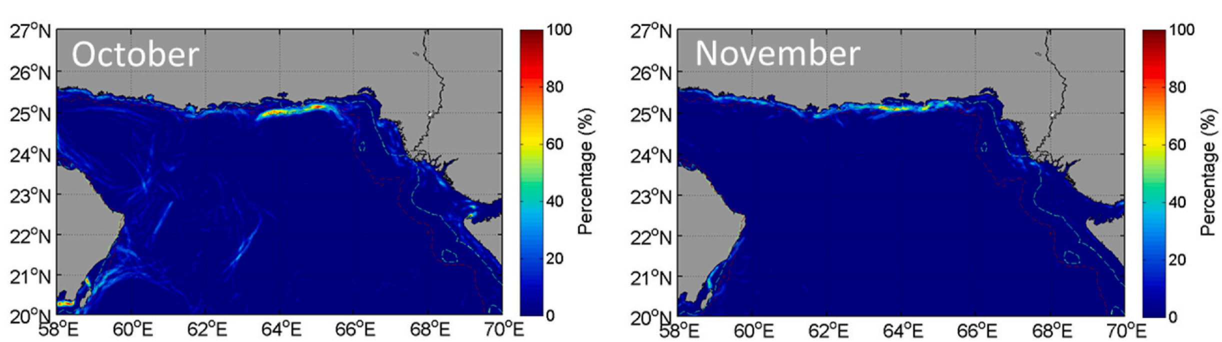

Fig. 8. The occurrence probability of SST fronts in October 2010 (a) and November 2010 (b). The probability is the percentage of SST GM greater than 0.06 °C km^{-1}. The dashed lines showing the isobaths of 50 m and 200 m. (The satellite data was presented using MATLAB v.R2020a).

operational detection of oceanographic parameters that impact fish distribution. This capability helps fishermen reduce search time and increase catch efficiency. In this study, satellite MODIS-Aqua SST data were utilized to observe the distribution of SST fronts and their impact on the spatial and temporal distribution of jellyfish in northern Arabian Sea. SST fronts were primarily identified along the 200 m isobaths off the Balochistan coast, while low SST front patches were observed at the 20 and 50 m isobaths off the Sindh coast during October–November. The results demonstrate that high jellyfish catches were associated with or located near these SST fronts. Based on the environmental conditions described by the *in-situ* CTD and fish catch data, as well as satellite observations, a high probability catch map was developed to guide fishermen, enabling better catches with reduced effort.

While this research was not specifically designed to target SST front areas, nor was it focused solely on SST fronts. Future studies should include synchronous observations of SST, salinity, Chl-a, and nutrients, with CTD stations placed as close as possible to the SST front areas, complemented by satellite data for more detailed analysis of oceanographic processes. Additionally, long-term datasets on fish catches and oceanographic parameters at SST frontal zones would enhance our understanding of the effects of SST fronts on fish distribution. This study suggests that satellite remote sensing can assist fishermen in reducing fuel costs and decreasing the uncertainty regarding their catches. Fishing activities for jellyfish should be concentrated near SST fronts to minimize effort and maximize yield. In addition to existing management recommendations, this study suggest to adopt management strategies to monitor environmental changes. Promote eco-friendly fishing practices that could reduce bycatch and habitat degradation. Engage local fishermen in decision-making enhance compliance and effectiveness. Fostering research partnerships on climate change impacts will inform proactive measures for long-term sustainability in fisheries. Furthermore, it is recommended that government organizations establish a fisheries advisory board to provide fishermen with guidance based on satellite data, promoting better fishery conservation and management. Collaboration between research institutions and government agencies is crucial for a comprehensive understanding and effective management of the fishery sector.

CRediT authorship contribution statement

Muhsan Ali Kalhoro: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **HaiJun Ye:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Chunli Liu:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Lixin Zhu:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **Zhenlin Liang:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Data curation. **DanLing Tang:** Writing – review & editing, Validation, Software, Funding acquisition, Formal analysis, Data curation.

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Declaration of competing interest

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

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Data availability

Data will be made available on request.

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